First published January 1992

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The National Library of Australia Cataloguing-in-Publication data:

Forestier, A.M. (Anthony Marc), 1959-
Into the Fourth Dimension: An ADF Guide to Space.

Bibliography.
ISBN 0 642 17080 0.

1. Astronautics, Military - Australia - Handbooks, manuals, etc.
I. Australia. Royal Australian Air Force. Air Power Studies Centre.
II. Title. (Series: Fellowship paper (Australia. Royal Australian Air Force. Air Power Studies Centre);2).

358.8

ISSN 1037-7077

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ACKNOWLEDGEMENTS

I would like to express my grateful thanks to those people from the defence, government, scientific, industrial and academic communities who assisted me in the research and preparation of this book. There are too many to name individually, but your contributions were of enormous benefit in broadening my understanding of space, and most importantly, of space in Australia.

Particular thanks must go to Squadron Leader Wayne Gale, my Air Power Studies Centre colleague in space, for his assistance throughout 1991: and also to Squadron Leader Kev Davey for his work in thoroughly proof reading my early draft.

Finally, thanks to my wife, Anne, for your tolerance, assistance and support throughout what was a very demanding year.

INTO THE FOURTH DIMENSION:

AN ADF GUIDE TO SPACE

SQUADRON LEADER A.M. FORESTIER

AIR POWER STUDIES CENTRE
ROYAL AUSTRALIAN AIR FORCE

1991

TABLE OF CONTENTS

CONTENTS **PAGE**

CHAPTER ONE: INTRODUCTION

CHAPTER TWO: THE SPACE ENVIRONMENT

TABLE OF CONTENTS

CONTENTS **PAGE**

CHAPTER THREE: ORBIT AND LAUNCH MECHANICS

TABLE OF CONTENTS

CONTENTS **PAGE**

TABLE OF CONTENTS

CONTENTS **PAGE**

CHAPTER FOUR: SATELLITE OPERATIONS

CHAPTER FIVE: SENSORS FOR RECONNAISSANCE AND SURVEILLANCE

TABLE OF CONTENTS

CONTENTS **PAGE**

TABLE OF CONTENTS

CONTENTS **PAGE**

CHAPTER SIX: REMOTE SENSING

CHAPTER SEVEN: COMMUNICATIONS

TABLE OF CONTENTS

CONTENTS **PAGE**

CHAPTER EIGHT: NAVIGATION

TABLE OF CONTENTS

CHAPTER NINE: SPACE SYSTEM VULNERABILITY

TABLE OF CONTENTS

CONTENTS **PAGE**

ANNEXES

LIST OF FIGURES

FIGURE **PAGE**

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

TABLE **PAGE**

CHAPTER EIGHT

CHAPTER NINE

GLOSSARY

2D	Two Dimensional
2DRMS	Two Dimensional Root Mean Square
3D	Three Dimensional

A

A	Amperes
ABM	Anti-Ballistic Missile
AC	Alternating Current
ACOPS	Assistant Chief of Defence Force Operations
ACRES	Australian Centre for Remote Sensing
ADF	Australian Defence Force
ADFA	Australian Defence Force Academy
ADMI	Area of Direct Military Interest
AEW&C	Airborne Early Warning And Control
AFB	Air Force Base (US)
AGPS	Australian Government Publishing Service
AIDC	Australian Industry Development Corporation
ALIC	Australian Land Information Council
ANU	Australian National University
AOCS	Attitude and Orbit Control Sub-System
ARIS	Australian Resource Information System
ARM	Australian Regional McIDAS
AS	Anti Spoofing
ASAT	Anti-Satellite
ASB	Australian Space Board
ASO	Australian Space Office
ASW	Anti-Submarine Warfare
AURISA	Australasian Urban and Regional Information Systems Association
AUSLIG	Australian Land Information Group
AVHRR	Advanced Very High Resolution Radiometer

B

BDA	Bomb Damage Assessment
BMEWS	Ballistic Missile Early Warning System
BRIAN	Barrier Reef Imagery ANalysis

C

C	(computer programming language)
C	Temperature measured in °Celsius (0°C = 273°K)
C^3	Command, Control and Communications
C^3I	Command, Control, Communications and Intelligence
CAD	Computer Aided Drafting
CCD	Charge-Coupled Device
CCT	Computer-Compatible Tape
CIA	Central Intelligence Agency (US)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CW	Continuous Wave
CZCS	Coastal Zone Colour Scanner

GLOSSARY

D

DASETT	Department of the Arts, Sport, the Environment, Tourism and Territories
DBMS	Data Base Management System
DC	Direct Current
DCCP	Defence Communications Corporate Plan
dB	decibels
dBW	decibel Watts
DEFAUSSAT	Defence AUSSAT Project
DEM	Digital Elevation Model
DGI	Department of Geographic Information (Queensland)
DGMSC	Director General Military Strategy and Concepts, HQADF
DGPS	Differential GPS
DISCON	Defence Integrated Secure Communications Network
DMA	Defence Mapping Agency (US)
DMCN	Defence Mobile Communications Network
DOA 87	The Defence of Australia 1987
DoD	Department of Defence
DSCS	Defence Satellite Communications System (US)
DSTO	Defence Science and Technology Organisation

E

ECCM	Electronic Counter-Countermeasures
ECM	Electronic Countermeasures
EDE	Engineering Development Establishment
EHF	Extremely High Frequency
EIRP	Effective Isotropic Radiated Power
ELF	Extremely Low Frequency
ELINT	Electronic Intelligence
EM	Electromagnetic
EMP	Electromagnetic Pulse
EO	Electro-Optic
EPS	Electrical Power Sub-System
ERDAS	Earth Resources Data Analysis Systems
ERIN	Environmental Resources Information Network
ERS	Earth Resources Satellite
ERTS	Earth Resources Technology Satellite
ESA	European Space Agency
ESM	Electronic Support Measures
ESRI	Environmental Systems Research Institute
EW	Electronic Warfare

F

FLIR	Forward Looking Infrared
FLTSATCOM	Fleet Satellite Communications (US)
FORTRAN	(computer programming language)
FOV	Field of View
FPA	Focal Plane Array

GLOSSARY

G

GARP	Global Atmospheric Research Program
GBE	Government Business Enterprise
GEO	Geosynchronous Earth Orbit
GIS	Geographic Information System
GMS	Geostationary Meteorological Satellite
GOES	Geostationary Observational Environmental Satellite
GPS	Global Positioning System
GPSPO	GPS Project Office
GPSUE	GPS User Equipment

H

HEMP	High Altitude EMP
HF	High Frequency
HQADF	Headquarters Australian Defence Force

I

ICBM	Inter-Continental Ballistic Missile
IDIMS	Interactive Digital Image Manipulation System
IFOV	Instantaneous Field of View
INMARSAT	International Maritime Satellite
IONDS	Integrated Operational Nuclear Detection System
IR	Infrared
IS	Information System

J

JERS	Japanese Earth Resources Satellite
JORN	Jindalee Operational Radar Network

K

K	Temperature measured in °Kelvin (0°K = -273°C)

L

LEO	Low Earth Orbit
LF	Low Frequency
LIDAR	LIght Detection And Ranging
LIS	Land Information System
LM2E	Long March 2E (Chinese three-stage launch vehicle)
LOS	Line of Sight

M

MC&G	Mapping, Charting And Geodesy
McIDAS	Man-computer Interactive Data Access System
MF	Medium Frequency
MHD	Magnetohydrodynamic
MILSATCOM	Military Satellite Communications Project
MOS	Marine Observation Satellite
MSS	Multi-Spectral Scanner

GLOSSARY

N

NASA	National Aeronautical and Space Administration (US)
NASIS	North-east Australia Satellite Imagery System
NAVSTAR	NAVigation Satellite Timing And Ranging
NOAA	National Oceanic and Atmospheric Administration (US)
NORAD	North American Aerospace Defence Command
NRIC	National Resource Information Centre
NUDET	Nuclear Detonation
NWS	Naval Weather Station

O

OPM	Orthophoto Map
OTC	Overseas Telecommunications
OTHR	Over-the-Horizon Radar

P

P	(SPOT panchromatic sensor)
PARAKEET	ARA long haul tactical communications project
PC	Personal Computer
PGM	Precision Guided Munition
pixel	picture element

R

R&D	Research and Development
RADAR	RAdio Detection And Ranging
RASVY	Royal Australian Survey Corps
RAVEN	ARA single channel combat radio net
RCS	Radar Cross Section
RMS	Root Mean Square
RORSAT	Radar Ocean Reconnaissance Satellite
RPSI	Region of Primary Strategic Interest
RT	Rise Time

GLOSSARY

S

SA	Selective Availability
SALT	Strategic Arms Limitation Treaty
SAM	Selective Availability Management
SAR	Search and Rescue
SAR	Synthetic Aperture Radar
SARSAT	Search And Rescue SATellite
SATCOM	Satellite Communication
SBR	Space-Based Radar
SDI	Strategic Defence Initiative
SEP	Spherical Error Probable
SHF	Super High Frequency
SLAR	Sideways Looking Airborne Radar
SLBM	Submarine-Launched Ballistic Missile
SPANS	SPatial ANalysis System
SPOT	Systeme Probatoire de l'Observation de la Terre (France)
SS	Structural Sub-System
STS	Space Transportation System (or Space Shuttle).
SWIR	Shortwave Infrared

T

TCS	Thermal Control Sub-System
TDRSS	Tracking and Data Relay Satellite System
TIGRIS	Topologically Integrated Geographic and Resource
TINES	Transportable Iterra Network Earth Station
TIR	Thermal Infrared
TM	Thematic Mapper
TOVS	TIROS Operational Vertical Sounder
TT&C	Telemetry, Tracking and Command
TTFF	Time to First Fix

U

UE	User Equipment
UHF	Ultra High Frequency
UN	United Nations
USAF	United States Air Force
USN	United States Navy
UV	Ultra-Violet

V

V	Volts
VHF	Very High Frequency
VLF	Very Low Frequency
VNIR	Visible and Near Infrared

W

WGS	World Geodetic Standard

X

XS	(SPOT Multi-spectral sensor)

CHAPTER ONE

INTRODUCTION

On 4 October 1957 the Soviet Union successfully launched the 84 kg Sputnik[1] 1 into a low earth orbit. The Soviets had beaten the US into space. Whilst Sputnik 1 had no military value, the effect its launch caused in the US was profound, both within the scientific community and the general public. Edward Teller, father of the H-bomb, declared on national television that the US had lost *'a battle more important than Pearl Harbor'*[2]. The US responded to the challenge by launching Explorer 1 into low earth orbit on 31 January 1958. The 'Space Race' had begun.

Space-based systems have developed with enormous rapidity since the early years; in number, complexity and cost. The technology has been embraced internationally by military, scientific and commercial users. The exploitation of space by the super powers created a new dimension of military activity. Space is often referred to as the 'fourth dimension' of warfare, characterised by its own doctrines, strategies and operations.

An ADF Guide to Space

Ongoing ADF management of current space-based communications and navigation programmes, as well as future investigations into the applicability of other space-based technologies, will require an increasing number of Defence personnel to become familiar with the theory and practice of space operations. Whilst there are many texts available on space and space-related subjects, most tend to be overly technical for those requiring a broad overview; and most are written from a US perspective. This guide seeks to address those deficiencies, and in doing so, provide a useful tool for the Defence professional requiring a general background in space operations. This book is not written to satisfy the 'expert' in space, but for those seeking to broaden their horizons in the subject.

The aim of this book is not to catalogue space-based systems, but rather to provide an educative overview covering space, space operations and space applications. Exceptions to this general approach are made where the ADF is procuring a specific system or capability, for example: the GPS NAVSTAR space-based navigation system, or the MILSATCOM satellite communications project. Such systems and capabilities will be presented in detail, as they directly impact ADF operations.

Layout of the Guide

This book contains nine chapters. This first chapter covers military space operations in overview, and positions space relative to the ADF's current strategic guidance. Space law will also be briefly discussed. The next eight chapters present specific subjects from a technical rather than strategic perspective. They can be separated into three functional groups: space and space operations, specific space-based missions, and vulnerability.

Chapters Two to Five cover the basics of space and space operations. Chapter Two discusses the space environment, what it is, where it starts, what it contains and the hazards the environment presents to space operations. Orbital and launch mechanics are covered in Chapter Three, and satellite operations in Chapter Four. Chapter Five discusses those sensor

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[1] Sputnik means 'travelling companion' in Russian.

[2] Richelson, J., *America's Secret Eyes in Space*, Harper and Row, New York, 1990, Chapter 1.

technologies applicable to space-based surveillance and reconnaissance systems, but does not propose a specific system for the ADF. Consideration of that question is well covered by Gale.[3]

Chapters Six to Eight discuss those space-based force enhancement missions of interest to the ADF. These respectively include remote sensing, communications and navigation.

The final chapter, Chapter Nine, deals with the important subject of space system vulnerability. There is no concluding chapter to this work. Chapter One provides a broad strategic outline. Each of the following chapters is technical in nature and is essentially self contained.

SPACE AND THE ADF[4]

> *'Australia has been slow to accept the military use of space and its untapped potential; indeed, the issue of space was not even addressed in the 1987 Defence White Paper. Space, as the newest dimension of military warfare, must overcome political, economic, and organisational prejudices before acceptance as a unique military dimension with its own unique policy, doctrine and strategy. Space can provide a very positive contribution to defence throughout the range of credible contingencies. Thus, to ensure Australia is provided with the best defence capability within budgetary constraints, the ADF must recognise the importance of the dimension of space. Accordingly, the future challenge for the ADF is to formulate a viable military space policy and doctrine that provides a vision for the future employment, organisation and integration of space assets into the ADF in order to provide the optimum defence structure for Australia's continued security.'*[5]

The aim of this section is to present the various military space missions and their applicability to Australia and the ADF. It will also position space in relation to Australia's strategic position, current strategic guidance, and the ADF's force structure. This section will place the theoretical work of the following chapters into strategic perspective.

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[3] Gale, SQNLDR W., *The Potential of Satellites for Wide Area Surveillance of Australia*, Air Power Studies Centre, RAAF Fairbairn, 1991.

[4] Drover, WGCDR K., *Space Power: Military Imperatives in Australia's Environment*, USAF Air University, Maxwell Air Force Base, Alabama, 1989, passim.

[5] ibid, p iii.

MILITARY SPACE MISSIONS

Generically, military space missions fall into four functional categories: space support, force enhancement, space control and force application. These divisions are illustrated in Figure 1.1.

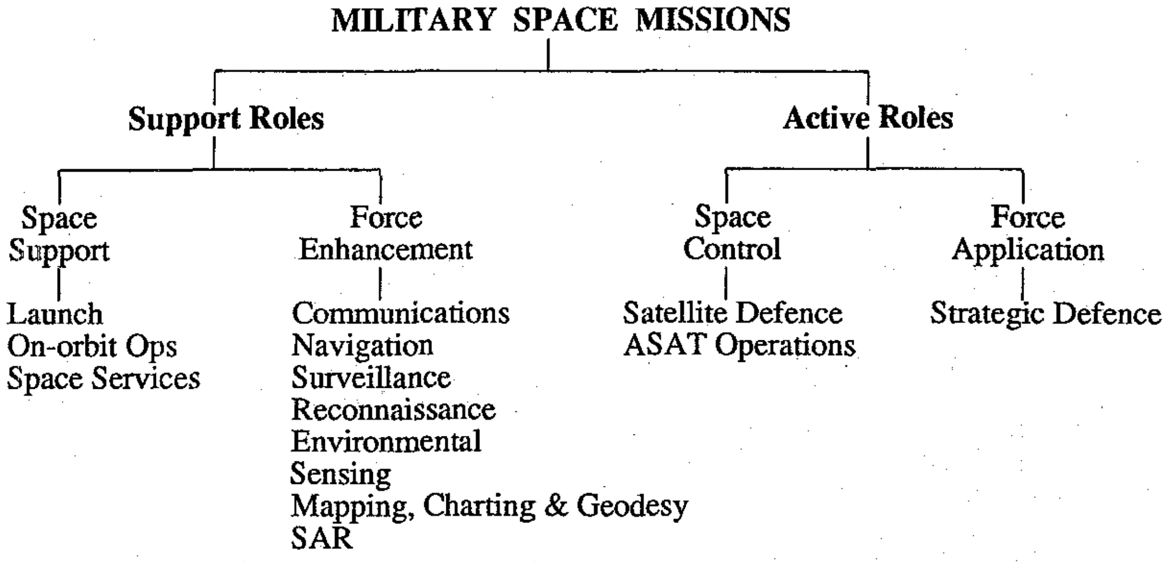

Figure 1.1. Military Space Missions[6]

Support Roles. Military space support roles include:

a. Space Support. Space support includes functions required to deploy and maintain military equipment in space. These include launch operations, on-orbit satellite operations, R&D and the command and control infrastructure to support such activities.

b. Force Enhancement. Force enhancement functions are *'those space related support operations conducted to improve the efficiency and effectiveness of both terrestrial and space-based forces'*[7]. Figure 1.1 lists these functions.

Active Roles. Active (or war-fighting) space roles include:

a. Space Control. Space control consists of *'operations that ensure freedom of action in space for friendly forces while limiting or denying enemy freedom of action'*[8]. Space control operations include: satellite defence, which requires military space systems to be hardened and operated in such a way that their survivability is ensured; and anti-satellite (ASAT) operations.

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[6] Adapted from: Drover, op cit, p 29.
[7] loc cit.
[8] ibid, p 30.

b. Force Application. Force application includes strategic defence through combat operations conducted from space. Such operations require the development of effective and reliable space-based laser, particle beam and kinetic-kill weapons.

Space Applications for Australia and the ADF

The Australian Government has consistently opposed the active military use of space. It has not supported the US Strategic Defence Initiative (SDI) or its Russian[9] counterpart, and has declined to participate in SDI research. It has used *'political and diplomatic initiatives as well as many public statements to actively encourage the use of space only for peaceful purposes'*[10]. Given the Government's stated position, the active use of space is not in contention for the ADF. Another reason is cost. The active use of space is extremely expensive. It requires that a nation be able to undertake leading edge R&D in a wide variety of fields and demands a considerable space support infrastructure. For these reasons, the active use of space has been the province of the superpowers, although the disintegration of the USSR in late 1991 could well mean that the US will be the only country capable of undertaking such activities in the future.

From Australia's perspective, its relatively benign geo-political environment, limited budget, and its government's stated opposition to either conducting or supporting war in space preclude the ADF from undertaking active space roles. However, this is not to say consideration of such activities should be removed from academic and military debate. Future circumstance may require a realignment of strategic thought.

It is in the support role that Australia can use space to its advantage. Australia's scientific, commercial and defence communities can each exploit the force enhancement roles listed in Figure 1.1. These communities now realise that if Australia is to develop a cost effective and internationally competitive space industry, it must do so on a co-operative basis. For example, the ADF is already making use of Australian civilian space communications infrastructure through the DEFAUSSAT project[11]. Given the development of the appropriate indigenous infrastructure and capability, there is scope in the future to combine ADF surveillance and reconnaissance missions with commercial and scientific remote sensing operations. Each of these missions uses similar space-borne sensors and supporting infrastructure. However, if Defence is to make use of shared space systems, then consideration must be given to hardening those systems to military standards.

There is no denying that space is an expensive business, and no single end user could hope to justify an indigenous space capability. It is on a national co-operative basis that Australia must consider a move into the international space industry. Such an industry would allow Australia to participate in the burgeoning international aerospace industry, currently estimated to be worth US$60 billion per annum[12].

AUSTRALIA'S STRATEGIC SITUATION

Strategic Defence Policy

Australia's strategic defence policy is detailed in the 1987 White Paper *'The Defence of Australia'* (DOA 87). The basic tenant of the policy is defence self-reliance within a framework of alliances and regional commitments. The White Paper states that self-reliance can be best achieved through a strategy of defence in depth. Defence in depth implies the maintenance of *'the optimum mix of forces operating synergistically to provide the capability to*

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[9] Since the disintegration of the USSR, the status of its space programme is extremely uncertain. As Russia always held the controlling hand over the USSR's space systems, the USSR's space capability has been conferred to Russia for the purposes of this book.

[10] ibid, p 34.

[11] See Chapter Seven.

[12] Harris, G., *Remote Sensing for Global Change*, presentation at CSIRO Headquarters, Canberra, 14 August 1991.

defeat any credible levels of threat in Australia's Area of Direct Military Interest (ADMI)[13]. *Of fundamental importance to this strategy is the control of the air-sea gap that separates the island continent of Australia from all other nations.'*[14]

Australia's Strategic Problems

Australia's ADMI, with an area of 35 million square kilometres, covers almost 10% of the Earth's surface. Continental Australia itself covers an area of 7.62 million square kilometres, yet Australia's population is only 17 million people. The relatively small size of the population limits the nation's ability to generate wealth, which constrains the development of national infrastructure and, *ipso facto*, the size of the defence force. These features make Australia's geo-strategic position unique, and have had a major impact on the formulation of Australia's defence policy and force structure.

Australia's geo-strategic features are two-edged from a defence perspective. Continental Australia's isolation is beneficial in that it forces any potential aggressor to traverse an air or sea approach (providing Australia with useful early warning if these approaches are well surveilled). The aggressor must then operate in a physically hostile environment whilst maintaining long lines of supply, all the while being harassed by Australian forces. Such a scenario cannot be appealing to a potential aggressor.

On the other hand, these same features place a heavy burden on the ADF to maintain a capable, mobile mix of force elements able to meet an aggressor preferably in the air-sea gap; or if that is not possible, on continental Australia. Additionally, the ADF must be able to complete operations on Australia's outlying territories, such as Cocos and Christmas Islands. Surveillance, reconnaissance and intelligence are of paramount importance in ensuring that aggressive build-ups or incursions are detected as early as possible. The ADF's force elements must be positioned to meet any potential threat on favourable terms. The ADF's limited capacity to wage war means that any incursion must be met with an appropriate amount of force, both structurally and temporally: too little and valuable defence assets will be lost to no benefit; too much and valuable defence assets will be needlessly be drawn away from other important areas, leaving them under defended. Given such a scenario, only a highly developed surveillance, reconnaissance, intelligence and information distribution network can provide and fuse data into the information necessary for accurate force structure judgements to be reliably made.

The Need For Force Multipliers

The limited resources of the ADF must be structured to achieve maximum operational efficiencies over the entire ADMI. Force multipliers are essential to *'expand the effectiveness of man and machine without increasing the numbers of either; in that way lies economy'* (Lord Trenchard)[15]. Force multipliers range in extent from the employment of simple but effective tactics to the mastery and assimilation of complex technologies.

The ADF is already using, or planning to use, force multiplying technologies. Examples include: improved communication, command and control and intelligence facilities (C^3I); the Boeing 707's air-to-air refuelling capability; precision guided munitions (PGMs) for the F111, F/A-18 and P3C; the Jindalee Operational Radar Network (JORN); airborne early warning and control aircraft (AEW&C); and so on. However, one important force multiplier is not mentioned by the White Paper, except as a medium for communications and navigation, and that is space. Nor is it mentioned in the *'Force Structure Review 1991'* except for the comment

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[13] The ADMI includes *'Australia, its territories and proximate ocean areas, Indonesia, Papua New Guinea, New Zealand and other nearby countries of the South-West Pacific'*. *The Defence of Australia 1987*, Department of Defence, AGPS, Canberra, 1987, p 2.

[14] Drover, op cit, p 9.

[15] Mason, AVM R., *Current Air Power Developments: A European View*, speech delivered at the *Conference on Air Power in the Defence of Australia*, Canberra, 14-18 July 1986: quoted in, Drover, op cit, p 14.

'Defence will continue to monitor developments in space-based surveillance technology, which has advanced rapidly in recent years.'[16].

Space as a Force Multiplier

The force multiplication capabilities offered by space systems are well recognised by the US Space Command:

> *'Using space systems, whether for communications, reconnaissance, surveillance, environmental monitoring, tactical warning or navigation provides a force multiplier for tactical, operational and strategic forces throughout the spectrum of conflict. Space-based sensors serve as an integral part of the early warning and attack assessment structure....'*[17].

The performance of US space assets during the 1990/91 Gulf War vindicated this statement in a most dramatic and conclusive way. Space assets were pervasive; Coalition forces used them extensively for: inter and intra-theatre communications; navigation; intelligence assessment, including bomb damage assessment (BDA); targeting; mapping, charting and geodesy (MC&G); and meteorological services. It was interesting to note the use the Coalition forces made of Western civilian space assets: these were 'drafted' to contribute to the communications (INMARSAT), reconnaissance (SPOT and Landsat) and MC&G (Landsat) missions. The ADF could easily and cost effectively employ these same civilian assets for similar purposes, provided that full or partial ownership of the assets by foreign commercial concerns is strategically acceptable. Alternatively, Australia could develop its own national joint space infrastructure.

Space has the potential to provide an efficient means of surveilling the enormous area of the ADMI.[18] A satellite in low earth orbit can cover a north south swath of the ADMI in less than 15 minutes.[19] A constellation of such satellites could provide regular surveillance of the entire area. The intelligence derived from the data gathered by such a constellation would improve the ADF's ability to concentrate force temporally, spatially and structurally. Additionally, space recognises no physical boundaries. Space systems provide the capacity to gather intelligence from areas inaccessible to other platforms. This unique ability can be used to provide warning of aggressive military build-ups or internal instabilities. Reliable surveillance is in itself a useful deterrent to such build-ups, and the information obtained can be used to prepare and pre-position appropriate force elements to meet the potential threat. Overall, space-based surveillance could make a proactive positive contribution to regional stability.

Space-based sensors also provide a means of obtaining the strategic intelligence data so essential to Australia. Such data can be obtained from allies, from commercial civilian remote sensing agencies[20], or Australia could develop its own indigenous capability.

Use of Space in Various Levels of Conflict

DOA 87 defines three levels of threat against Australia, short of global war. These are low level conflict, escalated low level conflict and more substantial conflict. Low level conflict includes; *'The use of military force to harass remote settlements and other targets in northern Australia, off-shore territories and resource assets, and shipping in proximate areas, ... to force political concessions over some disputed issue.'*[21]. Escalated low level conflict is similar to low level conflict, however raids would increase in frequency and intensity, with enemy forces

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[16] *Force Structure Review*, Department of Defence, Canberra, May 1991, p 11.

[17] *Space Systems Handbook for Staff Planners and Operators*, US Space Command Centre for Aerospace Analysis, January 1988, p 1: quoted in, Drover, op cit, p 16.

[18] Gale, op cit, Chapter Seven.

[19] The width of this swath is not defined, as it dependent on the characteristics of the particular sensor and the mechanics of the particular orbit.

[20] See Chapter Six.

[21] *The Defence of Australia 1987*, op cit, p 24.

being prepared to confront Australian forces directly. More substantial conflict effectively means invasion of the Australian continent or outlying territories.

Space-based support assets could be used to support ADF operations both in peacetime and during each of the contingency levels defined by DOA 87. Table 1.1 summarises how the ADF could employ space to support a range of contingencies. The list is by no means exhaustive.

Table 1.1. Space Support For Credible Contingencies[22]

Condition	Possible Situation	Potential Space Support
Peacetime	Forward deployed forces in Malaysia, Cocos Is., PNG and SW Pacific	Strategic warning, Communications, Navigation, Weather, Surveillance, MC&G
Increased Tension or Special Ops	Potential for limited military operations	As above, plus near real-time reconnaissance and C^3I
Low Level Conflict	Enemy forces harassing shipping, remote settlements and outlying territories	As above, plus global communications, weather and navigation
Escalated Low Level Conflict	Increased sea & air harassment, frequent intense raids, direct confrontation	As above, but increased emphasis on near real-time reconnaissance
More Substantial Conflict	Attempts by enemy to secure lines of approach & invade Australia or territories	All systems at full war capacity

Of course, the support functions listed in the table can be at least partially achieved using conventional assets, but space-based assets do provide advantages over their terrestrial counterparts, both strategically and tactically. Strategically, space assets can provide wide area coverage of both Australia and the enemy's homeland. This is not possible using any other means. Such coverage provides a significant deterrent to enemy action, as well as providing warning time for planning and preparing appropriate counter measures should any such action eventuate. At the tactical level space support assets can provide inter and intra-theatre communications, accurate navigation, updated MC&G products, meteorological information, and strategic and tactical intelligence.

Force Structure Considerations

The preceding discussion does not mean to imply that the ADF should embrace space technologies simply because they exist, nor because they can overtly improve the effectiveness of the Force. The defence dollar is limited, and a real cost benefit must be proven before ***any*** particular technology or system is integrated into the force structure. However, space-based systems must always be considered against, or in conjunction with, their terrestrial counterparts.

For space-based assets to become part of the ADF inventory, trade-offs against other assets which perform similar missions would be necessary. For example, could a space-

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[22] Drover, op cit, p 53.

based reconnaissance system based on developing ***'lightsat'***[23] technologies be used to reduce the required number of AEW&C aircraft? Would a space-based surveillance or reconnaissance system provide a usable, cost effective adjunct to JORN and AEW&C? Space-based surveillance sensors are an excellent way of covering very large areas very quickly. Any detected anomalies can be followed up using terrestrial sensors. This would imply less dependence could be placed on conventional forms of surveillance: in fact, it may be possible for the bulk of strategic surveillance to be done from space whilst a reduced number of terrestrial sensors could be used primarily for tactical surveillance and reconnaissance. How could data from space assets, JORN and AEW&C be synergistically fused to produce a sum greater than the total of its components? These issues are yet to be fully debated in Defence and academic circles.

Space and terrestrial systems differ in their procurement and logistic requirements. For example, the planned number of a particular terrestrial platform can be reduced should budgetary or force structure considerations demand it. This is not the case with the components which make up a space system. Limitations imposed by satellite orbits, sensor technologies and data down-link capacities will dictate a minimum space and terrestrial infrastructure required to support a specific mission. If the mission is to be effective, the minimum requirement cannot be reduced. To go into space demands commitment. These facts have an impact on where space will sit relative to the rest of the ADF's force structure. Once the decision to go into space is taken, it is irrevocable, and other competing elements within the force structure would have to acquiesce to that fact.

SPACE LAW[24]

Under international law, if an act is not specifically prohibited, then within reason, it is permitted. Whilst a number of international agreements and treaties exist on the exploitation of space, there are very few legal restrictions on the use of space for non-aggressive military purposes. Internationally, an 'open skies' approach has been adopted. International law implicitly permits the use of space for military support activities such as surveillance, reconnaissance, navigation, meteorology and communications. It permits the deployment of military space stations; the testing and deployment in earth orbit of non-nuclear, non anti-ballistic missile (ABM) weapons systems; the use of space for individual and collective self-defence or any conceivable activity not specifically constrained or prohibited.

It is important to note that in most instances, treaties are designed to regulate activities between signatories in peace time only. Unless the international agreement clearly states that its terms and provisions apply during times of hostility, or the signatories can deduce this from the agreement's content, they must presume that armed conflict will suspend the provisions of the treaty. Thus, the scope of space activity in times of hostility may broaden considerably.

Briefly stated, the following space activities are prohibited or constrained as indicated:[25]

Multilateral Agreements

a. The appropriation by claim of sovereignty, use or occupation, or by any other means, of any portion of outer space to include the moon and celestial bodies.

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[23] A lightsat is a small uni-mission satellite, with an upper weight limit of approximately 1000 kg. This subdivision may be extended to include ***'smallsats'*** (over 150 kg) and ***'microsats'*** (150 kg or less).

[24] Adapted from: Cochran, C., et al (ed), *Space Handbook*, Air Command and Staff College, Air University, Maxwell Air Force Base, January 1985, pp 15-1 to 15-4.

[25] The restriction on activities listed are derived from multilateral and bilateral agreements. Where treaties are bilateral, and Australia is not a signatory, the author assumes that Australia would be similarly constrained should it ever field military space systems.

b. Threatening to use or actually to use force against the territorial integrity and political independence of another state.

c. Testing nuclear weapons or other nuclear explosive devices, even peaceful nuclear devices.

d. Placing in earth orbit, installing on celestial bodies, or stationing in space in any other manner weapons of mass destruction (generally defined as nuclear, biological or chemical weapons).

e. Building military bases, installations or fortifications on the moon or other celestial bodies.

f. Testing weapons of any kind on the moon or other celestial bodies.

g. Conducting military manoeuvres on the moon or other celestial bodies.

h. Initiating activities that could cause harmful interference with the activities of other states without first consulting those states.

i. Causing harmful contamination of the moon or other celestial bodies.

j. Using environmental modification techniques to destroy, damage or injure another state.

k. Launching space objects without notifying the Secretary-General of the United Nations.

Bilateral Agreements

l. Developing, testing or deploying space-based anti-ballistic missile (ABM) systems or components.

m. Developing future ground based ABM systems based on physical principles other than and including components capable of substituting for conventional ABM interceptor missiles, launchers or radars, without first discussing with Russia possible limitations on such systems.

n. Interfering with Russian national technical means of verification provided such systems are operating in accordance with generally recognised principles of international law and are in fact being used to verify provisions of the ABM treaty, SALT and Threshold Test Ban Treaty.

Table 1.2 lists the international agreements which limit activities in space.

Table 1.2.
International Agreements that Limit Activities in Space[26]

Agreement	*Prohibition/Constraint*
Outer Space Treaty (Cont'd)	A state's space stations, installations, equipment, and vehicles located on the moon may be visited by representatives of other states provided that reasonable advance notice is given and that the visiting state permits reciprocal visits. The purpose of advance notices is to permit consultations over the appropriate timing of the visit so as to ensure the safety of the occupants and that the visit will not interfere with the normal operation of the facility. (Article XII)
Antiballistic Missile (ABM) Treaty and agreed statements thereto (1972)	Treaty between the United States of America and the Union of Soviet Socialist Republics on the limitation of antiballistic missile systems. The United States and the Soviet Union may not develop, test, or deploy space-based ABM systems or components. (Article V) This is a comprehensive ban. It includes currently understood ABM technologies (that is, interceptor missiles) as well as those concepts based on technologies yet to be fully developed or understood (that is, directed energy weapons). The United States and the Soviet Union may not interfere with the national technical means of verification of the other providing that such systems are operating in accordance with generally recognized principles of international law and are used to assure compliance with treaty provisions. (Article XII) A similar provision is contained in the Threshold Test Ban Treaty (Article II) and the SALT II agreement (Article XV). A case presumably could be made that either country was free to interfere with a "national technical means of verification" system that was operating in violation of generally recognized norms of international law <u>or</u> with a reconnaissance system that was not being used to verify treaty compliance—admittedly a difficult distinction to make—whether or not such a system was operating in accordance with the norms of international law. If ground-based ABM systems based on other physical principles and including components capable of substituting for conventional ABM interceptor missiles, launchers, or radars are created in the future, the parties agree to discuss limitations on such systems. (agreed statement D)
Convention on Registration (1974)	Registration of objects launched into outer space. States must notify the UN Secretary General of all objects launched into space and must provide the following information: name of the launching state; date of launch; territory from which the object was launched; a designator or registration number for the object; basic orbital parameters to include nodal period, inclination, apogee, and perigee; and the general function of the object. (Articles II, III, and IV) States must also notify the secretary general when the object is no longer in space. (Article IV)
Environmental Modification Convention (1980)	Convention on the prohibition of military or any other hostile use of environmental modification techniques. States may not use environmental modification techniques to destroy, damage, or injure another state if such usage has widespread (on the order of several hundred square kilometers), long-lasting (a season or more), and severe (serious or significant disruption or harm to human life, natural and economic resources or other assets) effects. Environmental modification techniques are defined as any technique for changing the dynamics, composition, or structure of the earth or outer space through the deliberate manipulation of natural processes. (Article I)

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[26] Cochran, op cit, pp 15-2 to 15-3.

Table 1.2 (continued)
International Agreements that Limit Activities in Space

Agreement	*Prohibition/Constraint*
United Nations Charter (1947)	Does not specifically mention space; however, its provisions are made applicable to outer space by the Outer Space Treaty. Article 2(4) of the Charter prohibits states from threatening to use, or actually using, force against the territorial integrity of political independenece of another state. This prohibition is qualified, however, by Article 51 which recognizes a state's inherent right of individual or collective self-defense in the event of armed attack. Customary international law has expanded this qualification to include a state's right to defend its territorial integrity and political independence against impermissible coercion—a right that in turn has been interpreted by many states, the United States and Soviet Union included, to legitimize "anticipatory" self-defense, or the right to act in self-defense to remove a danger or threat of imminent armed attack. It is this right of "anticipatory" self-defense that the United States and Soviet Union have used to legitimize the development of antisatellite systems.
Limited Test Ban Treaty (1963)	Treaty banning nuclear weapon tests in the atmosphere, in outer space and under-water. States may not conduct nuclear weapon tests or other nuclear explosions (that is, peaceful nuclear explosions) in outer space or assist or encourage others to conduct such tests or explosions. (Article 1)
Outer Space Treaty (1967)	Treaty on principles governing the activities of states in the exploration and use of outer space, including the moon and other celestial bodies. States may not place in earth orbit, install on celestial bodies, or station in space in any other manner weapons of mass destruction (generally defined as nuclear, chemical, and biological). (Article IV) States may not build military bases, installations, and fortifications; test weapons of any kind; or conduct military maneuvers on the moon or other celestial bodies. Celestial bodies are not completely demilitarized, however, because the treaty does not permit the "use of military personnel for scientific research or for any other peaceful purpose" as well as the "use of any equipment or facility necessary for peaceful exploration," which presumably includes military equipment and facilities. (Article IV) If a state plans an activity which could cause potentially harmful interference with the activities of other states, the state is obligated to consult with those states possibly affected prior to initiating the activity. Conversely, if a state believes that an activity by another state may cause potentially harmful interference, it may request consultations. However, there is no requirement that the state planning the activity must agree to consultations. (Article IX) States must carry out their exploration and use of space in such a way as to avoid harmful contamination of the moon or other celestial bodies as well as to avoid the introduction of extraterrestrial matters that could adversely affect the environment of the earth. (Article IX) Astronauts of one state are required to render all possible assistance to astronauts of other states either in outer space or on celestial bodies. (Article V) This requirement presumably refers only to accidents, situations of distress, or other emergencies, and presumably would require the assisting astronauts to provide shelter to the affected astronauts. States are asked to inform the secretary general, the public, and the international scientific community of the nature, locations, and results of any activities they conduct in outer space. This is not an absolute requirement; rather, it is caveated "to the greatest extent feasible and practicable." (Article XI) As might be expected, the details of military activities in space are typically obscured by launching states.

CHAPTER TWO

THE SPACE ENVIRONMENT

To understand the difficulties involved in the design and launch of a space-based system, it is necessary to have a basic understanding of the environment in which these systems operate and the hazards that environment imposes. For the purpose of this book, it is only necessary to consider that portion of interplanetary space that lies between the Earth and the Moon, or ***cislunar space***. Cislunar space comprises the Earth's atmosphere and the adjoining interplanetary space, out to the Moon's average orbital radius at 386,000 km.

THE ATMOSPHERE

The examination of cislunar space logically begins at the Earth's atmosphere, as that is the first obstacle the launch vehicle and payload must breach to gain access to space. The atmosphere surrounds the Earth with layers and mixtures of gases, liquids and solid particles. The product of the Earth's gravitational force and the density of gaseous atmospheric constituents produces a force called ***atmospheric pressure***.[1]

Atmospheric pressure reduces with altitude. This is caused by the Earth's gravitational force decreasing with the inverse square of distance from its centre and the decrease in gas density with altitude. At an altitude of 5.5 km, the atmospheric pressure is half that of sea level. At 11 km, it has halved again. Table 2.1 lists altitude against atmospheric pressure and temperature.

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[1] *Encyclopaedia Brittanica*, 1968, p 702.

Table 2.1. The Standard Atmosphere[2]

Altitude		Temperature		Pressure
km	ft	°K*	°C	mb
0.00	0	288	15	1013
11.02	36,152	217	-56	226
20.06**	65,824	217	-56	55
25.10	82,345	217	-56	25
32.16	105,518	238	-35	9
47.35	155,348	283	10	1
53.44	175,346	283	10	.6
75.90	249,001	197	-76	.02
91.29	299,516	197	-76	.002
128.55	421,745	274	1	.00001
179.95	590,400	669	396	.0000006
314.86***	1,033,003	974	701	.00000001

Notes:
* 0° Kelvin (K) = -273° Celsius (C).
** Top of 1952 ICAO Atmosphere.
*** Top of United States Extension to the Standard Atmosphere.

Regions of the Atmosphere

The atmosphere is divided into four regions, each of which is characterised by its pattern of vertical distribution of temperature. These regions are:

a. the troposphere,

b. the stratosphere,

c. the mesosphere, and

d. the thermosphere.

Figure 2.1 illustrates these regions. The first three of these are termed the ***lower atmosphere***, whilst the last is termed the ***upper atmosphere***. The upper and lower atmospheres are briefly discussed below. As illustrated by Figure 2.1, the atmosphere may also be sub-divided with regard to density. The only density-related division of interest to us is the ***ionosphere***. The characteristics of the ionosphere are discussed later in the chapter.

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[2] *Encyclopaedia Brittanica*, op cit, p 703.

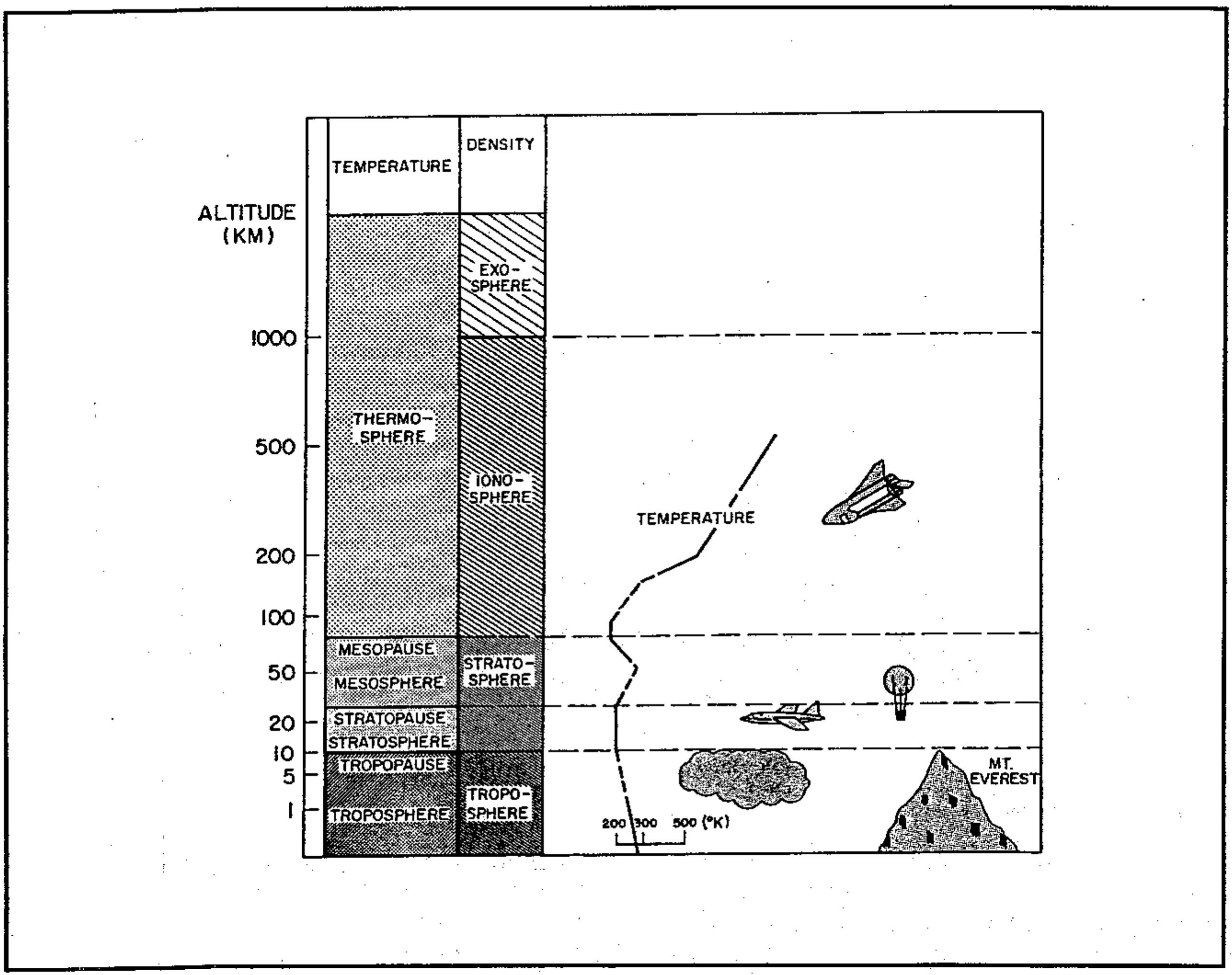

Figure 2.1. Regions of the Atmosphere[3]

<u>The Lower Atmosphere</u>

The lower atmosphere consists of the troposphere, stratosphere and mesosphere, and terminates at the mesopause at an altitude of approximately 85 km. The precise altitude of the mesopause depends on season and latitude. The lower atmosphere consists primarily of a mixture of gases made turbulent by atmospheric pressure and temperature differentials. This turbulence produces our weather. The turbulence of the lower atmosphere means that the gases at the various levels are well mixed, whereas in the upper atmosphere, the gases, under the influence of gravity, start to separate into distinct layers dependent upon their molecular weight. Figure 2.2 illustrates average atmospheric particle densities in the lower atmosphere, the exosphere, and deep space.

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[3] Measures, R., *Laser Remote Sensing*, John Wiley and Sons, New York, 1984, p 3.

	Lower Atmosphere		Upper Atmosphere	Inter-Planetary Space	Deep Space
Altitude (km)	0-11	11-80		1000-2000	2000+
Particle Density (average per cm^3)	10^{18}	10^{14}		10^2	10^1

Figure 2.2. Atmospheric Particle Densities

The lower atmosphere has direct effect on:

a. Launch Operations. Adverse weather and turbulence can cause problems during the launch phase of a space operation.

b. Space Operations. The cloud, atmospheric dust and gaseous matter of the lower atmosphere degrade the performance of space-based reconnaissance, surveillance, communications and navigation sensors by attenuating the transmission of electromagnetic radiation, particularly visible, infrared (IR) and radio frequency (RF) radiation.

The Upper Atmosphere

The upper atmosphere, or thermosphere, extends from the mesopause at 85 km up to 1000 km and beyond. However, above the thermopause (which lies between 200-500 km, depending on the degree of solar flare activity), the nature of the atmosphere changes. Gas molecules no longer exhibit the thermal behaviour with which we are familiar in our near-earth environment. Rather, they behave as if they were in free space. The low particle density and absence of turbidity means that gravity holds the controlling hand. Consequently, the gases lie in layers according to their molecular weight. The atmosphere above about 600 km consists largely of helium, with a layer of hydrogen above that. Particle densities at altitudes above about 1,000 km are close to those of interplanetary space, and in fact, the vacuum found at these altitudes is harder than any that can be manufactured on earth. At these altitudes, temperature ceases to have its customary meaning.[4]

The upper atmosphere has a significant impact on space operations up to an altitude of several thousand kilometres. Aerodynamic drag on satellites in low orbits will cause their orbit to gradually decay. The rate of decay accelerates as the satellite's altitude decreases and the aerodynamic drag imposed by the more dense lower atmosphere increases. Unless its altitude is maintained by regular boosting, the satellite will begin a spiral decay, until eventually it will impact the Earth. The effect of atmospheric drag on space operations is discussed in more depth in the next chapter.

The Ionosphere

The ionosphere consists of layers of ionized atmospheric gases lying between 50 and 500 km altitude. An ion is defined as an atom or sub-atomic particle carrying an electric charge. Gaseous atoms and molecules are turned into ions primarily by solar ultra-violet (UV) radiation 'knocking' electrons from the outer shell of individual gas atoms. The loss of this negatively charged electron means the parent atom or molecule carries a positive charge.

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[4] See 'The Temperature of Space' later in this chapter.

The Importance of the Ionosphere. Why is the ionosphere considered important? Simply because without it, there would be no long distance terrestrial radio communication. The various layers of the ionosphere are efficient reflectors of long wave radio frequencies. The higher the frequency, the higher the altitude of the reflecting layer. Radio frequencies in the High Frequency (HF) band[5] and below are reflected by the ionosphere and can be effectively 'bounced' around the world. The ability to bounce radio energy off the ionosphere also enables HF over-the-horizon-radar (OTHR) systems, such as Jindalee, to detect targets over long distances. Intense solar activity can severely disrupt the ionosphere. This effectively makes HF communication impossible, sometimes for days on end. However, radio frequencies higher than HF pass straight through the ionosphere and out into space, so are not directly affected by ionospheric disturbances. By using radio frequencies higher than HF, space-based communications systems can overcome the limitations imposed on terrestrial long range communications systems by ionospheric disruptions.

Layers of the Ionosphere. There are four primary layers of the ionosphere:

a. the D-layer, extending from 50 to 90 km;

b. the E-layer, extending from 90 to 160 km; and

c. the F-layer, which is further sub-divided into:

  i. the F1-layer, extending from 160 to 260 km; and

  ii. the F2-layer, extending from 260 to approximately 500 km.

The position of these layers is determined by the amount of incident solar UV radiation. The amount of UV radiation varies diurnally and seasonally. These variations cause complementary changes in the altitude and density of the ionospheric layers. These variations are illustrated by Figure 2.3. Also, the ionospheric layers can be violently disrupted by solar flare and sunspot activity. These phenomena are discussed later in the chapter.

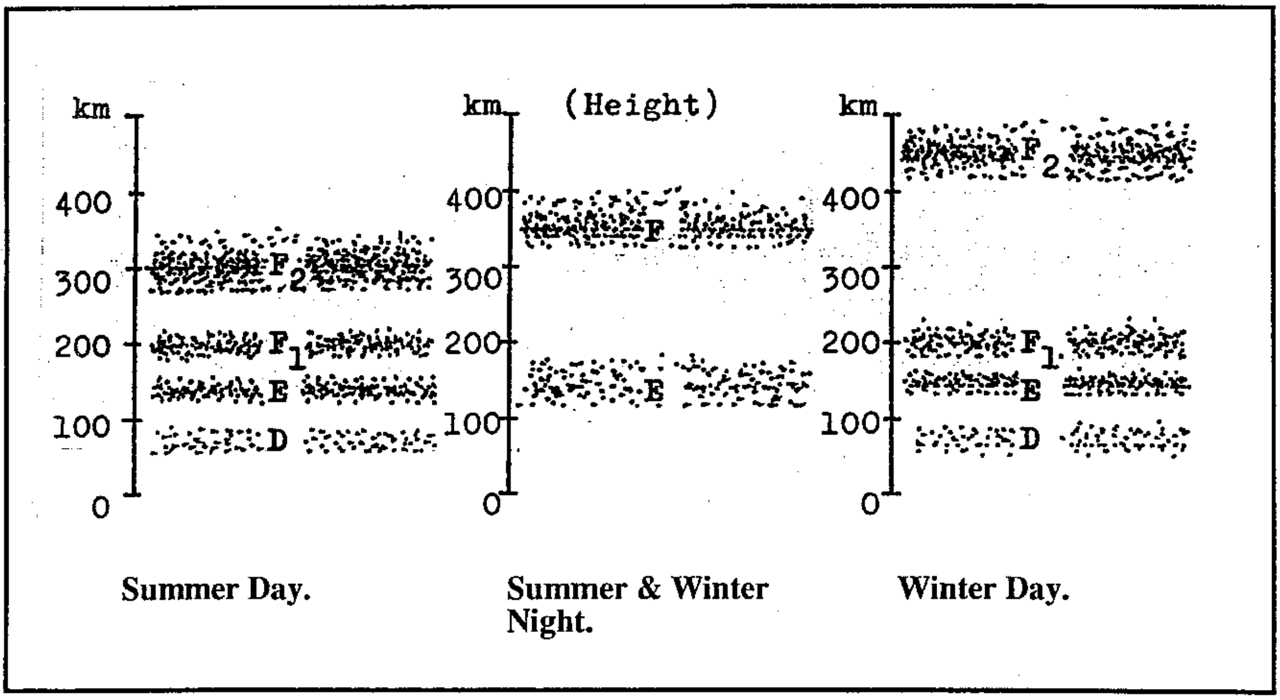

Figure 2.3. Variations in the Layers of the Ionosphere

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[5] The radio frequency bands are listed in Chapter Five, Table 5.4.

SPACE

Where Does Space Begin?

The answer to the question 'where does space begin?' is not particularly clear cut, and largely depends upon from which perspective the question is being asked. As documented in the preceding discussion, the atmosphere extends for at least 1000 km above the Earth, but the atmosphere does not provide a clearly delineated boundary from which space can be said to begin. From a human perspective, the US allows astronauts to wear their Wings once they have exceeded an altitude of 50 miles.[6] However, from an operational perspective, space can be said to begin at the altitude from which an orbit is sustainable without continuous thrust being required. This occurs at an altitude of 150 km. Thus, for our purposes, space can be said to begin at this altitude.

Electromagnetic and Corpuscular Radiation

Even though the particle density of space is so low that it may be considered a void for all practical purposes, space is not empty. It is flooded with ***electromagnetic*** (EM) and ***corpuscular radiation***. While the majority of readers would be familiar with the characteristics of EM radiation[7], this is probably not the case with corpuscular radiation. Simply, corpuscular radiation refers to the constant stream of high energy charged particles emitted by stellar bodies. The intensity of EM and corpuscular radiation at any particular location depends upon the observer's proximity to the source of the radiation. Considering cislunar operations, solar EM and corpuscular radiation is predominant, although high energy corpuscular radiation from galactic sources (sometimes called cosmic rays) cannot be ignored. The EM and charged particle spectra are shown at Figures 2.4 and 2.5 respectively.

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[6] Cochran, C., et al (ed), *Space Handbook*, Air Command and Staff College, Air University, Maxwell Air Force Base, Alabama, January 1985, p 1-4.

[7] EM radiation is thoroughly covered in Chapter Five.

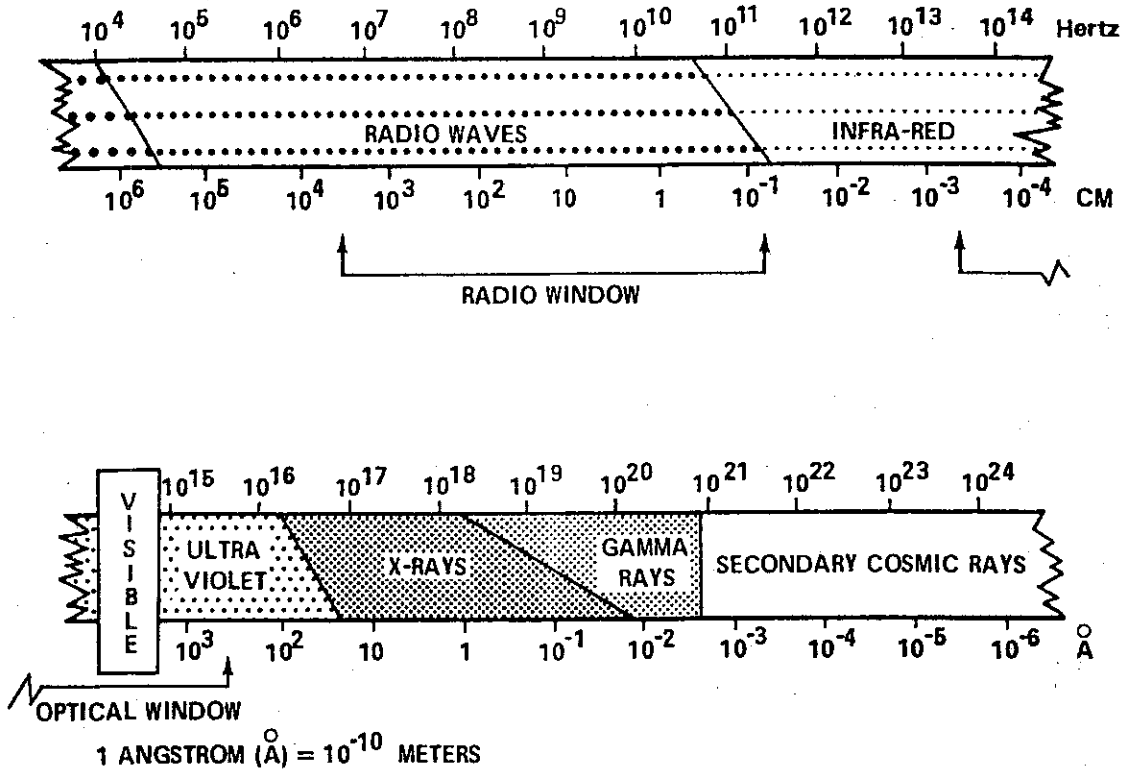

Figure 2.4. The Electromagnetic Spectrum[8]

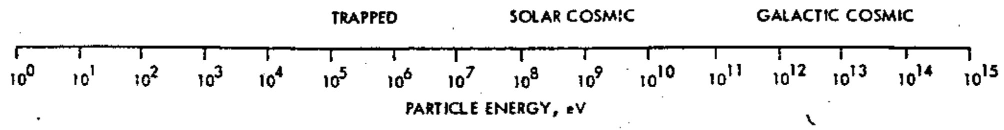

Figure 2.5. The Charged Particle Spectrum[9]

Solar Radiation. As with any other stellar body, the sun produces both EM and corpuscular radiation. The intensity of these radiations vary with the sun's 27 day period of rotation and with the level of solar activity. Both types of radiation can present a threat both to manned space operations and to the electronic equipment found onboard satellites. Electronic systems can be protected from the effects of radiation by using an appropriate level of shielding, as illustrated by Figure 2.6. Whilst shielding can protect men in space from low intensity radiation, high energy corpuscular radiation can easily penetrate metres of shielding. The

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[8] Cochran, op cit, p 1-5.
[9] Nagler, R., et al, *Sensor Capability Handbook and Data Sheets, Volume 1*, Jet Propulsion Laboratory, Pasadena, California, July 1977, p 4-1.

accumulated radiation dose received by astronauts in space is very carefully monitored, and once the allowable maximum is reached, their career in space is over.

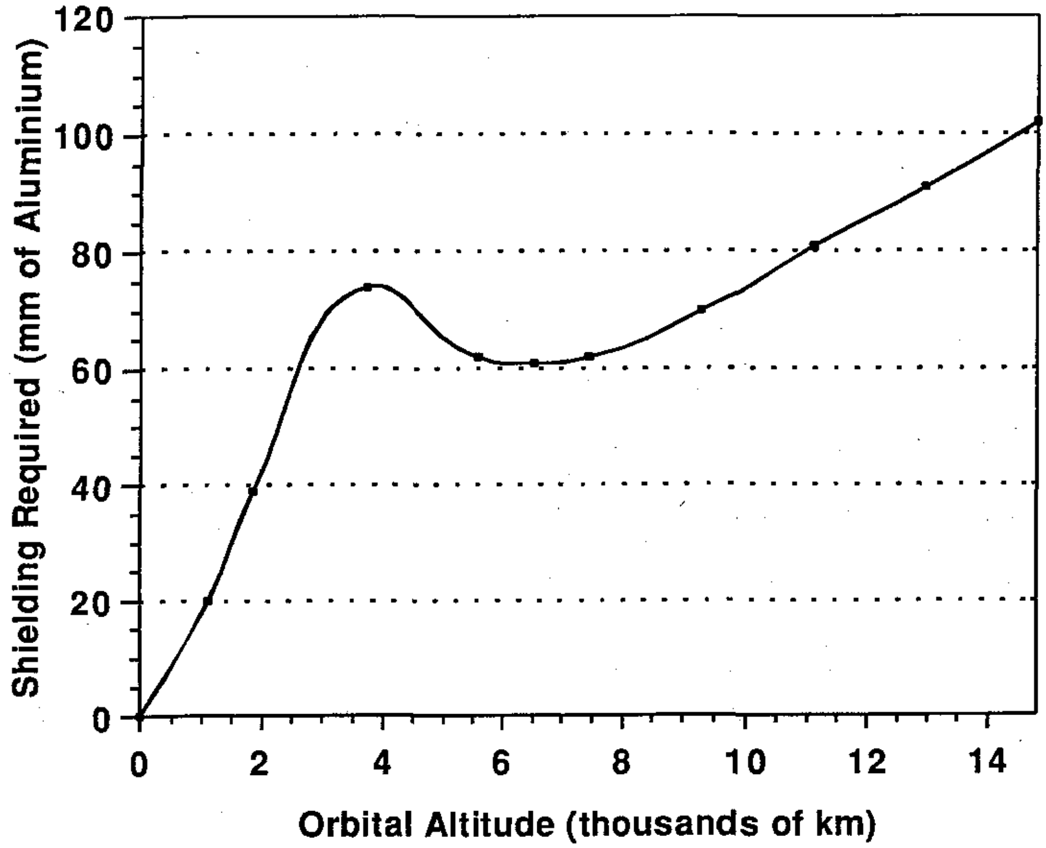

Figure 2.6. Depth Of Shielding Required At Various Orbital Altitudes[10]

<u>Solar Electromagnetic Radiation.</u> The spectrum of solar EM radiation covers from radio to X-ray frequencies, with radiated frequency and intensity increasing during solar flares. Light shielding is sufficient to protect space vehicles and personnel from the effects of normal levels of solar EM radiation. However, the intensity of EM radiation rises during periods of intense solar activity, and may cause disruption to radio communication and navigation systems.

<u>Solar Corpuscular Radiation and the Solar Wind.</u> Solar corpuscular radiation produces an effect known as the ***solar wind.*** The solar wind is a plasma[11] wind, rather than a gas wind as experienced on earth. It it is produced by the steady isotropic stream of corpuscular radiation emitted by the sun. The intensity of the solar wind is dependent on the level of solar activity. At the Earth's orbital radius, the velocity of the solar wind never falls below 250 km/sec. Normally, it has a particle density of 0.5/cm^3 . During intense sun spot activity, the solar wind may reach velocities of 1,600 km/sec and particle densities may increase to 10,000/cm^3. The solar wind has a considerable effect on the behaviour of the Earth's magnetic field and upper

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[10] Brookner, E. and Mahoney, T., *Derivation of Satellite Radar Architecture for Air Surveillance*, Microwave Journal, February 1989, p 182.

[11] A plasma, sometimes considered the fourth state of matter, is a hot, ionised, low density gaseous material. A plasma is electrically conductive.

atmosphere. It distorts the Earth's magnetic field, compressing it on the side of the Earth facing the sun and elongating it on the other side. This interaction, particularly during times of increased solar activity, is believed to cause electromagnetic discharge, or auroral activity, commonly called the Aurora Borealis in the northern hemisphere, and the Aurora Australis in the southern hemisphere. The effect the solar wind has on the Earth's magnetic field is illustrated by Figure 2.7. The solar wind does not pose a serious threat to manned space operations. However, it can cause excess electrical charge to accumulate on spacecraft surfaces. Spacecraft electrical systems may be disrupted if the build up of excess charge causes electrical arcing.

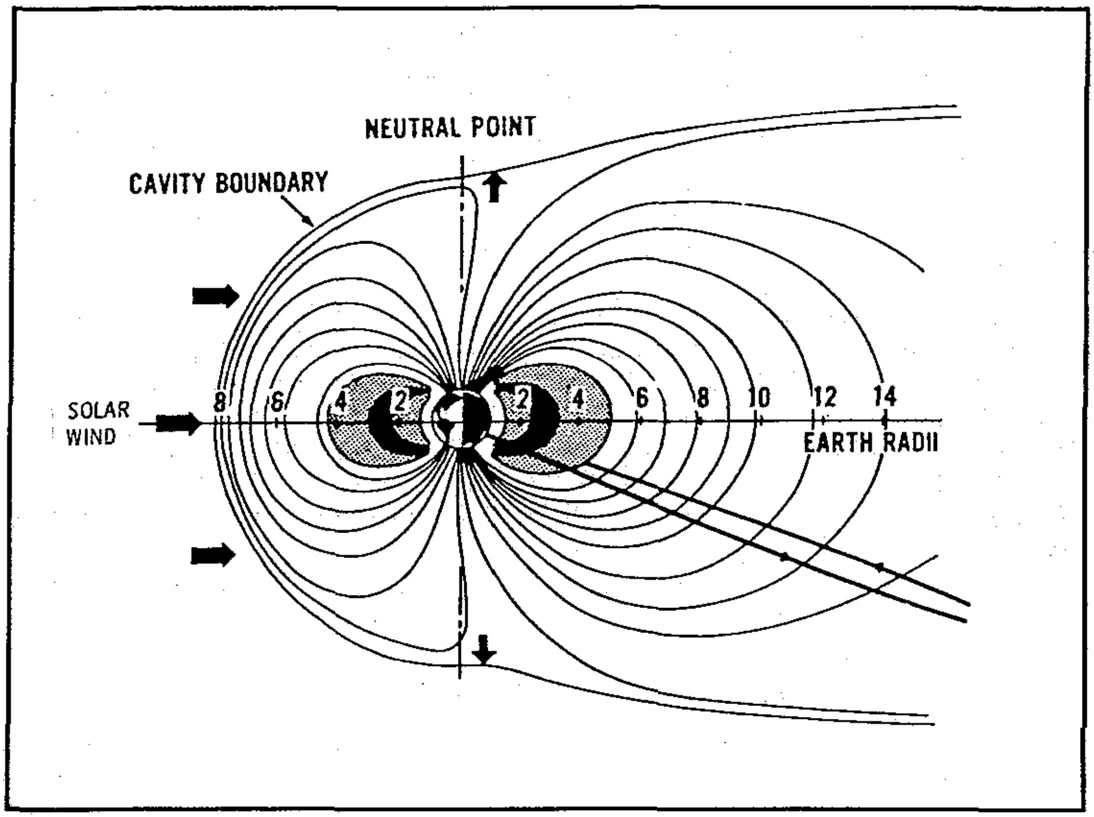

Figure 2.7. The Earth's Magnetic Field Distorted by the Solar Wind[12]

Solar Flares. The sun sometimes produces an area of energy of such intensity that it cannot be contained by the its magnetic field. This energy erupts from the sun's surface as a solar flare. Solar flares produce intense streams of corpuscular radiation that can reach velocities of up to 25% of the speed of light. Corpuscular radiations of this intensity are called ***solar cosmic rays***. Solar cosmic rays are described below. Solar flare events may last from minutes to several hours, and the X-ray and proton radiation they produce can deliver a lethal dose to men in space. Fortunately, solar flares are generally produced just after complex sun spot activity, so they are reasonably predictable. If a large solar flare is forecast, manned space operations may have to be abandoned. Solar flares can also cause severe disruption to radio communication and navigation systems.

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[12] Damon, T., *Introduction to Space*, 1989, Orbit Book Company, Malabar, Florida, February 1989, p 55.

Cosmic Rays

The term 'cosmic rays' is really a misnomer. Cosmic rays are streams of high energy corpuscular radiation travelling at very high speed, and not rays at all. Cosmic rays originate from two different sources:

a. Solar Cosmic Rays. Solar cosmic rays are comprised primarily of protons accelerated to high speed by intense solar flare activity. The radiation associated with solar cosmic rays can deliver a lethal dose to humans in space in a relatively short time.

b. Galactic Cosmic Rays. A steady stream of galactic corpuscular radiation flows through the solar system. Galactic cosmic rays are comprised of 85-90% protons, 10-12% alpha particles, 1% electrons and 1% heavy atomic nuclei.[13] Whilst extremely energetic, galactic cosmic rays are found at such low densities that they pose no threat to manned space operations.

The Van Allen Radiation Belts

The Van Allen Radiation belts are two torroidal (or doughnut) shaped zones of solar corpuscular radiation trapped by the Earth's magnetic field. The trapped particles, primarily protons and electrons, originate from solar corpuscular radiation. The belts are most intense over the Earth's equator and virtually absent over the poles. The lower belt, which lies between one and two Earth radii[14], is primarily comprised of protons. The higher belt, which lies between three and four Earth radii, is primarily comprised of electrons. The area of low particle density between the regions is often referred to as the 'slot'. The general arrangement of the Van Allen radiation belt is shown at Figure 2.8.

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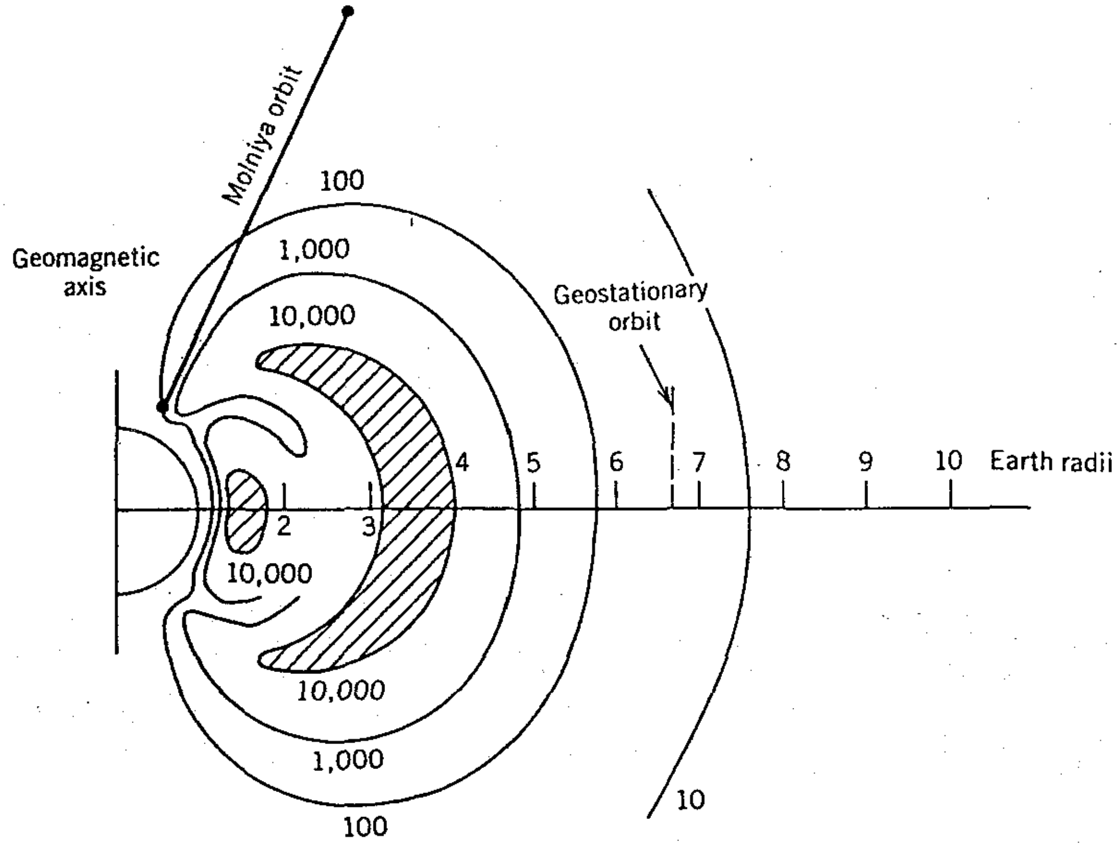
[13] Damon, op cit, p 50.
[14] Mean equatorial earth radius = 6,378 km.



Note: **Mean equatorial earth radius = 6,378 km.**
Numbers represent Geiger count.

Figure 2.8. The Van Allen Radiation Belts[15]

The Van Allen radiation belts are in a constant state of flux. Radiation levels and distributions, as well the depth of each belt, vary constantly with the changing levels of solar activity. Because the belts are contained by the Earth's magnetic field, they are similarly distorted by the solar wind. The physics and behaviour of the Van Allen radiation belts is still not well understood.

The Van Allen belts do present a radiation hazard to space operations, particularly the lower belt. The minimisation of accumulated radiation dosage must be considered when designing orbits for manned operations. The electronics onboard unmanned spacecraft must be well shielded if sustained operations in the Van Allen radiation belts are planned.

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[15] Morgan, W. and Gordon, G., *Communications Satellite Handbook*, John Wiley and Sons, New York, 1989, p 548.

Radiation Hazard Summary

The radiation hazards of space can be summarised as follows:

a. Spacecraft can be shielded from EM radiation.

b. Solar corpuscular radiation does not present a hazard except during solar flare activity, when solar cosmic rays threaten manned space operations. They can also cause ionospheric disturbances, which can disrupt radio communication and navigation systems.

c. Trapped radiation in the Van Allen radiation belt presents a potential hazard to manned space operations, but dosage can be minimised through careful orbit design. Satellites whose orbits traverse the Van Allen can be shielded.

Atmospheric Windows

Much of the radiation incident upon the Earth is absorbed by the atmosphere. If this were not the case, life on Earth as we know it could not exist. There are, however, two important 'windows' in the Earth's atmosphere through which EM radiation can pass with little attenuation. These windows are indicated in Figure 2.4. They include portions of the radio, IR and UV spectra, and all of the visible spectrum. These windows become very important when determining which frequencies are most suitable for earth observation or communication from space-based platforms. This issue will be discussed in depth in Chapter Five.

The Temperature of Space

The concept of 'temperature' in space is not the same as the concept of temperature on Earth. On Earth, an object's temperature is determined by either the temperature of its surrounding environment, or by its own internally generated heat. However, in space, where there is no insulating atmosphere, the temperature of a body is directly proportional to:

a. the amount of stellar radiation incident on the body;

b. the amount of radiation generated within the body;

c. the conduction of those radiations to other parts of the body; and

d. the rate at which heat can be lost by radiation into space.

From the perspective of a satellite operator, the most useful method of referencing temperature in space is by determining the equilibrium temperature of a small black sphere. The sphere will be heated by incident radiation. The temperature of such a body in earth orbit typically varies between 60°K in eclipse (that is, in the Earth's shadow) and 280°K when subject to direct solar radiation. Spacecraft mounted solar panels remain slightly warmer than the reference sphere due to their shape. The equilibrium temperature of space itself ranges from 3-4°K in deep space, to 20°K in areas containing many tightly clustered galaxies, such as the Milky Way. The kinetic temperature of the gas molecules found in space is actually quite high, at around 10,000°K. However, because of their extremely low density, they have a negligible effect on the temperature of a structure in space. Figure 2.9 illustrates the various concepts.

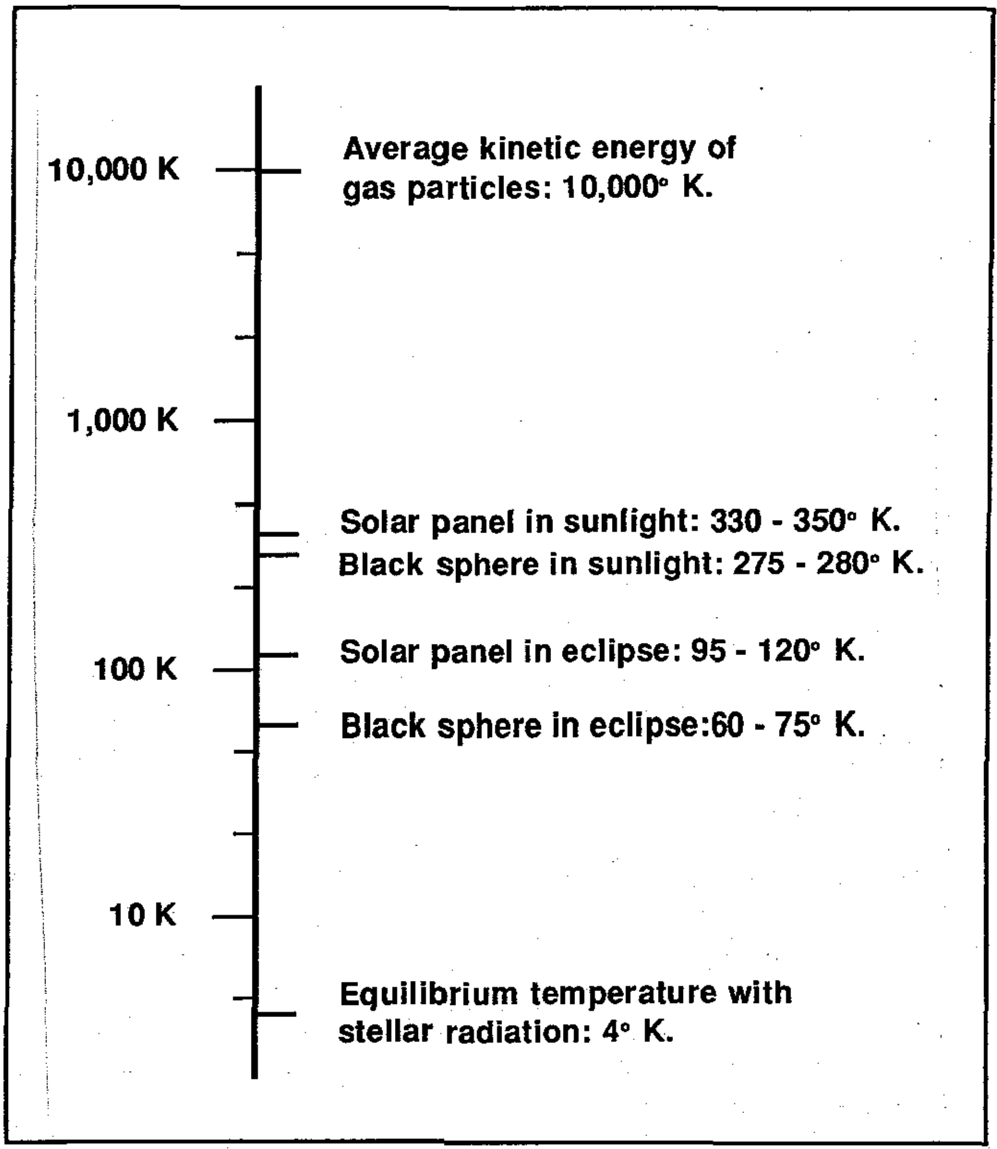

Figure 2.9. Various Concepts of Temperature in Space[16]

Whilst warm bodies on earth can lose heat through convection, conduction and radiation, this is not the case in the hard vacuum of space. In space, heat can only be lost through radiation. The requirement to maintain a spacecraft's thermal equilibrium requires rigorous design of its environmental control system.[17]

The Vacuum of Space[18]

The hard vacuum of space has various effects on the metallic and non-metallic solids used in the construction of a spacecraft. These effects include: sublimation, outgassing, and cold welding.

Sublimation and Outgassing. In a vacuum, metals and semiconductors will tend to sublimate and outgas. Sublimation means the conversion of a solid directly into a vapour, whilst outgassing means the loss of internal gas from within a structure. Both effects are accelerated as

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[16] ibid. p 544

[17] Satellite systems will be dealt with in Chapter Four.

[18] Maral, G. and Bousquet, M., *Satellite Communications Systems*, John Wiley and Sons, 1986, pp 198-199.

temperature increases. Over time, sublimation will cause the loss of structural material from the satellite and its components. Outgassing can cause structural failures if pockets of gas are trapped in materials or components during their manufacture. The trapped gas expands as the launch vehicle and its payload experiences an increasing vacuum as altitude increases during launch. Sublimation can be successfully controlled by using materials not excessively prone to the problem and keeping spacecraft and component temperatures well controlled. Damage from outgassing can be prevented by good component design and careful quality control during manufacture.

Cold Welding. In a vacuum, surfaces in direct contact can diffuse into one another and bind solidly. This process is called cold welding. The cold welding process can also lead to an increase in the amount of friction in bearings and rotary joints. This problem can be countered by enclosing moving pieces in insulated pressurised enclosures, using special lubricants or using ceramic bearing materials. Cold welding is much less of a problem on earth, as surfaces which are seemingly in direct contact actually have a layer of gas separating them.

One advantage of operating in a vacuum is that metal structures do not corrode.

Meteoroids and Micrometeoroids

Objects of various sizes are continually moving through space in a seemingly random fashion. A particle moving through space is called a ***meteoroid.*** A small meteoroid is called a ***micro-meteoroid.*** When a meteoroid enters the atmosphere and begins to glow it is called a ***meteor.*** If the particle survives passage through the atmosphere and actually impacts the Earth's surface it is called a ***meteorite.***

Meteoroids are of interest due to the finite possibility of a space vehicle being damaged or destroyed by meteoroid impact. The various components of a spacecraft must be made strong enough to withstand the projected probability of meteoroid impact over the vehicle's design life. Figure 2.10 provides an indication of meteoroid hit probability on a 10 m^2 surface over a 10 day period. Note that the probability of an impact with a particle weighing 10^{-5} gm is 1.0. That means that over a 10 day period, our 10 m^2 surface will on average be struck once by a particle of this mass, which would penetrate 0.05 cm into an aluminium skin. Obviously, the design of any spacecraft must provide sufficient protection from likely meteoroid impact. Whilst the probability of a hit from a meteoroid large enough to incapacitate or destroy a spacecraft is extremely small, it is finite, and poses one of the risks inherent in space operations.

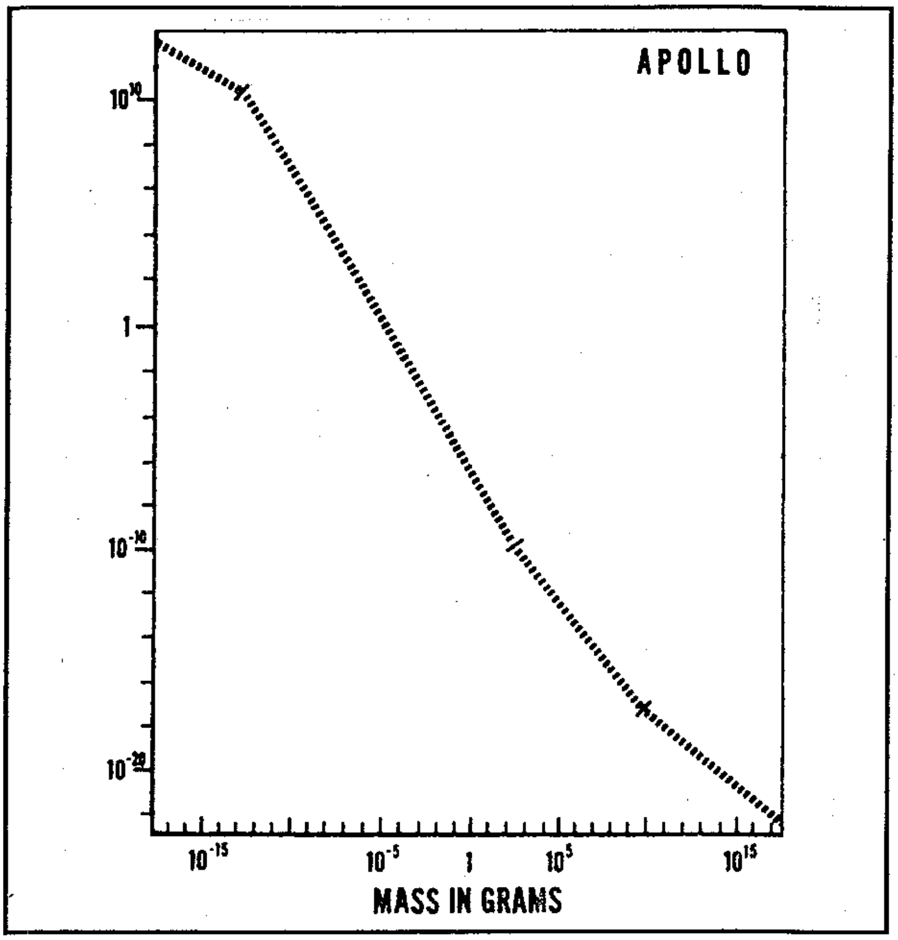

Figure 2.10. Meteorite Hit Probabilities[19]
(10 m^2 plate over 10 days)

Space Debris[20]

In 1988 there was two million kilograms of material orbiting the Earth. Of that two million kilograms, almost half was man-made, consisting of equal portions of spent rocket bodies and satellites. Eighty percent of those satellites are non-functional. A count of objects in earth orbit yields:

a. 2,000 spacecraft;

b. 5,000 large pieces of debris;

c. 30,000 marble to cricket ball sized pieces of debris; and

d. 100 million smaller particles.

This debris is already posing a large threat to space operations, probably greater than that posed by meteoroids. For example, in 1983 the shuttle Challenger's windscreen was struck by a paint flake less than 0.3 mm in diameter. The impact of the collision caused a large crater in Challenger's 20 mm thick windscreen. In the US, space debris is tracked and catalogued by NORAD, which issues collision warnings to shuttle crews and satellite operators. An Australian company, Spaceguard, is providing a satellite collision prediction service to help satellite operators determine orbits which minimise the risk of collision. Spaceguard is currently negotiating to provide their services to several US companies and has already advised the French

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[19] Cochran, op cit, p 1-7.
[20] Damon, op cit, pp 72-74.

satellite operator, SPOT, of the risks to their latest remote sensing satellite, SPOT 2.[21] As the amount of space debris around the Earth increases, risk prediction will increase in importance. The information is already of enormous interest to the insurance companies who indemnify commercial space system operators!

Space debris also poses a risk to the inhabitants of the Earth. The process of orbital decay means that ultimately, space debris in low earth orbit will re-enter the lower atmosphere. Whilst smaller pieces of debris will burn up, larger pieces may complete their journey to the Earth's surface. Examples of such incidents have already occurred. In 1978, the nuclear electrical generator from the Soviet satellite Cosmos 954 crashed to earth in Canada. Parts of the generator irradiated a large area of frozen tundra. In 1979, the US' Skylab space station came to earth, spreading debris across the southern Australian desert and the Indian Ocean. Luckily, nobody was killed or injured by either accident, but the threat posed by space debris is quite real. The problem will not disappear, nor is a simple solution on the horizon. In the near term, vigilant monitoring of space debris would seem to be the only means by which the problem may be addressed.

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[21] *Space Junk: Creating a Lethal Shell Around Earth*, Genesis, Technology Development Corporation, Adelaide, South Australia, August 1991, p 8.

