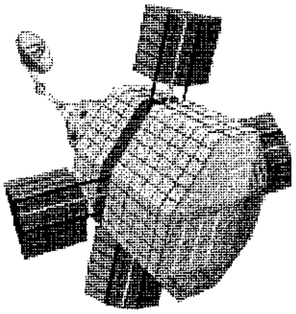
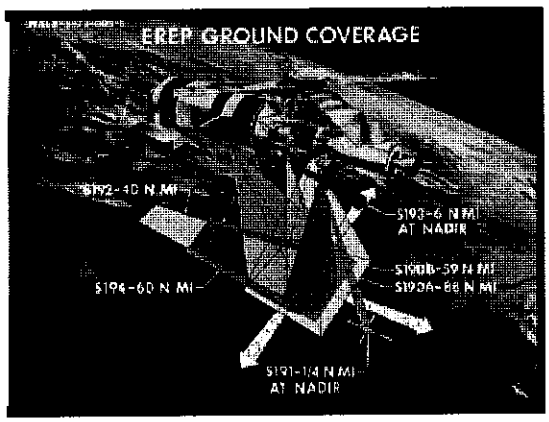


The Potential of Satellites for Wide Area Surveillance of Australia



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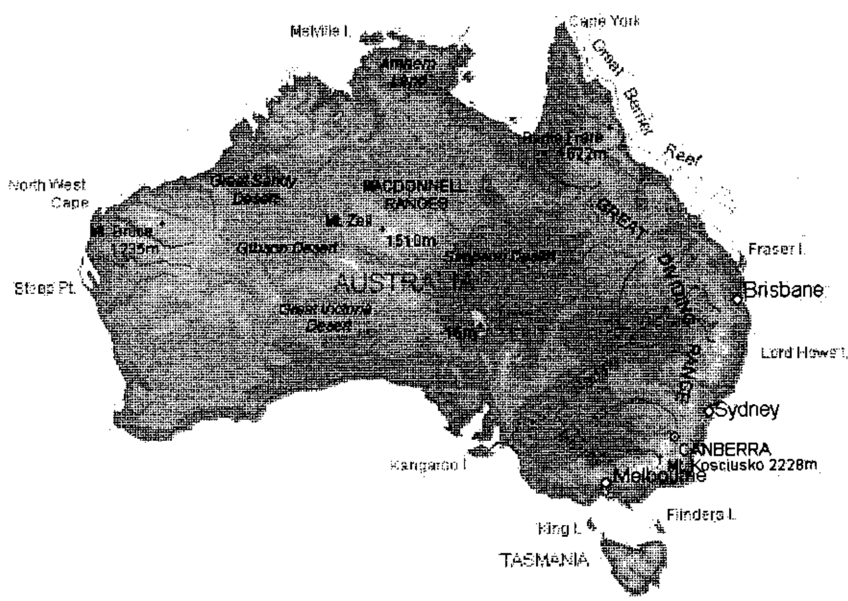

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THE POTENTIAL OF SATELLITES

FOR WIDE AREA SURVEILLANCE OF AUSTRALIA

By

Squadron Leader Wayne Gale

Royal Australian Air Force
Air Power Studies Centre

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PREFACE

This research has been conducted by Squadron Leader Wayne Gale as part of the Chief of the Air Staff Fellowship program, established in 1990. The capabilities of existing and proposed future satellite sensors are examined for their ability to provide wide area surveillance of Australia, and recommendations are made regarding future potential of space-based surveillance.

Australia's fundamental wide area surveillance needs are examined and the characteristics of a surveillance capability are outlined. This is followed by a review of existing and planned area surveillance capabilities. The space environment, remote sensing and spaceborne sensors fundamentals are then summarised to outline the advantages and limitations of conducting surveillance from space. Finally a systems study approach is used to examine the potential of space-based surveillance sensors, including existing and near future technologies, to address the shortfalls in Australia's wide area surveillance capabilities. This systems approach provides a methodology for analysing surveillance system options and gives a readily adaptable framework within which additional research, future system options, changed priorities and new requirements can be incorporated.

Acknowledgements

During my research I have had the opportunity to discuss and research aspects of satellite systems, remote sensing, military systems and operations with a number of industry, academic and defence experts in Australia. I have not documented their contributions individually, but it is worthwhile to recognise that considerable space systems expertise exists within Australia.

I wish to thank Squadron Leader Tony Forestier for his assistance throughout the year, in particular for his contributions to the structural development of my work and for our numerous discussions on remote sensing and military operations. I am grateful for the academic freedom Group Captain Hamwood has allowed me during the year. My thanks also go to Squadron Leader Kevin Davey, for his comprehensive review of my initial draft.

Finally, I deeply appreciate the support of my wife, Margaret, who has patiently shouldered additional family responsibilities while I developed this work.

Vita

Wayne Gale is an Electronics Engineer in the Royal Australian Air Force (RAAF), having served for 21 years as of January 1992. After joining the RAAF in 1971, he trained as an Instrument Fitter until 1973 and worked mainly on Mirage aircraft instrumentation, flight controls and navigation systems for five years.

In 1982 he completed Bachelor of Engineering in Electronics Engineering with distinction at the Royal Melbourne Institute of Technology (RMIT). He was commissioned in the RAAF and has had numerous engineering posts including: Officer in Charge of ground radio, radar and navigation equipment maintenance; systems engineer responsible for installation of computers, data communications and microwave radio link equipment; engineer in charge of aircraft radar warning receiver software development; and instructor of communications doctrine and procedures for joint warfare operations.

In May 1987, he was posted to the United States Air Force Institute of Technology, Wright Patterson Air Force Base, Dayton, Ohio, and graduated with the degree of Master of Science in Space Operations in December 1988.

In January 1991 he was posted to the Air Power Studies Centre, RAAF Base Fairbairn, ACT, to undertake Fellowship research.

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DEFINITIONS

This section provides a number of definitions used in this book.

a. Targets. Targets are objects, places, structures, persons and the characteristics by which they can be detected, classified and identified or described.

b. Surveillance. The systematic observation of aerospace, surface and subsurface areas, places, persons, or things, by aural, electronic, photographic, or other means.[1]

c. Tactical Surveillance. The systematic observation of aerospace, surface and subsurface places, persons, or things, where the time between observations is critical.

d. Strategic Surveillance. The systematic observation of target areas where the time between observations is not a critical factor.

e. Reconnaissance. A mission undertaken to obtain by visual observation or other detection means, 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.[2]

f. Strategic Intelligence. Intelligence which is required for the formation of policy and military plans.

g. Remote Sensing. The measurement of the physical state and properties of an object without touching.[3]

h. Data Fusion. The compilation and integration of related data from a number of either local or remote sensors or sources, in order to provide additional and more accurate information about a target.

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1 *Australian Joint Service Publication JSP(AS)101*, Part 1, Headquarters Australian Defence Force, Edition 3, February 1984, p S-25.

2 ibid, p R-7.

3 Griersmith, D.C. and J. Kingwell, *Planet Under Scrutiny - An Australian Remote Sensing Glossary*, Australian Government Publishing Service, Canberra, April 1988, p 57.

CHAPTER 1

THE POTENTIAL OF

SATELLITES FOR WIDE AREA SURVEILLANCE OF AUSTRALIA

Introduction

> The Australian Defence Force requires a manifest capability to conduct surveillance of our vast sea and air approaches. The capability must provide the means to detect, identify and, if necessary respond to sea and air activity in our sovereign air and sea space.[1]

Australia's need to regularly monitor the land and maritime approaches is a vital one for defence, security and economic reasons. The Defence of Australia 1987 (DOA87) policy paper supports this with the statement that two Australian Defence Force (ADF) development priorities are intelligence and surveillance.[2] However, the assets available are inadequate to conduct surveillance to satisfy military or civil requirements across the enormous region that Australia has declared an interest in. The thesis is that satellite sensors may be able to address this problem since they can observe part or all of the Earth rapidly and regularly. This book, therefore, examines the potential of space-based sensors to provide wide area surveillance capabilities for Australia in the future. A systems study approach is used to examine a number of typical satellite sensor types and evaluate their expected performance and effectiveness for surveillance over the next 15 years.

While it is recognised that satellite systems are unlikely to provide a complete surveillance solution for Australia in the near future, their Earth area coverage capability far surpasses that of conventional sea, air and ground systems. However, sea and air platforms will still be needed to conduct surveillance of limited areas, reconnaissance, and if necessary, intercept targets. In addition, the exploitation of information obtainable from the sensors and systems available is vital to make the best use of all surveillance resources.

The Systems Approach

Chapter's Two and Three illustrate the need and extent of the problem Australia has in providing adequate wide area surveillance. The following two Chapters are introductory material, provided for understanding of the satellite sensor system analysis in Chapter Six, and can therefore be skimmed or ignored by those readers familiar with space systems principles and sensors. Chapter Six uses a systems study approach to analyse typical sensors and systems to determine their suitability for Australia's

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1 *The Defence of Australia 1987*, Australian Government Publishing Service, Canberra, March 1987, p 34.

2 ibid, p 32.

surveillance needs. This technique provides a framework to allow users to readily review and re-compile the analysis if required.

Every attempt has been made to provide valid conclusions, but there are some subjective aspects in Chapter Six where the author has used personal judgement. These aspects include: the potential sensor options, criteria used to assess options, measures of importance between different criteria and sensor performance evaluations. The potential for disagreement with these subjective judgements is recognised, which was one of the main reasons for using the systems study approach.

Australia's Surveillance Needs

The ADF, as with other defence forces, has a mission to maintain military control over national territory, airspace and territorial waters. To achieve this, the ADF needs to collect intelligence throughout the area of interest and conduct operations across Australia, its territories and the maritime approaches. Government authorities are also interested in the detection and prevention of illegal fishing, drug trafficking, illegal immigration and wildlife smuggling, and also the monitoring of land and ocean resources. As an example, the cost to Australia's livestock industry of illegally imported and diseased animals could be enormous. These factors indicate that Australia needs a substantial surveillance capability to ensure that national defence and economic security needs are satisfied.

Australia has about 17 million people on an island continent with a land area of about 10 million square kilometres; an economic resource zone extending to 200 nautical miles from territorial coastlines; a population is distributed mainly on the East coast and many areas are sparsely populated, particularly in the North and North West; and an area of direct military interest (ADMI) occupying about one tenth of the Earth's surface[3]. For strategic intelligence, surveillance beyond the ADMI is also desirable. Maintaining surveillance of all this region is difficult however with a small defence force and few civil surveillance assets.

Surveillance and reconnaissance are conducted across the region by the ADF and the Australian Coastwatch Service (ACS), using conventional sea, air and land resources. However, these conventional capabilities cannot be considered as wide area surveillance assets since they are generally limited in terms of coverage speed and area viewing capability. The Jindalee operational radar network (JORN), currently under development, is the only true wide area surveillance capability that Australia has planned for the future, although airborne early warning aircraft may be able to provide some additional capability in the future.

Both the ADF and ACS are physically unable to monitor all incursions into the economic resource zones, let alone all the ADMI. Conventional surveillance assets include RAN patrol boats and ships, submarines, RAAF P3C maritime patrol aircraft, air defence radars, Coastwatch aircraft and patrol vessels, and various ground resources. JORN development has been pursued, at a cost of nearly $1,000 million, to enable a large part of the Northern approach to Australia to be monitored for air and sea traffic.[4] This

3 ibid, p 2.
4 Stackhouse, J., 'Jindalee Project Proceeding on Target', *Australian Aviation*, p 89.

Northern region is the priority because an aggressor could rapidly act through the chain of islands to the North. Focusing attention on this region is justifiable, but JORN still does not monitor all the ADMI and both the detection and area coverage performance will vary significantly with ionospheric changes, particularly during day/night transitions and solar disturbances.[5]

Space-based assets are already used in support of a number of Australia's key strategic surveillance activities, with reliance on foreign satellite networks for weather forecasts, and for ocean and land resources monitoring. The potential of these systems indicate the long term benefits and potential uses of space-based surveillance. However, the perceived high cost of purchasing and maintaining a space-based capability is generally uppermost in the minds of planners. Space systems have been expensive in the past but spacecraft and sensor technology advances in small satellite systems are of particular interest since they may provide the basis for an affordable space-based surveillance capability for Australia in the future.

Australia can benefit in many ways from involvement in space programs, apart from just obtaining a surveillance capability. Some of these benefits include: industrial and economic development opportunities, participation in the research and development of new technologies, technology transfers, and scientific advancement opportunities from research and development spin-offs.[6] The technological and industrial skills required to develop spacecraft and the supporting infrastructure encompass a vast field of expertise including: project management, logistics, fundamental sciences, and also mechanical, electrical, electronic, aeronautic, astronautics, computer and software engineering. These skills would enhance Australia's long term industrial, economic and technological capability and ultimately improve international competitiveness by moving away from the existing resource based economy.

Australia's long term involvement in the development of a significant space-based capability for surveillance needs to be examined in detail. However, this study only examines the suitability of satellite sensors and systems to satisfy Australia's wide area surveillance needs.

Limitations

In order to limit the scope and keep the discussion at an unclassified level, the following aspects have not been examined:

a. electronic intelligence gathering from space-based platforms;

b. the potential use of surveillance data from allied sources other than commercial suppliers;

c. detailed consideration of the integration of a satellite surveillance system with other surveillance assets; and

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5 Sinnot, D.H., 'Jindalee Over-The-Horizon Radar', in Ball, D. (ed), *Air Power: Global Developments and Australian Perspectives*, Pergamon-Brassey's Defence Publishers, Rushcutters Bay, 1988, pp 230-231.

6 *A Space Policy For Australia*, Canberra Publishing Company, Canberra, 1985, pp 17-52.

d. weather surveillance using satellites.

CHAPTER 2

AUSTRALIA'S WIDE AREA SURVEILLANCE REQUIREMENTS

This Chapter examines Australia's fundamental military and civil surveillance needs and derives a number of characteristics required in the surveillance system. The discussion is not intended to focus on those aspects satellites are uniquely placed to provide, but is more concerned with the extent of the wide area surveillance problem. In order to keep this book in an unclassified form, specific and detailed surveillance needs are deliberately avoided, in favour of a more conceptual approach. However, since military force capability developments are requirements driven, essential and desirable characteristics are established for both military and civil users. These characteristics provide a focus for a surveillance system specification, and for the criteria used to analyse potential satellite sensor options.

Australia has both military and civilian requirements for surveillance of the mainland, off-shore territories and maritime approaches. Current surveillance capability developments concentrate on the North and North-West approaches, that are recognised as the main axes of military and civil threat.[1] The targets and coverage required are dependent on the specific missions of the ADF and civil organisations involved. Most of the available surveillance assets are controlled and operated by the military, but they are often used in support of civilian coastal surveillance activities. The emphasis on civil activities like coastal surveillance does not seem particularly high but it is vital to Australia's economic security and threats occur regularly.

Conventional sea and air platforms are the main components of Australia's surveillance capabilities, although JORN will be a significant step forward in wide area surveillance beyond the year 2000. The Defence assets can conduct surveillance over only part of the ADMI. This is not unreasonable, however, given the vast area involved and the limited population available to fund the capability. Surveillance to the North has priority on the basis that it is the nearest approach of any credible threat and JORN is directed Northward in response to this need. This presumes that an aggressor will not have the capability to act through other parts of Australia's coastline. The emphasis is logical, however, since the overall surveillance task is enormous and even the United States of America (USA), which has a similar continental area, has difficulty funding a complete wide area surveillance system.

To satisfy surveillance requirements a system with a range of sensors and characteristics will be required. They may not all be space-based sensors but space is the ideal location from which to conduct surveillance of all the region of interest. Consequently, spaceborne sensors may be able to address many of Australia's wide area surveillance needs in the long term. The cost of developing extensive satellite capabilities has been very high in the past, but small satellite technologies may significantly reduce the costs in the future, while still providing a significant capability.

The fusion or integration of data from surveillance sensors and sources and centralised co-ordination is also required so that the limited resources available are fully

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1 *The Defence of Australia 1987*, Australian Government Publishing Service, Canberra, March 1987, p 20-21.

exploited. In recognition of this need within the ADF, there have been recent discussions on the potential value of data fusion for surveillance information and the initial development of Defence geographic information systems.[2]

Defence Surveillance

DOA87 identifies two overlapping areas of interest; the smaller region is the ADMI and the larger encircling area is the region of strategic interest.[3] Australia's security and sovereignty requirements within these boundaries are paramount and imply the need for the ADF to exercise military control over the continent, off-shore territories, maritime approaches and airspace. DOA87 specifies a self-reliant policy for Australia in the pursuit of national security. However, effective surveillance of the ADMI is an enormous task, given the size of the region illustrated in Figure 2.1.[4] Rapid and continuous surveillance of all the ADMI is not envisaged, since the focus of DOA87 is the Northern maritime approaches, but in the long term, the capability for surveillance of all maritime approaches is required.

Defence surveillance requirements can be separated into tactical and strategic aspects, which generally differ in terms of the time-frame involved and the target detail required. Tactical surveillance is concerned with activities such as detecting and tracking hostiles, targeting, battlefield intelligence and damage assessment, all of which can be time-critical. Strategic surveillance, however, involves activities that would normally be conducted in peace-time as preparation for military action. This includes activities such as survey, mapping and the collection of intelligence on infrastructure such as airfields, ports, buildings, factories, and weapon systems.

The surveillance products required for tactical and strategic requirements depend on user needs and the targets to be exploited. For strategic surveillance, high spatial resolutions are usually required to provide specific technical intelligence, although lower resolutions may be adequate for larger targets. Tactical surveillance may be adequately performed with low resolution sensors if just detection of targets is important, given that after detection other assets may need to be deployed for reconnaissance or interception. Multi-spectral sensors can also provide more target information than just the physical size and shape of targets. Overall these factors illustrate the need to examine and use various surveillance sensors and capabilities.

ADF Surveillance Objectives

Ideally, in order to support military operations ADF surveillance assets need to:

a. detect, track and identify aircraft, small boats, ships and submarines, day or night and in all weather conditions;

2 Personal interview with Air Commodore O'Loghlin, Director General Military Strategic Concepts (DGMSC), Headquarters Australian Defence Force (HQADF), 28 August 1991.

3 *The Defence of Australia 1987*, op cit, pp 1-2.

4 ibid.

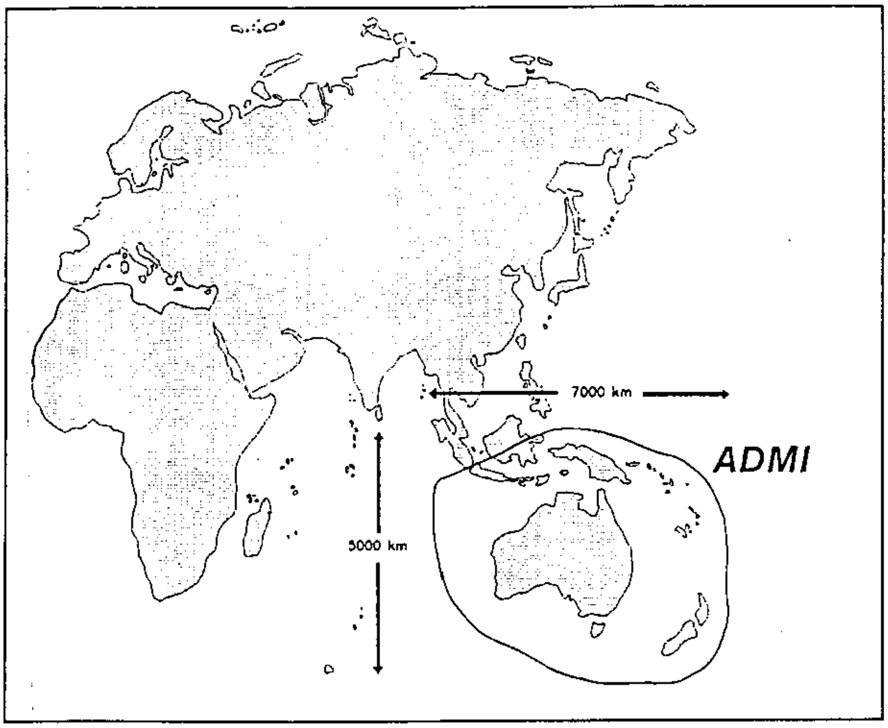

Figure 2.1 Australia's Area of Direct Military Interest[5]

b. detect, track and identify foreign military incursions and operations on Australia's territorial lands;

c. gather strategic and tactical intelligence in Australia's area of interest;

d. survey and map Australia's land and sea regions; and

e. collect meteorological data within the ADMI.

Items c, d and e do not need to be conducted by ADF assets but access to the surveillance products is required.

Civil Surveillance

There is considerable overlap between Australia's defence and civil surveillance needs, with activities like coastal surveillance, air traffic control, remote sensing, survey and mapping being common to both. The task of coastal surveillance is a significant one given that the declared exclusive economic zone - a zone to which Australia has claimed exclusive resource rights - extends to 200 nautical miles from the territorial coastline, as illustrated in Figure 2.2. The problem for Australia is that having declared this zone, it is obliged to police the region, otherwise there would appear to be no point in making the claim. A limited civil coastal surveillance capability exists at the moment with the civil Coastwatch Service, supplemented with ADF support. Recent well-publicised failures of the system to detect the arrival of illegal immigrants into the Northern Territory

5 Derived from *The Defence of Australia 1987*, op cit, pp 1-2.

has highlighted the heavy reliance placed on intelligence to support the inadequate physical surveillance capabilities.

Coastal surveillance and air traffic control are two civil activities that require similar area coverage and response times to that required by the ADF. However, civil air traffic control is localised to regional centres and is progressing more toward the use of transponders rather than search radar for surveillance. Therefore the civil system will not be able to detect unknown aircraft, or those that do not want to be detected, at locations other than near principal airfields.

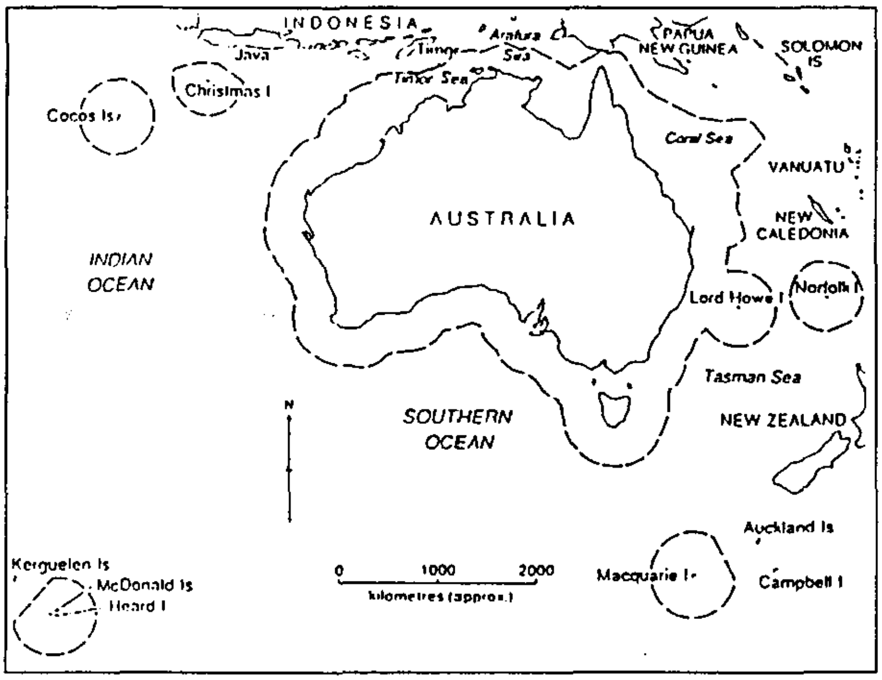

Figure 2.2 Australia's Exclusive Economic Zone[6]

Many civil surveillance applications are not time-critical and can use commercial remote sensing products. Typically, applications can be found by those responsible for the environment, weather, agriculture, natural and rural resources, forestry, customs, police, maritime safety, fisheries and wildlife, science and technology, land and surveying, seismology, shipping, intelligence, aviation, mineral resources, fire fighting, search and rescue and geology. In order to adequately provide for these applications, civil surveillance coverage would certainly need to extend at least to the limit of the resource zone around the mainland and island territories. Medium resolution strategic surveillance of this region is available from commercial satellite imagery sources in Australia, all of which use foreign owned satellites.

An example of the high potential value of remote sensing data, to a resource dependent nation like Australia, would be the need to analyse crop performance of competitive nations; which would appear to be logical for a nation trying to compete in a global resource market.[7] The only way to easily provide this capability is through the use

6 Adapted from Babbage, R., *A Coast Too Long: Defending Australia Beyond the 1990s*, Allen & Unwin Australia, Sydney, 1990, p 75.

7 These aspects were introduced during a lecture by Dr G. Harris, Director CSIRO Office of Space Science and Applications, on Remote Sensing and Global Change, CSIRO, Canberra, 14 August 1991

of space-based sensors. Less time-critical applications can be supported by imagery from commercial sources, but data on foreign competitor regions may be more difficult to obtain and could create sensitive liaison issues. Time-critical applications are more difficult to satisfy and suggest the need for an indigenous surveillance capability.

Civil Surveillance Objectives

The following list summarises surveillance objectives of civil organisations and the Government, for other than Defence:

a. detect, track and identify aircraft, ships and small vessels across Australia and out to the limit of the exclusive economic zone, day or night and in all weather conditions;

b. remote sensing of the continental and off-shore economic resource zones;

c. survey and mapping of land and sea regions; and

d. collect meteorological data in the region.

Most of these are similar to the military objectives above, although the extent of coverage is more limited. Most strategic civil surveillance needs can be satisfied with foreign owned space-based capabilities.

Australia's Surveillance System Characteristics

To specify Australia's wide area surveillance system characteristics, some of the issues to be examined include: the area of interest, target types, target information required, warning time and system availability. Essential and desirable performances are derived to satisfy existing and future surveillance needs.

Area of Interest

The areas of interest have already been described and are summarised as follows:

Military.

a. North and North-West maritime approaches - *essential*,

b. remainder of the ADMI maritime region - *desirable*, and

c. continent and off-shore territories - *desirable*.

Civil.

a. 200 nautical mile exclusive economic zone - *essential*, and

b. continent and off-shore territories - *desirable*.

Targets and Resolution Requirements

The detection of a substantial military force either by sea or air is a high priority for military surveillance. This implies a need to detect larger aircraft and medium to large vessels. In the case of civil coastal surveillance, key targets are generally smaller and surveillance is more demanding in terms of resolution and detection requirements. Typical targets have been listed in the objectives above, but the operational and physical characteristics of these targets need to be considered. Target characteristics can vary dramatically, and they include aspects such as size and shape, reflective, spectral and emission properties. The time interval between observations may also be important.

Table 2.1 provides an indication of the sensor resolution required to detect and resolve the physical characteristics of some targets. However, this table is only really relevant for visible spectrum imaging sensors, consequently it over-specifies the resolution needed to just detect targets. This means that they can indicate the size and shape of targets with reasonable accuracy but this is not necessary for 'trip-wire' type detection. For visible spectrum imagery, detection can probably be achieved if a target nearly fills the field of view of the detector. In the case of infrared sources, small but hot objects that are well contrasted against the background may be detectable in larger resolution cells, and real aperture radar sensors typically have large fields of view but can use Doppler processing to detect targets.

These considerations imply that sensor resolution does not necessarily need to be smaller than the physical dimensions of a target, and characteristics other than physical dimensions can be used to detect targets. Therefore, the specification of resolution requirements for a surveillance system is complicated by the need to consider the method of operation and characteristics of sensors, as well as target characteristics and the background expected. Nevertheless, resolution needs are initially specified here in terms of visible spectrum imaging requirements, in a similar way to Table 2.1, but resolution considered to be adequate if a target almost fills the sensor field of view. This means that the resolution in Table 2.1 is too precise for just target detection. These spatial resolution requirements are indicative of a sensor type that is in common use for surveillance. Other sensor performance aspects will be used in the analysis but they cannot be as easily specified in terms of physical target characteristics.

Maritime Vessels. Most of the vessels encountered by surveillance assets will simply be exercising their right of free passage through international waters, or conducting authorised fishing operations. The targets typically include large and small military vessels, tankers, container vessels, ocean-going fishing boats and also the small wooden hull boats that are often used by refugees. A spatial resolution of about 15 metres should be adequate to detect medium-size surface vessels, and about 60 metres is needed for vessels the size of surfaced submarines or large ships. Small wooden hull vessels about 10 metres in length may be difficult to detect with a radar sensor, but 10 metre resolution visible spectrum sensors should be adequate. The following resolution specifications are therefore proposed for visible spectrum imaging:

Table 2.1 Resolution Required For Different Levels of Precision[8]

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

Military.

a. medium-size ships - at least 15 m - *essential*, and

b. small ships - 10 m - *desirable*.

Civil.

a. fishing boats - 15 m - *essential*, and

b. wooden hull boats - 10 m - *essential*.

Submerged Submarines. These targets are difficult to detect with conventional sensors and the capability is only a concept being considered for space-based surveillance; therefore, it is not examined here.

Aircraft. Table 2.1 indicates that a resolution of 4.6 metres is required to detect small aircraft, but 10 metres is probably adequate for detection with visible spectrum imaging sensors, and 15 metres for large aircraft. Small aircraft detection is vital for civil

8 Adapted from Richelson, J., 'The Keyhole Satellite Programmes', *Journal of Strategic Studies*, Volume 7, Number 2, June 1984, p 124.

surveillance. Therefore, for military requirements a resolution of 15 metres is *essential* and 10 metres is *essential* for civil surveillance.

Strategic Intelligence. Resolutions of about 10 metres appear to be adequate to distinguish buildings and large infrastructure developments; this capability is *essential* and may be satisfied by commercial satellite surveillance. Better than one metre resolution imagery is required for more detailed intelligence, but this is only considered to be *desirable* when considering wide area surveillance requirements.

Remote Sensing. Commercial satellite sensors appear to satisfy a significant proportion of Australia's existing civil remote sensing requirements. For these applications, multi-spectral sensor specifications are generally more important than high spatial resolution. Commercial satellite sensors such as SPOT, Landsat and NOAA will provide these capabilities for the foreseeable future, consequently an Australian owned remote sensing capability is only considered to be *desirable.*

Survey, Mapping and Terrain Analysis. These activities typically use aircraft, ships, satellite and ground resources to collect, produce and validate data. Commercial satellites such as SPOT and Landsat can provide resolutions adequate for mapping to 1:100,000 scales and better, depending on sensor resolution.[9] Terrain information can be extracted from commercial multi-spectral, imagery, although ground truthing is generally required to validate the data. While the ability to conduct survey and mapping is vital for many civil and military operations, significant data collection and analysis capabilities already exist within existing commercial and military organisations; therefore, duplication of this capability is only considered to be *desirable*.

Warning and Revisit Time

As indicated in DOA87, the island chain to the North is the most credible avenue of military action against Australia. Figure 2.3 illustrates representative crossing times from the islands across the North for transport aircraft and ships. These indicate the revisit times that would be required for a surveillance system monitoring the region. After initial detection, a revisit time of about 30 minutes is needed for aircraft targets and 11 hours for ships. This is based only on distance to nearest landmass with no accounting for intelligence data or likely threat scenarios. These aspects are left to military planners and intelligence analysts, since any significant military build-up is likely to be identified by intelligence sources well before any military operations. Refugee activities across this region are said to be known to intelligence agencies very early in their transit period, according to news reports, but little action can be taken until landing appears imminent, even if detection has occurred.

The warning time for a civil surveillance system cannot be realistically specified in terms of a time period, since the activities to be monitored are restricted to

9 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, pp 19-20.

within the exclusive economic zone. Consequently a more stringent revisit time exists, even though the targets involved are generally slower than those of military interest. To satisfy defence needs, large ships and aircraft crossing the sea and air gap to the North must be detected. Therefore, a revisit time of 30 minutes is *desirable*, but it is *essential* to revisit within 90 minutes. These revisit times are also used as representative of civil surveillance since it is difficult to quantify the times needed.

Availability of Surveillance Coverage

Ideally a surveillance system should be capable of 24 hour, all weather, target detection and tracking, but no one space-based sensor is likely to provide all that is required. Visible sensors are significantly affected by poor weather and low illumination conditions, and cloud cover can be a problem for both visible and infrared sensors, particularly in the tropical Northern region that is the focus of ADF surveillance activities. Microwave radar sensors can potentially overcome the weather and lighting problems, but they have some technical, operational and cost limitations.

Given the warning times illustrated in Figure 2.3, there appears to be insufficient time available to tolerate delays in target detection due to poor weather and inadequate solar illumination. Therefore, the following ADF surveillance system availability is proposed:

a. all weather, day and night for North and North-West maritime approaches is *essential*,

b. all weather, day and night for remainder of the maritime region of the ADMI is *desirable*, and

c. daytime coverage of continent is *desirable*.

The civil surveillance system availability characteristics include:

a. all weather, day and night coverage of the exclusive economic zone is *essential*,

b. all weather, day and night coverage of the continent and off-shore territories is *desirable*,

Summary of Surveillance System Characteristics

Surveillance system characteristics for civil and military applications are summarised as follows:

Essential

a. Military - Area of Interest. - North and North-West maritime approaches,

b. Civil - Area of Interest. - 200 nautical mile exclusive economic zone,

c. Military - Resolution. - at least 15 metres for visible spectrum imaging sensors,

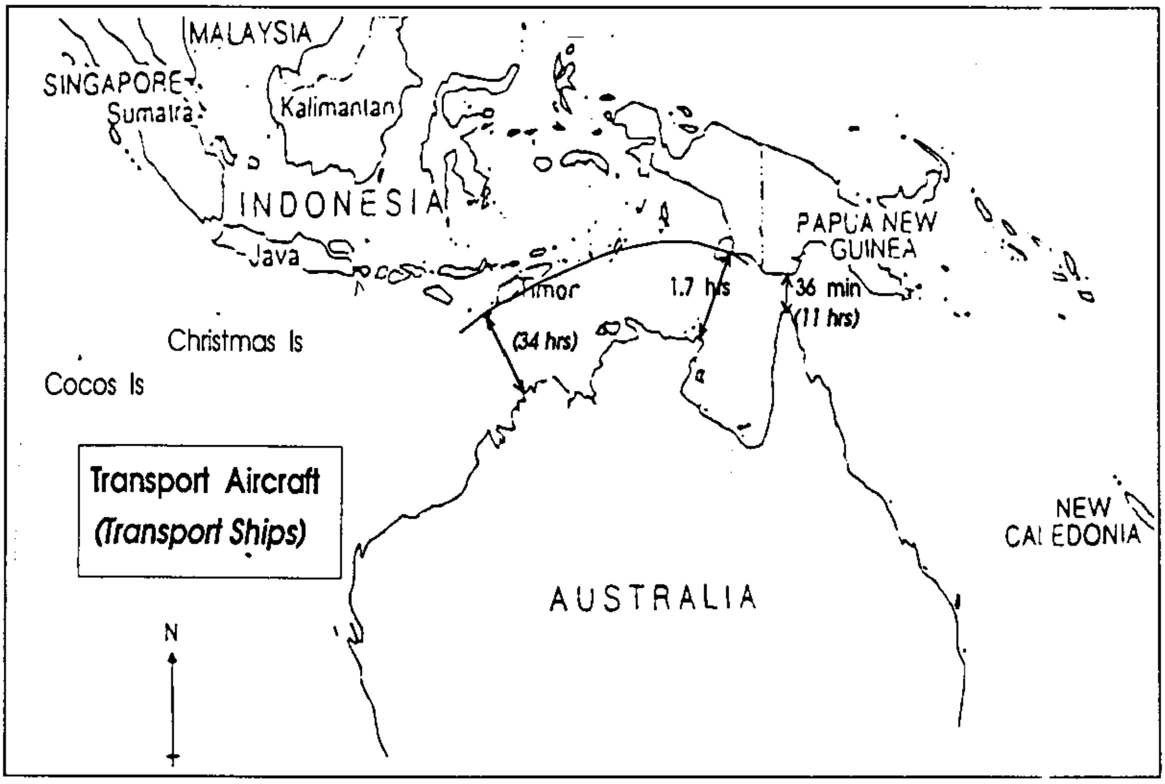

Figure 2.3 Transport Platform Crossing Time

d. Civil - Resolution. - at least 10 metres,

e. Military System Availability. - all weather, day and night coverage of the North and North-West maritime approaches, and

f. Civil System Availability. - all weather, day and night coverage of the 200 nm exclusive economic zone.

Desirable

a. Military - Area of Interest. - remainder of ADMI,

b. Civil - Area of Interest. - continent and off-shore territories,

c. Military - Resolution. - at least one metre.

e. Military System Availability. - all weather, day and night of all the ADMI, and

f. Civil System Availability. - all weather, day and night coverage of remainder of the continent and off-shore territories.

Data Fusion

Data fusion offers the potential to greatly improve Australia's overall surveillance system capabilities by integrating data and information from a range of different sensors and sources. For example, the ADF can make use of data routinely available from agencies such as the Civil Aviation Authority and the Coastwatch Service, and intelligence organisations to assist in developing and maintaining an overall surveillance 'picture'. JORN should provide a target detection capability to support the air defence system, but accurate positioning information must be provided by other sensors with higher angular resolution. Collaborative sources such as civil aircraft flight plans, shipping schedules and other intelligence sources can also provide supporting information to assist in making platform intercept decisions.

Data fusion can involve the overlaying of data from different sources, as well as the manipulation and interpretation of data. For instance, multi-spectral data processing techniques have reduced the effectiveness of army camouflage.[10] Panchromatic images can also be used with multi-spectral imagery to enhance specific details such as building structures, roads and other infrastructure; this has been demonstrated through multi-variate statistical techniques on imagery from commercial sources such as SPOT and Landsat satellites.[11] However, this type analysis generally requires fusion by a specialist imagery analyst with sophisticated image processing hardware and software, which means a significantl increase in the time to respond to surveillance inputs.

The cost of surveillance is high and fusion may help to optimise the effectiveness of the systems available. Therefore, data fusion should be a key element in any future comprehensive surveillance network.

National Surveillance System

The civil and military surveillance system characteristics discussed have a significant number of common elements, particularly with regard to coastal surveillance needs. Integration of surveillance systems can only be developed, coordinated and implemented through a long term program with a national commitment. In the USA a program called the exploitation of national capabilities (TENCAP) was established in recognition that optimum use of resources is vital, and that co-ordination is needed at the national level.[12] In the past, the US Department of Defence (US DoD) and other Government organisations have embarked on individual, and very costly research and development programs that often resulted in similar capabilities. TENCAP was initiated in an attempt to prevent this unwanted duplication of effort and to improve the value for each dollar spent. In Australia's situation, the cost to develop a comprehensive surveillance system may be significant for the defence budget alone, but it could be

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10 Weilbrenner, J.M., *Space-based Multispectral Imagery: Current and Future Applications to the United States Army*, US Army War College, Carlisle Barracks, 2 February 1990, p 35.

11 Shettigara, V.K. and K. Fridstrand, 'Surveillance Using Commercial Multispectral Remote Sensing Satellites', *The Aries Association Symposium Proceedings*, Canberra, March 1991, p 1.

12 Phillips, R., 'High Ground of Outer Space', *Marine Corps Gazette*, March 1987, pp 34-38.

affordable and justifiable if it is provided as a national capability with defence, civil anc commercial applications.

CHAPTER 3

AUSTRALIA'S WIDE AREA SURVEILLANCE CAPABILITIES AND DEFICIENCIES

This Chapter examines, in general terms, the capabilities and deficiencies of Australia's current and planned surveillance capabilities. An attempt is made to quantify, in simple terms, the wide area surveillance capability that these assets can provide.

Australia's maritime surveillance capability is vested in RAAF P3C Orion aircraft; RAN ships, submarines and patrol boats; the civil Coastwatch Service; and by the year 2000 JORN should add significantly to the capability. Other surveillance capabilities include the ADF air defence system and in the future, airborne early warning and control aircraft (AEW&C). Land surveillance of Australia's North is conducted by both the ADF and the Coastwatch Service. The Civil Aviation Authority (CAA) has responsibility for civil air traffic, although the actual surveillance radar coverage available to the CAA is limited to major regional centres. Near real-time weather surveillance is available for all of Australia's region of interest from the World Meteorological Organisation satellite network. In addition, commercial satellites can provide regular imagery of any location across the continent and out some distance from the coast, with data received directly from satellites via an Australian based receiving station.

Military Maritime Surveillance

Military maritime surveillance is conducted by RAAF P3C long range maritime patrol (LRMP) aircraft and RAN vessels. Civil Coastwatch operations are also supported by the ADF.

LRMP

The RAAF has 19 P3C aircraft which undertake a number of specialised defence activities, one of which is area surveillance. An initial but highly improbable assumption is made that all P3C aircraft are to be used for surveillance, with an annual rate of effort of 10,000 hours available[1]. For surveillance operations the following flight characteristics are assumed:

a. a cruising altitude of 7,000 feet,

b. a speed of 240 knots, and

c. a flight duration of 10 hours.

The radar range at this altitude is about 100 nautical miles. This simplified view illustrates that the area that one aircraft can cover in a flight is about 823,000 km^2, which gives a potential short term coverage of about 15.5 million km^2 if all aircraft are

1 Babbage, R., *A Coast Too Long: Defending Australia Beyond the 1990s*, Allen & Unwin, Sydney, 1990: p 67.

used. However, a realistic aircraft availability figure is about 60%, and the effective r. te of surveillance coverage can quickly be reduced by more than 50% when diversions are necessary to investigate targets[2]. Therefore, far less than the maximum area may actua ly be covered in a surveillance mission.

LRMP aircraft are based at RAAF Base Edinburgh which means long tra sit times to the high priority surveillance areas on the North coast. Coverage is further limited because surveillance is only one role of LRMP aircraft. Consequently, a maximum LRMP surveillance effort is likely to cover less than about 10% of the maxin um coverage possible, which equates to about 1.5 million km^2 or about 4% of the ADMI ai :a. A revisit time of about 25 days can be achieved with this rate of surveillance coverage. The mainland is included in this total surveillance area but it would not generally be the subject of surveillance using P3C aircraft; however, the aircraft still need to traverse th mainland so the revisit time is still significant. Detailed estimates of the coverage capability would require more knowledge of P3C operations.

RAN[3]

Babbage identified the following two limitations with using RAN vessels for continuous surveillance of the Northern sea and air gap: inadequate coverage given the vast distances involved, and insufficient platforms to provide wide area surveillance. These surface vessels have limited speeds and radar horizons of only about 50 km. Babbage illustrated that the entire RAN fleet would, at maximum effort, have difficulty maintaining adequate coverage over only Northern Australia, with each vessel being required to cover about 300 km of the coast each day. Therefore, while the RAN fleet has a significant surveillance role, it is not considered as a wide area surveillance asset.

Civil Coastal Surveillance

The main emphasis of civil coastal surveillance is for detection and intervention in illegal activities within the coastal region and the 200 nm exclusive economic zone. The civil Coastwatch Program has been part of the Australian Custom s Service (ACS) activities since August 1988 and it co-ordinates commercial charter aircr ıft, the ADF, ACS and other agencies to conduct air, sea and land surveillance. Operatior s are conducted on behalf of the ACS and organisations such as the Australian Quarantine Service, National Parks and Wildlife, the Great Barrier Reef Marine Park Authority, Immigration and Fisheries.[4] ACS surface vessels have the same basic limitations as th RAN fleet and they have fewer vessels available, therefore only the ACS aircraft fleet capability is examined.