CHAPTER THREE

ORBIT AND LAUNCH MECHANICS

Chapter Two briefly presented the nature of space and the space environment. This chapter will discuss the characteristics of satellite orbits, or ***orbital mechanics***, and how a satellite is placed into orbit, or ***launch mechanics***. Whilst the theory of launch mechanics will be discussed, launch systems *per se* will not. From an operational viewpoint, it is far more important to be familiar with the use and nature of the basic orbits and how launch into those orbits is achieved. For those requiring data on the capabilities of current launch systems, a directory is included at Annex A.

ORBITAL MECHANICS

The science of orbital mechanics originated with the observations of Tycho Brahe (1546-1601), the computations of Johannes Kepler (1571-1630) and the explanations of Isaac Newton (1642-1727). Kepler's first two laws reworded to apply to geocentric orbits are:[1]

a. Each satellite moves in an elliptical orbit with the centre of the Earth's mass as one foci (see Figure 3.1).

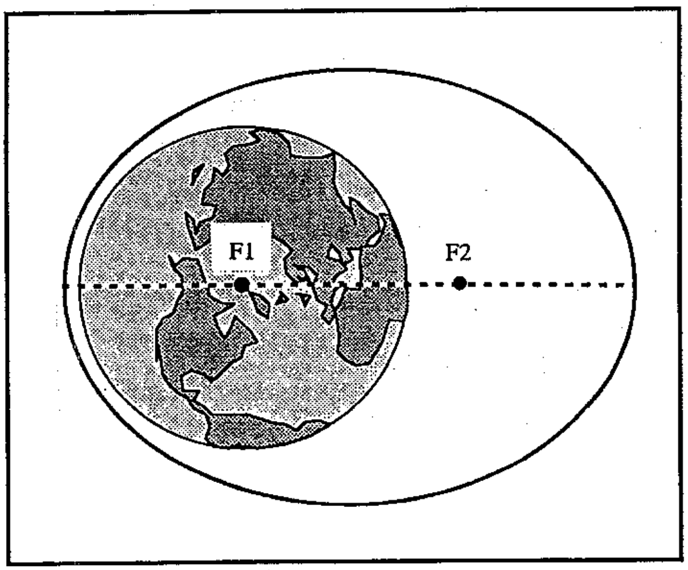

Figure 3.1. Satellites Move in Elliptical Orbits[2]

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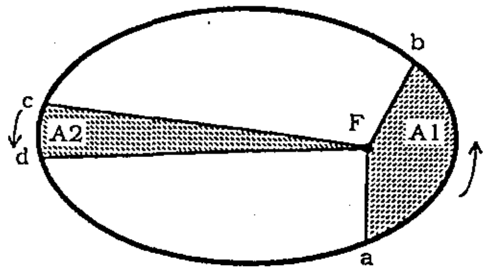
[1] Cantafio, L., *Space-Based Radar Handbook*, Artech House, Norwood, Massachusetts, 1989, p 47.

[2] Damon, T., *Introduction to Space*, Orbit Book Company, Malabar, Florida, 1990, p 30.

b. The radius of a vector drawn from the centre of the earth to the satellite sweeps equal areas in equal times (see Figure 3.2).



Area A1 = Area A2.
Time to travel from a to b =
Time to travel from c to d.

Figure 3.2. Satellites Cover Equal Areas in Equal Times[3]

The laws listed above assume that all bodies can be treated as point masses, and that each body is attracted solely by one large mass. The conditions required to validate the Keplerian model do not exist in reality, where third body effects and the Earth's non-uniformity will cause perturbations from the predicted orbit. The effects of and counters to these perturbations will be discussed later in the chapter. Our discussion begins with the basics of orbital mechanics.

Terms and Definitions[4]

The study of orbital mechanics requires the reader to become conversant with a number of the basic terms used to describe the characteristics of an orbit. These terms are defined below.

Orbital Mechanics. The determination of orbits and trajectories in space.

Satellite. A satellite may be described as 'a small body which revolves around a planet .... a man made device, usually containing recording and transmitting instruments, for launching into orbit around the Earth or another planet, for the purpose of communications, research, etcetera'[5].

Perigee. The point in an orbit closest to the Earth (see Figure 3.3); and the point where a satellite's velocity is at a maximum.

Apogee. The point in an orbit farthest from the Earth (see Figure 3.3); and the point where a satellite's velocity is at a minimum.

Period. The amount of time taken for a satellite to complete one full orbit.

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[3] ibid, p 30.

[4] Morse, R. et al, *Space Operations Orientation Handbook 2nd Edition*, 1013th Combat Crew Training Squadron, Air Force Space Command Operations, Peterson AFB, Colorado, 1 Jan 91, passim.

[5] *Macquarie Dictionary.*

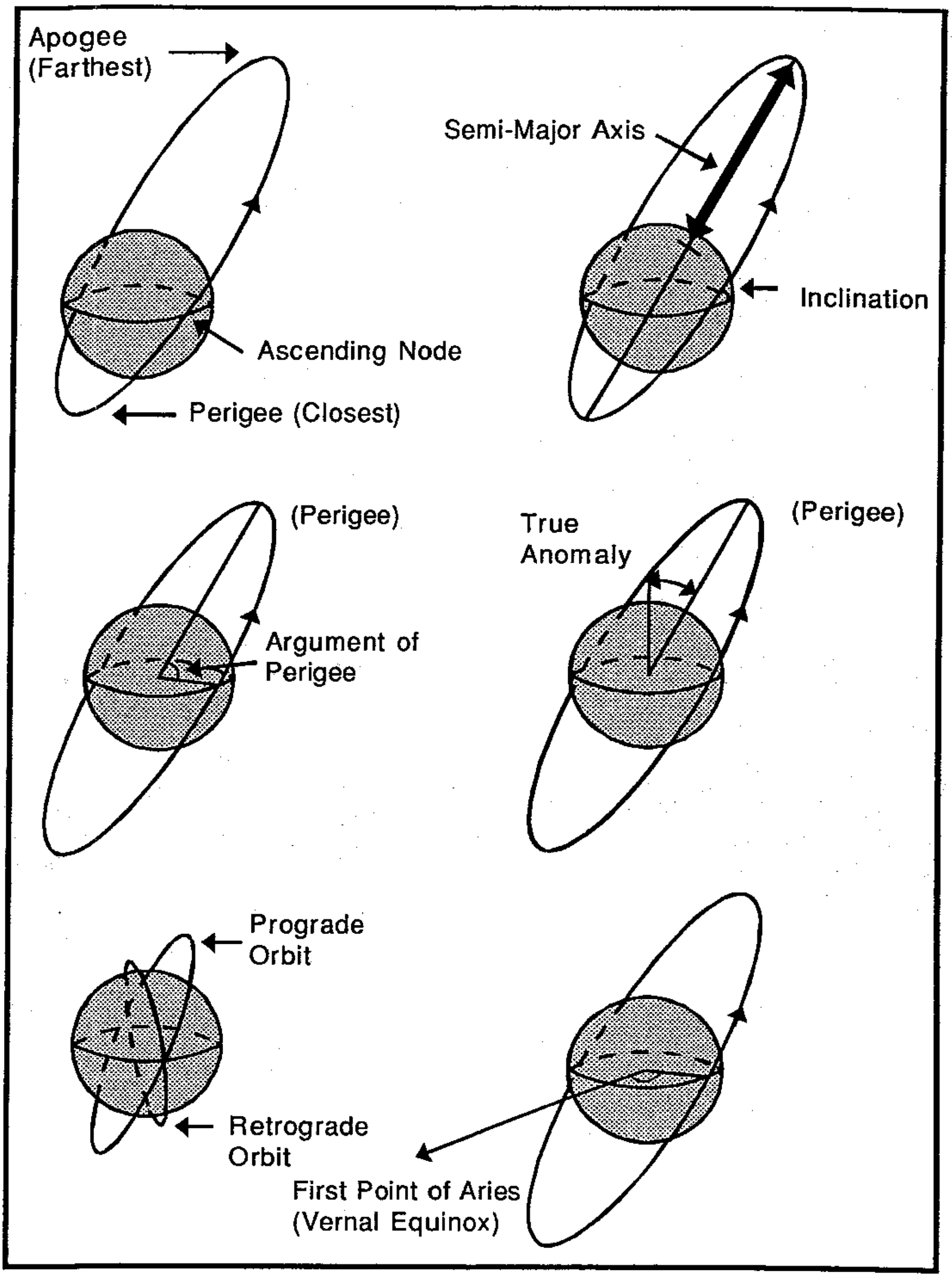

Figure 3.3. The Orbital Element Set

Ascending Node. The point in space where the satellite's orbital plane intersects the Earth's equatorial plane on a south to north pass.

Descending Node. The point in space where the satellite's orbital plane intersects the Earth's equatorial plane on a north to south pass.

Orbital Element Set. A set of parameters used to define a satellite's orbit. The orbital element set defines the shape, size and orientation of an orbit; as well as the position of the satellite within that orbit at a particular time. The orbital element set includes:

a. epoch time.

b. semi-major axis;

c. eccentricity;

d. inclination;

e. right ascension of the ascending node;

f. argument of perigee; and

g. true anomaly.

These terms are defined below and illustrated in Figure 3.3.

Epoch Time. The reference time for the parameters of the orbital element set.

Semi-Major Axis. Half the distance between apogee and perigee.

Eccentricity. The amount the orbit deviates from circular. Eccentricity can range between zero, a circular orbit, and 0.99', a highly elliptical orbit. An orbit with an eccentricity of 1.00 is parabolic, and with an eccentricity greater than 1.00, hyperbolic. The four basic orbits discussed above are illustrated by Figure 3.4. Satellites launched into parabolic or hyperbolic orbits will not enter an earth orbit, so these orbits will not be considered further.

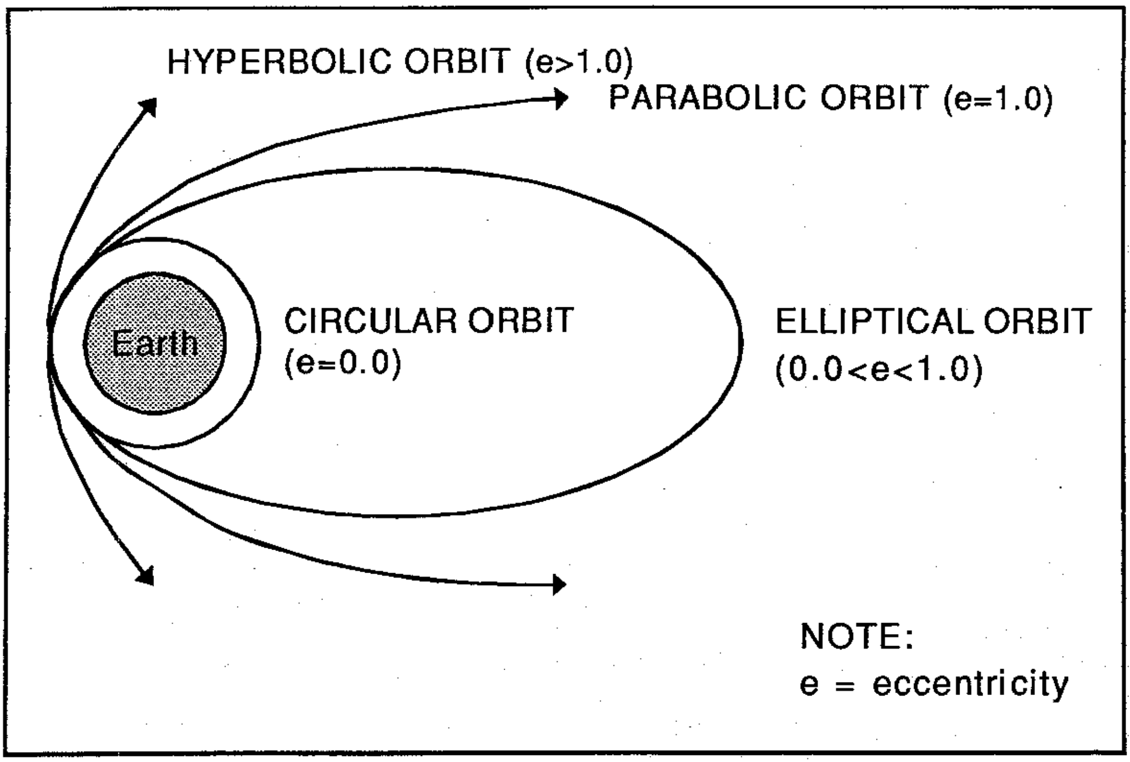

Figure 3.4. Circular, Elliptical, Parabolic and Hyperbolic Orbits

<u>Inclination.</u> The angle subtended by the Earth's equatorial plane and the satellite's orbital plane (measured in a counter clockwise direction from the equatorial plane). Inclination orientates the orbital plane to the Earth.

<u>Right Ascension of the Ascending Node.</u> The angular measurement from the first point of Aries (or Vernal Equinox) measured eastward along the equator to the ascending node. The Right Ascension of the Ascending Node orientates the orbital plane to the rest of the universe.

<u>Argument of Perigee.</u> An angular measurement made from the ascending node, in the direction of satellite travel, to the point of perigee on the orbital path. This orients the orbit within the orbital plane.

<u>True Anomaly.</u> An angular measurement in the direction of motion from the point of perigee to the instantaneous position of the satellite at epoch time. This measurement positions the satellite within its orbit at epoch time.

<u>Ground Trace.</u> The normal intersection between the surface of the Earth and a satellite's orbital plane.

<u>Perturbation.</u> Any force which causes a disturbance or deviation from the ideal two body orbit. Perturbations may be proportional to time (secular perturbations) or period (oscillatory perturbations).

<u>Line of Apsides.</u> The line joining the points of perigee and apogee.

<u>Prograde Orbit.</u> An orbit of inclination less than 90°.

<u>Retrograde Orbit.</u> An orbit of inclination greater than 90°.

First Point of Aries, or Vernal Equinox. A reference point from which astronomical data is measured. On the first day of spring a line from the centre of sun through the centre of the Earth points directly towards the constellation of Aries.

An Orbit is a Balance of Forces

As a satellite orbits the Earth, there is a balance of forces keeping the satellite in position. The satellite is moving with a velocity tangential to the Earth's surface. This velocity was imparted during launch. If there was no other force involved, the satellite would escape into space. However, in opposition to the satellite's tangential velocity, the Earth's gravitational force tries to pull the satellite directly towards its centre. Thus, gravity and the satellite's tangential velocity in opposition produce a smoothly curving orbital path, on which the satellite is always falling and always moving tangentially to the Earth.

The Relationship Between Orbital Altitude and Period

The altitude of an orbit bears a direct relationship with its period. The Earth's gravitational force decreases with the inverse square of distance from its centre. Therefore, the tangential velocity required to balance the gravitational pull will also decrease with altitude. Also, the higher the orbit, the longer the orbital path. In combination, these factors dictate that as the altitude of the orbit increases, so does the period. This relationship is quantified in Table 3.1. This table lists orbital period against radius and altitude for satellite velocities in increments of 0.2 km/sec, with the exception of the first entry at zero altitude, and the last entry at geosynchronous altitude. The period of the geosynchronous altitude equals one ***mean solar day*** (23 hr 56 min 4.091 sec).

Table 3.1 is presented for circular orbits, but the data can be adapted for eccentric orbits. To use the table to determine the period of an eccentric orbit, substitute the dimension of the eccentric orbit's semi-major axis as the radius. The velocity indicated by the table will then equal the geometric mean velocity[6] of the eccentric orbit.

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[6] The geometric mean velocity is obtained by taking the square root of the product of the maximum and minimum velocities of the eccentric orbit.

Table 3.1. Period and Velocity of Circular Orbits[7]

Period	Period		Radius	Altitude	Velocity
(sec)	hr	min	(km)	(km)	(km/sec)
5,069	1	24	6,378	0	7.9074
5,278	1	28	6,552	173	7.8
5,705	1	35	6,901	523	7.6
6,180	1	43	7,279	901	7.8
6,710	1	52	7,689	1,311	7.2
7,302	2	02	8,185	1,757	7.0
7,965	2	13	8,620	2,242	6.8
8,711	2	25	9,151	2,772	6.6
9,554	2	39	9,731	3,353	6.4
10,509	2	55	10,369	3,991	6.2
11,595	3	13	11,072	4,694	6.0
12,836	3	34	11,849	5,471	5.8
14,261	3	58	12,710	6,332	5.6
15,905	4	25	13,669	7,291	5.4
17,812	4	57	14,741	8,363	5.2
20,036	5	34	15,944	9,566	5.0
22,646	6	17	17,300	10,922	4.8
25,730	7	09	18,837	12,459	4.6
29,401	8	10	20,589	14,211	4.4
33,804	9	23	22,596	16,218	4.2
39,133	10	52	24,913	18,534	4.0
45,642	12	41	27,604	21,226	3.8
53,680	14	55	30,756	24,378	3.6
63,721	17	42	34,481	28,103	3.4
76,431	21	14	38,926	32,548	3.2
86,164	23	56	42,164	35,786	3.0747

BASIC ORBITS

Satellite orbits may be grouped by altitude into the following categories:

a. ***low earth orbits*** (LEOs), covering altitudes from 150 to 1,500 km (see Figure 3.5);

b. ***medium altitude orbits***, from 1,500 to 35,786 km; and

c. ***high altitude orbits***, from geosynchronous earth orbit (GEO) at 35,786 km and higher (see Figure 3.7).

Each of these is discussed in turn.

Low Earth Orbit

Depending on its altitude, a satellite in LEO travels with at a velocity between 7.8 km/sec (or 28,000 km/hr) and 7.1 km/sec; which correspond to periods between 88 and 117 minutes. Figure 3.5 is a scale illustration of a satellite in a LEO with apogee at 555 km and perigee at 185 km. The figure usefully indicates that space is not very far away!

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[7] Morgan, W. and Gordon, G., *Communications Satellite Handbook*, John Wiley and Sons, 1989, p 785.

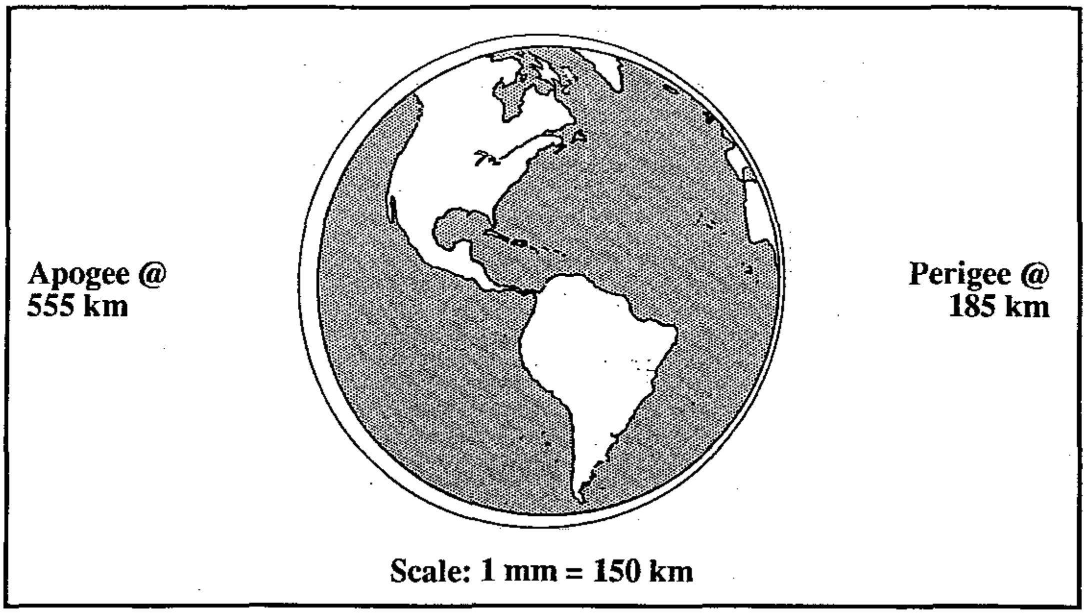

Figure 3.5. Low Earth Orbit (to scale)[8]

<u>Atmospheric Drag.</u> As discussed in Chapter Two, the Earth's atmosphere extends for many thousands of kilometres above its surface. The atmosphere induces considerable aerodynamic drag on a satellites in LEO. The effect of this drag is to cause the satellite's orbit to steadily decay (that is, reduce in altitude), until the satellite either burns up due to aerodynamically induced heating or it impacts the earth. The rate of orbital decay due to atmospheric drag is proportional to altitude, as illustrated by Figure 3.6. The effect of atmospheric drag must be countered by regularly boosting the satellite to maintain its altitude. The lower the satellite's orbit, the greater the drag, and the more frequently boosting will be required. This means a considerable amount of fuel must be carried onboard satellites in very low orbits, otherwise the satellite will have a very short life. Given that launch vehicles have limited performance, fuel can be traded directly against payload. This means a compromise must be struck between orbital altitude, satellite life and payload requirements. You will find as you read further that this is only the first of many compromises to be made in designing a space-based system.

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[8] Bate, R., Mueller, D., and White, J., *Fundamentals of Astrodynamics*, Dover Publications Inc., New York, 1971, p 154.

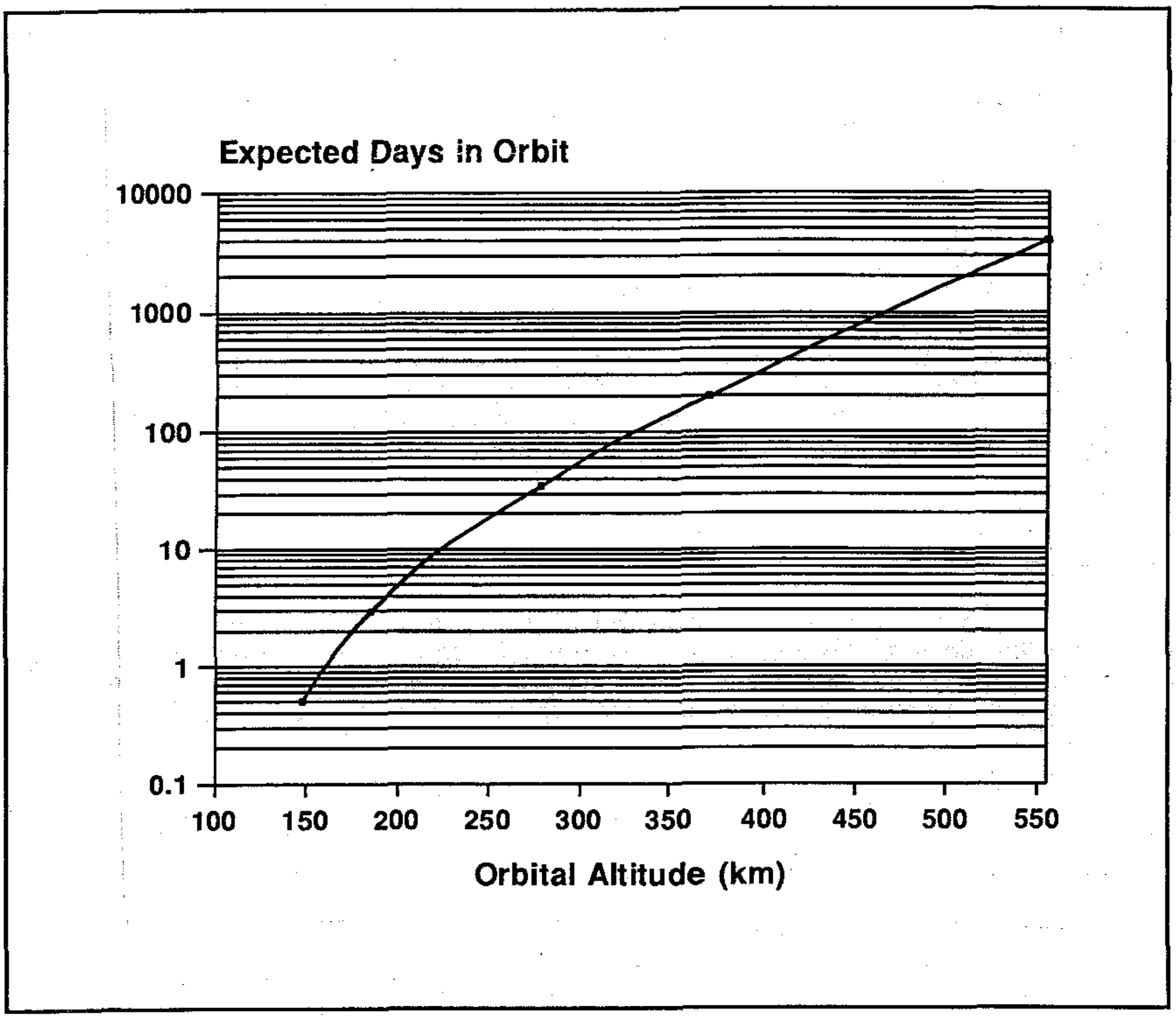

Figure 3.6. Rate of Orbital Decay Due to Atmospheric Drag

Uses of LEO. LEO is particularly important for military surveillance and reconnaissance operations and civilian remote sensing operations. Whilst the low altitude imposes a penalty in a sensor's overall field of view (FOV), it also allows ground targets to be highly resolved. For example, the US KH-11 reconnaissance satellites, operated by the CIA, use a LEO. This series of satellites, active since 1976, has used the following average orbital parameters:[9]

Mean Perigee:	261 km;
Mean Apogee:	611 km;
Mean Lifetime:	1053 days; and
Mean Period:	90 minutes.

The KH-11 satellite reportedly has a ground resolution of 150 mm.[10] The orbit of the KH-11 is biased towards achieving the best possible resolution at the expense of longevity. The fact that the KH-11 is able to achieve a mean lifetime of nearly three years is due to its size and weight (KH-11 is estimated to weigh 11,400 kg)[11]. Much of that weight must be fuel. Of course, a satellite of KH-11's size and weight is very expensive to build and launch. No commercial supplier of satellite imagery could hope carry the cost overheads of such a system.

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[9] Richelson, J., *America's Secret Eyes in Space*, Harper and Row, New York, 1990, Appendix B.
[10] ibid, Appendix B.
[11] *Specifications: US Spacecraft*, Aviation Week and Space Technology, 19 March 1990, p 172.

By way of comparison, most civilian remote sensing satellites are quite small, and operate at higher altitudes; usually about 700-800 km. These factors, in combination, achieve a reasonable compromise between resolution, lifetime, and construction and launch cost. NASA's Landsat 5 remote sensing satellite is a typical example. Landsat 5 operates at a mean altitude of 705 km, from which it achieves a ground resolution of 30 m in the visible and near infrared band. The Landsat 5 satellite has a design life of five years, and weighs 2000 kg[12].

Medium Altitude Orbits

Satellites in medium altitude orbits (1,500-35,786 km) have orbital periods ranging between 117 minutes and 23 hours 56 minutes. Probably the most important system to occupy a medium altitude orbit is the US owned Global Positioning System (GPS) NAVSTAR space-based navigation system. When fully operational, the system will use a constellation of 21 satellites plus three on-orbit spares to provide accurate world-wide three-dimensional navigation. The satellites will be at an altitude of 20,200 km, which equates to a period of just over 12 hours.[13]

High Altitude Orbits

High altitude orbits may be divided into two groups: GEO, and orbits higher than GEO. At an altitude of 35,786 km, a satellite moves through space at the same relative speed as a point on the Earth's equator. Satellites at this altitude are said to be in GEO. GEO satellites appear to be stationary to an observer on the Earth. Figure 3.7 provides a scale diagram of a satellite in GEO.

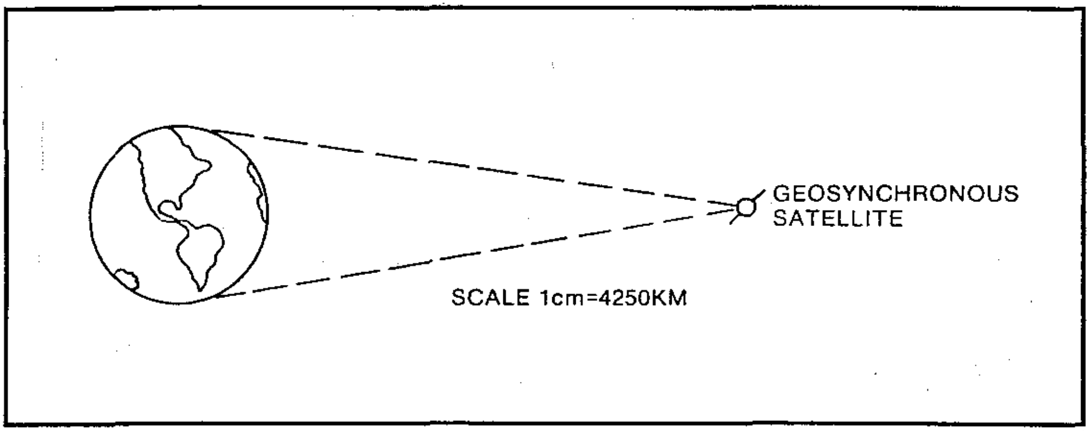

Figure 3.7. Geosynchronous Earth Orbit (to scale)[14]

<u>GEO.</u> GEO is most commonly used for communications satellites. Three satellites space at 120° intervals can provide complete coverage of the globe, except for the polar regions. Despite the attraction of being able to 'stare' at a particular part of the globe from GEO, the altitude of the orbit makes it unsuitable for most reconnaissance or surveillance missions as it is not possible to achieve sufficient resolution. However, there are exceptions: some signals intelligence (SIGINT) and ballistic missile early warning systems (BMEWS) operate from GEO. However, the altitude still poses a problem. For example, consider the SIGINT mission. The antenna required to achieve an acceptable ground resolution is enormous. The US MAGNUM electronic intelligence (ELINT) satellite reportedly uses a 100 m diameter antenna,[15] which you

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[12] ibid, p 172.

[13] GPS is discussed in detail in Chapter Eight.

[14] Roseland, L. (ed), *Space: The Fourth Military Arena*, Air University, Maxwell Air Force Base, Alabama, May 1986, p 20.

[15] Ball, D., *Pine Gap*, Allen and Unwin, Sydney, 1988, p 27.

can be sure would be even larger if it were possible. The design, launch and deployment of such a system into GEO is an expensive undertaking, and quite an amazing feat of engineering.

Orbits Higher than GEO. From earth, satellites in orbits higher than GEO appear to regress through the sky. Very few satellites operate at such high altitudes. Those that do are there to meet very specialised requirements. One example of such a system is the US VELA satellite constellation, launched between 1963 and 1970. The purpose of VELA was to detect nuclear detonations on earth and in space. Twelve VELA satellites were placed in near circular orbits with the following average parameters:

Mean Altitude:	108,000 km;
Mean Inclination:	35.6°; and
Mean Period:	4.46 days.

VELA is no longer operational.

SATELLITE GROUND TRACES

The path traced by a satellite over the Earth is dependent on the parameters of its orbit, and is known as the ***ground trace***. Effectively, the ground trace references the satellite's position with respect to the Earth. Satellite operators go to enormous trouble to position satellites in particular orbits to achieve ground traces that meet specific terrestrial requirements. For these reasons, it is important to establish a sound understanding of ground trace diagrams, and to be able to correlate them to particular orbital parameters.

A ground trace is formed by the intersection of the surface of the Earth and the plane of the satellite's orbit. The ground trace is produced by a combination of two motions:

a. the satellite's orbit, which is fixed in inertial space; and

b. the Earth's rotation under this orbit.

Hence, the ground trace is formed as the satellite follows its orbital path and the Earth rotates underneath it.

Ground traces have many purposes. Ground traces of foreign satellites can be analysed to determine their likely missions. Ground traces of friendly satellites can be modelled to determine an optimum orbit to satisfy the requirements of a specific mission. Examination of the ground trace will reveal when a satellite will be visible to a particular ground station, or when it will pass over an area of interest. Common ground traces are illustrated in the subsequent sections.

Geosynchronous and Geostationary Earth Orbit

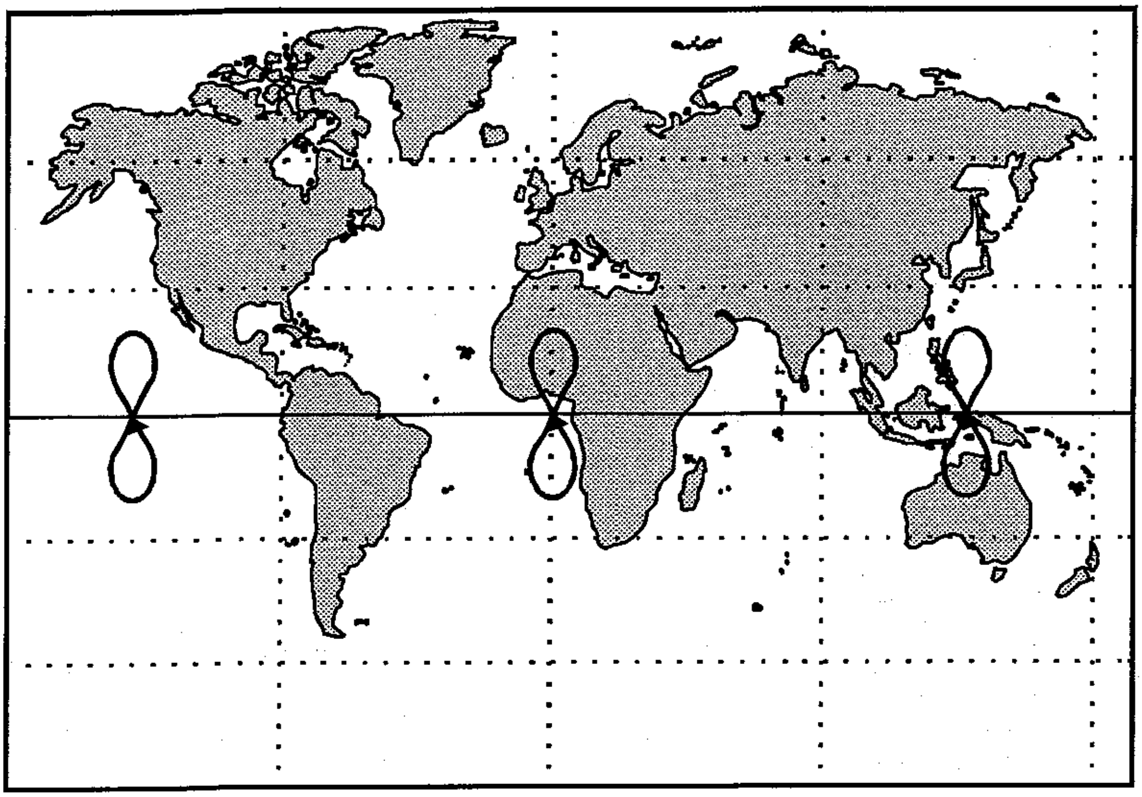

Figure 3.8. Geosynchronous Orbit

GEO. The ground trace of a GEO looks like a figure eight. The latitude extremes of the eight are determined by the inclination of the orbit. As the orbital period equals one solar day, the ascending and descending nodes are effectively stationary in longitude. Figure 3.8 depicts the ground traces of three satellites. Three satellites in GEO, placed 120° apart in longitude can effectively view the entire globe (except for the polar regions due to the curvature of the Earth).

Geostationary Earth Orbit. If the inclination of a GEO is reduced to zero, the orbit will effectively become a dot over the equator. This orbit, called geostationary, is a specific type of GEO. Maintaining a satellite within a defined limit about a particular longitude is called ***station-keeping***.

Apparent Regression of Nodes

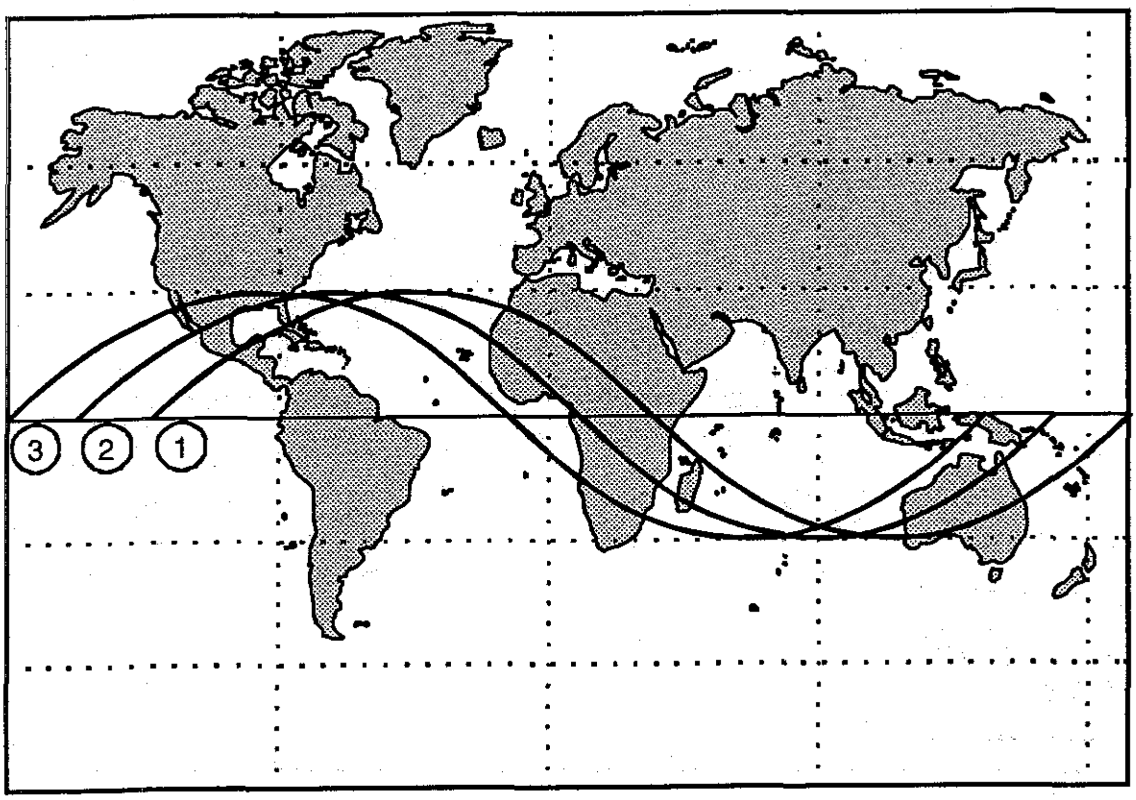

Figure 3.9. Apparent Regression of Nodes

The Earth rotates at 15.04° per hour, whilst the orbit of a satellite is fixed in inertial space. The effect of the Earth's rotation on the ground trace depends on whether the satellite is in an orbit lower than GEO, at GEO, or higher than GEO. It must be emphasised that the ***apparent nodal regression*** discussed here is caused solely by the Earth's rotation under the satellite's orbital plane. The rotation of the satellite's orbital plane in inertial space, or ***real nodal regression***, is an orbital perturbation. Perturbations are discussed later in this chapter.

Orbits Lower Than GEO. For satellites in orbits lower than GEO, the ground trace will be displaced westward by the number of degrees the Earth rotates during the period of one orbit. This case is shown in Figure 3.9. The effect may be referred to as the 'apparent regression of nodes'. Eventually, the ground trace will cover a band about the Earth bounded by the latitudes equal to the inclination of the orbit. By choosing and maintaining the altitude of an orbit carefully, it is possible to make the satellite cyclically repeat the same ground trace sequence. This could be useful for the surveillance of a particular area.

GEO. GEO is described in the preceding section.

Orbits Higher Than GEO. Orbits higher than GEO have periods longer than one solar day. Accordingly, the ground trace will move eastward by the number of degrees the Earth rotates in each orbital period.

The Effect of Inclination

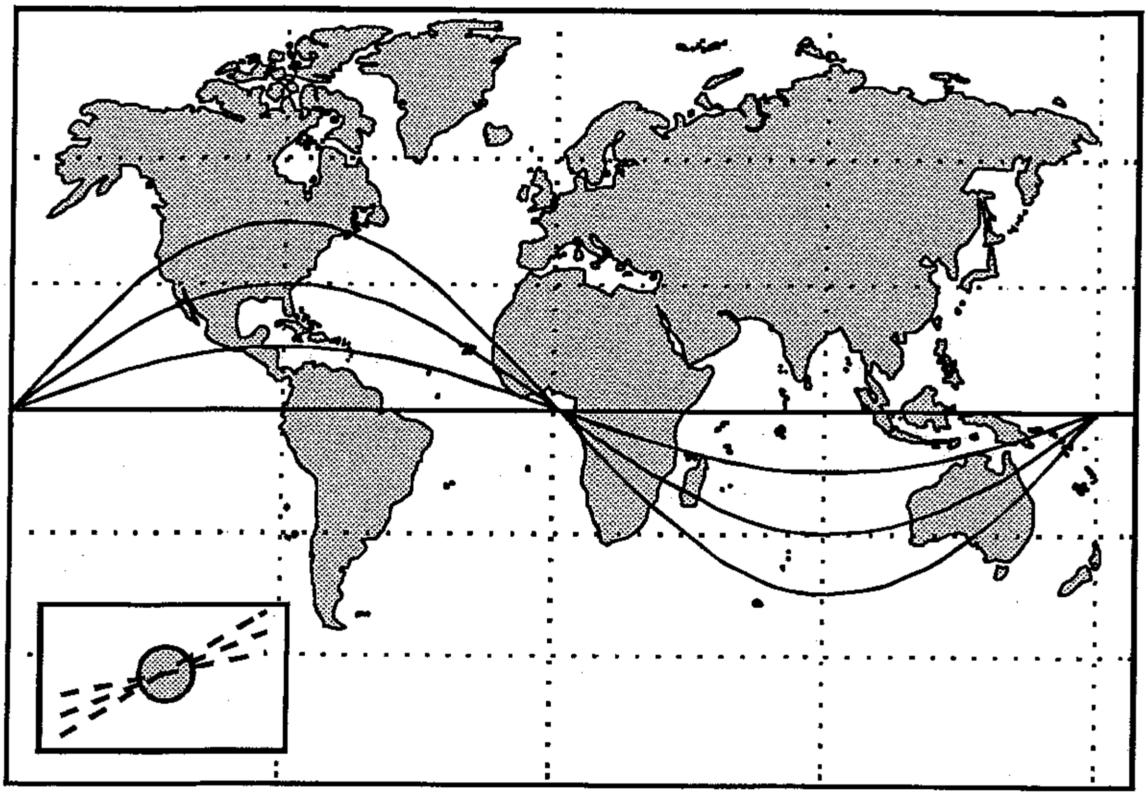

Figure 3.10. The Effect of Inclination

Figure 3.10 depicts the ground traces of three satellites in LEOs which vary only in their inclination. The period of each is identical. The inclination of the orbits shown are approximately 17°, 34° and 51° respectively. If a satellite's inclination is unknown (if, for example, the observer is trying to determine the orbital elements of a foreign satellite by observation), it can be determined by simply measuring the latitude of the northern-most turning point as indicated by the ground trace. The inclination will equal the measured latitude for prograde orbits, and (180° minus the measured latitude) for retrograde orbits.

Note that changing a satellite's inclination has no effect on its period. Period is determined solely by altitude.

Polar Orbits

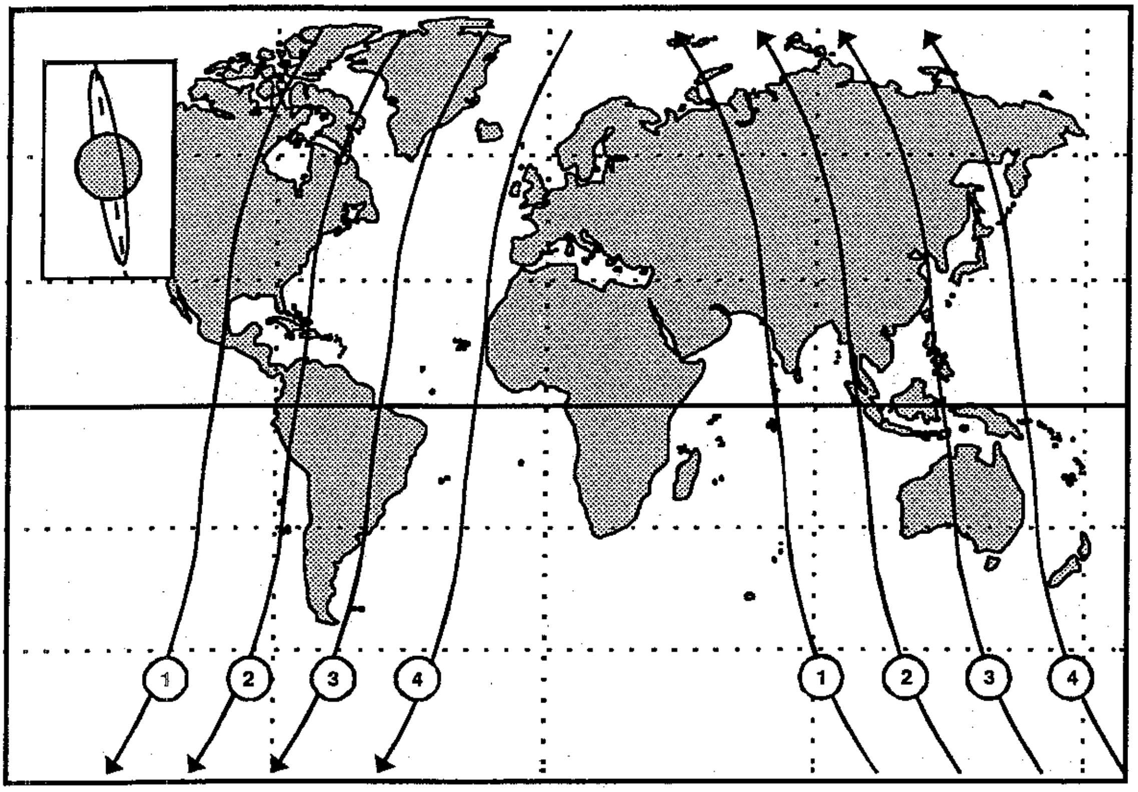

Figure 3.11. Polar Orbit

Polar orbits have inclinations at or near 90°. In reality, the term 'polar orbit' is a generic one used to describe highly inclined LEOs. If the inclination of the orbit is exactly 90° then the satellite will traverse both poles during each orbit. If the inclination is slightly less than 90°, then the satellite's ground trace will 'turn' at the latitude of the inclination, as with any other LEO. If the inclination is more than 90°, (a retrograde orbit), then the ground trace will turn at a latitude of (180° minus inclination). A satellite in polar orbit inclined at 90° will eventually cover the entire Earth's surface, whilst a satellite in a polar orbit inclined at either more or less than 90° will cover the entire Earth's surface except for the extremes of latitude. The polar orbit is useful for weather, reconnaissance and remote sensing satellites, where total, or near total, earth coverage is required.

Note that the polar orbit depicted in Figure 3.11 is slightly retrograde: that is, it has an inclination of greater than 90°. The ground trace moves east with each orbit.

The Effect of Eccentricity

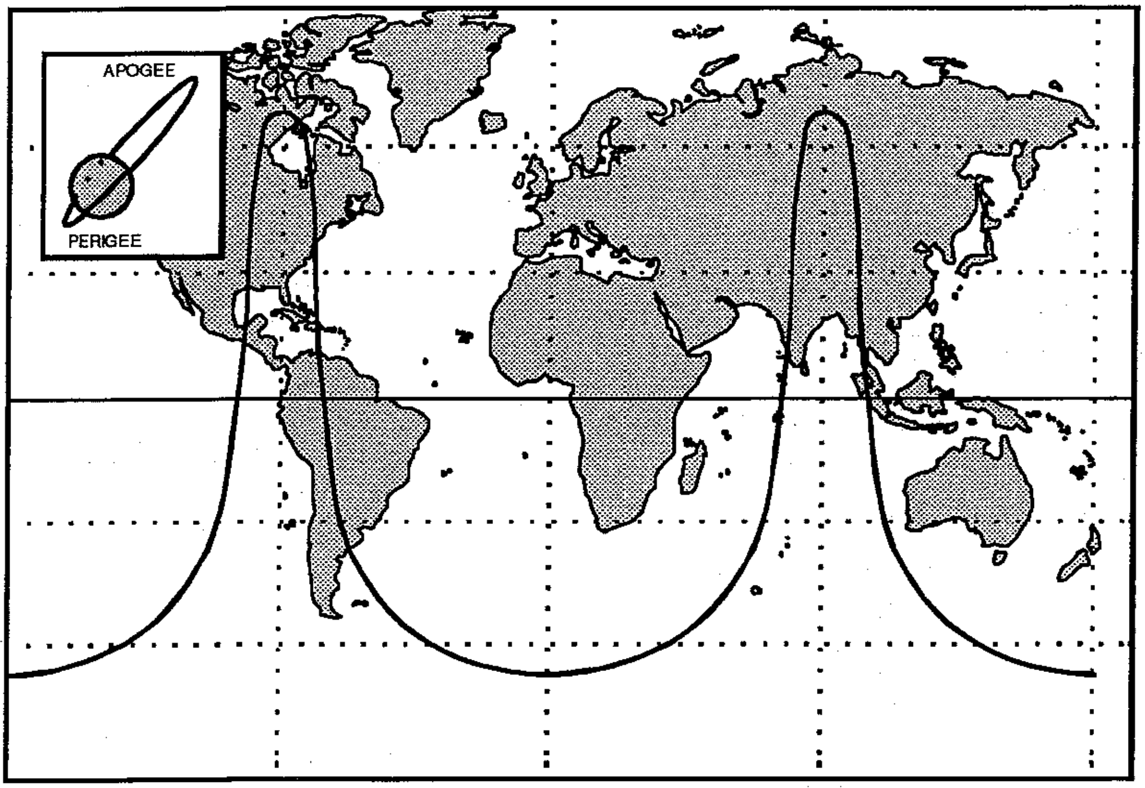

Figure 3.12. Effect of Eccentricity

Figure 3.12 represents the ground trace of an highly eccentric orbit with an inclination of 63°. Perigee, where the satellite is moving fastest, is over the southern hemisphere, while apogee, where the satellite is moving slowest, is over the northern hemisphere. The Soviet Union had a particular application for an orbit such as the one depicted in Figure 3.12, which they call a 'Molniya'[16] orbit. The Molniya orbit will be discussed in more detail later in this chapter.

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[16] Molniya means 'lightning' in Russian.

The Effect of Period

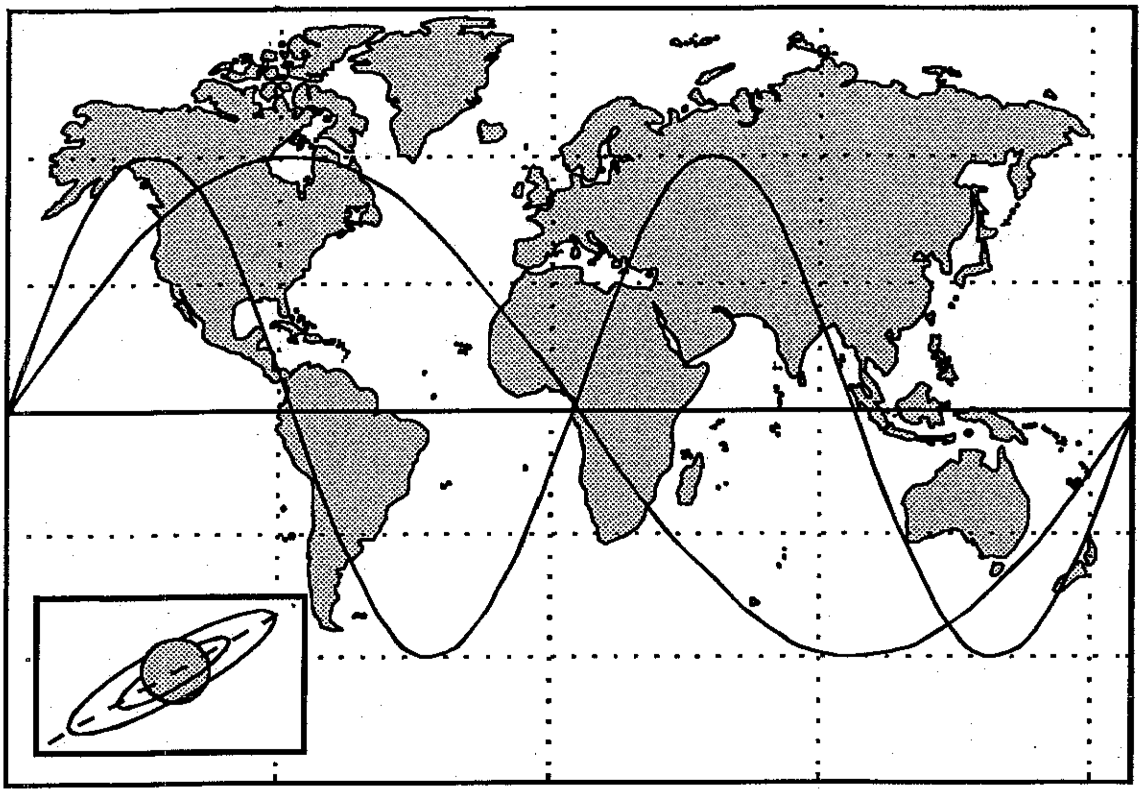


Figure 3.13. The Effect of Period

As the altitude of an orbit increases, so does its period (recall Table 3.1). In Figure 3.13, the satellite in the higher altitude orbit, with its correspondingly longer period, is represented by the ground trace with the lower frequency. This is a logical result, if you think back to the earlier discussion on the relationship between orbital period, altitude and velocity. The satellite at the higher altitude is travelling more slowly than its counterpart at the lower altitude. Hence, in a given period of time, the higher satellite will cover a smaller angular distance, as measured along the Earth's equatorial plane, than will the lower satellite. Consequently, the higher satellite's ground trace will exhibit the lower frequency.

Note that both of the orbits illustrated have the same inclination.

PERTURBATIONS

As mentioned at the beginning of this chapter, the Earth does not conform to the idealised model we have considered so far, and because of that, satellite orbits will deviate from their theoretical Keplerian paths. These deviations are called perturbations. Perturbations can be related to:

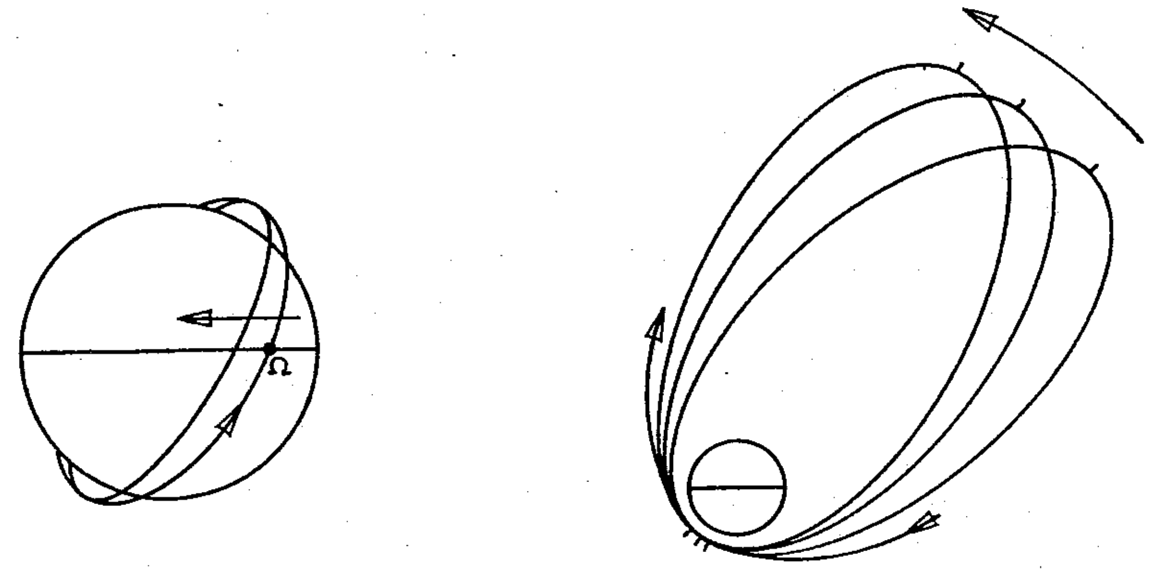
a. time (secular perturbations); or

b. period (oscillatory perturbations).

Oscillatory perturbations are generally small, self correcting and generally of little concern. Secular perturbations can be substantial, and must be accounted for when considering the satellite's design life to ensure enough fuel is carried to correct for them.

Secular perturbations arise primarily from the fact that the Earth is not circular, but is an oblate spheroid. That is, the Earth has a distinct equatorial bulge. The gravity gradient produced by this uneven distribution of mass imposes an unbalanced force on the satellite as it moves along it orbital path, causing a perturbation. Secular perturbations tend to cause a long term evolution of the orbit. Most notably, the position of the ascending and descending nodes (henceforth, simply referred to as the 'nodes') and the point of perigee of the orbital plane will precess by a few degrees each orbit. The precession of an orbit's nodal points is referred to as the ***'regression of nodes'*** as opposed to the ***'apparent regression of nodes'*** described earlier in the chapter. Precession of the point of perigee is called ***'the rotation of apsides'***. The rate of rotation of apsides is proportional to satellite altitude and inclination. Inclinations of 63.4° and 116.6° present a special case: at these inclinations the rate of rotation of apsides is zero.

Figure 3.14 illustrates the effect of the regression of nodes and the rotation of apsides. These perturbations must be monitored and corrected if orbital integrity is to be maintained.



a. Regression of Nodes **b. Rotation of Apsides**

Figure 3.14. Perturbations Due to the Earth's Oblateness[17]

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[17] Bosher, V., *Uses of Satellites in Reconnaissance*, WRE Technical Note 1339(AP), Weapons Research Establishment, Department of Defence, 1984, Figure 4.

Orbital perturbations may also be caused by atmospheric drag. Atmospheric drag particularly affects satellites in very low circular orbits or eccentric orbits with low perigees. The effect of atmospheric drag on a satellite in a circular orbit has already been discussed. Atmospheric drag on a satellite in an eccentric orbit will decrease the orbit's eccentricity. The altitude of apogee is lowered with each rotation until the orbit is circularised. This effect is illustrated by Figure 3.15. If the desired eccentricity is to be maintained over time, the orbit must be adjusted by regular boosting at perigee.

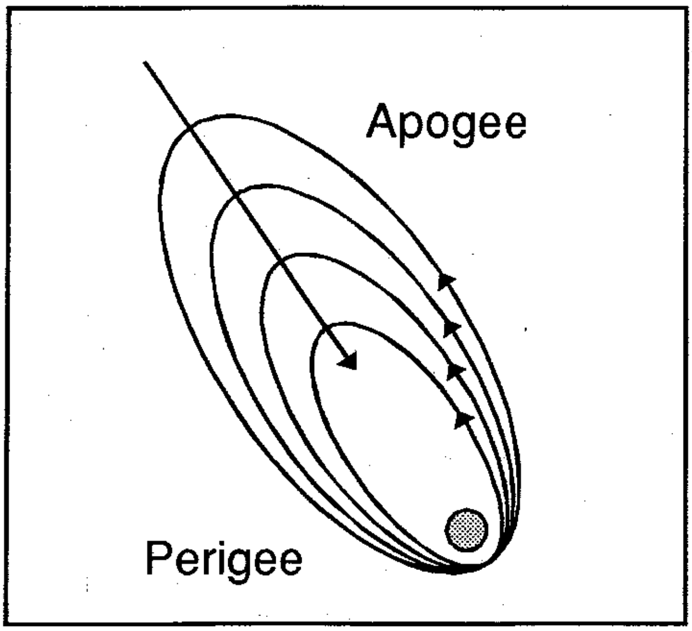

Figure 3.15. The Altitude of Apogee Decreases Due to Atmospheric Drag at Perigee

SPECIALISED ORBITS

There are two specialised orbits which require closer examination. These are the sun-synchronous orbit and the Molniya orbit.

Sun-Synchronous Orbit

Many civilian remote sensing satellites and military reconnaissance LEO satellites employ sensors which operate in the visible and near IR bands of the EM spectrum. The primary source of energy in these parts of the EM spectrum is reflected solar radiation. To optimise the amount of reflected solar radiation at the sensor, orbital parameters are chosen which cause the satellite to cross any given latitude at the same local mean time each day. The orbit must also be designed to account for the rotation of the Earth about the sun. Whilst the satellite is orbiting the Earth, the Earth is orbiting the sun at a rate of just under 1° per day. To maintain its orientation with the sun, the satellite's orbital plane must be rotated about the Earth at the same rate, such that the point of the satellite's ascending node rotates about the equator once per year. An orbit designed to achieve these requirements is called ***'sun-synchronous'***. Table 3.2 lists a small selection of orbital elements which deliver low earth sun-synchronous orbits. Figure 3.16 illustrates the concept of the sun-synchronous orbit.

Table 3.2. Sun Synchronous Orbital Parameters[18]

Orbital Altitude (km)	Inclination (deg)	Period (min)	Orbital Velocity (km/sec)
250	96.19	89.52	7.750
500	97.41	94.68	7.607
800	98.57	100.92	7.446
1000	99.49	104.10	7.344

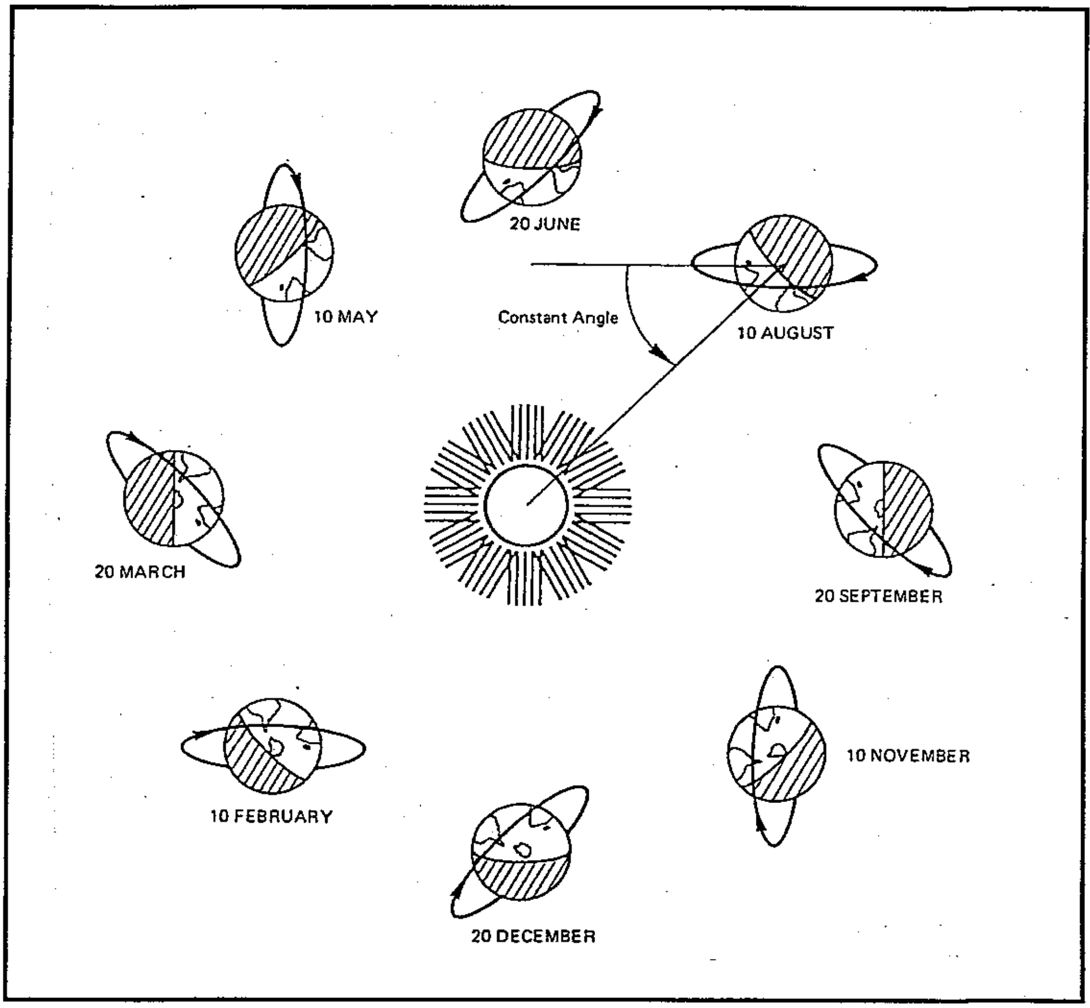

Figure 3.16. The Sun-Synchronous Orbit[19]

Molniya Orbit

The Soviets required an orbit that could provide satellite communication across the USSR's high northern latitudes. GEO was of little use, as satellites in that orbit could not 'see' up into the higher latitudes. The Soviets needed an orbit that would allow their communication satellites to spend as much time as possible over the polar regions of the northern hemisphere. The Molniya orbit was devised to satisfy that need. Molniya's orbital parameters are as follows:

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[18] Chen, H.S., *Space Remote Sensing Systems*, Harcourt Brace Jovanovich, 1985, p 205.
[19] *SPOT User's Handbook*, Volume 1, SPOT Image, Toulouse, 1988, p 2-8.

Semi-Major Axis: 23,554 km;
Period: 11.967 solar hours;
Eccentricity: 0.69 - 0.74;
Inclination: 63.4°[20];
Right Ascension of the Ascending Node: 0° - 360°; and
Argument of Perigee: 270°.

Figure 3.17 illustrates a Molniya orbit and its associated ground trace. Note that the satellite spends over 10 hours of its 12 hour period over the northern hemisphere, where it could service the USSR's, and presumably now Russia's communications needs.

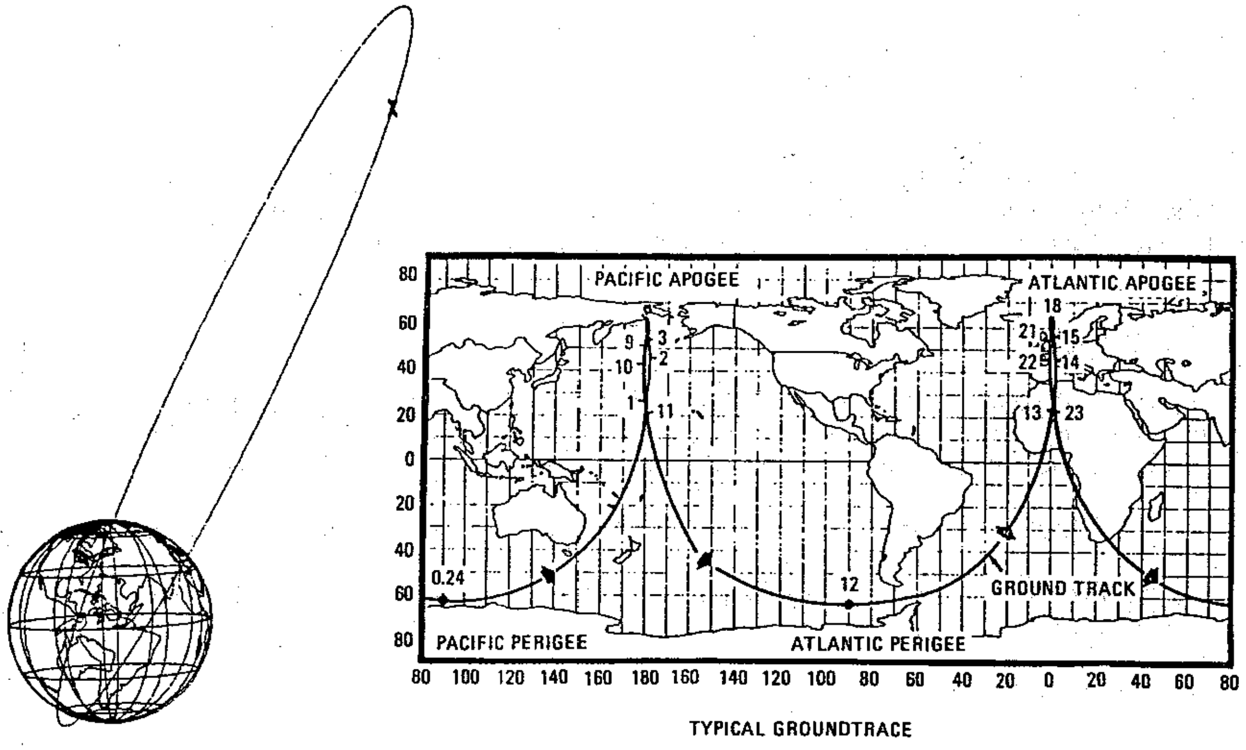

Figure 3.17. The Molniya Orbit[21]

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[20] The inclination of 63.4° is chosen to prevent the rotation of apsides.
[21] Cantafio, op cit, p 70.

ORBITAL MANOEUVRING

Orbital manoeuvring is required for three basic reasons:

a. to insert a satellite into its desired orbit,

b. to make adjustments to maintain the desired orbit, and

c. to change orbital elements to achieve specific mission requirements.

Before proceeding any further with this subject, it must be emphasised that significantly changing a satellite's orbital path is not a trivial task. Satellites travel at extremely high velocities, and to effect a change in orbital parameters requires the expenditure of a large amount of energy. The popular fallacy that satellites can be positioned as required to meet specific contingencies is simply incorrect. Satellite orbits are dictated by the laws of physics, not the latest contingency. Whilst changing a satellite's orbit may be possible if the satellite is carrying enough fuel, the satellite's design life will almost certainly be shortened by completing such a manoeuvre. An overwhelming tactical or strategic imperative would have to arise before such a course of action could be considered.

The major point to be made is that satellites and satellite orbits are designed to satisfy the requirements of a specified mission for a specified period. Any significant deviation from that specification will ultimately compromise the original mission.

Modifying an Orbit

The orbit of a satellite can be modified through the application of thrust. If thrust is applied in the direction of travel, the orbit will increase in size. If the satellite is turned and thrust applied in the opposite direction, called ***'retro-firing'***, the orbit will decrease in size.

There is a simple rule to remember concerning changes in orbital parameters:

> ***A satellite will always return to the point at which the application of thrust was terminated.***

This point can be best illustrated by example.

Changing Eccentricity. Consider Figure 3.18. The satellite is boosted or 'kicked' at perigee. Energy is added to the orbit and it becomes more eccentric. Note that the point of perigee, where thrust was applied, has not changed.

Figure 3.19 illustrates what happens if the satellite is boosted at apogee. Again, energy has been added and the orbit increases in size, but in this case, it becomes less elliptical. If the correct amount of boost is applied, the orbit will become circular. This technique, called ***apogee kick***, is useful for circularising eccentric orbits.

Changing Altitude. Altitude changes, for example, moving from one circular orbit to a higher circular orbit, are generally achieved by either:

a. Hohmann Transfer. The Hohmann transfer is named after the man who first proposed the method in 1925. Orbital altitude is increased by two kicks. one at the original perigee to make the orbit more eccentric, and one at the new apogee to circularise the orbit at the higher altitude. The Hohmann transfer is the most fuel efficient, but also the slowest method of increasing orbital altitude. The Hohmann transfer may also be used to decrease orbital altitude through the use of two retro-firings.

b. Fast Transfer. The fast transfer, as the name implies, takes less time to complete than a Hohmann transfer, but it does use more fuel as overall, the change is satellite vectors are more extreme. To initiate the fast transfer, the satellite is kicked from any point in the lower orbit into an elliptical orbit that will intersect the final higher orbit. As the satellite approaches the point of intersection with the higher orbit, another kick injects it into the new orbit.

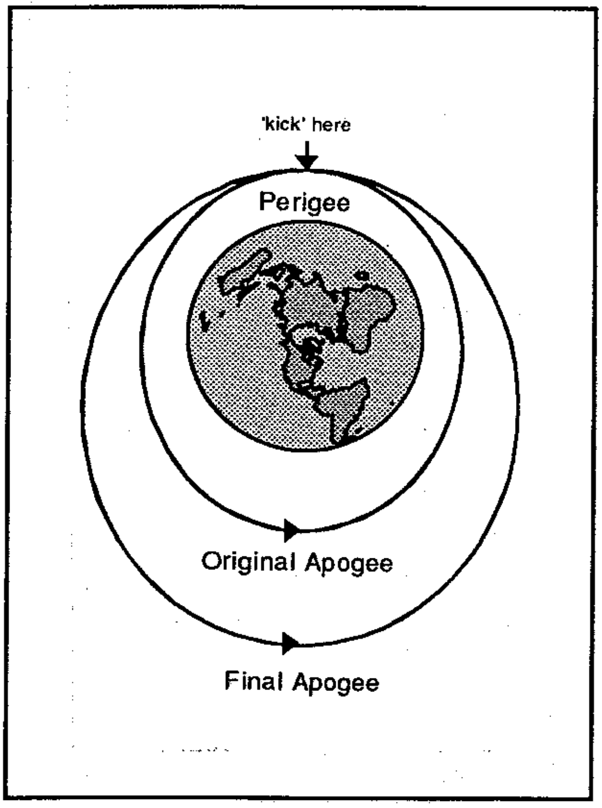

Figure 3.18. Boosting at Perigee Increases Eccentricity[22]

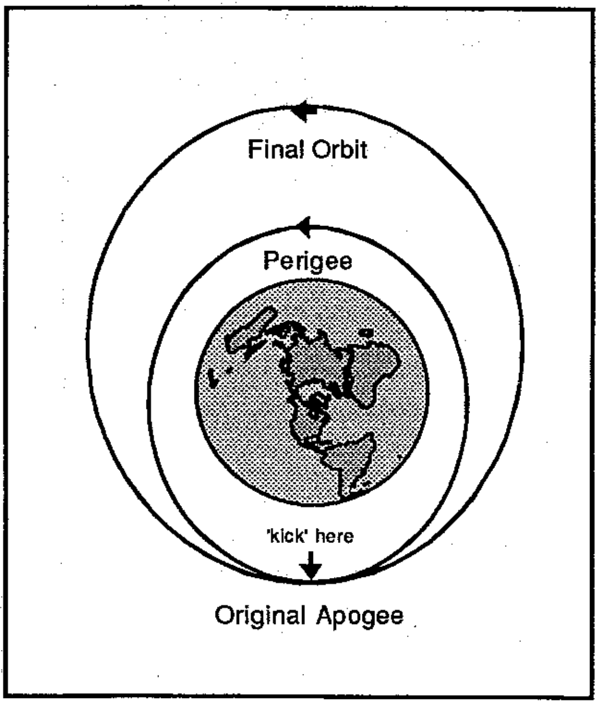

Figure 3.19. Boosting at Apogee Decreases Eccentricity[23]

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[22] Adapted from: Damon, op cit, p 39.
[23] ibid. p 39.

Launch to Geosynchronous Orbit. Figure 3.20 illustrates the steps to GEO using a Hohmann transfer.

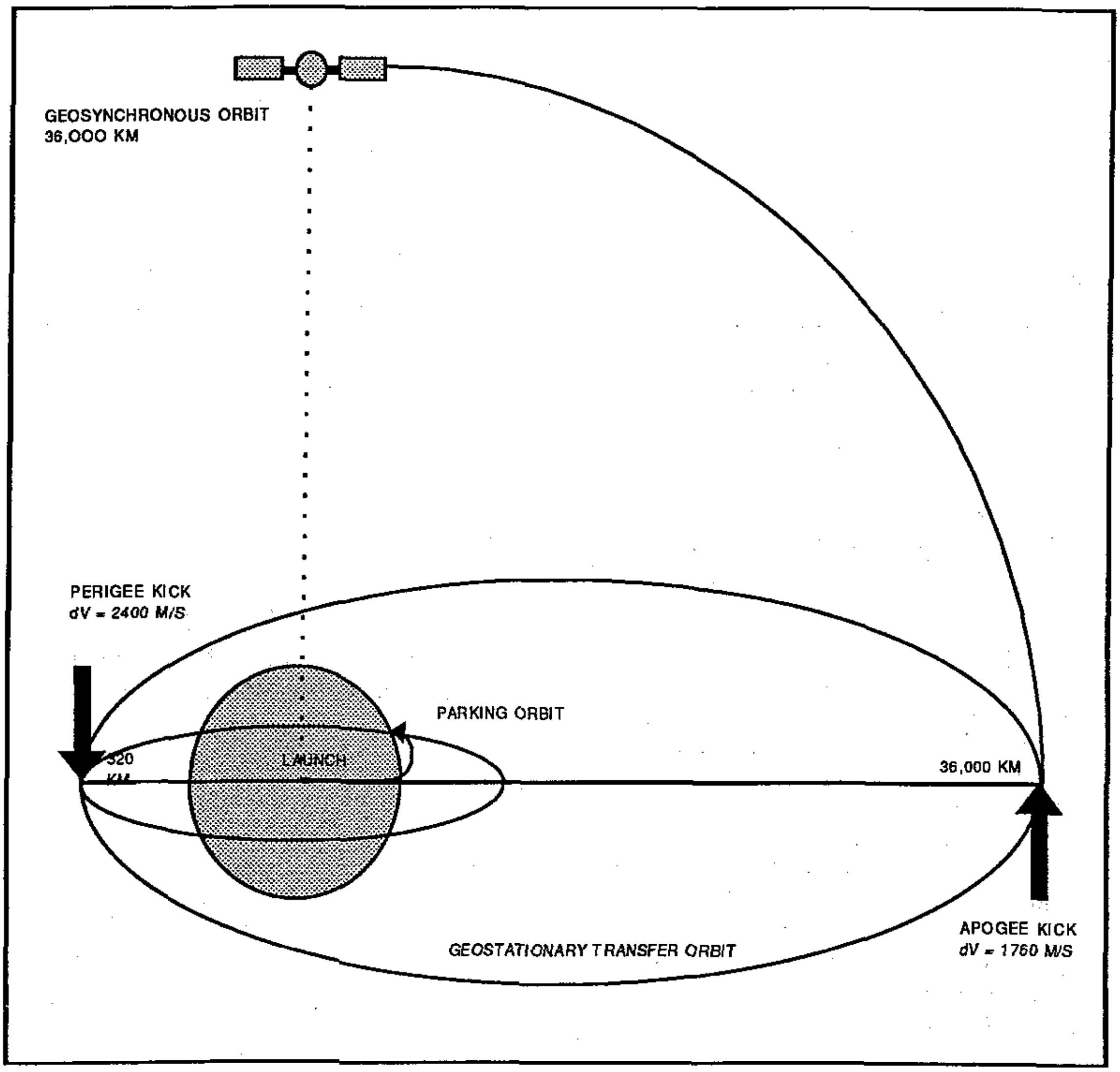

Figure 3.20. The Steps to Geosynchronous Earth Orbit[24]

Plane Changes. So far we have only considered changing orbital parameters whilst maintaining the same orbital plane. But what if a plane change is also required, for example, to change orbital inclination without changing any other parameter? To achieve this, boost must be applied to affect the plane change at a common point in both orbits. If the other orbital parameters are to be maintained after the manoeuvre, then the plane change must occur at either the ascending or descending node of the original orbit.

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[24] Adapted from: Elbert, B., *Introduction to Space Communication*, Artech House, Norwood, Massachusetts, 1987, p 262.

De-orbit. De-orbit and re-entry into the Earth's atmosphere is achieved by retro-firing to facilitate a transfer to an orbit which intersects the surface of the Earth (see Figure 3.21). The location and the duration of the retro-fire must be tightly controlled to ensure that the satellite lands in the correct location. However, despite accurate calculation, the vagaries of atmospheric drag will always distort the re-entry profile, making exact determination of the '***splash-down***' point difficult.

Other Parameters. Any of the parameters of the orbital element set can be changed with the appropriate application of vectored thrust and a sufficient quantity of fuel. It is not possible to cover all of the permutations of orbit modification in this book. However, the basics discussed above should be sufficient to establish the principles involved.

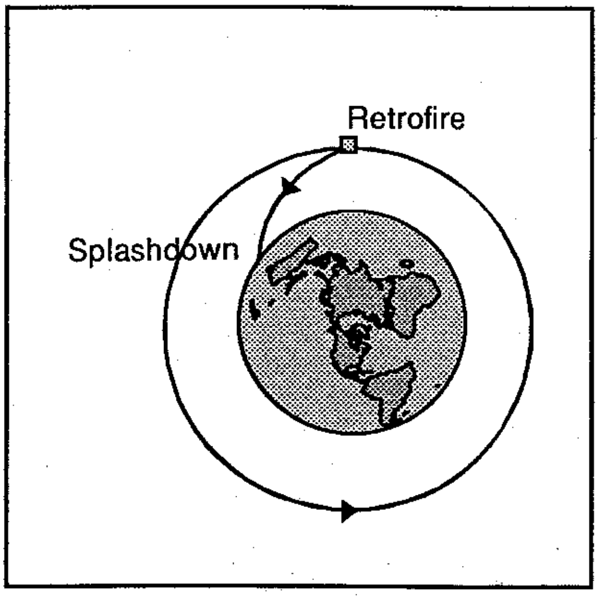

Figure 3.21. De-orbit Manoeuvre[25]

LAUNCH MECHANICS

The objective of the launch system is to place the payload into its correct orbit. It is not the aim of this chapter to discuss specific launch systems, but rather present the factors that must be considered when launching a payload.

The Launch Sequence

The sequence of events required to launch a satellite will be largely dictated by the final orbit into which it must be placed. For example, Figure 3.20 depicted the sequence of on-orbit events required to place a satellite into GEO, a complex task usually requiring the use of a two or three-stage launch vehicle. Table 3.3 lists the sequence of events required to place a satellite into GEO from the point of lift-off onwards. Whilst examination of the table indicates that the task is quite complex, it does not do justice to the amount of underlying development and planning.

Launch into orbits lower than GEO can generally be achieved in fewer steps, with a commensurately more simple task profile. However, Table 3.3 is indicative of the general effort required to achieve orbit.

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[25] Damon, op cit, p 41.

Table 3.3. Sequence of Events for Launch into GEO[26]

Sequence	Event
1.	Lift Off Using Main Booster.
2.	Injection Into Parking Orbit.
3.	Perigee Kick Motor Firing.
4.	Injection Into Transfer Orbit.
5.	Telemetry, Tracking and Control Link Established With Ground Control.
6.	Re-Orientation of Satellite to Apogee Motor Firing Attitude.
7.	Apogee Kick Motor Firing.
8.	Orbital Adjustments.
9.	Drift to Assigned Geosynchronous Longitude.
10.	Orbit And Attitude Adjustment.
11.	Satellite Fixture Deployments.
12.	Satellite Bus Testing.
13.	Satellite Payload Testing.
14.	Start Operations.

Launch Windows and Launch Vehicle Performance[27]

Satellites cannot be launched at any time that happens to suit the operator. Factors which dictate when a launch is possible include:

a. the ***'launch window'***, and how it is affected by launch site latitude and launch azimuth;

b. the excess performance of the launch vehicle; and

c. the Earth's rotational velocity.

Launch Windows. The term launch window defines the times when the most efficient launch can be achieved from a particular launch site into a particular orbit. The launch window is determined by two factors:

a. the excess performance of the launch vehicle, and

b. the latitude of the launch site.

Launch Vehicle Excess Performance. Excess performance gives the launch vehicle the capability to both lift and steer the payload. The launch vehicle's excess performance will determine the length of the launch window. The greater its excess performance, the longer the launch window remains open. As well as extending the launch window, the availability of excess performance also makes it possible to overcome less than optimal launch geometry (that is, the relationship between the plane of launch site and the plane of the desired orbit). Within the limits of the launch vehicle's excess performance, the length of the launch window and the amount of steering available for a plane change can be directly traded against each other.

Latitude of the Launch Site. The latitude of the launch site restricts the inclination into which a satellite can be directly inserted (that is, inserted without undertaking a plane change). Inclinations available for direct insertion are restricted to values greater than or equal to the latitude of the launch site. A launch due east or west of the launch site determines the minimum inclination of the orbit; any other launch azimuth will result in an inclination greater

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[26] Elbert, op cit, p 263.
[27] Morse, op cit, p 14.

that of the latitude of the launch site. Table 3.4 compares the number of direct insertion opportunities per day with launch site latitude.

Table 3.4. Launch Opportunities per Day

Latitude of Launch Site	Direct Insertion Opportunities per Day
Latitude < Desired Inclination	2
Latitude = Desired Inclination	1
Latitude > Desired Inclination	0

The direct insertion limitations listed in Table 3.4 can be overcome by undertaking an energy expensive plane change manoeuvre at some point during the launch phase. The completion of such a manoeuvre would require the use of launch vehicle with sufficient excess performance and agility. Use of such a vehicle (assuming it was available) would increase the cost of the launch significantly.

The Earth's Rotational Speed. The Earth's east-west rotational speed is a maximum at the equator (1,680 kph) and zero at the poles. Consequently, any launch in an easterly or prograde direction will receive a velocity boost in proportion to the latitude of the launch site. Conversely, a westerly or retrograde launch must overcome the Earth's rotational velocity before the payload can achieve orbital velocity.

Equatorial Launch Sites. Theoretically, the most advantageous launch geometry can be obtained by launching from the equator in an easterly direction. First, it allows direct injection to any inclination. Second, it makes full use of the boost given to the launch by the Earth's rotation. Unfortunately, there are no launch sites located on the equator at present. The closest is the French site at Kourou, in French Guiana, South America. That site has a latitude of 5°N.

Proposed Australian Launch Sites. There are two proposed Australian launch sites: Cape York, at a latitude of 12°S; and Woomera, at a latitude of 31°S. Each of these, with its associated launch trajectories, is shown in Figure 3.22. Satellites could be launched into GEO and LEO from Cape York. A refurbished Woomera could be used to launch into LEO.