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2 Personal conversation with former P3C Orion Navigator, Squadron Leader L. Hughes, RAAF Navigator, Defence Science and Technology Organisation, Directorate of Trials, 2 September 1991.

3 Babbage, R., op cit, p 71.

4 Moremon, J., 'Coastwatch Enters New Jet Era', *Australian Aviation*, July 1991, p 25.

Coastwatch Aircraft Operations[5]

The Australian Coastwatch Service aerial operations component has an annual budget of about $19 million, and its activities were contracted to Skywest for five years from December 1990. They operate 12 Aerocommander Shrikes, three GAF Nomad Searchmasters and recently three Seascan specialist maritime reconnaissance aircraft were added to the fleet. The Seascan aircraft offer extended range for operations further from the mainland than was previously possible. This now gives coverage of Lord Howe, Norfolk, Cocos and Christmas Islands. The Shrike aircraft can conduct visual surveillance of the coastal zone. Searchmasters can detect targets day and night with a 360 degree search radar; however, they are probably restricted to daylight operations due to an inability to identify targets at night. Seascan aircraft can operate at long range and are fitted with both radar and a forward looking infrared sensor for day and night operations.

Most Coastwatch operations are flown out of the primary bases at Broome, Darwin, Cairns and Horn Island, with some operations from remote runways when required. Coastal surveillance is a demanding task, particularly with the need to visually sight boats in low visibility conditions or in dense mangroves. Nevertheless, since the inception of the ACS Coastwatch program, they have made about 200 apprehensions for illegal activities: more than 100 Indonesian fishing vessels being intercepted and impounded, and five refugee boats of Asian origin have been detected. Therefore, the Coastwatch Service has a capacity for daytime surveillance, but with only three aircraft capable of surveillance at night, a significant shortfall exists.

JORN[6]

Australia's only true wide area surveillance capability, JORN, is currently under development by Telecom Australia, and is contracted for completion before the year 2000. Two radars will be constructed, one at Longreach in Queensland and the other at Laverton in Western Australia. The radar images will be transmitted to a single site at RAAF Base Edinburgh in South Australia for 'integration' and interpretation,[7] and the data is to be distributed to users within the surveillance network. With the contracted network of two radars operating, JORN coverage will extend around the North coast from Carnarvon in Western Australia to Cooktown in Queensland. Construction of a third radar site is an option available to the Government under the existing contract.

Air surveillance was the prime capability requirement for the Jindalee over the horizon radar network; Jindalee is JORN's research and development system. The research and development showed that JORN may also be useful for surface vessel surveillance.[8] JORN is expected to be able to detect and track steel-hulled ships of ocean-going size and aircraft down to about fighter size, at ranges from about 1000 km to 3000 km. Targets should be located to within about 18 km, although this will vary with range to the target and the frequency used.[9] There are, however, a number of significant problems that will affect JORN's performance and most of these are due to the

5 ibid, p25.
6 Sinnot, D.H., 'The Jindalee Over-The-Horizon Radar System', *Air Power In The Defence Of Australia*, Conference, Australian National University, Strategic and Defence Studies Centre, 14-18 July 1986, p 1-25.
7 Brice, C., 'Green Light for $45m Edinburgh Radar Plan', *The Advertiser (SA)*, 14 June 1991, p 3.
8 Grazebrook, A.W., 'Jindalee Moves Forward', *Asia-Pacific Defence Reporter*, August 1990, p 32.
9 Stackhouse, J., 'Jindalee Project Proceeding On Target' *Australian Aviation*, July 1991, p 89.

inconsistency of the ionosphere as a reflective medium for the radio frequencies being used.

Ionospheric Effects

JORN operates over the horizon by the reflection of high frequency (HF) radar energy off charged particle layers in the ionosphere. Some of the transmitted signal is reflected from ionospheric layers into the target area, as illustrated in Figure 3.1. Energy scattered by the target can return via reflection in the ionosphere and be detected by the radar receiver. This process is complicated by the ionosphere's continuously varying refractive properties, which is mainly caused by changes in solar radiation and the solar wind as it interacts with particles in the atmosphere.

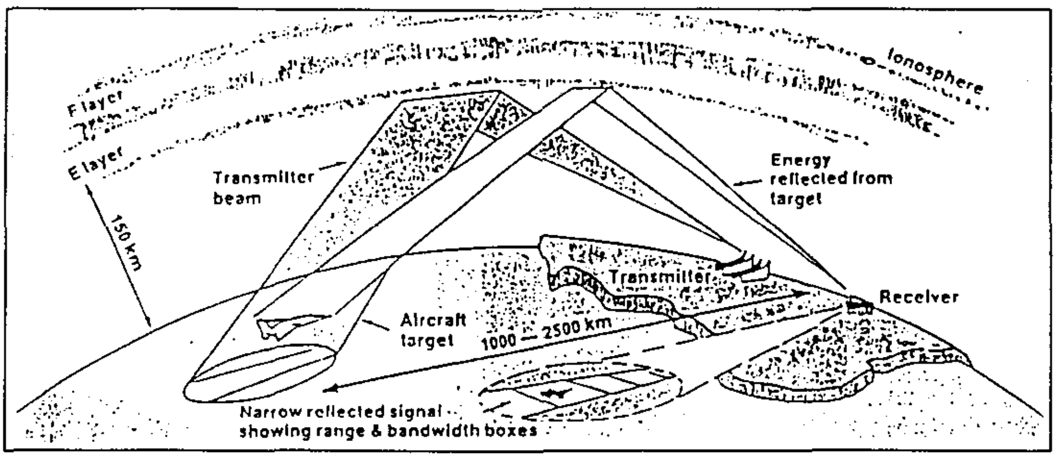

Figure 3.1 Principle of Over-the-Horizon Radar Operation[10]

Multi-Path Effects. Inhomogeneities in the refractive layers of the ionosphere can cause the HF radar beam to spread and propagate via multiple paths to and from targets. Multiple returns from a single target can occur and cause separate target indications at different ranges. These multi-path effects are complex, if not impossible to resolve, without adequate knowledge of the state of the ionosphere. A comprehensive network of ionospheric sounders is planned to monitor, study and predict ionospheric changes; however, multiple-path effects are still likely to provide a significant target range determination problem.

Night Detection Range.[11] The loss of local solar heating on the atmosphere at night causes ionised particle layers of the ionosphere to change both in characteristics and position, some layers may even disappear for a time. With concentrations of ionised particles in the ionospheric layers reduced at night, there will also be a significant reduction in the amount of energy returned from targets. Therefore, the range at which targets can be detected at night may be significantly reduced.

Disruption of the Ionosphere. There are both regular and irregular events that can disrupt the ionosphere. The transitions between night and day are regular events

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10 Young, P.L., 'Over-The-Horizon Radar: Magic Solution or Costly Illusion?', *Asian Defence Journal*, November 1987, p 26.

11 'Ionospheric Physics', *The New Encyclopedia Britannica*, Volume 2, p 325.

that cause rapid variations in ionospheric conditions and JORN may have difficulty maintaining surveillance coverage during these periods. Changes in solar heating of the atmosphere during the day/night transitions cause this problem. Figure 3.2 illustrates typical changes in the maximum useable frequency (MUF) for HF communication systems that use the ionosphere. This Figure shows that the sunrise transition is more dramatic; therefore, disruptions to JORN may be more severe at sunrise. Solar flares and sun spots are the usual sources of unpredictable ionospheric disturbances. Some of these events can disturb the ionosphere for periods ranging from minutes to hours and JORN's detection performance may suffer significant disruption.

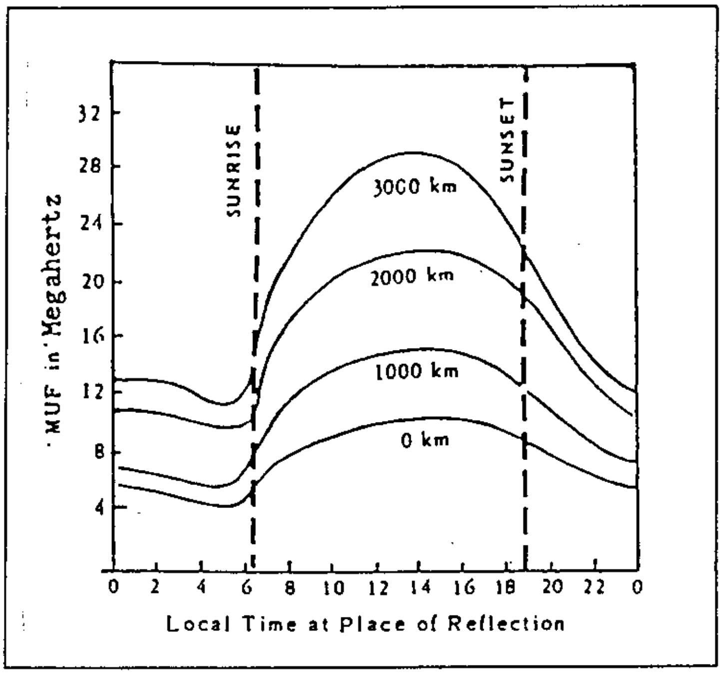

Figure 3.2 Variations in the Ionosphere and the Maximum Usable Frequency[12]

Dealing With Ionospheric Changes

One key to the performance of JORN, given the inconsistencies of the ionosphere, appears to be in the prediction of ionospheric changes and the management of transmitter frequencies. A significant component of Jindalee research has been in the development and implementation of a sophisticated real-time frequency management system.[13] However, the interactions between solar activity, the Earth and the ionosphere are not well understood. Monitoring the dynamics of the ionosphere where beam refraction is difficult, consequently predicting changes across a large region will be difficult.

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12 Cochran, C.D. et al (eds), *Space Handbook, AU-18*, Air University Press, Maxwell Air Force Base, Alabama, January 1985, p 7-7.

13 Earl, G.F. and B.D. Ward, 'The Frequency Management System of the Jindalee Over-The-Horizon Backscatter HF Radar', *Radio Science*, March/April 1987, pp 275-291.

Target Detection and Tracking

Sinnot illustrates that with Jindalee's detection range bracket of about 2000 km, there is a possibility that an aircraft may be able to cross the detection region, if the radar is not scanning that particular area.[14] However, this is unlikely because it would take an aircraft travelling at 500 knots about two hours to cross the range bracket. In addition, JORN will have two radars operating, which means that the situation will be even less likely.

Targets travelling tangentially to a single radar beam cannot be detected because the radar uses Doppler processing for target detection, and targets moving tangentially to the beam direction do not provide a Doppler return. The use of multiple radar sites is expected to address this problem by ensuring that no target can travel tangentially to both radar beams at once. However, since JORN detects targets with Doppler processing, it is worthwhile noting that the detection of some slower moving targets like ships may be difficult.

Target Identification and Interception

For a sensor to determine the shape and size of a target, the spatial resolution of the sensor must small relative to target dimensions. JORN has range resolution from 3-40 km and an azimuth resolution of 3-130 km at 1000 km range;[15] therefore, the system may be able to detect the presence of a target but it will be unable to determine any information about the structure of that target. Sinnot suggests that friendly targets could be fitted with transponders to identify them and reduce the target analysis and processing workload.

This inability to obtain accurate range and azimuth co-ordinates is a significant problem when proposing to use JORN for air defence, which requires the capability to provide intercept vectors to aircraft. It is highly undesirable for an intercepting aircraft to need to activate a search radar since this may alert the target to the in-bound aircraft.

Operational Employment of JORN

JORN has the capability to provide near real-time air and surface surveillance over a vast area of Australia's Northern maritime region; however, the operational value of this system for maritime surveillance, air defence, intelligence and civil coastal surveillance is yet to be fully realised. The data computation requirements for compiling, processing and analysing detected targets are substantial, particularly considering the large area to be monitored. Data from sources such as flight plans, shipping schedules and intelligence agencies may be useful in processing targets. Therefore, to be used effectively as a wide area surveillance capability, JORN will need to be integrated with the national air defence, air traffic control, coastal surveillance and intelligence systems. Some of these systems are only somewhat loosely interfaced at the moment, which means that considerable effort will be required to make effective use of these surveillance capabilities in the future.

14 Sinnot, op cit, p 18.
15 Sinnot, op cit, Table I.

Summary of JORN Limitations

As illustrated above, JORN has a number of inherent and significant performance problems, most of which are due to its operating environment. These limitations are as follows:

a. appears unable to detect some slow moving targets ;

b. may be unable to detect light aircraft, or small vessels without steel hulls;

c. detection performance and range varies dramatically between day and night conditions due to different ionospheric layer characteristics;

d. detection performance is significantly affected by ionospheric disturbances during day/night transitions, solar flares and sun spot activity;

e. range ambiguities resulting from multi-path ionospheric propagation are difficult to resolve; and

f. range and azimuth accuracy are in the order of tens of kilometres, depending on range and ionospheric effects.

National Air Defence System Surveillance Capabilities

A well-developed concept exists, within the RAAF, for a national air defence airspace control system (NADACS)[16], but the resources are not available to implement all the surveillance, command, control and communications components. Current area surveillance capabilities are vested in ground based early warning surveillance radars which are limited by line-of-sight operation; therefore, they can only detect low flying aircraft at a range of about 50 km and high altitude targets out to about 550 km.

Australia's civil air traffic control system can also form part of the NADACS concept by assuming responsibility for monitoring and directing legitimate air traffic. However, a project now in place within the Civil Aviation Authority is providing an air traffic control system that has search radars at main regional centres only, with the remainder of the network being transponder based: about ten primary surveillance radars planned for the system. This means that aircraft more than about 60 km from one of the regional centres will need to have a transponder fitted to be identified and tracked. Therefore, the civil air traffic control system will be unable to contribute significantly to national air surveillance.

16 The NADACS concept is presented in a paper by the late Air Commodore S.S.N. Watson in Ball, D. (ed), 'Air Defence, Airspace Surveillance and Control: Problems and Policies', *Air Power: Global Developments and Australian Perspectives*, 1988, pp 181-208.

Airborne Early Warning and Control Aircraft

AEW&C aircraft are proposed for purchase by the ADF some time in the next decade. These aircraft types are likely to cost in the order of $A375 million each and at least $A200 million will be needed for ground support facilities.[17] In order to maintain three aircraft operational, about six would have to be purchased. This amounts to an investment of about $A2,500 million, which is a significant outlay in terms of the total Defence budget and may be the extent of such a purchase.

These aircraft could be used for wide area surveillance in Australia, just as they are in the USA to combat drug trafficking. However, considering the limited numbers that are likely to be purchased, they will probably be designated primarily as air defence response platforms, to be used in conjunction with JORN's early warning capability. Even if they were tasked to conduct wide area surveillance as a primary role, the limited numbers of aircraft available would limit their effectiveness across the vast Northern approaches. Nevertheless, AEW&C aircraft will provide a capability for air defence operations in the North that is essentially non-existent at the moment.

Commercial Satellites

The Australian Surveying and Land Information Group (AUSLIG), within the Government Department of Administrative Services, operate the Australian Centre for Remote Sensing (ACRES) as a business unit to market satellite remote sensing products in Australia's region. ACRES can provide panchromatic and multi-spectral imagery from the Landsat, SPOT and NOAA satellites. Commercial imagery will also be available from the ERS-1 synthetic aperture radar satellite in the near future. ACRES has a satellite ground station near Alice Springs that can collect imagery of the entire Australian continent and out to at least 600 km from coastline, as illustrated in Figure 3.3 for the Landsat satellite. Satellite imagery of virtually any location on the Earth can be obtained by placing an order with ACRES, although data from other ground stations around the world may take some time to obtain.

Remotely sensed data products are used extensively in Australia, with ACRES having sales of more than $1.3 million in 1990, which represents about five per cent of world commercial Landsat imagery sales.[18] However, the ADF purchases very little of this imagery. While commercial imagery offers resolutions of up to 10 metres the problem is the time taken to get imagery processed. A priority commercial order from ACRES will take about five days if it is in stock, and there also a significant cost premium associated with this or any faster delivery time. Ordering specific images will take longer since the collection depends on such things as satellite availability and cloud cover over the target area.

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17 A price quoted as being too high for the Royal Thai Air Force for a fleet of four aircraft 'E-2C Buy Ruled Out', *Jane's Defence Weekly*, 21 September 1991, p 500.

18 ACRES News, Volume 4, Number 1, June 1991, p 5.

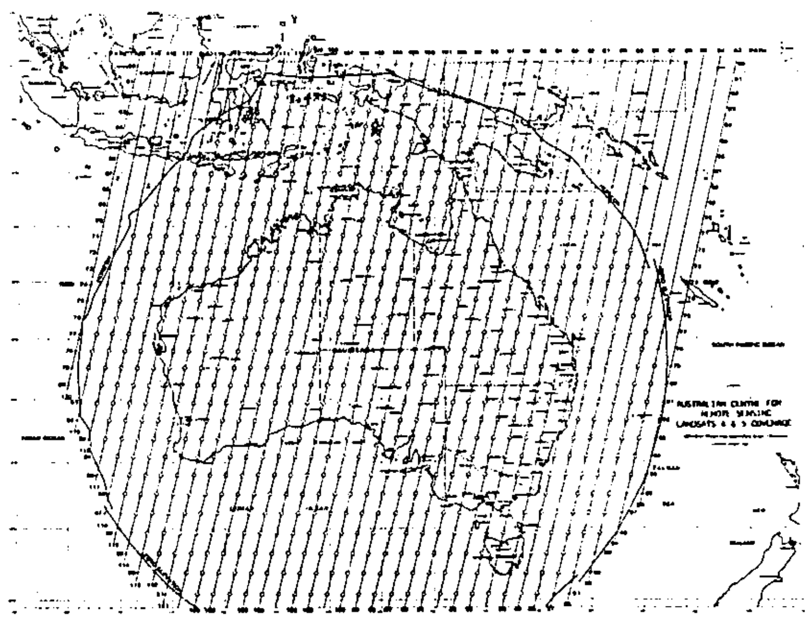

Figure 3.3 ACRES Ground Station Coverage for Landsat 5

Wide Area Surveillance Deficiencies

Australia's principal wide area surveillance capabilities are focused on the air and sea gap to the North. Surveillance is conducted by a range of mostly conventional air and sea assets controlled by both military and civil agencies, but the military has significantly more equipment and capability for the role. JORN is the only true wide area surveillance capability that Australia appears likely to have in the next decade, and it concentrates surveillance activities to the North.

In summary, the perceived deficiencies in Australia's existing and planned future surveillance capabilities are:

a. inadequate resources to conduct complete surveillance of the ADMI or even the 200 nm exclusive economic zone, although the Northern maritime region will ultimately have some wide area coverage with JORN;

b. identified performance shortfalls in JORN make the overall surveillance capability vulnerable;

c. a lack of fusion or integration of existing and planned surveillance capabilities.

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CHAPTER 4

FUNDAMENTALS OF SURVEILLANCE FROM SPACE

This Chapter introduces a number of fundamental physical and technical concepts related to remote sensing of targets from space, and it provides background information for the following chapters. Firstly the properties of electromagnetic (EM) radiation are discussed and this is followed by a review of how EM radiation is attenuated as it passes through the space environment. Basic satellite orbit mechanics aspects are discussed to illustrate the capabilities and limitations of different orbits for surveillance. This is followed by a discussion of typical surveillance sensors in Chapter Five.

Remote Sensing from Spacecraft

Surveillance of targets on the Earth or in the atmosphere, from space-based platforms, involves using a sensor to intercept the EM radiation propagating from the target area. The radiation detected originates from either natural sources such as the Sun or from man-made objects that either reflect or emit radiation. The amount of radiation collected by a sensor depends on the size of the aperture, the intensity and spectrum band of the radiation, atmospheric properties, range to the target, and also the reflective or emission characteristics of the target and the surrounding scene. Sensors are generally used to either image an area or detect specific target characteristics. They are also either passive or active in operation: passive sensors collect EM radiation reflected by or emitted from objects, and active sensors transmit EM radiation and collect the returned energy. Received radiation is processed by the sensor package or by ground resources, but current technology places most sensor systems in the latter category.

Atmospheric attenuation limits the EM radiation bands that can propagate between space and the Earth, and some bands are more highly attenuated than others. Therefore, the atmosphere provides a fundamental limit to the exploitation of certain EM bands by a spaceborne sensor. Consequently, space-based surveillance sensors are designed for use in bands of the EM spectrum where radiation is not significantly attenuated by the atmosphere. However, for some scientific applications, specific highly attenuated bands are exploited to examine atmospheric characteristics. For example, cloud cover measurements can be made by using wavelength bands that reflect off clouds.

The Electromagnetic Spectrum

EM radiation consists of waves of varying electric and magnetic fields. These waves propagate at the speed of light in a straight line, through the vacuum of space; unlike sound waves, which require the presence of the atmosphere to propagate. Equation 4.1 describes the fundamental relationship between wavelength, frequency and the velocity of EM radiation. Space has a vast number of EM radiation sources but the one of most interest here is the Sun, which radiates the spectrum shown in Figure 4.1. This Figure shows that only certain wavelength bands reach the Earth with little attenuation. It also shows that solar radiation peaks in the visible frequency band, providing the light by which we see, thermal radiation to warm the Earth, and other EM radiation corresponding to a body at a temperature of about 6000 degrees Celsius. Figure 4.2 provides a simplified breakdown of the EM spectrum into the most common bands used.[1]

$$c = f \times \lambda \qquad \text{(Equation 4.1)}$$

where:
- c = speed of light (3×10^8 m/s)
- f = frequency of EM radiation
- λ = wavelength of EM radiation

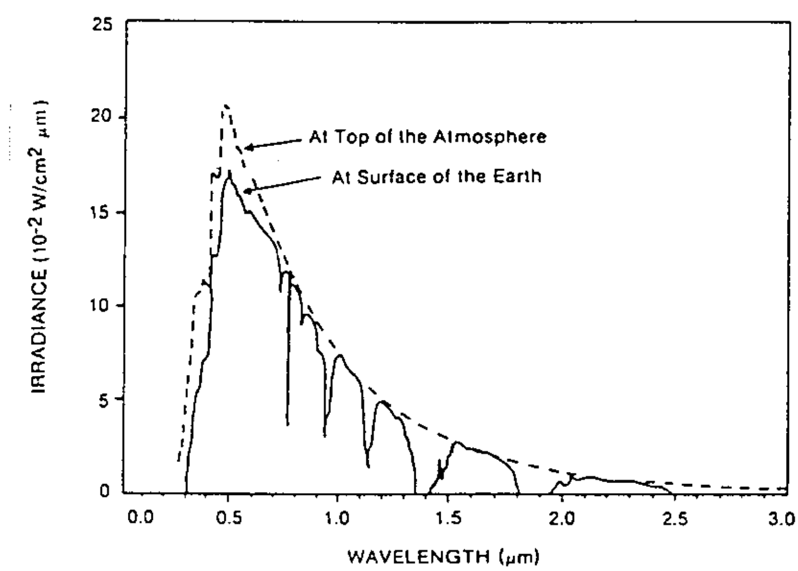

Figure 4.1 The Sun's Radiation Spectrum[2]

The EM radiation emitted by an object is dependent on its temperature. Equation 4.2 can be used to determine the approximate wavelength at which a body, at a given temperature, emits maximum EM radiation:[3]

$$\lambda_{max} = \frac{2897.8}{T} \qquad \text{(Equation 4.2)}$$

where:
- λ = wavelength in μm
- T = temperature in degrees Kelvin (conversion is $^0K = {}^0C + 273$)

1 Discussion of the EM spectrum in the ultraviolet, visible and infrared parts of the spectrum are usually in terms of the wavelength of the EM waves, and for the radio wave part of the spectrum frequency is generally used.

2 Chen, H.S., *Space Remote Sensing Systems: An Introduction*, Academic Press, Orlando, 1985, p 11.

3 Lange, J.J. and H.E. Evans, *The Near-Earth Space Environment Course Notes*, USAF Institute of Technology, Dayton 1987, p 15.

Applying this equation to the Sun's radiation spectrum in Figure 4.1 shows that the Sun has a temperature of about 6000⁰ C. Similarly, given that the Earth has an average daily temperature of about 25⁰ C, then its radiation emission peaks at a wavelength of about 10 micrometres, which is in the middle of the infrared band.

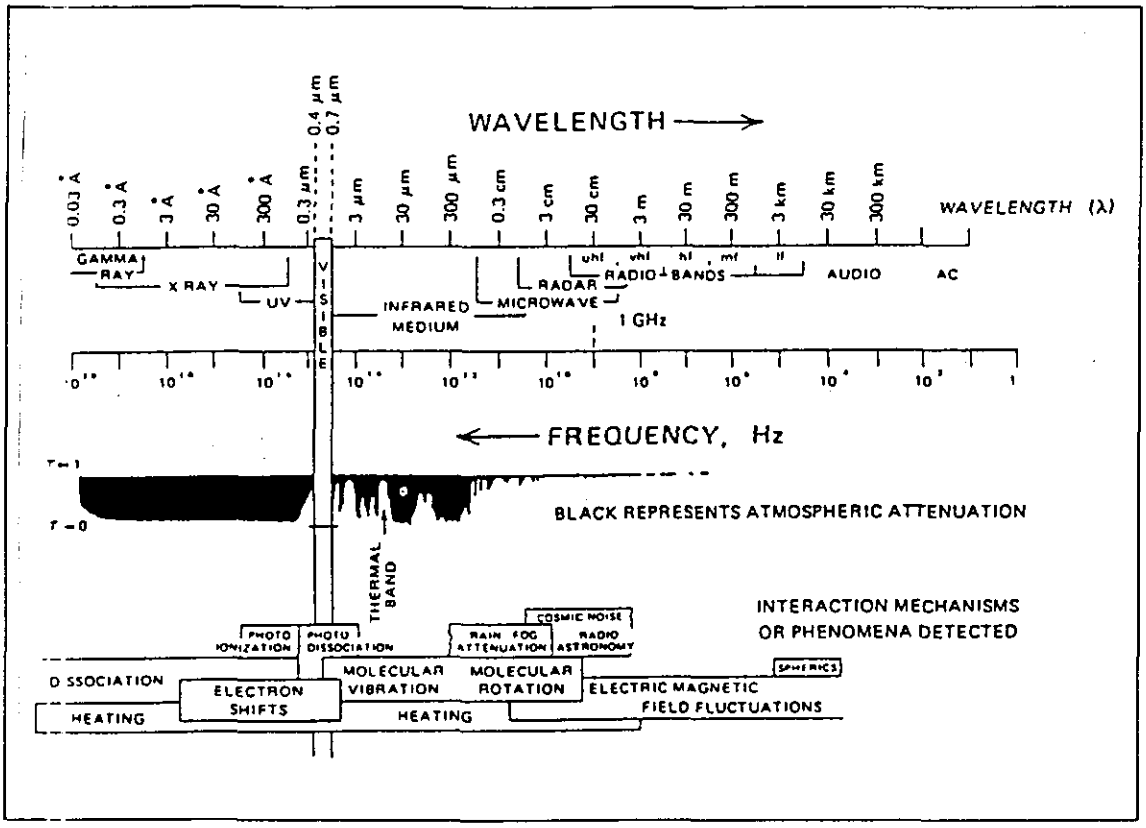

Figure 4.2 The Electromagnetic Spectrum[4]

The Space Environment

The space environment significantly affects the design characteristics of satellites, since spacecraft can encounter extremes in solar and cosmic radiation and can suffer damage from high speed particles and space debris. These phenomena can be studied in a number of texts on the space environment, but only those aspects that significantly affect spacecraft orbit selection and remote sensing from space are introduced.

Solar Activity

Energy emitted by the Sun arrives at the Earth either as EM radiation or as streams of particles called the solar wind. Travelling at the speed of light, EM radiation arrives on Earth about eight minutes after leaving the Sun. The solar wind, however, consists of highly ionised gas particles carried by the Sun's magnetic field; it typically travels at about 400 km/s and takes about four days to arrive at the Earth. The particle

4 Colwell, R.N. (ed), *Manual of Remote Sensing: Volume 1*, American Society of Photogrammetry, Falls Church, 1983, p 40.

stream travels in a radial direction outwards past the Earth and can significantly disrupt the Earth's magnetic field and the ionosphere.

Solar flares can inject high energy particles into the solar wind which can endanger astronauts, disrupt spacecraft systems and also disturb the atmosphere. One common example of this is the disruption to high frequency communications when large solar flares occur.

Van Allen Radiation Belts

Some of the ionised particles moving through space, most of which are carried in the solar wind, may be trapped by the Earth's magnetic field. These charged particles, mostly electrons and protons, are attracted into two distinct regions around the Earth called the Van Allen radiation belts, as shown in Figure 4.3. High energy protons are the dominant species in the belt closest to the Earth and electrons generally dominate the outer belt. However, the actual distribution is dependent on particle energy levels. These trapped particles can have sufficient energy to cause radiation damage to humans and spacecraft, particularly when high energy particles from solar flares are present.

Satellites that must operate in the Van Allen belts for long periods need to be shielded from the radiation. The amount of shielding needed depends on: orbit altitude and inclination, the radiation dosage expected over the life of the spacecraft mission, and also the radiation tolerance of the spacecraft systems or occupants. Satellites that are being transferred through the Van Allen belts to higher altitudes, such as geosynchronous orbits, usually spend only a short duration of the transfer orbit in the Van Allen belts and therefore may require little additional shielding.

Effect of the Atmosphere on Electromagnetic Radiation

The atmosphere interacts with various EM wavelength bands in different ways, depending fundamentally on the size of atmospheric particles and the molecular composition of the atmosphere. EM radiation is scattered by atmospheric particles; the

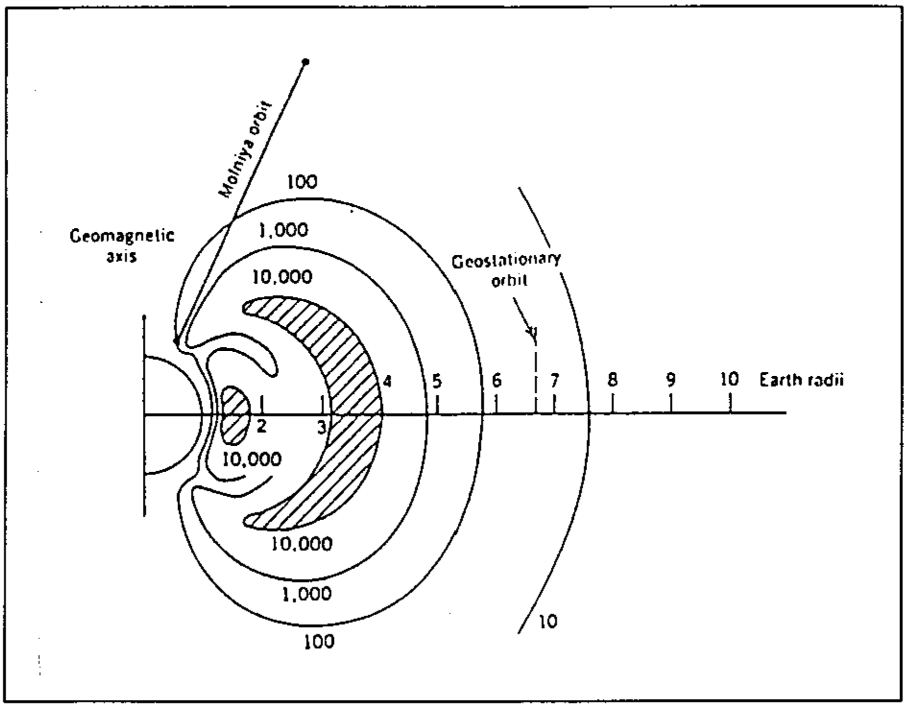

Figure 4.3 Van Allen Radiation Belts[5]
(The numbers represent the Geiger measurements expected)

amount of which is generally dependent on the size of the particles in relation to the radiation wavelength. Absorption of radiation can occur if there is enough energy to excite atmospheric molecules sufficiently to cause them to absorb energy. Energy absorbed in this way occurs in particular wavelength bands, corresponding the structure of atoms or molecules in the path. The high attenuation 'notches' in the millimetre wavelength bands of Figure 4.4 are characteristic of molecular absorption.

Figure 4.4 illustrates the attenuation characteristic of a clear atmosphere for part of the EM spectrum and Figure 4.5 illustrates the effects of rain and fog. These can be compared to the clear weather attenuation characteristic in Figure 4.2. They show that in clear weather the visible spectrum, parts of the infrared spectrum up to about the 15 μm wavelength and the radio spectrum below about 35 GHz, have relatively low attenuation. However, poor weather and other atmospheric pollutants can significantly attenuate some EM spectrum bands. The most common bands used for surveillance from space are microwave and millimetre wave, infrared and visible wavelengths, all of which have advantages and disadvantages in practical and technological implementation.

Visible and Infrared Spectrum

EM radiation in the visible and near infrared (IR) spectrum bands will propagate through a clear atmosphere with relatively low attenuation, as shown in Figure 4.4, although other IR wavelengths can be significantly attenuated. A number of low loss IR bands exist from 1.5-2.5μm, 3-5μm and 7-14μm. Characteristic IR emissions from objects may be detected by spaceborne sensors using these bands. However, propagation in the visible and IR spectrum is complicated by rain and fog conditions as shown in Figure

5 Morgan, W.L. and G.D. Gordon, *Communications Satellite Handbook*, 1989, p 548.

4.5 and clouds will also reflect much of the radiation in these bands. Absorption by water, carbon dioxide, and ozone molecules is also significant in the IR part of the spectrum. In average conditions, which includes atmospheric clouds, dust and pollutants, visible and near-IR energy from the Sun is about 31% reflected or scattered, about 17% is absorbed directly by atmospheric gases, and about 48% is absorbed by the Earth.[6]

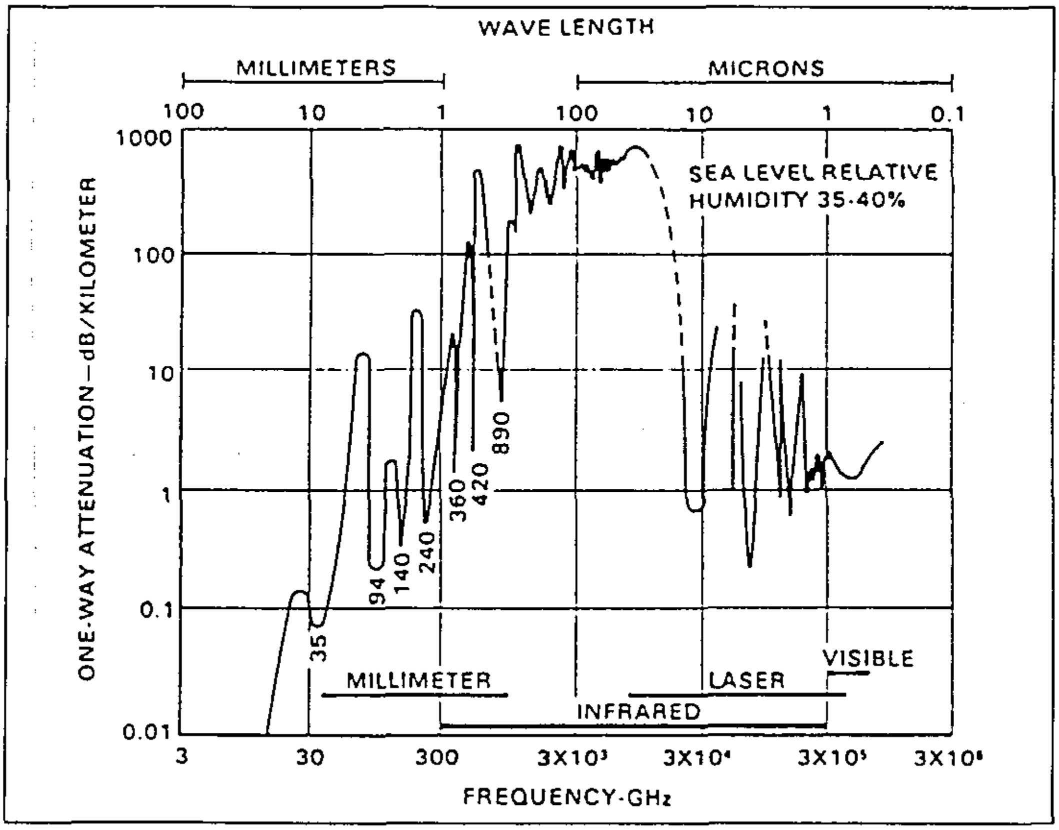

Figure 4.4 Atmospheric Transmission Spectrum[7]

Radio Frequencies

Table 4.1 outlines the effect of the atmosphere on various bands of the radio frequency spectrum. It shows that propagation between the Earth and space is generally restricted to frequencies above about 3 MHz, depending on the radio wave incidence angle. However, Figures 4.4 and 4.5 illustrate that the attenuation below 30 GHz is relatively low and frequencies much above 30 GHz are not currently in wide use for surveillance applications due to technology limitations.

Satellite Orbital Characteristics

Orbits can be described in terms of altitude, inclination and eccentricity, and the selection of an appropriate orbit is mission dependent. Surveillance of the Earth from spacecraft requires orbits or satellite configurations that bring the sensor field of view

6 Lange, J.J., op cit, p 27.

7 Hovanessian, S.A., *Introduction to Sensor Systems*, Artech House, Norword, 1988, p 7.

(FOV) across the area of interest when and as often as required. To conduct surveillance of all the Earth with one satellite, a polar orbiting satellite would be needed. For continuous observation of an area, either a geostationary orbit or a constellation of satellites must be used. Orbit selection trade-offs are also necessary to achieve the ground resolution required, some of the factors considered include: satellite lifetime, revisit time over the target area, and total EM radiation collected at the sensor.

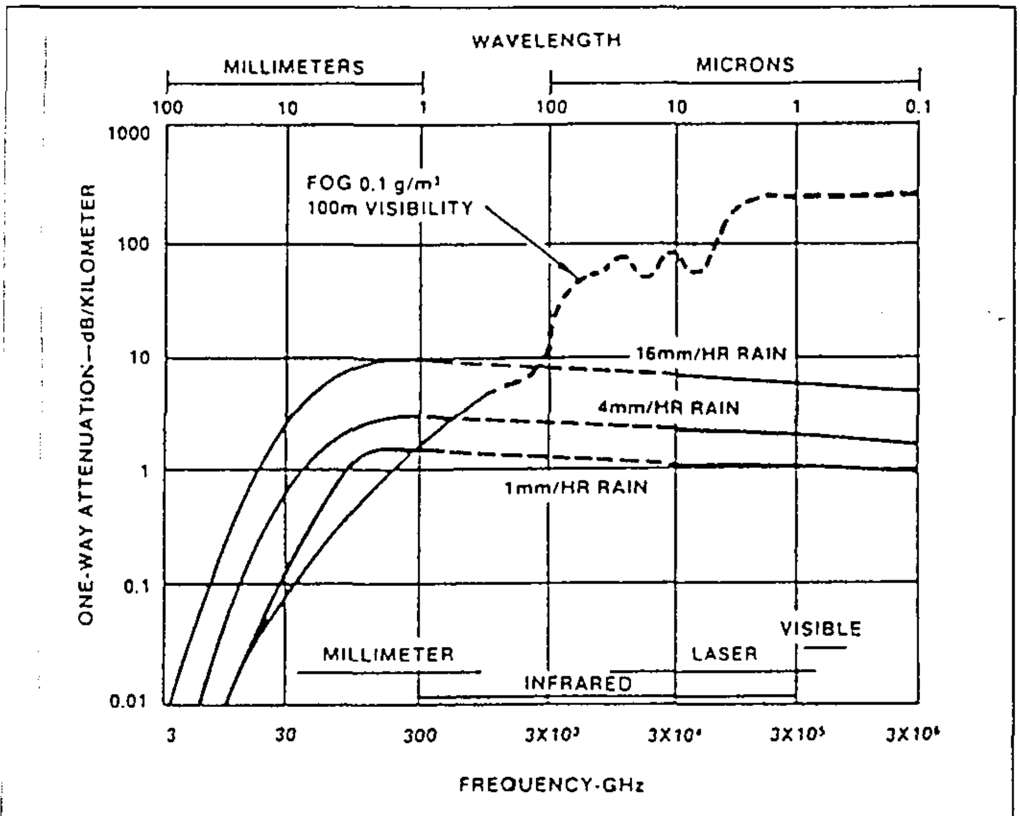

Figure 4.5 Rain and Fog Attenuation Versus Frequency[8,9]

Atmospheric Drag

Low earth orbit (LEO) satellites lose speed and suffer orbit decay due to atmospheric drag unless propulsion is periodically used to boost them back to the required altitude. The drag coefficient of a satellite increases as it get closer to the Earth and 150 km is about the lowest altitude that an orbit can be sustained; this corresponds to an orbital period of about 88 minutes. At this altitude de-orbiting due to atmospheric drag can occur within a few orbits. Spurious solar activity can also vary the altitude at which the atmospheric drag becomes significant, and this means that some altitude margin is needed to ensure that low altitude satellites are not lost before the end of their useful life. Most commercial LEO satellites operate at altitudes between 600 and 850 km and at these altitudes satellite lifetime due to drag alone would be in excess of 25 years. However, these satellites still require some altitude correction to maintain operation at the nominal orbit.

8 ibid, p 8.

9 Three decibels of attenuation represents a loss of half the power.

Table 4.1 Radio Wave Propagation[10]

Frequency Range	Primary Propagation Modes
Very Low Frequency (VLF) 3 - 30 KHz	Waveguide (between ground and lower ionosphere) and ground wave
Low Frequency (LF) 30 - 300 KHz	Waveguide (between ground and lower ionosphere) and ground wave
Medium Frequency (MF) 300 - 3000 KHz	Ground wave or reflection from night time ionosphere
High Frequency (HF) 3 - 30 MHz	Refraction from ionosphere
Very High Frequency (VHF) 30 - 300 MHz	Line of sight or scattering by ionosphere inhomogenetics (scintillations)
Ultra High Frequency (UHF) 300 - 3000 MHz	Line of sight or scattering by troposphere irregularities
Super High Frequency (SHF) 3 - 30 GHz	Line of sight or scattering by troposphere irregularities
Extremely High Frequency (EHF) 30 - 300 GHz	Line of sight or scattering by tropospheric irregularities

Orbital Altitude

Surveillance satellites generally use a range of altitudes from LEO to about 36,000 km or geosynchronous altitude, depending on the application. At 200 km it takes about 90 minutes to orbit the Earth and at 36,000 km it takes about 24 hours.

Low altitudes are needed to obtain high resolution because image resolution is proportional to the square of the altitude, but higher altitudes provide an increased line-of-sight field of view (FOV). Figure 4.6 shows the FOV possible from LEO satellites. This illustrates that LEO satellites have a very limited total FOV in relation to the size of the Earth. By contrast, about one third of the Earth's surface can be seen from a satellite at geosynchronous altitude. The observed FOV is further restricted by the surveillance sensor being unable to view all the region. Some of the trade-offs involved in selecting low or high altitude orbits include:

10 Lange, J.J., op cit, p 64.

a. increased cost to get a satellite to high altitude,

b. smaller payload possible when additional fuel is needed to propel a spacecraft into a higher orbit,

c. revisit time increases with altitude for other than geostationary satellites, and

d. received radiation levels decrease rapidly with range to the target.