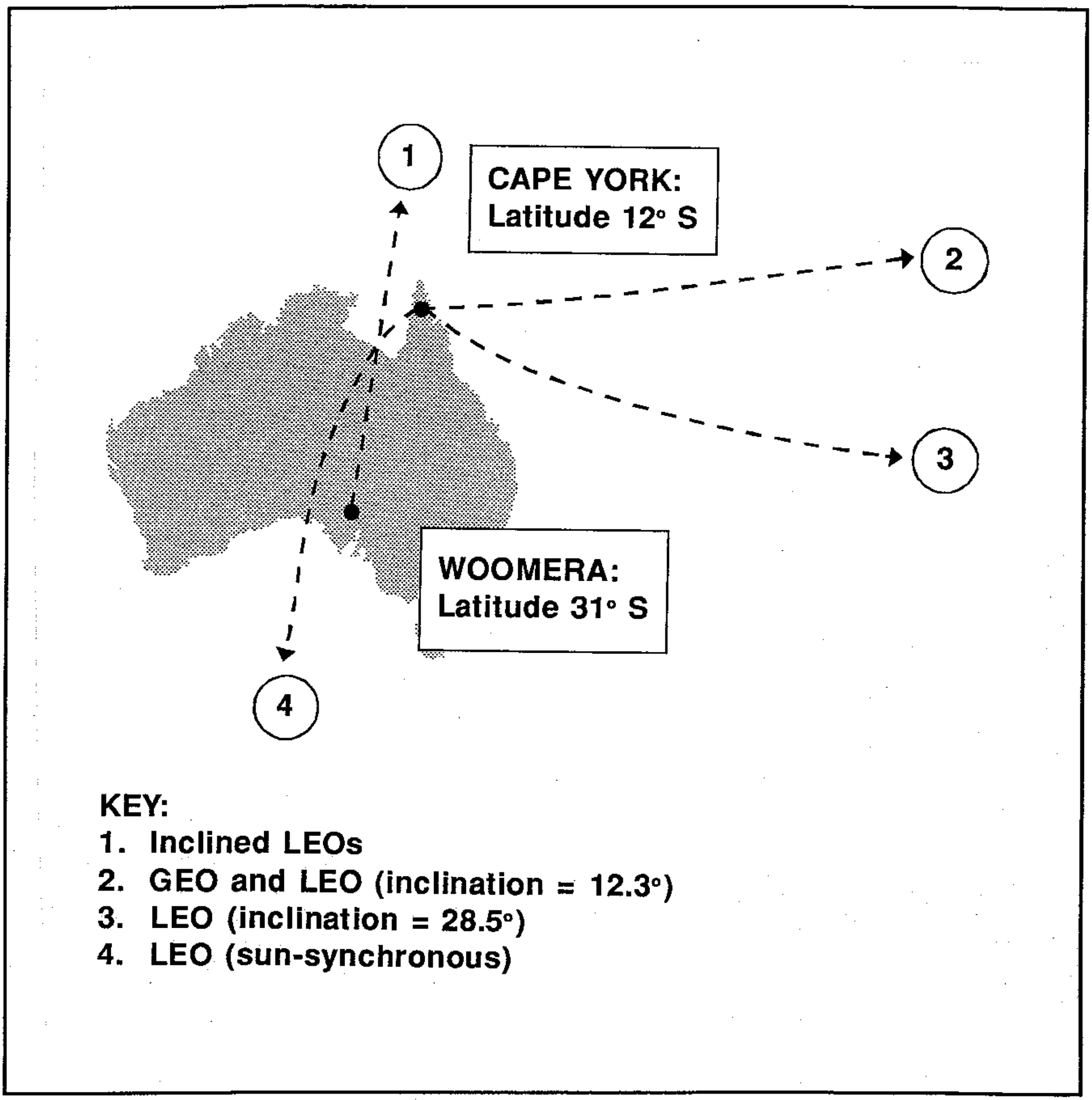

Figure 3.22. Proposed Australian Launch Sites

CHAPTER FOUR

SATELLITE OPERATIONS

In the previous chapters the environment in which spacecraft operate and the physical laws which govern their trajectories in that environment were presented. This chapter will examine the satellite and satellite operations in more detail. For those readers requiring data on current operational satellites, a directory is included at Annex B.

Satellite operations can be separated into three functional segments:

a. ground control systems,

b. satellite systems, and

c. user systems.

Each will be discussed in turn.

GROUND CONTROL SYSTEMS

Irrespective of size, complexity or mission, all satellites require a ground control system to monitor and control their operation. The ground control system will include a communications system for ground/space communications. Ground facilities range in complexity from master control stations responsible for several constellations of satellites down to simple remotely controlled monitor sites.

Irrespective of the specific arrangement employed, the ground system is required to complete three basic functions. These are:

a. ***telemetry***, to obtain data from the satellite;

b. ***tracking***, to locate and track the satellite in space; and

c. ***command***, to tell the satellite what to do and when to do it.

A testing or research and development (R&D) function may sometimes be added to this list. These functions combine to form what is generically entitled the ***Telemetry, Tracking and Command***, or TT&C system. The functional requirements of each component of the TT&C system will be briefly examined, before the system is considered as a whole.

Telemetry

Telemetry may be defined as *'the automatic measurement of something distant or inaccessible and the transmission of the results to a recording or display device'*[1]. As applied to space-based systems, telemetry refers to data gathered by sensors onboard the satellite for transmission to a ground station. Two basic types of data are telemetered to earth:

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[1] *Macquarie Dictionary.*

a. Satellite Health Data. Satellite health data includes the state of the onboard systems, such as battery condition, solar panel performance, thermal condition, computer status, mission status, etcetera.

b. Payload Data. Payload data pertains to the mission of the satellite. It represents the output of the primary sensors of the satellite, and may be transmitted in raw or processed, compressed or uncompressed forms.

Telemetry with a geosynchronous satellite is quite simple, as it effectively 'hovers' within the field of view (FOV) of its ground station. However, unless data relay satellites are used, data gathered by satellites in LEO can only be telemetered to a ground station as the satellite passes through its ground station's FOV. This limitation can be overcome by proliferating ground stations about the globe, but this approach introduces its own problems. The argument is expanded below.

Use of One Ground Station. When only one ground station is available for telemetry, the satellite must store each orbit's data and down-link it as it passes through that ground station's FOV. This may prove to be impractical for two reasons. Firstly, most satellites gather an enormous amount of data during each orbit. Insufficient time may be available to dump the data to the ground station as the satellite passes overhead, even using data compression techniques and high speed down-links. Secondly, one ground station offers no redundancy.

Use of Multiple Ground Stations. The use of multiple ground stations addresses the problems of a single site. However, multiple ground stations pose their own problems. Ideally, ground stations should be fairly evenly distributed about the globe. Whilst this may cause only a minor problem for civilian operators, the military may experience difficulty in finding suitable sites for ground stations in other countries. Problems with international treaties, sovereignty, and security may dramatically limit the choice of sites, and consequently the utility of the satellite system. Additionally, proliferating sophisticated satellite ground facilities is expensive.

Use of Tracking, Data and Relay Satellites. If siting ground stations on foreign soil is a problem, then one solution is to eliminate the requirement for them. Ground stations can be replaced by satellite-based data relay systems which direct TT&C data back to centralised facilities. NASA has implemented such a system with its Tracking, Data and Relay Satellite System (TDRSS). TDRSS uses two geostationary relay satellites (with two on-orbit spares) to provide TT&C for up to 40 satellites on a time-share basis, or 26 satellites simultaneously. Two new TDRSS satellites are due for launch in the mid 1990s. TDRSS links seven US ground stations with seven NASA satellites and an undisclosed number of US military satellites. The first TDRSS satellite was launched from the Space Shuttle in 1983. TDRSS has allowed NASA to close or transfer 15 ground stations which were located on foreign soil. The NASA site at Honeysuckle Creek, near Canberra, was one of the sites made redundant by TDRSS. However, technology such as TDRSS is expensive. If the mid 1990s launches are included, the total cost of TDRSS will be US$3.0 billion.

The speed at which payload data is able to be telemetered to the ground is usually the determining factor in an imaging systems resolution and swath width. The sensor can gather data at a rate far in excess of the telemetry system's capacity to transmit that data to a ground station, even if state of the art data compression techniques are used. In this situation, the user has to decide which factor is more important: swath width or resolution. These can be directly traded against each other within the limited capacity of the telemetry system. Which takes precedence will be determined by the satellite's primary mission.

Tracking

The tracking function of the TT&C system involves locating a specific satellite in space and following its movement. Satellites are tracked to enable the communication of command and telemetry data and the determination and monitoring of orbital elements.

Satellite track data, which typically include elevation, azimuth, range and range rate, are used to direct the ground station's antennae towards a particular satellite. Whilst it is easy to track satellites in GEO, satellites in LEO pose more of challenge due to their high ground trace velocities. To demonstrate this point, Figure 4.1 illustrates the FOV of the 9.14 m antenna located near Alice Springs owned by the Australian Centre For Remote Sensing (ACRES). The site tracks and obtains telemetry data from a number of LEO remote sensing satellites, including NASA's Landsat satellite. Landsat traverses the ACRES ground station's FOV in only 11 minutes. Over that period, the ground station accepts telemetered data gathered by the satellite across its 185 km swath width.

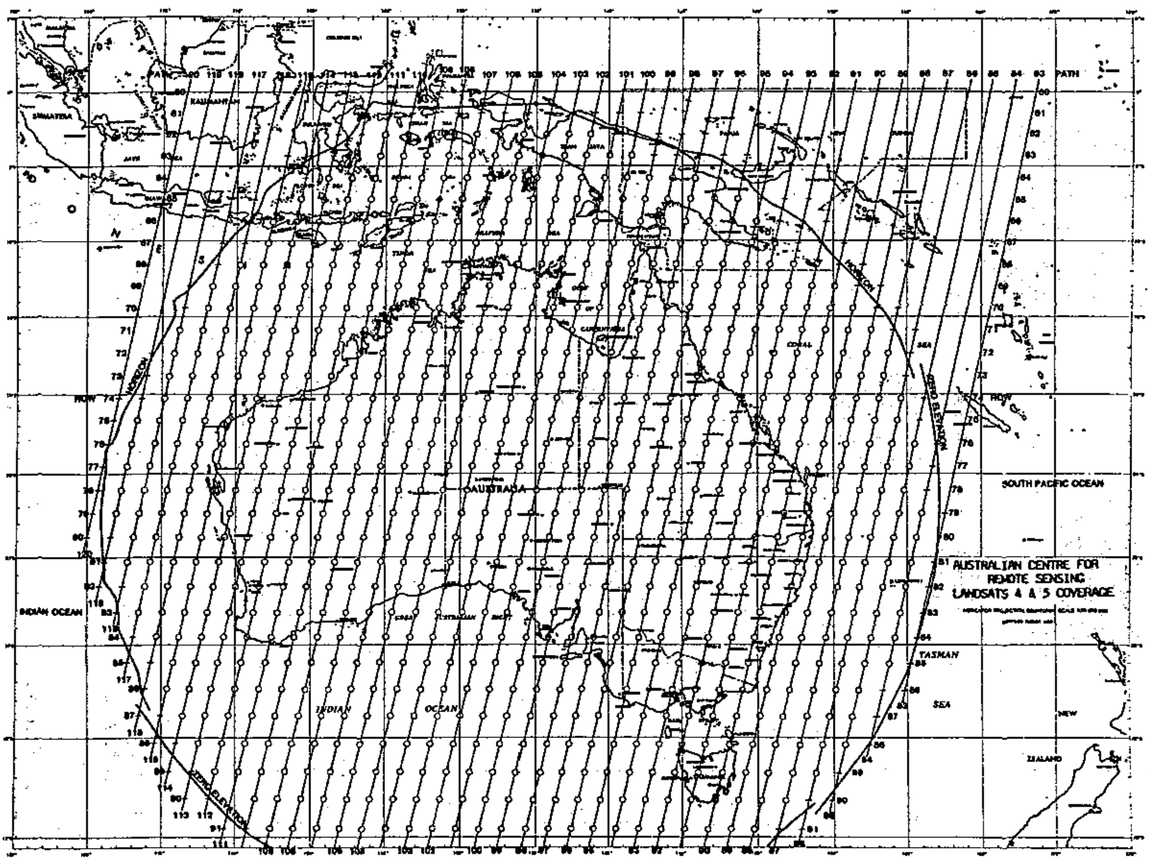

Figure 4.1. ACRES Landsat 4 & 5 Coverage[2]

Command

The command function of the TT&C link may be thought of as complementary to the telemetry function. Usually, commands are issued in response to data telemetered from the satellite. Commands can be issued for either real-time or delayed execution, and can range from simple on/off type instructions to complete mission re-programming. Unless a system such as TDRSS is used, commands can only be issued to a satellite whilst it is within the FOV of a ground station.

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[2] *ACRES Thematic Mapper Products*, Australian Centre For Remote Sensing, Canberra, August 1989, p 7.

TT&C Facilities

Figure 4.2 illustrates the general arrangement of a TT&C facility. The particular system shown is used to control two geosynchronous communications satellites, hence the use of limited motion communication antennas. A TT&C facility controlling LEO satellites would require full rate antennas. Full rate antennas are also required for launch and orbit adjustment procedures.

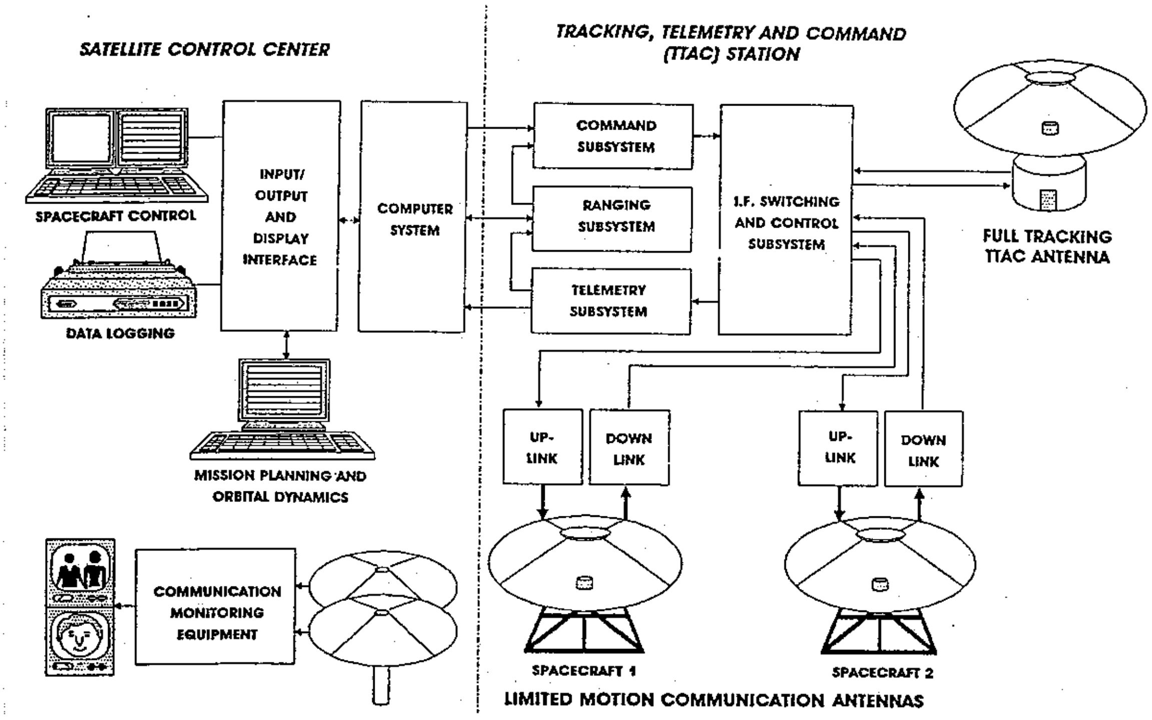

Figure 4.2. General Arrangement of a TT&C Facility[3]

Communications Links

Ground stations provide the communications systems necessary to:

a. access the satellite for TT&C; and

b. interconnect the satellite with terrestrial networks, or 'tails'.

Whilst detailed communication system design is beyond the scope of this book, generically the most important features of the communications link is its capacity and that it be robust. The communications system must be able to work reliably through noise, and military systems must be resistant to jamming[4].

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[3] Elbert, B., *Introduction to Satellite Communication*, Artech House, Norwood, Massachusetts, 1987, p 232.

[4] Space system vulnerability is discussed in Chapter Nine.

SATELLITE SYSTEMS

Satellites are very carefully designed and built. They must be completely reliable. They must be able to withstand years of service in the harsh environment of space. They must be light, yet the strong enough to withstand the rigours of launch. They must either carry or generate sufficient power to satisfy the lifetime demands of sensor, attitude, processing, thermal control, and communications sub-systems. The requirements listed above are common to all satellites, irrespective of mission. Consequently, all satellites include a standard set of sub-systems, encompassing:

a. the TT&C sub-system;

b. the electrical power sub-system (EPS);

c. the thermal control sub-system (TCS);

d. the structural sub-system (SS); and

e. the attitude and orbit control sub-system (AOCS).

Each sub-system will be briefly examined in turn.

The TT&C Sub-System

As with the ground station's TT&C facility, the function of the satellite's TT&C system is to support up and down-link TT&C communications. The TT&C system must:

a. receive commands from the ground station(s) for either immediate or delayed execution, and

b. transmit payload and health data to the ground station(s).

The Electrical Power Sub-System

The function of the EPS is to generate, store, control and distribute electrical power to the satellite's sub-systems. The power requirements of various satellites will vary considerably, depending upon their payload and mission. Current satellites have power requirements ranging from a few hundred to several thousand watts. Power requirements are steadily increasing as satellites become more sophisticated and their missions more demanding. For instance, the US is considering the deployment of a constellation of military radar surveillance satellites early next century. Each of these satellites could conceivably require up to 100 kW of power.[5]

Whilst the instantaneous power requirements of current satellites remains fairly modest, many modern satellites have very long design lives. For example, the B-Series AUSSAT spacecraft, the first of which is due for launch in 1992, are designed to live for 13.7 years. The EPS must be able to reliably supply power to the satellite to satisfy both instantaneous and lifetime demands.

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[5] Cantafio, L., *Space-Based Radar Handbook*, Artech House, Norwood, Massachusetts, 1989, p 37.

To date only three power systems have proven robust and reliable enough to be deployed into space. These are:

a. solar energy systems,

b. chemical energy systems, and

c. nuclear energy systems.

Each of these has particular advantages, disadvantages and applications, which are addressed in the following paragraphs.

Solar Energy Systems

Power production onboard the majority of satellites is achieved by converting solar radiation into electrical energy by means of solar cells. A solar cell is a photovoltaic device: that is, it produces a voltage when exposed to light. Several types of photovoltaic materials have the potential to be used for space power production, but only silicon based cells have been used to date. Silicon based cells have proven to be the best compromise between efficiency and reliability. Solar cells are formed into large panels which are then coated in special materials which enhance the cells' efficiency by protecting them from radiation. This keeps them cooler and enhances their longevity. The protective coating is very necessary, as exposure to radiation gradually destroys the cell. Even with the protective coating, a loss of 15% of the cells on a panel would be typical after five years. To address this problem, an excess number of cells must be available at platform deployment to maintain the system's electrical output above the minimum required level as cells fail over time.

The power density of solar radiation at the Earth's radius from the sun is approximately 1.4 kW/m^2, quite a considerable amount of power. Unfortunately, solar cells are rather inefficient, so only 10-11% of this energy can be usefully harnessed. Solar cells currently produce approximately 22 Watts of power per kilogram. This equates to 100 W/m^2 for a solar panel at 90^o to the incident radiation.

Large arrays of cells are necessary to produce sufficient energy to power a satellite. The solar cells can be either ***body mounted*** on the satellite, or fixed to separate panels which are kept ***oriented*** at 90^o to the incident radiation for peak performance. Some satellites actually employ both systems. Each system has particular advantages and disadvantages.

Body mounted panels are generally affixed to spin stabilised satellites. Effectively, this means only about one third of the cells can generate power at any one time as the others are in eclipse. The positive side to this is that the cells last longer as only the 'sunny' side is subject to radiation damage. Additionally, body mounting the solar cells reduces atmospheric drag. This can be an important factor for a satellite designed to operate in LEO if a long life is required. By minimising atmospheric drag, boosting to maintain orbital altitude is required less frequently. This means less fuel has to be carried onboard the satellite.

Oriented panels have size, weight and efficiency advantages over their body mounted counterparts, but are more complex to deploy and operate, and cause more atmospheric drag. Additionally, they do not last as long as body mounted panels as they are being constantly irradiated. Generally, oriented panels are only used on satellites in orbits higher than 325 km or when the satellite requires more than 500 W of electrical power.[6]

Generically, solar cells, irrespective of the method of mounting, have one major drawback. They do not work when eclipsed or shadowed. A satellite's solar panels will be eclipsed when the satellite is on the dark side of the Earth. This may be for up to 40% of its orbit for a satellite in LEO. Shadowing is caused by parts of the satellite shading the solar panels.

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[6] Cochran, C., et al (ed), *Space Handbook,* Air Command and Staff College, Air University, Maxwell AFB, Alabama, January 1985, p 4-7.

Shadowing can be reduced by good design. For a solar powered satellite, the direct consequence of eclipsing and shadowing is the requirement for battery back-up power.

Finally, one myth concerning solar power must be dispelled.

Solar power is not free.

Solar panels are heavy and bulky, and considerable energy must be expended to place the panels into orbit. The true cost of solar power is met at launch.

Developments in solar panel technology are making panels more efficient, lighter and cheaper.[7] In the future, perhaps around 2005, solar panels should be able to provide tens of kilowatts of power, making them suitable for use onboard the proposed military radar surveillance satellites.

Solar radiation can also be used to power solar heated generating systems. Such systems use turbo-electric, thermo-electric or thermionic devices to convert focussed solar energy into electricity. However, these systems will not be discussed further, as they are still undergoing R&D and are not currently deployed.

Chemical Energy Systems

Electrical energy from chemical sources can be derived from batteries, fuel cells and chemical dynamic systems. Of these, batteries are by far the most prolific, so we will concentrate on these. Virtually every space vehicle ever launched has contained a battery of some kind. They are reliable, cheap, simple and available.

Space vehicle batteries fall into two categories; ***primary*** and ***secondary***. Primary batteries are used as continuous energy sources and are not rechargable. Sounding rockets, which only complete very short missions, often use primary batteries for power. Secondary batteries are rechargable, and are used to back-up another primary power source. Most satellites require secondary batteries to help their EPS cope with uneven power demands. Solar powered satellites require battery back-up to provide power when the satellite is eclipsed. The EPS must ensure that the secondary batteries are fully charged just prior to eclipse.

Mercuric oxide/zinc batteries are generally used as primary batteries, whilst rechargable nickel/cadmium or nickel/hydrogen batteries are used as secondary batteries.

Nuclear Power Systems

Nuclear power systems have not found wide favour or application on spacecraft due to the obvious risks involved, particularly during the pre-launch, launch, and re-entry phases of a mission. The US considers that three design criteria must be met if nuclear power is to be used onboard a spacecraft:[8]

a. any failure during launch, transfer orbit or final orbit should not materially increase atmospheric background radiation;

b. any failure on the launch pad must not release harmful radiation beyond the device itself, nor within the exclusion area; and

c. the device should not produce a local hazard on return to earth.

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[7] Solar panels could be up to 20% efficient using a gallium arsenide (GaAs) instead of silicon substrate for photovoltaic power production.

[8] Cochran, C., op cit, p 4-13.

If these safety criteria can be met, nuclear power is very much in contention for those missions whose length, power requirements or distance from the sun make conventional power systems unsuitable.

Nuclear energy power units under development in the West use radioactive isotopes or nuclear fission to generate heat, which is then converted to electricity by a thermionic or thermo-electric generator.

The USSR was using nuclear power in space since 1967 to power its Radar Ocean Reconnaissance Satellites (RORSATs). This programme has not been without its failures. The catastrophic result of the unplanned re-entry of the RORSAT Cosmos 954 onto Canada in 1978 was mentioned in Chapter Two. This type of incident is not acceptable, particularly when radioactive material is involved, hence the US's caution in adopting nuclear power systems for their spacecraft.

Selection of Power System

The selection criteria for a satellite's power system may be directly derived from its mission requirements. Consideration of these requirements makes the choice of power source a custom solution. To date, the most frequently used power system has been primary solar photovoltaic/secondary battery. This combination has proven itself robust and reliable in a variety of applications, and it has the potential for further refinement. The principle limitation of the system is the overhead the weight and volume the solar panels place on the launch vehicle. Launch vehicle limitations mean that practically, the power output of these systems is limited to about 5 kW.[9] Platforms requiring large amounts of electrical power, such as space-based radar reconnaissance satellites, may demand the use of solar thermal or nuclear power systems.

The Thermal Control Sub-System

The TCS is an important part of any spacecraft. The temperature of each part of the payload must be kept within its operating limits to maintain its performance, reliability and longevity. The TCS must compensate for large environmentally imposed temperature variations and provide for the dissipation of internally generated heat.

TCS' can be categorised into four different types, listed here in order of increasing complexity:[10]

a. passively radiating,

b. expendable heat sink,

c. closed liquid loop, and

d. refrigerative.

The selection of the appropriate cooling system is dependent on the results of a temperature control analysis of mission and payload parameters. This analysis is extremely complex, and difficulties are still experienced in verifying TCS performance during system development.

Temperatures within the satellite are determined by both internal and external sources. Most of the internal heat is generated by electrical componentry. However, if the satellite has a kick motor onboard, considerable thermal control measures must be taken to protect the satellite from the heat it will generate. The most significant sources of external heat include direct solar radiation; and for satellites in LEO, aerodynamic heating of external surfaces.

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[9] Gale, SQNLDR W., *The Potential of Satellites for Wide Area Surveillance of Australia*, Air Power Studies Centre, RAAF Fairbairn, 1991, p 5-7.

[10] Morse, R. et al, *Space Operations Orientation Handbook 2nd Edition*, 1013th Combat Crew Training Squadron, Air Force Space Command Operations, Peterson AFB Colorado, 1 January 1991, p 70.

Generally, unmanned satellites will use a passive TCS. A passive system is simple and light, and works by using internal conduction and external radiation to control temperature. A passive system may employ a combination of thermostatically controlled louvres, internal heaters, reflective external walls and insulated blankets to control temperature. Figure 4.3 illustrates a passive TCS in cross-section.

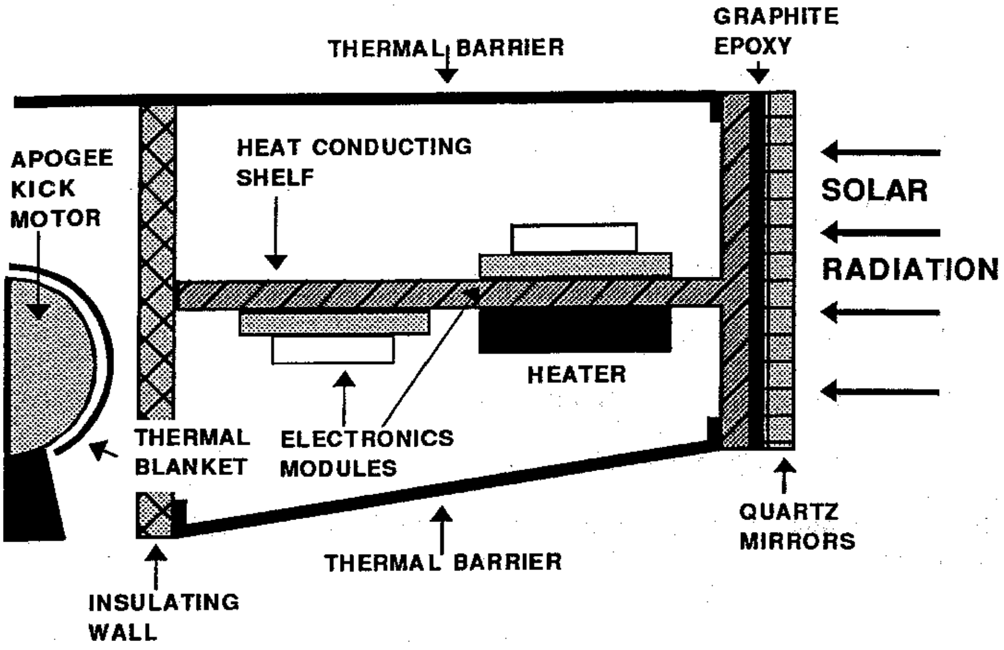

Figure 4.3. Passive Thermal Control System in Cross-Section[11]

Satellites which generate large amounts of heat, such as radar satellites, may demand the use of more a complex TCS, but the tradeoff is increased weight, size, and cost. In turn, heavy satellites increase launch costs and reduce the excess performance of the launch vehicle, which may impose undesirable limits on the selection of orbit.

Current space based radar satellites, most of which use power efficient synthetic aperture radar, are operationally temperature limited. Generally, the radar transmitter can only operate for approximately 10% of each orbit, not because the satellite cannot generate enough power to operate it for longer, but because it cannot be cooled sufficiently quickly.

The Structural Sub-System[12]

The SS provides physical protection for the satellite's payload and sub-systems. It provides the framework for mounting internal components and external equipment such as sensors, solar arrays, antennas and thrusters. The structure may be used to form part of the vehicle's radiation shield. The SS must be able to withstand the stress and strain of ground handling, launch and on-orbit operations.

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[11] Adapted from: Elbert, op cit, p 213.
[12] Morse, op cit, p 71.

The Attitude and Orbit Control Sub-System[13]

The AOCS is used to provide a stable platform from which to operate mission systems. It keeps the payload and communications system oriented and enables precise orbital manouevring and station keeping. Spacecraft attitude may be determined by one or more of the following sensors:

a. earth sensors,

b. sun sensors,

c. star trackers,

d. radio frequency sensors, or

e. gyroscopes.

Stabilisation is provided by one of four methods:

a. two-axis, or spin stabilisation;

b. three-axis stabilisation;

c. zero momentum stabilisation; or

d. gravity gradient stabilisation.

Figure 4.4 illustrates a generic AOCS. Stabilisation control can be completed either onboard the satellite, from the ground via the TT&C link or a combination of both.

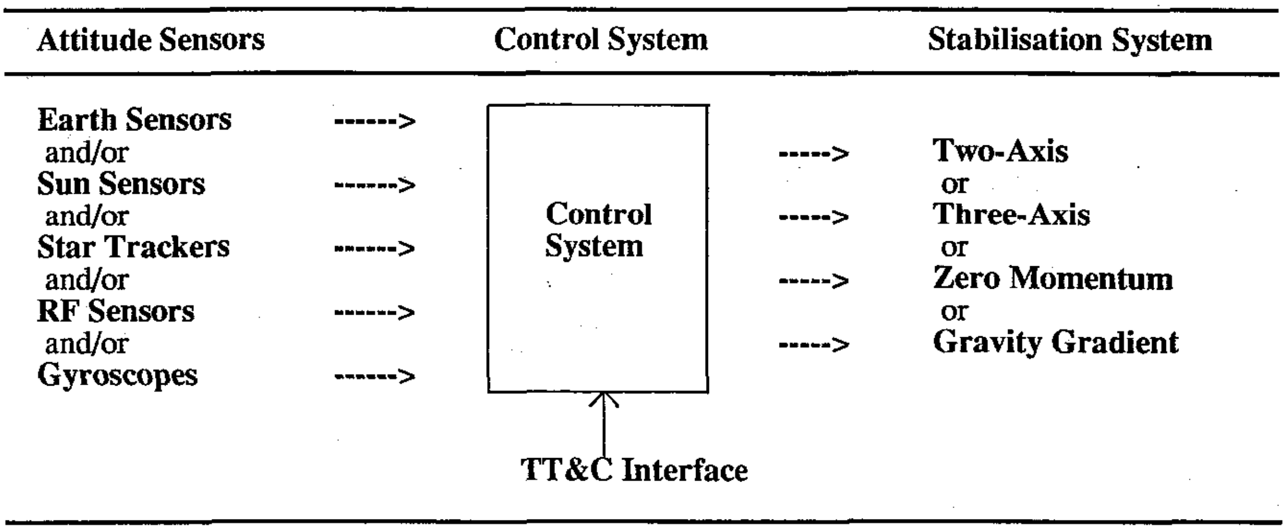

Figure 4.4. Attitude and Orbit Control Sub-System

Spin Stabilisation. Spin stabilisation is accomplished by spinning the main body of the satellite at a fixed rate. Attitude and spin adjustments are performed by onboard thrusters. The antenna and/or sensor platform of the satellite may be de-spun to provide a stable platform. Generally, spin stabilised satellites use body mounted solar panels, although some use a combination of body mounted and oriented panels. A spin stabilised platform is illustrated at Figure 4.5.

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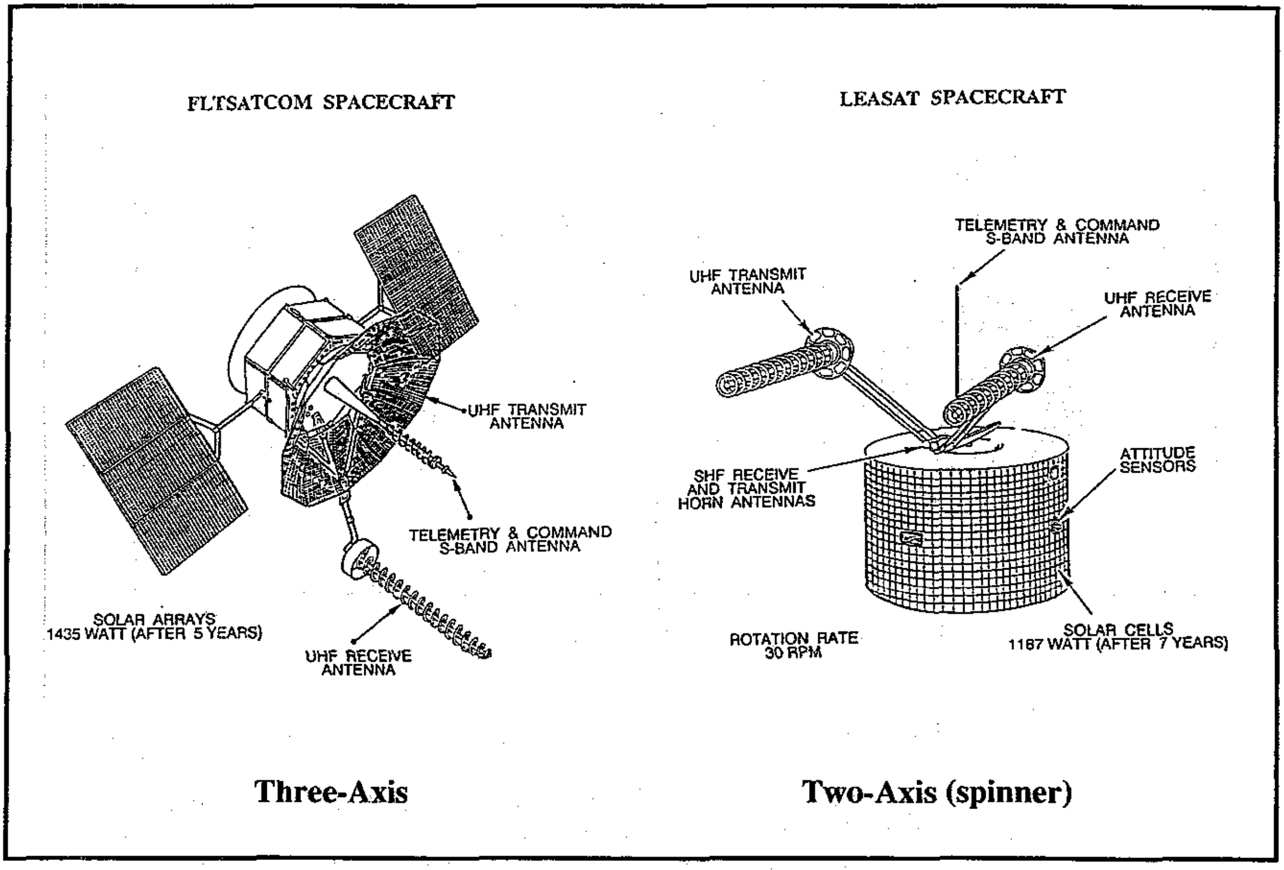
[13] ibid, p 71.

<u>Three Axis Stabilisation.</u> Three axis stabilisation is accomplished by using up to four spinning wheels and/or thrusters to maintain stability. The spinning wheels may be either ***reaction wheels***, which can spin either way, or ***momentum wheels***, which spin in only one direction. The thrusters are used when the wheels cannot maintain attitude. Three-axis stabilised satellites generally use oriented solar panels. A three-axis stabilised satellite is illustrated in Figure 4.5.

<u>Zero Momentum Stabilisation.</u> Zero momentum stabilisation, like spin stabilisation, is accomplished by spinning the satellite at a fixed rate. The difference between spin and zero momentum systems is that the zero momentum system employs a momentum wheel spinning in the opposite direction to satellite body rotation to cancel angular momentum. This design allows thruster, and hence fuel usage, to be reduced to an absolute minimum.



Three-Axis

Two-Axis (spinner)

Figure 4.5. Two and Three-Axis Satellite Stabilisation Systems

<u>Gravity Gradient Stabilisation.</u>[14] Gravity gradient stabilisation can be used on satellites in LEO which do not require a precise pointing capability. Gravity gradient theory dictates that a satellite will automatically try to align its axis of lowest inertia with the local vertical. For gravity gradient stabilisation to be effective, the satellite must have a large inertial momentum. This can be provided by means of deployable arm or arms (up to 100 m long) with a mass at the end. Satellite oscillation must be damped using energy dissipation devices, such as magnetic coils coupled to the Earth's magnetic field. The gravity gradient stabilisation technique is illustrated by Figure 4.6.

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[14] Maral, G. and Bousquet, M., *Satellite Communications Systems*, John Wiley and Sons, 1986, pp 210-211.

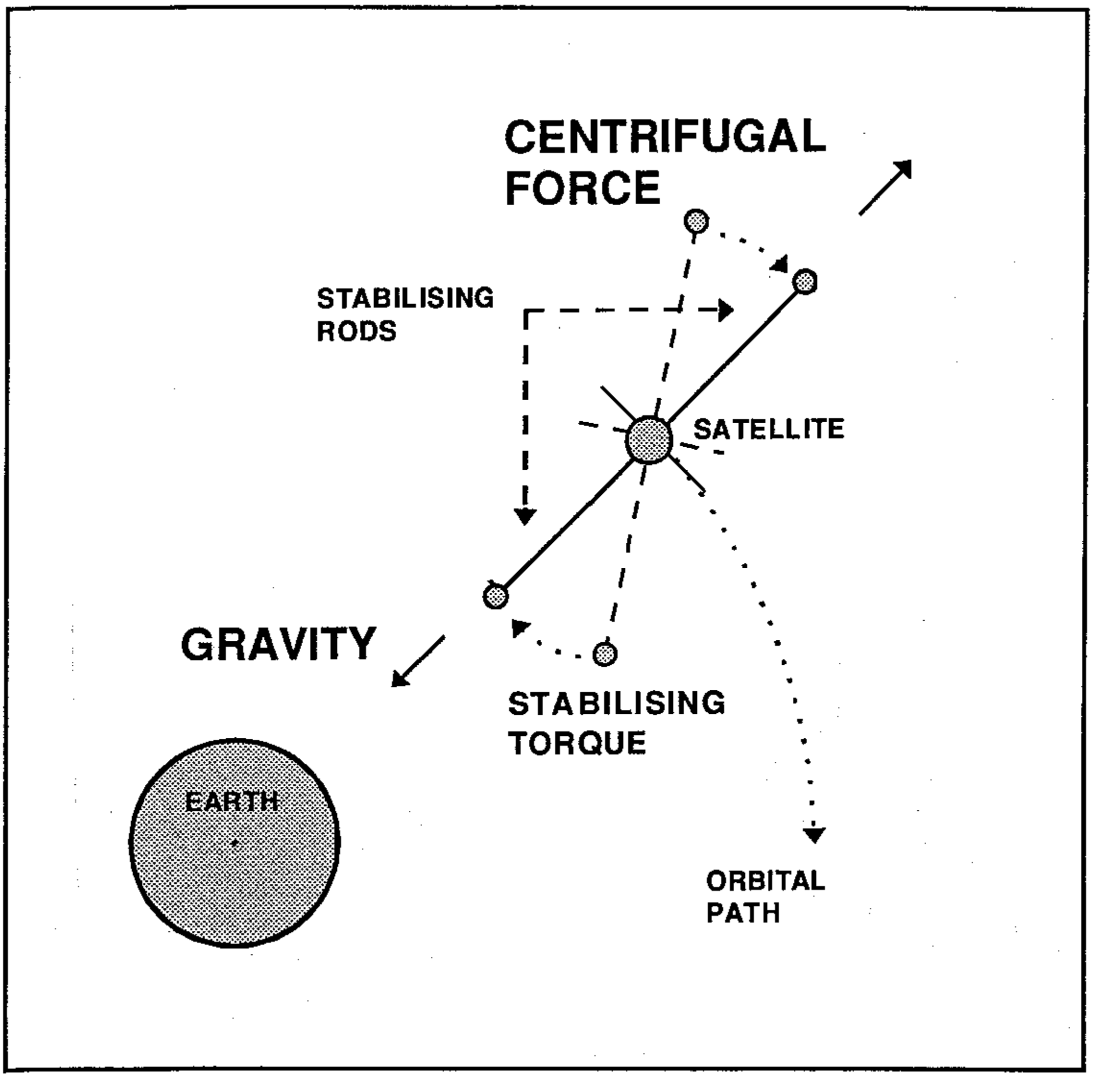

Figure 4.6. Gravity Gradient Stabilisation

Gravity gradient stabilisation cannot be used on satellites in GEO for two reasons:

a. The Earth's gravitational field decreases in proportion to the square of the distance from its centre. At the altitude of GEO, the Earth's gravitational field cannot, in practical terms, exert sufficient torque on a satellite to stabilise it.

b. The requirement for geostationary satellites to keep station over their assigned latitudes and gravity gradient stabilisation are not complementary.

The biggest advantage of gravity gradient stabilisation is its cost. As no fuel has to be carried for stabilisation, the satellite can be exceptionally small and light, minimising its launch cost. Nor are thrusters or momentum wheels and their associated control systems required. These factors make gravity gradient stabilisation very attractive for the new generation of ***'lightsats'*** currently undergoing R&D.

USER SYSTEMS

The user system is the terrestrial tail of a space system. Depending on the space system's function, the user system can take conditioned data from a ground station for further processing, analysis, re-transmission or distribution; or accept data directly from the space system (for example, navigation data). User systems will not be covered in any more detail. However, in a practical sense, the user is the sole reason for the space system's existence. The space system is only a means of satisfying a terrestrial need.

CHAPTER FIVE

SENSORS FOR RECONNAISSANCE AND SURVEILLANCE

This chapter will discuss sensor technologies from first principles. It begins by presenting the characteristics of EM radiation, its interaction with the Earth's atmosphere, and the utilisation of specific EM bands. From that base, the characteristics, uses, advantages and disadvantages of space-based sensors for reconnaissance and surveillance are considered. Such sensors include active and passive, optical, IR and radio frequency sensors. No attempt has been made to propose a specific space-based reconnaissance or surveillance solution for Australia. Rather, a broad based coverage of sensor capabilities has been attempted. The work of Squadron Leader Gale of the RAAF's Air Power Studies Centre has been focussed to address Australia's potential use of space-based surveillance assets.[1]

There is often confusion as to the difference between reconnaissance and surveillance. They may be defined as follows:

> '<u>Reconnaissance.</u> *A mission undertaken to obtain, by visual observation or other detection methods, information about the activities and resources of an enemy or potential enemy; or to secure data concerning the meteorological, hydrographic or geographic characteristics of a particular area....*
>
> <u>Surveillance.</u> *The systematic observation of aerospace, surface or sub-surface areas, places, persons, or things, by visual, aural, electronic, photographic or other means.*'[2]

Space-based platforms can and do undertake both reconnaissance and surveillance missions.

THE ELECTROMAGNETIC SPECTRUM

Units of Measurement

Before examining the EM spectrum, the reader must become familiar with some common units of measurement. Table 5.1 lists the decimal fractions and multiples in common use.

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[1] Gale, SQNLDR W., *The Potential of Satellites for Wide Area Surveillance of Australia,* Air Power Studies Centre, RAAF Fairbairn, 1991.

[2] *JSP (AS) 101*, Australian Joint Service Publication, Glossary, Part 1, Edition 3, February 1984, p R-7 and S-31.

Table 5.1. Decimal Fractions and Multiples

Fraction	Prefix	Symbol	Multiple	Prefix	Symbol
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^{2}	hecto	h
10^{-3}	milli	m	10^{3}	kilo	k
10^{-6}	micro	µ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	*f*			
10^{-18}	atto	a			

Note:
1. A unit of measurement known as the ***Angstrom*** (Å) is sometimes used to define wavelength. One Angstrom = 10^{-10} metres.
2. Micrometres (µm) are often referred to simply as ***microns*** (µ).

Travelling Waves

Wave motion is a common form of energy transport. For instance, sound energy is carried by acoustic waves, which propagate through the air at the local speed of sound. Similarly, ocean waves carry energy across the surface of the sea. Waves which carry energy in this progressive way are known as ***travelling waves***. EM energy is carried by EM travelling waves.

Electromagnetic Radiation

Electromagnetic waves radiate through free space at the speed of light, or 'c'. In free space,

$$c = 3 \times 10^{8}\ m/s.$$

In more dense media, such as the Earth's atmosphere, the speed of light is reduced in proportion to frequency and the nature of the medium. However, for practical purposes, the slowing effect of the Earth's atmosphere is so small that it may be ignored.

The Relationship Between Frequency, Wavelength and the Speed of Light.

Frequency, wavelength and velocity are linked by the formula:

$$Velocity = frequency\ (f) \times wavelength\ (\lambda);$$

however, the velocity of EM radiation equals the speed of light in free space, therefore:

$$c = f \times \lambda.$$

This formula can be used for any frequency to wavelength conversion or vice-versa. The nomograph at Figure 5.1 can be used for the same purpose, and should prove useful for quick conversions.

Whilst all objects emit EM radiation, the most pervasive and important source of terrestrial and cislunar EM radiation is the sun. The spectral distribution of the sun's radiance is illustrated in Figure 5.3. Figure 5.3 also illustrates the spectral distribution of solar radiation at the Earth's surface, after the radiation has been attenuated by the Earth's atmosphere. Note that solar radiation peaks at 0.5 μ; that is, the green portion of the visible spectrum. As an aside, and not surprisingly, the peak sensitivity of human colour vision corresponds to that same wavelength.

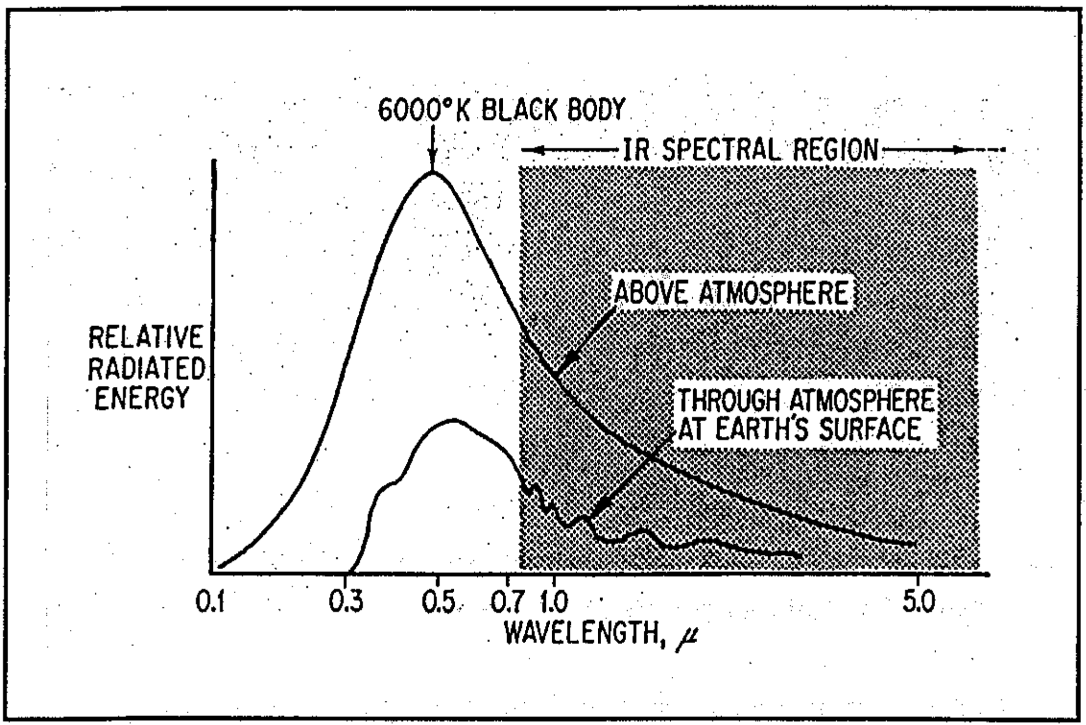

Figure 5.3. Spectral Distribution of Solar Radiation[5]

As well as emitting EM radiation, objects also reflect it. In fact, during daylight hours, reflected radiation exceeds emitted radiation in the visible and near IR spectra. How we, and the sensors used on space and terrestrial platforms view the world is dictated by:

a. the emissivity of the sun, and

b. the emissivity and reflectivity of the objects within the FOV.

Figure 5.4 illustrates the sources of emitted and reflected EM radiation in the terrestrial environment.

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[5] Dayerle, MAJ C. and Thomson, SQNLDR J. (eds), *Electro-Optics Notes, General Duties Aerosystems Course*, RAF Cranwell, Lincolnshire, 1988, p 9-9.

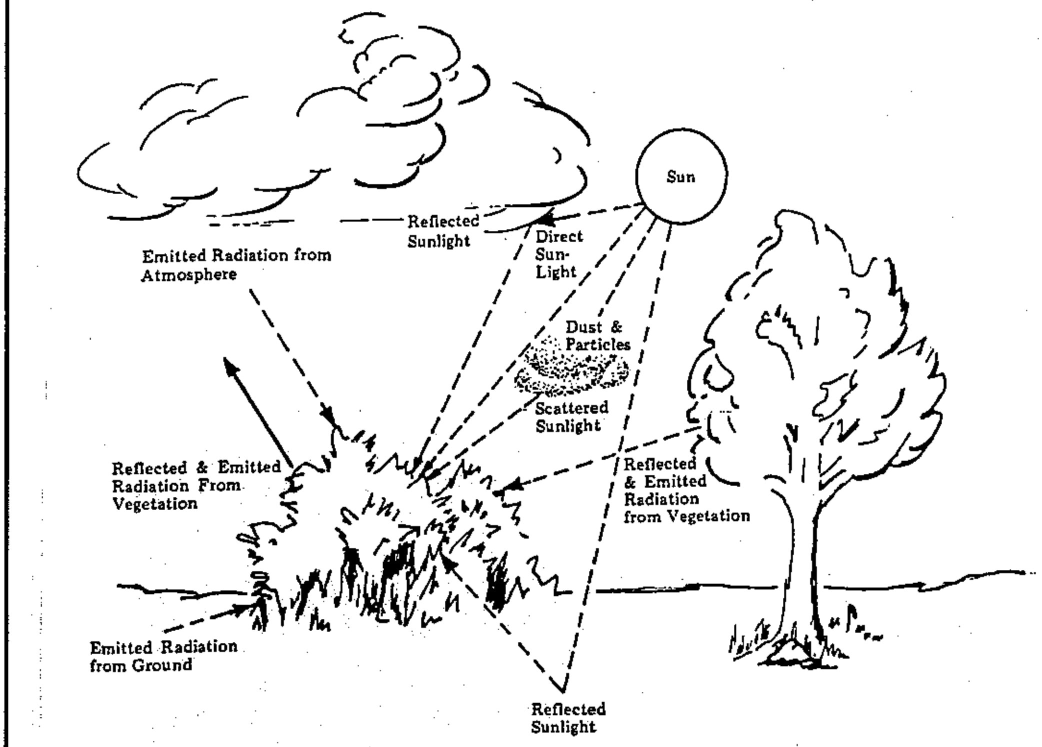

Figure 5.4. Emitted and Reflected Electromagnetic Radiation[6]

Of course, there is a considerable change in the EM spectrum as measured at the Earth's surface after sunset. At night, solar-sourced visible and near IR radiation disappears, and radiation from the night sky and the Earth itself predominates. Radiation from the night sky peaks at wavelength of 10.5 µ, which approximates a temperature of 276°K (3°C). Figure 5.5 illustrates the difference in the distribution of background EM radiation between day and night.

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[6] Damon, T., *Introduction to Space*, 1989, Orbit Book Company, Malabar, Florida, February 1989, p 76.

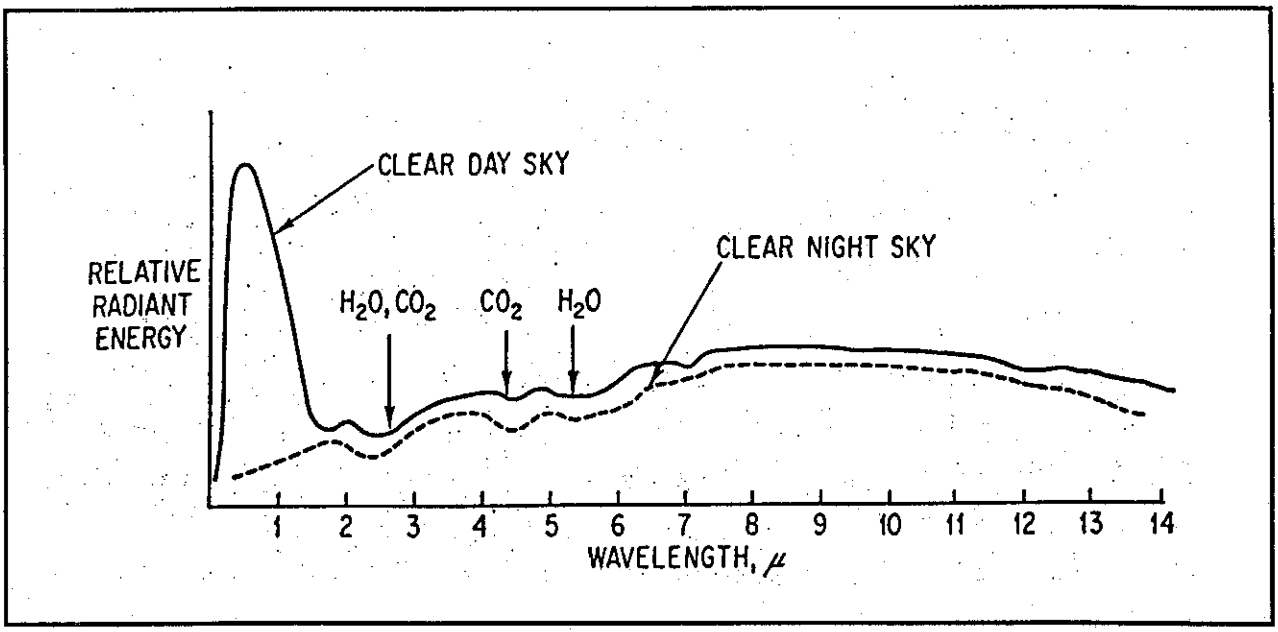

Figure 5.5. The Spectral Energy Distribution of the Background Radiation from Clear Day and Night Skies[7]

Atmospheric Attenuation and Scattering of EM Radiation

When EM radiation passes through a gaseous medium, such as the Earth's atmosphere, there is an interaction between the radiation and the molecules which comprise the medium. This interaction results in the EM radiation being ***attenuated***. Attenuation varies across the EM spectrum. The transmission characteristics of the atmosphere in clear conditions are illustrated in Figure 5.6.

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[7] Dayerle and Thomson, op cit, p 9-9.

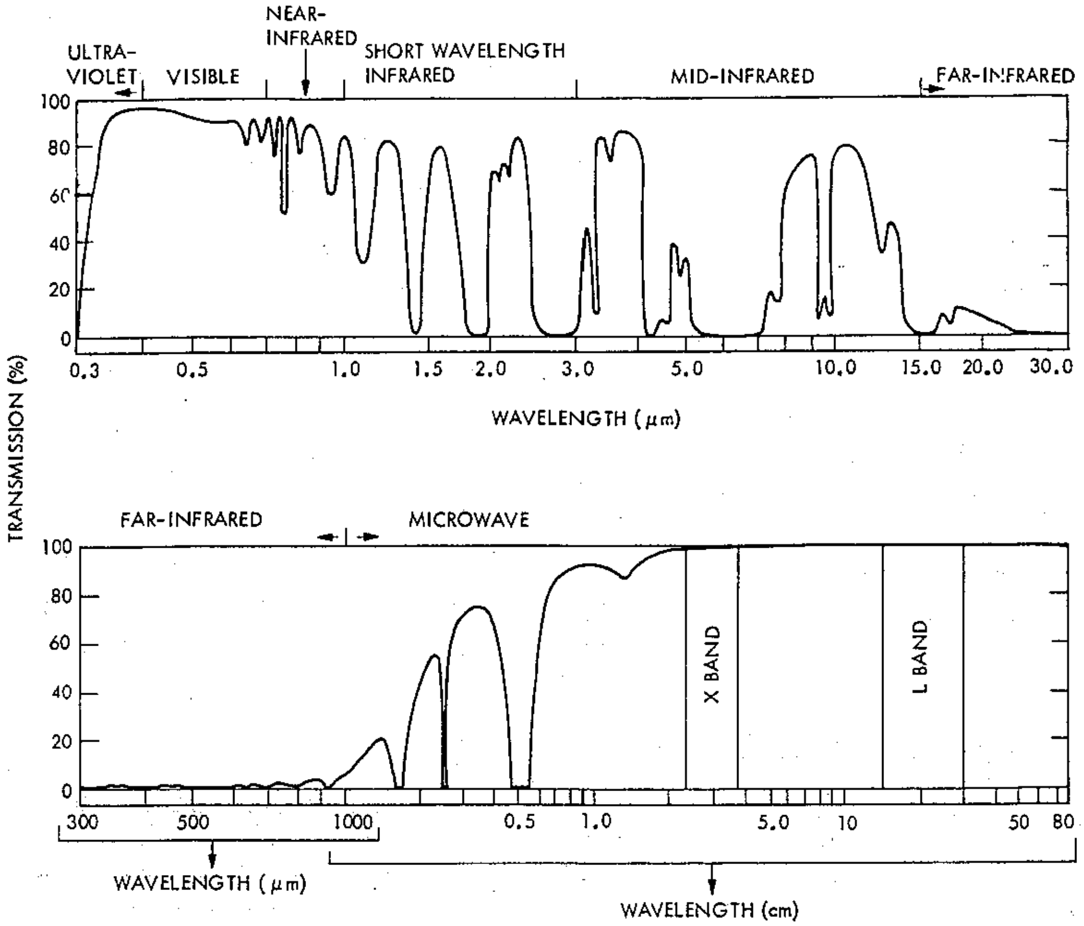

Figure 5.6. The Atmospheric Transmission Spectrum[8]

Note that there are particular regions within the EM spectrum where atmospheric attenuation is very low. These regions are called ***atmospheric windows***. They are of vital importance in both space and terrestrial sensor design. Sensors must be designed to utilise EM radiation at frequencies which fall within the atmospheric windows. As an aside, the spectrally related attenuation characteristics of the atmosphere can also be used to hide targets. To produce a stealthy military system, you must first minimise its radiation of EM energy, and then shift what radiation it does produce away from the atmospheric windows and into those spectral regions where attenuation is high. This will have the effect of reducing the range at which a sensor can detect the target.

As well as being attenuated by the gaseous constituents of the atmosphere, EM radiation is also attenuated by the water and water vapour contained in clouds, rain, fog; and airborne dust and other solid atmospheric pollutants. Attenuation due to water held in the atmosphere is called ***hydrometeoric attenuation***. The effect of hydrometeoric attenuation is illustrated by Figure 5.7. Note that the magnitude of the attenuation is frequency dependent.

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[8] Colwell, op cit, p 572.

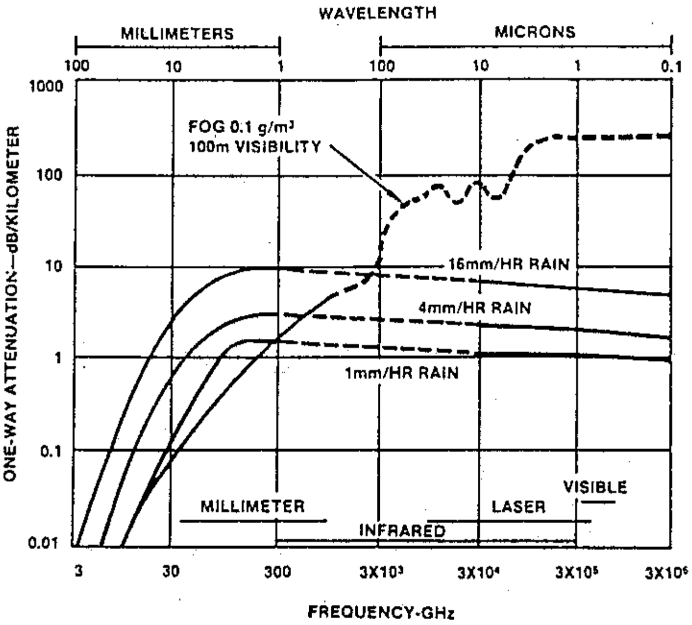

Figure 5.7. Hydrometeoric Attenuation Versus Frequency[9]

Spectral Bands of Interest

There are three spectral bands commonly used by both terrestrial and space-based sensor systems to exploit atmospheric windows. These are :

a. the visible spectrum;

b. the IR spectrum; and

c. the radio frequency (RF) spectrum.

The interaction between these spectra and the Earth's atmosphere is expanded below. It may help to refer back to Figure 5.6 whilst reading the following sections.

THE VISIBLE SPECTRUM

The visible spectrum covers wavelengths between 0.38 µ (violet) and 0.76 µ (red). Table 5.2 lists the divisions within the spectrum. Whilst radiation in the visible spectrum will propagate through a clear atmosphere with little attenuation, visibility can be reduced by precipitation, cloud, fog, mist and haze. Sensors operating in the visible spectrum are only effective when ambient illumination, and hence contrast, is good. The effects of atmospheric attenuators notwithstanding, sufficient ambient illumination for visible spectrum sensor operation is only available during the day, or on clear moonlit nights.

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[9] Hovanessian, S., *Introduction to Sensor Systems*, Artech House, Norwood, Massachusetts, 1988, p 8.

Table 5.2. The Visible Spectrum

Nomenclature	Wavelength (μ)
Violet	0.38 - 0.45
Blue	0.45 - 0.49
Green	0.49 - 0.56
Yellow	0.56 - 0.59
Orange	0.59 - 0.63
Red	0.63 - 0.76

THE INFRARED SPECTRUM

Table 5.3 lists the divisions within the IR spectrum.

Table 5.3. The IR Spectrum

Nomenclature	Wavelength (μ)
Near IR (NIR)	0.76 - 1.0
Short wavelength IR (SWIR)	1.0 - 3.0
Mid wavelength IR (MWIR)	3.0 - 15.0
Far IR (FIR)	15.0 - 1000.0

Atmospheric attenuation in the IR band is frequency dependent. Specific gaseous molecules within the atmosphere cause sharp attenuation spikes in the NIR, SWIR and MWIR bands. Attenuation in the FIR is uniformly high. IR radiation is subject to severe specular reflection (or scattering) by cloud and fog, but is largely unaffected by atmospheric pollutants or mist. The discriminatory effects of these scatterers arise from their average particle size.

The primary source of radiation in the NIR and SWIR is reflected solar radiation, whereas in the MWIR and FIR emitted radiation is predominant. The SWIR is particularly useful for surface reflection measurements and surface feature mapping. The 3-5 μ window in the MWIR can be used to detect thermal emission from targets at temperatures between 300 and 700°C, such as rocket and jet engine exhausts. The 8-14 μ MWIR window is centred at the peak of the Earth's thermal emission and is therefore extremely useful for imaging terrestrial targets whose temperatures fall between -70 and 90°C. The 8-14 μ band is often referred to as the ***thermal IR (TIR).***

THE RADIO FREQUENCY SPECTRUM

Whilst there are many varying definitions covering the breadth and internal delineation of the RF spectrum, for our purposes it can be considered to include the microwave, radar, audio and AC spectra. These are illustrated in Figure 5.2. The RF spectrum covers frequencies between 300 Hz and 300 GHz. These frequencies equate to wavelengths of 1000 km and 1 mm respectively. Table 5.4 defines the internal delineations within the RF spectrum.

Table 5.4. The RF Spectrum

Nomenclature	Frequency	Wavelength
Extremely Low Frequency (ELF)	300 Hz - 3 kHz	1000 km - 100 km
Very Low Frequency (VLF)	3 kHz - 30 kHz	100 km - 10 km
Low Frequency (LF)	30 kHz - 300 kHz	10 km - 1 km
Medium Frequency (MF)	300 kHz - 3 MHz	1 km - 100 m
High Frequency (HF)	3 MHz - 30 MHz	100 m - 10 m
Very High Frequency (VHF)	30 MHz - 300 MHz	10 m - 1 m
Ultra High Frequency (UHF)	300 MHz - 3 GHz	1 m - 10 cm
Super High Frequency (SHF)	3 GHz - 30 GHz	10 cm - 1 cm
Extremely High Frequency (EHF)	30 GHz - 300 GHz	1 cm - 1 mm

Figure 5.7 illustrated one way signal attenuation in the RF spectrum. Hydrometeoric attenuation is the prime attenuation mechanism, with rain having a significant attenuating effect at frequencies higher than 10 GHz, and fog on frequencies higher than 30 GHz. Particular molecular resonances also have an effect centred on specific frequencies. Again referring to Figure 5.7, note that there is insignificant attenuation at frequencies below 10 GHz. For this reason, most terrestrial communications and radar systems operate in this part of the spectrum. However, it is often desirable to operate at higher frequencies to utilise the higher data rates they permit. Additionally, equipment generally gets smaller and lighter as its operating frequency increases, a desirable feature for space-based systems.

SENSOR TECHNOLOGIES[10]

Sensor systems are used to exploit incident emitted and reflected EM radiation to detect, track, recognise, identify and evaluate of targets of interest. The sensors that will be considered are those typically used for reconnaissance and/or surveillance of terrestrial and atmospheric targets from space. The sensors are designed to exploit visible, NIR, SWIR, MWIR, and radio frequencies. They include electro-optical (EO), real and synthetic aperture radar and passive RF sensors. EO systems encompass passive visible and IR sensors and active laser radars.

Sensors can be either ***passive*** or ***active***: passive sensors collect radiation emitted from or reflected by a target, whereas active sensors firstly radiate EM energy into the target area and then collect the reflected energy. The radiation collected by the sensor is initially used to enable a processor or operator to detect the target. More sophisticated processors or well trained operators may also attempt to learn something of the nature of the target by analysing its characteristics.

Space-based sensors generate one of two types of data:

a. digital or analogue ***imagery***; or

b. ***signals intelligence*** (SIGINT) data.

If imaging satellites represent the eyes of military intelligence, then SIGINT satellites are the ears. Much of the discussion in this chapter deals directly with imaging systems. However, many of the basic concepts presented can be equally applied to SIGINT systems. SIGINT systems are discussed briefly towards the end of the chapter.

Sensor Sub-Systems

In general, a passive space-based reconnaissance or surveillance system will include the following components:

a. a ***radiation detector*** (or ***sensor***) sensitive to the specific EM radiation of interest;

b. a ***scanning system*** to systematically move the sensor over the required area, unless the sensor is specifically designed to 'stare' rather than scan;

c. a ***data processing and storage system***;

d. a ***TT&C system*** to transmit the data to a ground station for further processing and distribution; and

e. a ***ground station*** or stations to receive, process and distribute the data.

An active sensor package will also include a ***transmitter*** and a ***receiver***.

Scanning Systems. By scanning the sensor about the satellite's ground trace as it moves along its orbital path, the sensor's total FOV, or footprint, can be increased. Common scanning techniques include:

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[10] See Gale, op cit, passim.

a. <u>Offset-Spin Scanning.</u> If a sensor is mounted to a spin stabilised satellite offset from the satellite's axis of rotation, the sensor's FOV will scan a conical pattern at the spin rate of the satellite. Offset-spin scanning is well suited to surveilling a fixed area on the Earth's surface from GEO. Figure 5.8 illustrates such an application.

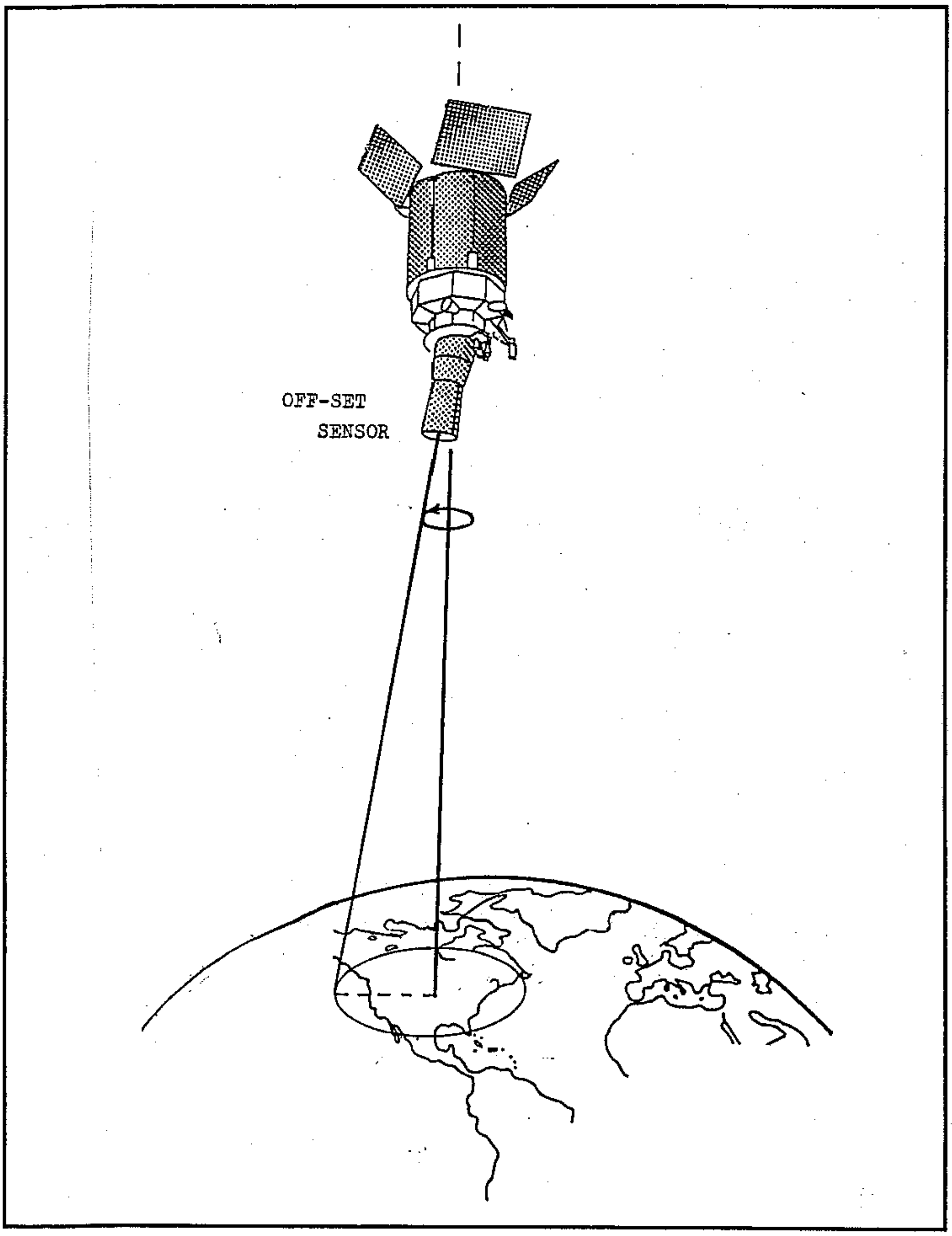

Figure 5.8. Offset-Spin Scanning (not to scale)

b. <u>Whisk-Broom Scanning.</u> A whisk-broom scanning system, illustrated in Figure 5.9, forms an image by mechanically scanning the sensor from side to side as the satellite travels along its orbital path. A whisk-broom scanning technique is used by NASA's Landsat series of LEO remote sensing satellites.

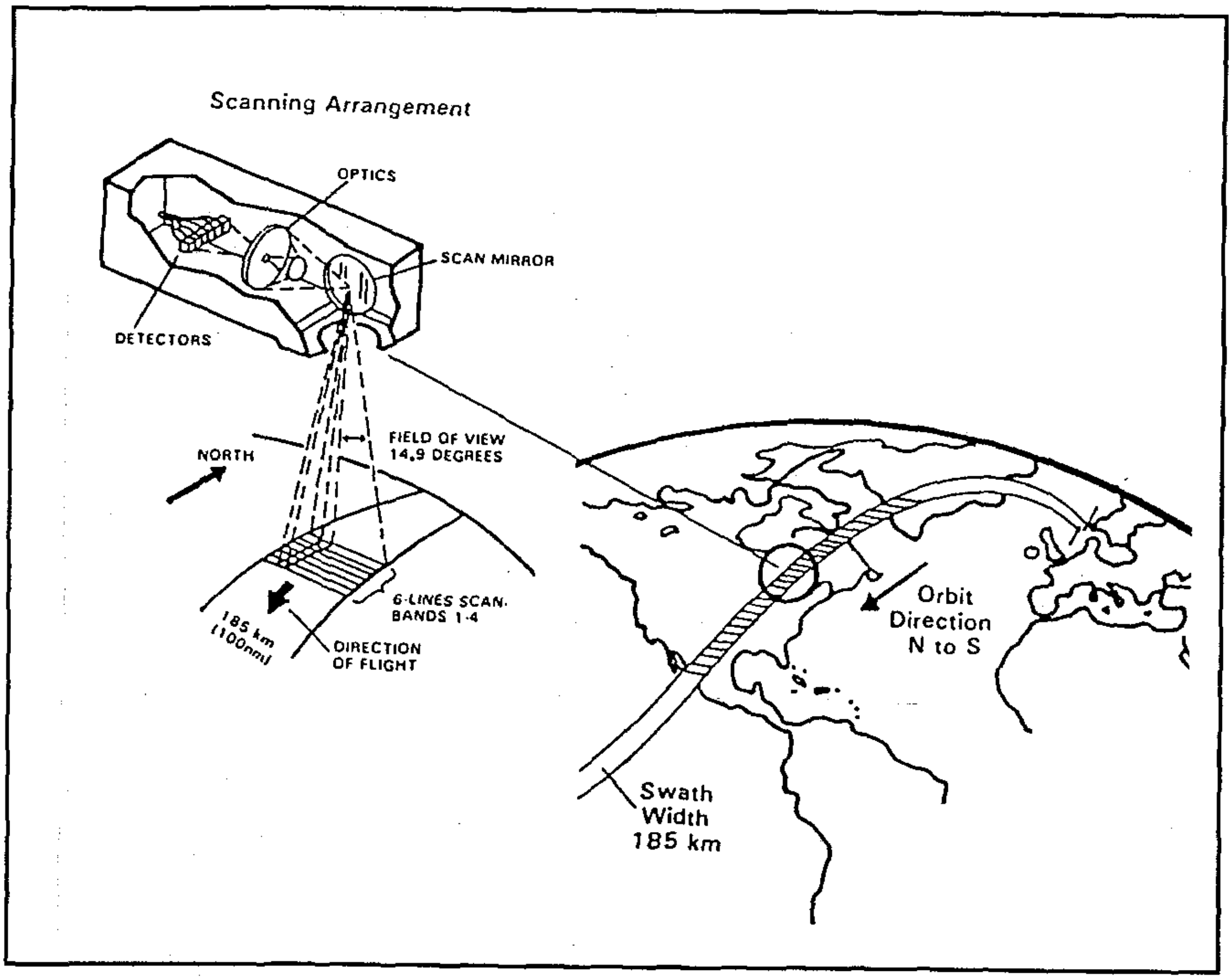

Figure 5.9. Whisk-Broom Scanning[11]

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[11] Chen, H., *Space Remote Sensing Systems*, Academic Press, Orlando, Florida, 1985, p 22.

c. Push-Broom Scanning. The push-broom scanning system, illustrated in Figure 5.10, uses the forward motion of a satellite to sweep a linear array of detectors along the area of interest. The linear sensor array gives a wide FOV without mechanical scanning. The French SPOT LEO remote sensing satellite uses a push-broom scanning technique.

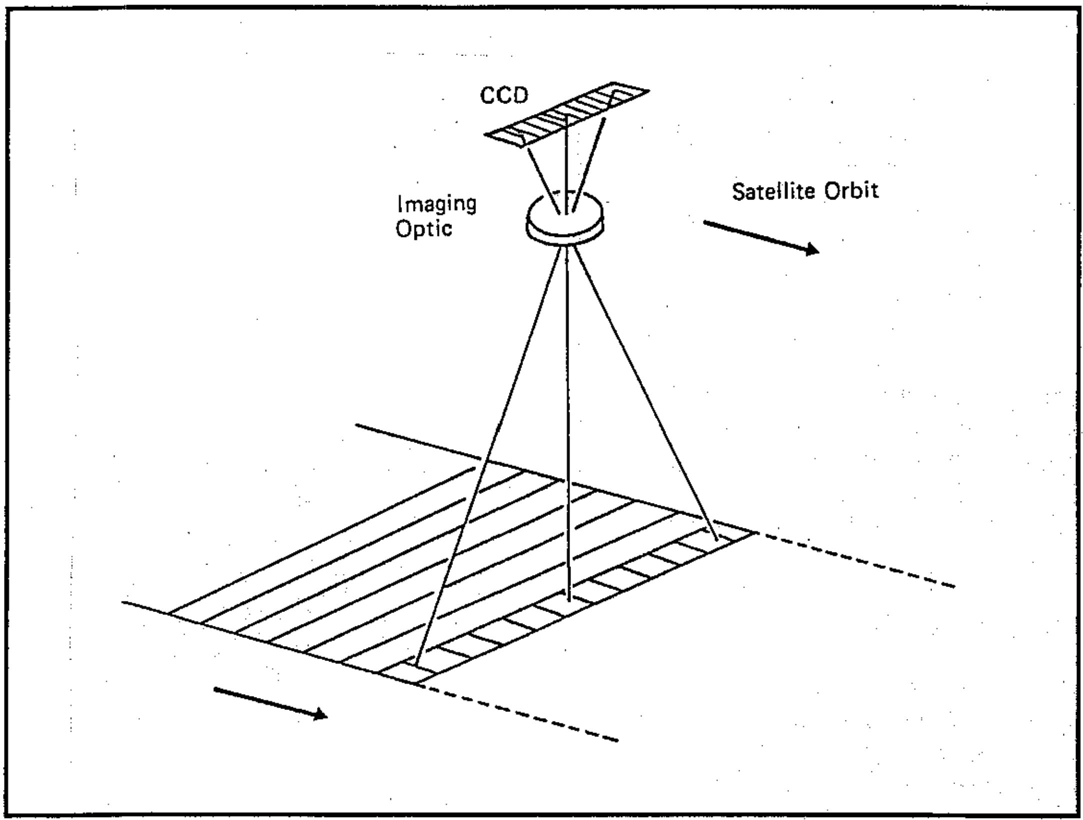

Figure 5.10. Push-Broom Scanning[12]

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[12] Chen, op cit, p 21.

Staring Systems, or Focal Plane Arrays (FPAs). FPAs are made up of a matrix of individual sensor elements which stare at a scene to form an image before moving on to the next adjacent scene. Staring gives the array time to temporally integrate the returns from the scene, improving the FPA's signal to noise ratio and therefore sensitivity in comparison with scanned arrays. Figure 5.11 illustrates the FPA concept. The area coverage and the sensitivity of the FPA would seem to make it ideal for use in both space-based and terrestrial sensor systems. Unfortunately, FPA sensor technology is not particularly mature. FPAs are far more complex and expensive to manufacture than simple linear arrays, and significant difficulties have arisen in constructing large detector arrays using preferred detector materials. Whilst an FPA detector package has not yet been fielded in an operational space-based system, it is only a matter of time before the technology matures to the point where this is possible.

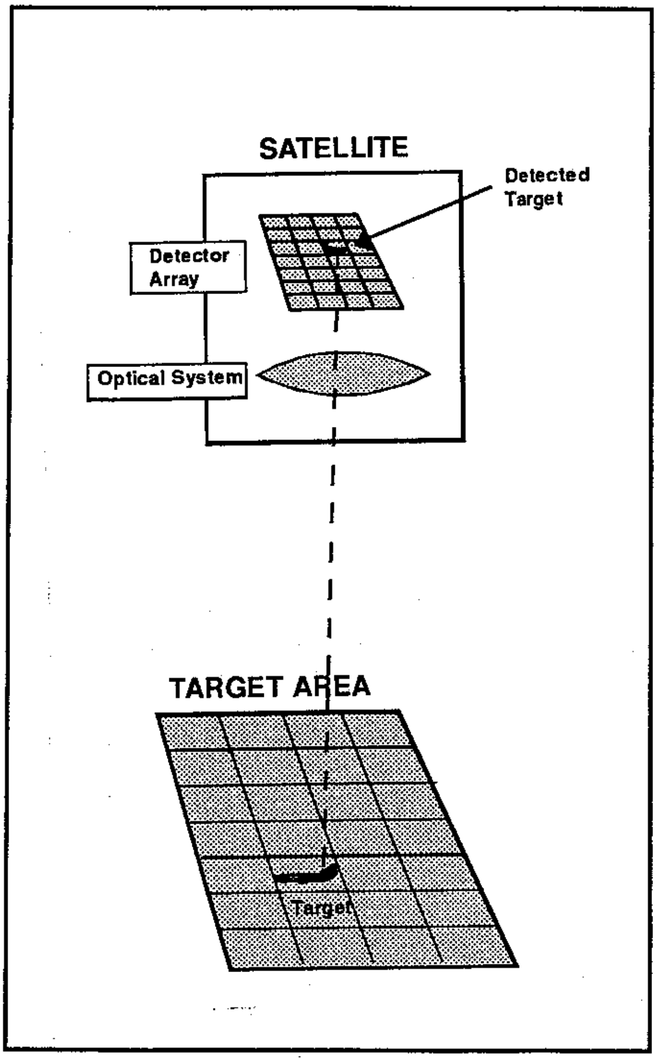

Figure 5.11. Focal Plane Array[13]

Characteristics Of Targets

A target is ***'an object which is to be detected, located or identified'***, usually from a cluttered background. Clutter may be defined as ***'any unwanted return'***. It is important to realise that one man's target is another man's clutter, and the ability to discriminate the target of interest from a cluttered background is the hallmark of an effective sensor system. Targets can be described in terms of their ***spectral, spatial, radiometric*** and ***temporal*** characteristics.[14] Spectral characteristics refer to the band(s) of the EM spectrum reflected or emitted by the target; spatial characteristics define the physical dimension and shape of the target; radiometric characteristics indicate the amount of energy the target reflects or emits across the spectrum of interest; and temporal factors describe how a target changes or moves over time. Sensor characteristics and system configurations are chosen with the aim of discriminating targets from their backgrounds by using one or a number of these characteristics.

Sensor Resolution

Sensor resolution requirements can be specified in terms of the spectral, spatial, temporal and radiometric requirements needed to detect the target(s) of interest. In selecting the best sensor for the mission, trade-offs often have to be made between these resolution requirements due to the interdependencies between them.

Provision of a specific resolution directly impacts on the design of a system's space and ground segment, and may ultimately be constrained by the current limits of technology.

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[13] Adapted from: May, J.J. and M.E. Van Zee, *Electro-Optic and Infrared Sensors*, Microwave Journal, September 1983, p 130.

[14] Chekan, R., *Use of Commercial Satellite Imagery for Surveillance of the Canadian North*, Canadian Armed Forces, Thesis, USAF Institute of Technology, USAF University, Ohio, November 1988, p 13.

Factors such as spacecraft size and weight, orbital mechanics, on-orbit propulsion, power requirements, onboard processing capability, link capacity, and ground facility location and data processing capacity are all inter-related, and heavily influenced by mission requirements. The specialised nature of space-based reconnaissance and surveillance sensor systems means they are custom designed for specific applications.

Spectral Resolution

A sensor's spectral resolution determines which spectral bands it can detect, and to what degree those bands can be resolved. For example, a sensor which is receptive to wavelengths between 0.4 and 0.5 would be sensing blue light. Discrimination of this wavelength would represent a single spectral band, or channel, which could be used to form an image. However, images are generally composed by integrating the output of several channels. These channels are carefully chosen to exploit combinations of specific characteristics that are unique to the particular target. Effectively, this type of processing 'pulls' the target out of the background clutter. The real difficulty lies in the determination of each target's unique spectral characteristics. Spectral resolution is important to both imaging and SIGINT sensors.

Spatial Resolution

Spatial resolution may be defined as ***'the smallest separation between two objects such that the sensor is able to resolve that they are distinct objects'***. User requirements, such as the need for target detection, identification or description; and the nature of the target will determine the spatial resolution required to satisfy a particular need. Figure 5.12 illustrates how the features of a target are clarified as spatial resolution improves.

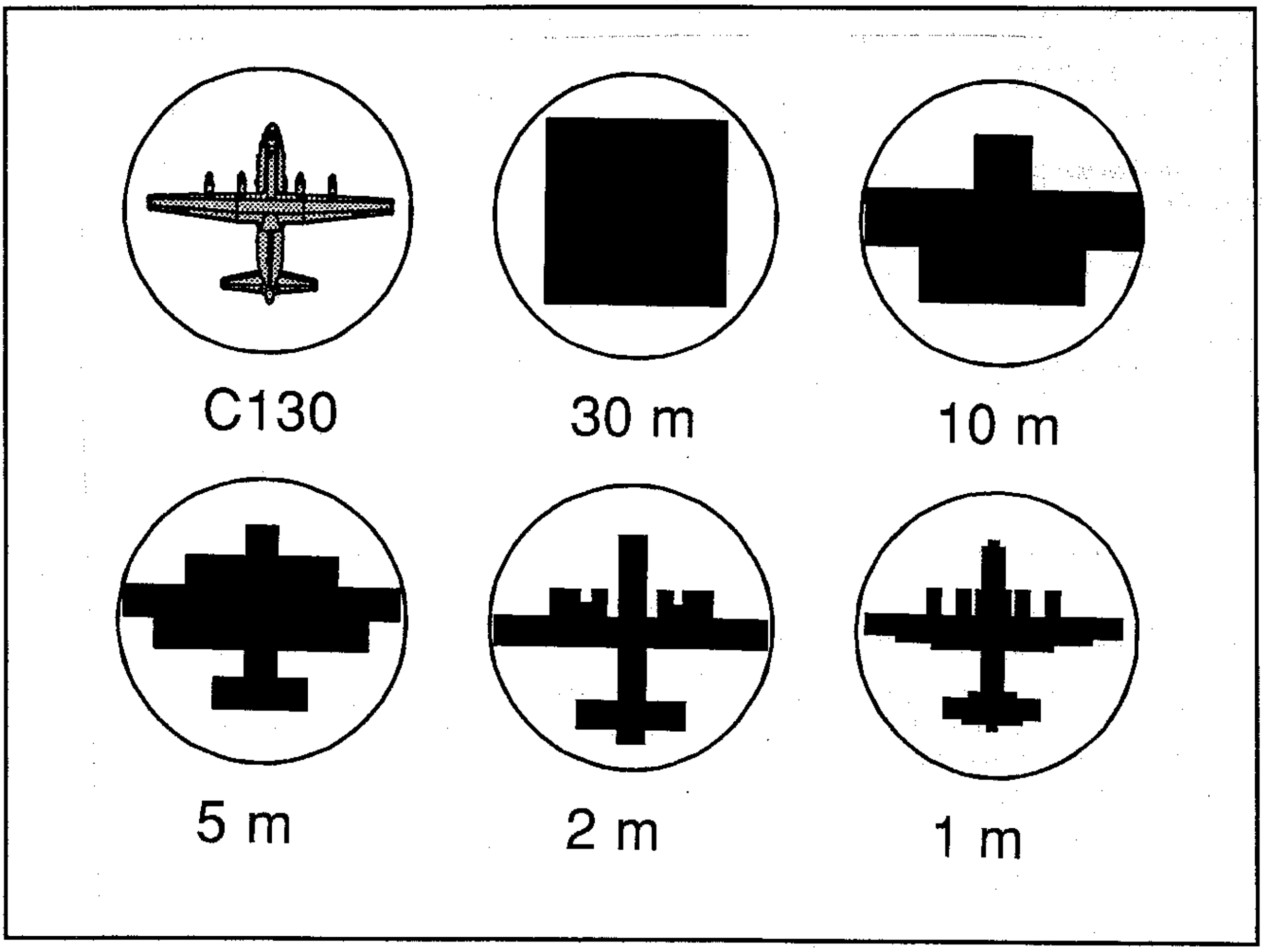

Figure 5.12. Target Features are Resolved as Spatial Resolution Improves

Spatial data is valuable for:

a. detecting and locating a weak point source against a bright uniform background,

b. characterising an object by shape and size, and

c. discriminating small target objects from small background objects by exploiting their characteristic shape and size.

Different levels of spatial resolution are required to detect, identify and describe targets of interest. Table 5.5 lists spatial image resolution required for different levels of target discrimination.

Table 5.5. Spatial Image Resolution Required For Different Levels of Target Discrimination[15]
All measurements in metres.

Target	Detection	Identification		Description	Technical Intelligence
		General	Precise		
Rockets and Artillery	0.9	0.6	0.152	0.051	0.01
Supply Dump	1.5	0.6	0.3	0.025	0.025
Vehicles	1.5	0.6	0.3	0.05	0.025
Nuclear Weapon Components	2.4	1.5	0.3	0.025	0.01
Communications Radar	3.0	0.9	0.3	0.15	0.038
Communications Radio	3.0	1.5	0.3	0.15	0.15
Command & Control HQ	3.0	1.5	0.9	0.152	0.025
Missile Sites (SSM/SAM)	3.0	1.5	0.6	0.3	0.076
Aircraft	4.6	1.5	0.9	0.152	0.025
Bridge	6.1	4.6	1.5	0.9	0.3
Troop Units (bivouac, road)	6.1	2.1	1.2	0.3	0.076
Airfield Facilities	6.1	4.6	3.0	0.3	0.152
Surface Ships	7.6	4.6	0.6	0.3	0.076
Land Minefields	9.1	6.1	0.3	0.025	-
Roads	9.1	6.1	1.8	0.6	0.152
Ports and Harbours	30.5	15.2	6.1	3.0	0.3
Coasts and Landing Beaches	30.5	4.6	3.0	1.5	0.076
Railroad Yards and Shops	30.5	15.2	6.1	1.5	0.6
Surfaced Submarines	30.5	6.1	1.5	0.3	0.025
Urban Area	60.0	30.5	3.0	3.0	0.3
Terrain	-	91.0	4.6	1.5	0.152

Spatial Resolution and Instantaneous Field of View

The size of a target area that a sensor can cover with 'one look' is called the ***instantaneous field of view*** (IFOV). An IFOV may also be attributed to each picture element, or pixel. These concepts are illustrated by Figure 5.13. The pixel IFOV will usually determine a sensor's spatial resolution.

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[15] Adapted from: Richelson, J., *The Keyhole Satellite Programme*, Journal of Strategic Studies, Vol. 7, No. 2, June 1984, p 124.

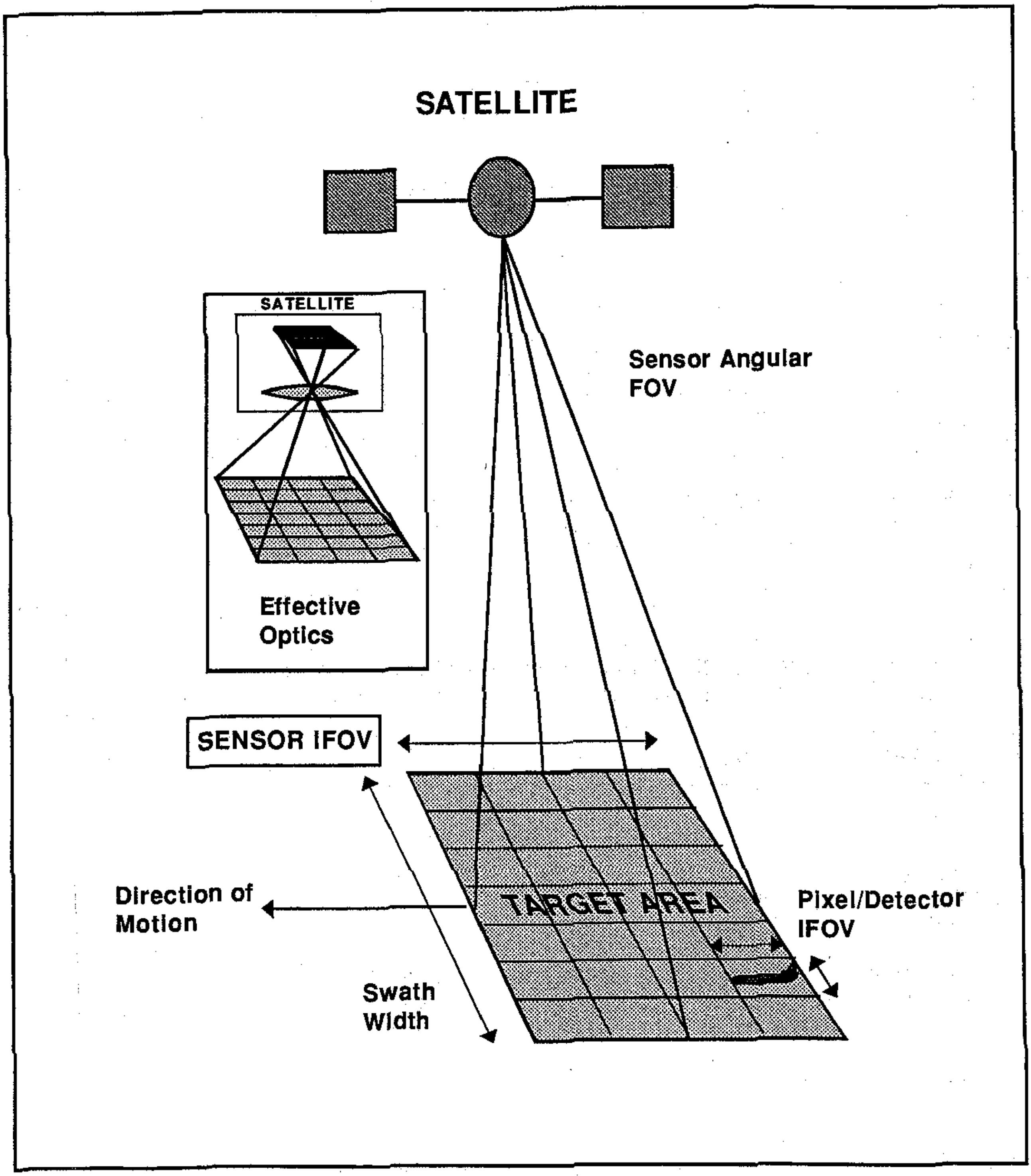

Figure 5.13. Instantaneous Field of View[16]

A sensor's IFOV is dependent on its beamwidth and the range from the sensor to the target. The sensor's beamwidth is directly proportional to the wavelength of the EM energy the sensor is designed to exploit and inversely proportional to the aperture[17] dimension. Therefore, IFOV can be increased by:

a. decreasing the size of the aperture, thus increasing the beamwidth;

b. increasing the range from the sensor to the target; and

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[16] Adapted from: Gale, op cit, Chapter Five.

[17] The aperture is physical dimension of that part of the sensor system designed to collect EM energy.

c. for a given aperture size, exploiting EM radiation of a longer wavelength.

The IFOV can be decreased by applying the same factors in the opposite sense. Table 5.6 lists the size of the aperture required to achieve a range of ground resolutions from GEO at various frequencies. Table 5.7 lists similar parameters but from a 700 km altitude LEO.

Table 5.6. Resolution Parameters at GEO[18]
Aperture required for a given ground resolution as a function of wavelength.

Resolution (m) ->	**0.1**	**1**	**10**	**100**	**1000**
Wavelength					
0.5 μ (Visible)	350 m	35 m	3.5 m	35 cm	3.5 cm
1.0 μ (NIR)	700 m	70 m	7.0 m	70 cm	7.0 cm
10.0 μ (TIR)	7 km	700 m	70.0 m	7 m	70.0 cm
1 mm (300 GHz)	700 km	70 km	7.0 km	700 m	70.0 m
1 cm (30 GHz)	7,000 km	700 km	70.0 km	7 km	700.0 m
10 cm (3 GHz)	70,000 km	7,000 km	700.0 km	70 km	7.0 km

Table 5.7. Resolution Parameters at LEO (700 km)[19]
Aperture required for a given ground resolution as a function of wavelength.

Resolution (m) ->	**0.1**	**1**	**10**	**100**	**1000**
Wavelength					
0.5 μ (Visible)	7 m	0.7 m	7.0 cm	7.0 mm	0.7 mm
1.0 μ (NIR)	14 m	1.4 m	14.0 cm	14.0 mm	1.4 mm
10.0 μ (TIR)	140 m	14.0 m	140.0 cm	140.0 mm	14.0 mm
1 mm (300 GHz)	14 km	1.4 km	140.0 m	14.0 m	1.4 m
1 cm (30 GHz)	140 km	14.0 km	1.4 km	140.0 m	14.0 m
10 cm (3 GHz)	1,400 km	140.0 km	14.0 km	1.4 km	140.0 m

These tables usefully illustrate the utility of each particular spectral band at different orbital altitudes given a specific resolution requirement. For example, it would clearly be impractical to use a real aperture sensor operating at 30 GHz from LEO if a 1 m resolution were required. The antenna would have to be 14 km long! Only a visible or NIR sensor could practically satisfy that particular requirement. The selection of the appropriate sensor for a particular mission always involves some degree of compromise between resolution, IFOV, swath width, and exploitation of particular sensor and spectral characteristics. These considerations are summarised by Table 5.9 and Figure 5.15 at the end of this section .

<u>Effect of Background and Contrast.</u> The contrast between the target and its background affects the sensor's ability to detect the target, and in practice may limit the sensor's spatial resolution to less than its theoretical maximum. What this means in a practical sense is that an object much smaller than the sensor's IFOV but with good contrast in relation to its

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[18] Cartwright, D., *Space and Defence*, lecture at CSIRO Headquarters, Canberra, 31 July 1991.
[19] loc cit.

background will be detected; whilst a much larger object with poor contrast in relation to its background may not. Contrast is important in all classes of target discrimination, whether it be detection, identification or description. From a countermeasures perspective, the art of camouflage is to reduce the contrast between the target its background in the spectra of concern to the point where detection is made almost impossible.

The Compromise Between Spatial Resolution and FOV. In summary, this discussion indicates that if a high spatial resolution is required, a narrow beamwidth sensor located comparatively close to the target must be used. Practically, the aperture size of a space-borne sensor is limited; and range to the target (which equates to orbital altitude for a space-based system) may also be constrained if the spacecraft is to have a reasonable lifetime. For these reasons, high resolution military reconnaissance spacecraft always utilise visible and/or NIR imaging systems. They also trade life in favour of resolution by operating from very low orbits. However, a high spatial resolution is not always of paramount importance. A wide FOV allows a larger area to be covered, and this factor may well be of higher priority than a high resolution. Mission requirements will dictate the necessary compromise between FOV and spatial resolution. Figure 5.14 illustrates some of the trade-offs.

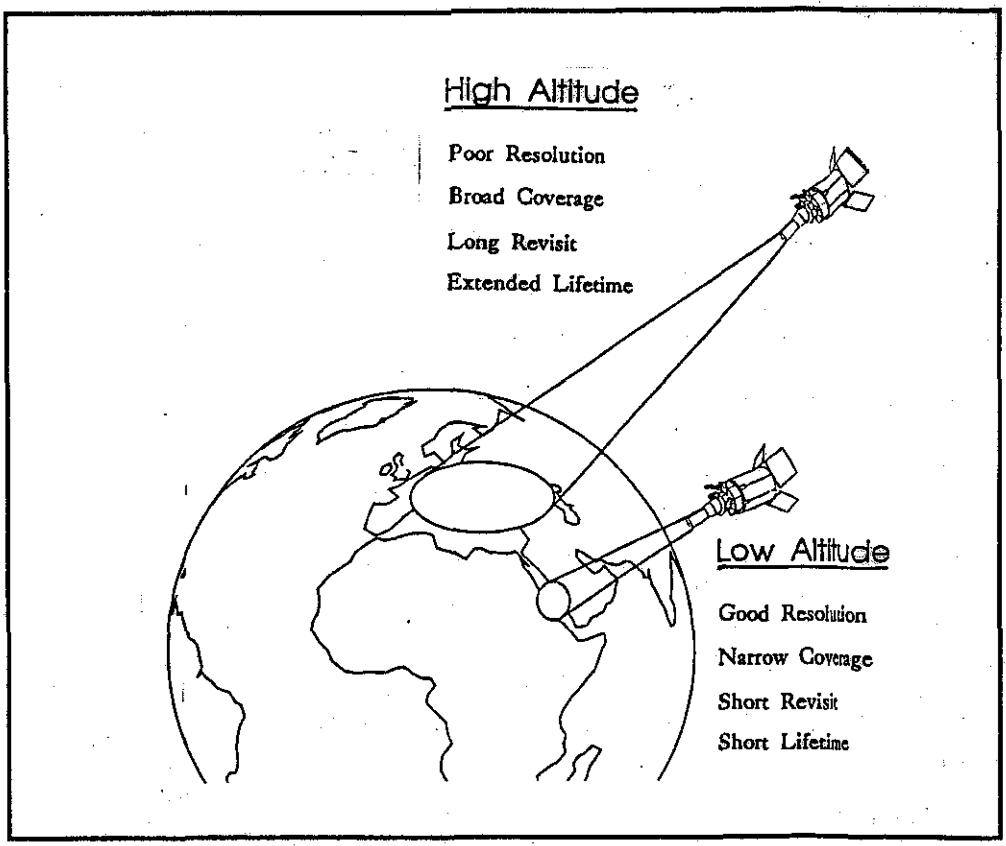

Figure 5.14. Sensor Performance Trade-Offs from High and Low Altitudes[20]

Radiometric Resolution

Radiometric resolution is defined as ***'the amount of energy required to increase a picture element (pixel) by one quantisation level or count'***[21]. A sensor's radiometric resolution refers to its dynamic range. The dynamic range is defined by the number of quantisation levels the sensor may discern within its spectrum of operation. Most current digital space-based imaging sensors use 256 quantisation levels. This means that the detected radiation can have an intensity ranging from zero (the minimum detectable signal) to 255 (the maximum which can be

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[20] Figure obtained from: Davey, SQNLDR K,. Headquarters ADF, Department of Defence, Canberra.
[21] Harrison, B. and Jupp, D., *Introduction to Remotely Sensed Data*, CSIRO Publications, Melbourne, 1989, p 50.

imaging sensors use 256 quantisation levels. This means that the detected radiation can have an intensity ranging from zero (the minimum detectable signal) to 255 (the maximum which can be recorded). *Radiometric resolution in a digital image can be related to tone in a photographic* image: both relate to a measure of contrast.

Quantisation levels are often expressed as a number of bits rather than as an integer. These values are related by:

$2^{(\text{number of data bits})}$ = number of quantisation levels.[22]

Table 5.8 compares the number of data bits to the number and range of quantisation levels available in a digital imaging system.

Table 5.8. Digital Quantisation Levels[23]

No. of Bits	No. of Quantisation Levels	Range of Quantisation Levels
1	2	0-1
2	4	0-3
3	8	0-7
4	16	0-15
5	32	0-31
6	64	0-63
7	128	0-127
8	256	0-255
9	512	0-511
10	1024	0-1023

Temporal Resolution

Temporal resolution refers to the time elapsed between obtaining each set of data from a target area. Factors which will affect temporal resolution include: the satellite's re-visit time to the target area, the time taken to process and disseminate the data obtained, the time taken for further image processing and analysis, and time taken to deliver the product to the user. Further, the time required to obtain the data on a particular target can be considerably extended by environmental considerations, such as cloud cover (affecting optical and IR imaging systems) or ionospheric disturbance (affecting RF sensors).

The temporal resolution required of a sensor system is dependent on user defined mission requirements. For example, whilst a re-visit time of once per week may be sufficient to obtain strategic intelligence from a construction site, it is not sufficient to track shipping or monitor a build up of enemy forces.

SUMMARY AND SENSOR SELECTION

Sensor Summary

Table 5.9 summarises the discussion on reconnaissance and surveillance sensors.

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[22] loc cit.
[23] loc cit.

Table 5.9. Space-Based Sensor Comparison [24]

SENSOR TYPE	Day/Night Capability	Effect of Weather	Atmospheric Attenuation	Aperture Size	Resolution	Detection Method	Tx Data Rate	Processing Complexity	Weight	Cost	Power Req'd	Technology Available
<u>Passive</u>												
Visible/NIR	Day	Severe	Low	Small	High	Imaging	High	Low	Low	Medium	Low	Yes
SW, MW and LW Infrared	Both	Severe	Low in bands	Small	Medium	Imaging	Medium	Low	Low	Medium	Low	Yes
<u>Active</u>												
LIDAR												
a. Visible	Both	Severe	Low	Small	High	Imaging/ Doppler	High	Low	High	High	High	Near Term
b. Infrared	Both	Severe	Low in bands	Small	Medium	Imaging/ Doppler	Medium	Low	High	High	High	Near Term
RAR	Both	Low	Low	Large	Low	Processed Return/ Doppler	High	Medium	High	High	High	Near Term
SAR	Both	Low	Low	Medium	Medium to High	Imaging	Very High	High	Medium	High	Medium	Yes

KEY

RAR = Real Aperture Radar
SAR = Synthetic Aperture Radar

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[24] Adapted from: Gale, op cit, Chapter Five.

Sensor Selection

Figure 5.15 presents a model which lists some of the factors which might be considered in selecting a sensor for a particular mission. The model is not exhaustive, but it does usefully summarise principal factors and trade-offs.

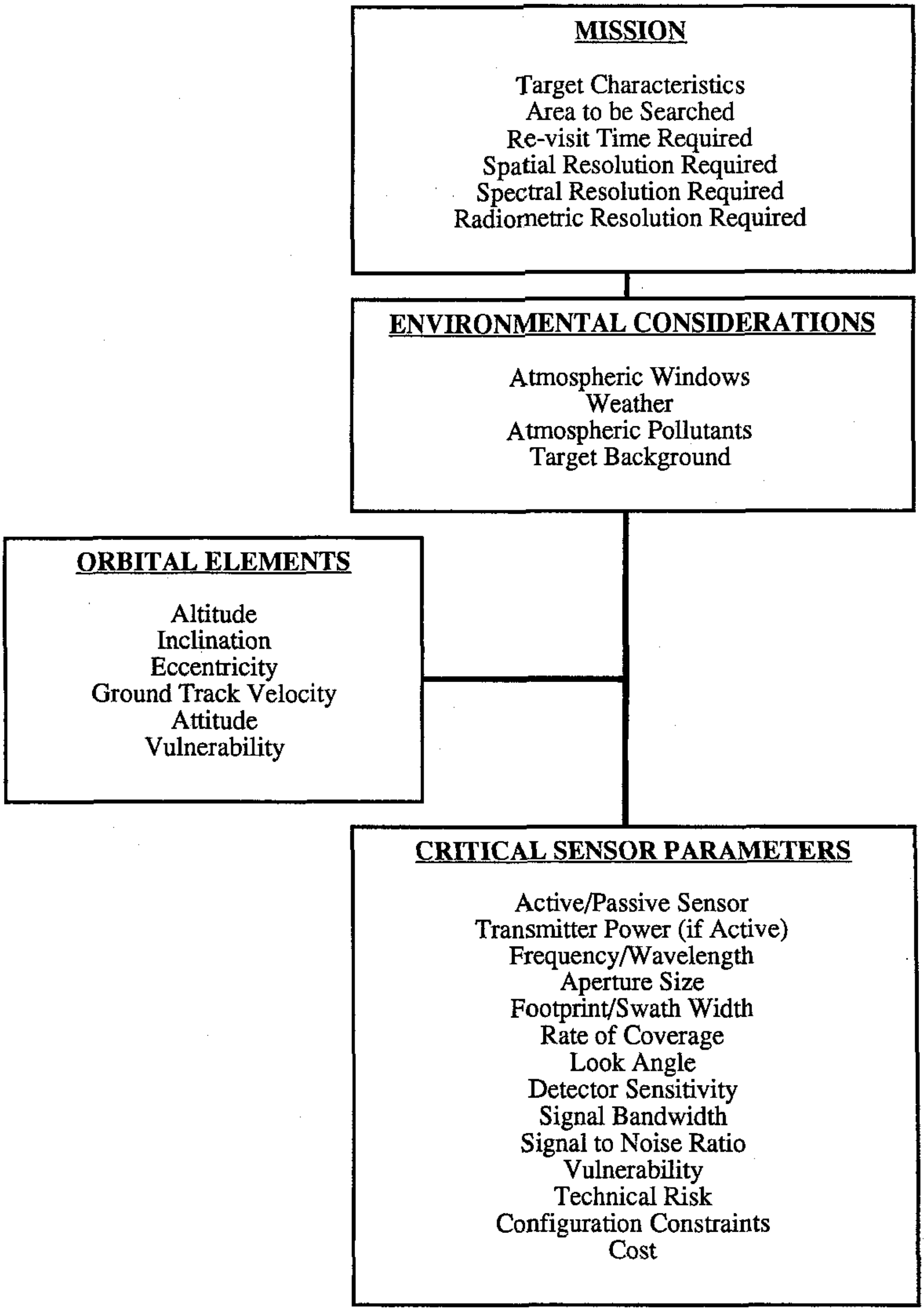

Figure 5.15. Sensor Selection Criteria

Having briefly discussed sensor resolution and the relationship between the sensor and the target, specific sensor groups will be examined, including active and passive EO and RF sensors.

PASSIVE EO SENSORS

EO sensors use lenses and mirrors to collect visible and/or IR radiation. The radiation is focussed onto a detector which produces an electric signal proportional to its intensity. Different detector materials are responsive to different EM wavelengths. The output from each scan of the sensor is combined to form an image, which is stored onboard the satellite until it can be transmitted to a ground station. The trend over the years has been for sensor resolution to increase, increasing the amount of data contained in each image. This in turn has demanded an increase in: the data storage capacity onboard the satellite; the telemetry capacities of the down-link; and the number of sophisticated ground stations.

Passive EO sensors include radiometers and spectrometers. A radiometer measures the intensity of the incident radiation, whilst a spectrometer determines its distribution. Spectrometers are generally used for scientific work and will not be considered further.

A black and white camera presents a simple example of a radiometer. It collects light reflected from the scene (in this instance the scene may be effectively equated to a target) and records its intensity by forming an image on a photographic film. Space-based radiometers operate on a similar principle, but most use digital imaging systems.

Advantages and Limitations of Passive EO Sensors

Generically, passive EO sensors have two prime advantages for military users: the fact that they are passive, and their good spatial resolution. Their prime limitation is high levels of background noise interfering with target detection. Typical sources of noise include:

a. sun glint from:
    i. cloud edges,
    ii. water, and
    iii. man-made objects such as buildings, windows, etcetera; and

b. man-made interference from:
    i. lights, and
    ii. fires.

Visible Spectrum Radiometers

Space-based visible spectrum radiometers produce the highest resolution images currently available. They are used by the military and civil communities to create images and to measure environmental parameters.

With regard to imagery, the best target resolution is obtained from low altitudes. Consequently, a compromise between satellite lifetime and resolution must be struck. Military systems bias this compromise towards resolution. The US DoD's KH-11 reconnaissance satellites operate from an altitude of about 400 km, and are said to be able to provide resolutions down to

15 cm[25,26]. The former Soviet Union's fifth generation reconnaissance satellites systems orbit at even lower altitudes, down to 225 km[27]. Civilian systems, such as the French SPOT satellite, are smaller than their military counterparts and orbit at an higher altitude. These two factors reduce launch costs and increases satellite longevity respectively. SPOT's resolution from its orbital altitude of 832 km is 10 m in the visible spectrum. Table 5.5 indicates that a 10 m resolution can provide a limited detection and identification capability against targets of military interest. The performance of visible spectrum sensors may be affected by cloud induced target occlusion or a reduction in resolution due to atmospheric pollution and water vapour content.

IR Spectrum Radiometers

The IR spectrum is extensively exploited for both scientific and military applications. Like sensors in the visible spectrum, sensors operating in the NIR spectra primarily detect reflected radiation, whereas sensors in the thermal IR band detect emitted radiation. Consequently, thermal IR sensors can be used for imaging at night. Any target or scene which emits heat, such as: the general landscape, fires, internal combustion engines, factory power plants, ships, aircraft and missiles, will be readily detectable by a thermal IR sensor day or night.

ACTIVE EO SENSORS

Laser Radar or LIDAR

Active EO sensors, such as laser radars, or LIDARs (**LI**ght **D**etection **A**nd **R**anging), typically generate pulsed EM energy at a specific wavelength. LIDARs operate in the visible and IR spectra. Laser energy is transmitted through a set of optics, reflected by the target and gathered by a receiver. LIDAR can be used to either determine the range and bearing to a specific target, or the nature of the propagation path, depending upon the application. As LIDAR is active, it functions equally well day or night. It also delivers very high resolution, due to its short wavelength of operation.

Space based LIDAR has both scientific and military applications. It may be used for remote sensing of atmospheric constituents, cloud physics measurements, high resolution vertical temperature profiles, earth surface reflectance evaluation and radiative transfer modelling.[28] LIDAR has the potential to be used by the military for high resolution target imaging and target tracking.

Sources of Interference. Apart from attenuation caused by adverse atmospheric conditions, LIDAR can be jammed or dazzled, either deliberately or accidentally. Typical sources of interference include:

a. sun glint and reflected energy from clouds, sea surfaces, and man made objects;

b. other laser sources such as atmospheric sounders and range-finders (either accidently or deliberately directed); and

c. natural or man made energy sources such as the sun, fires, lightning and rocket plumes.

Power Requirements. The power needed to operate a laser radar depends on the specific application and the particular type of laser used. Lasers are only about 10% efficient, so

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[25] Cline, R.S. et al, *The Intelligence War*, Lansdowne Press, Sydney, 1983, p 103.
[26] Atmospheric scattering theoretically limits resolution to 10 cm.
[27] Johnson, N., *The Soviet Year in Space: 1987*, Teledyne Brown Engineering, Colorado Springs, Colorado, January 1988, p 31.
[28] Chen, op cit, p 171.

a typical power requirement is in the order of thousands of watts.[29] The solar power generation capability of a large satellite is in the order of five thousand watts, so ultimately the LIDAR's power output will be constrained by the satellite's power resources. The use of a nuclear power source could alleviate the problem, but nuclear power poses its own problems, as discussed in Chapter Four.

Advantages of LIDAR. LIDAR offers the following advantages:

a. high spatial and spectral resolution,

b. high operating frequency, allowing small component sizes, and

c. day and night operation.

Disadvantages of LIDAR. LIDAR has the following disadvantages:

a. LIDAR's frequency of operation is limited to the atmospheric windows, to minimise atmospheric attenuation.

b. LIDAR can be highly attenuated by atmospheric water vapour content and other atmospheric pollutants.

c. LIDAR's narrow beamwidth limits the dimensions of its search area and demands a high pointing stability.

d. LIDAR's operating efficiency is quite low, leading to a high power requirement.

e. The lack of tunability of the laser prevents operation at other than a narrow wavelength band.

f. Target discrimination can be significantly complicated by background clutter.

Applications of LIDAR. LIDAR systems can be separated by application into three categories:[30]

a. Window LIDAR. Window LIDAR is useful for examining the 'roughness' of the Earth's surface as well as vertical atmospheric aerosol profiling.

b. Absorption LIDAR and Differential Absorption LIDAR. Absorption systems are used to monitor the distribution of atmospheric particle species.

c. Doppler LIDAR. Doppler LIDAR can be used to measure wind fields and to track target movement.

A number of LIDAR sensors have been flown in spacecraft for scientific applications. Whilst the technology is immature for military applications, it does hold considerable potential. The US is investigating LIDAR for space surveillance, target acquisition, target tracking and target destruction as part of its SDI programme. Other military applications include the generation of high resolution imagery and the detection and identification of combustion products from missile plumes, factory smoke stacks and nuclear debris clouds.[31] LIDAR can also be used for submarine detection or submarine communications.

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[29] ibid, p 181.
[30] ibid, p 178.
[31] Evans, op cit, p 227.

Submarine Communication and Detection. Blue-green lasers are able to penetrate water to a considerable depth. Blue-green lasers are being adopted by the US for communicating with submerged submarines. It may also be possible to detect either the hull or the wake disturbance of a submerged submarine using a blue-green LIDAR.[32]

ACTIVE RF SENSORS

Space-Based Radar (SBR): Basic Principles

Active RF sensors, or ***radar*** (radio direction and ranging), offer a mature technology which can provide all-weather, 24 hour reconnaissance and surveillance from space-based platforms. Radar may be used for target detection, imaging, altimetry, sounding and scatterometry. Two types of radar are used for space-based reconnaissance and surveillance: real aperture radar (RAR) and synthetic aperture radar (SAR). The trend in space-based radar has been towards SAR to exploit its high resolution imaging capability. However, SAR cannot detect moving targets. If the user has a requirement to detect and track moving targets then either RAR or multi-mode radar must be used. In theory, multi-mode radar can combine the best features of both SAR and RAR into one system, but the technology is still immature. There are no space-based multi-mode radars on the drawing board for launch in the current decade.

Both RAR and SAR operate by illuminating a target area with pulsed microwave radiation directed by an antenna. The elapsed time between the transmitted and the received pulse allows the range from the sensor to the target to be determined. Whilst both RAR and SAR are capable of determining target range in this manner, they differ dramatically in their other capabilities, and hence their applications. The advantages and limitations of each type of radar are discussed in subsequent sections. Some general points on SBR are discussed below.

Cooling. Both radar types generate a considerable amount of heat when actively transmitting. This limits the time for which they are able to operate to about 10% of each orbit before the transmitter must be turned off and allowed to cool.

Operating Altitude. The range at which a radar can detect and track a target depends upon transmitted power, antenna gain, receiver sensitivity and the radar cross section (RCS) of the target. The amount of radar energy returned to the receiver from a target is inversely proportional to the fourth power of range. Given the limitations of satellite electrical power systems and current radar technologies, it is not possible for a SBR stationed at geosynchronous altitude to transmit sufficient power to detect targets of interest. Consequently, all SBRs operate from LEO.

Real Aperture Radar

Resolution. The range resolution of RAR is determined by the time taken to transmit each pulse, or the pulse width. Azimuth resolution is determined by both the beamwidth and the range to the target. Beamwidth is determined by the frequency in use and the dimensions of the antenna. Because microwave sensors operate at long wavelengths in comparison with EO senors, they require very large antennae if they are to provide a high spatial resolution (refer back to Tables 5.6 and 5.7). Current restrictions on spacecraft size and weight limits the size of the antenna to about 10 m. In turn, this limits RARs spatial resolution to about 2 km (assuming a frequency of 30 GHz and an orbital altitude of 700 km).

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[32] Stefanick, T., *The Nonacoustic Detection of Submarines*, Scientific American, Volume 258, Number 3, March 1988, pp 27-28.

Advantages of RAR. Real aperture SBR offers the following advantages:

a. RAR can provide target range, and with pulse Doppler processing, range rate.

b. RAR can detect and track moving targets.

c. RAR can provide a wide FOV.

Disadvantages of RAR. Real aperture SBR suffers the following disadvantages:

a. RAR's resolution is inadequate for imaging from space.

b. To achieve a signal to noise ratio comparable to that of SAR, a RAR requires more transmitter power.

c. RAR has limitations in its target detection capability in what is termed the 'nadir hole'. The nadir hole is an area approximately 15° around antenna boresight in which moving targets cannot be detected due to excessive background clutter.[33]

d. RAR is vulnerable to jamming.

Applications of RAR. The applications of space-based RAR include range measurement, scatterometry, ocean wave spectrometry, and geological analysis and sounding.[34] Range measurement can be used for ocean and land mapping and target tracking. Scatterometers detect back-scattered energy and use the Doppler characteristics of the radar return to determine the movement of a target; surface winds can be detected using this method. RAR can be used for ice depth sounding.

RAR Systems. The Soviet Union operated the only space-based RAR system, called Radar Ocean Reconnaissance Satellite (RORSAT). As the name implies, RORSATs are used for ocean reconnaissance. RORSATs are nuclear powered in order to provide sufficient energy for the radar. Their antennas measure about 8.5 by 1.4 m, which provides a ground resolution of about 2 km[35] from an orbital altitude of about 250 km. Their orbits are inclined at 65°. RORSATs are probably only able to detect vessels down to destroyer size in good weather, and down to aircraft carrier size in rough weather.[36]

The Future. Real aperture radar has the potential for either reconnaissance or wide area surveillance from space. The USAF has shown considerable interest in the development of a space-based RAR to form the basis of a programme known as the Space-Based Wide Area Surveillance System (SBWASS). A number of studies were commissioned in the 1980s, and from them preliminary programme milestones were established with the aim of deploying a SBWASS.[37] The SBWASS programme was subsequently deferred due to cost and competing priorities. Despite the delay, it is likely that such a system will be developed at some time in the future to provide the US with a global, wide-area, all-weather surveillance capability. The system will probably employ multi-mode radar, which should be available by the time the system is fielded.

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[33] This is only true for pulse Doppler radars; simple pulse radars do not suffer from a nadir hole.

[34] Kostiuk, T. and B. Clark, *Space-borne Sensors (1983-2000 AD): A Forecast of Technology*, National Aeronautics and Space Administration, Greenbelt, NASA Technical Memorandum 86083, April 1984, p 32.

[35] Johnson, op cit, p 69.

[36] ibid, pp 69-74.

[37] Piotrowski, J.L., *Space Based Wide Area Surveillance*, Signal, May 1989, pp 31-32.

Synthetic Aperture Radar

Resolution. SAR provides all-weather, high resolution imagery of the Earth's surface. SAR achieves its resolution by effectively increasing the size of the radar antenna by sequentially delaying and integrating the returns from a specific target area as the satellite moves along its orbital path. This increases the apparent length, or synthesizes, the aperture of the antenna. The theoretical resolution of a SAR in the along track direction is half the length of its antenna. Resolution is independent of range to the target. The principal of aperture synthesis is illustrated by Figure 5.16.

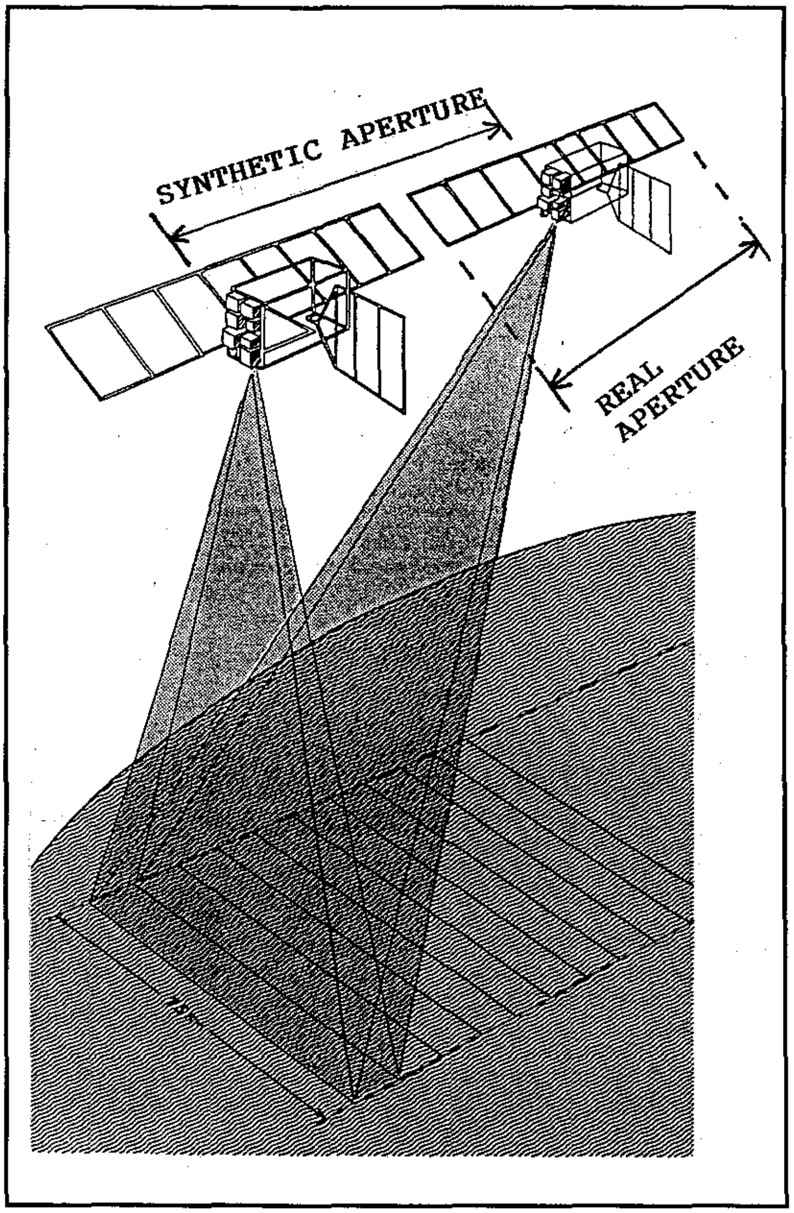

Figure 5.16. Aperture Synthesis[38]

However, processing successive radar returns to form an image takes time, and in practice, current processor limitations do not allow the theoretical resolution to be achieved. This limitation will probably be overcome as space-qualified computer hardware gets smaller, lighter and faster. SAR's resolution in the across track dimension is dependent upon the transmitted beamwidth, as it is with RAR.

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[38] Adapted from: Jones, I., *Satellite Measurement of Directional Ocean Wave Spectra*: in, Conference Proceedings, Fifth National Space Engineering Symposium 1989, Canberra, 27 November - 1 December 1989, p 248.

The fact that SAR integrates successive radar returns from a target area provides a considerable processing gain. This improves SAR's signal to noise ratio considerably over a RAR of comparable transmitter power. In practice, this means that for a given transmitter power, a SAR is able to detect targets of smaller radar significance. Alternatively, a SAR would require far less power than would a RAR to achieve the same level of detection, and still provide superior spatial resolution. While these advantages would seem to indicate that SAR offers the complete solution, this is not the case. SAR is not able to detect moving targets. However, whilst SAR has difficulty in detecting ships directly, it can usefully detect their wakes.

Image Processing. The amount of processing required to produce a SAR image makes it impossible for the image to be compiled onboard the satellite. Instead, SAR images have to be compiled in ground facilities equipped with dedicated and specialised high speed digital processors. By way of example, the European Space Agencies ERS-1 SAR satellite launched in 1991 uses a custom built fast delivery processor, developed by British Aerospace Australia, to process its data. This state of the art product can process SAR data in 10% of the time taken to acquire it.[39]

Data Transmission. High speed data transmission links are required for SAR data down-link. The sheer amount of data generated by space-based high resolution SAR poses a challenge to develop high speed data down-link systems that can cope with the data in real-time.

Advantages of SAR. The advantages of using synthetic aperture SBR include:

a. SAR offers high resolution imagery. Resolution is independent of spacecraft altitude, and in a practical sense, antenna size.

b. Pulse integration allows SAR to use a low transmitter power yet still produce a good signal to noise ratio.

Disadvantages of SAR. The disadvantages of synthetic aperture SBR include:

a. SAR is unable to track moving targets, although slow moving ships and their wakes have been seen in processed images.

b. SAR requires high speed data transmission links.

c. SAR requires specialised, complex, and expensive ground-based signal processing hardware and software to generate imagery.

d. SAR's image processing time can be lengthy.

e. SAR is vulnerable to jamming.

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[39] Fensom, D.S., *The Australian Fast Delivery Processor for the Synthetic Aperture Radar of ERS-1:* in, Conference Proceedings, Fifth National Space Engineering Symposium 1989, Canberra, 27 November - 1 December 1989, p 273.

Applications of SAR. SAR applications include:

a. high resolution surface imagery;

b. MC&G;

c. monitoring of ocean wave patterns and their interaction with the coastline;

d. determining land and sea surface roughness, surface material differentiation and condition, vegetation evaluation, moisture levels in soil and crops; and land structure mapping;

e. snow and ice coverage and dynamics; and

f. evaluation of environmental change.

SAR Systems. A number of space-borne SARs have been successfully fielded. SEASAT, launched in 1978, was the first. SEASAT was used as the basis for the Shuttle Imaging Radars (SIR), SIR-A (1981) and SIR-B (1984). The European Space Agency (ESA) launched its SAR satellite, ERS-1, in 1991. Several more SARs are planned, including: JERS-1 (Japan); RADARSAT (Canada); and EOS (US). The only military SAR fielded to date is an experimental US system called LACROSSE, first launched in 1988. LACROSSE was used during the Gulf War to obtain high resolution imagery for intelligence and BDA.[40] LACROSSE's resolution has been quoted as being between 1.5 and 3 m from an altitude of about 680 km.[41] To date, SIR-B, with a resolution of 17 m, has provided the best resolution of any civilian SAR.[42] However, Canada's RADARSAT, due for launch in 1994, should offer resolutions down to 8 m.

PASSIVE RADIO FREQUENCY RECEIVERS

Space-based passive microwave sensors are used to measure microwave radiation naturally emitted from the Earth's surface and atmosphere. Such data can be used to determine a range environmental parameters. Similar sensors can be used to collect man-made microwave radiation.

SIGINT. The military use space-based passive RF receivers principally to gather SIGINT data. Both the US and Russia currently field space-based RF intelligence gathering systems in a variety of orbits, including LEO, GEO and highly eccentric orbits. Orbit and sensor parameters are chosen to optimise the detection and localisation of the target signal. SIGINT may be sub-divided into the categories listed in Figure 5.17. All of the intelligence gathering activities listed are currently undertaken from space, where there are no national borders to restrict access.

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[40] Starr, B., *Satellites Paved Way to Victory*, Jane's Defence Weekly, 9 March 1991, p 30.

[41] Richelson, J.T., *America's Secret Eyes in Space: The US Keyhole Spy Satellite Program*, Harper & Row, New York, 1990, p 227.

[42] Brown, R.J., *Land Applications of RADARSAT*, IGARSS 1989, Remote Sensing: An Economic Tool for the Nineties, Volume 1, 1989, p 210.

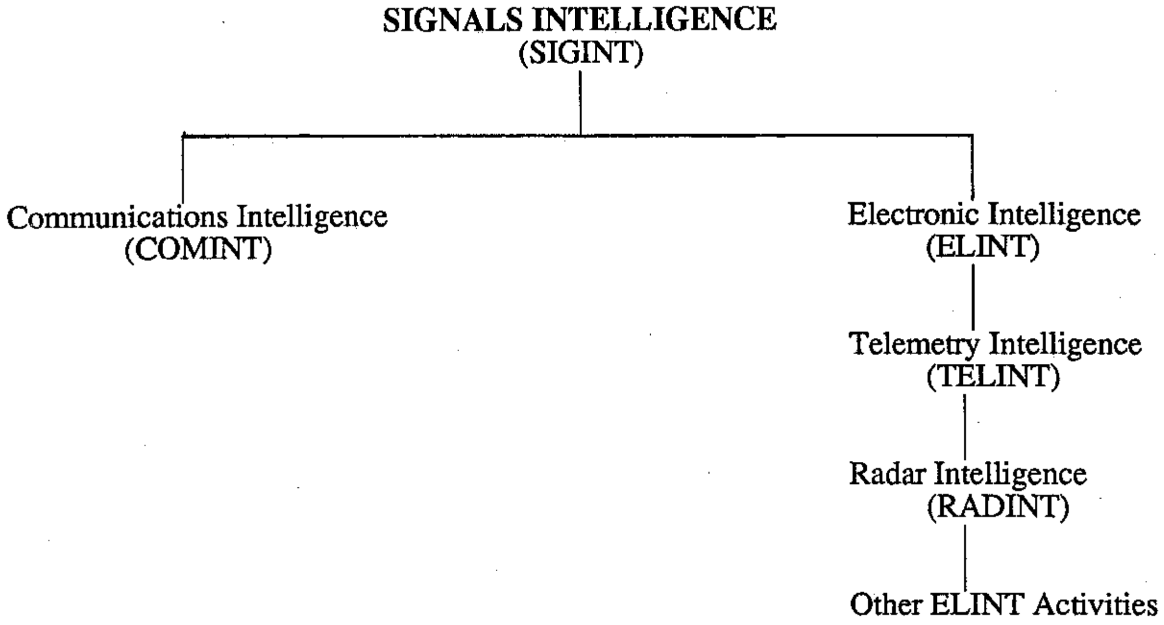

Figure 5.17. Signals Intelligence: Functional Divisions[43]

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[43] Adapted from: Ball, D., *Pine Gap*, Allen and Unwin, Sydney, 1988, p 3.

CHAPTER SIX

REMOTE SENSING

Authors Note

The content of this chapter is an amalgam of my own work and that of Ken Granger, who, as an employee of the Defence Intelligence Organisation completed a Defence Fellowship at the Centre for Resource and Environmental Studies, Australian National University, entitled ***'Geographic Information And Remote Sensing Technologies In The Defence Of Australia'***[1]. Granger's work has been extensively modified and condensed for inclusion in this chapter. This was done for three reasons. First, the data have been updated to reflect current system status. Second, I have deleted those parts which have been covered in previous chapters; and third, I have added and rearranged data where I thought it necessary. I have not delineated which is Granger's work and which is mine. Whilst this does not conform to strict convention, it does allow the chapter to flow without interruption. I recommend Granger's paper to those requiring a more detailed treatise on geographic information systems *per se*.

> *'Australia faces a major challenge in preparing an effective defence of its national territory with a high level of independence. The land and off-shore maritime areas of relevance are vast and the personnel and financial resources that can be devoted to the task limited. One very important and potentially decisive advantage that Australia can work to exploit is knowledge and understanding of the local environment.'*[2]

INTRODUCTION

The aim of this chapter is to discuss current civilian space-based remote sensing programs; the integration of data available from these and other sources using a geographic information system (GIS); and potential Defence applications of remotely sensed data and GIS. Remote sensing and GIS technologies offer Defence the opportunity and means to learn more about its own 'backyard', and by doing so gain a decisive advantage over any aggressor should he choose to mount a challenge in that arena.

REMOTE SENSING

The term 'remote sensing' was coined in the 1960s. Remote sensing has been defined as:

> ***'the use of electromagnetic radiation sensors to record images of the environment which can be interpreted to yield useful information'***[3].

More than 150 years of photography, from platforms ranging from carrier pigeons and kites to sophisticated reconnaissance aircraft and satellites, lies behind the modern science of

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[1] Granger, K., *Geographic Information and Remote Sensing Technologies in the Defence of Australia*, Centre for Resource and Environmental Studies, Australian National University, Canberra, January 1990.

[2] Babbage, R., *Planning the Future of Defence Geographic Information Systems*, p 233: in, Ball, D. and Babbage, R.(eds), *Geographic Information Systems: Defence Applications*, Pergamon, Sydney, 1989.

[3] Curran P.J., *Principles of Remote Sensing*, Longman Scientific & Technical, New York, 1985.

remote sensing. Whilst photography still holds a very significant place, it has been overshadowed in less than two decades by the use of EO sensors. Much of this development was promoted by the competing national security interests of the USSR and the US. From that base, the growth of civilian applications areas as diverse as surveying and mapping, monitoring and management of natural resources and the monitoring of the Earth's environment have expanded quickly. Public exposure to remotely sensed data has also grown rapidly, particularly with the routine use of satellite imagery in nightly television weather presentations and news reports of events such as the Chernobyl disaster and the Gulf War. Techniques for extracting information from imagery have expanded beyond human 'photo interpretation' to include powerful computer tools for processing and analysing digital data and facilitating its integration with information obtained from other sources.

The launch of the Earth Resources Technology Satellite (ERTS - later renamed Landsat 1) by NASA on 23 July 1972 brought together for the first time a high resolution EO sensing system and a dedicated satellite platform. Since then the USSR, France, the European Space Agency (ESA) and Japan have orbited operational remote sensing satellites, whilst China and India have orbited experimental systems. Canada and Brazil have each announced plans to launch systems by the turn of the century. Very high resolution aircraft-mounted multi-spectral scanners, developed mainly in North America, Europe and Australia, have also proliferated and are increasingly competing with conventional panchromatic and colour photography for coverage of small areas. These provide a useful adjunct to satellite imagery.

Current remote sensing systems can be broadly divided into three functional areas. These are:

a. earth resource sensing systems,

b. environmental sensing systems, and

c. oceanographic sensing systems.

Each will be discussed in turn.

EARTH RESOURCE SENSING SYSTEMS

Remote sensing systems designed to assist in the exploration and monitoring of the Earth's resources typically employ multi-spectral sensors covering the visible and NIR spectra. To achieve global coverage at optimum illumination and resolution these systems use polar and sun-synchronous orbits at altitudes ranging from 250 to 850 km. The US Landsat, the French SPOT and the various systems carried on the former USSR's (now Russia's) Kosmos satellites are representative of this group. Their characteristics are summarised in Table 6.1.

Table 6.1. Remote Sensing Systems For Earth Resource Monitoring

System	Bands	Resolution (m)	Swath (km)	Average Altitude (km)	Re-visit Cycle (days)
Landsat MSS (USA)	4 in VNIR 1 in TIR	80 237	185 185	705	16
Landsat TM (USA)	6 in VNIR-SWIR 1 in TIR	30 120	185 185	705	16
SPOT (France)	3 in VNIR 1 panchromatic	20 10	60 60	832	26*
KATE-200 (Russia)	3 in VNIR	15-30	216	250	**
MFK-6 (Russia)	6 in VNIR	20	140	352	**
KFA-1000 (Russia)	2 in VNIR	5-10	75	250	**
Daedalus (Canada)	11 in UV to SWIR (aircraft mounted) 2 in TIR				
Geoscan I (Australia)	9 in VNIR to SWIR (aircraft mounted) 4 in TIR				

Note:
* SPOT's average revisit cycle at the equator is 3.7 days if its off-nadir capacity is employed, with this period reducing as latitude increases.
** Film return systems of limited orbital life.
VNIR = Visible and near IR.
TIR = Thermal IR.

The sensors onboard these earth sensing systems gather information which can be used to support a wide range of applications. Research objectives to which data from these systems has been applied include:

a. agricultural management, such as crop production estimates, disease and crop stress monitoring;

b. surveillance of illicit crops such as opium and cannabis;

c. inventory and monitoring of forest resources and other vegetation features;

d. geological survey to aid mineral and petroleum exploration and ground water inventory;

e. urban and regional planning and environmental impact assessments;

f. land management surveillance to detect degradation and erosion;

g. wildlife habitat evaluation and monitoring;

h. water conservation and flood control planning;

g. archaeology;

i. disaster management in events such as floods, fires, drought, pollution and volcanic eruption; and

j. topographic and shallow-water map compilation and revision.

Landsat

The Landsat mounted Multi-Spectral Scanner (MSS) is the oldest civilian space-based sensor. It has been carried on each of the five Landsat satellites launched since 1972 and has built up a very significant global archive of medium resolution imagery. The higher resolution Landsat Thematic Mapper (TM) sensor has been carried on Landsat 4 and 5. In Australia, imagery from Landsat is collected daily at the ACRES ground station at Alice Springs. This station has a radius of access of about 4,000 km which covers continental Australia and much of New Guinea and the Moluccas.[4] It takes the satellite about 11 minutes to pass from horizon to horizon. A narrow strip of the Western Australia coast is also covered by the Landsat station near Djakarta.

Images are received as a continuous strip 185 km wide. Overlap between strips is minimal at the equator, however, at latitudes higher than 40° the between-strip overlap increases to the point where effective stereoscopic coverage is available. Stereoscopic coverage is a prerequisite for topographic mapping applications.

Data from the satellite are available either in digital form on computer-compatible tapes (CCT), or as photographs. Landsat 6 is due to be launched in July 1992. Landsat 6 will carry a 15 m resolution panchromatic sensor in lieu of the MSS.

SPOT

France's SPOT-1 (Systeme Probatoire de l'Observation de la Terre) was launched in February 1986. SPOT-2, which is identical to SPOT 1, was launched in January 1990. Further launches are planned before the end of the century.

SPOT provides multi-spectral (XS) imagery at 20 m resolution and panchromatic (P) imagery at 10 m resolution. An example of SPOT's panchromatic imagery is at Figure 6.1. SPOT has two identical sensors, each with a 60 km swath width. When both are operated in the adjacent vertical mode they cover an effective swath width of 117 km. A unique feature of SPOT is its ability to image areas up to 27° either side of satellite ground track, giving it an effective FOV 950 km wide. This capacity enables it to produce stereoscopic images of any point on the globe (from different orbits). It also has the potential to image the same area as frequently as 7 times during each 26 day orbital cycle at the equator and 11 times at 45° latitude. Images are recorded as single scenes on command from SPOT control at Toulouse (France) and 'dumped' to ground stations at Toulouse, Kiruna (Sweden) and the ACRES site.

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[4] The coverage of this station was illustrated in Chapter Four, Figure 4.1.

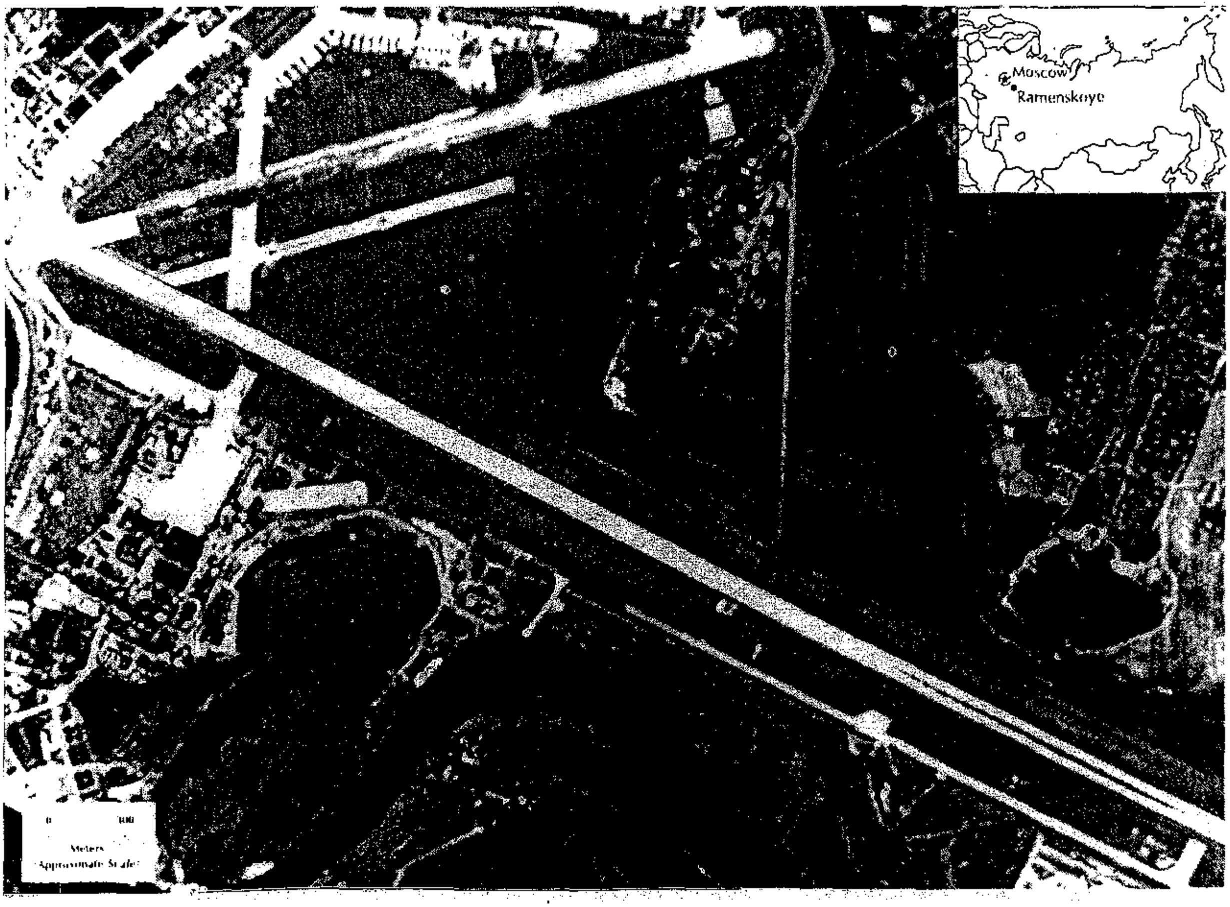

Figure 6.1. A SPOT Panchromatic Image[5]
This 10 m resolution image is of the Russian Flight Research Institute near Moscow. Unfortunately, some fidelity has been lost in the reproduction process.

<u>Russian Systems</u>

Russian (former Soviet) systems are unique in that they still employ photographic technology to obtain their imagery rather than the EO technology used by Western systems. This delays imagery recovery, and limits the useful life of the satellite to that of its film capacity. On the other hand, the short life imposed on the satellite by its film capacity does allow the use of very low (250 km) orbits without the fuel overhead demanded by longer lived systems. This makes spatial resolution down to 5 m possible. Conventional along track stereoscopic coverage with 60% overlap is provided. Products include a full range of colour and panchromatic photographic products and scan-digitized versions of photographic masters are available as CCT through the Sydney-based firm Technical and Field Surveys. Figure 6.2 shows the coverage of Australia that is available from the high resolution KFA-1000 system.

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[5] Lindsey, G., *Space Surveillance and Canada*, Canadian Defence Quarterly, October 1991, p 11.

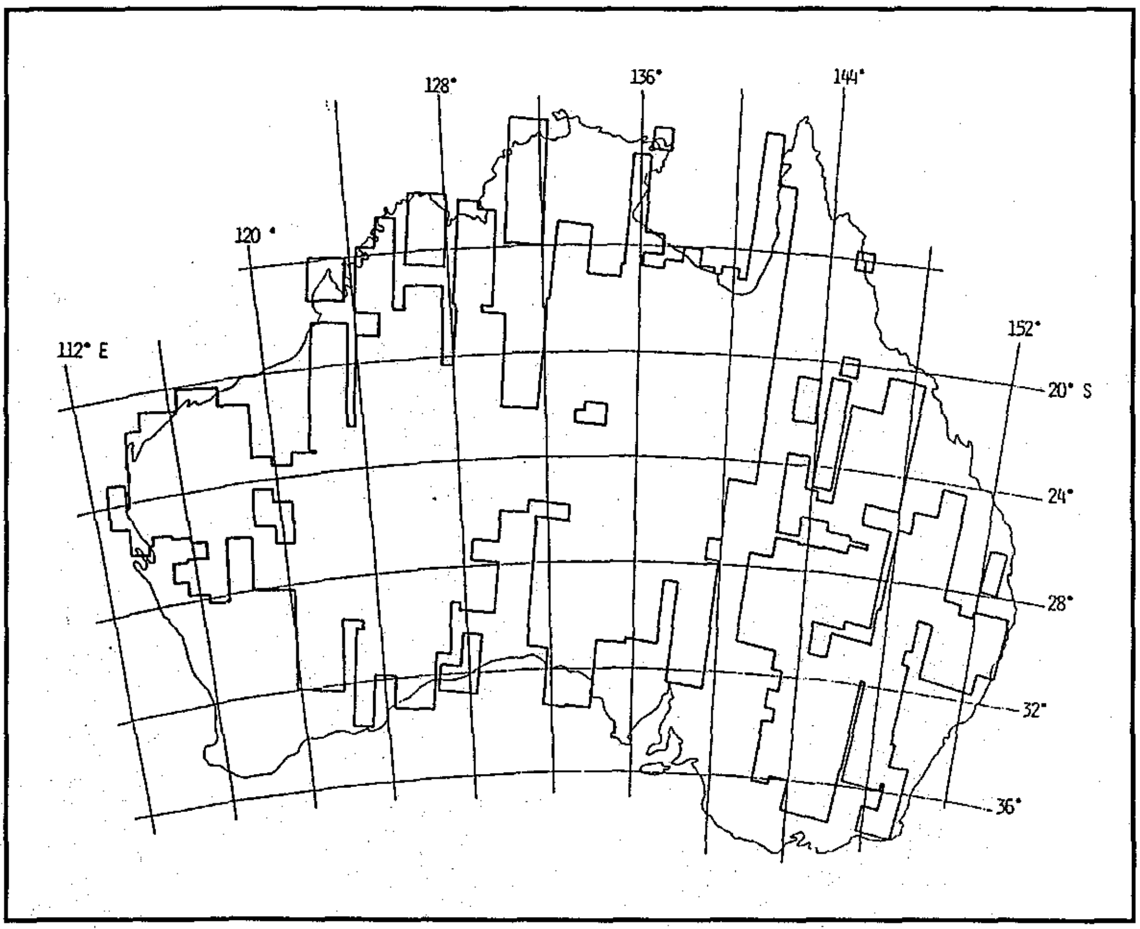

Figure 6.2. Russian KFA-1000 Photographic Coverage of Australia[6]

Airborne Systems

Airborne systems are presented for comparison with their space-based counterparts. Airborne imaging systems have proliferated during the past decade. Their spatial and spectral resolution is superior to that of space-based platforms. Absolute spatial resolution is dependant on the height of the aircraft above the ground (as is the case with aerial photography). For example, a Daedalus scanner (with an instantaneous field of view of 2.5 milli radians) would provide an image with a resolution of 2.5 m from an altitude of 1000 m; from 2000 m the resolution would be 5 m. However, difficulty can be experienced in geo-referencing data from airborne scanners because of the level of accuracy required and inherent instability of the platform. The introduction of the GPS NAVSTAR space-based navigation system in 1994 will help address this problem. Thermal IR line-scanners, sideways looking airborne radar (SLAR), SAR and camera-based remote sensing systems are also used from aircraft platforms. Despite their superior resolution, airborne systems are far more expensive to operate than their space-based counterparts (see Table 6.3), and cannot search large areas as quickly.

In fact, air and space-based systems are complementary in nature: the space-based system provides a broad overview of an area of interest while the airborne system is more suited to examining sub-sets of that area in more detail.

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[6] Technical and Field Surveys Pty. Ltd., Crows Nest, NSW.

ENVIRONMENTAL SENSING SYSTEMS

Satellite systems designed to monitor atmospheric and meteorological conditions have been in use longer than other types. The earliest were the US Vanguard and Explorer satellites launched in 1959. Modern systems are placed either in medium altitude sun-synchronous polar orbits or are at GEO. Sensors operate mainly in the near and thermal IR bands at medium to low spatial resolutions. Passive microwave sounding instruments are also carried on some satellites. The emphasis of these systems is on achieving a frequent synoptic view. Figure 6.3 illustrates the positioning of environmental satellites about the Earth, whilst Table 6.2 lists the prime characteristics of representative systems.

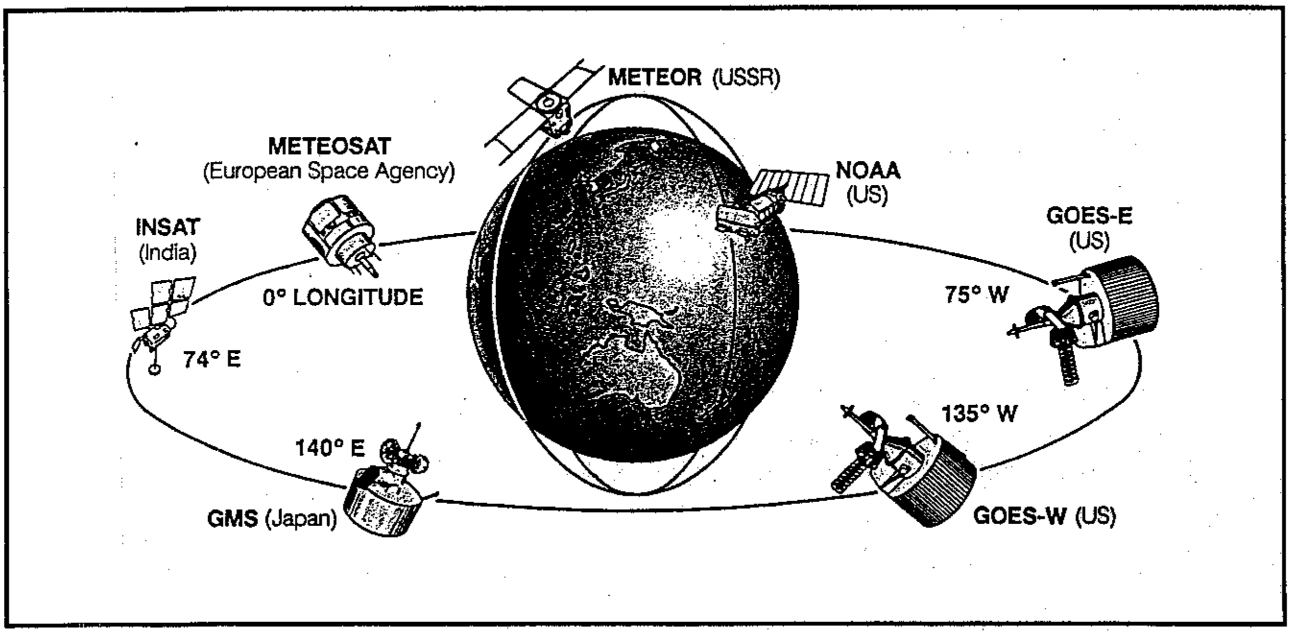

Figure 6.3. The Global Meteorological Satellite System[7]

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[7] *'The Weather by Satellite'*, Bureau of Meteorology, Melbourne, 1990.

Table 6.2. Remote Sensing Systems For Environmental Monitoring

System	Bands	Resolution (m)	Swath Width (km)	Average Altitude (km)	Re-visit Cycle (days)
GOES	8 in VNIR	1,000		35,800	**
(USA)	12 in TIR	7,000			
GMS	1 in VNIR	1,250	*	35,800	**
(Japan)	1 in TIR	6,000			
Meteosat	1 in VNIR	2,500	*	35,800	**
(ESA)	1 in TIR	5,000			
		1 in TIR		5,000	
NOAA AVHRR	2 in VNIR	1,100	3,000	829	0.5
(USA)	3 in TIR	1,100			
Meteor 2	1 in VNIR	2,000	2,100	950	0.5
(Russia)	1 in VNIR	1,000	2,400		
	1 in TIR		8,000	2,600	
	8 in TIR		30,000	1,000	

Note:

*	Complete 'Earth disk' hemispheric view.
**	Geostationary satellite in constant view, scanning at least hourly.

The meteorological applications of the data derived from these systems include:

a. weather and nephanalysis from which short-term forecasts are made;

b. tracking tropical cyclones and other hazardous weather conditions;

c. atmospheric temperature profiles;

d. the analysis of climatic characteristics and climate change;

e. monitoring of the Earth's albedo and ozone layer;

f. monitoring the development of, and recovery from, drought conditions by reference to vegetation vigour;

g. measuring sea surface temperatures to monitor climatic influences such as the El Nino Southern Oscillation phenomenon; and

h. measuring the height of cloud tops and atmospheric water vapour.

In addition to these applications, increasing use is being made of data from these systems to support other environmental assessment activities, including:

a. estimating soil moisture;

b. estimating the flamability of vegetation and monitoring major bush fires;

c. tracking the spread of ash clouds from volcanic eruptions to provide warnings to aviators;

d. monitoring sea surface colour to measure marine biomass and sediment content; and,

e. monitoring the spring break-up of polar ice and glaciers to detect ice floes and bergs.

Global Meteorological Satellite (GMS)

Meteorological data covering the Australian region are currently obtained free from the Japanese owned GMS. GMS is representative of the geosynchronous meteorological satellites operated under the auspices of the Global Atmospheric Research Program, or GARP. Similar systems include the US's Geostationary Operational Environmental Satellites (GOES) East and West and ESA's Meteosat. These satellites are designed to provide a view of an entire hemisphere, although curvature of the Earth effectively means that useful data is only available between the latitudes of 60° north and south. The geosynchronous satellites' inability to cover the polar regions probably influenced the USSR to delay proceeding with the three satellites for which it was allocated positions in the network.

GMS' image acquisition rate is limited by the time it takes to scan each hemispheric view (about 25 minutes). Imagery from GMS is received hourly at the Bureau of Meteorology (BoM) in Melbourne, with four additional half hourly transmissions each day. This imagery is routinely used to monitor weather systems, measure sea surface temperatures and estimate wind speeds derived from the motion of clouds. This imagery is processed through the Australian Regional Man-computer Interactive Data Access System (McIDAS) (ARM) network. The Naval Weather Station (NWS) at HMAS Albatross and BoM staff at RAAF airfields are connected to the ARM network. The McIDAS system is also used to produce a video loop of successive GMS images to provide an animated picture of regional cloud pattern movement. This is used by some television stations to illustrate their nightly weather reports.

National Oceanic and Atmospheric Administration (NOAA)

NOAA's Advanced Very High Resolution Radiometer (AVHRR) has a primary mission of meteorological observation, but its output has also found many applications in the resource and oceanographic fields. It is arguably the most versatile and economical of all remote sensing systems currently in operation. Two satellites (and occasionally three) operate in tandem in sun-synchronous polar orbits provide global coverage four times in each 24 hour period. Data may be freely accessed using relatively simple antenna systems.

Six stations gather AVHRR imagery in Australia. The BoM operates NOAA stations in Melbourne, Perth and Darwin. ACRES operates the Alice Springs station, CSIRO operates the Hobart station and the North-East Australia Satellite Imagery System (a consortium of James Cook University, CSIRO, the Great Barrier Reef Marine Park Authority, the Queensland Department of Geographic Information and the Australian Institute of Marine Science) operates the Townsville station. Figure 6.4 shows the area coverage of the Australian NOAA stations excepting Darwin, which was only recently commissioned. Darwin's coverage extends well into South-East Asia and the fringes of Indo-China. Imagery from the BoM-operated AVHRR stations is available through the ARM network.

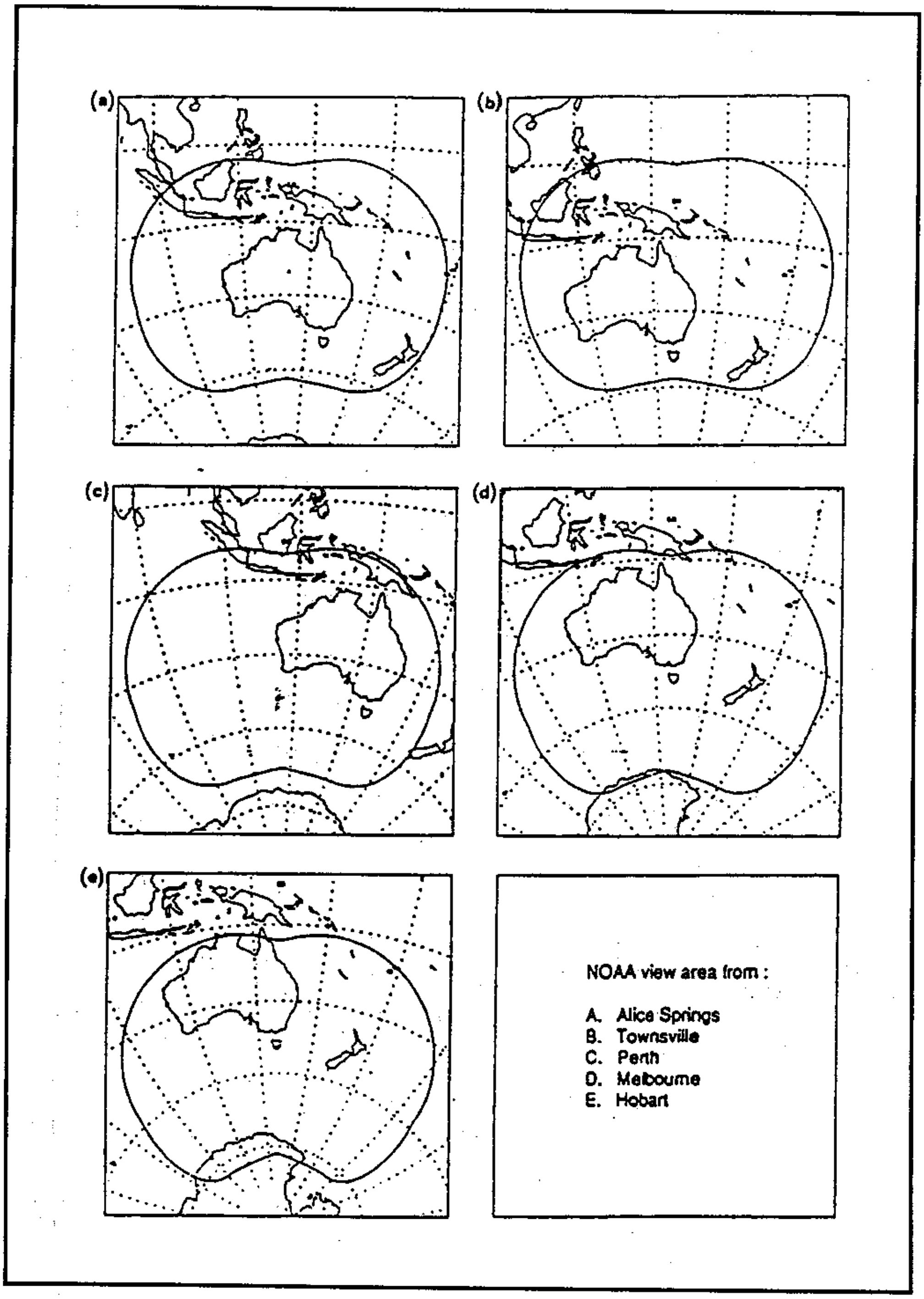

Figure 6.4. NOAA Advanced Very High Resolution Radiometer Coverage[8]

In addition to the AVHRR sensor, the NOAA satellites carry a TIROS Operational Vertical Sounder (TOVS), a three component instrument used to derive atmospheric vertical temperature and moisture profiles and measure total ozone concentrations. The NOAA satellites also carry transponders for the Search and Rescue satellite system (SARSAT).

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[8] Harrison, B. and Jupp, D., *'Introduction to Remotely Sensed Data'*, CSIRO Publications, Melbourne, 1989, p 36.

Meteor 2

The Russian Meteor 2 polar-orbiting system was designed to provide information on cloud, ice and snow coverage, temperature fields, cloud-top heights and near-space radiation. Like its American NOAA counterpart, it has a wide range of potential applications beyond meteorology. The first of a follow-on series of Meteor 3 satellites was launched in October 1984.

OCEANOGRAPHIC SENSING SYSTEMS

Oceanographic sensing systems have been designed to monitor such things as sea ice, salinity, turbidity, sea surface colour, phytoplankton distributions, eddy genesis, sea surface wind velocities and sea surface temperatures. They usually operate from medium altitude orbits. Some systems, such as the US SEASAT of the 1970s and the current Russian system, employ imaging radar, whilst others, including Japan's Marine Observation Satellite (MOS), employ multi-spectral sensors. There is significant overlap between the roles and applications of the environmental and the multi-spectral oceanographic systems. Indeed, instruments such as the Nimbus 7 Coastal Zone Colour Scanner (CZCS) and the NOAA AVHRR are multi-functional. A widely employed application of the data from the multi-spectral systems is the identification of upwelling areas and temperature fronts in which fish often congregate. Such information is routinely transmitted to fishing fleets in many parts of the world. A comparison of the oceanographic systems is provided in Table 6.3.

Table 6.3. Remote Sensing Systems For Oceanographic Monitoring

System	Bands	Resolution (m)	Swath Width (km)	Average Altitude (km)	Re-Visit Cycle (days)
MOS-1 (Japan)	4 in VNIR	50	100	909	17
	1 in VNIR	900	1,000		
	3 in TIR	2,700	1,500		
	1 microwave	32,000	317		
Nimbus 7 CZCS (USA)	5 in VNIR	825	1,566	955	6
	1 in TIR	825	1,566		
Kosmos 1500 (Russia)	Radar	1,500	460	640	7
	4 in VNIR	200		600	
	4 in VNIR	1,500	2,000		
ERS-1 (ESA)	SAR	25	99.5	785	35

MOS carries a multi-spectral instrumentation package designed specifically for ocean observation, particularly surface temperature and ocean colour. It also carries a passive microwave sensor to measure water vapour, snow and ice in the atmosphere. Whilst MOS-1 is essentially a developmental system. data from it is being operationally processed in several countries including Australia. Data from MOS-1 was received by ACRES at Alice Springs during 1989.

COSTS OF REMOTELY SENSED DATA

Table 6.4 indicates costs per square kilometre for data obtained from space and airborne remote sensing systems. Data from space is far cheaper to purchase but its resolution is poorer than that of airborne systems. Airborne systems can also be more flexibly employed and directed than can space systems.

Table 6.4. Remote Sensing Costs[9]

Sensor	Working Scale	Scene Cost ($)	Cost/km ($)	Scene Coverage	Resolution (m)	Frequency
NOAA-AVHRR	1:1,500,000	125 (CCT)	-	2700 x 5000	1,000	8 hours
LANDSAT-MSS	1:100,000 to 1:250,000	960 (CCT) 420 (print)	0.03 0.01	185 x 185	80	16 days
LANDSAT-TM	1:50,000 to 1:100,000	4,500 (CCT) 700 (print)	0.13 0.02	185 x 185	30	16 days
SPOT-XS	1:50,000 to 1:100,000	3,100 (CCT) 2,989 (print)	0.86 0.83	60 x 60	20	1-5 days
SPOT-PA	1:25,000 to 1:50,000	3,815 (CCT) 3,295 (print)	1.06 0.92	60 x 60	10	1-5 days
AERIAL PHOTO (existing)	1:50,000	20 (print)	0.20	10 x 10	0.5	5-10 years
AERIAL PHOTO (existing)	1:25,000	20 (print)	0.80	5 x 5	0.25	5-10 years
AIRCRAFT SCANNER	1:1,000 to 1:50,000	dependent on location: $200,000 to $500,000 (CCT)	69.00	dependent on height	1-20	as required

DATA PROCESSING AND ANALYSIS

Extracting information from the data captured by film-based remote sensing systems originally relied on visual examination of photographic media using image characteristics such as tone (or colour), texture, shape, size, shadow and association. Typically this work was undertaken by personnel with background and training in the relevant discipline as well as the skills of 'photo interpretation'. The advent of digital imaging sensors has given rise to the rapid development of computer systems to process and aid in the analysis of the imagery.

A significant amount of pre-processing is usually required to transform the raw data direct from the sensor into a form that is readily usable in an image processing system. This generally involves corrections for radiometric and geometric distortions produced by sensor balance and atmospheric distortions, as well as the curvature and rotation of the Earth. Processing to 'clean' the data to account for missing scan lines, to enhance the contrast and to remove data artifacts is also carried out.

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[9] Sourced from: Millane, T., Army Scientific Adviser, Department of Defence, Canberra, 1990.

Increasingly, data processing systems are being given the capability to integrate processed images with other data such as digital elevation models, cadastral boundaries and environmental recording instrument data. These so-called 'image-based GIS' provide the most potent of tools currently available to users of geographic information.

The transformation of image data to information involves a range of analytical, transformation and classification techniques. To maximize the accuracy of this process ground truthing (that is, field measurement) remains essential. The quality of information can be further improved by integrating data from multiple sources (for example, merging aerial photography with satellite imagery) with collateral data from non-image sources.

GEOGRAPHIC INFORMATION SYSTEMS

The term GIS emerged in the 1960s with the early application of computer technology to mapping and spatial data processing in geography. It has, over the ensuing years, come to mean many things to many people. Disciplines that have embraced GIS, or which have had an influence on its evolution, include: geography; cartography; remote sensing and image processing; computer science; surveying, geodesy and photogrammetry; land administration and management; earth and biological sciences; urban and regional planning; resource exploitation and management; and the management of infrastructure and utilities; and many others.

Given the wide range of users, it is not surprising that definitions of GIS range in their emphasis from the technology involved to all embracing views that regard GIS as models of reality. A whole vocabulary of synonyms has also developed, including: spatial information system; land information system (LIS); geo-base information system; natural resource information system; geo-data system; multi-purpose cadastre; and automated mapping facilities management (AM/FM) system. The ADF has adopted the term Military GIS (MGIS), or simply MGI.

Regardless of the name applied or definition used, there is little dispute about the rapidly growing importance of GIS to users such as the military who need geographic information and the potential if has to facilitate decision making. GIS may be defined as:

> ***'a decision support system involving the integration of spatially referenced data in a problem solving environment'***[11].

The typical conceptualisation of a GIS is illustrated at Figure 6.5. By integrating remotely sensed data with data from other sources, a GIS can provide a very complete picture of a particular region or country. Annex C lists a catalogue of the essential elements which constitute geographic information.

The power of a GIS is certainly greater than the sum of its individual parts. Within the Australian defence community this realisation has been slowly gaining momentum over the past few years. This has been fostered largely by two major seminars, the first arranged by the Strategic and Defence Studies Centre of the ANU in 1987[12] and the second organised jointly by HQADF and ADFA in 1988[13].

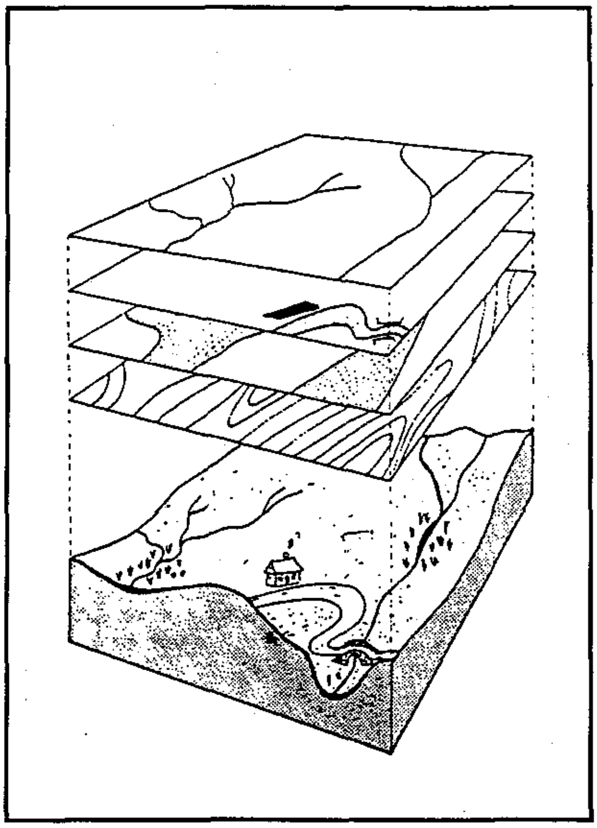

Figure 6.5: Typical Conceptualisation of a Geographic Information System[10]

Data Sources

There is virtually nothing that cannot be learned about the geography of Australia and its attributes from existing publicly available sources of information. However, an alarming amount of the data that have been collected appears to have been rarely exploited or published. It is simply 'filed and forgotten'. The problem is finding out who has the data and whether they can be easily related to other data.

Those data sets that have been analysed and published are extensive, both in area and range of topics covered. There is, unfortunately, no central repository for such data and the

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[10] Burrough P.A., *Principles of Geographical Information systems for Land Resources Assessment*, Clarendon Press, Oxford, 1986.

[11] Cowen D.J., *GIS versus CAD versus DBMS: What Are The Differences?*, *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 11, pp 1551-1555, American Society for Photogrammetry and Remote Sensing, Falls Church, Virginia, 1988.

[12] Ball D. and Babbage R.(eds), *Geographic Information Systems: Defence Applications*, Pergamon, Sydney, 1989.