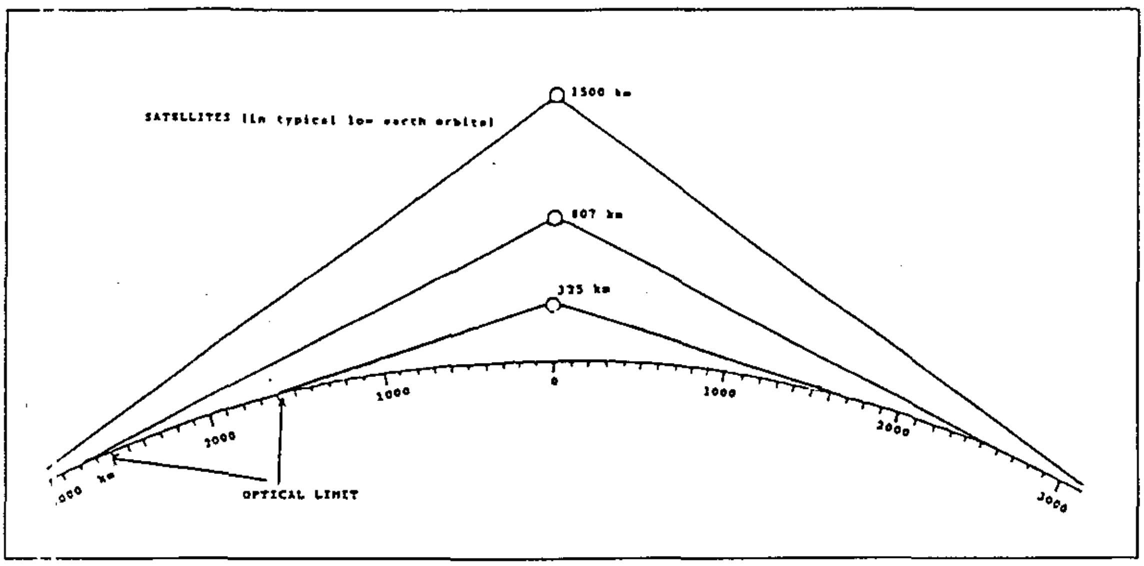

Figure 4.6 Line of Sight Viewing From Space[11]

Satellite Ground Traces

For surveillance of the Earth, a satellite must be in an orbit that will cause it to move across the desired target area. With a given FOV, satellite sensors observe the Earth with respect to the satellite ground trace which is the path across the Earth's surface that would be made by a line drawn vertically from a satellite to the centre of the Earth.

As satellites orbit, the Earth also rotates on its axis at about 15 degrees per hour. This means that the ground trace of a LEO satellite which orbits about every 90 minutes, will not retrace the same path on subsequent orbits. For a satellite with an inclination between zero and 90^{o}, called a pro-grade orbit, the ground trace moves Westward by the number of degrees that the Earth has rotated since the satellite last crossed the same latitude As inclination increases past 90^{o}, retro-grade orbits, the ground trace can be seen to move Eastward. Here, this phenomenon is called the apparent regression of nodes and is represented in Figure 4.7 for three passes of a satellite in a pro-grade orbit. Eventually the satellite ground trace will cover virtually all the area on the Earth between the Southern and Northern limits of the ground trace. These limits are set by selection of the orbit inclination.

11 Adapted from: Lindsey, G. and G. Sharpe, *Surveillance Over Canada*, Working Paper 31, Canadian Institute for International Peace and Security, December 1990, p 26.

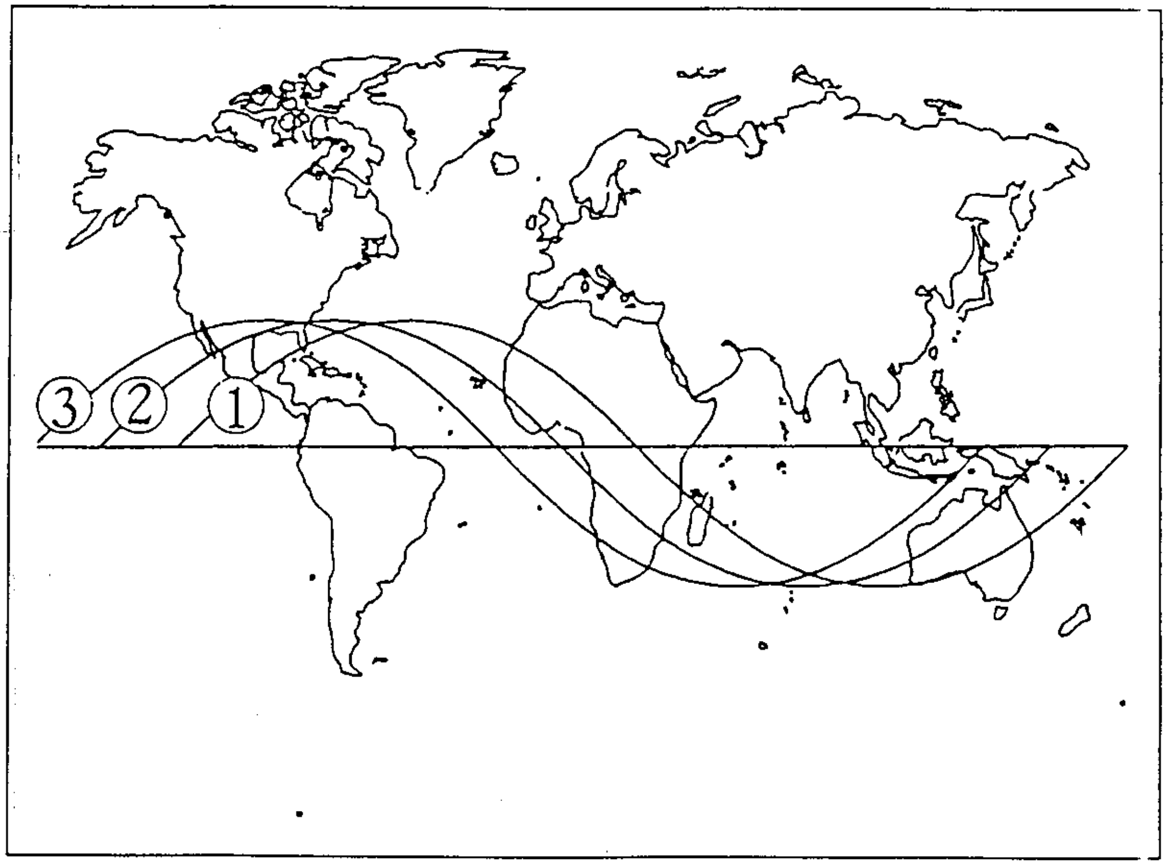

Figure 4.7 Apparent Regression of Nodes
(Only part of the continuous ground trace is shown for simplicity)

There is also a real regression of nodes in which the orbital plane, of other than polar orbiting satellites, precesses slowly due to forces on the satellite as it orbits. This is caused by the oblate shape of the Earth where gravity attracts the satellite more at the equator than elsewhere in the orbit, causing the orbit plane to precess at a rate determined by the orbital parameters. Sun-synchronous satellites utilise this real regression of nodes and a retro-grade orbit to synchronise the satellite orbit to the Earth's rotation around the Sun.

<u>Orbital Inclination</u>

Inclination is the angle that the orbital plane makes with the equator, measured in the anti-clockwise direction from the equator, as the satellite traverses from South to North across the equator. Selecting an inclination is a fundamental consideration in surveillance applications because a satellite ground trace will not move to a latitude in excess of the orbital inclination, as shown in Figure 4.8. This means that a satellite with a 20 degree inclination will have a ground trace that moves between 20 degrees North and 20 degrees South of the equator. Polar orbits, with a 90 degree inclination, can ultimately view all of the Earth's surface as the Earth rotates under the satellite orbit.

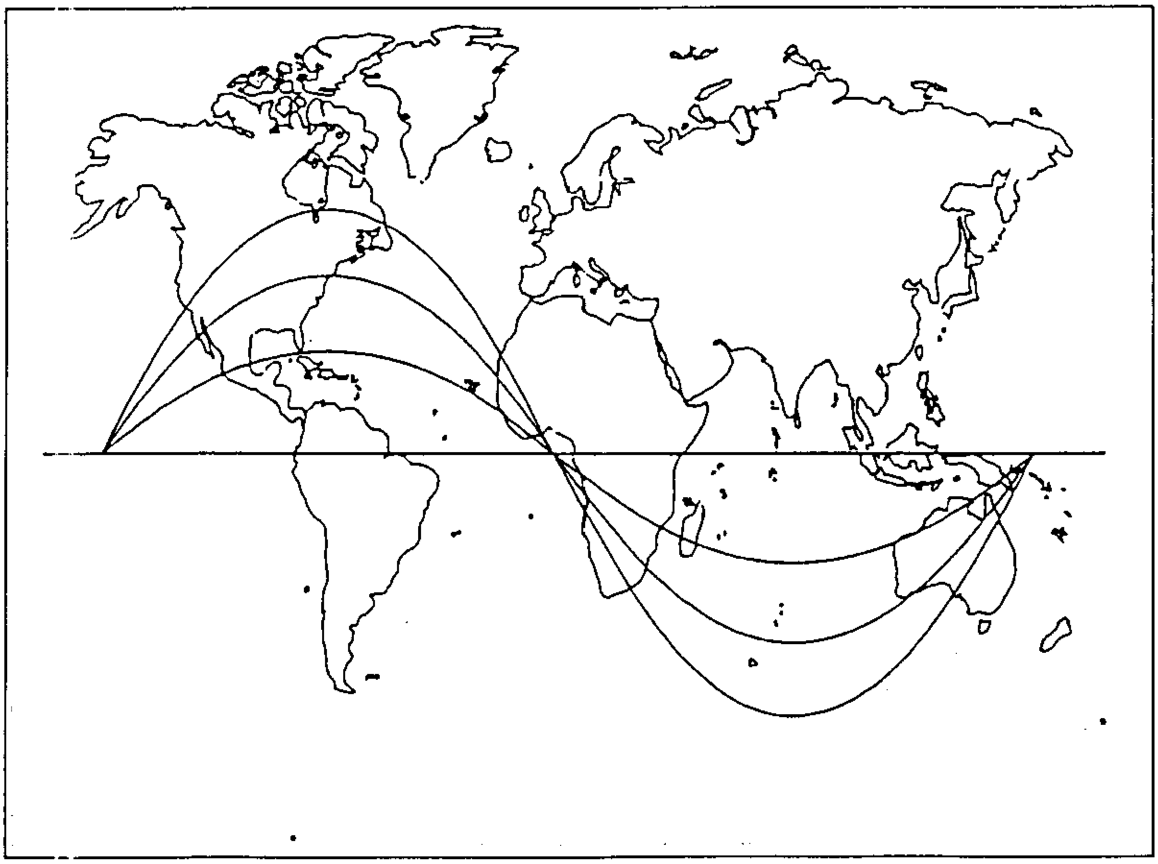

Figure 4.8 Effect of Inclination on Ground Traces
(Only part of the continuous ground trace is shown for simplicity)

Eccentricity

Eccentricity is a measure of the elliptical shape of an orbit. All satellite orbits are elliptical in shape, since a circle is just a special case of an ellipse. However, even circular orbits are slightly elliptical because the Earth is not a perfect sphere, and the process of injecting, transferring and keeping a satellite in a particular orbit is never exact. Highly elliptical orbits can be used to maximise the time that a satellite dwells over a region. This orbit type is often used for near polar communications since geostationary satellites cannot communicate beyond about 70 degrees latitude.

Special Orbits

Sun-Synchronous

These obits are used for periodic observation of locations on the Earth at the same local mean time each day. The inclination and altitude are specifically selected to achieve a real nodal regression that will maintain a constant angle between the orbital plane and the Sun. Sun-synchronous orbits are generally used to ensure that imaging of certain locations is obtained with a known solar illumination angle.

Geosynchronous

These orbits have an orbital period equal to the rotation period of the Earth, which is about 24 hours. A geosynchronous satellite will effectively remain over one longitude and its ground trace will move between the North and South latitudes equal to the inclination.

Geostationary

A geostationary orbit is a special geosynchronous orbit that has an inclination of zero degrees. Satellites in these orbits will effectively remain over the one point on the equator as the Earth rotates. These orbits are commonly used for communications satellites so that communications can be maintained 24 hours a day for users at latitudes less than about 70 degrees.

Molniya

Molniya orbits have high inclinations and eccentricities. These orbits typically have a perigee[12], from about 600 km and an apogee[13] out to about 40,000 km. The former Soviet Union has utilised Molniya orbits for many years to give their satellites more time over the Northern hemisphere, for applications such as communications at high latitudes where geostationary satellites do not have line-of-sight coverage.

12 Perigee is the location in the orbit where the satellite is closest to the Earth.

13 Apogee is the location in the orbit where the satellite is farthest from the Earth.

CHAPTER 5

INTRODUCTION TO SENSOR SYSTEMS

This chapter provides background on the operation, characteristics, applications, advantages and disadvantages of sensors that have potential for use in the space-based surveillance role. Surveillance sensor systems are used to intercept and exploit EM radiation for detecting and tracking, and identification of targets of interest. Sensor performance on space-based platforms can vary significantly with atmospheric attenuation and weather effects, as shown in the Chapter Four. Spacecraft surveillance sensors are therefore used to intercept reflected, scattered or emitted radiation in those frequency bands that are least attenuated in the clear atmosphere.

Sensors are either active or passive in operation: active sensors transmit energy to illuminate the target area and subsequently receive and process the returned energy, but passive sensors just receive and process radiation within the sensor field of view. The sensors examined include both passive and active electro-optical (EO) types, and also real and synthetic aperture radars. Passive visible and infrared EO sensors and laser radars are also introduced.

Sensor systems consist of the following components:

a. an aperture to collect the incident EM radiation (EO systems use lenses and mirrors for apertures and radio frequency systems have antennas);

b. a scanning system to increase the total field of view of the aperture;

c. a detector, sensitive to the wavelengths bands of interest, to convert the incident EM energy into an electrical signal;

d. an amplifier, data processing, storage and communications to transmit received signals to a ground station; and

e. a ground station to process and distribute data to users.

Active systems also include a transmitter to generate the EM radiation to be directed toward the target area.

Characteristics of Targets

Targets are the objects or characteristics in a scene to be detected or observed and they can be described in terms of the spatial, spectral, radiometric and temporal characteristics they exhibit.[1] Spatial means the physical dimensions and shape of

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

an object or scene; spectral refers to the EM spectrum band reflected, emitted or scattered by a target; radiometric characteristics indicate the amount of EM radiation collected; and temporal refers to how a target or scene changes over time. The contrast between a target and the scene or background will determine the clarity with which targets are distinguished. Sensors and system configurations are therefore chosen to exploit one or a number of these target characteristics.

Sensor Resolution

Resolution requirements can be specified in terms of the spatial, spectral and temporal characteristics needed to detect targets. Definitions of these resolution aspects are provided here. There are trade-offs needed between these different resolutions, since it is generally neither practical nor desirable to achieve all these resolution characteristics on the one sensor.

Spatial Resolution

The spatial resolution of a sensor is defined here as the smallest separation between two objects, such that the sensor is still able to determine that they are distinct objects. However, there are two concepts to consider: the instantaneous field of view (IFOV), which is determined by physical size of the sensor aperture and detector and also range to the target; and spatial resolution, which is dependent on the IFOV and the wavelength, and also the ability to distinguish detail in a target scene. IFOV is known precisely from physical quantities in the satellite system, but resolving a target from its background also depends on radiometric characteristics of both the target and scene.

User needs will dictate spatial resolution requirements. Target detection identification, description and technical intelligence missions may need to be satisfied, which implies the need for various levels of precision, as previously illustrated in Table 2.1. The high spatial resolution shown is relevant for imaging operations; however, targets can also be detected by Doppler processing from a large field of view or by selectively using wavelength bands at lower resolutions, to resolve specific target characteristics. Therefore, high spatial resolution may not be vital since it only provides some target information.

Instantaneous Field of View. Figure 5.1 illustrates the relationship between sensor FOV, IFOV and detector element size. It shows the difference between 'detector element IFOV' and 'detector IFOV'. The detector elements or pixels are the smallest detecting components of a detector, which generally consists of a linear array or group of arrays of detector elements. Some sensors scan the full detector IFOV to provide a larger FOV which is called the 'sensor FOV' here.

Figure 5.2 shows the relationship between IFOV, spatial resolution and the physical attributes of the aperture and sensor. This equation for IFOV is valid for computing detector and detector element IFOV; the 'd' term can correspond to either the size physical of an individual detector element or the size of the entire detector, depending on whether the detector element IFOV or the detector IFOV is being computed. Detector element IFOV specifies the resolving power of the sensor, since for two objects to be resolved as separate, they must lie mostly in adjacent detector cells and provide sufficient EM energy to be detected. If this occurs then spatial resolution is equal to IFOV; however, the contrast of a target against its background can complicate this detection process and provide much worse spatial resolution.

Spatial data from imaging sensors are useful for:[2]

a. characterising objects by shape and size,

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

c. detecting and locating small targets situated with other small background objects by being able to identify shape and size characteristics.

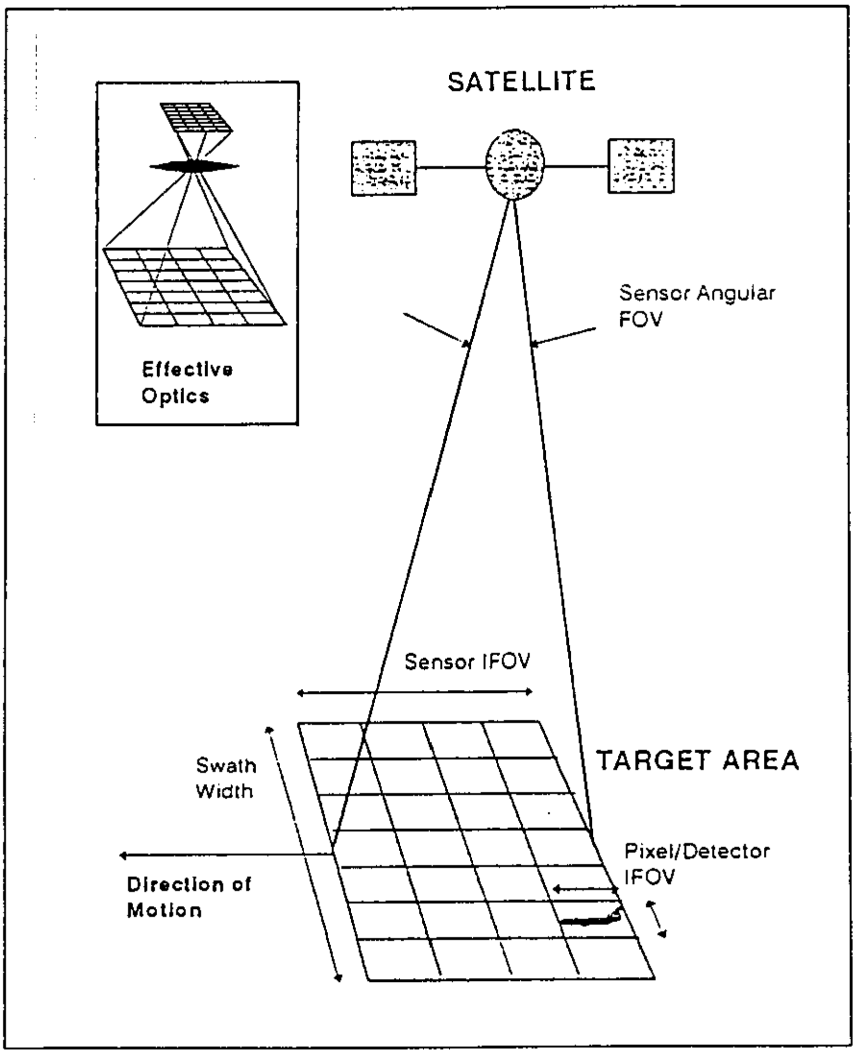

Figure 5.1 Instantaneous Field of View in Target Area

2 Evans, H.E., *Electro-Optical Space Systems Technology*, PHYS 6.21, Course Notes, USAF Institute of Technology, Dayton, Ohio, 1988, p 79.

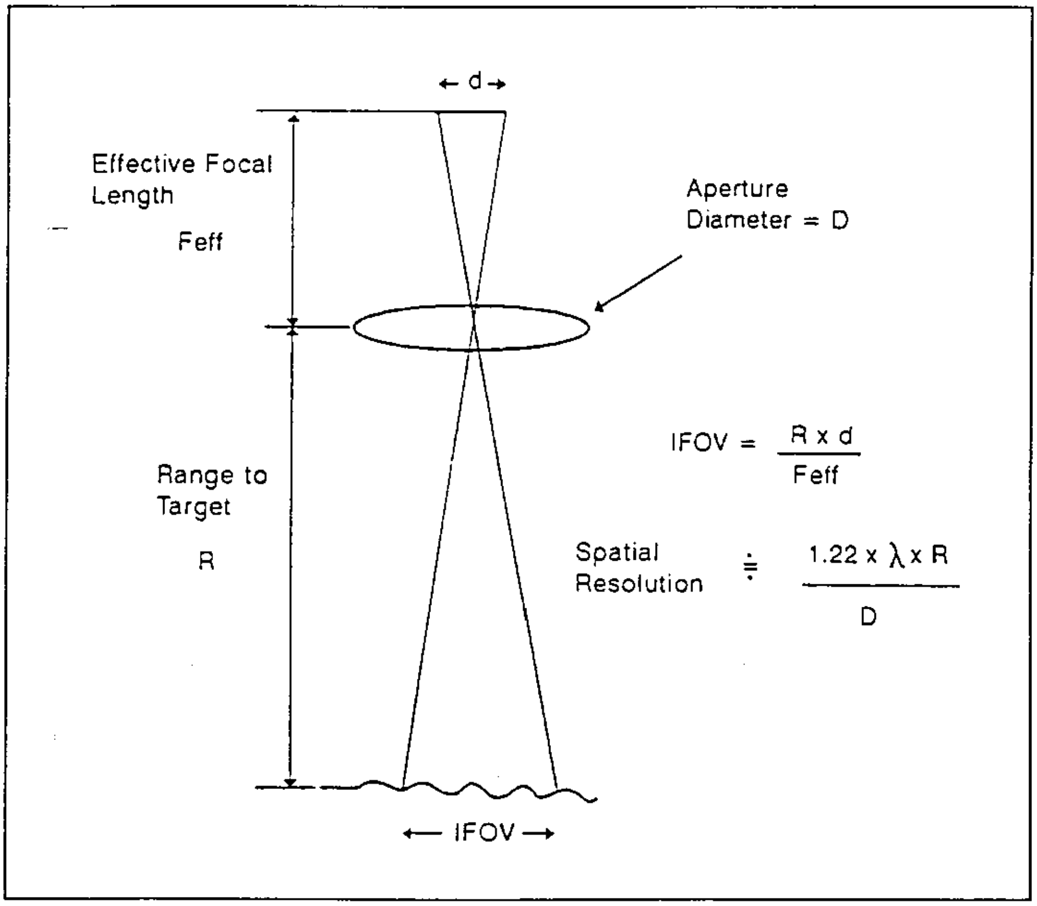

Figure 5.2 Aperture, IFOV and Spatial Resolution

An example of the effect of sensor IFOV on resolving capability is given in Figure 5.3. Each shaded square or pixel represents the detector element IFOV that is scanned across the scene. It illustrates that a 30 m pixel can provide target detection and 10 m is adequate to approximate the aircraft target size. As the image pixel size is reduced to one metre, much more detail of the aircraft can be obtained, and the aircraft type appears to be identifiable as a C-130 aircraft at this IFOV.