[13] HQADF, *Geographic Information in the Defence of Australia*, Seminar sponsored jointly by the Directorate of Intelligence, Headquarters Australian Defence Force and the Department of Geography and Oceanography, Australian Defence Force Academy, Canberra, 1988.

task of accumulating and matching it (especially across political boundaries) is daunting. Fortunately the establishing of the National Resource Information Centre (NRIC), a resource information brokerage established within the Commonwealth Department of Primary Industries and Energy, has greatly assisted in identifying the location and nature of the principal data sets held around Australia. The service offered by NRIC is publicly available.

The imagery record of Australia is certainly comprehensive. A complete cloud free coverage of Australia by both Landsat and SPOT systems is available and Landsat 5 continues to cover Australia completely every 16 days. The digital data from that imagery is commercially available from ACRES (Canberra) and SPOT Imaging Services (Sydney). Comprehensive collections of aerial photography are also held by AUSLIG and by the RAAF Central Photographic Establishment. Most state and territory governments also maintain similar archives of photographic material.

The 'geographic information industry' in Australia is growing rapidly. All state and territory governments, several Commonwealth departments, many local government and utilities bodies, major instrumentalities such as Telecom and many of the larger companies such as BHP and Alcoa have each established systems and programmes of data capture and management. Much of this activity is monitored and loosely coordinated by the Australian Land Information Council (ALIC), a joint Commonwealth/State body at Departmental head-level (because of its mapping and charting roles, Defence is represented on ALIC by ACOPS). The focus of ALIC, however, has been on survey and cadastral information and technical issues such as data transfer standards rather than on broader thematic information.

The growing political significance of environmental issues is leading to an increased effort being devoted to building systems that can aid in environmental policy-making and management. These activities are beginning to draw attention to the vast amounts of spatially referenced thematic data that are available in museums, government departments, CSIRO, universities and so on. They have also given impetus to data capture and collation programmes such as the Environmental Resources Information Network (ERIN) set up within the Bureau of Flora and Fauna of DASETT.

Much relevant information is held within the Defence community itself. Much of it, unfortunately, falls into the 'filed and forgotten' category. Field notes of detailed 'map intelligence' collected by RASVY parties, for example, contain significant amounts of primary data that are never used directly in the production of topographic maps. A similar situation almost certainly exists within other areas of Defence. The full potential value from the investment that is made each year by the defence community on 'information collection' is not realised because those activities are not co-ordinated or adequately managed.

DEFENCE APPLICATIONS OF REMOTE SENSING AND GIS

Within the Defence community the application of remote sensing has been confined largely to mapping and strategic intelligence activities, and then limited mainly to the exploitation of conventional aerial photography.

There are five areas of activity in which the data obtained from remote sensing systems, particularly applied in conjunction with GIS, would prove valuable to the defence community. These are:

a. the derivation of MC&G information;

b. the derivation of terrain and environmental intelligence;

c. the derivation of strategic intelligence;

d. the derivation of tactical and operational intelligence; and

e. surveillance.

MC&G

Satellite images provide a map-like perspective of the Earth's surface. Consequently, there is great scope for data from Landsat, SPOT and Russian systems to be applied to the production of maps, charts and geodetic products.

The compilation of accurate maps and charts is a most exacting process which involves correlating points on the ground for which the location is precisely known, with the representation of the same point on an image. The more control points there are, the more accurate the resulting map will be. In areas where existing ground control is available, or where ground control can be established, Landsat TM data is suitable for the compilation of planimetric detail (that is two-dimensional information only) for maps with scales as large as 1:50,000 in areas of low to moderate relief. Where no ground control is available Landsat TM data can be used to compile planimetric detail for maps to scales of 1:100,000 with accuracies to military B2 standards (that is, features are located to ± 100 m of their absolute position). Landsat TM data are not generally suited to the derivation of elevation data except at higher latitudes where limited stereoscopic coverage is provided by overlapping image swaths.

SPOT data must also be used in conjunction with detailed ground control to achieve acceptable accuracies at scales of 1:100,000 and larger. SPOT's stereo capability gives it the added capacity of deriving elevation data. Work done in the Queensland Department of Geographic Information (DGI) indicates that SPOT stereo imagery used with ground control is capable of obtaining accuracies as great as 6.2 m in planimetry and 3.1 m in elevation. This is well within acceptable 1:50,000 scale military A1 standards (that is, ± 50 m in plan and half a contour interval in elevation). A trial application of SPOT imagery for mapping an area around Kununurra at 1:100,000 scale has been conducted with satisfactory results and RASVY, in collaboration with AUSLIG, used SPOT to produce an image map for Exercise Diamond Dollar (held in western NSW) in 1987.

There is no information available on the use of Russian satellite photography for map compilation. From examples of KFA-1000 studied it would appear suitable for compilation, with control, of maps to at least 1:100,000 and possibly 1:50,000. The stereo coverage is particularly good and its use would present fewer technical difficulties than would use of SPOT, given that it is essentially identical in form to the conventional aerial photography traditionally used in mapping.

The use of satellite imagery in the production of shallow water charts has been successfully demonstrated. The multi-spectral imagery from SPOT and the Landsat TM instruments are particularly good for this. By using the water penetration characteristics of the different spectral wavelengths, isobaths at 2, 5, 10 and 20 m can be derived. Information produced from the CSIRO developed Barrier Reef Imagery Analysis (BRIAN) system has been used to chart new passages through the Barrier Reef from Landsat imagery and AUSLIG have employed similar techniques for shallow water mapping around North West Cape. The BRIAN project, which has mapped the entire Barrier Reef, has been estimated to have saved $21 million on using traditional surveying and mapping techniques. It must be emphasized, however, that this satellite derived charting is not as detailed or as accurate as charting compiled by traditional hydrographic methods and is limited to depths of 20 m, but it is certainly preferable to having little or no shallow water charting. The seasonal turbidity of the coastal waters of the north and north-west of Australia may impose some limitations on the application of these techniques in these areas.

In crisis situations, where standard mapping products are not available or are seriously out of date, satellite imagery can be used to rapidly produce map-substitute products such as pictomaps, to scales as large as 1:100,000. Such imagery can also be used in the production of orthophoto maps (OPM). In near-featureless areas such as the Great Sandy Desert, OPM can provide a better representation of the subtle differences in land and vegetation that are important to users, but impossible to convey by traditional map portrayal methods. The Russian photography would be well suited to this application.

It is in the updating of maps and charts that the use of remote sensing data is particularly valuable. With an existing map base, cultural features such as roads and changes in vegetation boundaries can be readily updated from satellite imagery and the information transferred to GIS. The mapping of recent fire scars in the north-west to assess mobility potential is a case in point. This opens the prospect of maps being issued to troops in the field with information that is only a matter of days or weeks old, rather than the existing situation where the information shown can be many years out of date by the time the map comes off the printing press.

The US Army Defence Mapping Agency (DMA) made excellent use of remotely sensed data to support operations in the Gulf War. To quote Brigadier General Pratt, Deputy Director, DMA:

> *'Prior to the invasion of Kuwait on 2 August 1990 our requirements were for very limited coverage of Kuwait and frankly were orientated toward a different potential war in the Middle East....*
>
> *Advanced delivery of our new Digital production system gave us the opportunity to rapidly exploit Landsat data and create 1:100,000 scale image maps as an interim product until we could produce the 1:50,000 topographic maps required....*
>
> *As one commander put it; "Maps equated in importance to weapons and ammo and were only 'bumped' for Patriot missile spare parts and mine clearance equipment."....*
>
> *We saw the results and learned the importance of DMA MC&G data in the operational use of advanced weapons.'*[14]

It is also worth noting that the US DoD signed a contract with SPOT Image in 1990 worth US$4.7 million for the provision of imagery. In the Gulf War, the US used 108 SPOT images to produce digital terrain maps for strike direction.[15] In contrast, the ADF spent only approximately $60,000 on satellite imagery for MC&G purposes in Financial Year 1990/91. The imagery was used by RASVY for the development of experimental mapping and image products.

RASVY has submitted Major Capability Submission (Land) 42.3, also called Project PARARE. If approved, PARARE would provide digital topographic support for the ADF and provide data to support a MGIS. Digital imagery from Landsat and SPOT would form an important part of the data to be input into the system.

Terrain and Environmental Intelligence

The wide area coverage afforded by remote sensing satellites makes them ideal for the economic generation of thematic information, such as vegetation cover, geology, soils, etcetera. By using the data integration capability of a GIS, remotely sensed digital thematic data can be readily related to the underlying cartographic data. The product can be used to generate customised maps which can facilitate things such as cross country movement (or 'going'), concealment and intervisibility. These can be quickly produced and easily modified and updated.

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[14] Pratt, Brigadier General J., Media release, Defense Mapping Agency Public Affairs Office, Fairfax, VA, 25 March 1991, pp 2-5.

[15] Roos, J., *SPOT Images Help Allies Hit Targets in Downtown Baghdad*, Armed Forces Journal International, May 1991, p 54.

As with the production of MC&G data, the accuracy and level of thematic detail extracted from remotely sensed data is dependant on the level of ground truth and collateral information available to support the interpretation of the imagery. Such collateral information might include existing thematic maps and conventional aerial photography. (Multi-spectral imagery is not a substitute for aerial photography or field surveys; it is an additional tool.)

The application of data from the various meteorological satellites can provide valuable information on militarily significant factors such as cloud cover under which to conceal troop movements from hostile surveillance activities or mobility conditions based on soil moisture indices. Information that would assist greatly in combating natural disasters such as bush fires or to aid the management of training areas, in which the environmental impact of training activities is a concern, can also be derived from such data. They also have potential for providing the Navy with oceanographic information such as sea surface temperatures and the pattern of currents over very large operational areas.

Strategic Intelligence

A heightened level of planned military activity is frequently preceded by the development and upgrading of infrastructure such as road and rail networks, the dispersal of fuel storages and the expansion of industrial and power generation capabilities. The monitoring of such activities within the RPSI might, therefore, provide early indications and warnings of a deteriorating strategic situation. The role of infrastructure intelligence can not be over-emphasised in this process. Successive remotely sensed images can provide information on both what is 'normal' and what has changed.

Some measure of the capacity of the higher resolution remote sensing satellite systems to provide infrastructure details can be gained from the experimental mapping done in DGI. SPOT imagery was used to map an area of Brisbane at a scale of 1:25,000. Infrastructure features were initially plotted from the imagery directly, without reference to other information. A check against collateral information (an existing map) was carried out and some additional features were added. Table 6.5 summarises the results.

Table 6.5. Infrastructure Identified from SPOT Imagery[16]

Feature Type	% Identified Directly	% Added After Map Check	% Missing	Total On Map (km)
Sealed road	79	6	15	46.7
Unsealed road	67	11	22	41.7
Track	24	14	62	82.4
Urban road	65	5	30	11.9
Railway	78	3	19	17.9
Power line	100	0	0	12.4
Fence	14	0	86	345.5
Dam	5	16	79	469
Building	30	8	62	554

These figures should be seen as 'best case' results given that the people carrying out the analysis of the imagery had a high level of direct local knowledge (ground truth) of the area being worked. The initial results would certainly have been poorer had they been less directly familiar with the geography of the target area.

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[16] Priebbenow R., *Cartographic Applications of SPOT Imagery: the Queensland Experience,* paper presented to the 7th Australian Cartographic Conference, Sydney, 1988.

Unfortunately, commercial imagery would be largely incapable of defeating any camouflage techniques that might be employed to conceal strategically sensitive activities. Also, the long re-visit times inherent in civilian space-based remote sensing systems limits their value in times of increased tension. When warning times are reduced to days or weeks, the availability of imagery once every 3 days or more is clearly inadequate. Additionally, the inability of EO systems to image through cloud or at night limits their value.

Tactical And Operational Intelligence

At the tactical and operational level, the data provided by the meteorological and oceanographic satellites have the most direct application.

Air Operations. In air operations, weather satellites can contribute close to real-time meteorological information that can be critical to the success of a mission. The capacity to derive digital elevation models (DEM) from SPOT imagery has been demonstrated. These DEM can be processed by a GIS to produce perspective views of the terrain. These can be used to generate animated scenes to emulate the pilot's view during a strike sortie, a very useful capability for mission planning and rehearsal in a simulator.

Maritime Operations. In the maritime environment, close to real-time information on weather and sea conditions, such as sea surface temperature and currents, may be of operational value, particularly in planning and conducting anti-submarine warfare (ASW) operations.

Land Operations. In the land environment, terrain information derived by remote sensing and integrated within a GIS can provide basic intelligence on fundamental factors such as going, lines of advance, cover, engineering support resources, and so on. It can be used to model the likely action of an enemy through its inclusion in battle simulation routines and to aid in siting defences and lines of communication for logistics support. Vehicle tracks left in soft surfaces can be detected by the higher resolution space-based systems, giving some indication of lines of advance or the conduct of training or rehearsal activities. Planning for amphibious operations would be aided by the shallow water mapping capabilities of multi-spectral systems, whilst drop zones and helicopter landing zones can clearly be identified through vegetation mapping. The ability of the imagery to be used to update and amplify the cultural and ground cover information contained on conventional maps and in GIS is a significant benefit in this regard.

Army Engineering Development Establishment (EDE) has developed a prototype 'Mobility Modelling and Terrain Analysis' system to provide vehicle mobility map overlays. A series of mobility maps is being produced for use in Kangaroo 92. This pilot programme makes extensive use of paper charts and satellite imagery to model vehicle mobility with reference to terrain, vegetation, vehicular capabilities, season and obstacles.

Temporal resolutions from commercial remote sensing satellite systems are inadequate to support real time tactical and operational intelligence activities.

Surveillance

Existing civilian remote sensing satellites have no capacity or potential for use in surveillance, other than for fortuitous target detections, and then only if the material could be exploited in close to real-time. The capacity to process and analyse Landsat and SPOT imagery directly does not exist at ACRES Alice Springs receiving station.

Spatial resolution is also important. Many of the objects of interest in the ADMI, such as Indonesian fishing vessels, require system resolutions of better than 10 m to be detected. These vessels also tend to enter Australian territory at night to avoid conventional surveillance patrols, which also makes VNIR sensors ineffective.

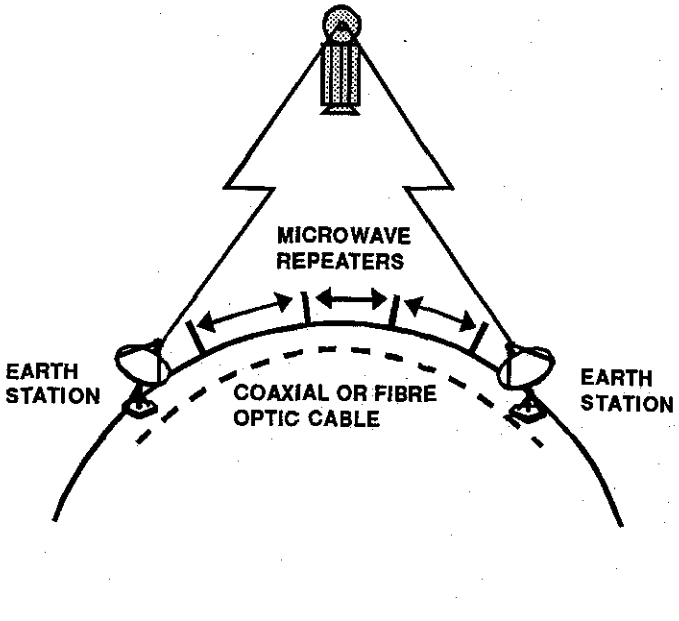
CHAPTER SEVEN

COMMUNICATIONS

This chapter will present the ADF's plan for integrating satellite communications (satcom) into a communications system called the Defence Integrated Secure Communications Network, or DISCON. However, before discussing that project, a little background is required on satcom in general, including the characteristics of satcom, Australia's commercial carriers, and the generic requirements of military communications systems.

CHARACTERISTICS OF SATCOM

A communications satellite is basically a radio relay platform. It has advantages over conventional terrestrial links in that it can provide single hop communications anywhere within its footprint (see Figure 7.1). Radio relay on board the satellite is done by the ***transponder***. A transponder is a device which accepts an up-link signal within its frequency and bandwidth parameters; filters, translates and amplifies the signal; and re-transmits it the down-link frequency. Communications satellites usually have a number of transponders. For example, the current A-Series AUSSAT satellite has 15.



Terrestrial links require multiple hops whilst a satellite system can provide the same capability in a single hop.

Figure 7.1. Terrestrial Versus Satellite Communication Links[1]

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[1] Adapted from: Elbert, B., *Introduction to Space Communication*, Artech House, Norwood, Massachusetts, 1987, p 6.

Global Communications

Three geostationary satellites placed 120° apart in longitude could provide global communications except to the polar regions (see Figure 7.2). It is also possible to provide global communications using a constellation of 12-18 satellites at medium altitude, or using a very large constellation of small satellites in LEO. A LEO communications constellation is being seriously proposed by Motorola, in a project called Iridium[2]. It is planned to have Iridium operational by 1996. Iridium would use 77 small satellites in seven circular polar orbital planes, with 11 satellites in each plane. Unlike existing cellular systems, Iridium could provide global two-way communications to mobile users.

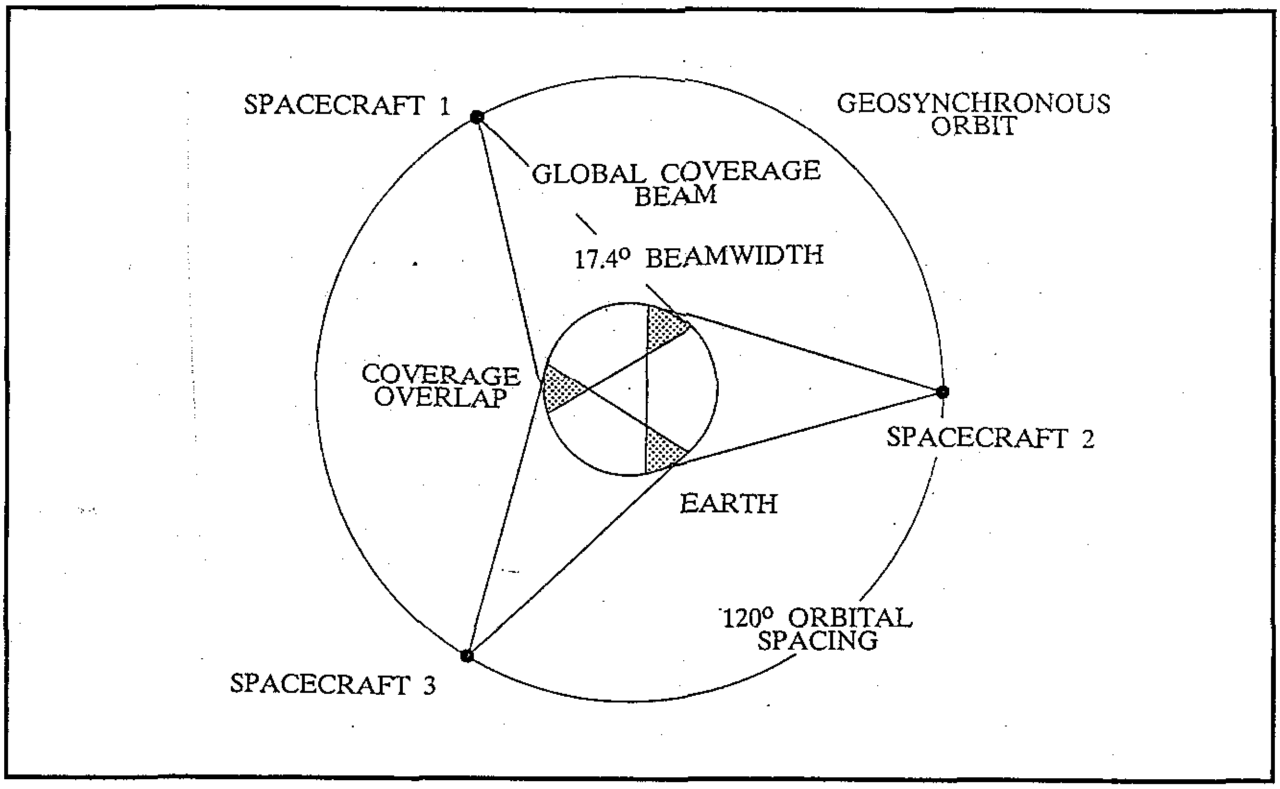

Figure 7.2. Global Communications Using Three Geosynchronous Satellites[3]

Satcom Frequencies

Satcom utilises the RF portion of the EM spectrum to carry communications data.[4] The allocation of telecommunications frequency bands is controlled by the International Telecommunications Union, a United Nations Agency. Table 7.1 defines the specific RF bands allocated to satcom. Satcom bands are divided into two halves, one for the ground to space link (or ***up-link***) and one for the space to ground link (or ***down-link***). The standard nomenclature for the split is ***up-link frequency/down-link frequency***, for example, 6/4 GHz. Up and down link channel separation is required so that each does not jam the other at the satellite. The up-link is generally higher in frequency and power than the down-link. There are specific reasons for this, including:

a. it is easier to generate high RFs in the ground station than onboard the satellite; and

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[2] The project is called *Iridium* as it will use 77 satellites. The element Iridium has an atomic number of 77.

[3] Mahoney, T., *Military Satellite Communications Course Notes*, Communications Division, Electronics Research Laboratory, Defence Science and Technology Organisation, Salisbury, South Australia, June 1991.

[4] The RF spectrum was described in Chapter Five, Table 5.4.

b. the RF power amplifiers generally used onboard satellites are more efficient when converting AC power to lower RFs rather than higher.

c. Large antennae are more easily facilitated on the ground than in space. Also, a large antenna allows the ground station to detect the relatively weak signal from the satellite.

Table 7.1. Satcom Radio Frequency Bands

Frequency Band	Frequency (Up/Down-link)	User	Service
UHF	225 to 400 MHz	Military	mobile
L-Band	1.6/1.5 GHz	Commercial	mobile
C-Band	6/4 GHz	Commercial	fixed
X-Band or SHF	8/7 GHz	Military	fixed/mobile
Ku-Band	14/12 GHz	Commercial	fixed
Ka-Band or EHF	30/20 GHz	Commercial	fixed
Ka-Band or EHF	44/20 GHz	Military	fixed/mobile

Each frequency band has particular advantages and disadvantages which must be considered when designing a satcom system. A few basic rules to consider when selecting an RF band are:

a. The higher the RF frequency, the wider the bandwidth, and thus more data can be carried.

b. Wider bandwidths allow more noise to enter the system. In turn, more signal power is required to maintain an acceptable signal to noise ratio.

c. Broadly, the higher the RF frequency, the greater the atmospheric attenuation. Rain is a particular problem at higher frequencies (see Figure 7.3).

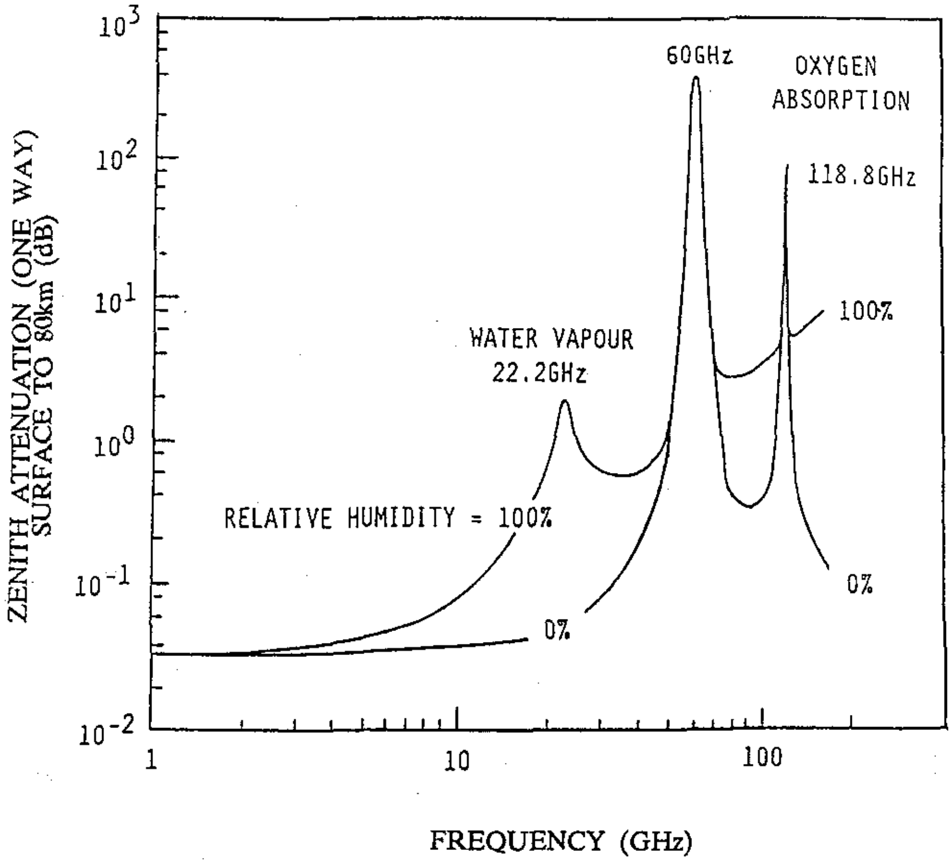

Figure 7.3. Atmospheric Attenuation of Radio Frequencies[5]

d. For a given antenna size, the higher the RF frequency the narrower the transmitted beamwidth. Narrow beamwidths necessitate very accurate antenna pointing systems, making high frequency systems unsuitable for mobile users. For this reason, up-links to and down-links from mobile users generally operate in UHF or L-band, although the link from the satellite to the ground station is generally at a higher frequency.

The RF bands listed at Table 7.1, with the exception of EHF, are in general use in satcom systems today. Whilst EHF systems offer very wide bandwidths and high data rates, they are still at an early stage of development. The considerations presented above are summarised by Table 7.2.

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[5] Mahoney, op cit.

Table 7.2. A Comparison of Satcom Frequency Bands[6]

Criteria	UHF	SHF	EHF
Cost	Low	High	Higher
Technology	Simple Mature	Harder Mature	Complex Developing
Antenna Pointing	Easy	Harder	Demanding
Bandwidth	Narrow	Wide	Very Wide
Resistance to Jamming	Low	Medium	High
Susceptibility to Enemy Direction Finding	High	Medium	Low
Steerable Spot Beams on Satellite Antennae	No	Yes	Yes
Multi-Beam Forming Antennae	No	Yes	Yes
Susceptibility to Rain Attenuation	Low	Medium	High

AUSTRALIA'S COMMERCIAL CARRIERS: OPTUS, TELECOM AND OTC

While the acquisition of a dedicated Defence communications satellite is under investigation as part of the ADF's Military Satellite Communication (MILSATCOM) project, it is by no means guaranteed that the ADF will acquire a dedicated satcom capability. In the interim, the ADF is relying on Australia's commercial carriers to provide satellite communications services which can be integrated into DISCON. Three commercial carriers currently offer satcom services: Optus through AUSSAT, Telecom and OTC.

OPTUS

Background

The Australian Government announced on 19 December 1991 that it had accepted Optus' bid to become Australia's second commercial carrier. Optus will be in direct competition with a merged Telecom and OTC. Fifty one percent of Optus is owned by a consortium of Australian companies, including Mayne Nickless, AMP, National Mutual and a series of AIDC managed institutional investors . The remaining 49% is controlled by two foreign telecommunications companies, Bell South from the US and Cable and Wireless from the UK. As part of the agreement, Optus has taken over AUSSAT. Whilst no firm detail was available at the time of writing, it can reasonably be assumed that Optus will continue to meet AUSSAT's existing contractual agreements. Working from that assumption, the remainder of this section

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[6] Adapted from: O'Neill, COL D., *An Australian Defence Satellite Communications Capability*, p 21: Paper presented at the *Australia and Space* conference, Strategic and Defence Studies Centre, Australian National University, Canberra, 27-29 November 1991.

will discuss AUSSAT's existing and planned satcom infrastructure, and Defence plans to use that infrastructure.

AUSSAT. AUSSAT was a Government Business Enterprise (GBE) formed in 1985. The aim of the enterprise was to provide Australia with a national satellite communications system. Eighty percent of AUSSAT's satcom capacity was taken up by the end of 1987. This is an exceptionally high take up rate by international standards, and is indicative of the shortfall in Australia's communications infrastructure which existed at the time.

Satcom Hardware

Table 7.3 outlines AUSSAT's spacecraft program.

Table 7.3. AUSSAT's Spacecraft Program

Vehicle	Orbital Location	Launch Date (Vehicle)	Lifetime	Replacement Date
First Generation (A-Series) - Hughes HS 376 (spin stabilised)				
A1	160°E	Aug 85 (STS)	7.5 yrs	Dec 92
A2	156°E	Nov 85 (STS)	7.5 yrs	Jun 93
A3	164°E	Sep 87 (Ariane)	10 yrs	Sep 97
Second Generation (B-Series) - Hughes HS 601 (3-axis stabilised)				
B1	160°E	replace A1 Apr 92 (LM2E)	13.7 yrs	2005
B2	156°E	replace A2 Jul 92 (LM2E)	13.7 yrs	2005
Third and Fourth Generation				
Options under consideration.				

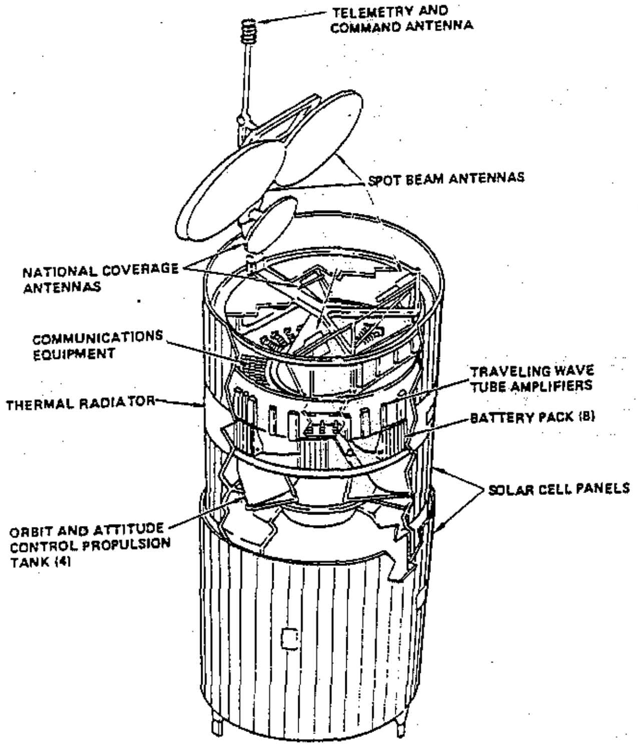
Notes:
STS = US Space Transportation System (or Space Shuttle).
LM2E = Chinese Long March 2E three-stage launch vehicle.

AUSSAT's first generation constellation comprises three Hughes HS 376 spin stabilised satellites. Figure 7.4 illustrates the satellite and lists its specifications. The A-Series spacecraft operate in Ku-band, and in addition to national coverage, provide shaped beams for communications into New Zealand and the South West Pacific. TT&C stations are provided at Belrose in Sydney and Lockridge in Perth.

The first two A-Series satellites will reach the end of their operational lives in 1992 and 1993 respectively. They will be replaced by two B-Series satellites. The B-Series will use a Hughes HS 601 spacecraft bus, which is three-axis rather than spin stabilised. Figure 7.5 illustrates the satellite and lists its specifications.

The B-Series satellites will have the same Ku-band coverage of Australia as the A-series, and will introduce a separate national beam for New Zealand and an L-band transponder for mobile services. Additionally, the power and beamwidth of the Ku band transponders have been increased.

Plans for the replacement of the A3 spacecraft in 1997 are still under consideration. It may be replaced with either another B-Series spacecraft, or perhaps a C-series.

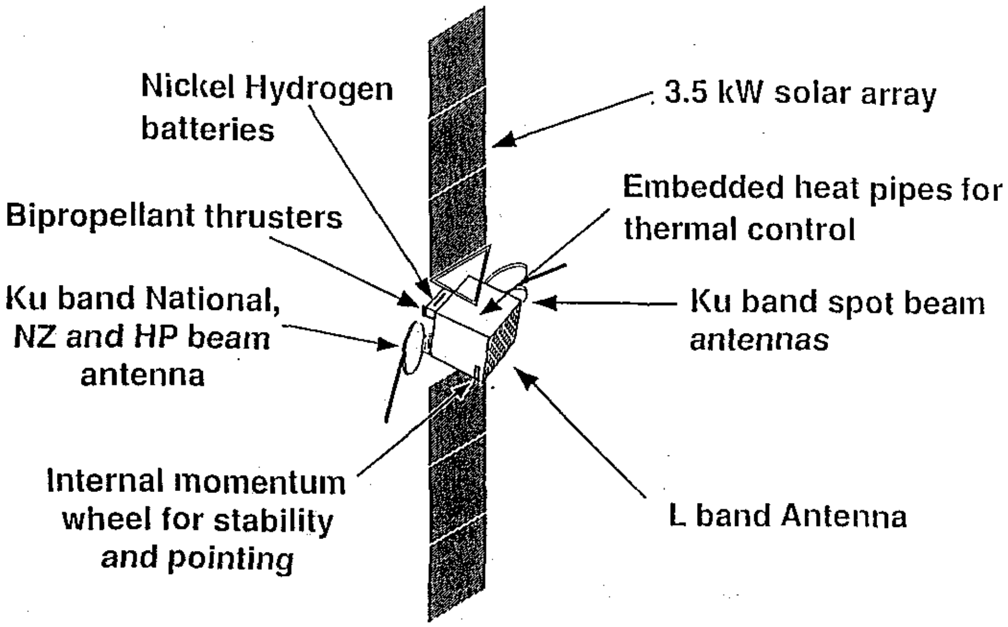


AUSSAT A-Series Specifications

Ku-Band

Up-Link Frequency Band	14.00 - 14.50 GHz
Down-Link Frequency Band	12.25 - 12.75 GHz
Transponders	15
Bandwidth	45 MHz
Available Bandwidth	675 MHz
Occupied Bandwidth	500 MHz
Co-Channel Separation	64 MHz
Cross-Channel Separation	32 MHz
Transmit Power	
(Transponders 7, 8, 14, 15)	4 @ 30 W
(Transponders 1-6, 9-13)	11 @ 12 W

Figure 7.4. AUSSAT First Generation Spacecraft and Specifications



AUSSAT B-Series Specifications

Ku-Band

Up-Link Frequency Band	14.00 - 14.50 GHz
Down-Link Frequency Band	12.25 - 12.75 GHz
Transponders	15
Bandwidth	54 MHz
Available Bandwidth	810 MHz
Occupied Bandwidth	500 MHz
Co-Channel Separation	62.6 MHz
Cross-Channel Separation	31.3 MHz
Transmit Power	15 @ 50 W

L-Band

Up-Link Frequency Band	1.6465 - 1.6605 GHz
(Ku-Band Down-Link)	12.2635 - 12.2775 GHz
Down-Link Frequency Band	1.545 - 1.559 GHz
(Ku-Band Up-Link)	14.0115 - 14.0255 GHz
Down-Link EIRP	46 dBW

Figure 7.5.* AUSSAT *Second Generation Spacecraft and Specifications

TELECOM[7]

Telecom is the only organisation authorised to provide common carrier or third party services through AUSSAT. Telecom has established a satcom service called 'Iterra'[8] through a leased AUSSAT transponder. Iterra can extend normal Telecom telephone services to a customer's fixed or transportable ground terminal through AUSSAT's transponder and an earth station in Bendigo.

The Transportable Iterra Network Earth Station or TINES is available in three configurations:

a. Truck Mounted. A truck mounted earth station with a 4.6 m antenna can provide up to 14 standard voice circuits.

b. Large Trailer Mounted. A trailer mounted earth station with a 3 m antenna can provide 7-8 voice circuits.

c. Small Trailer Mounted. A smaller terminal offering 2-4 voice circuits is also available.

Versions of the two smaller terminals have been designed to be air transportable by C130. TINES terminals can be leased on either a short or long term basis.

OTC[9]

OTC is the sixth largest shareholder in the International Telecommunications Consortium, INTELSAT, which has a membership of 121 countries.

OTC currently transmits approximately 60% of Australia's international communications via a constellation of geosynchronous satellites over the Pacific, Indian and Atlantic Oceans. OTC owns and operates four earth stations in Australia, located at:

a. Perth, operating into the Indian Ocean satellite;

b. Ceduna, operating into the Indian and Pacific Ocean satellites; and

c. Moree and Healesville, operating into the Pacific Ocean satellite.

These earth stations are connected to Telecom's domestic network.

OTC is also a shareholder in International Maritime Satellite Communications, or INMARSAT. INMARSAT's primary interest lies with the provision of satcom services and terminals to mobile users such as shipping and aviation.

It must be noted that international agreements preclude the use of these civilian services by organisations or countries engaged in warlike activity. However, this limitation does not apply to United Nations sanctioned activities.

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[7] Davey, SQNLDR K., *Presentation on Satellite Communications in the ADF*, Headquarters ADF, Department of Defence, Canberra, 23 August 1991.

[8] Iterra is an aboriginal word meaning 'be quick'.

[9] Davey, op cit, p 15.

THE DEFENCE COMMUNICATIONS ENVIRONMENT

'Policy

Australia's policy of defence self reliance is underpinned by a strategy of defence in depth. This strategy envisages Joint operations in our ADMI, with priority focussing on northern Australia and the approaches thereto. It portends operations generally being conducted by small numbers of widely dispersed groups of military assets. The command and control of such operations necessitates robust, long range communications....

Defence Beyond the ADMI

Beyond the direct defence of Australia, the development of Defence communications capabilities must also have regard to wider Defence policy and aims, particularly promoting strategic stability and security in our region, and meeting the mutual obligations we share with our allies. Communications should be able to support regional deployments and training exercises pursued for these aims.'[10]

To meet these objectives, Defence requirements for the communications mission are:[11]

a. Performance. The system must be able to provide responsive communications systems with adequate capacity.

b. Coverage. The system must provide communications coverage of the ADMI, and satisfy the needs of wider Defence policy and aims.

c. Security. The system must provide security of transmitted information, consistent with Government policy.

d. Survivability. The system must be designed to ensure survivability of essential communications.

e. Interoperability. The system must provide interoperability within Defence, between different Defence systems, with civilian standards both within Australia and overseas and with our allies.

The Defence Communications Corporate Plan (DCCP) acknowledges deficiencies in the ADF's ability to satisfy its communications requirements, and recognises that augmenting our conventional communications assets with satellite communications can address those deficiencies.

'Performance and Coverage

The network of ADF HF radio stations provides a generally reliable communications service to ADF static and mobile assets within and beyond the ADMI. HF radio is the only long range communications capability owned by the ADF. Current tactical networks are developed, operated and maintained by single Services.

HF radio has limitations. During periods of high solar activity, and as a result of daily and hourly variations in atmospheric conditions, HF radio communications can be disrupted, response times slowed and coverage reduced. These effects were apparent on Exercise K89. HF radios have a limited capacity to pass information.

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[10] *Defence Communications Corporate Plan 1991-2001*, Department of Defence, Australian Government Publishing Service, 1991, p 1.

[11] ibid, pp 3-4.

> *Satellite communications have the potential to provide mobile, high capacity, reliable communications. Depending upon the nature of the specific systems, mobile satellite communications can provide coverage of Australia, the ADMI, or beyond. ADF tactical applications for satellite communications require more stringent electronic security and network control than do civil applications. However, AUSSAT expect to offer mobile services'* from mid 1993 *'which can be configured to comply with many ADF requirements.'*[12]

ADF Satcom Applications

Satcom can meet many of the ADF's communications requirements. Specific applications (with a subjective performance assessment) are listed in Table 7.4.

Table 7.4. Potential ADF Satcom Applications[13]

Two-Way Communications Link	UHF	SHF	EHF
Combat Net Radio	(1)		
Trunk Links	#	##	##
Ship-Shore	##	##	
Ship-Ship	##	#	
Ground-Air	##	#	
Air-Air	##		
Covert and Specialist	##	#	

Key:
= Applicable.
= Very Applicable.

Note:
(1) Whilst satcom in not considered practical for combat net radio, it could be used for command nets above battalion level.

The ADF has adopted satcom as part of DISCON to connect its strategic and tactical communications systems. The DISCON system provides secure voice, data, facsimile and telegraphic message services. It uses leased Telecom and AUSSAT services as well as Defence owned facilities. Figure 7.6 illustrates the major DISCON elements.

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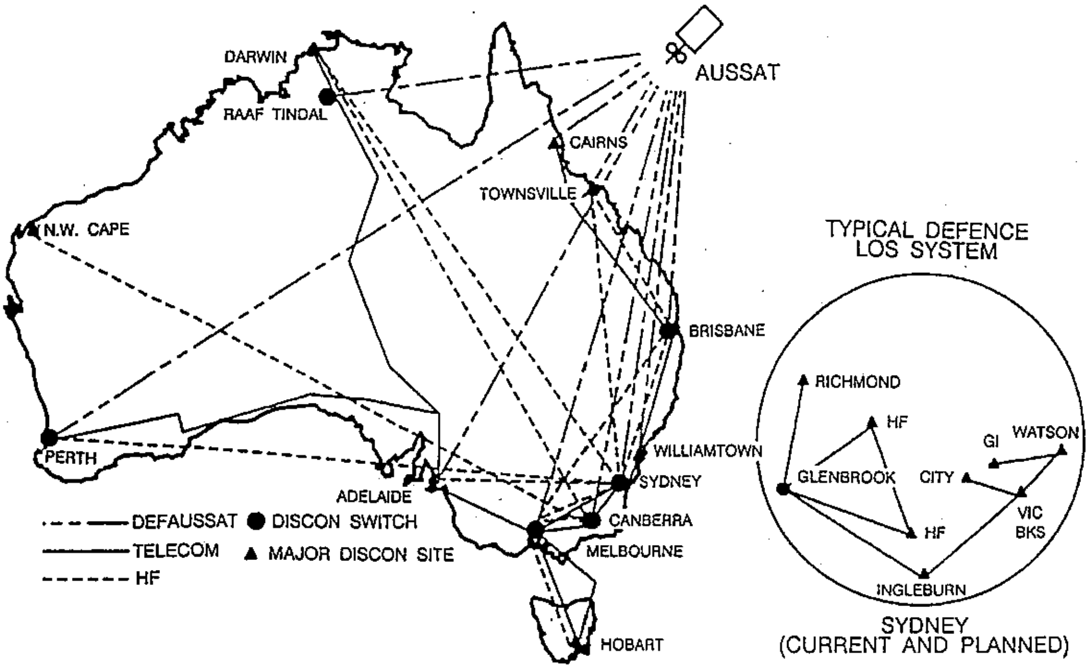
[12] ibid, p 10.
[13] O'Neill, op cit, p 23.



Note: **LOS = Line of Sight**

Figure 7.6. Major DISCON Elements[14]

<u>Current ADF Use of Satcom</u>[15]

The RAN and Army have been working with satcom for many years. Army Signal Corps has been operating an earth terminal at Simpson Barracks in Melbourne utilising a US Defence Satellite Communications System (DSCS) satellite.

The RAN, through a Memorandum of Understanding with the USN, have utilised the USN's Western Pacific Fleet Satellite Communications (FLTSATCOM) satellite for fleet communications since 1981. FLTSATCOM uses UHF links between the satellite and the mobile user, which limits its data transmission capacity. FLTSATCOM receive terminals are currently fitted to RAN FFGs and DDGs, whilst three FFGs, two DDGs and two auxiliaries also have a send capability. It is planned to fit the send capability to additional ships. The RAN also has INMARSAT terminals fitted to six ships to provide a voice link to Maritime HQ in Sydney.

The RAAF and Army lease TINES terminals from Telecom. The RAAF has two purpose built C130 transportable terminals on long term lease. Army leases standard terminals to meets specific requirements, such as the provision of satcom to major exercises.

Army also has custody of eight portable INMARSAT terminals acquired to support UN peace keeping and ADF operations. The terminals offer secure and insecure voice as well as facsimile transmission.

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[14] *Defence Communications Corporate Plan 1991-2001*, op cit, p 6.

[15] Davey, op cit, passim, pp 19-20: and Mahoney, T., *An Overview of MILSATCOM Within the Australian Department of Defence*, passim, in: Mahoney, T., *Military Satellite Communications Course Notes*, Communications Division, Electronics Research Laboratory, Defence Science and Technology Organisation, Salisbury, South Australia, June 1991.

DEFAUSSAT[16]

Capabilities

The DEFAUSSAT project uses a single low power (12 W) transponder leased from AUSSAT to integrate satcom into DISCON. The DEFAUSSAT network configuration is shown at Figure 7.7. Defence is currently negotiating to have the lease transferred to a B-Series satellite in 1993. The B-Series satellite will be able to provide greater transponder power and link capacity than could the A-Series.

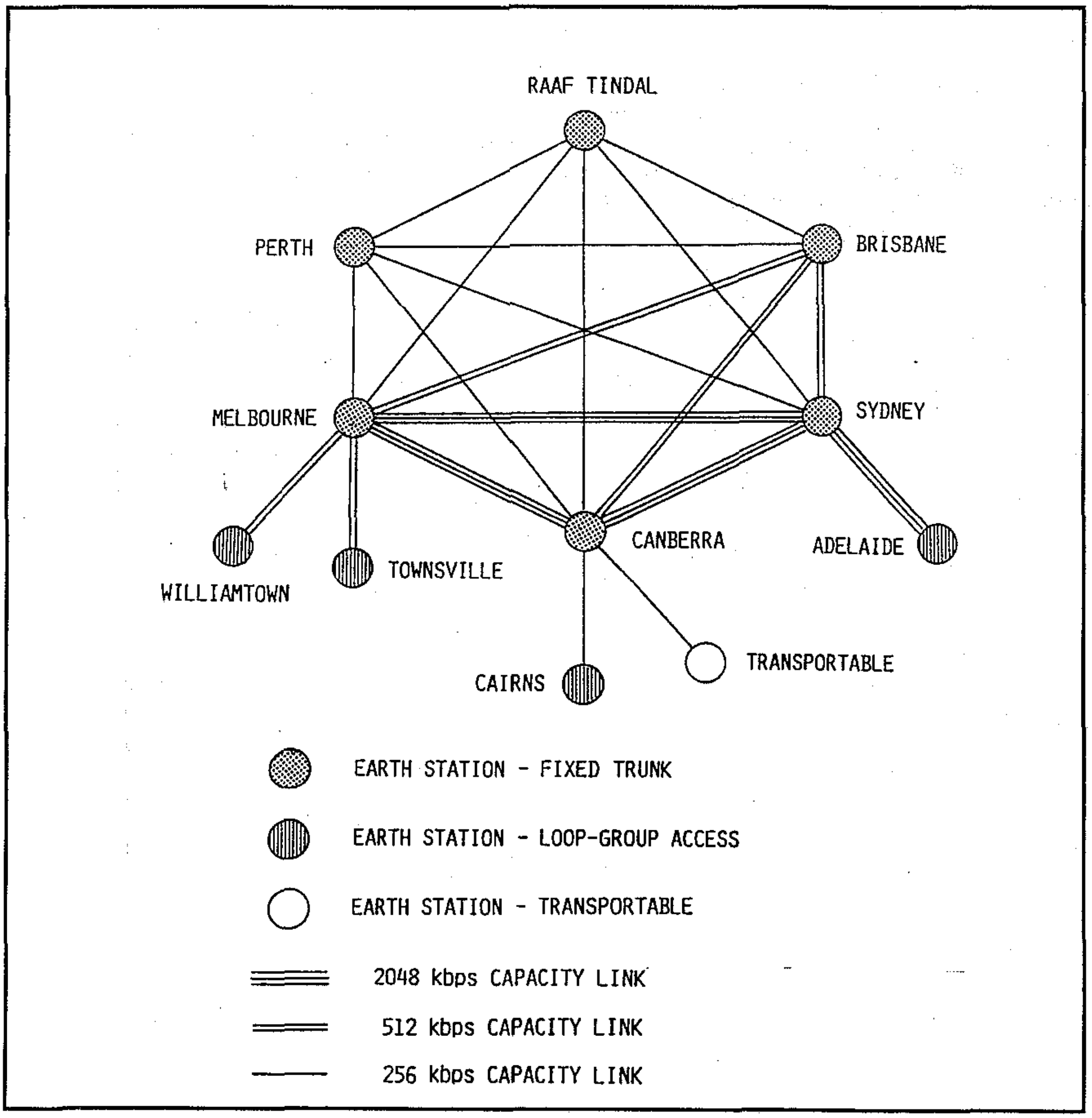

Figure 7.7. DEFAUSSAT Network Configuration[17]

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[16] Davey, op cit, pp 19-21.

[17] Mahoney, T., *Military Satellite Communications Course Notes*, Communications Division, Electronics Research Laboratory, Defence Science and Technology Organisation, Salisbury, South Australia, June 1991.

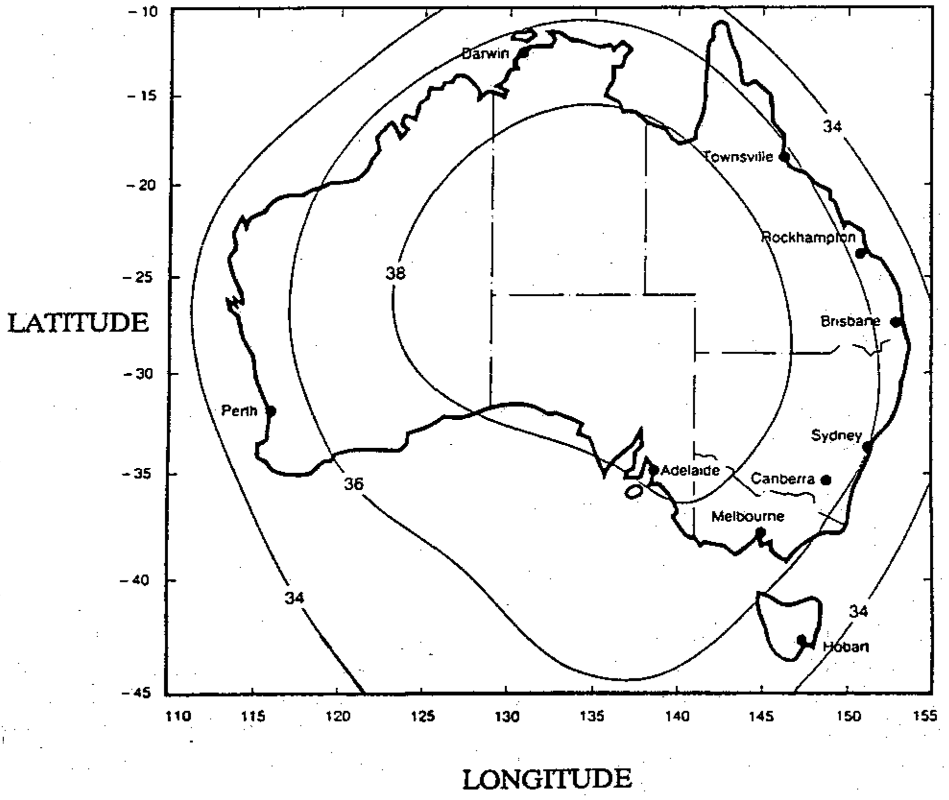
The DEFAUSSAT network will provide high data rate communications between major DISCON switching centres. Other defence installations will access the network using a lower capacity loop-group link. Earth stations in the network will be Defence owned and operated. Responsibility for supervision and control of the DEFAUSSAT network lies with 6 Signals Regiment at Simpson Barracks. A contract to construct the ground segment was let with NEC in 1988.

DEFAUSSAT will enhance the survivability of the DISCON network and extend the strategic network with the provision of two mobile earth stations with 3 m antennas. The mobile terminals should be commissioned by the end of 1991, and there are plans to make extensive use of them during K92.

Limitations

The DEFAUSSAT mobile terminals are suitable only for strategic communications and do not posses the mobility or robust design required by tactical earth stations. The DEFAUSSAT mobile terminals will be limited to carriage by C130 and travel on first and second class roads. The terminals are under the operational control of HQADF and will be operated by 2 Signals Regiment. Provision exists to man the terminals using Air Force and Navy personnel if required.

The DEFAUSSAT system utilises the AUSSAT national beam. As a result, the DEFAUSSAT system is limited to communications within continental Australia and the littoral only. There is no capability to cross link to other beams. Figure 7.8 depicts the extent of the AUSSAT national beam with a 12 W transponder.



Note: **Contours = 12 W Transponder EIRP (in dBW).**

Figure 7.8. AUSSAT National Beam[18]

<u>Project PARAKEET</u>

PARAKEET is Army's long haul tactical communications project designed to provide deployed Army and Air Force units with secure multi-channel communications. It will also incorporate interfaces with the DISCON strategic network, the Telecom-OTC network and RAVEN single channel combat radios. Trunking will be via broadband radio-relay and satellite links. Provision will also be made to interface into tropospheric-scatter radio-relay.

PARAKEET's bandwidth requirement calls for the use of an AUSSAT B-Series satellite Ku-band transponder. It may be possible for DEFAUSSAT and PARAKEET to share the same B-Series transponder. PARAKEET equipment is being designed for easy conversion to a military satcom band such as SHF should the requirement arise in the future.

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[18] ibid.

JOINT PROJECT 2008: MILSATCOM[19]

The MILSATCOM project proposes that Defence acquires a satcom capability for:

a. long distance strategic communications, and

b. command and control of mobile ADF assets.

The first component of the project proposes early acquisition of commercial mobile satcom services using AUSSAT's L-band Mobilesat service. AUSSAT plans to offer the Mobilesat service from 1993. The service will use the L-band transponder on the B1 satellite. Defence implementation of the service will be called the Defence Mobile Communications Network (DMCN).

DMCN is intended to provide Defence with an early, low cost entry into mobile satcom. The system will have limitations in coverage and capacity, but will provide a complementary capability to the fixed services available through DEFAUSSAT. Acquisition of a more capable mobile satcom service operating in a military frequency band is proposed for the end of the decade. Several options are under consideration, including:

a. the incorporation of a dedicated Defence transponder on a commercial satellite,

b. negotiating for access to allied systems, and

c. procuring a dedicated defence communications satellite.

Both Options A and C would provide Defence with an autonomous service structured to its specific needs and requirements. However, only option C gives Defence complete freedom in system design and architecture, allowing the system to be tailored to specific needs and requirements. Feasibility studies to investigate the options are currently being undertaken by HQADF. Proposed tactical satcom systems for Army and Special Forces, RAAF and RAN are shown at Figures 7.9 to 7.11 respectively.

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[19] Davey, SQNLDR K, *Background Brief on Military Satellite Communications Project*, Headquarters ADF, Department of Defence, Canberra, August 1991, passim.

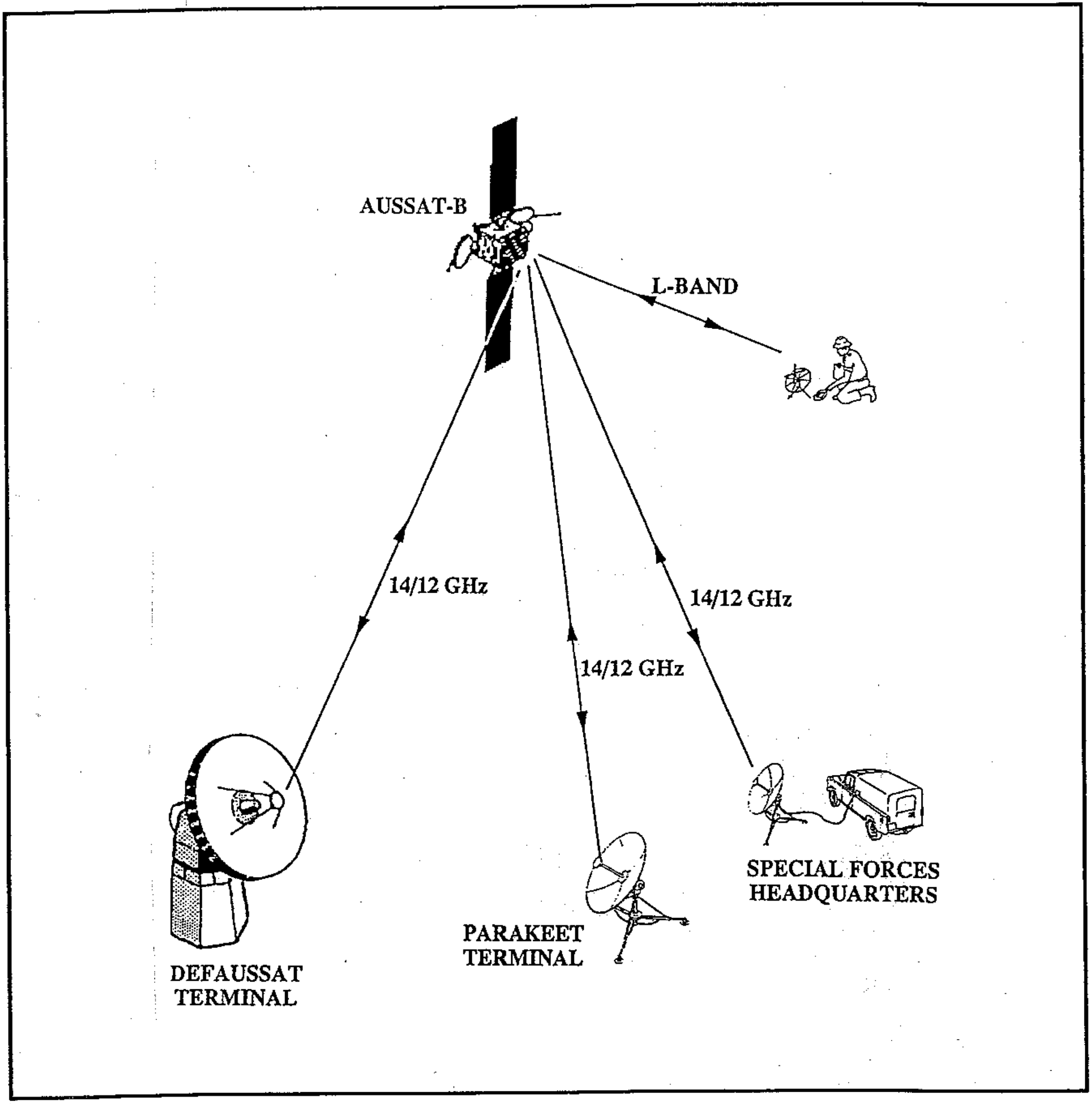

Figure 7.9
ADF Tactical Satcom: Army and Special Forces[20]

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[20] Mahoney, op cit.

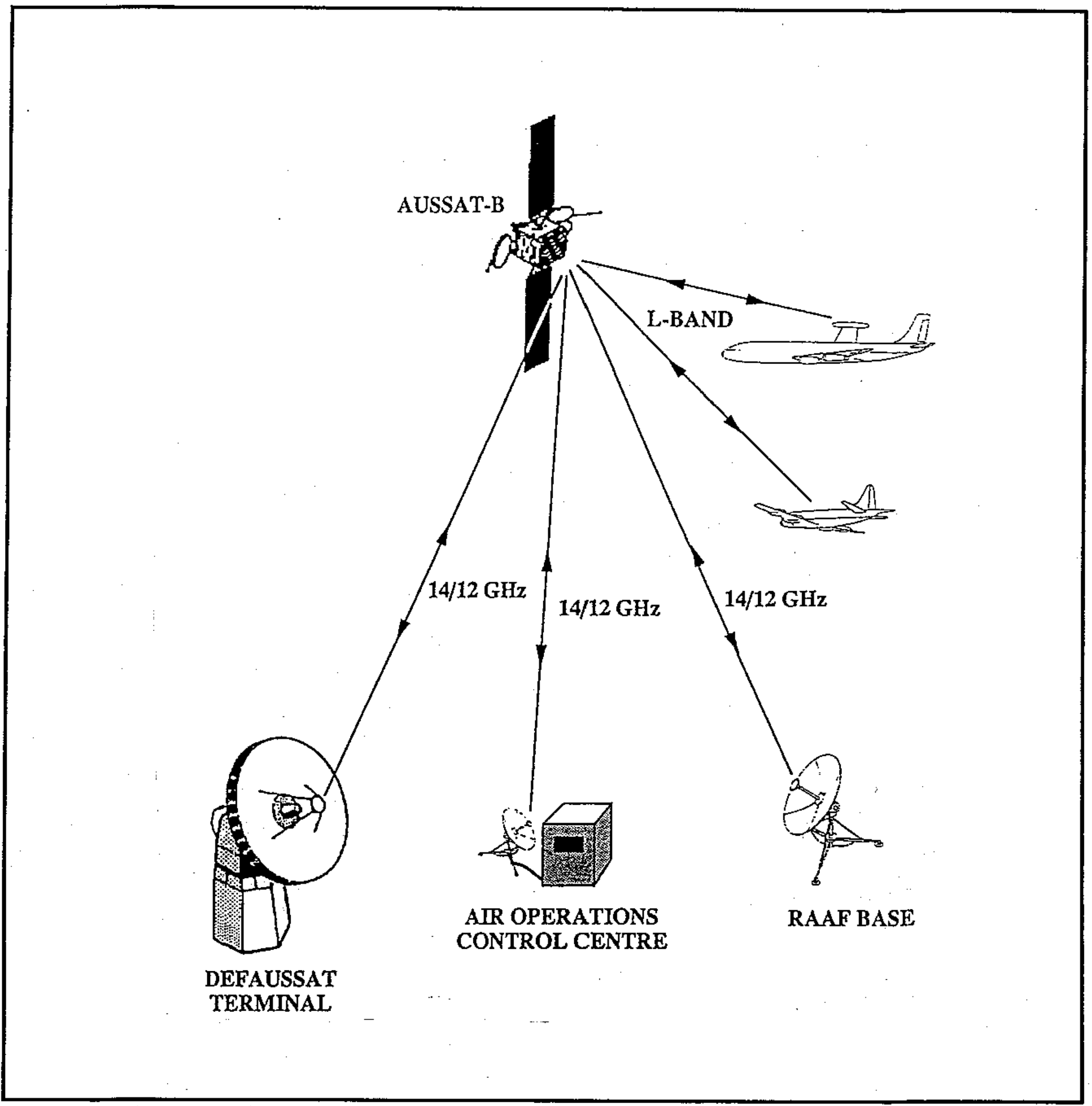

Figure 7.10. ADF Tactical Satcom: RAAF Air Operations[21]

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[21] Mahoney, op cit.

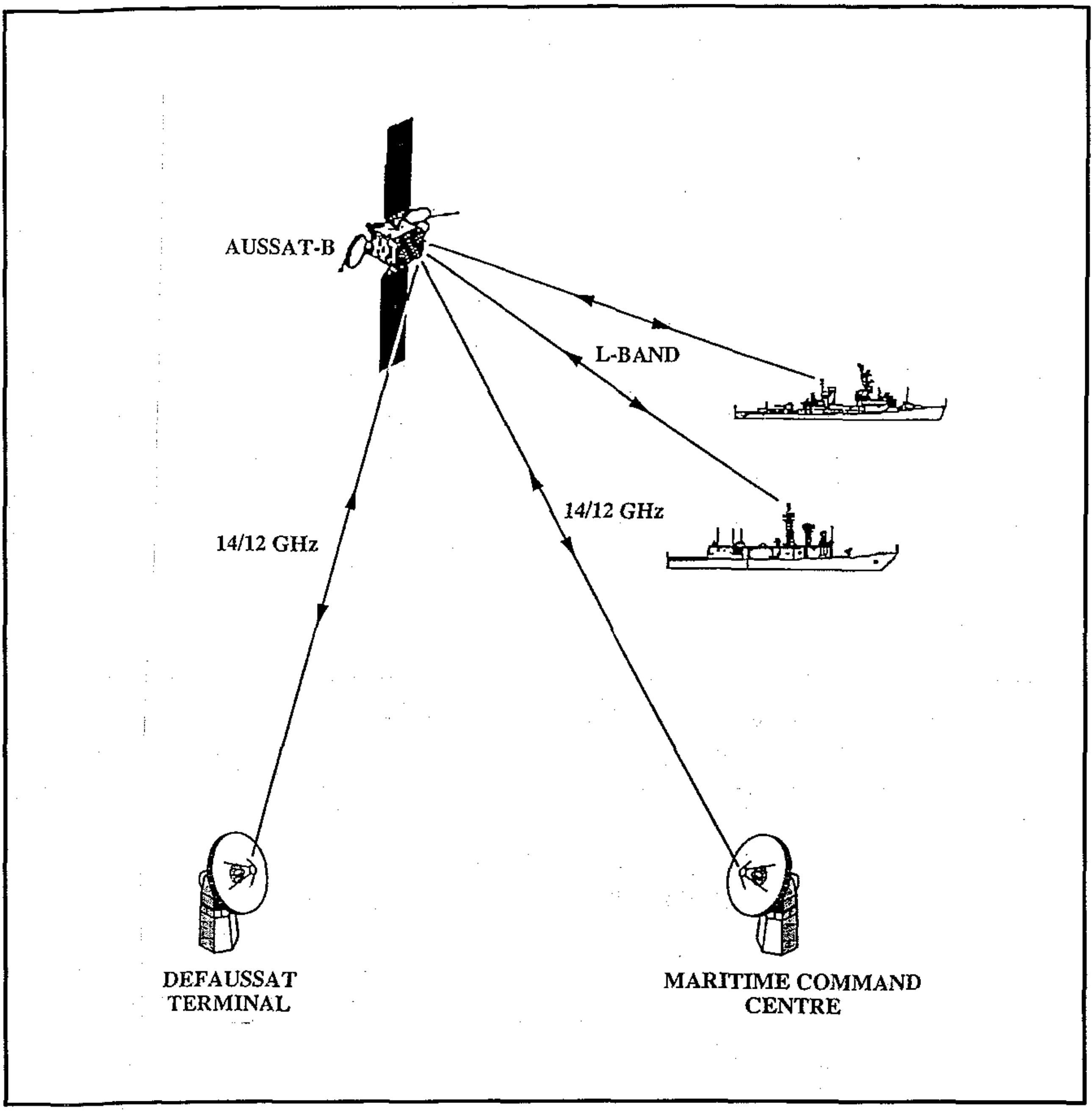

Figure 7.11. ADF Tactical Satcom: RAN Operations[22]

Defence Mobile Communications Network (DMCN)

Phase 1 of the MILSATCOM project, the DMCN implementation study, has been approved. The study, planned for early 1992, will examine how AUSSAT's Mobilesat service may be best integrated into the ADF. Several network implementations are possible, including:

a. Defence operating as a standard user under AUSSAT control (Figures 7.12 and 7.13);

b. Defence and AUSSAT operating into the Mobilesat system with common signalling protocols (Figure 7.14); and

c. Defence operating a private L-Band network (Figure 7.15).

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[22] Mahoney, op cit.

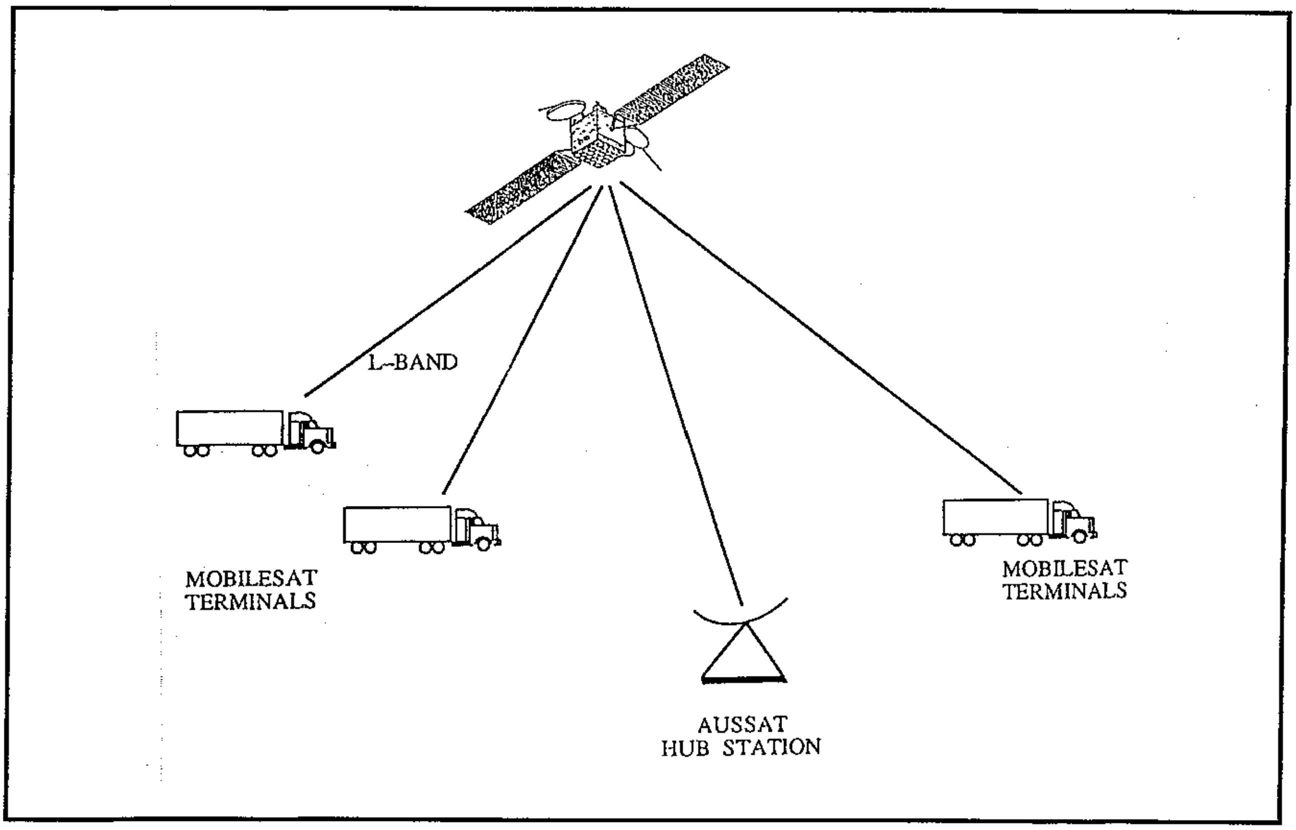

Figure 7.12. AUSSAT's Mobilesat Service[23]

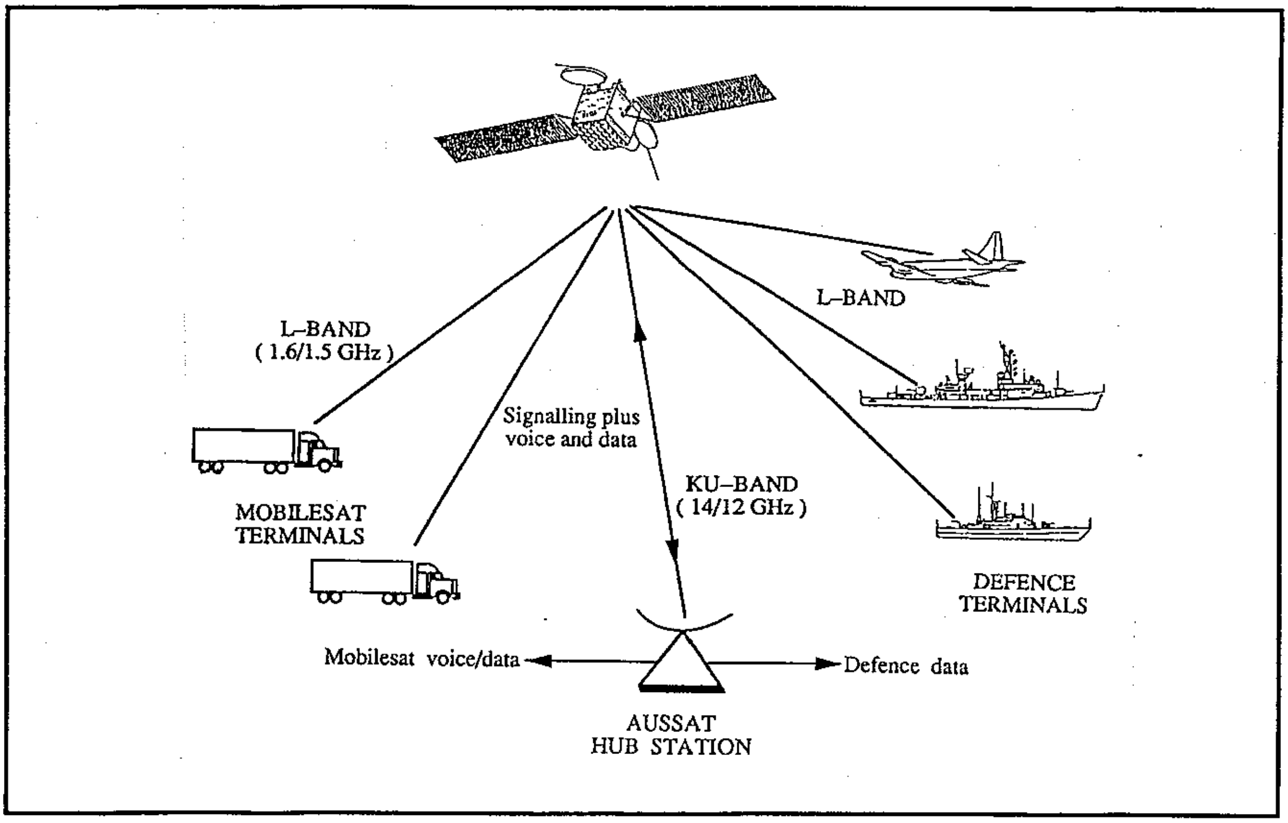

Figure 7.13. Defence Integration of AUSSAT's Mobilesat Service (or DMCN)[24]

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[23] Mahoney, op cit.
[24] Mahoney, op cit.

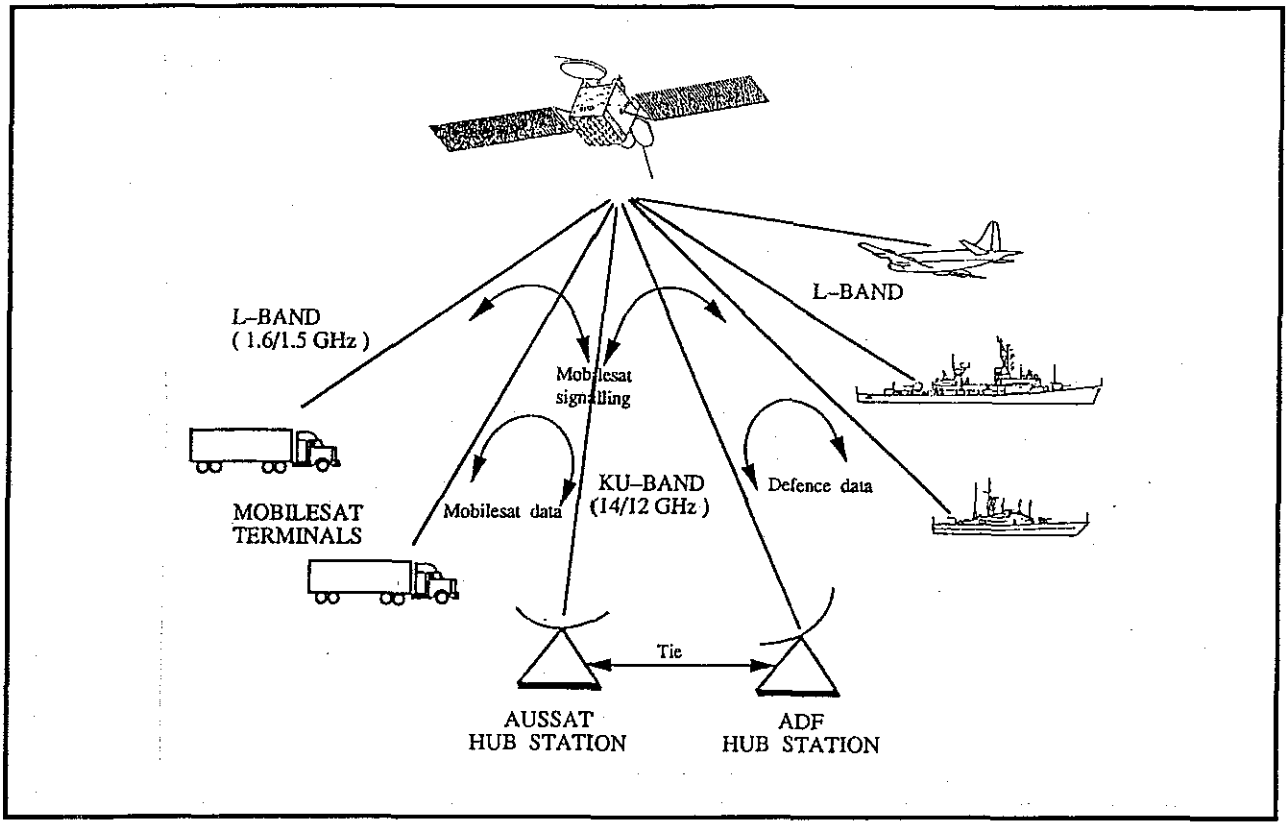

Figure 7.14. DMCN and AUSSAT with Common Signalling Protocols[25]

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[25] Mahoney, op cit.

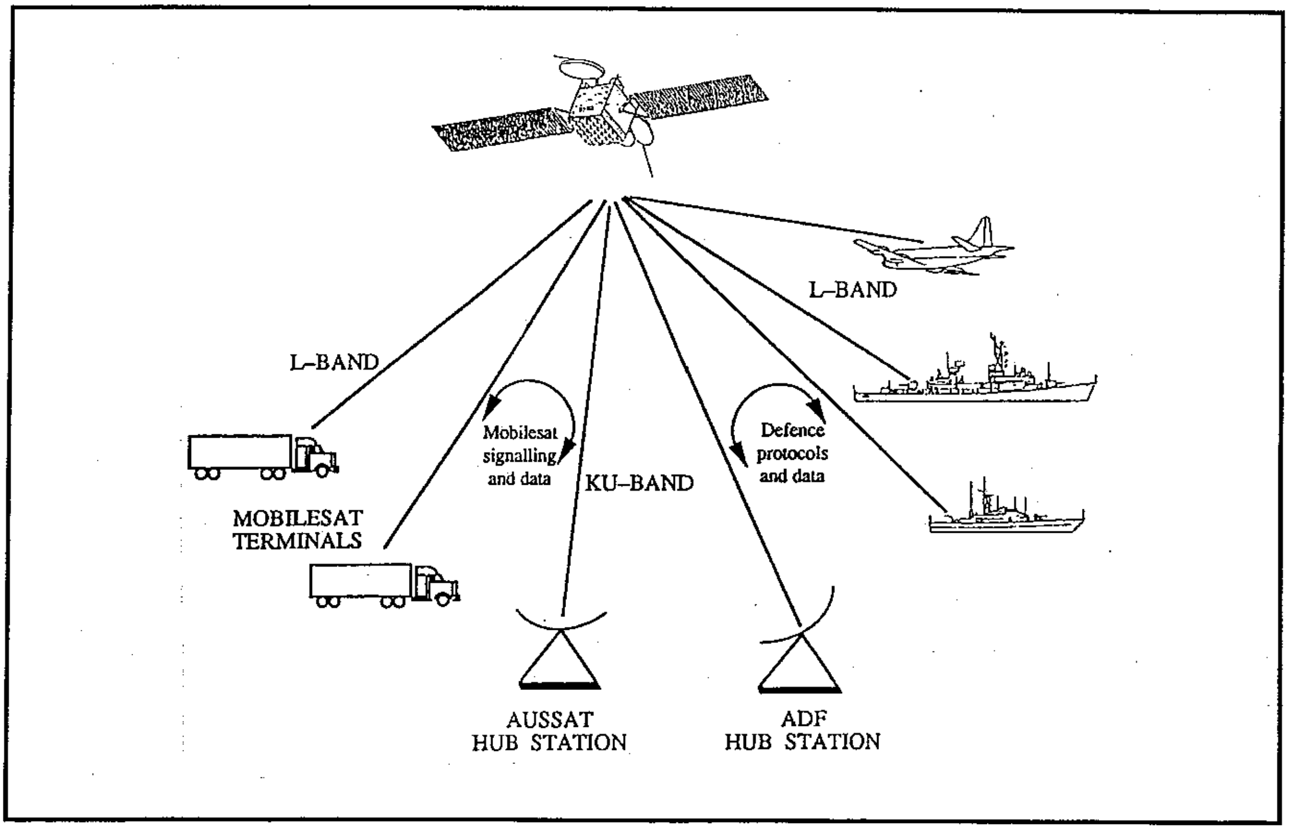

Figure 7.15. DMCN Private Network[26]

Phase 2 of the MILSATCOM project, DMCN acquisition, involves the procurement of satellite capacity and ground terminal equipment. Phase 2 is planned for late 1993.

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[26] Mahoney, op cit.

CHAPTER EIGHT

NAVIGATION

Accurate, reliable, all-weather, 24-hour global navigation is a basic military support requirement. However, until the advent of the US owned GPS (Global Positioning System) NAVSTAR (NAVigation Satellite Timing And Ranging) no existing radio navigation system could truly satisfy the military's navigation requirements. This is not to say GPS is perfect; it just comes closer than any other system that has gone before. The system should be fully operational by early 1994. GPS data will be available free of charge to military and civilian communities alike. The system offers enormous user growth potential, and over the next decade exploitation of the services offered by GPS will be commonplace.

Despite being pre-operational, GPS has already proved its utility in combat. The clinical decimation of Iraq's infrastructure during the 1990/91 Gulf War is indicative of the pervasive nature of modern technology on the battlefield. GPS is widely regarded as a determining factor in the success of the Coalition Forces in the Gulf. The force multiplication arising from the melding of precise position and navigation data with conventional and PGMs has changed the nature of modern warfare.

GPS is being adopted by the ADF for use on a number of platforms in various configurations. Consequently, this chapter will concentrate primarily on the GPS. However, GPS is not the only space-based navigation system in existence. There are currently three other systems of interest. These are:

a. TRANSIT (US);

b. TSIKADA (Russia); and

c. GLONASS (Russia).

Transit is an old system, first fielded in 1964. It will be largely superseded by GPS. Accordingly, it will only be discussed briefly. Russia's satellite navigation systems, TSIKADA and GLONASS, are similar to the US TRANSIT and GPS systems respectively. A brief description of TSIKADA and GLONASS will be provided at the end of the chapter.

GPS

Introduction

GPS is a space-based radio navigation system owned and controlled by the US DoD. When the satellite constellation is complete (in early 1994) the GPS system will provide users with the following services:

a. Position, Velocity and Time. Precise position and velocity will be available in three dimensions. Two positioning services will be provided:

  i. Standard Positioning Service (SPS). SPS is actually a degraded GPS service, whose accuracy is held by the US DoD at 76 m Spherical Error Probable (SEP)[1]. If SPS is operated without

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[1] SEP is a statistical term defining an error sphere about the user's assumed position in which the user's actual position will lie 50% of the time. Readers may have seen the accuracy of the SPS quoted as 100 m. This figure refers to the SPS' two dimensional root mean square (2DRMS) accuracy.

degradation, as was done during the Gulf War, its accuracy improves to 25 m SEP.

ii. Precision Positioning Service (PPS). Access to PPS is currently available only to authorised users. The ADF is an authorised user. How the US controls access to the PPS is discussed later in the chapter. The PPS is accurate to:

Position:	16 m SEP;
Velocity:	0.1 m/sec; and
Timing:	10^{-7} sec.

GPS is the only radio navigation system able to offer precision velocity and time data.

b. GPS data is available for satellites in LEO.

c. GPS offers world wide all weather navigation and timing data, 24 hours per day, to a common World Geodetic Standard (WGS) grid.

d. GPS allows an unlimited number of users.

e. GPS is resistant to jamming due to the nature of the transmitted signal.

f. From a user's perspective, GPS is passive: that is, the user is not required to radiate to access the system.

g. GPS offers redundancy, survivability and graceful degradation. This is achieved by combining a multi-satellite constellation and on-orbit spares.

The GPS constellation also has a secondary function. Each satellite is fitted with an integrated operational nuclear detection system (IONDS) to detect nuclear detonations.[2]

The GPS system is comprised of three major segments:

a. the space segment,

b. the control segment, and

c. the user segment.

Figure 8.1 illustrates GPS's overall architecture. Each GPS segment is discused later in the chapter, but let us begin with GPS's theory of operation.

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[2] Boutacoff, D. and Gumble, B., *Strengthening C^3 in Space*, Defense Electronics, No. 20, February 1987.