Tables 5.1 and 5.2 illustrate the approximate aperture size which would be required to achieve a range of resolutions using the frequencies of interest here. Note the dramatic change in aperture size required for altitudes of 700 km and 36,000 km. To achieve high spatial resolutions, a small IFOV is required and this implies the use of short wavelengths, large apertures and low altitudes. However, the two main limiting factors are short orbit lifetimes at low altitude, and the weight and size limits for launching spacecraft with large apertures.

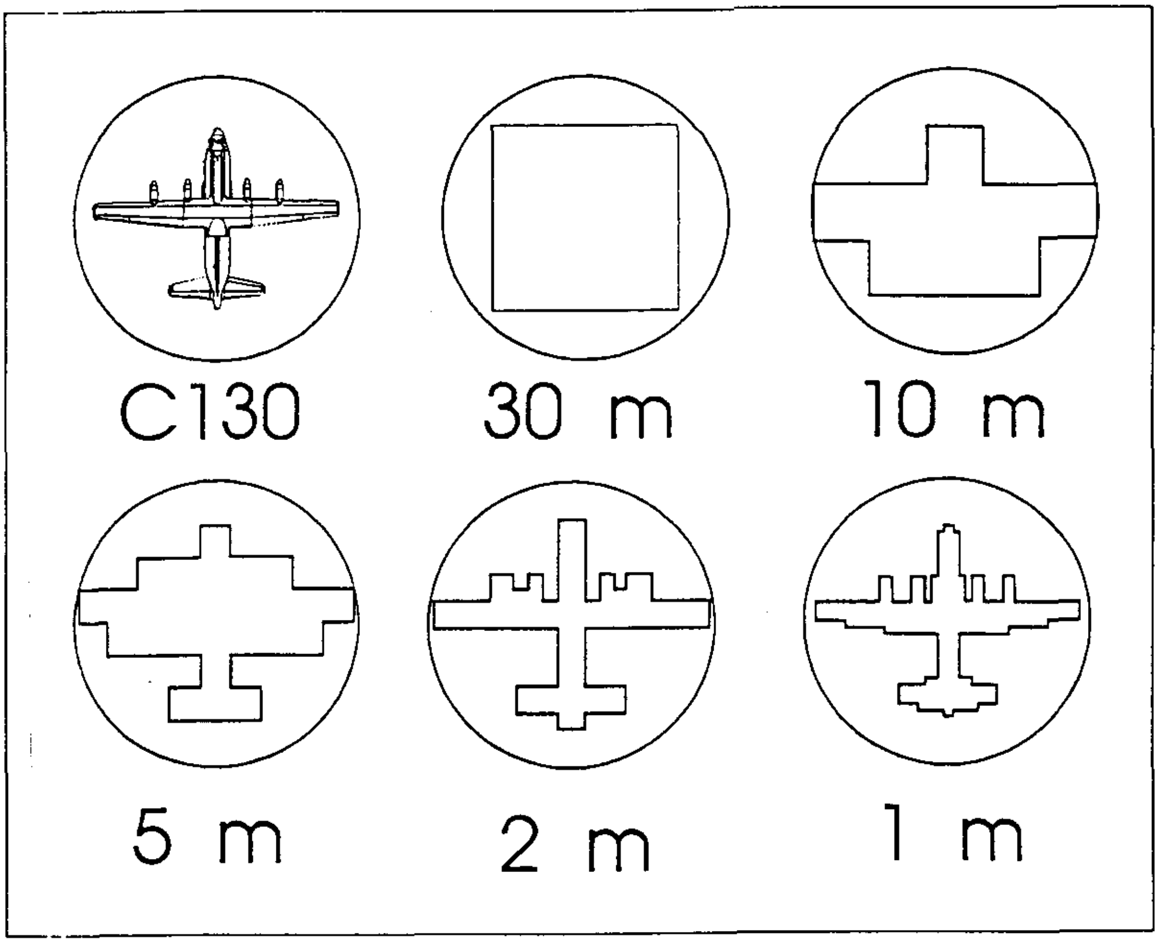

Figure 5.3 Effect of Spatial Resolution on Satellite Images[3]

Table 5.1 Resolution Parameters at Geosynchronous Earth Orbit (36,000 km)[4]

Aperture required for a given ground resolution as a function of wavelength.

Resolution (m) ->	0.1	1	10	100	1000
Wavelength					
0.5μ (Green)	350 m	35 m	3.5 m	35 cm	3.5 cm
1.0 μ (Near IR)	700 m	70 m	7.0 m	70 cm	7.0 cm
10.0 μ (Thermal IR)	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)	7000 km	700 km	70.0 km	7 km	700.0 m
10 cm (3 GHz)	70000 km	7000 km	700.0 km	70 km	7.0 km

3 Concept adapted to a C-130 aircraft by Squadron Leader A.M Forestier, RAAF, Air Power Studies Centre, from Din, A.M., 'Satellite Surveillance Goes Commercial', *International Defense Review*, June 1988, p 619.

4 Cartwright, D., Space and Defence, Lecture at CSIRO Headquarters, Canberra, 31 July 1991.

Table 5.2 Resolution Parameters at LEO (700 km)[5]

Aperture required for a given ground resolution as a function of wavelength.

Resolution (m) -> 0.1		**1**	**10**	**100**	**1000**
Wavelength					
0.5 μ (Green)	7 m	.7 m	7.0 cm	7.0 mm	0.7 mm
1.0 μ (Near IR)	14 m	1.4 m	14.0 cm	14.0 mm	1.4 mm
10.0 μ (Thermal IR)	140 m	14.0 m	140.0 cm	140.0 mm	14.0 mm
1 mm (300 GHz)	14 km	1400 m	140.0 m	14.0 m	1.4 m
1 cm (30 GHz)	140 km	14 km	1.4 km	140.0 m	14.0 m
10 cm (3 GHz)	1400 km	140 km	14.0 km	1.4 km	140.0 m

Radiometric Resolution

Radiometric resolution is the ability of a sensor to distinguish a number of levels of brightness in images.[6] Brightness level discrimination provides image products with levels of contrast that permit more precise scene representation. Typical radiometers can measure up to 256 discrete levels of brightness, although for high spatial resolution sensors, very low radiometric resolution would be used to limited the amount of data produced.

Spectral Resolution

The spectral resolution of a sensor indicates the spectrum band width in the sensor. High resolution is obtained using spectrometer sensors. Typical applications include accurate temperature measurements and the identification of atmospheric molecule emission characteristics. The combination of a number of specific spectral bands may be used to detect targets in a scene that may be undetectable with sensors that examine only broad spectrum bands.

Temporal Resolution

Temporal resolution is the time frame associated with obtaining an image. For example, images taken every month may be adequate to monitor crop condition. In the case where identification of changes to a construction site is required, images obtained weekly may be sufficient. However, to conduct real-time tracking of moving aircraft, sensor revisit times must be such that aircraft targets do not move out of the FOV on successive sensor imaging passes.

Some of the time factors to be considered include: the physical time for a satellite to revisit and image a target area, the time to process and communicate images to

5 ibid.

6 Chekan, R., op cit, p 13.

an image analysis centre, the time for image processing and analysis, and also the time to deliver products to the user. Further delays can occur, in the case of visible and infrared spectrum imaging, when cloud cover obscures a target while a sensor is overhead. Cloud cover conditions may also persist for many orbits before useful images can be obtained.

Effect of Background and Contrast

Target background, just like a target, reflects and emits EM radiation corresponding to its physical structure. The contrast across targets and between targets and the background can complicate the process of resolving the size and shape of individual objects, which can limit the resolution obtainable. This occurs whether the purpose is to just detect targets or to image them for size and shape. For example, a small object that is much smaller than the IFOV may be easily detected when it is highly contrasted against the background, but an object that is poorly contrasted may need to almost fill the IFOV to be detected.

In order to distinguish a target from background noise or clutter, the amount of energy received from the target must be sufficient to be detectable above the noise. Processing may some background noise but internal detector and amplifier noise cannot be eliminated. Detectors and amplifiers are generally cooled to reduce this inherent noise but cooling devices can cause size and weight restrictions on spacecraft.

Data Transmission Rate

As the resolution of sensor images increases, the amount of data required to reproduce an image can increase rapidly. For a fixed swath width, improving the spatial or radiometric resolution by two times increases the number of pixels in the scene by four, thereby increasing the data rate by four times. This rapid increase in data rate is illustrated in Table 5.3. State-of-the-art military space data transmission capabilities are estimated to be about 500 Mbps which probably illustrates the current technological limit to gaining higher resolution. Generally, swath width and field of view are traded for resolution to satisfy user requirements, while keeping within data transmission rate technology limitations. Table 5.3 estimates the swath width and resolution that are achievable for a range of data rates.

The trend toward higher resolution applications has led to considerable research and development into high-speed data transmission design and also data compression techniques, since real-time data transmission is vital for continuous sensor operation. A 10 to 1 data compression ratio for image data is achievable with existing technology. This can reduce a 500 Mbps data rate to 50 Mbps, depending on the type of data. Spacecraft on-board data storage is used in situations where the data rate is too high for the communications channel or access to a ground station is not possible; however, only limited amounts of data can be stored and the time delays between collection and down-linking may not be tolerable. The development of data relay satellites has provided a means of transmitting data continuously, although the cost of these facilities can be high and is would be limited to use by world super-powers.

Table 5.3 Data Transmission Rate Per Channel at 700 km Altitude[7]

An orbital period of 99 minutes provides a sub-satellite point speed of about 6.8 km/sec. This assumes a radiometric quantisation of 64 bits/pixel per sensor channel. The data rate is in data bits per second (bps .

Resolution (m) ------------> Swath Width		0.1	1	10	100	1000
100	m	4.3 G	43.5 M	435.0 k	4.3 k	43.5
1	km	43.5 G	435.0 M	4.3 M	43.5 k	435.0
10	km	435.0 G	4.3 G	43.5 M	435.0 k	4.3 k
100	km	4.3 T	43.5 G	435.0 M	4.3 M	43.5 k
1000	km	43.5 T	435.0 G	4.3 G	43.5 M	435.0 k

$k=10^3$, $M=10^6$, $G=10^9$, $T=10^{12}$

The Infrared Spectrum

There is some inconsistency in the definition of the IR spectrum so Table 5.4 is used to categorise the bands. The near infrared (NIR) band is similar to the visible band in that the radiation is highly scattered or reflected by the Earth, clouds, rain and fog. As wavelengths increase toward the far-infrared (FIR) and depending on the temperature of objects in the scene, IR emission from targets can become significant; although much of the FIR band is highly attenuated by the atmosphere. There is a noticeable transition from reflection being dominant in the shorter wavelengths, as in the NIR band, to emission becoming most significant as the wavelength increases to the long wave infrared (LWIR). This transition region occurs around 3 μm where the reflected and emitted energy is about the same and difficulty can occur in determining the source of radiation when measuring at the sensor output.

The short-wavelength infrared (SWIR) band is particularly useful for surface reflection measurements, surface feature mapping and detection of missile plumes; at temperatures from 730-1700°C.[8] Middle-wavelength infrared (MWIR) can be used to detect emissions from hot targets such as aircraft exhaust plumes, engines, fires and factory burners; at temperatures from 250-650°C. The LWIR band is centred at the peak of the Earth's thermal emission, at about 27°C, and is therefore useful for thermal imaging of the Earth.[9]

7 Adapted from Cartwright, D., op cit.

8 Evans, H.E., op cit, p 15.

9 Chen, H.S., *Space Remote Sensing Systems: An Introduction*, Academic Press Inc., Orlando, 1985, p 44.

Table 5.4 Infrared Wavelength Regions[10]

Spectrum	Wavelength (micrometres)
Near infrared (NIR)	0.8 - 1.5μm
Short-wavelength infrared (SWIR)	1.5 - 3.0μm
Middle-wavelength infrared (MWIR)	3.0 - 5.0μm
Long-wavelength infrared (LWIR)	5.0 - 15.0μm
Far infrared (FIR)	15.0 - 300.0μm

Scanning Systems

Scanning increases the total field of view of a sensor by allowing a large area to be focused onto a small detector. Common scanning techniques include:

a. Spin Scan. This involves spinning the spacecraft while the sensor FOV is offset from the spacecraft axis of rotation, as illustrated in Figure 5.4.

b. Whiskbroom Scan. This scanning method, illustrated in Figure 5.5, typically uses a mechanical method to scan the sensor FOV across the track as the satellite carries the sensor along the track. The current Landsat series of satellites uses this technique.

b. Pushbroom Scan. This method, shown in Figure 5.6, uses the forward motion of a satellite to sweep a linear array of detectors along in the direction of the satellite ground trace, and therefore eliminates the need for mechanical across-track scanning.

c. Staring Array. Focal plane array (FPA) detectors fill the sensor FOV and allow detectors to stare at each scene for a period of time as the satellite moves along. This integration time gives the staring arrays detectors a higher sensitivity than that of the above methods. Figure 5.7 illustrates this staring array concept.

Sources of Interference for Electro-Optical Sensors

Apart from the high attenuation at many EO wavelengths due to propagation through both clear and adverse atmospheric conditions, EO receivers can be jammed or dazzled by deliberate and spurious radiation. Typical sources of interference include: glint or reflected energy from clouds, sea and lake surfaces; laser sources such as atmospheric sounders and range-finders, either unintentionally or deliberately directed; and natural or man-made energy sources like the Sun, fires, lightning and rocket plumes.

10 ibid, p 9

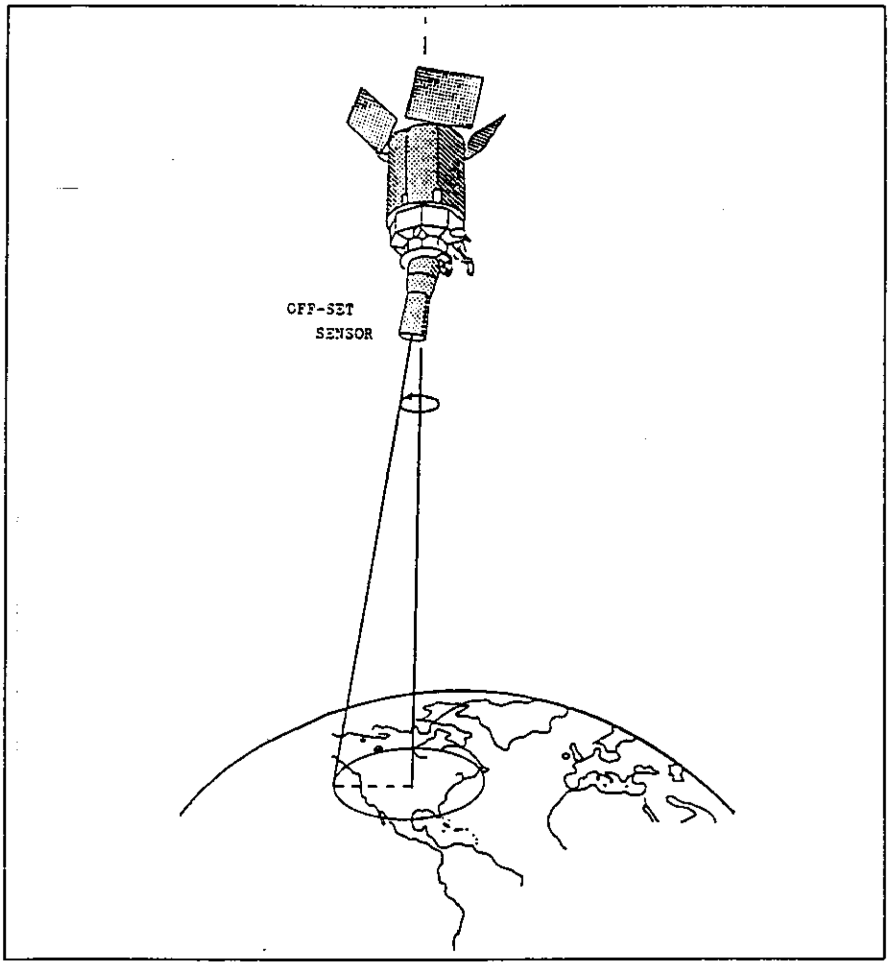

Figure 5.4 Spin Scan[11]

Passive EO Sensors

Passive EO surveillance sensors are typically used to collect visible and infrared energy through the use of radiometers or spectrometers. These sensors use telescopes with optical lenses and mirrors to collect and focus received EM radiation onto a detector material. Detectors convert the energy into electrical signals for processing and transmission to a ground station. Radiometers can use either imaging or non-imaging modes: a camera is one simple example of an imaging radiometer, which records the light reflected from a scene onto photographic film. Most modern spacecraft radiometers, however, use digital imaging techniques and are able to electronically store and transmit images. Spectrometers determine the spectral characteristics of the received radiation by using narrow band filters. Multi-spectral sensors of this kind have applications in spectral signature analysis and classification for automatic target recognition; however, spectrometers are not examined further here.

11 Forestier, A.M., *Into the Fourth Dimenson: An ADF Guide to Space*, Air Power Studies Centre, RAAF Base Fairbairn Chapter 5, 1991.

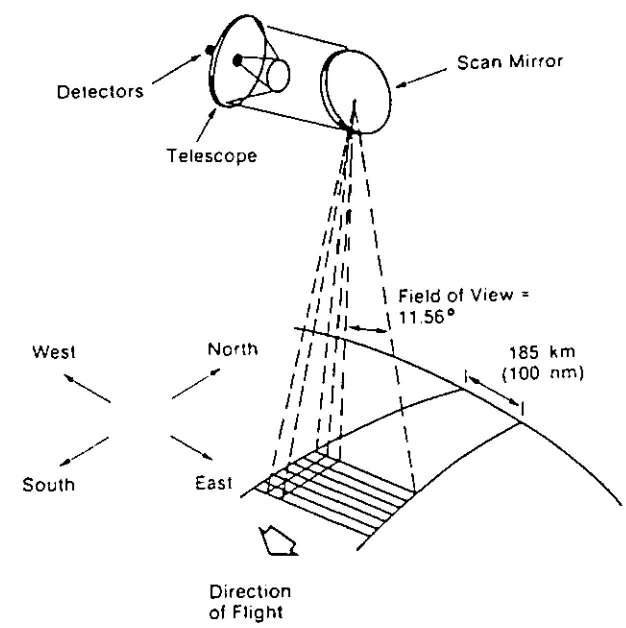

Fig. 2.3. Satellite whiskbroom scanning technique.

Figure 5.5 Whiskbroom Scanning Technique[12]

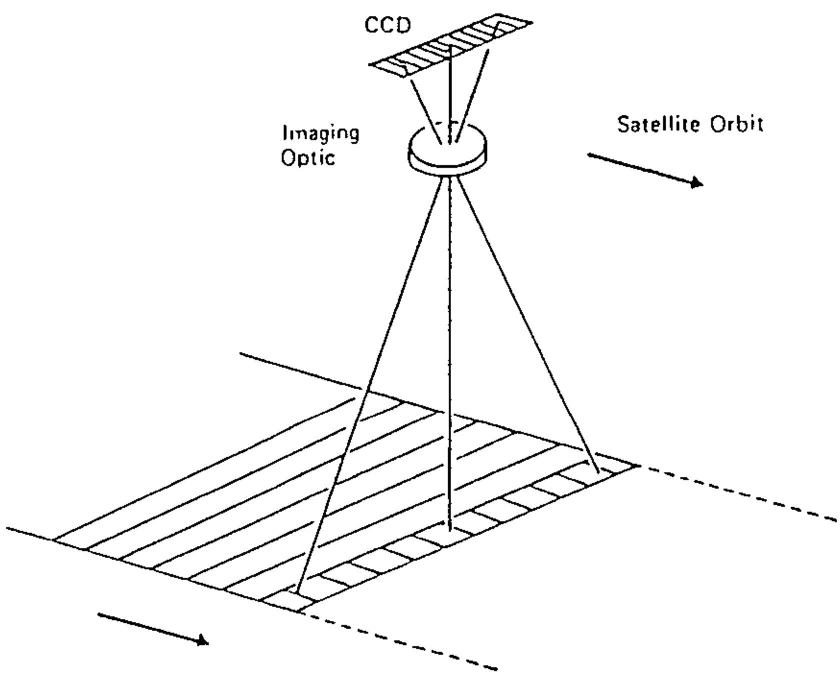

Figure 5.6 Pushbroom Scanning Technique[13]

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12 Chen, H.S., op cit, p 22.

13 Ball, D. and R. Babbage (ed), *Geographic Information System: Defence Applications*, Pergamon Press (Australia), 1989, p 49.

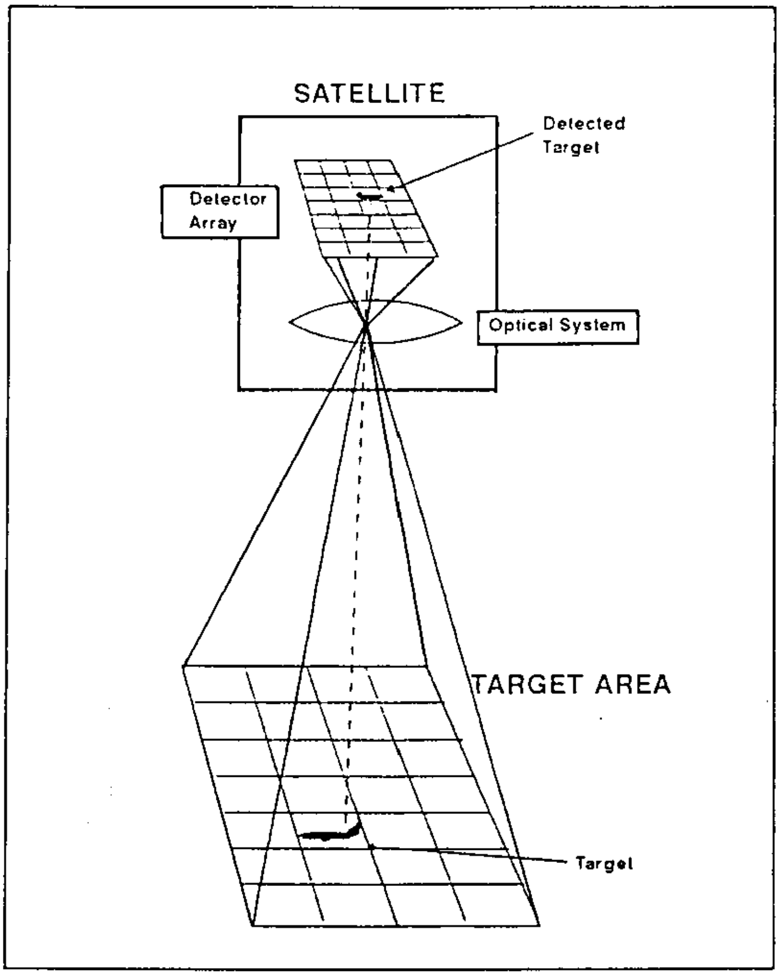

Figure 5.7 Staring Sensor Using a Focal Plane Array[14]

Multi-spectral radiometer operation can be described using the human eye as an analogy. The eye detects the intensity and colour of light, where the colour perceived is dependent on the intensity of radiation from the bands making up the visible spectrum. Passive EO sensors also detect the intensity of EM radiation and by using filters to detect different wavelength bands or 'colours', the intensity and colour information can be used to discern characteristics of a scene; just as the eye is able to distinguish objects by colour and intensity.[15]

Visible Spectrum Radiometers

Visible spectrum imaging radiometers are able to produce the highest spatial resolution of all the sensors of interest, and they are used by both the military and civil communities. Military requirements generally specify the highest spatial resolution practicable for technical intelligence purposes. However, broader military applications do exist for lower resolution sensors as evidenced by the significant annual purchases of commercial imagery by the US DoD. US military KH-11 series reconnaissance satellites,

14 Adapted from: May, J.J. and M.E. Van Zee, 'Electro-Optic and Infrared Sensors', *Microwave Journal*, September 19[illegible]3, p 130.

15 Robinson, I.S., *Satellite Oceanography: An Introduction for Oceanographers and Remote-Sensing Scientists*, Ellis Horwood Ltd, Chichester, 1985, pp 45-46.

operating at altitudes from about 400 km are said to be able to provide spatial resolutions of about 0.15 m, although in theory the resolution may be as small as 10 cm.[16] By comparison, the SPOT commercial imagery satellite can provide resolutions of 10 m from about 800 km.

Multi-spectral sensors are also extensively exploited. Table 5.5 illustrates a number of the environmental and weather sensing applications for both visible and infrared sensors. As sensor technology improves, image resolution and multi-spectral sensors capabilities will significantly improve the intelligence available to purchasers of commercial imagery, which in principle can be anyone.

The main shortfall with visible radiometers is the need for clear line-of-sight and daylight conditions to operate effectively. Time delays and lack of 24 hour coverage for imagery must be tolerable in a system that relies on these sensors.

Table 5.5 Environmental and Weather Sensor Spectral Band Selections[17]

Spectral Range (μm)	Applications
0.58 - 0.68	Cloud mapping
0.50 - 1.10	Surface albedo mapping
0.725 - 1.0	Surface boundaries
0.725 - 0.755	Clear atmosphere
0.759 - 0.762	Cloud height
0.761 - 0.763	Cloud height
1.059 - 1.219	Water vapour correction
1.548 - 1.70	Snow/cloud descriminator
2.05 - 2.28	Cloud particle size
3.55 - 3.93	Water vapour correction
5.70 - 7.00	Upper tropospheric wind field
9.60 - 9.80	Ozone total burden
10.30 - 11.3	Thermal mapping
11.50 - 12.5	Water vapour correction

Infrared Spectrum Radiometers

IR radiometers operate in the same way as visible spectrum radiometers, but only a limited number of wavelength bands are useful for space-based surveillance sensors. These bands are extensively exploited for both scientific and military applications, as indicated in Table 5.5. IR emissions depend on temperature therefore some targets may be detectable day and night; however, sensor detection performance can be complicated by reflected solar energy and background IR emission. Objects that are hot from daytime solar heating will start to cool after sunset, therefore IR emissions will only be distinguishable from background emissions for a limited time. Targets with other sources

16 Cline, R.S. et al, *The Intelligence War*, Lansdowne Press, Sydney, 1983, p 103.

17 Chen, H.S, op cit, p 56.

of energy such as fires, internal combustion engines and factory power plants will not b affected by the loss of sunlight conditions. In fact, these targets are likely to be more highly contrasted against the background at night.

Infrared spectrum sensors suffer the same shortfalls as visible spectrum sensors, in that they are significantly affected by cloud cover, rain, fog and some atmospheric pollutants. Therefore, IR emissions may be detectable at night but clear li e-of-sight atmospheric conditions are needed. In addition, IR detector sensitivity will lir it the ability of a sensor to detect emissions from long range.

Active EO Sensors

Laser Radar

Laser radars or LIDARs (light detection and ranging) typically generate a d transmit coherent pulsed EM radiation, and use receivers similar to passive radiometers o detect the backscattered radiation from an illuminated area. They mostly operate in the visible or IR wavelength bands which implies that they can be severely affected by poor weather conditions. However, LIDARs provide the illuminating source so they can operate at night. Better performance would also be expected at night because there is less chance of interference from reflected sunlight.

LIDAR Receivers[18,19]

Laser radar receivers operate in either direct or heterodyne mode. In dir ct mode, they are similar to passive EO receivers in that detector output current is directly proportional to the received energy. However, phase information in the received signa is lost in the direct detection process. Heterodyne receivers mix a stable oscillator signal with the radar return signal to decrease the frequency for ease of amplification and processing. They also offer increased sensitivity and higher spectral resolution than dir ct mode receivers but they are more complex. Heterodyne receivers also preserve the frequency and phase of the returned signal, which allows them to use Doppler processin to detect moving targets.

Power Requirements and Efficiency

The power required for space-based laser operation for surveillance is typically in the order of thousands of watts,[20] but existing large spacecraft electrical pow r generating capabilities, based on solar cells, are limited to about 5,000 Watts.[21] Therefore, laser radar will be constrained by satellite electrical power sourcing capabilit es.

18 Hovanessian, S.A., op cit, p 33.

19 Chen, H.S., op cit, p 172.

20 Chen, H.S., op cit, p 181.

21 Capability deduced from estimated improvements in solar cell capabilities since 1980s communications satellites, such a West Germany's TV-SAT, which was able to provide about 3,000 Watts, from Velupillai, D., 'International Satellite Directory', *F ght International*, 14 May 1983.

Nuclear reactor power sources could provide the power required, but they are generally considered to be risky and past accidents have made them a politically unfavourable choice.

Laser efficiency typically ranges from about 1-10% therefore considerable waste energy is dissipated in high power lasers, mostly in the form of heat. Radiating this excess heat from a spacecraft is difficult so high power lasers will need to be turned off regularly for cooling. The ratio of on-time to cooling time is likely to be about 1:10, which means that a LIDAR will probably only operate for a few minutes per orbit, for a LEO satellite.

Applications[22]

LIDAR applications can be separated into four main categories: atmospheric window, absorption, differential absorption and Doppler operation. Window LIDAR is useful for measuring the Earth's surface roughness and atmospheric aerosol vertical temperature and pressure profiles. Absorption systems are used to monitor atmospheric particle species. Doppler LIDAR can be used to measure wind fields and track the movement of specific targets. A number of these sensors have been flown in spacecraft for scientific applications with Space Shuttle-based packages being developed to study clouds, Earth surface albedo, weather and atmospheric particle characteristics.

Surveillance, Targeting and Tracking. The US strategic defensive initiative (SDI), for ballistic missile defence of the USA, is one recent program that requires laser radars. Significant research and development are needed, however, to provide just a part of the space surveillance, acquisition, tracking and kill assessment segments of SDI. Other military applications include high resolution imagery, and detection and identification of combustion products in missile plumes, factory smoke stacks and nuclear debris clouds.[23]

Submarine Detection. Submarine detection may also be possible by reflecting blue-green laser light, which can penetrate sea-water, off submarine hulls or perhaps off the disrupted particle flow in their wake.[24] Accurate ocean surface height measurements can potentially locate submerged submarines as they move along, by detection of the bow wave effect at the surface.

Advantages

Laser radars offer the following advantages for operation from space platforms:

a. high spatial and spectral resolution,

b. the use of small apertures and components,

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22 Chen, H.S., op cit, p 178.

23 Evans, H.E., op cit, p 227.

24 Stefanick, T., 'The Nonacoustic Detection of Submarines', *Scientific American*, Volume 258, Number 3, March 1988, pp 27-28.

c. day and night operation, and

d. potential for moving target detection and tracking.

Disadvantages

The following disadvantages are evident:

a. frequencies used are subject to high attenuation from clouds, rain, fog, haze and atmospheric pollutants;

b. high spatial resolution makes it difficult to achieve a wide area coverage capability and it demands precise sensor pointing control;

c. high electrical power required due to the inefficiency of lasers;

d. low duty cycle of operation due to the difficulty in radiating the excess heat generated into space;

e. EO receivers are easily jammed; and

f. lack of wide bandwidth tuning ability of lasers prevents operation in other than fixed and narrow wavelength bands.

Passive and Active Microwave Sensors[25]

Microwave surveillance sensors can be used in passive or active modes of operation. Passive sensors can provide reasonable imagery, particularly at higher frequencies; however, they are not considered further because they rely only on energy from the target area and are therefore less versatile than active sensors. Active sensors are capable of operating through clouds, rain, fog, pollution and vegetation cover, depending on the frequency used. Microwave radiation can even penetrate to some depth below the surface of the Earth and provide detail of subsurface structures. With these capabilities, active microwave sensors offer the potential for a space-based area surveillance system that can be effective 24 hours a day and in all weather.

The active sensors considered are real aperture radar (RAR) and synthetic aperture radar (SAR). Both radar types typically operate by illuminating a target region with pulses of coherent microwave radiation, directed and received through an antenna system. Range to the target is a fundamental output of radar and is determined from the time elapsed between the transmission and reception of a pulse, and pulse width determines the spatial resolution in the direction of the radar beam. Apart from these aspects, SAR and RAR differ dramatically in operation, capability and application, as a consequence of the way radar returns are processed.

25 Sensors operating in either the millimetre or microwave frequency bands are referred to as microwave sensors for simplicity.

Applications of radars can generally be categorised as either imaging, altimetry, sounding or scatterometry. SARs are typically used for surface imaging; altimetry requires real aperture pulse modes; sounding of surface and sub-surface structures also requires pulse mode operation, with the depth of penetration being dependent on the frequency used; and scatterometers typically use coherent pulse mode radars with frequencies selected to correspond to specific target characteristics. Scatterometers are typically used to measure wind speed.[26]

The trend in satellite microwave radar sensor development has been toward SARs to obtain high resolution imagery for both civil and military applications. However, in achieving high resolution with SAR, the ability to detect other than fixed or very slow moving targets has been lost. One principal need of a wide area surveillance system is to detect and track moving targets, including both fast and slow moving aircraft and maritime vessels. RAR has the potential to achieve this using pulse Doppler techniques to extract moving target information from radar returns. However, while spaceborne SAR technology is maturing, RAR has not been actively pursued by the Western world but the former Soviet Union has had a limited capability RAR ocean surveillance system for a number of years.[27]

Radar Efficiency

Research into a US space-based RAR has indicated that it would only operate for a short time each orbit due to power dissipation problems.[28] In addition, power consumption of these radars will be high in comparison to the energy sources available. Power system shortfalls are also evident in SARs with Canada's RADARSAT which is expected to operate for a maximum of 28 minutes in a 100 minute orbit and the ERS-1 SAR was expected to have a maximum on-time of only 7.5 minutes per orbit,[29,30] although it now appears that 12-15 minutes may be achievable on ERS-1[31]. The efficiency of these radars, and the methods of eliminating waste heat on spacecraft, are such that the excess heat generated cannot be removed fast enough to allow long periods of continuous radar operation.

Operating Altitude

The range at which radar can detect and track targets depends on the transmitted power, antenna gain, target radar cross-section and receiver sensitivity. When more power is transmitted the returned energy is greater which means that a given target

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26 Kostiuk, T. and B. Clark, *Spaceborne Sensors (1983-2000AD): A Forecast of Technology*, National Aeronautics an Space Administration, Greenbelt, NASA Technical Memorandum 86083, April 1984, p 20, p32.

27 The Soviet Union first launched a space based radar system for detecting and tracking ships in 1967, although it was some time before it became an operational system, from Peebles, C., *Guardians: Strategic Reconniassance Satellites*, Presidio Press, Novato, 1987, p 278.

28 Discussed by a member of the Canadian Space Briefing Team during a series of lectures in Australia on Space Operations and the Canadian Space Programme, 11 - 13 March 1991.

29 Capability of SAR is illustrated in a data sheet provided by ACRES *ERS-1: Satellite and Sensors Information Sheet*, Earth Observation Data Centre, Royal Aerospace Establishment, Farnborough, UK,August 1990, p 1.

30 Ahmed, S. et al, 'The RADARSAT System', Remote Sensing: An Economic Tool for the Nineties, *12th Canadian Symposium on Remote Sensing*, IGARSS '89, 10-14 July 1989, p 214.

31 Parker, I., 'Satellite See All', *Space*, November-December 1991, p 9.

can be detected at a greater range. However, radar energy has to travel to and from th target therefore the returned signal is inversely proportional to the fourth power of rang . This implies that at large ranges, such as at geosynchronous altitudes, typical surveillan e radar returns would be extremely small and difficult to detect with current technology equipment. In addition, the typical FOV is too large at this range to be useful for surveillance. Therefore, radar sensors are severely limited by range to the target. Th s appears to be the case with the former Soviet Union's ocean reconnaissance RAR that n ust operate at very low altitudes to detect even large ships.[32] However, SARs are not as limited in range due to the signal to noise ratio increase obtained from pulse integration this allows them to either use less transmitted power or operate over longer ranges.

Multi-Mode Radar

In the future, multi-mode radar will probably be able to provide both SA R and RAR capabilities in real-time with the one radar. However, this capability is man years away for space-based radar, since it is only a recent and state-of-the-art concept development in military aircraft radar.[33]

Real Aperture Radar

RARs typically transmit pulses of coherent microwave energy, focused b y an antenna system, and process the backscattered energy before the beam position is moved to the next location. The relationship between the radar and the target is fixed during the processing period. This is fundamentally different from SAR which moves in relation to the target and integrates returns received from the same target area as it moves along. RARs can use pulse Doppler processing techniques to detect moving targets. Therefor e, an instantaneous indication of target velocity is available and tracking is possible with regular illumination of targets. Targets that are not moving must present a significant radar return relative to the background clutter in order to be detected, and since the FO V will be very large from a space-based platform only large targets are likely to be detect d. Radar cross-section is dependent on the physical size, shape, material and structure of targets and the viewing aspect angle in relation to the wavelength of the radar signal.

Resolution

As previously indicated, the spatial resolution in the direction of the rad r beam is determined by the pulse width. For a simple pulse radar, range resolution is e qual to the distance the EM wave travels in half a pulse width. However, it is difficult to generate very short pulses so frequency modulation techniques are used to produce puls e compression, which effectively achieves short duration pulses.[34] Azimuth resolution is a function of antenna beamwidth and range to the target. Beamwidth is proportional to wavelength and inversely proportional to antenna dimensions; therefore, large antennas and short wavelengths are required for high spatial resolution from a given range.

32 Johnson, N.L., *The Soviet Year in Space: 1987*, Teledyne Brown Engineering, Colorado Springs, 1988, p 69.
33 Grossman, L., 'The Basic Beam', *Air Force Magazine*, Jul 1991, p 50-54.
34 Cantafio, L.J., *Space-Based Radar Handbook*, Artech House, Norwood, 1989, pp 127-128.

Antennas[35]

There are many factors to be considered in antenna design for space-based applications, some of which include: coverage required, beamwidth, scanning technique, power capability, weight, orbit, launch vehicle and physical launch effects, thermal and EM radiation, and distortion. The trend in antenna design for space applications is toward phased arrays that are lighter, will eliminate mechanical beam steering, are suitable for multi-mode operation and allow beam shaping for specific purposes such as jamming protection.

Power Requirements

Ground-based surveillance radars typically radiate millions of watts of power to generate enough returned energy for the detection and tracking of aircraft size targets. However, spacecraft electrical power generating capabilities are limited. The RORSAT RAR satellite uses a nuclear power source but at very low altitudes to provide sufficient power for detecting and tracking ships.[36] This has probably been done to optimise the power and beam footprint necessary for target detection, while keeping the spacecraft profile small to reduce drag at the low altitudes required.

Advantages

RARs offer the following advantages for surveillance from space:

a. detection and tracking of moving targets using pulse Doppler techniques;

b. potential for all weather, day/night operation, depending on the frequency used;

c. provide a wide field of view for area coverage applications; and

d. provide measurement of range to target.

Disadvantages

RAR has the following shortfalls when used for surveillance applications:

a. limited resolution and Doppler processing technique limits detection of small and slow moving targets;

35 Cantafio, L.J., op cit, pp 484-485.

36 Peebles, C., op cit, p 276.

b. a 'nadir hole' occurs at about 15 degrees around nadir, in which moving targets cannot be detected[37];

c. vulnerable to jamming; and

d. high transmitted power and short range is required to achieve adequate target signal to noise ratios.

Existing Capabilities[38,39]

RORSAT is the only operational military space-based RAR surveillance capability. They operate with two co-planar satellites at inclinations of 65 degrees and altitudes of about 250 km. The first satellite detects a target and tracks are established when the next satellite passes and detects the same target. The antenna size is suggested to be about 8.5 by 1.4m, which provides a resolution in the order of tens of kilometres and they have a swath width of about 1,200 km on either side of the ground track. At this operating altitude the orbits will decay in a few days, without boosting to maintain altitude, consequently they only have a lifetime in the order of months.[40]

The former Soviet Union also launched the Cosmos 1500 satellite in September 1983, with a RAR and EO sensor for oceanographic operations. This satellite was placed in a high inclination orbit for polar observations. It provided images of the Earth and polar regions; tracks ice movements; detects oil slicks, currents and wind fields; and enables guidance of ships trapped in Arctic ice regions.[41]

Future Capabilities[42]

In December 1988, the US Department of Defence (DoD) Defense Acquisition Board established a Milestone Zero for the development of a space-based wide area surveillance system (SBWASS), as a result of a program of studies commissioned by the US Air Force and Navy. Operational requirements were for a system to detect and track aircraft and ships over a wide area and to pass information directly to tactical commanders. The studies involved five leading aerospace companies and more than 25 subcontractors. They concluded that a RAR system to meet mission requirements was technologically feasible and involved relatively low risk. Avrin illustrated that RAR technology was sufficiently mature in 1981 for a space-based RAR to be developed and launched, given that the requirement and will existed.[43] However, there are still significant engineering challenges in placing a capable RAR on a spacecraft. To meet these challenges a memorandum of understanding was signed in March 1989, for co-

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37 The nadir hole occurs for pulse Doppler operation only; normal pulse mode radar does not have this problem. There is also a grazing angle limit of about three degrees from the horizon beyond which SBR is unable to detect energy backscattered from targets.

38 Peebles, C., op cit, pp 276-279.

39 Johnson, N.L., op cit, p 69-74.

40 Peebles indicates that they have a design life of only about 75 days.

41 Cantafio, L.J., op cit, pp 19-21.

42 Piotrowski, J.L., 'Space Based Wide Area Surveillance, *Signal*, May 1990, pp 31-34.

43 Cantafio, L.J., op cit, pp 19-21.

operative research and development of an SBWASS between the Canadian Defence Force and the US DoD.[44]

A fully operational system was proposed for development by the early 2000s. Unfortunately, the US component of this program has suffered from disagreements between the US Navy and Air Force in terms of the final system configuration. Consequently the US Congress was not prepared to approve funds for the program until agreement was reached. Despite these delays, a wide area surveillance system with the capabilities proposed is important to US defence and security, and is therefore likely to ultimately receive the emphasis and funding necessary.

Synthetic Aperture Radar

SARs were initially developed for high resolution imaging of the Earth's surface under all weather conditions. These systems achieve higher spatial resolutions than RARs by successively time delaying and integrating coherent radar returns from a specific target area, while the radar moves along a path nearly perpendicular to the beam direction. Figure 5.8 illustrates the aperture synthesis principle.[45] Along track pulse integration provides an effective antenna or aperture size, in the azimuth direction, that is much larger than the physical antenna length. Processed returns therefore provide image resolutions that are representative of much larger antennae, and the integration of successive radar returns also improves the signal to noise ratio obtained.