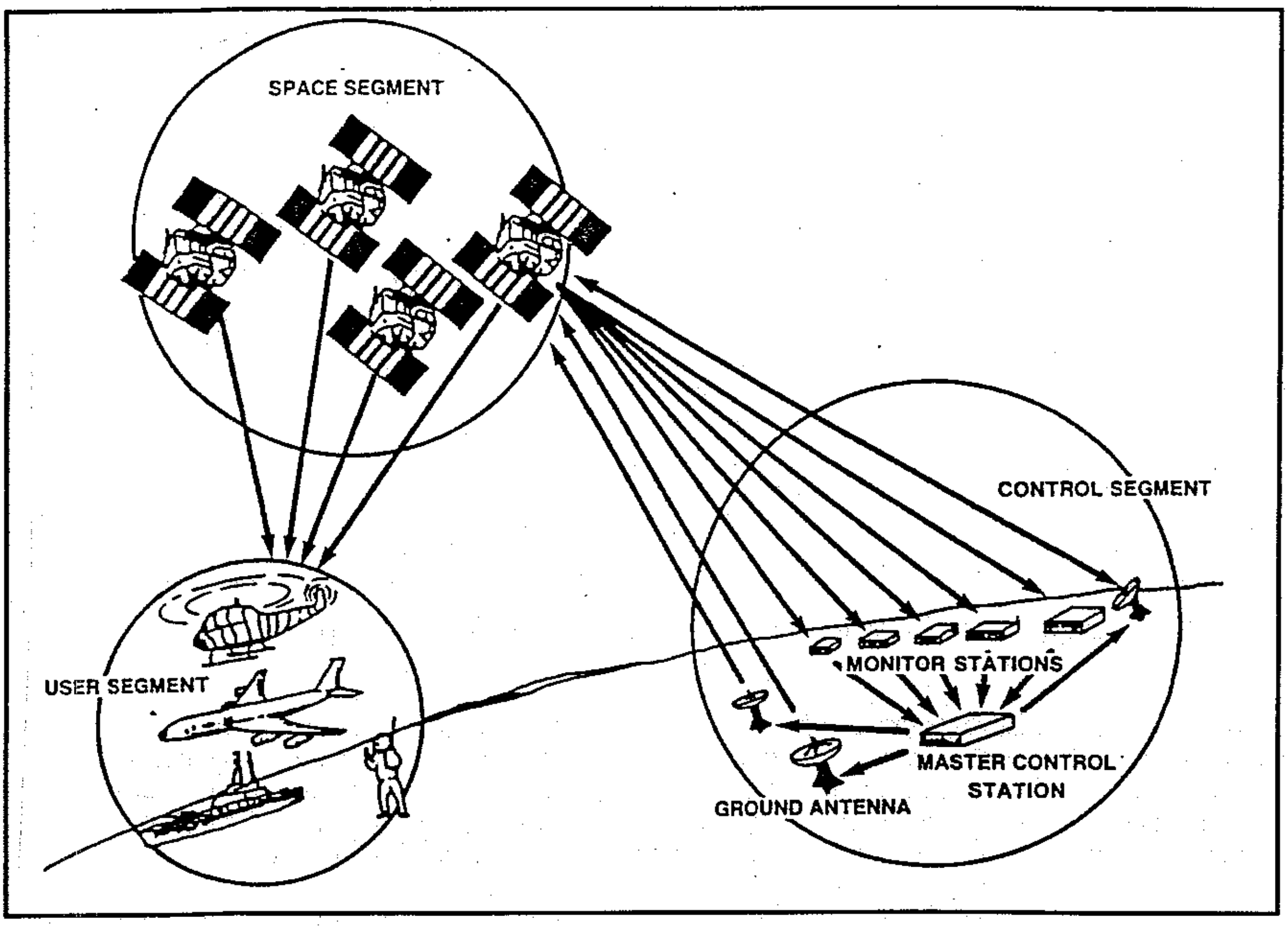

Figure 8.1. GPS System Architecture[3]

Theory of Operation

The basic principles on which GPS operates are quite simple, although the use of some high technology was required to implement those principles. Basically, GPS uses a technique called ***satellite ranging*** to determine position by measuring the distance from a group of satellites to the observer.

Satellite Ranging Establishes Position. Figure 8.2 illustrates how position is established using satellite ranging. If the observer is 22,000 km from one satellite (Figure 8.2a), 23,000 km from another (Figure 8.2b) and 24,000 km from a third, then the observer can only be in one of two places in the universe (Figure 8.2c).

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[3] NATO Team, *NAVSTAR GPS User Equipment: Introduction*, NAVSTAR GPS Joint Program Office, February 1991, p 1-1.

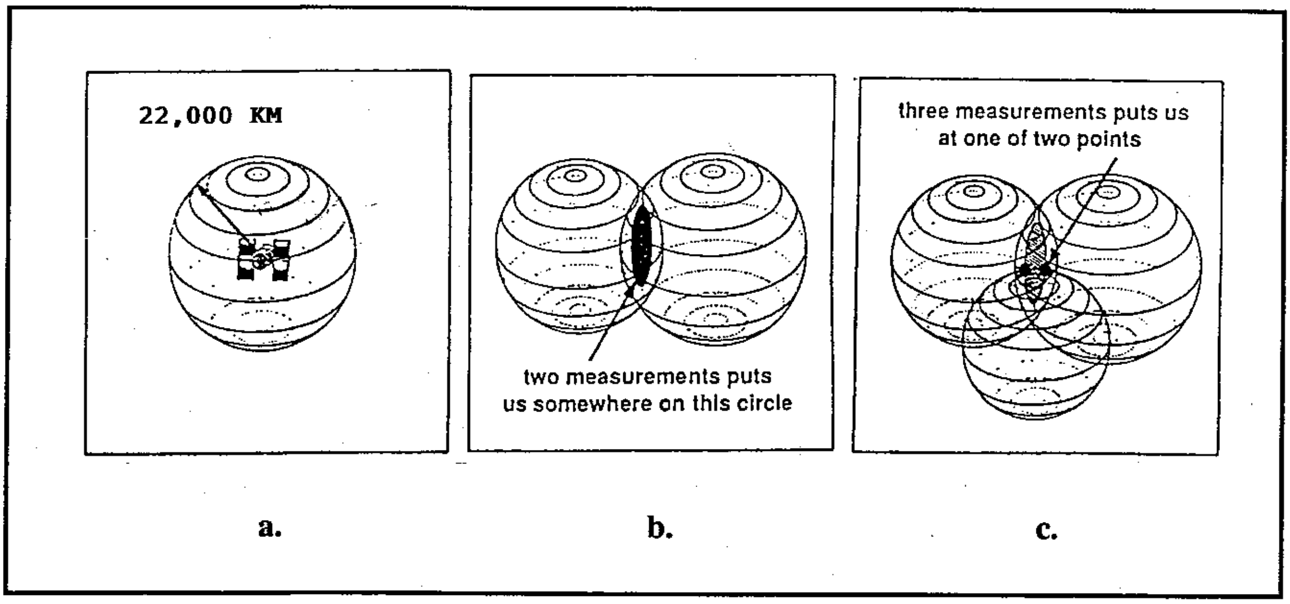

Figure 8.2. Determination of Position Using Satellite Ranging[4]

Geometry indicates that to determine three dimensional position unambiguously, range is required from four satellites. However, given a three satellite solution, one answer generally fails a common sense test and is discounted. Only two satellites are required to determine position in three dimensions if altitude is accurately known. Altitude can be used to determine the observer's distance from the centre of the Earth, and thus provide the third position sphere.

So much for theory. In practice, range measurement from four satellites, not three, is required to determine position in three dimensions. Why this is so is explained under the heading 'Satellite Timing'. However, before discussing that point, we must investigate how the observer's GPS receiver determines range from each satellite.

Determining Satellite Range. The range from each satellite is determined by measuring the time it takes for a radio signal transmitted by the satellite to reach the observer and converting that time into a distance. This is done using the formula:

Range = velocity x time;

where velocity = speed of light (3×10^8 m/sec).

Accurate measurement of time is technically quite demanding. The GPS signal takes approximately 0.07 seconds to travel from the satellite to earth. A timing error of only 0.001 seconds will cause a range error of 300 km. However, the real difficulty lies in determining when the signal actually left the satellite. This is done by generating identical pseudo-random codes in the satellite and the observer's receiver, and then calculating the time difference between receiving the code from the satellite and the time at which the observer's receiver generated the same code (see Figure 8.3). This time delay is then used to determine range.

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[4] Hurn, J., *GPS: A Guide to the Next Utility*, Trimble Navigation, Sunnyvale, California, 1989, p 15.

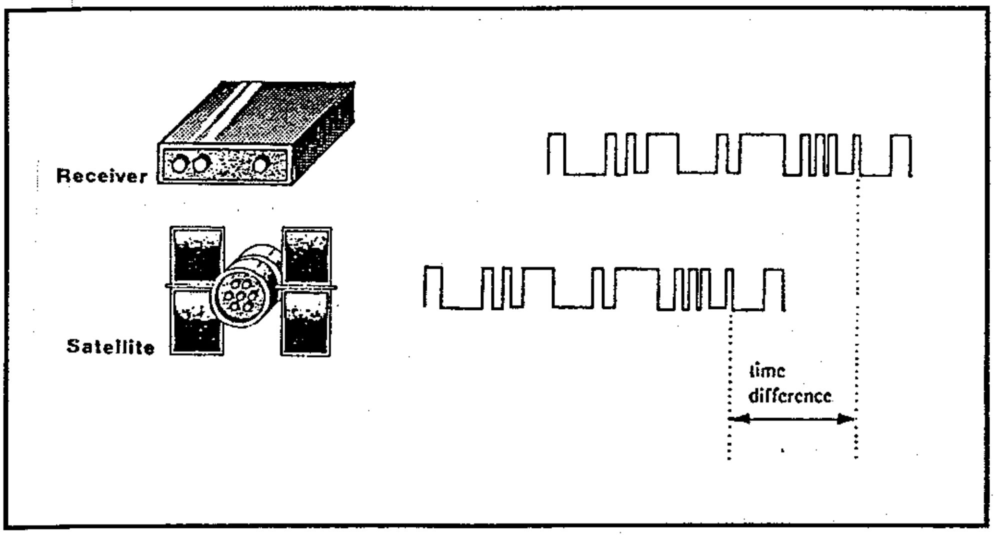

Figure 8.3. Determination of Satellite Range by Measurement of Time Delay[5]

Satellite Timing. The preceding discussion has not presented the whole solution. Establishing range from time is a simple, but how are the receiver and satellite synchronised such that they generate the same pseudo-random code at the same time?

The satellite side of the timing synchronisation problem is solved by fitting each satellite with four atomic clocks, each of which is worth US$100,000. These clocks are accurate to one second in 300,000 years. Their measurement of time is as absolute as man can presently make it. Obviously, putting an atomic clocks in the observer's GPS receiver would make it unacceptably expensive. Instead, a cheap quartz clock in used in the GPS receiver. The error introduced into the observer's receiver by the quartz clock can be corrected by measuring range from four satellites rather than three. Range from the fourth satellite is required to calculate what is called ***timing offset***. Understanding the concept of timing offset is absolutely fundamental to understanding how GPS works, and consequently, the concept will be dealt with in some detail. For simplicity, the diagrams are drawn in only two dimensions, but the theory applies equally to the third dimension. Additionally, in presenting the concept of timing offset, it is more convenient to present range in terms of time.

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[5] ibid, p 20.

Timing Offset. Consider Figure 8.4. Suppose an observer is four seconds from Satellite A and six seconds from Satellite B. That locates the observer at point 'X'. Move to Figure 8.5. Let us assume that in reality, the observer's clock is one second slow compared to those on the satellites. According to the observer he is five seconds from Satellite A and seven seconds from Satellite B. The observer thinks he is at position 'XX'. He has no way of knowing his position is incorrect.

To overcome the problem, we add a third satellite, Satellite C. The observer is in reality eight seconds from Satellite C, but with his clock error of one second he thinks the time delay is nine seconds. Study the situation in Figure 8.6. The thick lines show the pseudo-ranges resulting from the observer's slow clock. The thin lines show where the observer is in reality. The computer in the GPS receiver determines that the three pseudo-range lines from the satellites do not intersect at a single point as they should, and from that calculates the timing offset that has caused the error, corrects for it, and places the observer in his actual position at 'X'.

As mentioned, the situation presented provides position in two dimensions using three satellites. In reality, GPS provides position in three dimensions by timing and ranging from four satellites.

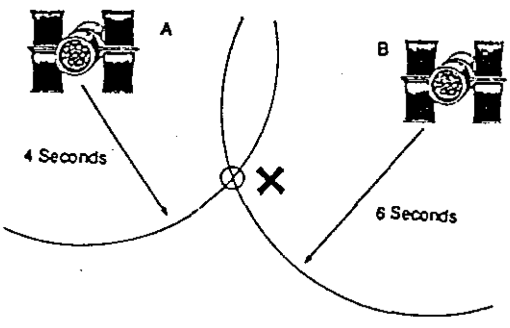

Figure 8.4[6]

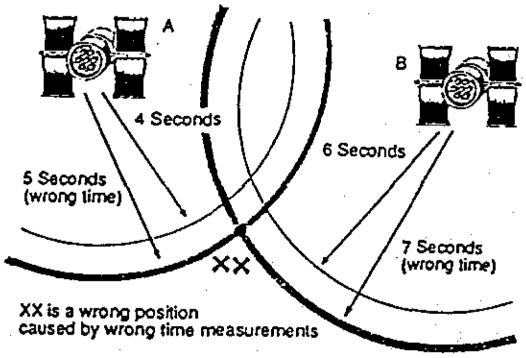

Figure 8.5[6]

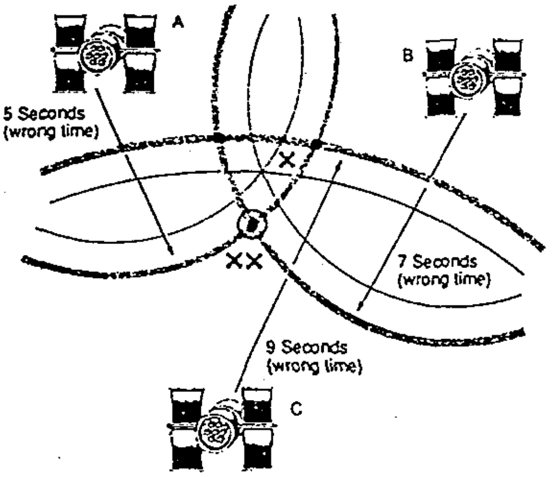

Figure 8.6[6]

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[6] ibid, pp 28-29

Errors. The most significant source of error in the GPS system is caused by the Earth's ionosphere slowing the RF energy transmitted by the GPS satellites.[7] The error can be accounted for in one of two ways:

a. SPS receivers take parameters transmitted by the satellites to predict average ionospheric propagation error. This method is not suitable for PPS receivers, as it is not sufficiently accurate.

b. EM radiation travelling through the ionosphere slows at a rate inversely proportional to its frequency squared. By transmitting the GPS signal on two frequencies and comparing the time difference between the arrival of the signal at each frequency, the GPS receiver can compute the delay induced by the ionosphere and correct for it. This technique is used in PPS receivers. The concept is explained more fully under the heading 'The Navigation Signal'.

As with other RF signals, the GPS signal can also be affected by atmospheric water vapour content. The error induced is not large, and is not generally corrected for.

The Space Segment

The GPS Constellation. When complete, the GPS constellation will consist of 24 satellites in six orbital planes, with three or four satellites in each plane. Twenty one satellites will be active and will form the operational constellation. The other three satellites will be maintained as on-orbit spares. Twenty one satellites guarantee global, 24-hour, three-dimensional navigation. Figure 8.7 illustrates the GPS constellation.

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[7] The speed of light is only constant in a vacuum. EM energy travelling through the ionosphere is slowed at a rate inversely proportional to frequency squared.

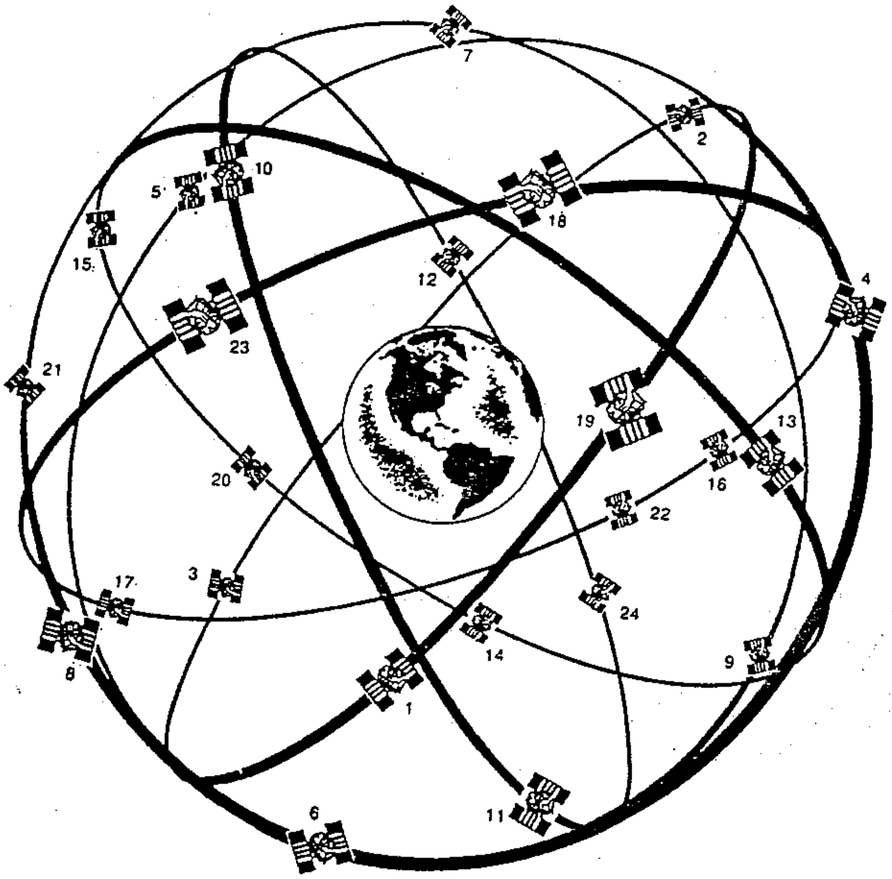

Figure 8.7. The GPS Constellation[8]

Even though incomplete, the constellation in-being can provide two-dimensional navigation for 21 hours a day, and three-dimensional navigation for 19 hours a day. Global 24 hour two-dimensional coverage should be available mid 1993. As already mentioned, GPS should be fully operational by early 1994.

Orbital Parameters. The orbital parameters of the GPS satellites are as follows:

Inclination:	55° in six orbital planes;
Altitude:	20,178 km;
Period:	12 hours.

GPS Satellites. The GPS satellite weighs 864 kg in orbit, are solar powered and three-axis stabilised. They are 5.2 m wide once the solar panels are extended. Each satellite is designed to last for 7.5 years.

The Navigation Signal. Each satellite continuously transmits two unique L-Band pseudo-random spread spectrum signals, designated L1 and L2. The L1 signal, at 1.57542 GHz, carries two pseudo-random codes: the Clear/Acquisition (C/A) code with a bandwidth of 1.023 MHz and the Precise (P) code with a bandwidth of 10.23 MHz. The L2 signal at 1.2276 MHz

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[8] NATO Team, op cit, p 1-3.

carries the same P code signal as L1. By using a spread spectrum signal, GPS' ability to resist jamming is markedly improved. The GPS signal structure and spread spectrum modulation technique are illustrated by Figure 8.8.

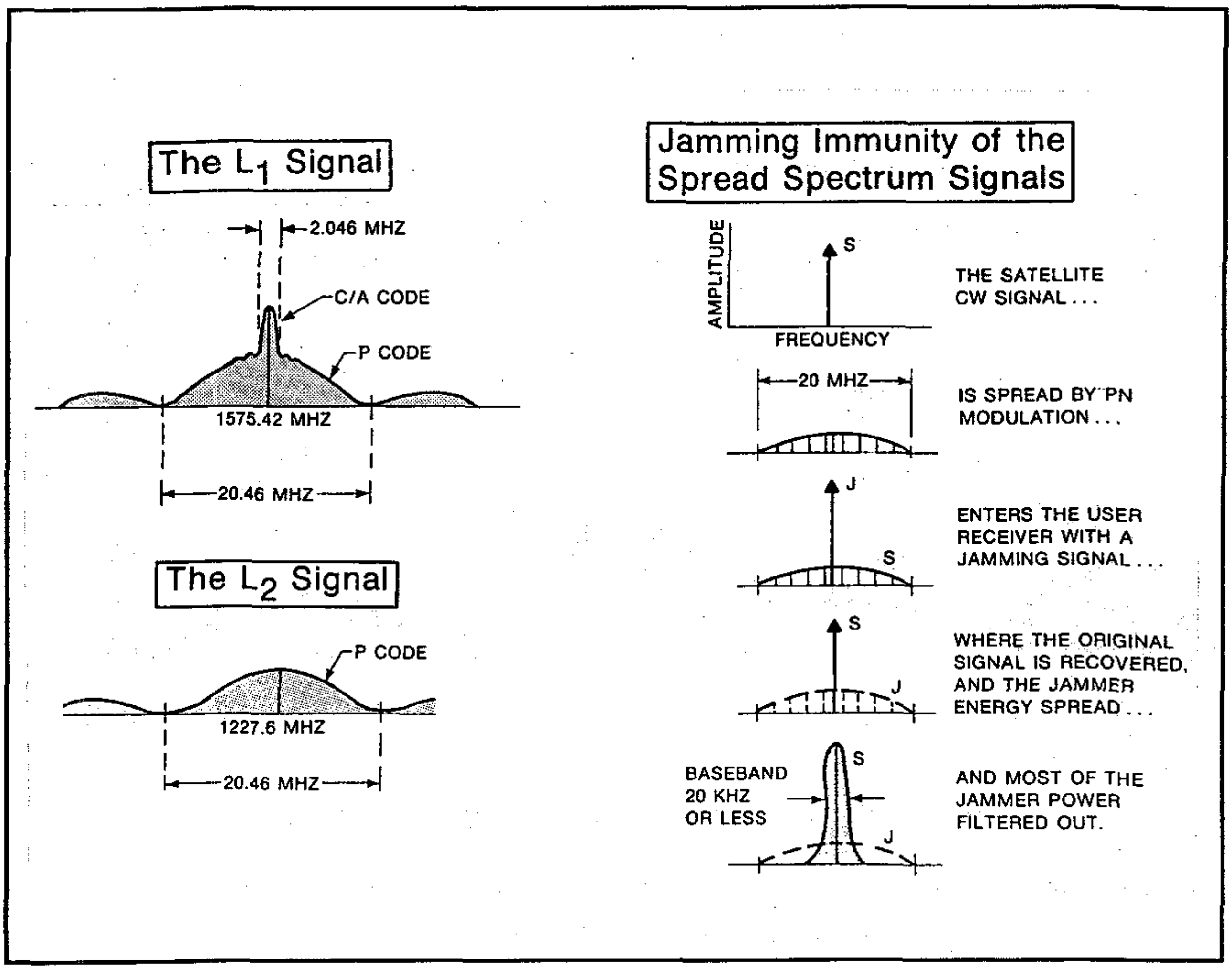

Figure 8.8. The Navigation Signal[9]

The C/A code has two functions. First, it provides the user with the coarse navigation signal used for the SPS. Second, the C/A code is used to synchronise the user's receiver with the P code signal from the satellite. Direct acquisition of P code requires a timing precision not available on most user equipment (UE). The P code signal provides full PPS accuracy.

The Navigation Message. The navigation message is superimposed on both the C/A and P code at a data rate of 50 Hz. It takes 12.5 minutes to receive the entire 25 page navigation message from each satellite, but the critical data is contained on each page and can be obtained inside 30 seconds. The navigation message contains GPS system time, a hand-over word to allow the transition from C/A code to P code, ephemeris data for that particular satellite, almanac data for the entire constellation, satellite health, and the ionospheric delay parameters used by SPS receivers.

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[9] Bjornsen, G. and Price, D., *NAVSTAR GPS System and User Equipment Description*, March 1985, p 3, in: *The Global Positioning System: A Compilation of Papers: Book Two*, Rockwell International Corporation, 1988.

The Control Segment

GPS is controlled by the US DoD through the Master Control Station (MCS) at Falcon AFB, Colorado Springs, Colorado. A world wide network of remote monitor stations and ground antennae is used for TT&C. TT&C is provided through an S-Band[10] up and down-link. Figure 8.9 illustrates data flow between the various elements that comprise the control segment, whilst Figure 8.10 illustrates GPS control segment locations.

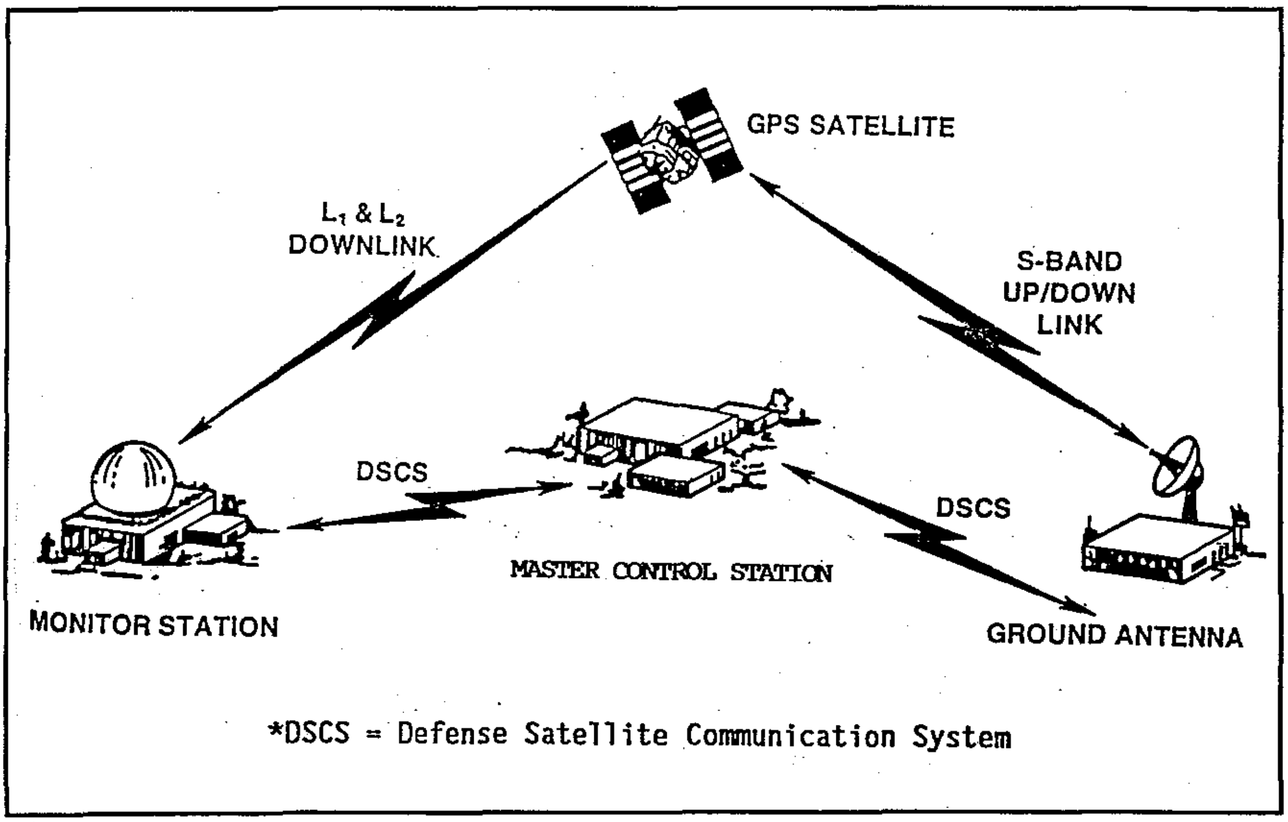

Figure 8.9. The Control Segment[11]

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[10] S-Band covers frequencies between 2 and 4 GHz.
[11] Bjornsen, op cit, p 4.

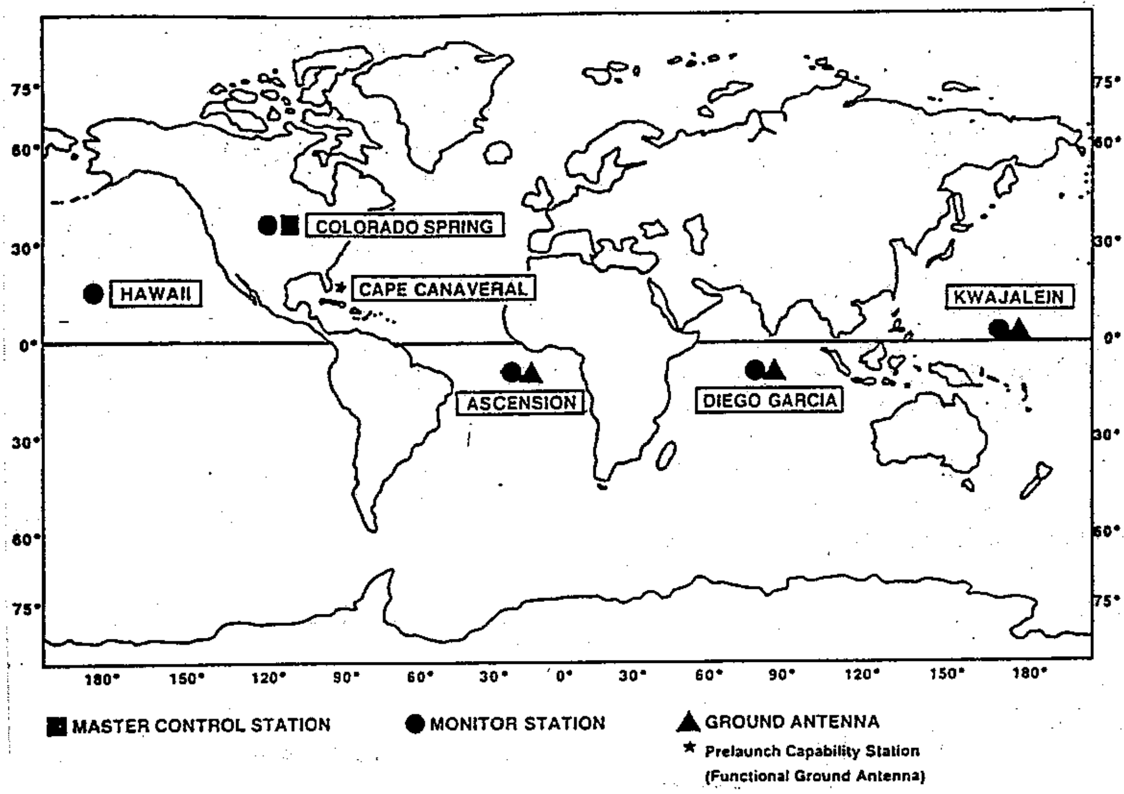

Figure 8.10. Control Segment Locations[12]

The User Segment

GPS will be used for a variety of purposes by a variety of users, and each user will require equipment optimised to their needs and budget. There are two broad categories of receiver currently on the market, those that track satellites sequentially, and those that track four or more satellites simultaneously.

Sequencing Receivers. As already discussed, information from four GPS satellites is required to correct the user's timing offset and calculate position in three dimensions. A single-channel sequencing receiver uses a single RF channel to sequentially interrogate four of those satellites in its FOV to provide the best positional data. Because satellites are interrogated the navigation function is interrupted while the receiver searches for each signal. Consequently, sequencing receivers are less able to cope with the large accelerations found on high-dynamic vehicles such as fighter aircraft or four wheel drive vehicles on a rough road. For this reason, single-channel receivers are often referred to as 'low-dynamic'. Also, a single-channel sequencing receiver may take up to six minutes to obtain its first fix after initial switch on (this time interval is referred to as 'time-to-first-fix', or TTFF). Despite these limitations, and because they are cheap, single-channel receivers have a place in low-dynamic applications: for example, as hand held personal receivers. A hand held C/A code single-channel set may cost as little as A$1,000, and the price will undoubtedly fall further as production rates increase.

Two or three-channel sequencing receivers, or 'medium-dynamic' sets, are disproportionately more capable than the addition of the extra channel or channels may suggest. These receivers use one channel to monitor data from a satellite while the other channel or channels acquire the next. Using this system, the navigation function is never interrupted, improving the receiver's signal to noise ratio and allowing more precise measurement of velocity.

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[12] NATO Team, op cit, p 1-5.

The TTFF is reduced to four minutes. Multi-channel sequencing receivers are employed on vehicles such as helicopters, surface ships and strategic transport aircraft, although the current trend is towards continuous receivers for these applications. Multi-channel sequencing sets are more expensive than their single-channel counterparts. A two channel PPS set currently costs about A$2,500.

Continuous Receivers. Continuous, or high-dynamic, receivers have four or more RF channels to simultaneously monitor four or more satellites. Usually, they have at least five channels. Four channels are used to track satellites. The fifth is used to read the navigation message from the next satellite to be used for navigation and to obtain the signal data required for dual frequency ionospheric compensation. Continuous receivers are generally used either on high-dynamic platforms or for high accuracy applications such as surveying. Their TTFF reduces to 1.5 minutes. Additionally, continuous receivers are more resistant to jamming than are sequencing receivers. Continuous receivers are quite expensive. A receiver suitable for a fighter aircraft may cost A$45,000. This figure does not include system integration and a suitable display or display interface. Most military GPS receivers are medium or high-dynamic.

Applications. Applications of GPS are limited only by the imagination of the user. Figure 8.11 lists some generic military applications. Tables 8.1 to 8.3 list applications specific to Air, Naval and Land Operations respectively.

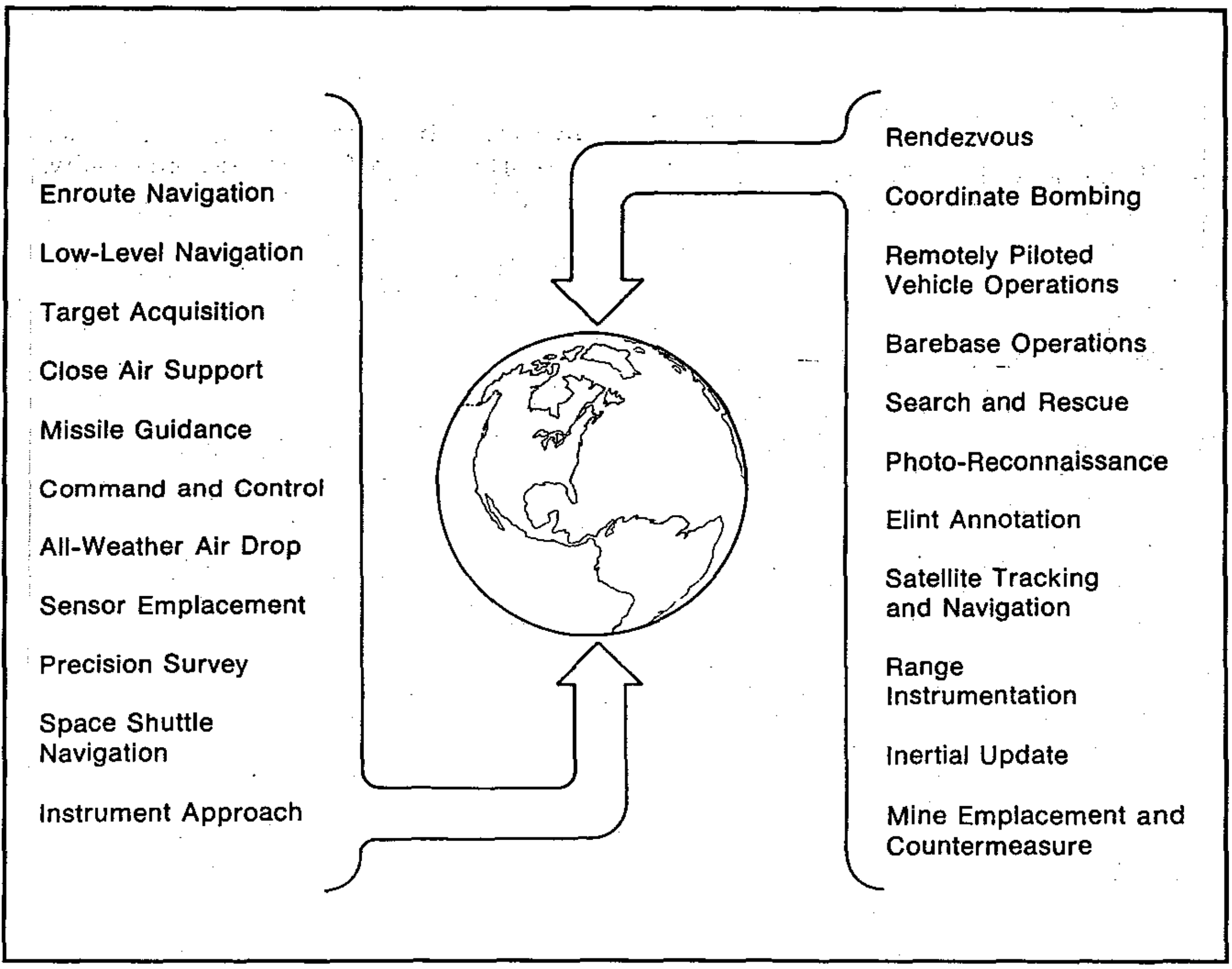

Figure 8.11. Military GPS Applications[13]

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[13] Bjornsen, op cit, p 9.

Table 8.1. Air Operations Applications of GPS[14]

FUNCTION / MISSION						ENROUTE NAVIGATION				WPN DELIVERY				
	TAKEOFF	FLYOUT	STRIKE FORCE ASSEMBLY	RENDEZVOUS	ATTACK COORDINATION	HIGH	LOW	THREAT AVOIDANCE	TARGET ACQUISITION	UNGUIDED WEAPONS	MID COURSE GUIDANCE	TERMINAL GUIDANCE	SAFE PASSAGE	RECOVERY & LAND
DEEP ATTACK	●	●	●		●	●	●	●	●	●	●	●	●	●
BATTLEFIELD INTERDICTION	●	●	●		●	●	●	●	●	●	●	●	●	●
COUNTER AIR ATTACK	●	●	●		●	●	●	●	●	●	●	●	●	●
CLOSE AIR SUPPORT	●	●		●	●	●	●	●		●	●	●	●	●
DEFENCE SUPPRESSION	●	●	●		●	●	●	●	●	●	●	●	●	●
ESCORT	●	●	●		●	●	●	●					●	●
FIGHTER SWEEP	●	●			●	●	●	●					●	●
INTERCEPT	●	●												●
RECONNAISSANCE	●	●			●	●	●	●	●				●	●
AEW/AWACS	●	●		●		●								●
ECM	●	●	●		●	●	●	●					●	●
ASW	●	●		●		●			●	●	●	●		●
MARITIME PATROL	●	●		●		●			●					●
ASSAULT	●	●			●	●	●	●	●					●
SEARCH & RESCUE	●	●	●	●			●	●	●				●	●
TANKER	●	●	●	●		●			●					●
TRANSPORT	●	●				●	●	●	●				●	●

Table 8.2. Naval Operations Applications of GPS[15]

FUNCTION / MISSION	GRID-LOCK			LONG RANGE TARGETING			COORDINATED OPS						COVERT RENDEZVOUS				MINE FIELD OPS		
	NAVIGATION	OWN FORCE LOCATION	TARGET LOCATION	OTH T	ASW SOW	POWER PROJECTION	VECTORING & HANDOFF	SEARCH OPS	AIRCRAFT/SUB ASW	TASK GROUP DEFENSE	OFF BOARD SENSORS	STATION KEEPING	FORCE ASSEMBLY	CARRIER LANDINGS	AERIAL REFUELING	COVERT LANDFALL	PLACEMENT	SWEEPING	PENETRATION
BARRIER OPS	●	●	●	●	●		●	●	●		●	●		●			●		
SLBM DEFENSE	●	●	●	●	●		●	●			●	●		●			●		
SURVEILLANCE & RECON	●	●	●				●	●			●	●			●		●	●	●
OCEAN AREA OPS	●	●	●	●	●		●	●	●		●	●		●	●		●	●	●
NAVAL FORCE PROTECTION	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●				
SHIPPING PROTECTION	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●				
OFFSHORE RESOURCE PROT	●	●	●	●	●		●	●	●		●				●		●		
OPERATIONAL LOGISTICS	●	●						●					●		●	●		●	●
MINE WARFARE	●	●	●								●	●			●		●	●	●
AMPHIBIOUS OPS	●	●	●	●	●	●				●		●	●			●	●	●	●
INSHORE WARFARE	●	●	●	●		●	●	●		●	●	●	●	●	●	●	●	●	●
STRIKES ON LAND TARGETS	●	●	●	●		●						●	●		●	●			

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[14] NATO Team, op cit, p 10-4.
[15] ibid, p 10-8.

Table 8.3. Land Operations Applications of GPS[16]

GROUND FORCE SYSTEMS	GROUND FORCE FUNCTIONS	NAVIGATION	OWN FORCE LOCATION	TARGET LOCATION	TARGET ACQUISITION	FIRE CONTROL	MIDCOURSE GUIDANCE	TERMINAL GUIDANCE & TARGET DESTRUCTION	RECOVERY
DIRECT FIRE WEAPONS	TROOPS WITH LIGHT GUNS	•	•	•					
	TANKS	•	•	•		•			
INDIRECT FIRE WEAPONS	MORTARS	•	•	•		•			
	ARTILLERY	•	•	•		•			
	ROCKET LAUNCHERS	•	•	•		•			
	S/S MISSILES	•	•		•	•	•	•	
	MINE LAYERS	•	•	•		•			
AIR DEFENCE WEAPONS	ANTI-AIRCRAFT GUNS	•	•	•	•				
	SAMS	•	•	•	•	•	•	•	
SURVEILLANCE SYSTEMS	RADARS & C3			•					
	LT OBS A/C & HELICOPTERS	•		•	•				•
	RPVS	•		•	•		•	•	•

Authorised and Non-Authorised Users. GPS was developed primarily as a military navigation system, and whilst the service is available to civilian users, the US DoD has decided to employ techniques to protect the full accuracy of the GPS signal from unauthorised use or tampering. GPS data is available to two categories of user, authorised and non-authorised. Authorised users have access to both SPS and PPS, with full PPS accuracy. Authorised users include:

a. the US military;

b. NATO military; and

c. other selected military and civilian users.

The Australian DoD is an authorised user. Non-Authorised users also have access to SPS only.

Non-Authorised Users. Two techniques are used to deny non-authorised access to full P code accuracy and to prevent spoofing.[17] The first comes under the heading of ***Selective Availability*** (SA). SA is used to degrade the accuracy of the C/A and P code signals by altering the position and time data being transmitted by the satellite. The implementation of SA is controlled by the MCS, using a process called Selective Availability Management (SAM). In peace time, the US DoD has stated that SAM will degrade C/A code accuracy to 76 m SEP. Degradation can be increased as desired. SPS would be accurate to approximately 25 m SEP if not for SA.

The second technique is termed ***Anti Spoofing*** (AS). AS involves encoding the P code signal, which is then designated either P(Y), or simply, Y code. With AS implemented, only P(Y) code receivers can access PPS. Effectively, this means that non-authorised users, even those with P code receivers, will only have access to the C/A code, and hence SPS.

SA and AS are independent functions, and can be implemented together or singly.

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[16] ibid, p 10-10.
[17] 'Spoofing' means the transmission of a duplicate signal with the intention to deceive.

Authorised Users. Authorised users can counter the effect of SA and AS to gain access to full PPS accuracy. Authorised receivers utilise crypto-variables to remove the errors imposed by SA and decode Y code into P code.

Limitations

GPS is a very robust system which suffers few major operational limitations. Every effort has been taken to make the system as survivable as possible. The specific features designed into GPS to aid the system's survivability are listed in Chapter Ten, Table 10.3. Some general operational limitations are presented below.

Access and Accuracy. For military users, GPS' biggest limitation is that GPS accuracy and access to the PPS is controlled by the US DoD. However, it is highly unlikely that the US would ever close GPS down, as they themselves are heavily reliant on the system. Nor are they likely to seriously degrade the SPS signal. The US military is a a large user of SPS itself. It currently has 10,000 SPS receivers in stock, and is still evaluating the best SPS/PPS mix for future procurement. Additionally, as increasing numbers of civilian users become dependent on GPS, the pressure to maintain the service at current or better SPS accuracy will be enormous. In fact, the Federal Aviation Authority wanted the US DoD to maintain SPS at its full accuracy at the conclusion of the Gulf War (which it declined to do), and eventually it wants unrestricted access to PPS.

Ultimately however, the fact remains that the US DoD controls GPS access and accuracy. Foreign military users of GPS such as Australia should never make themselves totally dependent on it, irrespective of their user status. Hybrid or mixed navigation systems should be used to provide a fall back capability should GPS be either unavailable or unacceptably degraded.

Hybrid Navigation Systems. Hybrid navigation systems, such as mixed GPS/inertial or GPS/Doppler systems, improve overall system performance and reliability while removing total reliance on GPS. There is a synergistic effect generated between each component of a hybrid system. This is best illustrated by example. Considering an mixed GPS/inertial system, the inertial system can assume navigation and attack functions should the GPS signal be jammed over a target area. In a complementary fashion, the regular updating of the inertial system with the precise position and velocity data available from GPS significantly improves its accuracy, giving it the capacity to provide target data to PGMs. Hybrid systems have enormous potential for military operators, a fact reflected in the RAAF's specification for preferred navigation systems.

Loss of Control Segment. Many have argued that GPS can be easily made redundant by destroying the control segment. In reality, that is not the case. TT&C for the GPS satellites is not only provided by the MCS. The GPS satellites possess an inter-constellation UHF data link which can provide a limited inter-satellite TT&C function. This enables the constellation to maintain navigation integrity for several months without ground support should it be required to do so.

DIFFERENTIAL GPS (DGPS)

For most users, GPS in its standard form provides sufficient accuracy, but for some specific applications greater accuracies are desirable. GPS accuracy can be improved by using a technique known as DGPS. DGPS also allows non-authorised users to reduce the effect of SA.

DGPS Concept

The DGPS concept is very simple. By placing a GPS receiver in a surveyed location, the difference between actual range from the GPS satellites and pseudo-range can be computed. The computed pseudo-range error is then transmitted to users to correct their navigation solution. Figure 8.12 illustrates the DGPS concept. DGPS can considerably improve GPS accuracy. Accuracies are compared in Table 8.4.

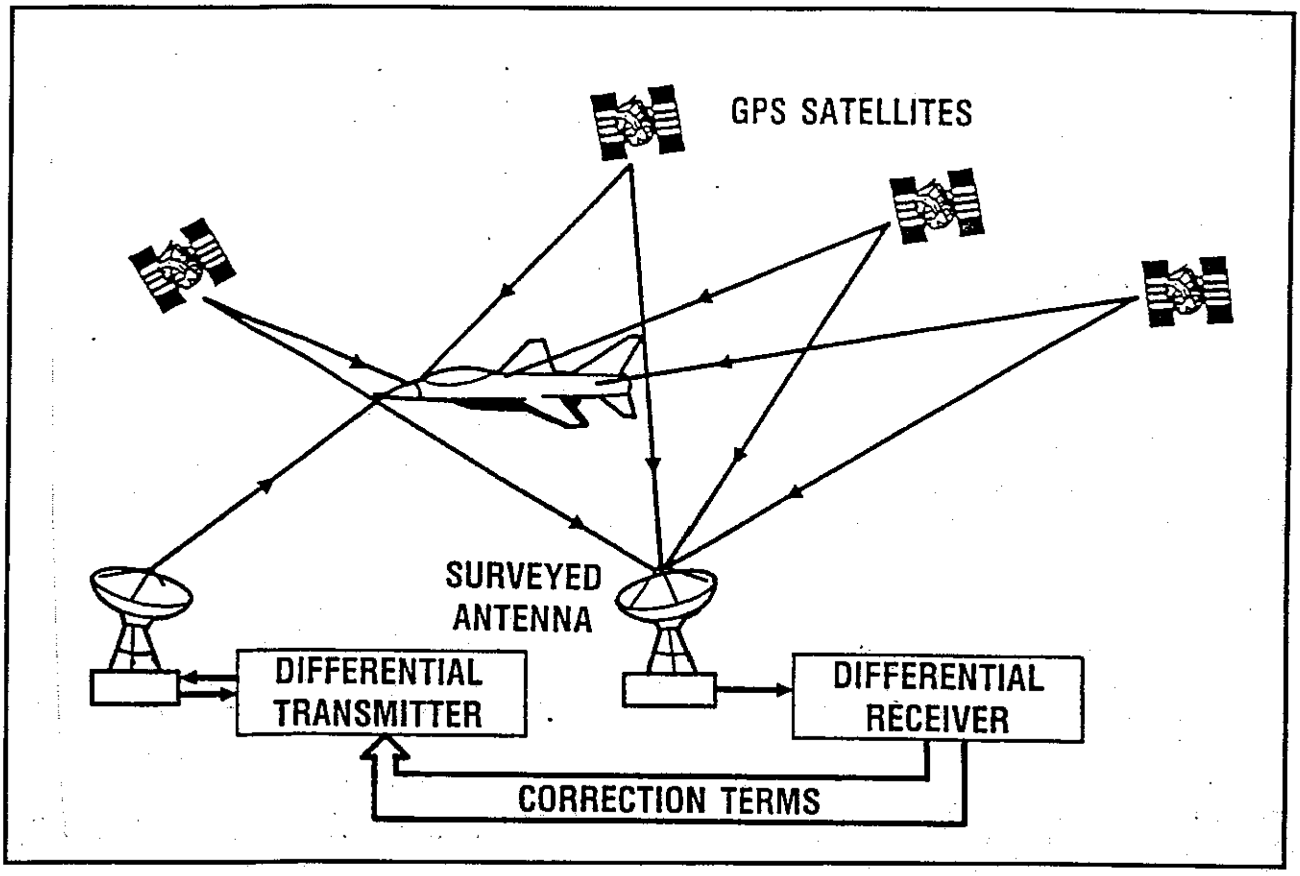

Figure 8.12. DGPS Concept[18]

Table 8.4. Comparison of GPS and DGPS Accuracies

GPS Mode	**GPS** (2DRMS)	**DGPS** (2DRMS)
C/A code with SA on	80 - 100 m	10 - 15 m
C/A code with S/A off	16 - 40 m	8 - 12 m
P code	12 - 20 m	4 - 6 m

DGPS Limitations

The correction signal generated by the surveyed site is only valid while the user is tracking the same GPS satellites as is the DGPS receiver. Additionally, ionospheric propagation errors will increase as the distance from the user to the DGPS station increases. Military users should be aware of the operational restrictions these limitations may impose.

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[18] NATO Team, op cit, 11-4.

Military Applications of DGPS

DGPS has many military applications. Some are listed below:

a. non-precision approach for aircraft;

b. all weather and night helicopter operations;

c. maritime operations in enclosed waters;

d. mining operations;

e. autonomous GPS control if control segment is lost;

f. provision of 'pseudolites' to replace lost or damaged satellites;

g. reference system for testing and calibration of navigation systems;

h. surveying, mapping and hydrography;

i. testing of avionic systems;

j. provision of telemetered air combat or electronic warfare ranges; and

k. artillery and naval gunfire direction.

GPS FOR THE ADF: JOINT PROJECT BRIEF (JPB) 5195[19]

GPS is proposed as the prime common navigation system for the ADF. Responsibility for tri-service implementation of GPS lies with the GPS Project Office (GPSPO), under JPB 5195. The GPSPO is a sub-office of the Space and Joint Systems Project Office, Material Division, RAAF. Negotiations between the ADF and the US DoD were completed in July 1991 to allow ADF users access to the PPS. Current plans indicate that GPS will be implemented into the ADF in five phases, which are described below. Revision of the implementation plan has meant that the five phases are no longer in chronological order.

Phase 1A. Phase 1A was approved by the Minister for Defence on 24 February 1988. Primarily an R&D phase, it involved the purchase of various GPS UE for evaluation to support the acquisition of operational UE under Phases 2 and 3. Evaluation of GPS manpacks, differential GPS and integrity monitoring, as well as concept development will be completed under this phase.

Phase 1B. Phase 1B was approved by the Minister on 6 January 1989. Phase 1B entails the acquisition of GPS receivers for high priority RAN and RAAF users, survey receivers for RAN hydrography, antennas for Oberon submarines and a satellite simulator for evaluating potential UE. To date, only the satellite simulator has been delivered. The remainder of the acquisition is still to be completed. The Minister approved a change of scope to Phase 1B to allow the procurement of civilian DGPS systems to support RAN hydrographic and mine warfare vessels, and military systems to support other selected RAN vessels.

Phase 2. Phase 2 will entail the procurement of GPSUE for those RAN and RAAF platforms not included in Phase 1B. Phase 2 is planned for 1994/95, but is not yet approved. The RAAF has decided to proceed with GPS acquisition on a case by case basis as aircraft undergo major upgrades. This will involve an eight to nine year implementation. The Caribou will be fitted under Phase 3B.

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[19] Wallis, SQNLDR S., *The NAVSTAR GPS Project Office*, GPS Project Office Brief, Materiel Division, Air Force Office, Department of Defence, Canberra, 1991, passim.

Phase 3A. Phase 3A was entails the procurement of 360 SPS manpack GPS receivers to support ADF ground operations. This phase is planned for 1992, and has been approved.

Phase 3B. Phase 3B entails the procurement of approximately 2000 PPS manpack GPS receivers, again to support ADF ground operations. Once the PPS receivers are available, the SPS receivers procured under Phase 3A will be passed on to lower priority users. This phase is planned for 1993/94.

GLONASS[20]

Russia's GLONASS system has been under development since the 1970s. The GLONASS system is still pre-operational. The first experimental GLONASS satellite was launched in 1982. Between then and November 1989 there have been 15 launches, with three satellites placed into orbit from each launch. Two launches were unsuccessful, leaving 39 satellites, of which two were passive laser range targets used to *'produce information for the increase in accuracy in the determination and prediction of motion of cosmic apparatus'*[21]. As of November 1989, 10 of the 37 functional satellites launched were still operating. GLONASS' theory of operation is very similar to that of GPS, so it will not be discussed. Rather, GLONASS assumed operational parameters are presented.

Orbital Parameters. GLONASS' orbital parameters are predicted to be as follows:

Spacecraft:	24 satellites, 8 in each of 3 orbital planes, each plane separated by 120° of right ascension;
Inclination:	64.8°;
Altitude:	19,100 km; and
Period:	11.25 hours.

Signal Characteristics. Like GPS, GLONASS transmits two L-Band spread spectrum signals. L1 is at 1600 MHz, while L2 is at 1250 MHz.

Accuracy. It can be assumed that the accuracy of the GLONASS system will be of the same order of magnitude as that of GPS. No firm figures are yet available.

TRANSIT

The TRANSIT space-based navigation system, first introduced in 1964, is owned by the USN. Access to the system open to all. TRANSIT provides global, two dimensional navigation. However, position fixing is not continuously available .

Theory of Operation

The breakthrough in the utilisation of space for navigation came in 1957. The scientists observing the Soviet Sputnik satellite noticed that the frequency plot of the 'beeps' received from Sputnik exhibited a Doppler shift as the satellite passed abeam the receiving station. A derivation of this principle is used by the TRANSIT system to provide navigation data. The signal frequency received from a satellite as it passes abeam an observer will change depending upon the relative path of the satellite and the observer's position. If the satellite's orbit is accurately known, and the Doppler shift in the transmitted signal as the satellite passes abeam

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[20] NATO Team, op cit, Annex E, passim.

[21] *Pravda*, 2 June 1989: quoted in, NATO Team, op cit, p E-1.

the observer is accurately recorded, it is possible to determine the exact location of the receiving station.

Constellation details are as follows:

Spacecraft:	five satellites, orbital planes separated by 36° of right ascension;
Inclination:	polar orbits;
Altitude:	1,075 km; and
Period: 106 minutes.	

Capabilities and Limitations

The TRANSIT system has three major limitations:

a. Each satellite must be tracked for a considerable period of time to measure Doppler shift and hence determine position.

b. TRANSIT is only suitable for slow vehicles.

c. Position fixes are only available at intervals varying between one half and two hours, depending on the latitude of the receiving station.

TRANSIT is accurate to approximately 200 m Circular Error Probable (CEP)[22], depending on receiving station latitude.

TRANSIT is currently used by RAN, but it will be superseded by GPS as UE is acquired under JPB 5195. As cost decreases and availability increases, the author predicts that GPS will also take over from TRANSIT in the civilian maritime sector.

TSIKADA

The Russian version of TRANSIT, TSIKADA, has been in operation since 1967. TSIKADA operates on precisely the same principle as does TRANSIT, employing similar Doppler measurement techniques to provide position data primarily to maritime assets. TSIKADA consists of two complementary yet separate systems, one military and one civilian.

The military constellation details are as follows:

Spacecraft:	six satellites, orbital planes separated by 30° of right ascension;
Inclination:	83°;
Altitude:	1,000 km; and
Period: 105 minutes.	

The civilian system uses four satellites whose orbital planes are separated by 45° of right ascension. The orbits are carefully configured to fill the gaps in the military system. TSIKADA's is claimed to be accurate to 80 to 100 m. Like most Russian satellites, TSIKADA satellites are quite short lived by Western standards, with three years being a fairly typical life time. Figure 8.13 illustrates the complementary nature of the civilian and military satellite constellations.

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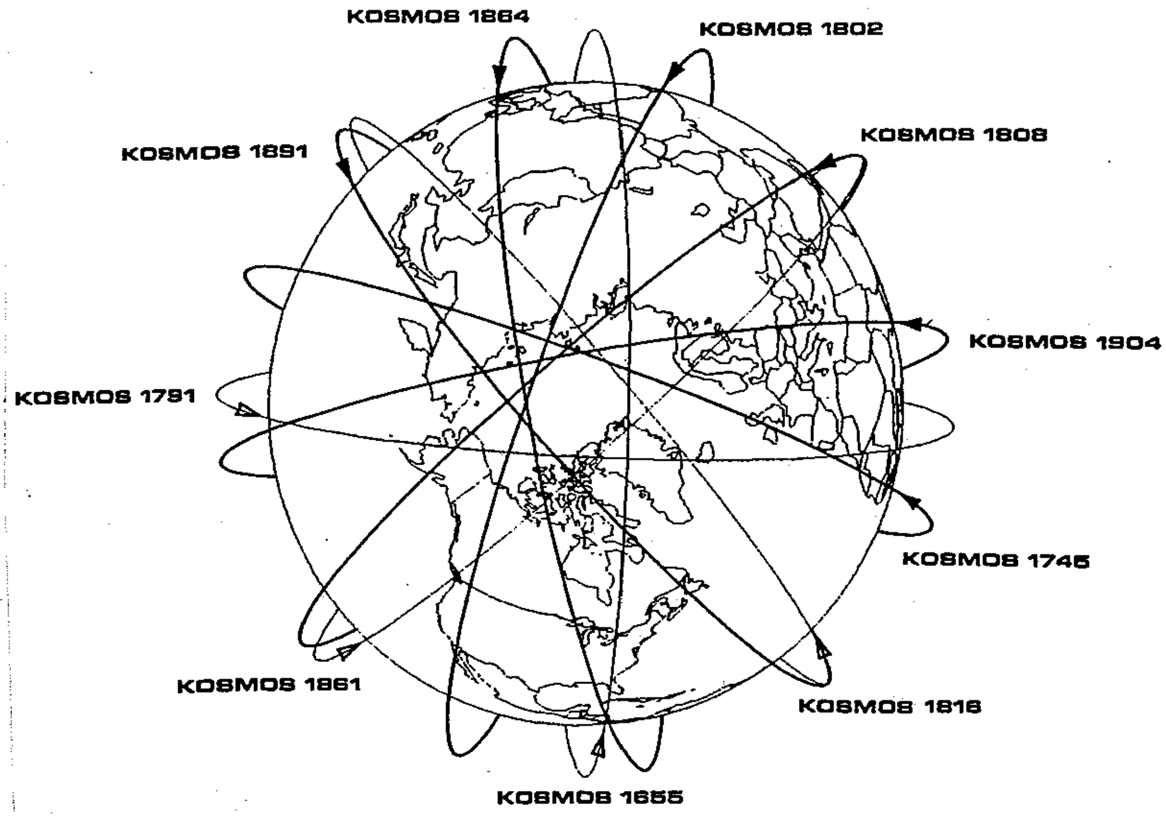
[22] CEP is a statistical term defining an error circle about the assumed position in which the actual position will lie 50% of the time. CEP applies to two dimensional systems.



Open Arrows = Civilian Satellites
Closed Arrows = Military Satellites

Figure 8.13. Russian TSIKADA Constellation[23]

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[23] Johnson, N., *The Soviet Year in Space: 1987*, Teledyne Brown Engineering, Colorado Springs, Colorado, January 1988, p 46.

CHAPTER NINE

SPACE SYSTEM VULNERABILITY

The purpose of this chapter is to discuss space system vulnerability, primarily from a regional perspective. However, space-based systems are pervasive by nature, and are capable of operating outside their region of intended influence. Despite the purpose or application of a nation's space systems, their global capability makes them a potential target for powers outside the region. The author does not wish to imply that the global threats presented in this section are either immediate or likely. Rather, they are exposed and discussed from an academic viewpoint.

The author's assessment of the potential threats Australian space-based assets may be listed in the following descending order:

a. electronic warfare (EW);

b. physical damage to, or destruction of, ground installations; and

c. physical damage to, or destruction of, space-based assets.

Regional Threats. Regional powers in Australia's ADMI may possess, or could acquire, the capacity to threaten Australian space assets through EW. Regional special force or terrorist groups certainly have the potential to cause damage to or destruction of ground installations. Additionally, it is possible (although difficult) to use inter-continental ballistic missiles (ICBMs) and submarine-launched ballistic missiles (SLBMs) as anti-satellite (ASAT) weapons. This point is expanded later in the chapter. Several countries within Australia's Region of Primary Strategic Interest (RPSI)[1] have access to ICBMs. Nuclear weapons also pose a significant threat to space operations. A high altitude nuclear detonation (NUDET) can threaten space and ground infrastructure from both direct effects and electromagnetic pulse (EMP). Several countries in the RPSI have access to nuclear weapons.

Global Threats. In addition to the regional threats discussed above, Russia and US are able to field a limited ASAT weapon capability. Russia's ASAT capability includes ballistic missiles, co-orbital killer satellites and ground based lasers. The US Army has a direct-ascent ASAT programme. Also, the US was developing an air launched ASAT weapon in the early 1980s. Whilst the program was cancelled by Congress, several weapons of unknown status still exist. The US has expressed some interest restarting the program, but that decision has yet to be taken. The US does possess an experimental high power ground-based laser which has potential as an ASAT weapon. The US is also pursuing research into new space weapons under the SDI. However, the break up of the USSR may well result in a reassessment of the US's entire space weapons programme.

Discussion on space system vulnerability will begin with the examination of the most likely threat, that of EW.

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[1] Australia's RPSI includes SE Asia, Indo-china, the eastern Indian and the SW Pacific Oceans. *The Defence of Australia 1987*, Department of Defence, AGPS, Canberra, 1987, p 2.

ELECTRONIC WARFARE

Electronic warfare (EW) may be defined as:

> *'military action involving the use of EM energy to determine, exploit, reduce or prevent hostile use of the EM spectrum; and action taken to retain friendly use of the EM spectrum'*[2].

Electronic Warfare can be divided into three categories. These, with their associated objectives, are as follows:

a. Electronic Support Measures (ESM). Action taken to make use of EM radiation released intentionally or unintentionally by the enemy.

b. Electronic Countermeasures (ECM). Action taken to interfere with the enemy's use of the EM spectrum in such a way as to render its use ineffective or dangerous.

c. Electronic Counter-Countermeasures (ECCM). Actions taken to defend one's own use of the EM spectrum.

Unfriendly EW in relation to space-based systems entails the application of ESM and ECM. Friendly forces will use ECCM to negate the enemy's use of ESM and ECM.

Jamming

Generally, ECM against a space-based system will involve the use of noise or deception jamming. The effect of jamming is maximised by directing the jammer's power into the target system's receiver. Applied to space systems, this can be a receiver in the satellite, the ground segment, or the user segment.

Noise Jamming

Noise jamming is used to impair the function of the TT&C system. Depending on the effectiveness of the jamming, the up and down-links will become either unreliable or inoperable. Conventional signal modulation techniques are very easy to disrupt by noise jamming. The signal strength of the noise jammer need be only one tenth that of the legitimate signal to disrupt the link (see Figure 9.1).

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[2] *Electronic Warfare*, 2/86 Aircraft Systems Course notes, School of Air Navigation, RAAF Base East Sale, 1986, p 1-2.

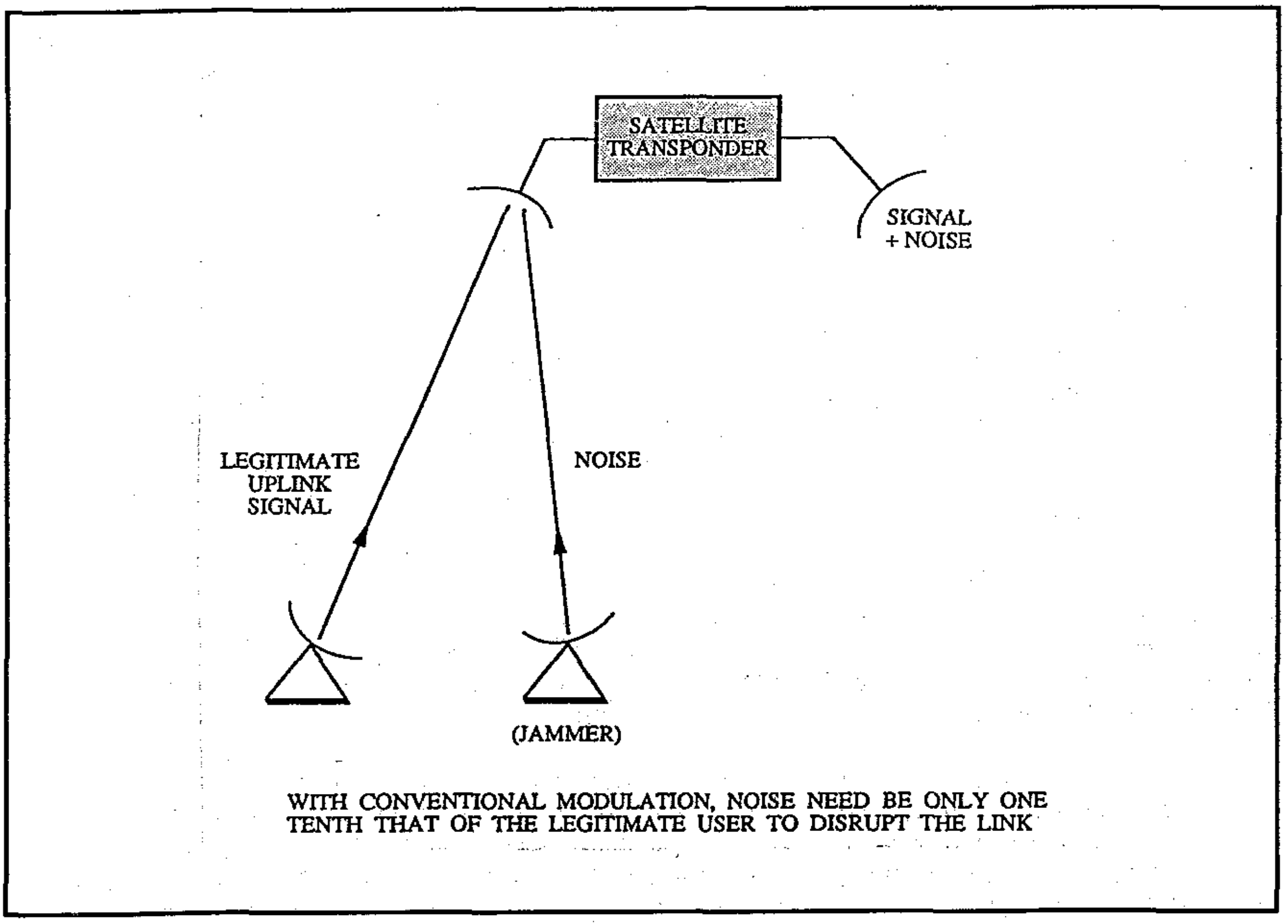

Figure 9.1. Noise Jamming a Conventional Signal[3]

Ultimately noise jamming is a power-play. The source (either the jammer or the legitimate signal) which injects the greatest amount power into the receiver will capture greatest proportion of the available bandwidth. The aim of the jammer is to occupy enough of the bandwidth such that the legitimate user cannot maintain a usable data rate. The TT&C system can be made more resistant to jamming, or ***hardened***, by employing ECCM techniques. ECCM is discussed later in the chapter.

Deception Jamming

Deception jamming is rather more subtle than noise jamming, and is more difficult to achieve. The enemy will analyse data obtained by his ESM systems to determine the signal characteristics of the target system. Once the signal characteristics are known, the target's TT&C links can be manipulated or imitated. If done well, the user may never be aware that he has been deceived, and will act on the erroneous information he has been passed.

It is often effective to combine noise and deception jamming. Just enough noise jamming is applied to allow the target system operator to overcome its effects. However, unknown to him, deception jamming has been simultaneously applied. The system operator is led to believe he has overcome the jamming and all is well, but in actuality he is accepting false data.

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[3] Mahoney, T., *Military Satellite Communications Course Notes*, Communications Division, Electronics Research Laboratory, Defence Science and Technology Organisation, Salisbury, South Australia, June 1991.

Jamming Fundamentals[4]

The choice of jammer is dependent on the quality of the intelligence the enemy has on the system he is attempting to jam. If he knows system parameters accurately, he can tailor his jamming techniques precisely to concentrate jammer power where it will do the most damage. However, if system parameters are known only loosely, then all probable signal structures must be covered. This will make his jamming considerably less effective.

When To Jam. Consideration must be given to the question 'when to jam?'. The answer largely depends upon the nature of the space system that the enemy intends to attack. For example, the enemy can attempt to jam communications satellites in GEO almost continuously, provided geographical considerations are satisfied, whereas satellites in LEO, such as reconnaissance satellites, would be best jammed as they are passing over their ground station and transmitting their gathered data. GPS satellite receivers would be best jammed when the user was over the target area, in an attempt to deny an aggressor accurate target acquisition and aiming. The intelligent development of EW tactics can play a large part in improving the effectiveness of a jamming programme.

However, before any type of EW against space systems is contemplated, the enemy must carefully analyse the cost benefit associated with such an action. Analysis should include: estimated system vulnerabilities, assessment of his own technology and its capacity to successfully complete the proposed action, resources available to complete the proposed action, and any external influences, such negative world opinion.

Once it has been decided that the space system should be attacked, and that EW presents the best option for successfully doing so, the mode of operation, jamming parameters and jammer position must be considered. Owing to the narrow beamwidths of many satellite up-links, and sometimes the down-link, positioning the jammer to allow access to the desired receiver becomes critical. In combination, the factors presented above will determine the optimum jamming approach.

Geographic Constraints. Jamming platforms attempting to penetrate a satellite receiver are geographically constrained to operation from certain locations. As a general rule, as a space-system's signal architecture increases in complexity and sophistication, so must that of the jamming system, and the tighter will become the geographic constraints on the jammer's location. Figure 9.2 illustrates the problem by example, using an aircraft mounted deception jammer against a frequency agile TT&C up-link. The jammer must be within LOS of both the satellite ground terminal and the satellite receiver to enable it to receive the ground terminal's transmission, analyse it and then broadcast its own deception signal. This process must be completed before the ground terminal completes its transmission on that frequency and hops to another. The area in which the jammer must operate to effectively complete its mission is tightly constrained by the LOS limitations imposed by the beamwidth of the ground station and the satellite receiver. Denial of access to that area denies the enemy the opportunity to jam. This is one form of ECCM.

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[4] *Satellite Jamming Design Considerations, Part 1,* Microwave Systems News & Communications Technology, September 1988, pp 35-51.

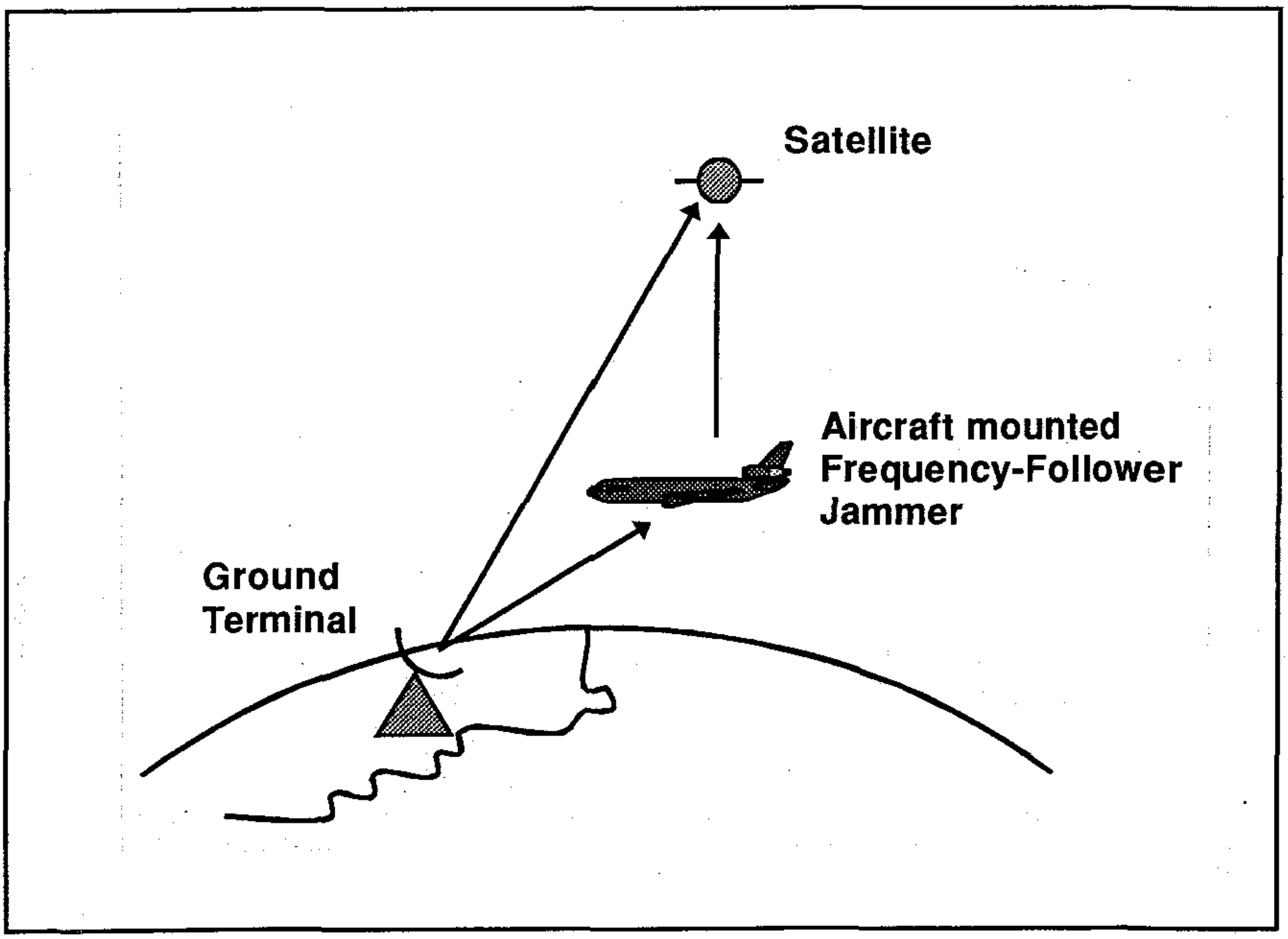

Figure 9.2. Jammer Positioning[5]

Jamming Platforms

Jammers may be ground-based (fixed or mobile), ship-based or aircraft-based. Each has its own advantages and disadvantages. Fixed ground platforms are able to generate extremely high EIRPs[6], but such systems lack mobility and consume enormous amounts of power. They also make excellent targets. Mobile ground systems are constrained in size, and their power output is limited by their inability to dissipate large amounts of heat. Consequently, their EIRPs are usually moderate.

Jammers placed on ships usually have sufficient power available to generate high EIRPs, but are often limited by antenna considerations. Large antennas suitable for high power sea-borne jamming operations are expensive to design, build and install. Small antennas are more cost effective, although their EIRPs are only moderate.

Airborne jammers are constrained in size, weight, and power availability. Antenna size and pointing ability tend to be limiting factors. They only generate low EIRPs. Figure 9.3 illustrates a selection of jamming platforms.

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[5] ibid, p 38.

[6] EIRP is standard nomenclature for Effective Isotropic Radiated Power, a measurement used to indicate power concentration. For a given range, the higher the jammer EIRP, the higher the jamming power at the receiver. EIRP is effectively a measure of antenna gain and transmitter power.

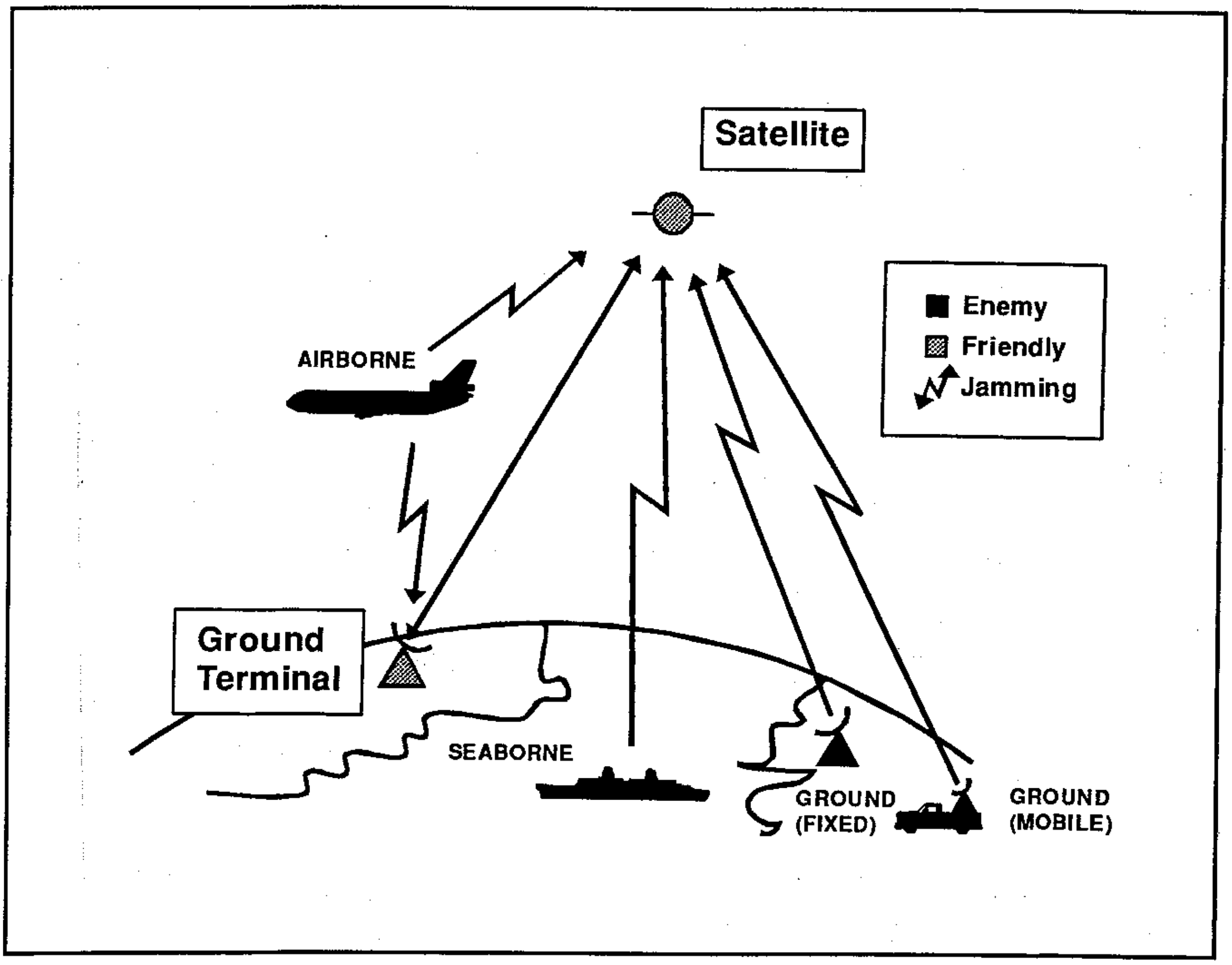

Figure 9.3. Jamming Platforms

ECCM

Whilst it is may not be possible to prevent jamming by a determined enemy, the intelligent use of ECCM can significantly increase the difficulty of the operation. ECCM aims to render enemy jamming operations ineffective. ECCM may be considered under three headings:

a. planning,

b. equipment design, and

c. tactics.

Planning

The planning of ECCM operations will not be discussed in any depth, as it is difficult to make any useful comment in an unclassified forum. The only point to be made is that such plans must be well developed, well practised, and provide sufficient operational flexibility to avoid predictability.

Equipment Design

The major difference between military and civilian satellite systems is that military satellites are hardened. When considering ECCM, this means military systems will utilise techniques to protect their communication links against EW. ECCM measures may include:

a. anti-jam capability;

b. signal encryption to prevent unauthorised use;

c. built in system flexibility; for example, space based signal switching (such as TDRSS) to reduce the reliance on ground stations, and down-link terminals able to handle several different signal architectures; and

d. backing up fixed ground installations with mobile terminals.

Specific anti-jam techniques, broken into functional groups, include:

a. Satellite.

Shaped beam antennas.
Steerable spot beam antennas.
Adaptive multi-beam antennas.
Transponder design.
On-board signal processing.

b. System Architecture.

Utilise spread spectrum and other high gain modulation techniques.
Frequency agility and diversity.
Increase link margins.

c. Up-Link Terminal.

Large diameter (high gain) antennas.
High power amplifiers.

d. Down-Link Terminal.

Narrow beamwidth antennas.
High efficiency antennas.
Adaptive cancelling antennas and reception techniques.

When all other ECCM techniques fail, it may be possible to maintain system operation by reducing data rates, repeating messages, and reducing the number of users. Of course, if the enemy's jamming has degraded the performance of the system to the extent that such measures are required, the jamming mission would be considered a success. Hopefully, with the implementation of appropriate ECCM plans and tactics, and by using suitably hardened equipment, this point would never be reached.

As a general rule, civilian space-based systems are not hardened to the degree required the military. This point must be borne in mind before military planners commit themselves to civilian space-based assets that may not be usable during time of conflict. Cost, operational utility and survivability must be carefully balanced.

As well as ECCM, military space systems may also include other features designed to harden them against other threats. Such features are presented later.

Tactics

Many tactics can be employed to improve ECCM, but the relative inflexibility inherent in space system architecture limit those applicable. Such inflexibility arises from:

a. the need for large, fixed ground installations; and

b. the rigidity imposed on the frequency and bandwidth of up and down-links by current link technologies, spectrum overcrowding and regulatory issues.

Siting. One tactical consideration that can be applied to space systems is siting. Where possible, ground receivers should be sited such that surrounding terrain will absorb signals in all directions except that to the transmitter. Terrain such as dry, well wooded hillsides will act as a barrier to jamming by reducing jammer EIRP at the receiver's antenna. A transmitter should be similarly sited, in which case the terrain will absorb EM radiation leaking from antenna sidelobes without reducing signal transmission along the antenna boresight. Suppression of signal leakage through the sidelobes makes ESM more difficult for the enemy.

Paradoxically, if a transmitter cannot be sited where RF energy is absorbed, it is best placed where the surrounding terrain will cause maximum reflection and scattering. This encourages isotropic signal spreading, reducing the signal strength available to enemy ESM platforms in any one particular direction. Additionally, numerous reflections produce a confused propagation pattern, which makes it more difficult for direction finding equipment to precisely locate a transmitter. Reflection and scattering of RF energy is provided by such environments as built-up areas, rocky hillsides and wet forests.

DESTRUCTION OF THE GROUND SEGMENT

Ground receiving and processing sites are vulnerable not only to EW, but also to:

a. conventional forces and weapons, special forces or terrorist groups; and

b. NUDET.

Conventional Attack. The ground segment is very vulnerable to physical attack using conventional weapons. The risk to the ground installation can be reduced by hardening the facility as much as possible (although the antennae will always remain vulnerable) and maintaining adequate security. Military systems with foreign-based ground stations may be particularly vulnerable to politically motivated attack. Overall system survivability can be enhanced by backing up fixed installations with mobile ground systems and reducing the number of foreign-based ground stations by using relay satellites, as the US has done with its GPS and TDRSS systems.

NUDET. NUDET presents a risk to both space and ground assets. The threat posed by NUDET will be discussed in some detail later in the chapter.

DESTRUCTION OF THE SPACE SEGMENT

Attacking space-based platforms is the most difficult and expensive way to try and damage a space system. Space-based assets can be directly attacked only by high altitude NUDET or ASAT weapons. ASAT weapons are presented below, whilst NUDET will be discussed in the next section.

ASAT Systems

Current ASAT weapons include:

a. anti-ballistic missiles (ABMs);

b. co-orbital ASATs;

c. ground-based directed energy systems;

d. EW systems; and

e. ICBMs and SLBMs.

Figure 9.4 indicates the relative altitude range and damage potential of the weapons listed.

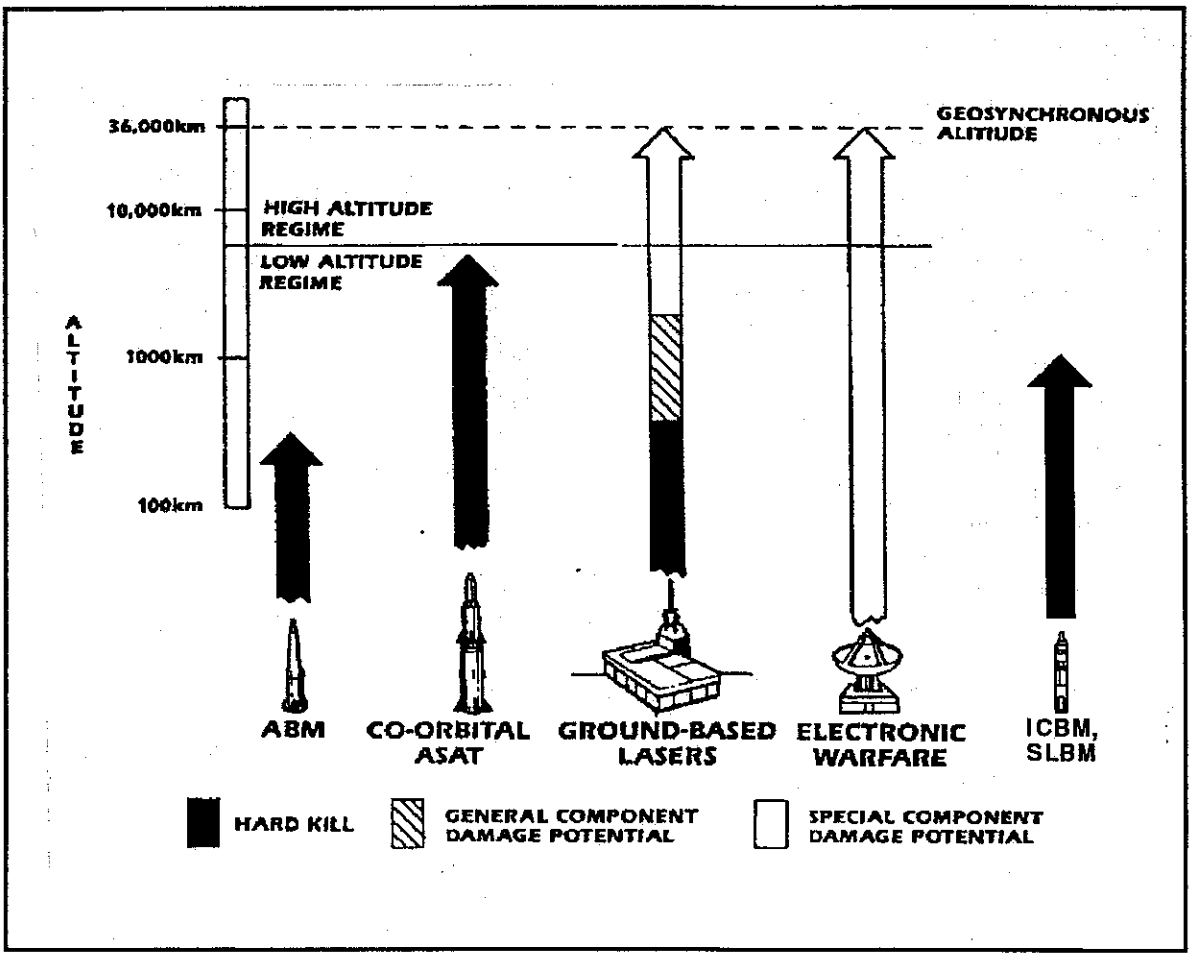

Figure 9.4. ASAT Altitude Range and Damage Potential[7]

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[7] Adapted from: Johnson, N., *The Soviet Year in Space: 1987*, Teledyne Brown Engineering, Colorado Springs, Colorado, January 1988, p 78.

There has been much debate over the need for, and viability of, ASAT systems. Conjecture as to when and why such systems would be employed and the escalatory consequences of doing so makes the utility of an ASAT system rather dubious. Arguments such as these helped in the demise of the US' air-launched ASAT weapon. Nevertheless, ASAT systems do exist, as does the potential to use them. They are discussed briefly below.

ABM Systems. Russia currently fields ABM systems around Moscow and the Sary Shagan test centre. These ABM systems, using nuclear tipped Gorgon exo-atmospheric missile based interceptors, reportedly have a capability to intercept satellites in very low earth orbits as they pass overhead. Tracking and guidance for the ABM system is provided by ground-based phased array radar. Some US reconnaissance satellites are vulnerable to Russia's ABM system. However, the utility of this system as an ASAT weapon is hampered by the collateral effect of the detonation of a nuclear warhead directly over one's own territory, and by limited target opportunities.

The Russian Co-orbital ASAT.[8] Russia currently possesses the world's only operational orbital ASAT. The system uses a co-orbital interceptor based at the Tyuratam launch site. The interceptor is capable of attacking polar orbiting satellites at altitudes up to 2,000 km. Its altitude potential increases as the target satellite's inclination decreases. To make a kill, the ASAT must catch its quarry and manoeuvre alongside. The final intercept is completed using either radar or optical guidance. The ASAT weapon must be co-orbital to make a kill using its fragmentation warhead. Vulnerable satellites include US military weather, reconnaissance and TRANSIT navigation satellites and civilian remote sensing satellites. Only about 17% of US military satellites lie within range of the Russian ASAT. In practice, the system is very limited in capability. Russia is believed to have only 12 interceptors. The interceptor must be launched as the target satellite flies over the Tyuratam launch site. It then normally takes two full orbits for the interceptor to catch and engage its target (see Figure 9.5), although single orbit intercepts have been tested. This process can take between 45 minutes and three hours. Given these limitations, operations can become rather cumbersome. For example, it would take at least 15 hours to destroy the TRANSIT constellation, assuming a 100% kill ratio. Observation of the system under test has indicated that its kill ratio is nowhere near 100%.

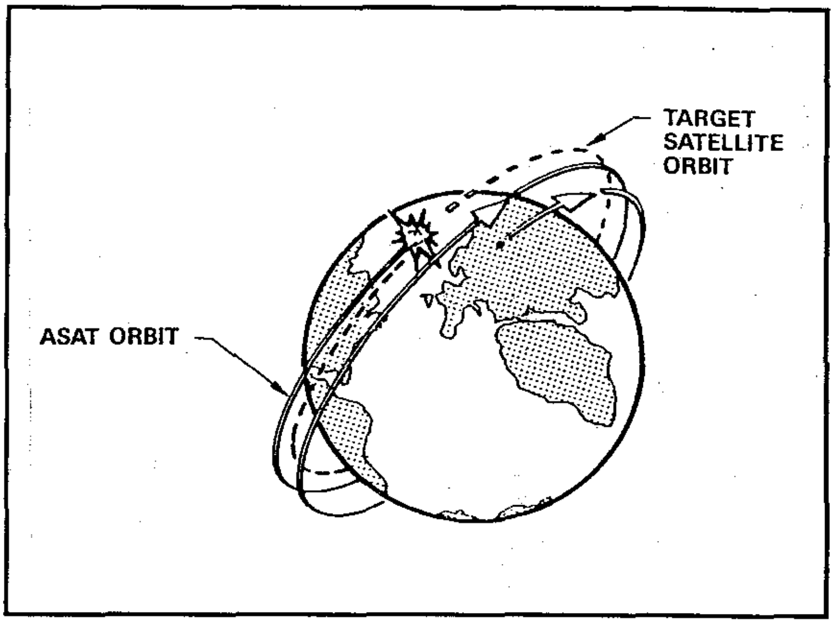

Figure 9.5. Russian Co-Orbital ASAT Attack Profile[9]

Ground-Based Directed Energy Systems. Both the US and Russia possess high-power ground-based lasers. These have the capacity to damage or disrupt satellites out to GEO. The US has a deuterium fluoride laser at the White Sands Proving Ground, whilst Russia has a system at the Tyuratam test centre. Both systems theoretically have the capacity to destroy, damage or disrupt satellites through laser induced heating as they pass within LOS of the sites . The US also believes that Russia is well ahead in developing high-energy RF weapons. These weapons also have the potential to damage satellites. Such a facility may exist at Nurek near Dushanbe, close to the Afghanistan border.

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[8] ibid, p 79.
[9] loc cit.

ICBMs AND SLBMs. The ballistic flight paths of ICBMs and SLBMs take them to apogees of over 1,400 km. If suitably fused, their warheads (nuclear or conventional) could be detonated at a point along their flight path in the vicinity of a targeted LEO satellite. If a nuclear warhead were used, it would have to be detonated on the descending portion of the missile's trajectory to prevent collateral damage of friendly infrastructure through EMP. Additionally, the detonation of a nuclear warhead in space would pose a significant collateral threat to the attacker's own satellites. In summary, whilst the use of ICBMs and SLBMs as ASAT weapons is technically possible, it is rather unwieldy. However, the potential to use these weapons in the ASAT role does significantly increase the number of countries possessing an ASAT capability.

The Future

Whilst there has been, and still is, much contention and debate over the deployment of ASAT weapons, the US is and the USSR was pushing ahead in their development. Areas of interest include ground and space-based directed energy weapons, space mines and direct-intercept weapons. At the same time, methods of reducing satellite vulnerability are also being investigated, such as:

a. satellite hardening;

b. satellite proliferation (large numbers of small satellites in many orbital planes, with on-orbit spares);

c. flexible launch systems (enhancing a nation's ability to quickly replace lost satellites);

d. using higher orbits, although this may involve a trade-off in mission effectiveness;

e. applying low-observable (or stealth) technologies to satellites to reduce their signatures to complicate targeting; and

f. making satellites more manoeuvrable to enable them to evade ASAT weapons.

Where such developments will eventually lead depends largely on whether the super-powers wish to escalate their abilities to conduct war in space, and indeed, whether Russia continues to remain a military super-power. If it does not, then the rate of development of space weapons and space weapon countermeasures may subside considerably.

NUDET

NUDET presents a serious threat to both civilian and military space and ground infrastructure. The threat may be divided into two primary categories:

a. direct nuclear effects, such as hard radiation; and

b. indirect nuclear effects, including:

    i. electromagnetic pulse (EMP);

    ii. thermal radiation;

    iii. ground shock; and

    iv. overpressure, or blast.

The effect of NUDET on a particular target is dependent on four factors: the altitude of detonation, the type of warhead (thermal or neutron), warhead yield, and range from the target.

The altitude of detonation will depend on the aim of the attack. Altitude of detonation can be separated into three broad categories:

a. surface burst (0-2 km altitude);

b. air burst (2-30 km altitude); and

c. high-altitude burst (30 km plus).

The broad effects of these three types of attack are illustrated in Figure 9.6.

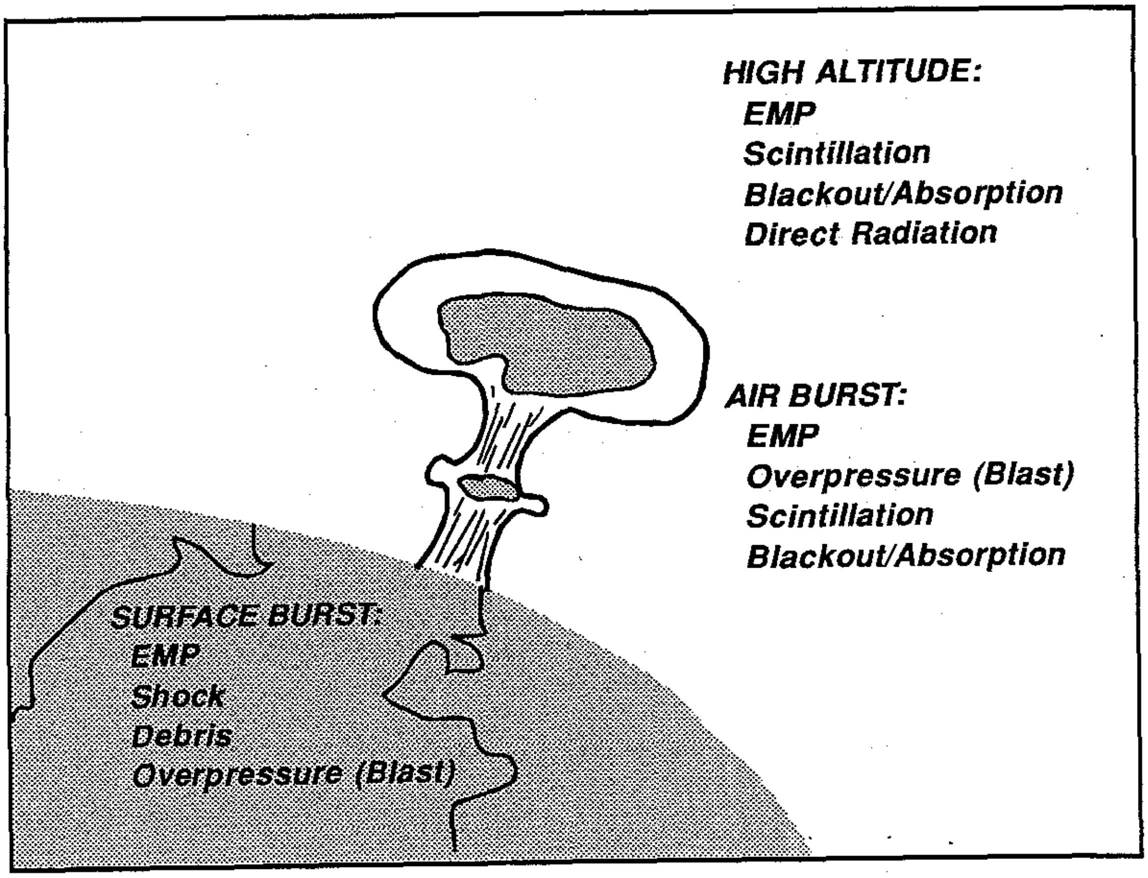

Figure 9.6. Effects of NUDET at Various Altitudes[10]

EMP is potentially the most damaging effect produced by NUDET, and EMP produced by air and high-altitude burst is more damaging than that produced by a surface burst. Air and high-altitude detonations will produce widespread propagation disturbances, affecting EM signal propagation between the radio and optical frequencies. Propagation disturbances include: ***Scintillation*** (distortion of EM energy transmission paths); and ***absorption/blackout*** (the denial of EM energy transmission within the effected area, particularly microwave energy). These effects are frequency dependent, as illustrated by Figure 9.7.

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[10] Adapted from: Morse, R. et al, *Space Operations Orientation Handbook 2nd Edition*, 1013th Combat Crew Training Squadron, Air Force Space Command Operations, Peterson AFB, Colorado, 1 January 1991. p 92.

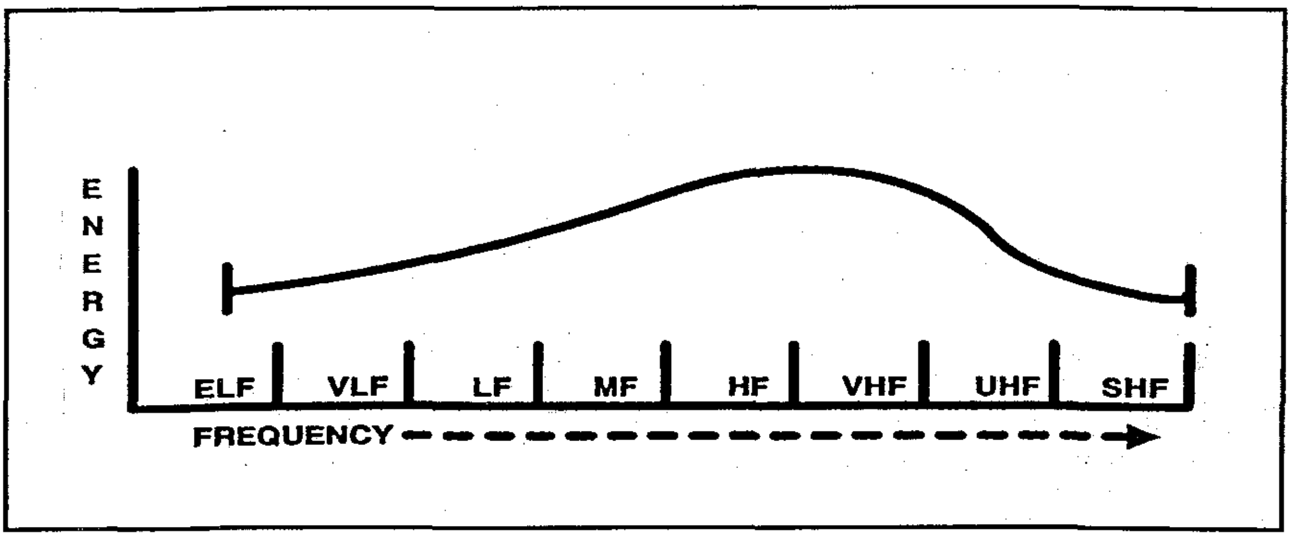

Figure 9.7. EMP Spectral Coverage[11]

The lower end of the spectrum tends to be affected more by absorption, while the upper end is affected more by scintillation. These effects can wreak havoc on satellite TT&C links. From a terrestrial perspective, HF communications would be very badly disrupted, with ionospheric disturbances lasting between seconds and days.

The impact of these effects on a space system can be minimised by avoidance, cross-link and signal manipulation. Avoidance means not using space and ground facilities in the affected area. This implies a loss of C^3 which may not be operationally acceptable. Redundancy and cross-link facilities must be designed into C^3 systems to counteract the EMP threat.

Signal manipulation has been addressed in the section on EW, but it basically consists of decreasing data rates and repeating messages until the signal gets through.

EMP

EMP is produced within nanoseconds of NUDET, and can cause disruption or damage to unprotected electronic circuits and components. EMP is an indirect nuclear effect resulting from the interaction between the gamma radiation produced by the detonation, gaseous molecules in the atmosphere and the Earth's magnetic field. This interaction occurs primarily in the ***EMP source region***, a band in the atmosphere located between the altitudes of 20 and 40 km.

EMP imposes a potentially devastating threat for two reasons. First, the peak amplitude and rise rate of the induced electric and magnetic fields are extremely high. These induced fields will induce damaging voltages and currents in unprotected circuits and components. Second, the area effected can be enormous. Simultaneously, power, communications and computer networks, ships, aircraft, spacecraft and ground vehicles are threatened. No other weapon poses such a widespread threat which is virtually instantaneous. Systems critical to military and civilian communities must be protected from EMP.

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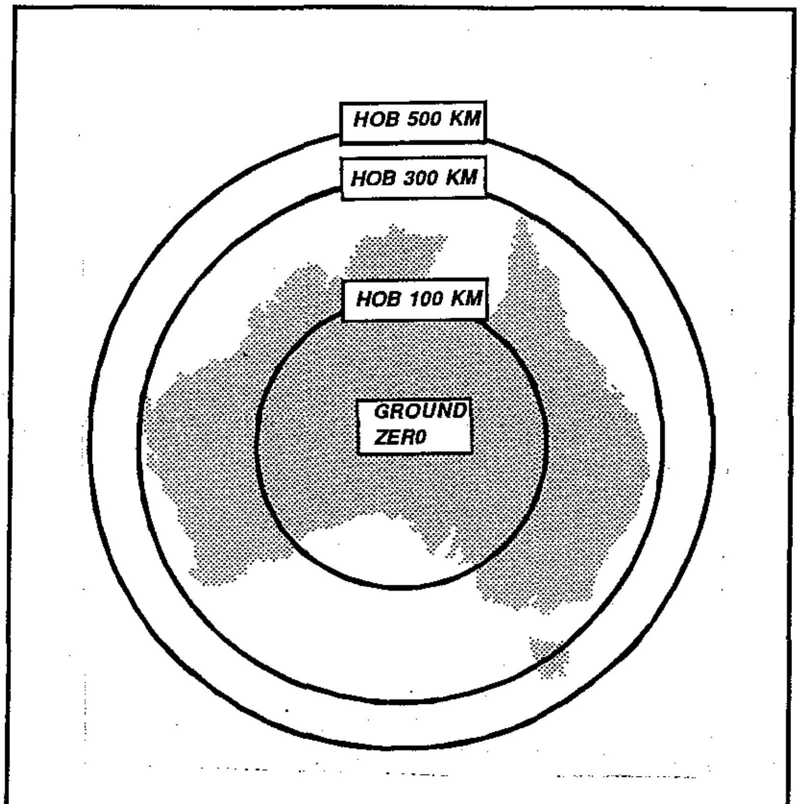
[11] ibid, p 99.

Area Effected

The size of the area effected by EMP is determined by the altitude of burst and the yield of the weapon. EMP propagates within LOS of the detonation, so the higher the detonation altitude, the greater the area covered. Consequently, high-altitude EMP (HEMP) will cause the most widespread damage. The peak intensity of the EMP field will diminish with range from ground zero. However, the EMP effect perseveres for longer with increasing range. Figure 9.8 illustrates the area over Australia that would be affected by EMP at detonation altitudes of 100, 300 and 500 km respectively. NUDET at 300 km will affect the entire Australian mainland.

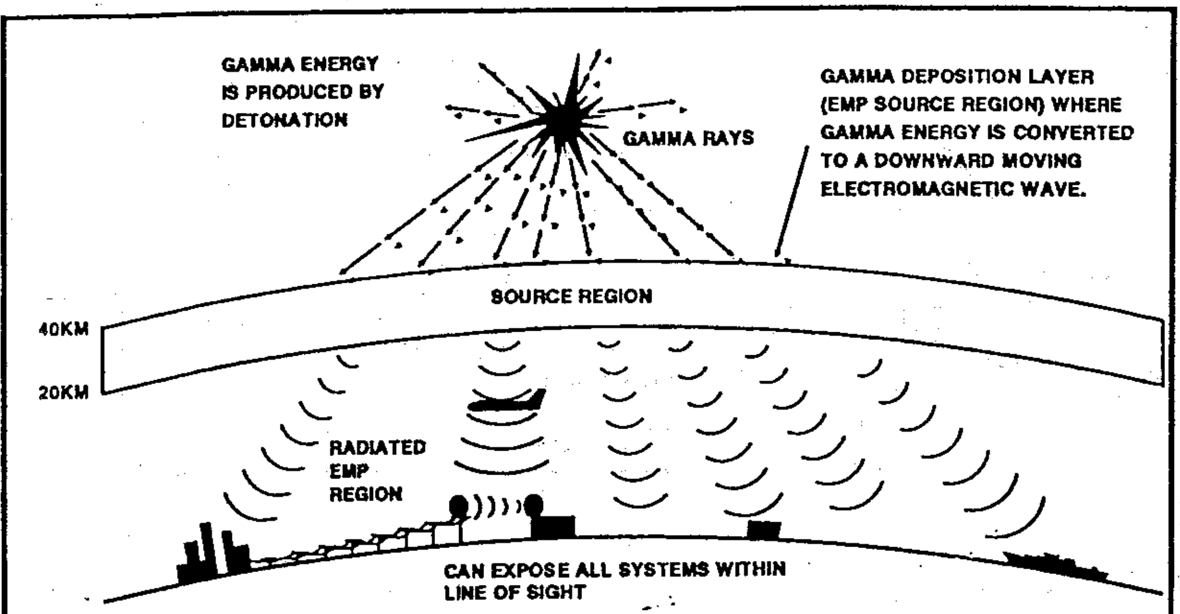


Note: **HOB = Height of Burst**

Figure 9.8. EMP Ground Coverage Overlaid on Australia

High-Altitude EMP (HEMP)

Figure 9.9 illustrates the production and effect of HEMP.



FEATURES OF EMP FROM A HIGH-ALTITUDE BURST

- **WIDE AREA COVERAGE**
- **HIGH FIELD STRENGTHS (50 KV/M)**
- **BROAD FREQUENCY BAND (NEAR DC-100 MHz)**
- **ABSENCE OF MOST OTHER NUCLEAR WEAPONS EFFECTS**

Figure 9.9. High Altitude EMP[12]

As illustrated, HEMP propagates towards the Earth as a coherent waveform. The intensity of the pulse can be enormous. HEMP can produce transient peaks of up to 50 kV/m. The frequency band of HEMP extends all the way from direct current (DC) to 100 MHz alternating current (AC). Figure 9.10 highlights the intensity and duration of the EMP pulse in comparison to the spectral distributions of man-made EM radiation, and also to that of lightning.

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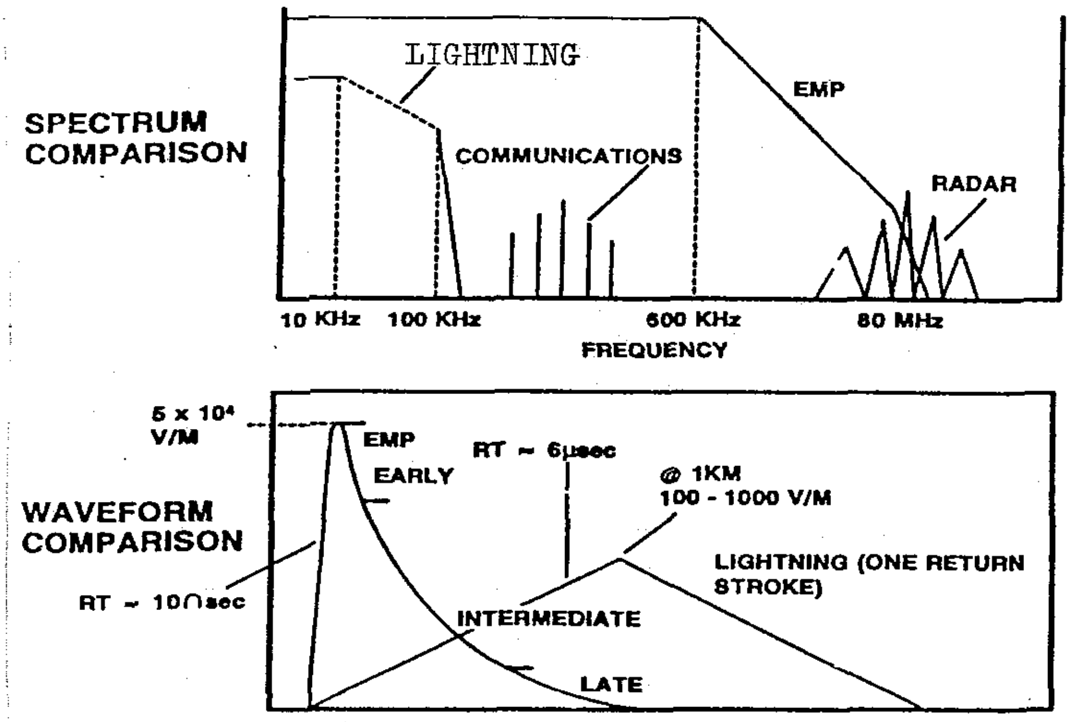
[12] Morse, op cit, p 93.



Note: RT = Rise Time.

Figure 9.10. EMP Field Comparison[13]

As indicated in Figure 9.10, the EMP pulse can actually be divided into three phases:

a. early-time EMP;

b. intermediate-time EMP; and

c. late-time EMP.

Early-time EMP, produced immediately after NUDET, lasts up to 200 ns. It produces the highest field transients and is the most damaging. Intermediate-time EMP tends to be overwhelmed by early-time EMP, and then late-time EMP takes over. Late-time, or magnetohydrodynamic (MHD) EMP, may last for up to 17 minutes. It produces a continuous low-intensity EM field. Late-time EMP primarily affects long conductors such as power and telephone cables. Table 9.1 summarises the quantitative effects EMP.

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[13] Morse, op cit, p 95.

Table 9.1. EMP Quantitative Environmental Variations[14]

Type	Peak Amplitude	Time-Frame
High Altitude Burst		
Early-Time EMP (HEMP)	50 kV/m	Few ns to 200 ns
Intermediate-time EMP	10 V/m	1 µs to 1 s
Late-time or MHD EMP	30 V/km	1 s to 1000 s
Surface Burst		
Source Region	1 MV/m	Few ns to 1 µs
	10 kV/m	1 µs to 0.1 s
Radiated Region	10 kV/m	1 µs to 100 µs
Air Burst		
Source Region	Similar to surface burst	
Radiated Region	Less than HEMP	Components similar to HEMP & Surface Burst
Exo-Atmospheric Burst	> 1 MV/m	Few ns to 100 ns

<u>EMP Hardening</u>

EMP is capable of inducing currents of up to 1000 Amperes (A) in long conductors, 100 A in shorter conductors, and through penetration into a target, up to 10 A in interior conductors. Induction at these levels is obviously going to have quite an effect on the ground segment of any space based system. Figure 9.11 illustrates how EMP may be coupled into a typical TT&C facility.

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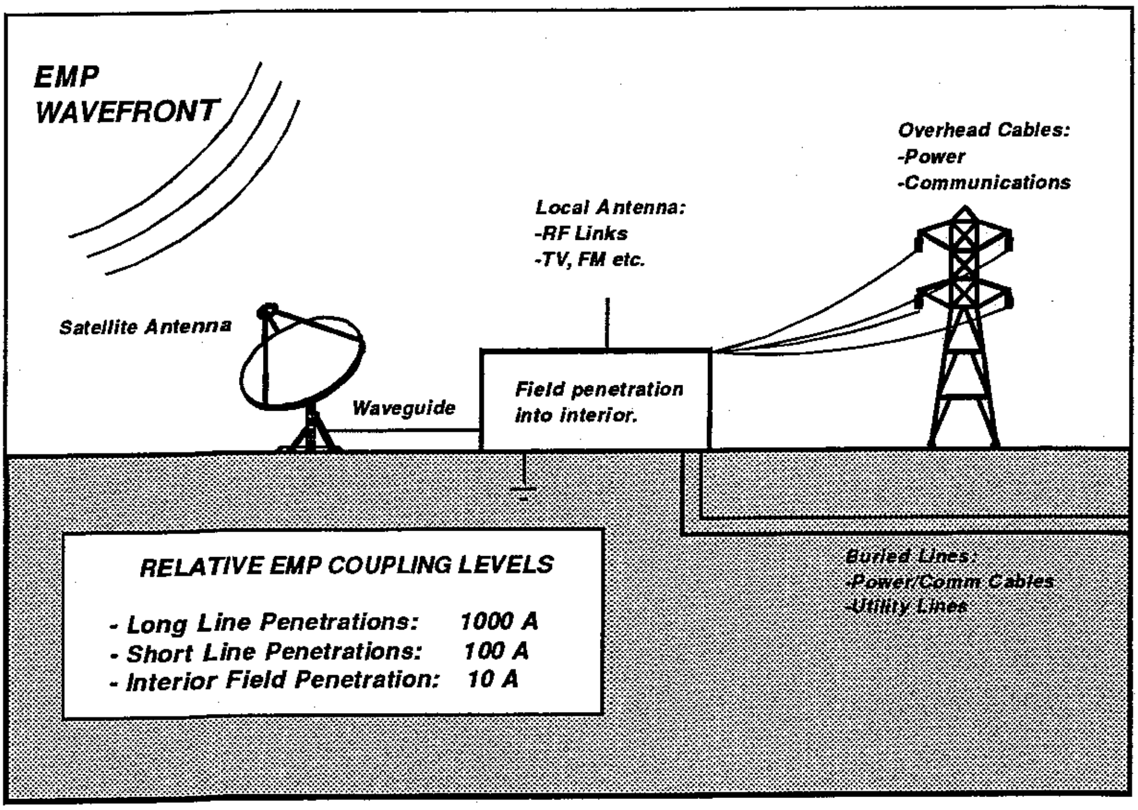
[14] Adapted from: Morse, op cit, p 97.



RELATIVE EMP COUPLING LEVELS

- Long Line Penetrations: 1000 A
- Short Line Penetrations: 100 A
- Interior Field Penetration: 10 A

Figure 9.11. EMP Coupling into a TT&C Facility

To protect a facility or vehicle from EMP a barrier is required between the induced effects of the pulse and the system or elements requiring protection. The choice lies in where the barrier is to be located. To protect a facility or vehicle perfectly it must be enclosed in a ***Faraday cage***, that is a fully closed conducting shell. In reality, this is a rather impractical solution. Facilities require entrances for people, power, ventilation etcetera. These entrances must be protected as follows:

a. Line Penetrations. Filters and arresters.

b. Windows and Other Transparent Openings. Wire mesh or transparent conductive film.

c. Ventilation Ports. Metallic honeycomb.

d. Doors and Hatches. Conductive gaskets.

If is not practical to effectively seal the facility, then individual elements within the facility must be protected. Local shielding, hardened piece parts, hardened circuits, fault tolerant logic design and filters and limiters are all employed to protect systems from EMP. Protecting individual elements is neither simple nor cheap, and the risk of incomplete protection is substantial. However, this technique must often be employed to implement system protection post initial design.

NUDET Effects on Spacecraft

The effects of NUDET in space are illustrated by Figure 9.12.

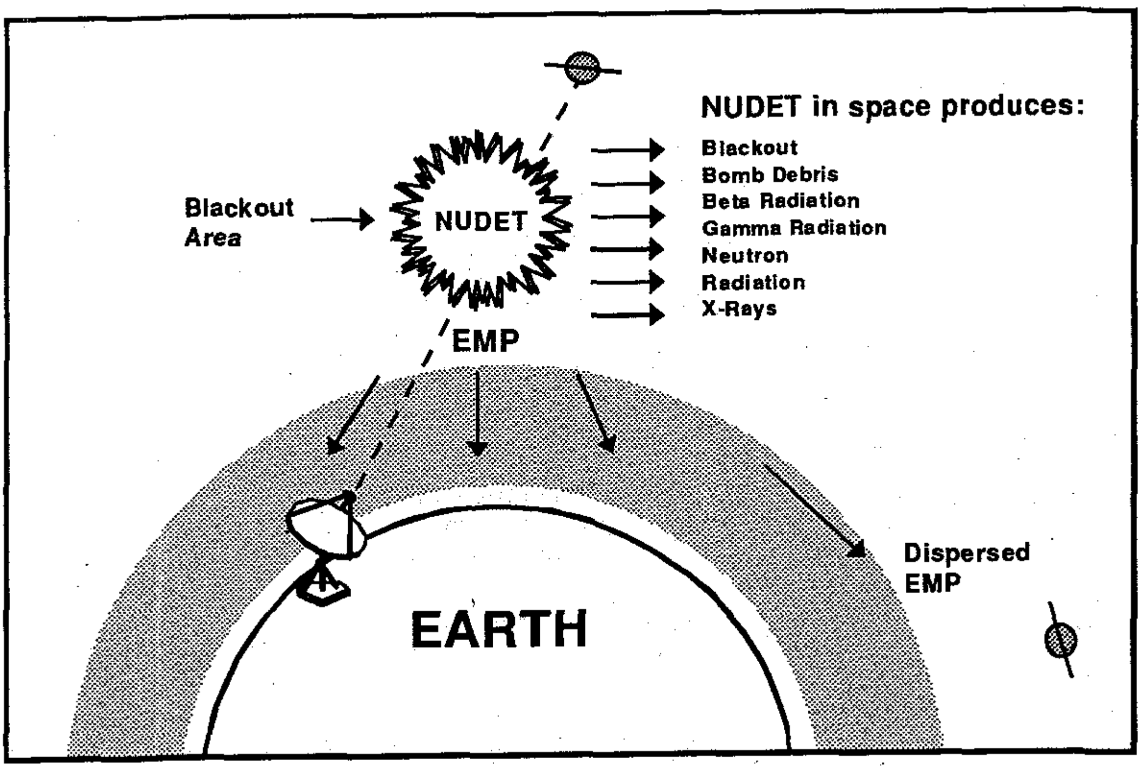


Figure 9.12. The Effects of NUDET in Space

NUDET in space can damage spacecraft through radiation, skin charge and internal arcing.

Radiation. NUDET at altitudes of more than 40 km produces considerably more radiation than at lower altitudes. Energy that is usually converted to blast and shock (about 50%) is released as thermal radiation due to the lack of atmosphere. The combined effect of thermal and hard radiation poses a significant threat to spacecraft. The magnitude of the threat is range dependent. Damage can range from simple computer logic errors to total destruction. Induced energy levels at the spacecraft rise to a peak very rapidly, followed by an equally rapid decline.

Skin Charge and Internal Arcing. EMP induced skin charge effects on a spacecraft can lead to the generation of internal arcing as the energy distribution over the spacecraft is equalised. Generally, a large percentage of spacecraft surfaces are constructed of non-conductive dielectric materials which tend to collect electrical static until sufficient charge has accumulated to cause an arc. Such arcs can damage computer logic, system components and ultimately, entire systems.

GPS: AN EXAMPLE OF A SURVIVABLE SYSTEM

GPS provides a good example of the types of features that can be designed into a satellite system to increase its overall survivability. Table 9.2 highlights these features.

Table 9.2. GPS Survivability Features[15]

Attack Method	Protective Measures
Intercept	Graceful degradation. Many orbital planes. Irregular plane phasing. On-Orbit spares. Nuclear hardening. Propulsion module to evade?
Laser	Resistant to warming.
Space Mines	Unique orbit.
Ground Segment Destruction	Inter-Satellite cross-links. Mobile ground stations. Satellite autonomy.
Electronic Attack	Encrypted P code links. Anti-jam by inter-satellite cross-links, spread spectrum signal protocols, nulling antennas and spatial diversity. Cross-Link anti-jam by nulling antennas and frequency hopping.
Nuclear Effects	Radiation hardened satellites. Auto restart after transient upset. EMP hardening of military receivers. Spatial diversity.

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[15] Carter, A., *Satellites and Anti-Satellites: The Limits of the Possible*, International Security, Vol. 10, No. 4, Spring 1986, p 91.

BIBLIOGRAPHY

A Space Policy for Australia, Australian Academy of Technological Sciences, Parkville, Victoria, 1985.

ACRES Thematic Mapper Products, Australian Centre For Remote Sensing, Canberra, August 1989.

Bailey R.G., *Problems With Using Overlay Mapping for Planning and Their Implications for Geographic Information Systems*, Environmental Management, Vol 12., No 1, January 1988.

Ball, D. and Babbage, R.(eds), *Geographic Information Systems: Defence Applications,* Pergamon, Sydney, 1989.

Ball, D., *Pine Gap*, Allen and Unwin, Sydney, 1988.

Bate, R., Mueller, D., and White, J., *Fundamentals of Astrodynamics*, Dover Publications Inc., New York, 1971.

Bjornsen, G. and Price, D., *NAVSTAR GPS System and User Equipment Description*, March 1985, p 2: in *The Global Positioning System: A Compilation of Papers: Book Two*, Rockwell International Corporation, 1988.

Bosher, V., *Uses of Satellites in Reconnaissance*, WRE Technical Note 1339(AP), Weapons Research Establishment, Department of Defence, 1984.

Boutacoff, D. and Gumble, B., *Strengthening C^3 in Space*, Defense Electronics, No. 20, February 1987.

Brookner, E. and Mahoney, T., *Derivation of Satellite Radar Architecture for Air Surveillance*, Microwave Journal, February 1989.

Brown, R., *Land Applications of RADARSAT*, International Geoscience and Remote Sensing Symposium 1989, *Remote Sensing: An Economic Tool for the Nineties*, Volume 1, 1989.

Burrough P., *Principles of Geographical Information systems for Land Resources Assessment,* Clarendon Press, Oxford, 1986.

Cantafio, L., *Space-Based Radar Handbook*, Artech House, Norwood, Massachusetts, 1989

Carter, A., *Satellites and Anti-Satellites: The Limits of the Possible*, International Security, Vol. 10, No. 4, Spring 1986.

Cartwright, D., *Space and Defence*, lecture at CSIRO Headquarters, Canberra, 31 July 1991.

Cavill M., Kirton P. and Zwart P., *Networking GIS Users - The Impact of Broadband Networks*: in Walsh B.J. (ed), *Information Systems: Assessing the Impact*, Proceedings of the 17th Australasian Conference in Urban and Regional Planning Information Systems, Perth, 1989.

Chekan, R., *Use of Commercial Satellite Imagery for Surveillance of the Canadian North*, thesis paper, USAF Institute of Technology, USAF University, Ohio, November 1988.

Chen, H., *Space Remote Sensing Systems*, Harcourt Brace Jovanovich, 1985.

Cline, R. et al, *The Intelligence War*, Lansdowne Press, Sydney, 1983.

Cochran, C., et al (ed), *Space Handbook*, Air Command and Staff College, Air University, Maxwell AFB, Alabama, January 1985.

Colwell, R. (ed) et al, *Manual of Remote Sensing*, Second Edition, Vol. 1, American Society of Photogrammetry, Falls Church, Virginia, 1983.

Cowen D., *GIS versus CAD versus DBMS: What Are The Differences? Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 11, American Society for Photogrammetry and Remote Sensing, Falls Church, Virginia, 1988.

Curran P., *Principles of Remote Sensing,* Longman Scientific and Technical, New York, 1985.

Damon, T., *Introduction to Space*, Orbit Book Company, Malabar, Florida, 1990.

Davey, SQNLDR K, *Background Brief on Military Satellite Communications Project*, Headquarters ADF, Department of Defence, Canberra, August 1991.

Davey, SQNLDR K., *Presentation on Satellite Communications in the ADF*, Headquarters ADF, Department of Defence, Canberra, 23 August 1991.

Dayerle, MAJ C. and Thomson, SQNLDR J. (eds), *Electro-Optics Notes*, General Duties Aerosystems Course, RAF Cranwell, Lincolnshire, 1988.

Defence Communications Corporate Plan 1991-2001, Department of Defence, Australian Government Publishing Service, Canberra, 1991.

Drover, WGCDR K., *Space Power: Military Imperatives in Australia's Environment*, USAF Air University, Maxwell AFB, Alabama, 1989.

Elbert, B., *Introduction to Satellite Communication*, Artech House, Norwood, Massachusetts, 1987.

Electronic Warfare, 2/86 Aircraft Systems Course notes, School of Air Navigation, RAAF Base, East Sale, 1986.

Encyclopaedia Brittanica, 1968.

Fensom, D., *The Australian Fast Delivery Processor for the Synthetic Aperture Radar of ERS-1*: in, Conference Proceedings, Fifth National Space Engineering Symposium 1989, Canberra, 27 November - 1 December 1989.

Force Structure Review, Department of Defence, Canberra, May 1991.

Furniss, T., *Launch Vehicle Directory*, Flight International, 17-23 April, 1991.

Gale, SQNLDR W., *The Potential of Satellites for Wide Area Surveillance of Australia,* Air Power Studies Centre, RAAF Fairbairn, 1991.

Granger K., *Defence Requirements for Geographic Information: A Survey,* restricted circulation Defence Fellowship report, Centre for Resource and Environmental Studies, Australian National University, Canberra, 1989.

Granger, K., *Geographic Information and Remote Sensing Technologies in the Defence of Australia*, Centre for Resource and Environmental Studies, Australian National University, Canberra, January 1990.

Gray, C., *American Military Space Policy*, Abt Books, 1982.

Griersmith D. and Kingwell, J., *Planet under scrutiny - An Australian Remote Sensing Glossary*, Bureau of Meteorology, AGPS, Canberra, 1988.

Grohavaz, E., *The Role and Functions of the Australian Space Office: An Engineer's Perspective*, Paper presented at the Aries Symposium, Canberra, 1991.

Harris, G., *Remote Sensing for Global Change*, presentation at CSIRO, Canberra, 14 August 1991.

Harrison, B. and Jupp, D., *Introduction to Remotely Sensed Data*, CSIRO Publications, Melbourne, 1989.

Hovanessian, S., *Introduction to Sensor Systems*, Artech House, Norwood, Massachusetts, 1988.

HQADF, *Geographic Information in the Defence of Australia*, Seminar sponsored jointly by the Directorate of Intelligence, Headquarters Australian Defence Force and the Department of Geography and Oceanography, Australian Defence Force Academy, Canberra, 1988.

Hurn, J., *GPS: A Guide to the Next Utility*, Trimble Navigation, Sunnyvale, California, 1989.

Johnson, N., *The Soviet Year in Space: 1987*, Teledyne Brown Engineering, Colorado Springs, Colorado, January 1988.

Jones, I., *Satellite Measurement of Directional Ocean Wave Spectra*: in, Conference Proceedings, Fifth National Space Engineering Symposium 1989, Canberra, 27 November - 1 December 1989.

JSP (AS) 101, Australian Joint Service Publication, Glossary, Part 1, Edition 3, February 1984.

Kostiuk, T. and Clark B., *Space-borne Sensors (1983-2000 AD): A Forecast of Technology*, National Aeronautics an Space Administration, Greenbelt, NASA Technical Memorandum 86083, April 1984.

Lindsey, G., *Space Surveillance and Canada*, Canadian Defence Quarterly, October 1991.

Mahoney, T., *An Overview of MILSATCOM Within the Australian Department of Defence, in* Mahoney, T., *Military Satellite Communications Course Notes*, Communications Division, Electronics Research Laboratory, Defence Science and Technology Organisation, Salisbury, South Australia, June 1991.

Mahoney, T., *Military Satellite Communications Course Notes*, Communications Division, Electronics Research Laboratory, Defence Science and Technology Organisation, Salisbury, South Australia, June 1991.

Maral, G. and Bousquet, M., *Satellite Communications Systems*, John Wiley and Sons, 1986.

Mason, AVM R., *Current Air Power Developments: A European View*, speech delivered at the *Conference on Air Power in the Defence of Australia*, Canberra, 14-18 July 1986.

May, J. and Van Zee,M., *Electro-Optic and Infrared Sensors*, Microwave Journal, September 1983.

Measures, R., *Laser Remote Sensing*, John Wiley and Sons, New York, 1984.

Morgan, W. and Gordon, G., *Communications Satellite Handbook*, John Wiley and Sons, New York, 1989.

Morse, R. et al, *Space Operations Orientation Handbook 2nd Edition*, 1013th Combat Crew Training Squadron, Air Force Space Command Operations, Peterson AFB, Colorado, 1 January 1991.

Morton, P., *Fire Across the Desert: Woomera and the Anglo-Australian Joint Project 1946-1980*, Commonwealth of Australia, 1989.

Nagler, R., et al, *Sensor Capability Handbook and Data Sheets, Volume 1*, Jet Propulsion Laboratory, Pasadena, California, July 1977.

NATO Team, *NAVSTAR GPS User Equipment: Introduction*, NAVSTAR GPS Joint Program Office, February 1991.

O'Neill, COL D., *An Australian Defence Satellite Communications Capabiliity*, p 21: Paper presented at the *Australia and Space* conference, Strategic and Defence Studies Centre, Australian National University, Canberra, 27-29 November 1991.

Parvey, C. and Walker, P., *Using ARIS to Evaluate Environmental Impact Assessment of Defence Facilities*, in: Walsh, B.J. (ed), *Information Systems: Assessing the Impact,* Proceedings of the 17th Australasian Conference in Urban and Regional Planning Information Systems, Perth, 1989.

Piotrowski, J.L., *Space Based Wide Area Surveillance*, Signal, May 1989.

Pratt, Brigadier General J., Media release, Defense Mapping Agency Public Affairs Office, Fairfax, VA, 25 March 1991.

Priebbenow R., *Cartographic Applications of SPOT Imagery: the Queensland Experience,* paper presented to the 7th Australian Cartographic Conference, Sydney, 1988.

Richelson, J., *America's Secret Eyes in Space*, Harper and Row, New York, 1990.

Richelson, J., *America's Secret Eyes in Space: The US Keyhole Spy Satellite Program*, Harper and Row, New York, 1990.

Richelson, J., *The Keyhole Satellite Programme*, Journal of Strategic Studies, Vol. 7, No. 2, June 1984.

Richelson, J., *US Space Reconnaissance After the Cold War*: Paper presented at the *Australia and Space* conference, Strategic and Defence Studies Centre, Australian National University, Canberra, 27-29 November 1991.

Roos, J., *SPOT Images Help Allies Hit Targets in Downtown Baghdad*, Armed Forces Journal International, May 1991.

Roseland, L. (ed), *Space: The Fourth Military Arena*, Air University, Maxwell AFB, Alabama, May 1986.

Satellite Jamming Design Considerations, Pt 1, Microwave Systems News & Communications Technology, September 1988.

Space Junk: Creating a Lethal Shell Around Earth, Genesis, Technology Development Corporation, Adelaide, South Australia, August 1991.

Space Systems Handbook for Staff Planners and Operators, US Space Command Centre for Aerospace Analysis, January 1988.

Specifications: US Spacecraft, Aviation Week and Space Technology, 19 March 1990.

SPOT User's Handbook, Vol.1, SPOT Image, Toulouse, 1988.

Starr, B., *Satellites Paved Way to Victory*, Jane's Defence Weekly, 9 March 1991

Stefanick, T., *The Nonacoustic Detection of Submarines*, Scientific American, Volume 258, Number 3, March 1988.

The Defence of Australia 1987, Department of Defence, Austalian Government Publishing Service, Canberra, 1987.

The Weather by Satellite, Bureau of Meteorology, Melbourne, 1990.

Wallis, SQNLDR S., *The NAVSTAR GPS Project Office*, GPS Project Office Brief, Material Division, Air Force Office, Department of Defence, 1991.

ANNEX A

LAUNCH VEHICLE DIRECTORY[1]

LAUNCH VEHICLE DIRECTORY

Launching satellites can best be described as a risky business but one with the potential, the companies detailed in this directory would maintain. It is probable that few listed are making a profit at present but there are signs of activity picking up.

While the military and those mainstays of the commercial communications satellite business — government-backed international agencies Inmarsat and Intelsat —continue to be the bedrock of the launcher-builders' business, recent contracts from regional operators suggest better times lie ahead.

COMPILED BY TIM FURNISS

Competition will be intense, however, and Atlas-builder General Dynamics (GD) has revised its profit forecasts to account for the commercial-launch aspirations of China, Japan and the Soviet Union.

So, too, does the USSR, although budget cuts are biting deep into the Soviet launcher industry. The European and Japanese launcher programmes have the full support of technology-conscious governments. Efforts in India, Iraq and Israel are still in their infancy.

Abbreviations used include: A50 Aerozine 50; GEO geostationary orbit; GTO geostationary transfer orbit; kerosene; LEO low-Earth orbit; LH liquid hydrogen; LOX liquid oxygen; HNO_2 nitric acid; N_2O_4 nitrogen tetroxide; MMH monomethyl hydrazine; Sun-synchronous orbit; UDMH unsymmetrical dimethyl hydrazine. ■

IN THIS DIRECTORY

Main picture *McDonnell Douglas Delta II launches a GPS.* **Clockwise from bottom left:** *ESA's Ariane 5, under development; the Soviet Energia, under test; and China's CZ-2C, on offer*

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[1] Furniss, T., *Launch Vehicle Directory*, Flight International, 17-23 April, 1991, pp 39-51.

AMROC

American Rocket Company, Flynn Road, Camarillo, California 93010, USA.

In 1985 AMROC became one of the first US private launcher organisations to attempt to enter the commercial market. It proposed an industrial launch vehicle (ILV) capable of placing 1,250kg into LEO, with later models reaching GTO. AMROC's innovation was to base the ILV on a single-module hybrid motor burning liquid oxygen and a hydrocarbon fuel and stacking 22 modules together in various combinations to form a four-stage satellite launcher. Agreement was reached with the US Air Force to launch from Vandenberg Air Force Base, California. Launches were to cost about $12 million.

As other private companies found, funding and customers proved elusive, and the company's aim became more modest. A single-module launch vehicle (SMLV) was proposed for initial suborbital missions, to be followed by three modules stacked together to form the TMLV. After this would come the ILV-S for orbital launches, before development began of the the 22-module ILV-1. The hybrid motor was test-fired successfully over 100 times, but setbacks occurred when AMROC chairman George Koopman was killed in a car crash and the first SMLV caught fire on its Vandenberg launch pad in 1989. No launches have been scheduled nor have any contracts been received.

Amroc was unsuccessful in its bid for the COMET launch contract in 1991 using a seven-module booster called Aurora and has launched a bid to use the ILV-S, renamed Aquila, to launch the proposed Motorola 77 Satellite Iridium network.

Arianespace

Arianespace, Boulevard de l'Europe, BP 177, 91006 Evry, France.

Arianespace was established in 1980 as the world's first commercial satellite launch vehicle organisation. France is the major shareholder with 56.65%, followed by West Germany with 18.65%. Arianespace's first operational commercial launch was the ninth Ariane mission, V9 in 1984, preceded by eight development and promotional flights under the auspices of the European Space Agency. ESA was responsible for the development of the launcher, which began in 1972 with 68% French backing.

The first Ariane launch vehicle took off from the Kourou launch base in French Guiana, South America, on 24 December, 1979, and was followed by three more test flights carrying ESA payloads, including Marecs 1A, which was leased to Inmarsat. A first-stage propulsion malfunction ended the second test flight. Four promotional missions followed, carrying "commercial" customers. The first of these, LO5, failed on 10 September, 1982, because of a third-stage malfunction and resulted in the loss of Marecs 1B. Three major satellites were launched, including two for Intelsat, before Arianespace assumed control for V9 on 22 May, 1984.

When the *Challenger* accident ended the Shuttle's commercial career in 1986, Arianespace had a virtual monopoly, despite the failures of V15 and V18 in 1985-6, a result of third-stage malfunctions; operations resumed in September 1987 after the third stage had been modified. By this time the three competitive US launcher companies had started business.

On 15 June, 1988, Arianespace launched the first Ariane 4 booster. This is intended to be the workhorse of the 1990s, providing a fleet of six models with differing launch capabilities. Fifty of the type were ordered in February 1989. The final Ariane 2 flew in April 1989 and the final Ariane 3 the following July. By February 1990 there had been 35 Ariane missions, with four failures, including the nine development and promotional missions of which two were commercial failures. The Ariane 4 had made seven flights, and a total of 40 commercial satellites had been launched since V9. From September 1987 there were 17 consecutive flawless missions, but this run ended when V36 failed in February 1990 because of two first-stage malfunctions. Operations were resumed successfully in late July with the launch of V37 which was followed by five more successes to March 1991.

A dedicated Ariane launch costs between $65 million and $95 million, depending on the Ariane version required. Sub-satellite and mini-satellite launcher services are available using the Spelda Dedicated Satellite Service (SDS) and the Ariane Structure for Auxillary Payloads (ASAP). The company expects to capture about half the world's annual market of 20 to 25 commercial and government satellites, although analysts predict only a quarter share if the US ELV companies make a major impact. Pad ELA 2 is used for launches from Kourou. Initial marketing has begun of the new Ariane 5 vehicle, under development by ESA.

On 26 March, 1990, there were 34 satellites outstanding in the orderbook. Payloads contracted, or expected to be confirmed and not yet scheduled for launch, are: Astra 1C and 1D; Brasilsats 1 and 2; MOP3; Spot 3; Telecom 2B; Topex; Satcom C4; Galaxy IV and VII; Intelsat VII F1, F4 and F5; Insat II A and B; Hispasat 1A and 1B; ISO; Locstar F1 and F2; Helios; Eutelsat IIF5; Turksat 1 and 2; PSDE-Sat 1; ATT 1. Later launches of Artemis and DRS are expected to be confirmed.

Future/planned models: Slightly uprated third-stage performance of 44L may increase payload capability, with a design goal of 4,400kg for an Ariane 44L launch in mid-1992. See ESA — Ariane 5.

US DoD

Department of Defense, The Pentagon, Washington DC, USA.

After the 1986 *Challenger* accident, which strengthened doubts about the capability of the Space Shuttle in the late 1990s, the USAF initiated a programme to develop an unmanned satellite launcher. It is to be capable of placing up to 72t into LEO by 2005, at one-tenth of the cost of current vehicles, the largest of which is the Titan IV. The first launch was set for 1996, but this no longer seems likely.

Teaming with NASA, the DoD started a system design study in 1987, awarding $5 million contracts each to seven leading launcher development companies. Three Phase 2 contracts were awarded in 1988 to General Dynamics, Martin Marietta-McDonnell Douglas and Boeing. General Dynamics favours an all-cryogenic booster with tandem boost stages which could be recoverable; Boeing's concept is similar. The Martin Marietta-McDonnell Douglas approach involves various configurations of all-expendable upper stages with cryogenic fly-back boosters.

Running concurrently with the Phase 2 design contracts, engine component design contracts were awarded to Aerojet, Pratt & Whitney and Rocketdyne. In August the DoD-USAF-NASA ALS team announced that the new launcher's engines would be conventional gas-generator power-cycle designs. The three engine companies also said that they planned a teaming agreement to reduce programme risk and cost. The final ALS concept could be decided for Phase 3 by 1991, following studies of the final Phase 2 designs at the end of 1990 although budgetary restraint may slow the pace of the projected development plan.

EER Systems

EER Sysytems Corporation, 1593 Spring Hill Road, Vienna, Virginia, 22182-2245, USA

One of the first privately funded US small satellite launcher companies, Space Services was established in 1980. It has yet to receive its first satellite launch contract. By 1990 just three Starfire suborbital commercial launches had taken place, one of which failed. The proposed Conestoga satellite launcher remained on the drawing board. It has undergone several redesigns over the past ten years. The first vehicle was to have been liquid-fuelled, and its Percheron first stage made a maiden flight off the Texas coast on 12 August, 1981, but exploded. An all-solid-propellant Conestoga was then designed; its proposed first stage, based on a Minuteman 1 second-stage motor and called Conestoga 1, was launched successfully on a suborbital, 313km-altitude flight on 9 September, 1982. Several rather tenuous launch agreements were made, and Space Services even signed an agreement with NASA to launch out of Wallops Island.

In 1991, however, the company was taken over by EER Systems and its fortune changed, with Conestoga being chosen as the COMET spacecraft launch vehicle. scheduled for September 1992.

Future/planned models: Conestogas 3 and 4 would be Conestoga 2s with four and six strap-on boosters respectively.

E Prime

E Prime Aerospace, PO Box 792, Titusville, Florida 32781, USA.

E Prime is one of several companies which attempted to enter the commercial US satellite launcher market in the 1980s, aiming to provide a service to smaller users requiring access to low Earth orbit. Bold plans for orbital launchers had to be modified in the light of a shortage of customers, and E Prime has lowered its sights to suborbital rockets.

Three Astra sounding rockets are being marketed. Loft 1 flew the first US commercial mission from Cape Canaveral in November 1988. Further launches have not taken place. E Prime hopes to follow these A-class rockets with a flexible fleet of Astra B satellite launch vehicles, based on a combination of solid-propellant stages from the Peacekeeper missile. Orbital launches costing about $30 million could take place from the old Saturn 1B Pad 37 at Cape Canaveral. No Astra B launches have taken place or are scheduled, nor have any launch contracts been received. GTO launches may be possible with the addition of a liquid-propellant upper stage.

ESA

European Space Agency, 8-10 Rue Mario-Nikas, 75738 Paris 15, France.

The European Space Agency (ESA)-developed Ariane satellite launcher was well established in commercial operations with Arianespace in 1985 when the Agency initiated the Ariane 5 project. Intended to take over from the Ariane 4 in the competitive market predicted for the later 1990s, Ariane 5 was also earmarked as the launch vehicle for France's proposed Hermes spaceplane. Launcher studies continued until November 1987, when the Ariane 5 project secured approval from most ESA member countries. The vehicle has to be uprated twice to meet Hennes requirements, although ESA is keen to emphasise that Ariane 5 is not being developed uniquely as the Hermes launcher.

Ariane 5 could make its first flight in 1995 and in 1996 will be assigned to Arianespace to meet the commercial role, providing up to eight launches a year. Its Hermes launcher role will begin in about 1998, but, once the first manned test flight has been completed (1999 at the earliest), it will be needed to loft the spaceplane just twice a year. In 1993-4, Arianespace has begun initial marketing of the new vehicle. Launches will be from Kourou's new pad ELA 3.

General Dynamics

General Dynamics Commercial Launch Services, San Diego, California 92138, USA.

The Atlas intercontinental ballistic missile (ICBM) was successfully tested on 17 December, 1957, after one earlier failure. As well as having an operational role from 1959 to 1965, it was used as a USAF and NASA space launcher on its own and with upper stages, including Agena and Centaur. Gradually uprated during its long service, 497 had been launched by March 1991. The latest version is Atlas I.

Only seven Atlas E space launchers remain. The type will be replaced later in the 1990s by the refurbished retired Titan II ICBMs. Three Atlas Es will be used to launch NOAA satellites and the others are available for DoD launches, which are by no means certain, since the Titan took over the DMSP launch role easier than planned. Launches are made down the Western Test Range from pads SLC-3 E and W at Vandenberg AFB. A new Atlas J may complement the Titan II in the 1990s, derived from the first stage of the new Atlas II, itself based on the Atlas Centaur.

The Atlas-Centaur combination first flew on 8 May, 1962, from Cape Canaveral and was a spectacular failure. There have been 69 Atlas-Centaur flights, eight of which were development missions and 58 were successful. The last of these was the CRRES booster mission on 25 July, 1990. The Atlas Centaur first stage has been gradually upgraded, and the latest vehicle used an Atlas I.

Like the other major expendable launch vehicle companies in the USA, General Dynamics' attempts to enter the commercial market in the mid-1980s were thwarted by the Shuttle monopoly. After the *Challenger* accident in 1986 and its failure to win the USAF Medium Launch Vehicle (MLV I) contract, GD made a bold $100 million investment the following year to produce 18 new Atlas Centaur vehicles for the commercial market, known as the Atlas I.

GD secured a $440 million USAF contract in 1988 to produce 11 MLV II vehicles, to launch the DSCS III communications satellites. The MLV II became known as the Atlas II and incorporates an upgraded first stage. General Dynamics is able to offer this vehicle as well as the Atlas I commercially, in addition to MLV II upgrades called the Atlas IIA and IIAS.

Hughes has contracted GD to launch up to ten follow-on Fltsatcom UHF satellites. Of the 60 Atlas vehicles in production, 13 are Atlas Is.

Thirty-seven Atlas launches are committed; the formal contract for two of these has still to be confirmed. The commercial career of the Atlas began with the launch on 25 July, 1990, of the NASA CRRES science satellite. The other payloads are: one Eutelsat, three GOES, two Galaxy, 11 MLV DSCS, Intelsat K, ten US Navy UHF satellites, SAX, two Intelsat VII, SOHO, two Orion, two Telstar 4 and the BS-3H for Japan. Options remain for further GOES, Eutelsat and Intelsat VII launches and the company is understood to be the only bidder for the launch of two US-Canadian M-SATs.

Launches from Pads 36A and B at Cape Canaveral will be at the rate of four a year from each pad, once the $30 million refurbishment of 36A is complete. The only operational pad until early 1991, 36B will be considered the commercial pad, while 36A will be used for military as well as for commercial customer launches. Competing mainly with Ariane, which can carry more than one satellite per launch, GD is promoting single-satellite launches which it believes offer greater schedule assistance to customers. The cost is approximately $60 million.

Despite its apparent success, the company has run into finanical difficulties and has had to wite off $300 million investment costs in the Atlas launcher programme.

Future/planned models: Atlas J, based on the first stage of the Atlas II, with or without thrust augmentation as used on the Atlas IIAS, may be available for DoD launches and could be offered commercially for polar and LEO flights. With four strap-on boosters and a perigee motor-equipped satellite, 1,900kg could be placed into GTO.

Glavkosmos

Glavkosmos, 9 Krasnoproletarskya, 103030 Moscow, USSR.

In 1985 Soviet civilian space agency Glavkosmos and trade organisation Licensintorg offered the Proton launcher for satellite delivery directly into geostationary orbit. Despite offering flights for about $30 million — one-third the price charged by some competitors — the Soviets had difficulty in overcoming Western reluctance to transfer technological expertise on expensive communications satellites. No contracts have resulted although Proton may be chosen to launch one of the new Inmarsat 3s as the Soviet Union is a member of the organisation.

There have been three models of the Proton: the SL-9 flew four times on demonstration flights in 1965 and 1966; the SL-13 first flew in 1968 and is used to carry Mir modules; and the SL-12 four-stager is used for flights to GEO and beyond. The latter is offered commercially at $35 million for flights to GEO, $28 million for GTO missions, $12 million for dual launches and $8 million with three satellites. The SL-13 is available for launches of large remote-sensing platforms or other payloads in the 20t class, for which the market is limited. A cost of about £20 million has been quoted.

In 1987 the Soviets added five more satellite launchers to the commercial inventory. Based on the first Soviet ICBM, the 1957 Sapwood, the Vostok SL-3 first flew in 1959 and is offered for LEO launches. One semi-commercial contract was to launch the first Indian IRS satellite in 1988. The second IRS is slated for a fully commercial mission in 1991 to be followed by the IRS 3. The Soyuz SL-4 (first flight 1963) and Molniya SL-6 (first flight 1961) — also based on the Sapwood ICBM — are available for higher orbital altitudes. All three are available for launches from either Baikonur or Plesetsk. The Cosmos SL-8 booster, first launched in 1962, is available for smaller satellite payloads for launches from Plesetsk (or possibly Kapustin Yar, a site near the Volga River last used five years ago). The three-stage Tsyklon SL-14, which first flew in 1977, is available for Plesetsk launches; the two-stage SL-11, first launched in 1966, is not on the commercial list, however.

Another booster, the Zenit SL-16 medium-lift vehicle (first flight 1985) was added to the commercial inventory in 1989 to provide for larger, 15t-class payloads. Launches are from Baikonur where the Zenit exploded soon after launch on 4 October, 1990. The Zenit has been associated with a bid by a consortium to market a proposed Cape York launch site in Queensland, Australia. Launches to GTO would match the capability of the Proton from Baikonur with an uprated version. The other Soviet booster, the Energia SL-17 (first flight 1987), is not yet commercially available.

Huge engines power the Soviet Energia

The first operational Indian Insat II may be launched on a Proton. The Vostok may gain a few more contracts for small LEO payloads, but the Western market for LEO launches is rather small. Launcher services are marketed in the USA by Space Commerce.

Future/planned models: Energia boosters with six to eight strap-on boosters and enhanced payload carrier engines, including a cryogenic upper stage, and a Soviet version of the US unmanned Shuttle C are planned, but no firm details have been announced.

A smaller Energia is also being planned and a vehicle-model has already been checked out at Baikonur. An enhanced Proton is also on the drawing board, which could increase GTO capability by 2.2 tonnes.

Great Wall Industry

Great Wall Industry Corporation, PO Box 847, Wen Chang Hutong Xidan, Beijing, People's Republic of China.

China's space programme began in the mid-1960s with development of the Long March national satellite launcher. This launched China 1 on 24 April, 1970, and was followed by the Long March 2, first launched in 1974. Ten years later the first Long March 3 geostationary satellite launcher made its maiden flight. In 1988 the Long March 4 was introduced, and in 1990 the Long March 2E made the 27th Chinese satellite launch. The payloads have included test satellites, recoverable remote-sensing spacecraft (some of which have carried piggyback commercial microgravity payloads), national test and operational geostationary communications satellites, polar orbiting meteorological satellites, a small test satellite from Pakistan, and Asiasat 1 — the first Chinese commercial satellite launch, which took place on a Long March 3 on 7 April, 1990.

China's entry into the commercial arena in 1985 was handicapped by technology transfer issues and what the West saw as unfair pricing. Great Wall's definitive list of launchers being flown or developed and available commercially: Long March 1D, 2C, 2E, 3, 3A and 4. Of these, the 2C, 2E, 3 and 4 have flown and two are uprated versions of already-flown vehicles. The 1D will become available in 1991 and the 3A in 1992.

China has won four commercial satellite launch contracts. The former Westar 6 Hughes communications satellite, which became Asiasat 1, was launched on a Long March 3 in 1990 only after the White House waived restrictions on the export of US technology. A similar waiver will be required to give the final go-ahead to the launch of the two Hughes-built Aussat B satellites in 1991 and 1992 aboard Long March 2Es. A Swedish technology satellite called Freja may also be launched on a Long March 4. The launch of Arabsat 1C on a Long March 3 and of Indonesia's Palapa B4 are still being negotiated.

International Satellite Communications (INSCOM) is a new joint venture between China and Brazil, formed in 1989 to market Long March vehicles as part of its services. Two Sino-Brazilian satellites may also be launched in 1992/4, but Brazilian budget restraint is likely to delay these projects considerably.

China operates from Xichang, Jiuquan and Taiyuan launch centres. Long March boosters are designated CZ (for Chang Zheng) and are referred to as such in the tables.

Future/planned versions: A version of the CZ-1D, known as CZ-1M, will be made available. Equipped with a new third stage, comprising the Italian 66kN-thrust, solid-propellant IRIS motor with 79s burn time, it would launch from Jiuquan 900kg to 57°, 300km; 830kg to 70°, 300km; 450kg to 99°, Sun-synchronous, 903km.

The CZ-2C's capability could be uprated with a solid-propellant upper kick stage to lift 500kg to high elliptical orbit at 63°. A CZ-2D is a possible variant equipped with a stretched second stage and US McDonnell Douglas PAM-D upper stage for launches to GTO of 1,250kg from Xichang.

A suggested eight attached booster CZ-2E could place 13,000kg into LEO.

A CZ-3A-4L has been announced by Great Wall. This is essentially a CZ-2E with the CZ-3A third stage, which could place 4,500 to GTO and between 4,500kg and 5,500kg to the Moon and planets fro 1995.

ISRO

Indian Space Research Organisation, Bangalore, India.

India's aims for a fully autonomous unmanned satellite and launcher capability have been thwarted recently by the failures of two launches of the Augmented Satellite Launch Vehicle (ASLV). This is a thrust-augmented version of the Satellite Launch Vehicle (SLV) which placed Rohini 1 into orbit on 18 July, 1980. Two successful SLV launches followed. Although India successfully developed its own Insat meteorological/communications satellites and the IRS remote-sensing spacecraft, launched by the USA and USSR respectively, progress with launcher development was slow.

The ASLV will increase LEO capacity from the SLV's modest 40kg to 150kg. A Polar Satellite Launch Vehicle (PSLV), incorporating India's first liquid-propellant engine, may fly in 1991. A further attempt is to be made at an ASLV launch, and the proposed Geostationary Satellite Launch Vehicle (GSLV) is expected to follow much later than planned originally. India had hoped to develop the GSLV in time to launch its pre-operational Insat II fleet, but these are now being carried by Arianespace and a later one on a Soviet Proton. There are no plans to go commercial. India launches satellites from Sriharikota Island off Andhra Pradesh.

Future/planned models: The three-stage GSLV could comprise a first stage made up of three stretched PSLV core stage-boosters, a stretched PSLV second stage with Vikas engine and a liquid-motor third stage. A second version could replace the PSLV second stage with a cryogenic second stage. Capability could be 2,000kg to GTO or Sun-synchronous orbit. Uprated versions could increase this to 5,000kg to GTO by the late 1990s.

ISAS

Institute of Space and Astronautical Science, 3-1-1
Yoshinodai, Kanagawaken 229, Sagamihara-shi, Japan.

Japan divides its space programme responsibilities between ISAS (science) and NASDA (applications) ISAS was the first agency to place satellites into orbit, making Japan a space nation on 11 February, 1970. This followed four launch failures between 1966 and 1970. The solid-propellant booster used at that time was the Lambda 4S, which has gradually been uprated through M4S, M3C, M3H and M3S versions to the present M3SII. This model has launched five of ISAS' 19 spacecraft, including two Halley's Comet probes and, in 1990, Muses — the first spacecraft to be sent to the Moon since 1976. The M3SII will be uprated to make it more powerful. Launches, from Kagoshima, are restricted by the Japanese fishing industry to January-February and August-September each year. There are no plans to go commercial.

Future/planned versions: ISAS plans to develop the M5 uprated solid-propellant booster for launches in 1995. It will place 2,000kg into LEO and could be used for planetary missions, including a new flight to the moon. It is 30m tall, weighs 115 tonnes and will cost $135 million to develop.

IAE

Instituto de Actividades Espaciais, Caixa Postale 6001,
CEP 12225 So José dos Campos, So Paulo, Brazil.

IAE, the Institute of Space Activities, is one of two national space agencies in Brazil. The other, Instituto Nacional de Pesquisas Espaciais (INPE), is concerned with research. IAE intends to develop a satellite launch vehicle, Veiculo Lançador de Satelites (VLS), based on the successful national Sonda 4 suborbital sounding research rocket. Sonda 1 was introduced in 1964 and Sonda 4 in 1984.

Brazil is planning a series of remote-sensing and digital communications satellites as part of an autonomous space programme, Misso Espacial Completa Brasiliera (MECB). INPE has joined forces with China to establish International Satellite Communications (INSCOM) to market the VLS or Long March boosters and associated space services, primarily to developing countries. INSCOM is involved in the development of a Sino-Brazilian remote-sensing satellite (CBERS) to be launched by China. The VLS, which was to have made its maiden flight in 1988/9, has not yet appeared. When it does, it will be launched from Alcantara equatorial base. As a result of a Sino-Brazilian agreement, this could be a base for Long March boosters. Budgetary restarint is likely to delay or even cancel these programmes.

Iraq

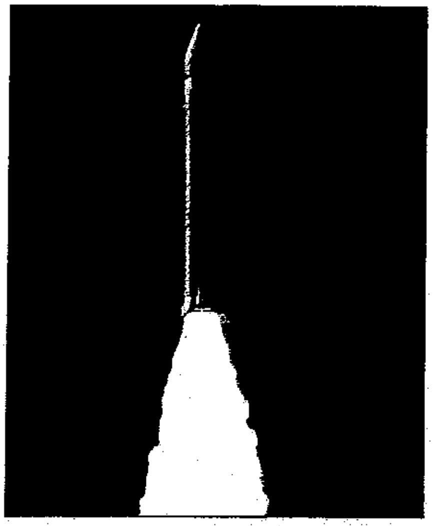
Iraq Industry and Military Industrialisation Ministry,
Baghdad, Iraq.

On 7 December, 1989, Iraq announced that it had test-fired two days earlier a potential satellite launch vehicle called Al Abid. The launch was said to have been from the Al Anbar space centre, 48km south of Baghdad. Western analysts have doubted the accuracy of the Iraqi announcement, but the country has given some details of a planned satellite launch vehicle.

Israel Space Agency

Israel Space Agency, PO Box 17185, 26A University
Street, Ramat-Aviv, 61171 Tel Aviv, Israel.

The Jericho 2 ballistic missile was developed using French technology based on the Dassault MD660 missile. It was built by Rafael and Israel Aircraft Industries. It made its first flight in May 1988, flying 1,400km across the Mediterranean Sea. This missile was converted for space use as the Shavit to launch small Offeq demonstration satellites for the Israel Space Agency. Larger astronomical and science satellites may follow.



Israel enters the space age with Shavit

LTV

LTV Missiles and Electronics Group, PO Box 650003,
Dallas, Texas 75265-003, USA.

In 1958, NASA awarded Chance Vought a contract to develop a four-stage solid-propellant satellite launcher capable of placing about 60kg into LEO. This vehicle, the Scout, made its first flight on 1 July, 1960. Sixteen versions of the booster were developed and flew 100 missions to 2 June, 1979, with 14 failures. The current Scout version, the G-1, was first launched on 30 October, 1979. Launches are made from pad SLC-5 at Vandenberg AFB, Launch Area 3 at Wallops Island, Virginia, and the Italian San Marco offshore platform in Formosa Bay, Kenya.

LTV has not offered Scout commercially but has joined with Italian company SNIA-BPD to develop the Scout 2, also called San Marco, for commercial operations. Launches will chiefly be from the San Marco platform for recoverable microgravity missions such as the proposed Italian Carina capsule.

Future/planned models: A Scout 3 with four strap-on boosters has been suggested.

Martin Marietta

Martin Marietta Space Launch Systems, PO Box 179,
Denver, Colorado 80201, USA.
Martin Marietta Commercial Titan, PO Box 179, Denver,
Colorado 80201, USA.

Martin Marietta Space Launch Systems provides Titan II and Titan IV launch vehicles for the USAF Space Systems Division. The first Titan II ICBM was test-flown on 16 March, 1962. A further 80 launches followed until the fleet was de-activated in 1982, by which time 140 ICBMs had been built. Twelve Titan II vehicles also carried Gemini spacecraft into orbit, ten of them manned, between 1964 and 1966, with a 100% success record. The Titan II also provided the first two stages of a family of Titan multi-stage launchers, from the Titan IIIA to the latest member of the fleet, the Titan IV.

In 1987 the final Titan ICBM was removed from its silo as Martin Marietta was working on a $483 million contract to refurbish up to 15 of 56 de-activated ICBMs as space launchers. The first refurbished Titan II flew in 1988 from a modified pad, SLC-4W, at Vandenberg AFB. Future launches of the remaining fleet of 15 are planned to continue to 1995, when further refurbished boosters may be required. The Titan II is relieving the Atlas E of the role to orbit USAF DMSP weather satellites in addition to flying other DoD satellites. There are no plans to commercialise the launcher, although it will fly NOAA satellites for the Department of Commerce and Landsat 6 for EOSAT. One of the refurbished boosters will be uprated, with strap-on boosters developed for the Strategic Defense Initiative Office (SDIO) which may result in a new version of the Titan II.

In 1985 the USAF, mindful of the Shuttle's inability to satisfy all its needs, ordered ten Complementary Expendable Launch Vehicles (CELVs) from Martin Marietta. Called the Titan IV, this was an uprated version of the Titan 34D which was still flying at the time. The order was progressively increased, particularly after the *Challenger* accident, and stands at 41, with an option for eight more. Four have already been launched, the first on 24 June, 1989. Titan IV is designed to carry Shuttle-class payloads, such as the KH-12 and Lacrosse reconnaissance, electronic-intelligence, DSP and communications satellites. There are five versions: one has an IUS upper stage, one (which has not yet flown) has the Centaur G upper stage originally designed to fly the Shuttle, and three versions which do not employ upper stages. Launches of the Titan IV-Centaur version have been delayed by the need to strengthen the payload-upper stage interface, which is subjected to higher flight stress than anticipated.

Launches are from Cape Canaveral's Pad 41 with orbital inclinations limited officially to 57°; although one Titan IV reached a 62° orbit. Pad 40 is the Commercial Titan (formerly the Titan 34D) base and is being refurbished to fly Titan IVs as well. At Vandenberg, the IUS-Titan IV version made its first flight from SLC-4E on 8 March, 1991 and the Centaur G version will fly from SLC-6 — the former Space Shuttle pad which was never used and which is set to be refurbished for the Titan IV. Launches from Vandenberg into polar orbit are now possible. Ten launches a year from both launch sites are expected by 1995.

An uprated Titan IV version is planned with Hercules Aerospace solid-rocket boosters. The Titan IV is tentatively programmed to launch planetary spacecraft for NASA.

Future/planned models: Versions of a Titan IIS with upper stages such as a Star 37, 48 or 63 could be introduced to increase polar-orbit/Sun-synchronous orbit capacity for the basic Titan II or Titan S and even provide GTO capability from Cape Canaveral, although a pad would have to be refurbished to accommodate a vehicle. The Titan II S version with strap-on boosters could also be made available to other agencies and commercially.

Hybrid versions of the Titan IV-Centaur with Hercules strap-ons, using different upper stages, and launches by Titan IVs with no upper stages, are possible.

After the 1986 *Challenger* accident, and having considered marketing its Titan 34D military space booster as a commercial launch vehicle, Martin Marietta announced that the Titan would be available from 1989 and known as Commercial Titan. The major difference from the 34D was to be a new-style payload fairing suplied by Contraves. Initial marketing of the vehicle placed emphasis on its versatility as a single- or dual-launch vehicle with a range of satellite upper stages from the Pam D to the IUS and TOS.

The company received five commercial launch contracts. Skynet 4A and JC Sat 2 were launched together on the first and only dual-satellite Commercial Titan on 31 December, 1989. Martin Marietta decided to market single-satellite launches only in the future. The second launch, of an Intelsat VI in 1990, failed to separate the satellite, but another Intelsat VI was launched successfully later that year. The fifth contract is from NASA to launch Mars Observer in 1992, which will the refurbished Pad 40 at Cape Canaveral.

The Titan 34D was the latest in a series of thrust-augmented Titan II boosters, starting with the Titan IIIC in 1965 and was introduced in 1982. It flew 15 times with two failures to 4 September, 1989. Together with the Commercial Titan launches so far, there have been 144 launches of the Titan III-class booster, with 137 successes. A Commercial Titan launch costs between $100 million and $125 million. Intelsat paid $115 million for an Intelsat VI launch.

McDonnell Douglas

McDonnell Douglas Commercial Delta, Space Systems Division, 5301 Bolsa Avenue, Huntington Beach, California, USA.

The Delta launch vehicle, based on the Thor intermediate-range ballistic missile (IRBM), first flew on 13 May, 1960. This unsuccessful mission was followed by the successful ascent to orbit of the 62kg Echo 1B balloon satellite the following August. As NASA's medium-class workhorse, Delta underwent 12 major upgrades, from 1964's then-innovative strap-on booster for thrust augmentation up to Delta 3920/25 in 1982. The present Delta II fleet was introduced in 1989.

By March 1991, 203 Delta launches had been recorded, with 12 failures, from Pad SLC-2W at Vandenberg AFB down the Western Test Range, and from Launch Complex 17's Pads A and B at Cape Canaveral down the Eastern Test Range. The last launch failure occurred in May 1986, since when there have been 20 straight successes. Of these, 14 were by the new Interim Delta II, including two by the Delta 6920 two-stage version and ten by the Delta 6925 three-stage model and three by the fully-fledged Delta II 7925. The final non-Delta II-class booster carried India's Insat 1D into orbit on 12 June, 1990.

The Commercial Space Act of 1984 encouraged McDonnell Douglas to enter the commercial launcher market, through a company called Transpace. The Arianespace-Shuttle commercial duopoly gave the Delta little chance. After the withdrawal of the Shuttle from the commercial launcher market in 1986, McDonnell Douglas itself began marketing the Delta. Production costs were underwritten by a $669 million contract from the USAF for 20 MLV 1 medium launch vehicles — the Interim Delta II 6925 and 7925 — to launch Block IIA and IIB satellites. McDonnell Douglas' first all-up commmercial satellite launch took place on 27 August, 1989, carrying BSB's Marcopolo 1 into GTO on a modified Delta 4925 booster. A Delta launch is thought to cost about $50 million.

Including the GPS launch contracts, McDonnell Douglas has received 37 "commercial" launch commitments. Already launched have been: nine Block IIA and one Block IIB GPS, three SDIO payloads, Cobe and Rosat for NASA, and Marcopolo 1 and 2 Inmarstas 2F1 and 2, NATO IV A and Palapa B2R. Launches to be made are: eight GPS; and for commercial-sector customers: NATO IVB, Contel-ASC 2, Aurora and Satcom C-3. EUVE, Geotail, Wind and Polar are to be launched for NASA, whose contract with McDonnell Douglas includes options for a further 12 science satellite launches to 1997.

Plans for a Delta III, with a cryogenic second stage, and widebodied and double-barrel versions which would to match General Dynamics' Atlas II launch capability appear to have been dropped. Launches from two pads, 17A and 17B at Cape Canaveral, are at a rate of 12 a year and can theoretically be made within seven days.

Eleven launches took place in 1990 and ten were planned for 1991 before dalays to the Navstar Block IIB fleet. Cape Canaveral Pads 17A and 17B have been modified to accommodate the 4.2m-taller Delta IIs. Pad SLC-2W at Vandenberg is also being modified to launch the Delta II.

Future/planned models: McDonnell Douglas has released details of possible but as-yet uncommitted upgrades. A Delta III 7930/7935 would have a cryogenic Pratt & Whitney Centaur second stage, larger payload fairing and enlarged first-stage fuel tank. Widebody and double-barrel, cryogenic and storable-propellant versions, with two first-stage engines strapped together and 12 GEMs, are planned. These would increase LEO and GTO capability to 6,660-9,820kg and 2,635-3,636kg respectively. Initial development and marketing of the Delta III has begun.

NASA

National Aeronautics and Sp ace Administration, Maryland Avenue SW, Washington DC 20025, USA.

The Space Shuttle reusable manned satellite delivery vehicle/space laboratory was authorised by President Nixon in 1972. It was to be capable of making up to 100 flights a year, "routinising" space operations. At a price of $5 billion per vehicle, its cost was to have been one-fifth of Project Apollo's. Technical compromises had to be made from the beginning. The intended totally reusable system was made part-expendable and liquid boosters were dropped in favour of cheaper solid-rocket boosters. The first manned orbital flight, by orbiter *Columbia*, did not take place until 12 April, 1981.

The four test missions were followed by STS 5, the first commercial Shuttle satellite mission in November 1982. The *Challenger* accident on the 25th mission on 28 January, 1986, led to Shuttle being pulled out of the commercial trucking business. The DoD —once the predicted major user of the Shuttle, its *raison d'être* and its main design influence — pulled out as a major user. Shuttle's current manifest reflects more its unique capabilities.

STS 26 *Discovery* resumed Shuttle operations on 29 September, 1988, following several major redesigns in systems. In 1989 there were just five missions and, although several more were scheduled for 1990, only three had taken place before the whole fleet was grounded in July 1990 when hydrogen leak problems were discovered. NASA then proceeded to launch three missions in 57 days — a record — in late 1990 but further technical problems delayed the first 1991 mission to April *Challenger*'s replacement, *Endeavour*, will be delivered in 1991 and will make its maiden spaceflight in 1992.

In the 37 space missions flown from April 1981 to March 1991, 32 operational Space Shuttles had deployed over 38 satellites and three planetary spacecraft, carried five Spacelab science missions, conducted seven classified DoD missions, operated several dozen scientific and commercial experiments, repaired and redeployed two satellites and returned three to Earth.

The Shuttle will be flying well into the 21st century, and several new orbiters will be required as first *Columbia* will be retired. The future of the programme is not assured however, since the recent Augustine Committee report urged its replacement. The original objective of 100 missions before major refurbishment will never be achieved. New liquid-fuelled boosters could be introduced in about 1996 to replace the SRBs, while the Morton Thiokol SRBs themselves will be replaced by Lockheed ARSMs in 1994.

Launches are made from Pads 39A and B at the Kennedy Space Center (26 and nine launches respectively). Plans to use Vandenberg from 1986 were scrapped. There have been six Kennedy Space Center landings, the latest by STS 38/Atlantis in November 1990 after a hiatus of five years. One landing was made at White Sands, and 30 at Edwards AFB. *Columbia* has made ten missions, *Discovery* eleven and *Atlantis* seven; *Challenger* was on its tenth planned mission when it broke apart at T+73s. The longest mission lasted nearly 11 days. Missions of 16 days or longer may be possible after 1992 when a new fuel-cell-based flight-extension package is introduced. As well as Spacelab missions which allow work in a pressurised module in the payload bay, a mid-deck extension module, called Spacehab, is also planned.

Future/planned models: NASA has studied designs of a Shuttle 2, but no funding for it has been approved. An unmanned Shuttle C cargo vehicle, with the orbiter being replaced by a cargo pod resembling the payload bay and powered by two SSMEs, has been proposed and a funded design phase is taking place. This could carry 55t to 400km orbit from the Kennedy Space Center by 1995. With three SSMEs the payload capability could increase to 70t. It has been suggested that a Shuttle C, either a non-recoverable or partly reusable system, could serve as an Interim ALS.

NASDA

National Space Development Agency, World Trade Centre Building, 4-1 Hammamatsu-cho 2-chome, Minato-ku, Tokyo 105, Japan.

NASDA was established in 1969 and has, since 8 September, 1975, launched 20 applications satellites and experienced one failure. Its N-I, N-II and H-I boosters are based on the McDonnell Douglas Delta first stage and Morton Thiokol solid-rocket boosters, built under licence in Japan. The final N-II was launched in 1986 and the first of nine planned H-I launches was on 27 August, 1987. The H-I utilises Japan's first cryogenic stage, the LE5. Technology experience has led to the development of the LE7 cryogenic first stage of the first totally indigenous liquid-propelled, large national launch vehicle, the H-II. Scheduled to fly in 1992, the H-II has been delayed by several problems with the LE7, which has caught fire in firing tests. The first launch could be put back to 1994. There are no plans to commercialise the H-II, and initial speculative forays into the market are being made by a Mitsubishi-based consortium called Rocket Systems. The delays to the H-II and the limitation of launches form Tanegashima to January-February and August-September windows are disadvantages if the H-II is being considered commercially.

Future/planned models: NASDA says that 15,000kg to LEO capability could be achieved with a six-booster version or the H-II. Replacing the existing two solid boosters with LE7-powered boosters could produce a capability of 24,000kg to LEO.

OSC/Hercules

Orbital Sciences/Hercules Aerospace, 12500 Fair Lakes Circle, Fairfax, Virginia 22033, USA.

In April 1987 OSC joined forces with Hercules Aerospace in a $60 million venture to develop the Pegasus air-launched satellite launcher. Within three years a successful first flight had taken place. Pegasus is based on solid-propellant motors used for the Trident and Pershing missiles and was developed with the help of a DARPA contract to launch small research and development satellites. Up to six launches were covered at a cost of $6.5 million per launch. Two of these launches have been subcontracted to the USAF.

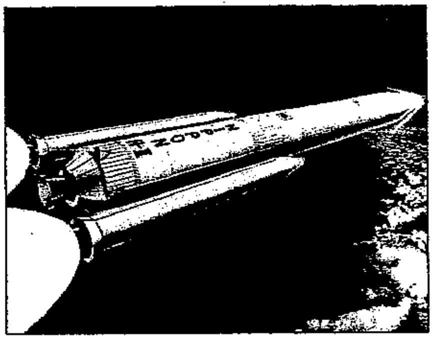
Pegasus has also been offered to the SDIO, NASA and commercial customers at $4.5 million per launch. Ball Aerospace has made two launch reservation agreements for small communications satellites and Sweden has made a firm reservation for the launch of Freja. The OSC-Virginia Center for Innovative Technology DataSats are also potential payloads for Pegasus launches.

OSC plans to launch its Orbcomm Lightsats on Pegasus, which is also to launch the US Air Force's APEX satellite. Pegasus has also received a contract from NASA for seven launches with three options as part of the Small ELV programme (SELV).

An uprated Pegasus has been proposed, while a ground-launched vehicle based on Peacekeeper missile stages, Taurus, is being developed under a Small Satellite Launch Vehicle contract from DARPA. A first launch has been set for 1992. This could also be offered commercially and may be used to launch some larger Ball Aerospace satellites into geostationary orbit. Taurus will launch Seastar. Pegasus launches are made from NASA's B-52 mother aircraft over the Pacific Ocean after take-off from Edwards AFB. Taurus can be launched from Vandenberg and Cape Canaveral.

Future/planned models: Uprated versions of Pegasus are planned. The first will incorporate lighter materials, improved performance and larger payload fairing. A version with a fourth stage could place 200kg into GEO.

Japan is developing the H-II



MANUFACTURER/Booster	Stage	Engine	Propellants	Thrust	Burn time	Payload fairing	Total length	Payload capability	Launch record/schedule Payload/Date/Site	Notes
→ **AMROC (USA)**										
ILV-S	1st 2nd 3rd	2 x hybrid (a) 1 uprated 1 restartable (b)	- - -	630kN (c) 630kN -	70s - -	-	20.7m	100kg (c) to 400km polar 200kg (d) to 200km 28°	None	(a) Later versions to have 4- or 6-module 1st stage (b) To be developed (c) 6-module 1st-stage thrust 1,890kN (d) 420kg with 6-module 1st stage (e) 550kg with 6-module 1st stage (f) Being developed
ILV-1	1st 2nd 3rd 4th	12-module 6-module 3-module 1-module	- - - -	3,780kN - - -	70s - - -	-	37.7m	1,250kg to 500km polar 1,750kg to 500km 28°	None	
ARIANESPACE (France)										
Ariane 40	1st 2nd 3rd	4 x SEP Viking 5 7 x SEP Viking 4 1 x SEP HM7B	UH25 + N_2O_4 UH25 + N_2O_4 LOX + LH^2	2,700kN 798kN 62kN	206s 130s 725s	SPELDA, SYLDA, ASAP, SDS	54-55m (a)	1,900kg to GTO (single) 2,700kg to Sun-sync	One (successful) ERS-1/May 91/Kourou	(a) Depending of fairing (b) Core (c) Boosters (d) Ignited 3s before main-engine ignition
Ariane 42P	1st 2nd 3rd	4 x SEP Viking 5 (b) 2 x SNIA-BPD (c) 1 x SEP Viking 4 1 x SEP HM7B	UH25 + N_2O_4 solid UH25 + N_2O_4 LOX + LH^2	2,700kN 1,300kN 798kN 62kN	206s 42s 130s 725s	As Ariane 40	54-58m (a)	2,600kg to GTO (single) 2,400kg to GTO (dual) 3,600kg to Sun-sync	One (successful)	
Ariane 44P	1st 2nd 3rd	4 x SEP Viking 5 (b) 4 x SNIA-BPD (c) 1 x SEP Viking 4 1 x SEP HM7B	UH25 + N_2O_4 solid UH25 + N_2O_4 LOX + LH^2	2,700kN 2,600kN 798kN 62kN	206s - 130s 725s	As Ariane 40	54-58m (a)	3,000kg to GTO (single) 2,500kg to GTO (SPELDA) 2,800kg to GTO (SYLDA) 4,100kg to Sun-sync	One (successful) Anik E2/Sep 91/Kourou	
Ariane 42L	1st 2nd 3rd	4 x SEP Viking 5 (b) 2 x SEP Viking 6 (c) 1 x SEP Viking 4 1 x SEP HM7B	UH25 + N_2O_4 liquid UH25 + N_2O_4 LOX + LH^2	2,700kN 1,500kN 798kN 62kN	206s 143s (d) 130s 725s	As Ariane 40	54-58m (a)	3,200kg to GTO (single) 2,700kg to GTO (SPELDA) 4,500kg to Sun-sync	None to date	
Ariane 44LP	1st 2nd 3rd	4 x SEP Viking 5 (b) 2 x SEP Viking 6 (c) 2 x SNIA-BPD (c) 1 x SEP Viking 4 1 x SEP HM7B	UH25 + N_2O_4 liquid solid UH25 + N_2O_4 LOX + LH^2	2,700kN 1,500kN 1,300kN 798kN 62kN	206s 143s (d) 42s 130s 725s	As Ariane 40	54-58m (a)	3,700kg to GTO (single) 3,200kg to GTO (SPELDA) 5,000kg to Sun-sync	Six (no failures) Eutelsat 2-F3, Inmarsat 2-F-3/Jul 91/Kourou	
Ariane 44L	1st 2nd 3rd	4 x SEP Viking 5 (b) 4 x SEP Viking 6 (c) 1 x SEP Viking 4 1 x SEP HM7B	UH25 + N_2O_4 liquid UH25 + N_2O_4 LOX + LH^2	2,700kN 3,000kN 798kN 62kN	206s 143s (d) 130s 725s	As Ariane 40	54-58m (a)	4,200kg to GTO (single) 3,700kg to GTO (SPELDA) 6,000kg to Sun-sync	Six (one failure) Telecom 2A or Superbird, Inmarsat 2-F4/Nov 91/Kourou	
E PRIME AEROSPACE (USA)										
Astra B1	1st 2nd 3rd	1 x Thiokol (a) 1 x Thiokol (b) 1 x Star 92 (c)	- - -	- - -	- - -	-	32m	680kg to LEO	None to date	(a) Peacekeeper missile 1st stage (b) Peacekeeper missile 2nd stage (c) Satellites inserted into orbit by Star 37/Star 36 combination
Astra BII	1st 2nd 3rd	1 x Thiokol (a) 2 x Thiokol (a) 1 x Thiokol (b) 1 x Star 92 (c)	- - - -	- - - -	- - - -	-	35m	5,440kg to LEO	None to date	
Astra BIII	1st 2nd 3rd	1 x Thiokol (a) 3 x Thiokol (a) 1 x Thiokol (b) 1 x Star 92 (c)	- - - -	- - - -	- - - -	-	35m	7,260kg to LEO	None to date	
ESA (Europe)										
Ariane 5	1st 2nd	1 x SEP HM60 Vulcain 2 x Euro Propulsion 1 x MBB-ERNO (a)	LOX + LH solid N_2O_4-MMH	1,120kN 14,700kN 28kN	584s 123s 800s	5.4m-diameter, or 19.2m long, for triple launch	51.6m (b)	5,115kg to GTO (triple) 5,950kg to GTO (dual) 6,920kg to GTO (single) 12,000kg to 800km Sun-sync 18,000kg to 550km 28° LEO	Ariane 5 01/1995/Kourou Ariane 5 02/1996/Kourou Hermes 01/1998/Kourou Columbus/1998/Kourou Hermes 02/1999/Kourou	(a) Required for satellite launches (b) With long fairing
GENERAL DYNAMICS (USA)										
Atlas E	1st	1 x Rocketdyne MA-3 Block I or Block II stage vehicle system	LOX + RP-1 solid	1,950kN -	288s (b) -	Conical, 2.1m	28m	907kg to 720km polar (c)	Four (all successful) NOAA D/May 91/Vandenberg NOAA I/Jun 91/Vandenberg	(a) Centre sustainer + 2 boosters (b) Sustainer engine. (c) From Vandenberg. (d) Formerly Atlas Centaur

MANUFACTURER/Booster	Stage	Engine	Propellants	Thrust	Burn time	Payload fairing	Total length	Payload capability	Launch record/schedule Payload/Date/Site	Notes
→ Atlas I (d)	1st 2nd	Modified Atlas G 2 x P&W RL-10	- LOX + LH	1,954kN 147kN	- 473s	3.3m dia, 10.4m long or 4.m dia 12.2m long	42m (e) 43.9m (f)	5,900kg to 184km 28° LEO(g) 2,340kg to GTO (g)	18 since 1980 (1 failure) BS-2H/Apr 91/Cape Canaveral Galaxy 5/Oct 91/Cape Canaveral GOES I/1992/Cape Canaveral Galaxy 1R/1992/Cape Canaveral GOES J/1992/Cape Canaveral UHF/1992/Cape Canaveral SAX/1994/Cape Canaveral GOES K/1995/Cape Canaveral	(e) With medium fairing (f) With large fairing (g) From Cape Canaveral (h) Core (i) Boosters (j) Increased propellant load (2.990kg) (k) With 12.2m-long fairing
Atlas II MLV II	1st 2nd	1 x Rocketdyne MA-5A 2 x Rocketdyne MA-5A 2 x P&W RL-10	LOX + RP-1 LOX + RP-1 LOX + LH (j)	2,109kN 2,109kN 147kN	244s 169s 473s	3.3m dia, 10.4m long for MLV II 4.2m dia, 12.2m long for commercial	45.6m (k)	6,780kg to 185km 28° LEO(g) 2,770kg to GTO (g)	Eutelsat 2/Aug 91/Cape Canaveral DSCS III/1991/Cape Canaveral DSCS III/1991/Cape Canaveral DSCS III/1992/Cape Canaveral Orion 1/1991/Cape Canaveral DSCS III/1992/Cape Canaveral DSCS III/1993/Cape Canaveral DSCS III/1993/Cape Canaveral DSCS III/1993/Cape Canaveral Orion 2/1993/Cape Canaveral	
Atlas IIA	1st 2nd	1 x Rocketdyne MA-5A 2 x Rocketdyne MA-5A 2 x P&W RL-10 (uprated)	LOX + RP-1 LOX + RP-1 LOX + LH (j)	2,109kN 2,109kN 185kN	244s 169s 473s	As Atlas II	45.6m (k)	7,120kg to 185km 28° LEO(g) 2,900kg to GTO (g)	Intelsat K/ 1991/ Cape Canaveral	
Atlas IIAS	1st	1 x Rocketdyne MA-5A 4 x Thiokol Castor I	LOX + RP-1 solid	2,767kN total	244s	As Atlas II	45.6m (k)	8,610kg to 185km 28° (g) 3,630 to GTO (g)	Intelsat VII/1993/Cape Canaveral Intelsat VII/1993/Cape Canaveral Telstar 4/1993/Cape Canaveral Telstar 4/1994/Cape Canaveral SOHO/1995/Cape Canaveral	
GLAVKOSMOS (USSR)										
Proton SL-12	1st 2nd 3rd 4th	6 x RD-253 (a) 4 1 1 x D1e Block DM (b)	N_2O_4 + UDMH N_2O_4 + UDMH N_2O_4 + UDMH LOX + kero	10,470kN 2,400kN 600kN 85kN	130s 300s 250s 600s (c)	3.7m dia	57.2m	4,600kg to GTO 2,200kg to GEO 5,700kg to Moon 5,300kg to Venus 4,600kg to Mars	147 launches (21 failures) (d) No commercial launches schedule	(a) Each in UDMH module, surrounding N_2O_4 tank (b) Restartable after length coast in orbit (c) In two burns (d) From Baikonur (e) Core, with 4 941kN engines and 4 vernier (f) Boosters, each with 4 engines and 2 verniers. (g) Unmanned. (h) Manned. (i) From Baikonur and Plesetsk (j) From Plesetsk (k) Comprising two engines (l) Exclusively ocean-reconnaissance satellite launches from Baikonur (m) Two-stage; Zenit 2 for commercial launches (n) Comprising four engines (o) With longer fairing (p) Three-stage: Zenit 3 for commercial launches (q) From Cape York, Australia (r) Piggyback payload carrier failed
Proton SL-13	1st 2nd 3rd	6 x RD-253 (a) 4 1	N_2O_4 + UDMH N_2O_4 + UDMH N_2O_4 + UDMH	10,470kN 2,400kN 600kN	130s 300s 250s	3.7m dia	44.7m	21,000kg to 51° LEO	26 launches (4 failures) (d) No commercial launches schedule	
Vostok SL-3	1st 2nd	1 x RD-108 (e) 4 x RD-107 (f) 1 x RD-448	LOX + kero LOX + kero LOX + kero	3,764kN 4,000kN 55kN	285-320s 120-140s 430-442s	3.3m dia	38.4m	4,730kg to LEO 1,840kg to 650km Sun-sync 1,150kg to 920km Sun-sync	148 launches (14 failures?) (d) No launches in 1990 IRS 2/1991/Baikonur	
Soyuz SL-4	1st 2nd	1 x RD-108 (e) 4 x RD-107 (f) 1 x RD-461 (g)	LOX + kero LOX + kero LOX + LH	3,764kN 4,000kN 298kN	285-320s 120-140s 230-245s	2.7m dia	42.5m (g) 49.5m (h)	6,900kg to 200km x 450km 7,500kg to LEO	950 launches (8 failures?) (i) 3 Soyuz TM launches in 1991 No commercial launches schedule	
Molniya SL-6	1st 2nd 3rd	1 x RD-108 (e) 4 x RD-107 (f) 1 * RD-461 (g) 1	LOX + kero LOX + kero LOX + kero LOX + kero	3,764kN 4,000kN 298kN 67kN	285-320s 120-140s 230s 200-207s	2.7m dia	45.2m	1,600kg to 400km x 40,00 900kg to 400km x 200,000	260 launches (13 total failure 22 failed to reach proper orbit No commercial launches schedule	
Cosmos SL-8	1st 2nd	2 x RD-216 No details	HNO_3 + UDMH -	1,726kN -	170s -	Conical, 2.4m	32m	1,700kg to 180km LEO 1,000kg to 800km x 1,500	375 launches (5 failures) (j) No commercial launches schedule	
Tsyklon SL-14	1st 2nd 3rd	4 1 x RD-219 (k) 1	HNO_3 + UDMH HNO_3 + UDMH N_2O_4 + UDMH	11,880kN 883kN 78kN	280s 125s 118s	2.4m dia	39.3m	5,500kg to 65° LEO	86 launches (1 failure) (j) No commercial launches schedule	
Tsyklon SL-11	1st 2nd	4 1 x RD-219 (k)	HNO_3 + UDMH HNO_3 + UDMH	11,880kN 883kN	280s 125s	2.4m dia	39.3m	4,000kg to 65° LEO	116 launches (2 failures) (l)	
Zenit SL-16 (m)	1st 2nd	1 x RD-170 (n) 1	LOX + kero LOX + kero	7,910kN 834kN	150s -	3.9m dia. Two available	57m (o)	15,000kg to LEO	15 launches (2 failures) (d) No launches in 1988 Exploded in pad October 1990	

MANUFACTURER/Booster	Stage	Engine	Propellants	Thrust	Burn time	Payload fairing	Total length	Payload capability	Launch record/schedule Payload/Date/Site	Notes
→ Zenit SL-16 (p)	1st	1 x RD-170 (k)	LOX + kero	7,911kN	150s	3.9m dia. Two	65m (o)	5,900kg to GTO (q)	No launches to date	
	2nd	1	LOX + kero	834kN	-	available		2,400kg to GEO (q)	Commercial launches available	
	3rd	1 x Proton D stage	-	85kN	600s					
Energia SL-17	1st	4	LOX + LH	1,961kN	275s	-	60m	140,000kg to LEO		
		4 x RD-170 (n)	LOX + kero	31,644kN	170s			18,000kg to GEO	Test flight/May 87/Baikonur (r)	
	2nd	Piggyback payload carrier or Buran shuttle, with Proton D-stage motor		85kN	-			32,000kg to Moon 28,000kg planetary	Buran flight/Nov 88/Baikonur Buran/1991/Baikonur Buran/1992/Baikonur	
GREAT WALL INDUSTRY (CHINA)										
CZ-1D	1st	4 x YF2A	HNO$_3$ + UDMH	1,101kN	130s	2.05m dia	28m	750kg to 300km, 57° LEO(a)	No launches to date	(a) From Jiuquan (b) With long fairing (c) With short fairing (d) With PAM perigee kick motor (e) From Xichang (f) Restartable, first burn to LEO, second to GTO (g) From Xichang or Jiuquan (h) Now in doubt (i) From Tuiyan
	2nd	2 x YF3	HNO$_3$ + UDMH	294kN	126s				No commercial contracts	
	3rd	1 spin-stabilised	solid	-	-					
CZ-2C	1st	4 x YF20	N$_2$O$_4$ + UDMH	2,785kN	132s	3.4m dia (long)	38.4m (b)	750kg to 900km Sun-sync	17 CZ-2 launches (3 failures)	
	2nd	1 x YF22	N$_2$O$_4$ + UDMH	761kN	110s	dia (short)	25.1m (c)	1,200kg to 200km x 900km	All 13 CZ-2C launches successful	
								2,000kg to 400km x 185km		
CZ-2E	1st	4 x YF20 (uprated)	N$_2$O$_4$ + UDMH	2,942kN	132s	4.2m dia, 11.9m long	51.2m	8,800kg to 200km 28.5° LEO(a)	One launch (successful)	
		4 x YF20 (uprated)	N$_2$O$_4$ + UDMH	2,942kN	132s			7,200kg to 400km 28.5° LEO(a)	BADR A test/Jul 90/Jiuquan	
	2nd	1	N$_2$O$_4$ + UDMH	-	-			2,494kg to GTO (d,e)	Aussat B1/1991/Xichang	
									Aussat B2/1992/Xichang	
CZ-3	1st	4 x YF20	N$_2$O$_4$ + UDMH	2,785kN	132s	3m dia, 7.2m long	45.3m (b)	1,400kg to GTO (e)		
	2nd	1 x YF22	N$_2$O$_4$ + UDMH	766kN	110s	2.6m dia, 5.8m long	43.9m (c)	5,000 to 200km LEO (g)	5 launches (1 partial failure)	
	3rd	1 x YF73 (f)	LOX + LH	44kN	800s			2,500kg to 1,200 LEO (g)	Arabsat 1C/Oct 91/Xichang (h)	
CZ-3A	1st	4 x YF20 (uprated)	N$_2$O$_4$ + UDMH	2,942kN	132s	3.4m dia, 8.9m long	52.3m	2,500kg to GTO (e)	No launches to date	
	2nd	1 x YF22	N$_2$O$_4$ + UDMH	766kN	110s			8,500kg to LEO (a)	Available in 1992	
	3rd	2 x YF75 (f)	LOX + LH	157kN	470s					
CZ-4	1st	4 x YF20 (uprated)	N$_2$O$_4$ + UDMH	2,942kN	132s	3.4m dia, 8.5m long	50m (b)	4,000kg to 200km LEO (a)	One launch (successful)	
	2nd	1 x YF22	N$_2$O$_4$ + UDMH	766kN	110s	2.9m dia, 4.9m long	46m (c)	1,000kg to 1,000km LEO (a)	No commercial contracts	
	3rd	1	N$_2$O$_4$ + UDMH	294kN	411s			1,500kg to 900km 96° LEO(i)		
ISRO (India)										
ASLV	1st	1 (a)	solid	702kN	45s	1.1m dia	23.5m	150kg to 400km 45° LEO (	2 launches (2 failures)	(a) Ignites at T+49.5s
		2	-	880kN	49.5s				SROSS 3/1991/Sriharikota	(b) From Sriharikota
	2nd	1	solid	241kN	36s					(c) Four ignite at launch and two at T+25s.
	3rd	1	solid	64kN	45s					
	4th	1	solid	21kN	33s					
PSLV	1st	1	solid	4,860kN	94s	3.2m dia, 8.3m long	44.2m	1,105kg to 904km 99° Sun-sync 450kg to GTO	No launches to date	
		6 (c)	solid	2,640kN	54s				First flight 1991?	
	2nd	1 x Vikas	N$_2$O$_4$ + UDMH	588kN	153s			3,000 to 400km LEO		
	3rd	1	solid	328kN	91s					
	4th	2	N$_2$O$_4$ + UDMH	14kN	388s					
ISAS (Japan)										
MS3II	1st	1 x Nissan	solid	1,275kN	70s	1.7m dia, 6.9m long	27.8m	720kg to 250km 31° LEO (a)	5 launches (all successful)	(a) From Kagoshima
		2 x Nissan	solid	327kN	38s			460kg to 500km 31° LEO (a)	Solar A/1991-2/Kagoshima	
	2nd	1 x Nissan	solid	524kN	73s			170kg Earth-escape veloc		
	3rd	1 x Nissan	solid	132kN	87s					
	4th	1 x Nissan	solid	32kN	44s					
IAE (Brazil)										
-	1st	4 x Sonda 4	-	-	-	-	-	115kg to 750km (c)	No launches to date	(a) Mounted centrally inside 1st-stage cluster
	2nd	1 (a)	-	-	-			160 to 650km circular (c)		(b) Small orbital circularisation motor
	3rd	1	-	-	-					(c) From Alacantara
	4th	1 (b)	-	-	-					
IRAQ										
Al Abid	1st	-	-	(70t)	-	-	24.4m	100-200kg to LEO	No launches to date	
	2nd	-	-	-	-					
	3rd	-	-	-	-					

MANUFACTURER/Booster	Stage	Engine	Propellants	Thrust	Burn time	Payload fairing	Total length	Payload capability	Launch record/schedule Payload/Date/Site	Notes
→										
ISRAEL										
Shavil	1st	-	solid	-	-	-	11m	150kg to 250km x 1,150km	2 launches (both successful)	(a) From Palmachin
	2nd	-	solid	-	-				Olfeq 3/-/Palmachin	
LTV (USA)										
Scout G-1	1st	1 x UTC Algol 3A	solid	465kN	82s	0.9m or 1.1m dia	22.9m	205kg to 555km 37° LEO (a)	14 launches (all successful)	(a) From Wallops Island
	2nd	1 x Thiokol Caster I	-	268kN	39s			165kg to 555km 99° LEO (b)	Profile/1991/-	(b) From Vandenberg
	3rd	1 x Thiokol Antares	-	81kN	46s			220kg to 555km 2° LEO (c	SAMPEX/Jun 92/Vandenberg	(c) From San Marco
	4th	1 x Thiokol Altair 3	-	26kN	34s				TOMS/Jun 93/Vandenberg	(d) Core
									FAST/Dec 93/-	(e) Boosters, Ariane 4-class
Scout 2	1st	1 x UTC Algol 3A (d)	solid	465kN	82s	1.4m dia	23m	520kg to 278km LEO (c)	First flight c1993	
		2 x SNIA-BPD (e)	solid	1,300kN	42s			450kg to 555km LEO (c)		
	2nd	1 x Thiokol Caster I	solid	268kN	39s			330kg to 1,000km (c)		
	3rd	1 x Thiokol Antares	solid	81kN	46s					
	4th	1 x SEP Mage 2	solid	45kN	43s					
MARTIN MARIETTA (USA)										
Titan II 23G (a)	1st	2 x A50jet LR87-AJ5	N_2O_4 + A50	1,913kN	170s	3.1m dia, 6.1m long	37.5m	2,180kg to 185km polar (b)	2 launches (both successful)	(a) Refurbished ICBM
	2nd	1 x A50jet LR87	N_2O_4 + A50	445kN	183s			3,082kg to 560km Sun-sync (c)	Landsat 6/1991/Vandenberg	(b) From Vandenberg
									NOAA K/1993/Vandenberg	(c) With satellite upper stage
									NOAA L/1995/Vandenberg	(d) Core
									NOAA M/1996/Vandenberg	(e) Boosters, up to 10
									Military launches include:	(f) 4,310kN with 10 boosters
									DMSP, N-ROSS, Starscan	(g) With 8 boosters
										(h) With 10 boosters
Titan II S	1st	2 x A50jet LR87-AJ5	N_2O_4 + A50	1,913kN	170s	As Titan II	33.5m	3,400kg to polar (g,i)	No launches to date	(i) From Vandenberg
		2 x Thiokol Caster I	-	962kN (f)	-			4,445kg to polar (h,i)	MSX-SDIO/1992/Vandenberg	(j) Ignite a T+108s
	2nd	1 x A50jet LR87	N_2O_4 + A50	445kN	183s					(k) From Cape Canaveral
										(l) With UTC strap-ons
Titan IV-IUS	1st	2 x A50jet LR87 (uprated)	N_2O_4 + A50	2,437kN	220s	5.1m dia, 17.1m long	54m	2,313kg to GEO (k)	4 launches (successful)	(m) GD Centaur G Prime stage
		2 x UTC seven-segment	solid	14,234kN	120s					(n) With Hercules strap-ons
	2nd	1 x A50jet LR91 (uprated)	-	467kN	245s					(o) Filament-wound
	3rd	1 x Boeing IUS -1st stage	solid	203kN	152s					(p) Ignite at T+118s
		2nd stage	solid	82kN	289s					(q) Using Transfer Orbit Stage
										(r) Intelsat VI-F3 failed to seperate
Titan IV-Centaur	1st	2 x A50jet LR87 (uprated)	N_2O_4 + A50	2,437kN	220s	5.1m dia, 26.2m long	63.1m	17,690kg to LEO (k)	No launches to date	
		2 x UTC seven-segment	solid	14,234kN	120s			4,540kg to GTO (k)	First launch due 1991	
	2nd.	1 x A50jet LR91 (uprated)	-	467kN	245s			14,525kg to Sun-sync (i)		
	3rd	2 x P&W RL-10 (m)	LOX + LH	147kN	-					
Titan IV-Centaur	1st	2 x A50jet LR87 (uprated)	N_2O_4 + A50	2,437kN	220s	As above	63.1m	5,5670kg to GEO (k)	No launches to date	
		2 x Hercules three-segment	solid	-	-				CRAF launch for NASA in 1995?	
	2nd	1 x A50jet LR91 (uprated)	-	467kN	245s				Cassini launch for ESA in 1996	
	3rd	2 x P&W RL-10 (m)	LOX + LH	147kN	-					
Commercial Titan	1st	2 x A50jet LR87 (p)	N_2O_4 + UDMH	2,429kN	160s	4m dia, 10.1m long	44m	14,742kg to LEO (k)	3 1990 launches (successful) (	
		2 x UTC $5^{1}/_{2}$-segment	solid	12,400kN	118s			4,990kg to GTO (k,q)	Mars Observer/1992/Cape Canaveral	
	2nd	1 x A50jet LR91	N_2O_4 + UDMH	463kN	225s			2,600 to Mars (k,q)		
McDONNELL DOUGLAS (USA)										
Interim	1st	1 x Rocketdyne RS-27	LOX + RP-1	920kN	264s	2.8m dia, 8.5m long	38.4m	3,983kg to 185km 28° LEO (d)	2 launches (both successful)	(a) Uprated Delta 3925 core stage, extended tanks
Delta 6920		9 x Thiokol Castor I	solid	3,879kN	56s	3.1m dia, 7.9m long		2,567kg to 833km Sun-sync (e)	EUVE/Aug 91/Cape Canaveral	(b)Boosters, 6 ignite at lift-off, 3 at T+62s
	2nd	1 x A50jet AJ-10 (c	N_2O_4 + A50	43kN	440s					(c) Restartable.
										(d) From Cape Canaveral.
Interim	1st	1 x Rocketdyne RS-27	LOX + RP-1	920kN	264s	As above	38.4m	1,447kg to GTO (g)	13 launches (successful)	(e) From Vandenberg.
Delta II 6925		9 x Thiokol Castor I	solid	3,879kN	56s			839kg to GPS (d)	Geotail/1992/Cape Canaveral	(f) Pam D1 stage
	2nd	1 x A50jet AJ-10 (c	N_2O_4 + A50	43kN	440s			962kg to Molniya-type (e)		(g) Expansion ratio up from 8:1 to 12:1
	3rd	1 x Thiokol Star 48B	solid	67kN	88s					(h) Each 439kN thrust - as (b)
Delta II 7920	1st	1 x Rocketdyne RS-27	LOX + RP-1	1,054kN	264s	As above	38.4m	3,175kg to 98° Sun-sync (e)	No launches to date	
		9 x Hercules GEM (h)	-	3,951kN	each 64s			5,039kg to 28° LEO (d)	Radarsat/1994/Vandenberg	
	2nd	1 x A50jet AJ-10 (c	N_2O_4 + A50	43kN	417s			3,819kg to 90° (e)	Lifesats 1-4/1994-6/Cape Canaveral	
Delta II 7925	1st	1 x Rocketdyne RS-27	LOX + RP-1	1,054kN	264s	As above	38.4m	1,819kg to GTO (d)	2 launches (both successful)	
		9 x Hercules GEM (h)	-	3,951kN	64s			1,134kg to GPS (d)	Contel ASC/1991/Cape Canaveral	
	2nd	1 x A50jet AJ-10 (c	N_2O_4 + A50	43kN	417s			1,275kg to Molniya-class	Aurora/May 91/Cape Canaveral	
	3rd	1 x Thiokol Star 48B	solid	67kN	88s				GPS 11/1991/Cape Canaveral	

MANUFACTURER/Booster	Stage	Engine	Propellants	Thrust	Burn time	Payload fairing	Total length	Payload capability	Launch record/schedule Payload/Date/Site	Notes
→									GPS 12/1991/Cape Canaveral GPS 13/1991/Cape Canaveral GPS 14/1991/Cape Canaveral GPS 15/1992/Cape Canaveral GPS 16/1992/Cape Canaveral GPS 17/1992/Cape Canaveral GPS 18/1992/Cape Canaveral Wind/1992/Cape Canaveral Polar/1993/Cape Canaveral	
NASA (USA) Space Shuttle	1st	3 x Rocketdyne SSME	LOX + LH	5,004kN	520s	18.3m long, 4m long 5.2m wide	56.1m (d) 37.2m (e)	24,990kg to 204km 28° LEO(f) 18,600kg to 204km 57° LEO (f)	38 missions (1 failure) STS39 Discovery/May 91/KSC STS40 Columbia/May 91/KSC STS43 Atlantis/Aug 91/KSC STS48 Discovery/Oct 91/KSC STS44 Atlantis/Dec 91/KSC STS42 Discovery/Feb 92/KSC STS45 Atlantis/Apr 92/KSC STS49 Endeavour/May 91/JSC STS50 Columbia/Jun 91/KSC STS46 Atlantis/Aug 91/KSC STS47 Endeavour/Sep 92/KSC STS52 Columbia/Sep 92/KSC	(a) Fed from external tank. (b) Recoverable and reuseable. (c) For retrofire and orbit insertion (d) Shuttle system (e) Orbiter (f) From Kennedy Space Center (KSC)
		2 x Thiokol SRB (b)	solid	29,360kN	120s					
	2nd	2 x Orbiter OMS (c)	N_2O_4 + MMH	-	-					
NASDA (Japan) H-I	1st	1 x Mitsubishi MB-3	LOX + kero	756kN	270s	2.4m dia, 7.9m long	40.3m	2,250kg to 1,000km 30° (c) 1,100kg to GTO (c) 550kg to GEO (c)	7 launches (successful) First launch was 2-stage version BS3b/1991/Tanegashima ERS 1/1992/Tanegashima	(a) Based on Delta 2914 stage and Rocketdyne engine (b) Each 22kN booster ignites at lift-off (c) From Tanegashima (d) Single burn to GEO, restartable 2-burn to LEO (e) For 2-stage burn to GEO
		9 x Thiokol-Nissan	solid	198kN	39s					
	2nd	1 x Mitsubishi LE5	LOX + LH	102kN	370s (d)					
	3rd	1 x Nissan	solid	77kN	68s					
H-II	1st	1 x Mitsubishi LE7	LOX + LH	912kN	316s	4.1m dia, 12m long	49m	9,400kg to 480km 30° LEO (c) 4,000kg to GTO (c) 2,000kg to GEO (c) 4,500kg to 800km Sun-sync (c) 2,000kg to lunar (c) 1,500kg to Venus-Mars	No launch to date Missions planned: ETS VI, HOPE, ADEOS, Polar Platform No launch before 1993	
		2 x Nissan	solid	3,138kN	95s					
	2nd	1 x Mitsubishi LE5A	LOX + LH	118kN	527s					
OSC/HERCULES (USA) Pegasus 1	1st	1 x Hercules (a)	solid	487kN	82s (b)	1.3m dia (c)	15.5m	272kg to 463km polar (d) 408kg to 463km equatorial	1 launch (successful) DARPA Lightsats/1991/- 2 x USAF-DARPA Orbcomm NASA SELVS SeaStar/1993/-	(a) Winged booster, 6.7m span (b) Ignites after air drop from B-52 (c) Accomodates 3rd stage (d) From air launch at 12,000m/M0.8 (e) Ground-launched, wingless, Peacekeeper 1st stage (f) From Cape Canaveral
	2nd	1 x Hercules	-	123kN	71s					
	3rd	1 x Hercules	-	35kN	65s					
Taurus	1st	1 x SSLV (e)	-	-	-	1.3m dia (c)	15.5m	1,500kg to LEO (f) 400kg to GEO (f)	First launch set for 1992 (g) At least 5 launches planned Reservation for BS-400 launches	
	2nd	1 x Hercules	-	123kN	71s					
	3rd	1 x Hercules	-	35kN	65s					
	4th	1 * Hercules	-	-	-					
SPACE SERVICES (USA) Conestoga 2	1st	1 x Thiokol Star 42B	-	-	-	-	-	190kg to 740km LEO	None to date	
		2 x strap-on	-	-	-					
	2nd	1 x Star 48B	-	-	-					

ANNEX B

SATELLITE DIRECTORY[1]

SPECIFICATIONS

U. S. Spacecraft

Spacecraft Name	Contractor/User	Weight (lb.)	Launch Vehicle	Remarks and Purpose/First Launch
NASA				
Space Shuttle		4.5 million total		Multi-role reusable space system/4-12-81.
Orbiter	Rockwell Int'l/Johnson S.F.C.	151,205-159,289		Cargo-lift 41,000-55,000 lb.; Three 393,800-lb.-thrust liquid-fuel engines. At sea level, 104%.
Main engine	Rockwell International//Marshall S.F.C.	7,000 each		
External tank	Martin Marietta/Marshall S.F.C	1.61 million		Expendable tank for main engines. 66,000 lb.
Solid booster	Morton Thiokol, MDAC, USBI, Marshall S.F.C.	1.3 million each		Two reusable 3.3 million-lb.-thrust boosters.
OMS engine	Aerojet Tech. Systems	300		Two reusable 6,000-lb.-thrust engines.
Orbital Maneuvering Vehicle	TRW/Marshall S.F.C	18,000 (fueled)	Space Shuttle	Satellite retrieval & repair vehicle. 1993.
Voyager 1, 2	JPL	1,742	Titan 3E/Centaur/ TE-364-4	Study of Jupiter (79), Saturn (80-81), Uranus (86), Neptune (89), Instellar (89)/8-20-77 9-5-77.
Landsat D/D Prime	GE/Goddard S.F.C./NOAA	4,400	Delta	Earth resources satellite program/7-16-82; 3/84.
NOAA D/I, J	GE/Goddard S.F.C./NOAA	3,127/5,000	Atlas E/Titan 2	Polar Metsats/ 4-91; 9-92; 11-93; 2-95; 6-96. K, L, M planned.
GOES-7/I, J	Ford Aerospace/Hughes/ Goddard S.F.C./NOAA	3,200/4,545 2,891 (I , J, K)	Delta/Atlas 1	Geostationary weather satellite. 6-91; 2-92; 7-95; 2-97, 7-2000. K, L, M planned.
Galileo	JPL/Hughes Probe/Spacecraft	5,986	Space Shuttle/IUS	Jupiter orbiter and entry probe/10-18-1989. MBB participation.
Hubble Space Telescope	NASA-Marshall, ESA/NASA-Goddard, Lockheed, Perkin-Elmer	25,001	Space Shuttle	2.4-meter optical instrument will be launched in 1989 for long duration orbit.
GRO	TRW/Goddard S.F.C.	35,000	Space Shuttle	Map gamma ray sources/6-1990.
TDRSS 3, 4, E, F	SPACECOM, TRW, Goddard S.F.C.	4,842	Space Shuttle/IUS	Tracking and data-relay satellite/9-88; 3-89; 1-91; 8-91.
Ulysses	ESA/JPL	807	Space Shuttle/IUS	Fly out-of-elliptic above solar poles/1990.
CRRES-Combined Radiation and Release Satellite	Ball Aerospace/Marshall S.F.C./Air Force	3,880	Atlas Centaur	First 60 days, NASA chemical rel. in GEO, then A.F. radiation mapping/effects/1990. meas. studies mission./89-92.
MPF-Materials Process Fac.	Ball Aerospace (commercial)	15,000	Space Shuttle	Comm'l mat. process. exp./1985.
COBE-Cosmic Background Explorer	NASA/Goddard S.F.C.	4,857	Delta 5920	900 Km. 99° inclination orbit to measure residual radiation from "Big Bang" 2-89. Launched 11-18-89.
AEROS	Ball Aerospace/Space America	436	Shuttle/Conestoga	Earth resources, 3-axis spin stabilized/1986.
UARS-Upper Atmosphere Research Satellite	GE/Goddard S.F.C.	15,000	Space Shuttle	Study physical process stratosphere, mesosphere and lower thermosphere 10-91.
ACTS-Advanced Communications Technology Satellite	GE/NASA	6,177 (approx.)	Space Shuttle/TOS	Ka-band.
Magellan	Martin Marietta/JPL	7,826	Space Shuttle/IUS	Venus radar mapper. 5-4-89.
Mars Observer	GE/JPL	5,515	Titan 3/TOS	Mars Orbiter. Sept. 1992.
LAGEOS	Aeritalia/NASA	900	Shuttle	Co-op Italio-US mission to study tectonic motion using lasers. 8/91.
Wind	GE/NASA	2,756	Delta	Obtain solar wind measurements. 12/92.
EUVE-Extreme Ultraviolet Explorer	U. of CA (Berkeley) Fairchild/Goddard S.F.C.	6,300	Delta 2	First use of explorer platform to perform sky survey in the EUV band. 8/91.
CRAF	JPL	—	Titan 4 - Centaur	Asteroid flyby/Extended comet study probe; 8-1995.
Polar	GE/NASA —	2,756	Delta	Obtain solar wind-plasma-Auroral data 7/93
X-Ray Timing Explorer (XTE)	UCSD/MIT/GSFC/Fairchild	16,200 (launch)	Shuttle	Explorer platform-on orbit-study X-ray sources.
FAR U/V Spect. Explorer (FUSE)	Johns Hopkins; U.C. Berkley; U. Colo.	2,400	Shuttle	Obtain 900-1200 Angstroms Data. Replace XTE payload, 1996-97.
Advanced Composition Explorer (ACE)	Johns Hopkins; CalTech; APL; GSFC	1,396	Delta	Compare elemental/Isotopic composition. Orbit L1 libration point.
AXAF — Advanced X-ray Astrophysics Facility	TRW/NASA/Marshall SFC	30,000	Space Shuttle	10 Meter telescope to map X-ray sources - launch, 1996.
Commercial				
Westar 4, 5, 6	Hughes/Western Union	1280	Delta/Shuttle	24 trans. sat./2-25-82; 6-8-82; 6 recov. 10-14-84.
Marisat 1, 2, 3	Hughes	700	Delta	Navy/Comm'l shipping /last 10/76.
Comstar 1, 2, 3, 4	Hughes	1,746	Atlas/Centaur	Four 24-trans., spin-stab. sats/last 2/81.
Spacenet	GE/GTE/Spacenet Corp.	2,634	Ariane 3	C, Ku-band./5-22-84; 11-8-84; 1988.
G STAR	GE/GTE Satellite Co.	2,667	Ariane 3	Ku-band 5-7-85; 3/86; 1988.
SBS 1, 2, 3, 4, 5, 6	Hughes	1,200/2,600	Delta/Shuttle/Ariane 3	10-channel digital data relay, 6 spare TWTs/11-15-80; 9-24-81; 11-11-82; 8-30-84. SBS-6; launch 6-90
Telstar 3 1, 2, 3	Hughes	1,483	Delta/Shuttle	24-transponder, 6/4 GHz satellites op. by AT & T/7-9-83; 9-1-84, 6-85.
Galaxy 1, 2, 3, 6	Hughes	1,222	Delta/Ariane	Hughes comm. sats.; 24 trans. 6/4 GHz. G-1 all cable/6-28-83; 9-27-83; 9-84.
American Satellite Co.	GE/American Sat. Co.	2,800	Space Shuttle	C, Ku-band 8/27/85; 1990.
GE/Americom Ku-band	GE/GE Americom	4,245	Space Shuttle	Ku-band 11/26/85; 1/86; 1990.
DBSC	Ford Aerospace	3,500	Ariane/Shuttle	Direct broadcast T.V./Mid-88.
Landsat 6	GE/Ecosat	—	—	Earth observation/scheduled 1988.
AsiaSat1	Hughes/Hong Kong/AsiaSat	1,300	Long March 3	Commercial services in SE Asia/China - Formerly Westar 6; 1990.
Military				
DSCS-16	TRW/Defense Dept.	1,195	Titan 34/Transtage	Synch. orbit. with earth-coverage and spotbeam antennas provides up to 1,300 duplex voice channels/10-82.
DSCS-3	GE/Defense Dept.	1,947	Titan 34D/Transtage Space Shuttle/Titan 4	Three-axis-stabilized, next-generation synchronous communications satellite/10-30-82.
FleetSatCom 7,8	TRW/Navy/Air Force	2,100 2,300	Atlas/Centaur	UHF Comm. between ships, shore-to-ship, ship-to-aircraft and SIOP forces. Carries USAF Satellite Comm. System (AFSATCOM)-12-86; 9-89.
Satellite Data System	Hughes/Air Force	—	—	Provides UHF communications for strategic forces, communications between Satellite Control Facility ground stations, strategic data relay.
Broad Coverage Photo Recon	Lockheed/Air Force	25,000 (est.)	—	Big Bird satellite provides both radio transmission and recoverable photo return; 155×100-mi. orbit at 96.4 deg.
KH-11 Strategic Recon	USAF/CIA	25,000 (est.)	—	Broad-coverage digital-image-transmission recon satellite; 275 × 185-mi. orbit at 97 deg./12-19-76.
High Resolution Film Recon	USAF	—	—	Highest resolution film return recon satellite; 80 × 215-mi. orbit at 96.4 deg.
Ocean Surveillance 1	Navy	—	Atlas F	All-weather sea surveillance/ 3-11-76, 3 spacecraft per launch.
Defense Support Program (Code 647)/Advanced	TRW/Aerojet/Air Force	2,000	—	To detect launch of ICBMs, SLBMs using IR sensors in synch. orbit/5-5-71; 1986.
Navy Navigation Satellite System (Transit)	GE/Navy	301	Scout	Satellites in 600-mi. polar orbits/1970, 1973. Still operational.
Nova	GE/Navy	—	Scout	Navigation/5-14-81; 10-11-84.
Global Positioning System (Navstar)	Rockwell/Defense Dept.	1,157 (Block 1) 2,000 (Block 2)	Atlas E/F, 1985 Delta 2	Six Block 1 satellites and Five Block 2 satellites operational 12-89. Five GPS launched in 1989.
Defense Meteorological Satellite Program	GE/Defense Dept.	1,131 (Block 5D-1) 1,161 (Block 5D-2) 3,775 (Block 5D-3)	LV-2F, Atlas E Atlas E Titan 2 SLV	Provide global meterological info./Block 5D-2,12-19-82/Block 5D-3 TBD. LV-2F, AtlasE Atlas E Titan 2 SLV
N-Ross	—/Navy	—	Titan 2 SLV	Oceanographic surface information. No launch date.
Ferret (Code 711)	Lockheed/Sanders/Air Force	500 (est.)	Thor/Agena	Second-generation electromagnetic-reconnaissance satellite to be superceded by new Hughes design (Code 711).
Clipper Bow	Navy	—	Space Shuttle	Ocean surveillance sat. with active radar.
Leasat	Hughes/Navy	2,900	Space Shuttle	Follow-on to FleetSatCom. 8-31-84.
S00S-Stacked Oscars on Scout	GE/Navy	—	Scout	Navigation-dual launches 8/85, 9/87.
Relay Mirror Experiment	Ball Aerospace/Defense Dept.	2,300	Delta	Relay Mirror Technology. 8/88.
UHF Follow-on	Hughes/Navy	2,300	Atlas	Follow-on to Leasat and Fleetsatcom; 1992.

Abbreviations
APL—Applied Physics Laboratory of Johns Hopkins University;
BA—British Aerospace Corp.;
CCE—Change Compositive Explorer;
Cesar-Consortium of ASAT, SETIS and Aerospatiale;
CNES—French National Center for Space Studies;
CNRS—French National Center for Scientific Research;
Cosmos—Consortium of ECTA, GEC Marconi, SAT, Selenia, Aerospatiale;
CRA—Centro Ricerche Aerospaziale;
ESC—European Communications Satellite;
GE—General Electric;
IRAS—Infrared Astronomical Sat.;
HEO—high earth orbit;
IRM—Ion Release Module;
ISAS—Japanese Inst. of Space & Astronautical Science;
JPL—Jet Propulsion Laboratory;
LEO—low earth orbit;
MBB—Messerschmitt-Boelkow-Blohm;
MCI—Matsushita Communications Industries;
MDAC—McDonnell Douglas Astronautics Co.;
Melco—Mitsubishi Electric Co.,
MESH—Matra, ERNO, Saab, HSD, Aeritalia;
MHI—Mitsubishi Heavy Industries;
NEC—Nihon Electric Co.;
NOAA—National Oceanic and Atmospheric Administration (U.S.);
NRC—National Research Council;
NTT—Nippon Telegraph & Telephone Public Corp.;
OMS—Orbital Maneuvering System;
SCATHA—Spacecraft Charging at High Altitude;
SEP—Societe Europeenne de Propulsion (France);
STAR—Thomson-CSF, SEP, Dornier, CGE, FIAR, Montadel Laben,Fokker-VFW, Sener, Ericsson, Contraves;
trans.—transponder;
UKS—United Kingdom Satellite;
USBI—United Space Boosters, Inc.

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[1] *Specifications: US and International Spacecraft*, Aviation Week and Space Technology, 19 March 1990, pp 172-174.

SPECIFICATIONS

International Spacecraft

Nation/Organization *Spacecraft Name*	**Contractors/** *Experimenters*	**Weight** *(lb.)*	*Launch Vehicle*	*Remarks and Purpose/First Launch*
ARAB LEAGUE Arab Satellite Communication Organization (ASCO)				
Arabsat	Aerospatiale	1,492	Ariane/Space Shuttle	Three satellites C-band comm., S-band T.V. Two operational, 3-85; 6-85; one spare.
AUSTRALIA				
Aussat 1, 2, 3	Hughes	1,430	Space Shuttle/Ariane	3 domestic 14/12 GHz satellites. 15 channels incl. T.V. broadcasting/July 85, Oct. 85, 9-87.
Aussat-B 1, 2	Hughes	3,488	Long March 2E	Second-generation, domestic satellite; 1991, 1992.
BRAZIL Embratel				
SBTS	Spar(Canada)/Hughes	2,700	Ariane	2 domestic 24-transponder, C-band satellites/Feb. 1985, Sept. 1985.
CANADA Telesat Canada				
Anik C1, C2, C3	Hughes, Spar	2,550	Space Shuttle	3 domestic comm. 14/12 GHz/11-11-82;6-83.
Anik D1, D2	Spar (Canada)/Hughes	2,720	Shuttle/Delta	2 domestic comm. satellites, 6/4 GHz/8-26-82; 11-84.
Anik E1, E2	Spar	5,500	Ariane 4	4th quarter 1990 - 1st quarter 1991.
CHINA (Beijing)				
China 9, 10, 11	—	—	CSL-2(FB-1)	Space Physics satellites launched in single booster. 9-10-81.
China 12, 13, 14	—	—	—	Scientific sats./10-9-82,8-19-83,1-29-84.
China 15 (STW-1)	—	—	—	Experimental comsat./4-8-84
China 16	—	—	CSL-2	Earth resources sat./10-21-85.
China 17	—	—	CZ-3	Second comsat. 1986
—	W. Germany	—	CZ-2	Test sat./9-88.
China	—	—	CZ-3	Operational Com. Sat. 3/88.
Fengyun 1	—	—	CZ-4	Weather sat./9-88.
EUROPEAN SPACE AGENCY (ESA)				
Meteosat P2	Aerospatiale led consortium	1,480	Ariane 4	Weather satellite. 6-88 ESA oversight.
Op. Meteosats MOP-1,-2,-3	Aerospatiale led consortium	1,550	Ariane 4	Geostationary weather satellite./3-89; 4-1990; 9-1993/Eutelsat oversight.
ECS- 3, 4, 5	Matra/BAe led consortium	1,345/1,500	Ariane 1/Ariane 3	Operational satcom/9/85 (launch failure), 9-87, 7-88.
OTS-2	MESH/BA/Telefunken	980	Delta 3914	Pre-operational satcom/5-11-78.
Marecs A/B2	Matra/BAe led consortium	1,350/1,375	Ariane 1	Maritime Communications/12-20-81;11-9-84.
Olympus	BAe led consortium	3,190	Ariane	Multipurpose platform 1989.
Ulysses	STAR, Dornier led consortium	770	Shuttle/IUS-PAM D	Measure interplanetary medium out of ecliptic plane/ 10-90.
ISO	Aerospatiale led consortium	4,949	Ariane 4	Infrared astronomy/5-93.
Hipparcos	Matra led consortium	2,508	Ariane	Space astrometry mission/8-19-89.
ERS-1	Dornier led consortium	5,300	Ariane 4	Remote sensing of oceans and ice zones/9-90.
Eureca	*MBB/ERNO led consortium*	*8,800*	*Space Shuttle*	*Retrievable carrier system/5-1991/ Retrieval 1-1992.*
Hermes	Aerospatiale (For spaceplane)	51,000	Ariane 5	CNES has management authority for most contracts. First launch 1998.
STSP/Cluster	Dornier led consortium	2,535	Ariane 5	Magnetosphere Physics. Launch: 7-95.
STSP/Soho	Matra led consortium	3,986	U.S. ELV	Magnetosphere Physics. Launch: 7-95.
Cassini	ESA/Jet Propulsion Lab	—	Titan 4-Centaur	Saturn orbiter-Titan probe Lanuch: 4-96.
Sat-2	Selenia/Spazio	4,851	Ariane 4	Advanced payload, Bus technology. Early, 1994.
DRS	Selenia/Spazio	5,292	Ariane 4	Data relay satellite for Columbus, Hermes; 1996.
EUTELSAT				
Eutelsat 2	Aerospatiale	2,167	Ariane/Atlas Centaur	Telecommunication TV distribution for Europe. 1990.
FRANCE National Space Research Center (CNES)				
Signe 3	Matra/CNRS	225	Soviet launcher	Gamma rays and solar UV/6-17-77
SPOT 1,2 (3-4)	*Matra*	*1,540 (4,035)*	*Ariane 1/Ariane 2 or 3*	*Earth resources. 1986-89. SPOT 3-4 to be announced.*
Telecom 1A,1B, 1C	Matra led consortium	1,521	Ariane 3	Data-to-telephone satcom/1984; 1985; 1988.
TV-Sat 2	MBB	4,625	Ariane 4	Direct Broadcast Satellite. Launched 11-87; 8-89.
TDF-2	Aerospatiale	2,900	Ariane 2	Direct Broadcast. Beginning 1990.
TOPEX/Poseidon	CNES-Fairchild-Jet Propulsion Lab	6,000	Ariane 4	Ocean circulation expt. 6-1992.
Telecom 2	Matra-Alcatel Espace	2,886	Ariane 4	Telephone Satcom; 1992.
GREAT BRITAIN				
Skynet	BAe/Marconi,	—	Ariane/Titan	UK; military communications; 12-88, 12-89.
BSB	Hughes	1,450	Marco Polo 1/2 - Delta 2	First direct broadcast satellite for Great Britian; 8-89, 8-90.
INTELSAT				
Intelsat 5 (F1-9)	Ford Aerospace	2,281	Atlas/Centaur; Ariane	12K circ.,K-band/80-84.
Intelsat 5A (F10-15)	*Ford Aerospace*	*4,300*	*Atlas/Centaur; Ariane*	*15,000 2-way circuits; K-band/85-86. F15 launched 1-89.*
Intelsat 6	Hughes	4,000	Shuttle; Ariane 4	30K circ., 6/4, 14/12 GHz, 50 trans./F1 Launched 10-89.
INDIA Indian Space Research Organization (ISRO)				
Insat-1B, 1C, 1D	Ford Aerospace	2,574/2640/2838	Shuttle, Ariane 3, Delta	Multi-purpose satellites. 8/83; 7/88; 3/89; 6/90.
IRS-1A, 1B	ISRO	2,145	Soviet Vostok	Remote sensing/3-1988-91.
Insat-2A, 2B	ISRO	4,200	Ariane 4	Multipurpose - 1991-1992.
INDONESIA				
Palapa 1, 2/B-1, B-2, B-2P, B-2R	Hughes	660/1,388	Delta 2914/Shuttle	Domestic satcom/7-8-76; 3-10-77; recov. 10-14-84, 1-87.
JAPAN National Space Development Agency (NASDA)				
GMS-3, -4, -5	NEC/Hughes/—	666/—/1,100	N-2/H-1/H-1	Geostationary Metsat./8-3-84, 9-6-89, 1993.
ETS-3 (Kiku 4)	Toshiba/GE	880	N-1	Engineering test satellite./9-4-82
MOS-1	NEC	1650	N-2	Maritime observation satellite/2/87.
CS-2A, -2B (Sakura-2A, -2B)	MELCO/Ford	770	N-2	Operational Com.-Sat/2/83; 8/83
BS-2A, -2B (Yuri-2)	Toshiba/GE	770	N-2	Operational Broad-Sat/1/84; 2/86.
ERS-1	MELCO	3,090	H-1A	Earth resources sat/1991.
CS-3a, -3b	MELCO/Ford	1,210	H-1A	Operational satcom/2-88; 9-88.
BS-3a, -3b	NEC/GE	1,210	H-1A	Operational Broad-Sat/1990, 1991.
JAS-1	NEC	110	H-1A	Comsat for amateur radio. 8-86.
MOS-1B	NEC	1,650	H-1A	Second maritime observation. Sat. 2-90.
ETS 5,-6	Melco	1,210/4,400	H-1/H-2	Engineering test sat. 8-78; 1992.
EGS	Kawasaki	1,507	H-1	Geosurvey. 8-86.
—	—	6,600	Space Shuttle	Free flyer. 1992.
BS-2X	Toshiba/GE	770	Ariane	Broadcast satellite; 2-90.
CS-4/A-B	—	—	H-2	Communications satellite; 1994.
Adeos	—	—	*H-2*	*Earth observation platform; 1993.*
GMS-6	—	—	H-2	Weather satellite; 1997.
JCSAT 1, 2	Hughes	2,914	Ariane 4/Titan Commer.	Private communications satellites for Japan.

SPECIFICATIONS

International Spacecraft *continued*

Nation/Organization Spacecraft Name	Contractors/ Experimenters	Weight (lb.)	Launch Vehicle	Remarks and Purpose/First Launch
ISAS				
MS-T5 (Sakigake)	NEC	265	Mu-3S-2	Halley's comet test mission/1-8-85.
EXOS-C (Ohzora)	NEC	265	Mu-3S	Study of magnetosphere/2-14-84.
EXOS-D	—	660	Mu-3S-2	Earth plasma observation/1989.
ASTRO-A (hinton)	NEC	265	Mu-3S	Astrophysical research/2-81.
ASTRO-B, -C	NEC	476, 880	Mu-3S, -3S-2, ..	Astrophysical research/2-20-83, 2-86.
Planet-A (Suisei)	NEC	265	Mu-3S-2	Venus/Halley's comet mission/8-85.
Geotail	—	1,650	Space Shuttle	Geophysics. 1992.
HESP-1	—	—	—	Solar physics. 1992.
MUSES-A	NEC	400	MU-3S-2	Lunar survey. 1990.
Solar-A	—	—	MU-3S-2	Solar observer. 1991.
Astro-D	—	—	MU-3S-2	Deepspace x-ray spectrum observation; 1992.
Muses-B	—	—	MU-3S-2	Lunar Survey; 1993.
VLBI	—	—	M-5	Very-long baseline intervention-Earth observation 1995.
LUXEMBOURG Societe Europeenne des Satellites (SES)				
Astra-1	RCA Astro-Electronics	—	Ariane 4	Communications-Ku Band. 1988 Launch.
MEXICO				
Mexico 1, 2	Hughes	1,467	Space Shuttle	Domestic comm. 6/4 & 14/12 GHz/Ap. 85; Sept. 85.
NATO				
NATO 3A, B, C	Ford Aerospace/NATO NICS	1,545	Delta 3914	Communications/4-22-76,1-27-77,11-18-78.
NATO 3D	Ford Aerospace/NATO NICS	1,675	Delta 3914	Comm., N. Hemisphere and Europe/9-84.
SWEDEN Swedish Space Corp.				
Tele-X	Aerospatiale	2,658	Ariane 2	Direct broadcast, video data trans./4-89.
Viking	Saab Space/Boeing Aerospace	1,179	Ariane	Electrical, magnetic, auroral studies/1985.
USSR				
Cosmos Series	—	200-10,500	Various	Observation, research, scientific applications, ferret, and hunter-killer satellites launched from Tyuratam (5-26-62), Kapustin Yar (3-16-62) and Plesetsk (3-17-65). Intercosmos carrier Soviet Bloc payloads.
Synchronous Cosmos	—	—	Proton SL-12	Technology/military EW sats. Cosmos 637/3-26-74.
Meteor 2	—	—	SL-3	Temperature sounders, multispectral scanners.
Molniya 1S	—	—	Proton SL-12	First synchronous-orbiting Molniya/7-29-74.
Soyuz	—	14,500	Soyuz SL-4	Crew of 2-3 in earth orbit/4-24-67. Modified 1979.
Salyut	—	42,000	Proton SL-13	Military recon. and scientific space station; 2-4 man crew/4-19-71; 4-19-82.
Ekran/Raduga/Gorizont	—	—	Proton SL-12	Synchronous operational satcom/12-22-75
Progress	—	14,500	Soyuz SL-4	Space tanker/1/20/78
Buran (Snowstorm)	—	235,000	Energia	Re-usable shuttle vehicle. 1st. Flt./1-15-88.
WEST GERMANY				
SPAS-01/01A	MBB	3,306	Space Shuttle	Reusable satellite/multipurpose free-flyer/6-18-83, 2-2-84.
ROSAT	Dornier Systems DFVLR/Goodard S.F.C.	5,400	Delta 2	German built, large X-Ray telescope with German, U.S. & U.K. experiments/TBD.
DFS Kopernikus-DFS 1,2	Siemens/MBB	3,080	Ariane 4	German Post Office communications satellites. 6-89, early 1990.
NASA/BMFT	JPLAB/MBB	5,883	Space Shuttle	Jupiter exploration. Launched 10-18-89. 8 year mission,

CATALOGUE OF ESSENTIAL ELEMENTS OF GEOGRAPHIC INFORMATION[1]

DIVISION A: LOCATION

This division contains information that provides the foundations upon which all spatial references are based and communicated. This is the field usually associated with cartography.

01: GEOLOCATION

01 01 Available Products

Standard map and chart series (JOG, ONC, etc)
Non-standard graphics (OPM, pictomaps, plans, etc)
Digital map products (point position databases etc)
Tabular data (almanacs, pilots, etc)

01 02 PRODUCT STANDARDS

Georeferencing system (AMG, UTM, WGS, lat long, etc)
Horizontal and vertical datums
Scale Projection
Accuracy
Currency

01 03 INFORMATION SOURCES AND AVAILABILITY

Aerial photography
Satellite imagery (Landsat, SPOT, etc)
Geodetic control network (survey monuments, levelling stations, etc)
Ground truth/ground control data ('map intelligence', GPS observations, gravimetric data, hydrographic data, etc)
Photogrammetric resources
Image processing systems
Astronomical observatories
Satellite tracking facilities
Map and chart compilation facilities (AUTOMAP, AUTOCHART, etc)
Map and chart reproduction facilities
Map and chart storage and distribution
Source archives
Directory of sources and authorities
Level of public access

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[1] Granger, K., *Geographic Information and Remote Sensing Technologies in the Defence of Australia*, Centre for Resource and Environmental Studies, Australian National University, Canberra, January 1990, Annex B.

DIVISION B: PHYSICAL

This division provides information that describes the face of the Earth, the atmosphere that surrounds it and the plant and animal communities that inhabit it. This field draws information mainly from the physical sciences such as geology, geomorphology, meteorology and biology.

02: PHYSIOGRAPHY

02 01 GEOLOGY

Structure (rock type, stratification, etc)
Processes (depositional, volcanic, tectonic, etc)
Hazards (earthquake, volcanic eruption, etc

02 02 SOILS

General classification (soil group, colour, structure, profile depth, etc)
Agricultural potential (pH, friability, moisture content, etc)
Mechanical characteristics (strength, grain size, plasticity, trafficability, etc)
Hazards (mud slide, etc)

02 03 OTHER SURFACE MATERIALS

Rock outcrops
Permanent snow-fields and ice
Evaporites (salt pans, etc)
Open water
Hazards (avalanche, etc)

02 04 HYDROLOGY

Ground water (water table depth, etc)
Surface drainage type (Eg. rivers, streams, lakes, swamps; nature Eg. intermittent, ephemeral, perennial, tidal; etc)
Surface drainage characteristics (flow velocity, depth, bank height, gap width, seasonality, natural & man-made barriers, etc)
Surface drainage density and pattern
Run-off
Erosion and erosion controls
Hazards (flood, salination, pollution, etc)

02 05 TERRAIN

Elevation (altitude, relief)
Slope (angle, aspect)
Geomorphology (landforms, caves, etc)
Micro-relief (roughness, grain, etc)

02 06 LITTORAL

Shore line
Beaches (gradient, composition, exposure, etc)
Immediate hinterland
Reefs (nature Eg. coral or rock; form; passages; etc)
Tidal and supra-tidal zones
Off-shore islands
Hazards(tsunami, storm surge, etc)

02 07 OCEAN

Seabed topography
Bathymetry
Tides
Currents
Salinity
Turbidity
Water temperature
Sea state
Hazards (sea ice, pollution, etc)

02 08 INFORMATION SOURCES AND AVAILABILITY

Monitoring & recording system (location, instrumentation, history, etc)
Data standards and reliability
Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Level of public access

03: CLIMATE

03 01 PRESSURE

Pressure systems
Winds (surface, upper atmosphere, local, etc)
Hazards (wind sheer, turbulence, tropical cyclone, etc)

03 02 TEMPERATURE

Value (actual, averages, etc)
Variability (range, maximum, minimum, extremes, etc)
Hazards (heat stress, expansion, contraction, etc)

03 03 PRECIPITATION

Form (rain, snow, hail, dew, frost, etc)
Volume (actual, averages, etc)
Variability (extremes, seasonality, etc)
Cloud formation
Effects on visibility
Humidity
Evaporation
Hazards (drought, fog, deluge, etc)

03 04 OTHER ATMOSPHERIC CONDITIONS

Solar radiation
Ionospheric predictions
Lightning
Pollution
Hazards (lightning strike, skin cancer, etc)

03 05 WEATHER

Current or immediate
Forecast (short, medium, long range)

03 06 INFORMATION SOURCES AND AVAILABILITY

Monitoring & recording systems (location, instrumentation, history, etc)
Data standards and reliability
Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Level of public access

04: BIOLOGY

04 01 VEGETATION

Type and distribution (forest, woodland, grassland, swamp, dry crops, wet crops, plantations, etc)
Species composition
Structure (canopy height & closure, stem spacing, undergrowth, density, etc)
Utilization (lumber, thatch, fibre, food, medicines, etc)
Seasonality (evergreen, deciduous, fruiting, harvest, etc)
Hazards (fire, poisonous, sting, pest, etc)

04 02 TERRESTRIAL ANIMALS

Types and distribution (mammals, birds, reptiles, insects, wild, feral, domesticated, etc)
Utilization (food, draught, etc)
Seasonality (migration, breeding cycle, etc)
Hazards (venomous, biting, pest, disease vector, etc)

04 03 MARINE ANIMALS

Types and distribution (mammals, fish, crustacea, molluscs, etc)
Utilization (food, pearl/shell, etc)
Seasonality (migration, spawning, etc)
Hazards (venomous, poisonous, biting, disease vector, etc)

04 04 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

DIVISION C: HUMAN

The information in this division provides insight into the human population, its distribution, and its cultural and political attributes. This is drawn largely from the social sciences such as demography, anthropology and political science.

05: POPULATION

05 01 SIZE

De jure
De facto
Patterns of growth or decline
Causes of growth or decline

05 02 STRUCTURE

Age/sex
Vital rates (birth, death, fertility, etc Ethnic composition

05 03 DISTRIBUTION

Urban
Rural
Density
Patterns of change
Causes of change

05 04 MIGRATION

Form (seasonal, short term, long term, permanent) Origin/destination
Size
Composition

05 05 INFORMATION SOURCES AND AVAILABILITY

Census history
Census boundaries (collectors districts, etc)
Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

06: SETTLEMENT

06 01 SETTLEMENT PATTERN

Characteristics (permanent, semi-permanent, shifting)
Function (urban, suburban, urban fringe, rural)
Distribution (high, medium or low density)

06 02 STRUCTURE

Dominant building material (brick, timber, wood, fibro, etc)
Dominant building form (single story, high set, multi story, etc)
Layout (linear, regular grid, irregular, etc)
Streetcar (tree plannings, fences, lighting, width of road, pavement, lines-of-sight, security fencing, etc)
Open spaces (parks, sporting fields, golf courses, etc)

06 03 REGULATION

Zoning (residential, light industrial, commercial, etc)
Engineering codes ('cyclone proofing', etc)
Environmental impact statements
Jurisdictions (state government, local or county council, etc)

06 04 EMERGENCY ARRANGEMENTS

Hazard history (flood prone, etc)
Emergency shelter (designated centres, tents, caravans, etc)
Evacuation centres

06 05 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities(thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

07: CULTURE

07 01 LANGUAGE

Official
Lingua franca
Local (including dialects)
Literacy
Place names
Translator and interpreter resources

07 02 RELIGION

Status (official, tolerated, banned, etc)
Adherence
Distribution
Resources and services (churches, schools, businesses, etc)
Jurisdictions (parish & diocesan boundaries, etc)
Hazards (source of conflict, etc)

07 03 CUSTOM

Status
Significance
Cult and pseudo-religious organizations
Taboos (sacred sites, etc)
Hazards (source of conflict, etc)

07 04 CULTURAL

Arts (theatres, galleries, libraries, etc)
Heritage (archaeological sites, monuments, historic buildings, etc)

07 05 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

08: POLITICS

Within this, and the next group (SOCIAL) the following generic elements are grouped as 'Basic characteristics ':

Name
Structure and organization
Responsibilities
Status
Level (national, state, regional, local)
Personnel (number, skill levels, training)
Management
Personalities;

and the following are grouped as 'Physical assets':

Location (including elevation)
Dimensions (including orientation)
Classification
Construction
Capacity, significance and vulnerability
Utilization
Alternatives.

08 01 EXECUTIVE

Basic characteristics
Physical assets (office, official residence, etc)

08 02 LEGISLATURE

Basic characteristics
Physical assets (parliament building, support offices, etc)

08 03 JUDICIARY

Basic characteristics
Physical assets (courts, prisons, etc)

08 04 ADMINISTRATION

Basic characteristics (departments, agencies, statutory bodies, etc)
Physical assets (headquarters, offices, outstations, etc)

08 05 DISCIPLINED FORCES

Basic characteristics (army, navy, air force, militia, paramilitary, police, fire service, civil defence, search & rescue, volunteer coast guard/watch, etc)
Physical assets (headquarters, outposts, etc)

08 06 EXTERNAL RELATIONS

Basic characteristics (treaties, pacts, agreements, etc)

Physical assets (diplomatic missions, etc)
Source of conflict (international, interstate, intrastate, etc)

08 07 JURISDICTIONAL BOUNDARIES

Political (international, state, local government, etc)
Administrative (police districts, PP Board districts, etc)
Other (post code districts, etc)

08 08 LAND TENURE

Basic characteristics (lands departments, land councils, customary, etc)
Physical assets
Cadastre

08 09 UNIONS AND ASSOCIATIONS

Basic characteristics (trade unions, guilds, lodges, professional associations, employer groups, etc)
Physical assets (offices, meeting places, etc)
Level of influence (compulsory, regulatory, etc)
Source of conflict (industrial relations, political dissent, etc)

0810 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

09: SOCIAL

09 01 HEALTH SERVICES

Basic characteristics (medical, dental, ambulance, etc)
Physical assets (hospitals, aid posts, pharmacies, clinics, radiology units, pathology labs, recompression facilities, etc)
Health risk factors (disease prevalence Eg. endemic; diet etc)

09 02 EDUCATION

Basic characteristics (primary, secondary, tertiary, special, etc)
Physical assets (schools, colleges, etc)

09 03 OTHER WELFARE SERVICES

Basic characteristics (community services, volunteer agencies, eg. Red Cross, St Vincent de Pauls, etc)
Physical assets (hostels, shelters, etc)

09 04 CRIME

Characteristics (nature, prevalence, etc)
Distribution ('hot spots', etc)

09 05 JURISDICTIONS

Administrative (hospital districts, school areas, etc)

09 06 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities(thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

DIVISION D: ECONOMIC

This division provides information on the utilization of natural resources, the manufacture of goods, the provision of services and the infrastructures that support those activities. It draws information from economics, commerce and engineering disciplines.

Throughout this division the following generic elements are grouped as 'Basic characteristics':

Name
Operating or administering body
Organization and management
Manpower (skilled, unskilled, training, etc)
Personalities;

and the following are grouped as 'Physical assets':

Location (including elevation)
Dimensions (including orientation)
Classification
Construction
Capacity, significance and vulnerability
Utilization
Alternatives.

10: PRIMARY PRODUCTION

10 01 AGRICULTURE

Form (market garden, cereal & fodder crops, stock grazing, animal husbandry, fibres, vineyards, orchards, plantations, etc)
Basic characteristics
Physical assets (bulk storages; basic processing Eg. abattoirs, flour mills, tanneries; specialized repair and maintenance facilities; etc)
Hazards (fire, accident, pollution, contamination, etc)

10 02 FISHERIES

Form (inland, coastal, off-shore, hatcheries 8 fish (farming, pearl culture, etc)
Basic characteristics
Physical assets (fishing fleet Eg. trawlers, factory ships; onshore processing facilities Eg. canneries & freezes; ice plants; specialized repair and maintenance facilities; etc)
Hazards (accident, pollution, contamination, etc)

10 03 FORESTRY

Form (harvesting, saw-milling, wood chip, silviculture, etc)
Basic characteristics
Physical assets (logging plant and equipment, sawmills, material stockpiles, product storage, plantations, treatment plants, specialized repair & maintenance facilities, etc)
Hazards (fire, accident, pollution, etc)

10 04 MINING

Form (ferrous and non-ferrous minerals; fuels Eg. coal, uranium & petroleum; non-metallic Eg. asbestos; materials Eg. clay, rock & sand; etc)
Basic characteristics
Physical assets (ore body, mine, extraction plant, basic processing and storage, material stockpiles & handling, product storage, waste treatment, dedicated repair & maintenance facilities, etc)
Hazards (fire, accident, pollution, etc)

10 05 JURISDICTIONS

Administrative (license areas, exclusive zones, etc)
Commercial (marketing authority, etc)

10 06 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

11: SECONDARY INDUSTRY

11 01 BASIC PROCESSING

Form (food & beverage processing Eg. bakeries & breweries; timber products; oil refining; metal smelting; cement production; textile manufacture; chemical & industrial gas production; dedicated repair and maintenance services; etc)
Basic characteristics
Physical assets (plant and equipment, associated material stockpiles & handling, storage facilities, spare parts inventory, waste disposal, etc)
Hazards (fire, accident, pollution, etc)

11 02 FABRICATION

Form (heavy industry Eg. ship building & heavy engineering; vehicle building; aircraft construction; light industry Eg. appliance, clothing & furniture manufacture; dedicated repair & maintenance services; etc)
Basic characteristics
Physical assets (plant and equipment, material stockpiles and handling, product storage facilities, waste disposal, spare parts inventory, etc)
Hazards (fire, accident, pollution, etc)

11 03 JURISDICTIONS

Administrative
Commercial (sales territories, distributorships, etc)

11 04 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

12: TERTIARY INDUSTRIES

12 01 RESEARCH AND DEVELOPMENT

Form (pure research, applied research)
Basic characteristics
Physical assets (laboratories, test facilities, specialized repair & maintenance facilities, etc)
Hazards (accident, etc)

12 02 CONSTRUCTION INDUSTRY

Form (design & architecture; horizontal construction Eg. roads & airfields; vertical construction Eg. buildings; tunnelling; concrete fabrication; repair and maintenance services; etc)
Basic characteristics
Physical assets (design shops; workshops; material stockpiles Eg. cement & lumber; plant & equipment pools; support facilities Eg. concrete batching plants; repair & maintenance facilities; etc)
Material resupply schedule
Reserve capacity
Hazards (accident, etc)

12 03 SERVICE INDUSTRIES

Form (computer services, hospitality, financial services, insurance, technical maintenance & repair services, laundries & domestic services, etc)
Basic characteristics
Physical assets (offices, accommodation Eg. hotels & resorts; specialist facilities Eg. secure storage; specialized repair and maintenance facilities; spare parts inventories; etc)
Hazards (accident, etc)

12 04 JURISDICTIONS

Administrative (tourist promotion areas, etc)
Commercial (distributorships areas, etc)

12 05 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

13: INFRASTRUCTURE AND LOGISTICS

13 01 LAND TRANSPORT

Cross country movement (vehicle-specific) (speed over ground, obstacles, avenues of advance, etc)
Infrastructure basic characteristics (roads, railways, rapid transit, pipelines, etc)
Physical description (tracks, roads, permanent ways, bridges, tunnels, ferries, pipelines, pumping stations, construction & repair facilities, material stockpiles, etc
Sectionalization (nodes, links, connectivity, etc)
Interfaces (road/rail, port, airfield, etc)
Transport services basic characteristics (road transport, rail transport, repair and maintenance services, etc)
Physical assets (vehicle park; rolling stock; cargo & passenger handling facilities; specialized resources Eg. low loaders & turn tables; repair and maintenance workshops; spare parts inventories, etc)
Services (scheduled, charter, etc)
Reserve capacity
Serviceability
Hazards (accident, pollution, etc)

13 02 WATER TRANSPORT

Infrastructure basic characteristics (ports, canals, pilot services, repair & maintenance services, etc)
Physical assets (anchorages; wharves; canal systems ie locks & tows; mooring buoys; landing craft hards navigation beacons; passenger and cargo facilities; bunkering; dry docks, slipways & repair yards; port maintenance stores and material; etc)
Interfaces (road, rail, pipeline, etc)
Maritime services basic characteristics (shipping services; naval sealift; harbour services Eg. tugs & lighters; port services Eg. customs & stevedoring; ship repair and maintenance; etc)
Physical assets (shipping register; naval sealift order-of-battle; specialized resources Eg. tankers; spares inventory; etc)
Services (scheduled, charter, etc)
Reserve capacity
Serviceability
Hazards (accident, pollution, etc)

13 03 AIR TRANSPORT

Infrastructure basic characteristics (airfields, flying boat bases, helicopter pads, repair and maintenance services, etc)
Physical assets (runways; parking aprons; lighting; ground services Eg. fuel supply, auxiliary power & oxygen; navigation aids Eg. NDB & INS calibration points; crash & fire services; cargo and passenger facilities; maintenance plant and material stockpiles; etc)
Aviation services basic characteristics (aviation industry, military airlift, aeronautical sciences, aircraft repair and maintenance services, noise curfews, etc)
Physical assets (civil aircraft register; military airlift order of-battle; air traffic control; met services; specialized facilities Eg. parachutes; dedicated repair workshops & spares inventory; etc)
Services Scheduled, charter, etc)
Reserve capacity Serviceability
Hazards (accident, etc)

13 04 POWER SUPPLY

Infrastructure basic characteristics (generation, reticulation, installation, maintenance, etc)
Physical assets (generation Eg. thermal, diesel, hydro, solar, etc; reticulation Eg. transformers, control centres, transmission lines, etc; dedicated workshops & material stockpiles; spares inventory; etc)
Characteristics (voltage, cycles, etc) Sectionalization (nodes, links, connectivity, etc)
Reserve capacity (stand-by generators, etc)
Serviceability
Hazards (accident, etc)

13 05 COMMUNICATIONS

Infrastructure basic characteristics (telecommunications, broadcast, postal services, couriers, print media, repair & maintenance services, etc)
Physical assets (cable, microwave, satellite, telephone, telex, facsimile, radio broadcast, TV broadcast, data transmission, printing and publishing, dedicated maintenance workshops & spares inventory, etc)
Sectionalization (links, nodes, connectivity, networking, etc)
Reserve capacity (stand-by transmitters, etc)
Serviceability

13 06 FUEL SUPPLY

Products (oil, petrol, diesel, Lubricants, LPG, coal, firewood, etc)
Basic characteristics (bulk storage & distribution; retail distribution; safety, repair & maintenance services; etc
Physical assets (bulk tankage; drum and tanker filling hydrants; mobile storage Eg. bladders & tanks; dedicated fire & safety assets; dedicated workshops & spares inventory; etc)
Resupply schedule
Reserve capacity
Serviceability
Hazards (fire, accident, pollution, etc)

13 07 WATER SUPPLY

Basic characteristics (supply, treatment, reticulation, irrigation systems, repair & maintenance services, etc)
Physical assets (source Eg. location, quantity & potability; pumping stations; treatment works; storage Eg. tanks, weirs, reservoirs; reticulation system; material stockpile; dedicated workshops & spares inventory; etc)
Reserve capacity
Serviceability
Hazards (pollution, contamination, etc)

13 08 WASTE TREATMENT

Basic characteristics (sewage, garbage, toxic nuclear waste, undertakers, pollution control, repair & maintenance services, etc)
Physical assets (sewage treatment; garbage disposal; toxic waste handling, storage & disposal; nuclear waste handling & treatment; cemeteries & crematoriums; pollution monitoring; pollution clean-up resources; material stockpiles; workshops & spares inventory; etc)
Reserve capacity
Serviceability
Hazards (accident, breakdown, spillage, etc)

13 09 FOOD STORAGE AND DISTRIBUTION

Basic characteristics (bulk storage & distribution, retail distribution, repair & maintenance services, etc)
Physical assets (warehousing; cold storage; bulk storage; retail stores; markets; liquor outlets; specialized repair facilities Eg. refrigeration; etc)
Resupply schedule
Reserve capacity
Serviceability
Hazards (contamination, etc)

13 10 OTHER ESSENTIAL STORAGE AND DISTRIBUTION

Products (clothing; footwear; toiletries & hygiene; drugs & medicines; chemicals Eg. insecticides; explosives; industrial gases; etc)
Basic characteristics (bulk storage & distribution, retail distribution, repair & maintenance, etc)
Physical assets (warehousing; specialized storage Eg. bunkered storage for explosives; specialized workshops & spares inventory; etc)
Resupply schedule
Reserve capacity
Serviceability
Hazards (fire, pollution, etc)

13 11 JURISDICTIONS

Administrative (air traffic control zones, water board catchments, county council supply areas, etc)
Commercial (distribution zones, dealership territories, etc)

13 12 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities (thematic maps, reports, government agencies, etc)
Data standards and reliability
Level of public access

DIVISION E: SPACE

This division provides information on extra-terrestrial issues. It draws information from astronomy and other space sciences.

14: SPACE

14 01 ASTRONOMY

Sun (time of rise, time of set, etc)
Moon (phases, time of rise, time of set, etc)
Stars and planets (positions, time of rise, time of set, etc)

14 02 SATELLITES

Function (communications, navigation, data relay, imaging, intelligence collection, scientific, meteorological, SAR, etc)
Orbital parameters (elevation, inclination, period, satellite ephemeris etc)
Operational parameters (frequencies, footprint, spatial & spectral resolution, etc)
Status (operational, reserve, dead, etc)
Access (open, commercial, military, etc)

14 03 INFORMATION SOURCES AND AVAILABILITY

Directory of sources and authorities (thematic charts, almanacs, government agencies, etc)
Data standards and reliability
Level of public access

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BOOKS

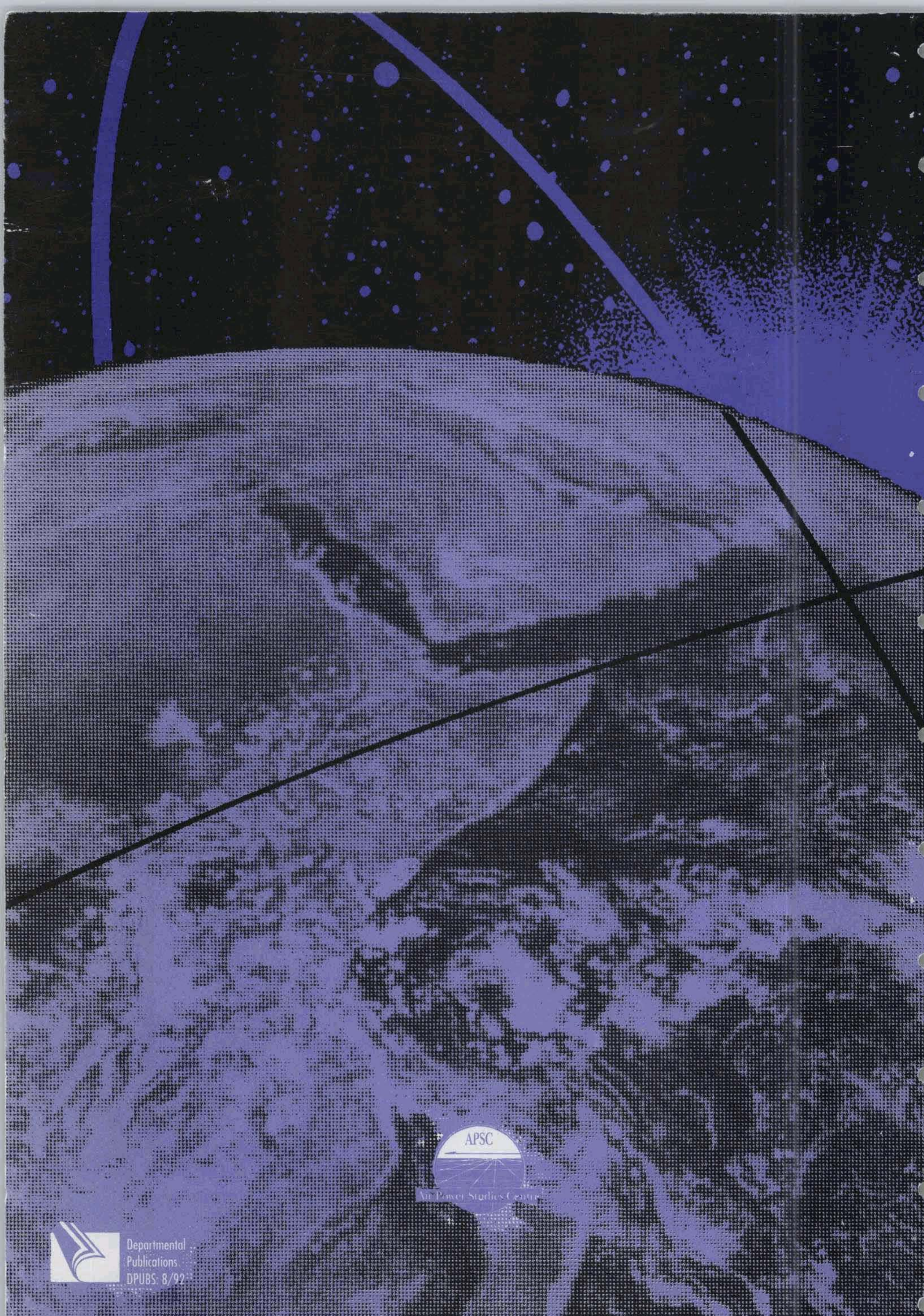
The Air Power Manual
RAAF, Air Power Studies Centre, Canberra, 1990

The Third Brother
by Coulthard-Clark, C.D., Sydney, Allen & Unwin, 1991

The Decisive Factor
Stephens, A.W. & O'Loghlin, B.,(eds), Canberra, AGPS, 1990

Smaller but Larger - Conventional Air Power into the 21st Century
Stephens, A.W.,(ed), Canberra, AGPS, 1991

Air Power Reading Guide
RAAF,Air Power Studies Centre, Canberra, 1991



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