Resolution

Spatial resolution in the beam direction is dependent on pulse width, as is the case with RAR, but in azimuth, resolution is effectively independent of range and operating frequency; it is dependent on the length of the antenna. Theoretically, azimuth resolution is equal to half the physical antenna length in the along-track direction, when integration occurs along the full synthetic aperture length, as illustrated in Figure 5.8. This would appear to indicate that the smaller the antenna the higher the resolution. However, obtaining an adequate signal to noise ratio may be difficult if the antenna is size is decreased significantly.

In civil applications, the maximum possible resolution is generally traded for increased area coverage, by integrating over a shorter path than the full synthetic aperture length. This may also be done to keep the data transmission rate low enough to be manageable while still providing adequate resolution. The maximum resolution obtained from the civilian SARs flown before 1991 is 17m, which was the SIR-B system.[46] RADARSAT is planned to provide an eight metre resolution mode; however, the US

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44 Discussed by a member of the Canadian Space Briefing Team during a series of lectures in Australia on Space Operations and the Canadian Space Programme, 11 - 13 March 1991.

45 The reference provides a detailed description of SAR operation.

46 Brown, R.J., 'Land Applications of RADARSAT', Remote Sensing: An Economic Tools for the Nineties, *12th Canadian Symposium on Remote Sensing,*,IGARSS 1989, Volume 1, 1989, p 210.

military SAR system called LACROSSE has been operational for some time and is suggested to have a resolution of from about 1.5 - 3m.[47]

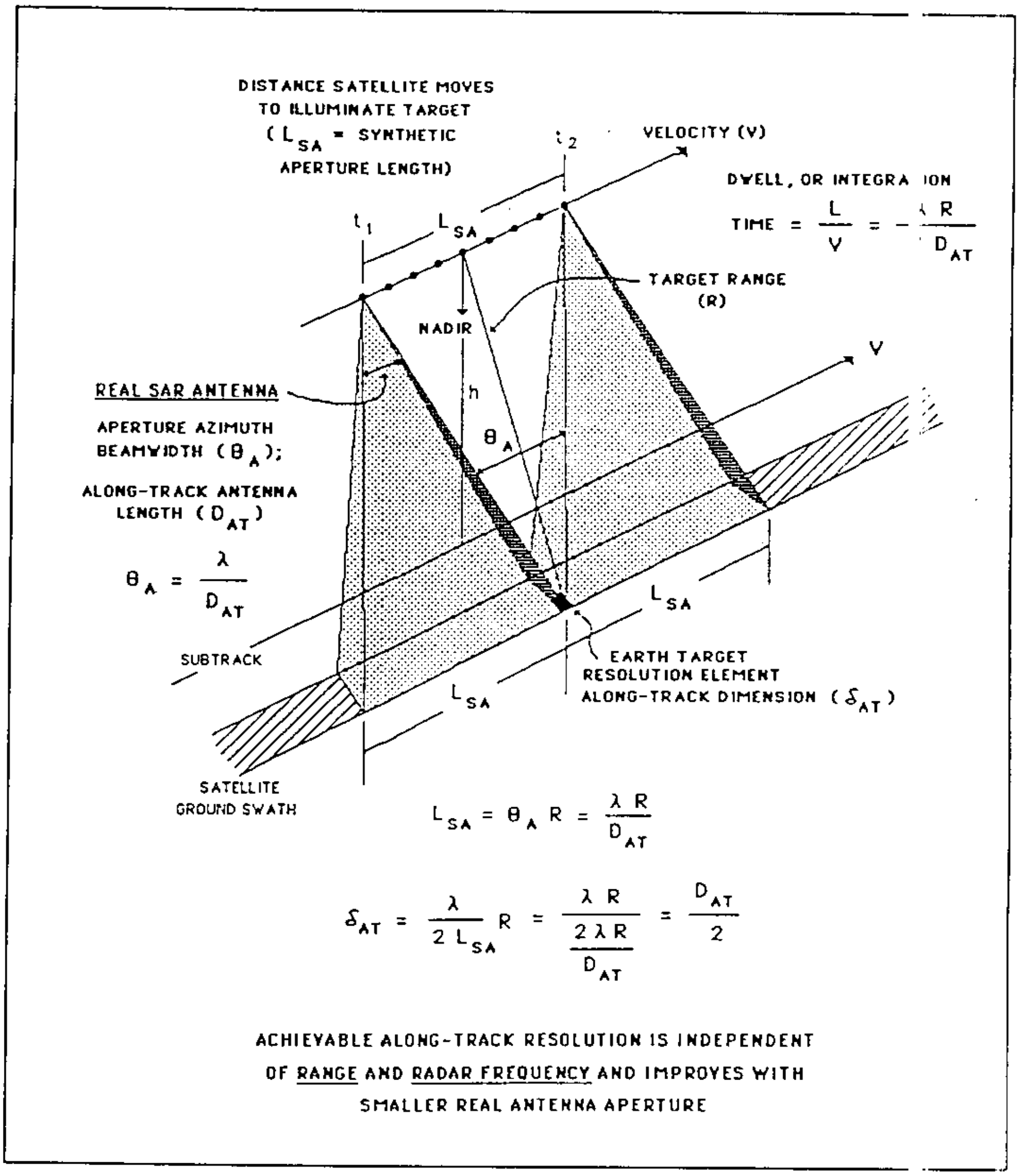

Figure 5.8 Aperture Synthesis[48]

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

48 Cantafio, L.J., op cit, p 124.

Signal and Data Processing

SAR processing needs are extensive and can generally be divided into signal processing and data processing components. Signal processing describes the complex operations involved in integrating successive coherent pulse radar returns to produce images. This requires the use of dedicated very high speed processors to cope with the high speed data stream from the satellite. Data processing relates to the follow-on processing of SAR image data.

The optimum solution for SAR signal processing is to have it all done on the satellite; however, signal processor technology is inadequate to achieve all the required operations on a satellite, given the weight and power constraints. Consequently, radar signals are typically digitised and transmitted to ground stations in a relatively unprocessed form. Therefore, data transmission rate is critical to SAR performance and is a significant limitation for high resolution imaging.

In the past, even ground signal processing of SAR data has been much slower than the real data reception rate due to the enormous amount of processing required; however, fast processors are being developed to process faster than the data reception rate. For example, the European Space Agencies (ESA) ERS-1 SAR satellite, launched in 1991, will use a custom built fast delivery processor in the near future that is being developed by British Aerospace Australia Pty Ltd for ground processing data. This processor is a state-of-the-art product that will process data at 10% of real data acquisition time.[49]

SAR Systems Development

A number of spaceborne SARs have been successfully launched for civil and military applications, with SEASAT being the first in 1978. SEASAT was used as the basis for the development of the Space Shuttle imaging radars SIR-A and SIR-B. ERS-1 was launched in 1991 and JERS-1 the Japanese satellite has been launched since then but some problems have occurred in the deployment. Several more SAR launches are planned, including RADARSAT from Canada; and one for the earth observation system (EOS) from the USA. The US military SAR system, LACROSSE, was used in the recent Gulf Conflict to obtain imagery for intelligence purposes. It was able to provide imagery during poor weather and also through the smoke, dust and haze from oil fires and other activities.[50]

Applications

Typical uses for SARs include:

a. high resolution surface imagery;

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49 Fensom, D.S., 'The Australian Fast Delivery Processor for the Synthetic Aperture Radar of ERS-1', *Fifth National Space Engineering Symposium 1989*, Canberra, 27 November- 1 December 1989, p 1.

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

b. monitoring of ocean wave patterns and coastal interactions;

c. determining land and sea surface roughness, surface materials differentiation and condition, vegetation cover evaluation, moisture levels in soil and crops, and land structures mapping;

d. monitoring snow and ice coverage and dynamics;

e. environmental change monitoring; and

f. geological mapping.

Advantages

The advantages of using spaceborne SAR include:

a. all weather, day and night operation is possible, depending on the frequency used;

b. high resolution imagery is possible;

c. a demonstrated ability to observe slow moving ships and their wakes;[51]

d. resolution obtainable is effectively independent of spacecraft altitude;

e. improved imaging capability and increased signal to noise ratio from coherent pulse integration; and

f. relatively small antenna required to achieve reasonable resolution.

Disadvantages

The disadvantages of spaceborne SAR include:

a. inability to track fast moving targets;

b. potentially long image processing time;

c. requires dedicated and specialised computer and signal processing hardware and software;

d. high speed data transmission required; and

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51 Capability of SAR is illustrated in a data sheet provided by ACRES *ERS-1: Satellite and Sensors Information Sheet*, Earth Observation Data Centre, Royal Aerospace Establishment, Farnborough, UK,August 1990.

e. limited area coverage possible at higher resolutions due to data transmission limitations.

Summary of Spaceborne Sensors

Figure 5.9 models some the main factors to be considered during sensor selection and system design. Table 5.6 provides a summary and performance comparison of the sensors examined in this Chapter.

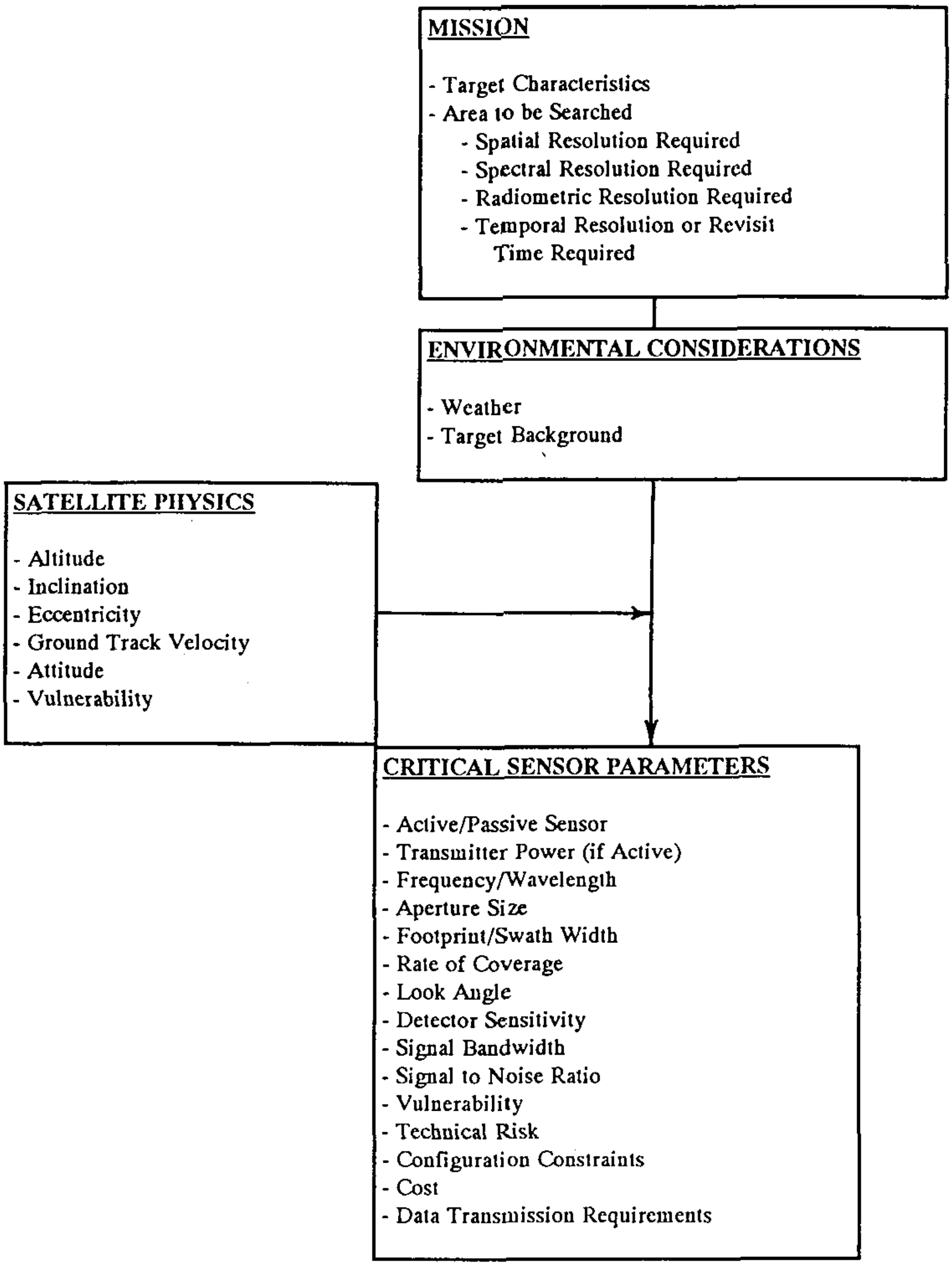

Figure 5.9 Sensor Selection Factors[52]

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52 Forestier, A.M., op cit.

Table 5.6 Sensor Summary

SENSOR TYPE	Day/Night Capability	Effect of Weather	Atmospheric Attenuation	Aperture Size	Resolution	Detection Method	Data Rate Req'd	Processing Complexity	Cost	Power Required	Technology Available
Passive											
Visible/NIR	Day	Severe	Low	Small	High	Imaging	High	Low	Low/ Medium	Low	Yes
Infrared - SW MW and LW	Both	Severe	Low in bands	Small	Medium	Imaging	Medium	Low	Low/ Medium	Low	Yes
Active											
Laser											
a. Visible	Both	Severe	Low	Small	High	Imaging/ Doppler	High	Low	High	High	Medium to Long Term
b. Infrared	Both	Severe	Low in Bands	Small	Medium	Imaging/ Doppler	Medium	Low	High	High	Medium to Long Term
RAR	Both	Low	Low	Large	Low	Doppler	High	Medium	High	High	Medium to Long Term
SAR	Both	Low	Low	Medium	Medium to High	Imaging	Very High	High	High	Medium	Yes

Legend

NIR, SW and LW = Near Wave, Short Wave and Long Wave Infrared
RAR = Real Aperture Radar
SAR = Synthetic Aperture Radar
Medium Term = 4 - 7 years
Long Term = 10 - 15 years

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CHAPTER 6

ANALYSIS OF SPACE BASED SURVEILLANCE SYSTEMS FOR AUSTRALIA

Introduction

Space-based sensors have the potential to provide Australia with a significant wide area surveillance capability for the future. This Chapter examines a range of typical sensors and satellite configurations that are available now and planned for the future, to determine which sensors may satisfy some or all the surveillance requirements. A systems study approach is used to provide a framework within which costs, benefits, user requirements, priorities and satellite technology issues can be systematically examined.[1] The intention is to provide a guide to those space-based sensor capabilities that may be worthwhile investigating in detail and to enable future needs to be readily assimilated into this work.

The study has been limited to significant technical, operational and dollar cost considerations, although many of these will require more analysis of the most suitable options, if implementation is to be considered. In addition, other factors including political and other economic aspects would need to be examined. The methodology used allows this research to be readily reviewed, changed and expanded as required. To assist with any future investigations, the process and logic of the systems study approach are deliberately explained.

Outline of Analysis

The analysis uses the wide area surveillance objectives identified in Chapter Two, orbital considerations from Chapter Four and a number of the sensor types introduced in Chapter Five, to propose surveillance sensor system options which may be achievable in a specified time horizon. Technical, operational, political and economic constraints are used to eliminate those options that are not considered to be achievable in this time frame.

Feasible options are judged against a number of specific criteria to measure how well the options meet surveillance system performance requirements. The criteria are measured in either quantitative or qualitative terms, depending on the aspect being measured and are ranked in order of importance. Numerical values are assigned to assist with relative performance scoring, particularly for the assessment of criteria that have to be expressed in qualitative terms. Options are simulated for each criterion in turn and judged in relation to expected levels of performance. The graded options are then compared to determine if a preferred option exists.

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1 The systems approach taken here follows the method proposed in Athey, T.H., *Systematic Systems Approach: An Integrated Approach for Solving Systems Problems*, Prentice-Hall, London, 1982.

Time Horizon

A 15 year time horizon is considered to be a reasonable time frame within which an Australian space-based capability could be obtained, and it is also a suitable time period for prediction of satellite sensor technology developments.

Surveillance System Characteristics

Australia's perceived wide area surveillance system characteristics, examined in Chapter Two, are repeated here for clarity. These essential and desirable elements provide the basis for examining sensor system performance.

Essential

a. Military - Area of Interest. - North and North-West maritime approaches,

b. Civil - Area of Interest. - 200 nautical mile exclusive economic zone,

c. Military - Resolution. - at least 15 metres for visible spectrum imaging sensors,

d. Civil - Resolution. - at least 10 metres,

e. Military System Availability. - all weather, day and night coverage of the North and North-West maritime approaches, and

f. Civil System Availability. - all weather, day and night coverage of the 200 nm exclusive economic zone.

Desirable

a. Military - Area of Interest. - remainder of ADMI,

b. Civil - Area of Interest. - continent and off-shore territories,

c. Military - Resolution. - at least one metre.

e. Military System Availability. - all weather, day and night coverage of all the ADMI, and

f. Civil System Availability. - all weather, day and night coverage of the remainder of the continent and off-shore territories.

Space-Based Surveillance System Options

Potential space-based surveillance systems are evaluated mainly in terms of the sensors, although some aspects of the satellite platforms and orbital characteristics need to be used. The potential sensor options considered are:

a. visible and near infrared multi-spectral sensor,

b. infrared sensor for hot body emission detection,

c. visible and near infrared spectrum laser radar,

d. thermal infrared laser radar,

e. real aperture radar,

f. synthetic aperture radar,

g. the above sensor types on small satellite platforms, and

h. use of commercial satellite imagery for surveillance requirements.

Constraints

Constraints are restrictions to one or a number of the options that may eliminate the option from further consideration. They are typically political, technical, operational or economic in nature and may or may not be under the control of the decision maker. Internal constraints are those under the decision makers control and external ones are not. For example, *cost* could typically be an internal constraint that may be changed if the benefits associated with achieving the objectives are significant enough. Options that do not meet the constraint requirements are considered to be infeasible and are eliminated from further analysis.

External Constraints.

Technical Risk. This constraint examines the level of technical development associated with a particular option. The question here is whether the option is at the conceptual stage and in need of significant research and development, or is it a tried and proven capability? The key is to determine what level of risk can be tolerated, consequently this constraint is not considered to be fixed. Any option that has significant potential may be pursued despite a high level of risk. JORN is one such example, where decision makers have been convinced that the benefits outweighed the risks.

Small Satellite Weight and Electrical Power. These are somewhat arbitrary constraints since there is no real definition of a small satellite. However, development activities and trends with these systems can provide a guide. The US Defense Advanced Projects Agency (DARPA) Lightsat, the US Air Force Tactical Satellite (Tacsat) and the US Navy Spinsat small satellite concepts are being designed with limited payload capability size, weight and lifetime requirements. US Orbital Science Corporation designed the Pegasus launch vehicle, which has a payload weight limit of about 200 kg, to compete in the small satellite market. DARPA has also contracted this company to develop a larger launch vehicle for launching 450 kg payloads into a 740 km polar orbit.[2] Therefore, the small satellite weight constraint used here is 450 kg or about 1000 lb, which is the generally accepted weight limit.[3] These satellites typically have power sourcing capabilities limited to only about 100 watts, depending on the size of the platform.

Satellite Launch Capability. Any satellite sensor payload that has a mission requirement to launch into an orbit that cannot be achieved, or with a size or weight that is too great for existing launchers, will be an infeasible option.

Lifetime. A minimum lifetime constraint of five years is proposed; however, this should not be a firm constraint given that smaller low cost satellites may be cost effective even if replacement launches are needed within the five year period.

Time. The option needs to be achievable within the time horizon.

Internal Constraints

Cost. As an estimate of cost, any space-based surveillance system with a capability comparable to JORN should not cost more than about $1,000 million. This is an indication of the level of expenditure that has been justified and approved in the past. However, cost cannot be an absolute constraint since approval for more funds may be possible if a significantly higher level of performance can be achieved.

Elimination of Infeasible Space-Based Surveillance System Options

Options that cannot satisfy the constraints are infeasible and are immediately removed from further consideration. Those remaining options form the feasible set that is examined in more detail.

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2 Rawles, J.W., 'A Big Boost for Lightsat?', *Defense Electronics*, March 1990, p 62.

3 Utsch, T.F. et al, 'Design Concepts for Space-borne Multi-Mission Sensors for Tactical Military Needs', *Fourth Annual AIAA/Utah State University Conference on Small Satellites*, 27-30 August 1990, p 1.

Real Aperture Radar

The US DoD perceived that a continental USA space-based wide area surveillance system using RAR could be achievable in the 15 year time horizon but the cost would be high.

Cost and Time. A figure of about $US1,000 million was estimated for each RAR satellite; however, research and development costs would total to about $US15,000 million.[4] The cost for only one satellite is at the limit of the somewhat arbitrary cost constraint, but the option is not be eliminated on this basis, given the need for moving target detection and tracking.

Weight and Electrical Power. In 1981, Avrin considered that development of a reasonably capable space-based RAR was feasible with existing technology.[5] The paper proposed two 'strawman' designs to operate at altitudes of about 1,650 km and 10,400 km, which required all up satellite weights of 3,600 kg to 4,300 kg respectively and also required about 15,000 Watts of electrical power. By comparison RORSAT is estimated to weigh about 4785 kg and requires about 10,000 Watts.[6] The weight, power and size of these satellites suggest that a RAR capability is not feasible using a small satellite. However, Cantafio illustrates that millimetre wavelength radar offers the potential for a relatively small and lightweight RAR for surveillance, although the prime power required is about 1,500 watts,[7] which is probably still too high for a small satellite.

Feasibility. RAR is directly applicable for wide area surveillance of moving targets but the technology is only likely on large satellites. In addition, significant research and development are needed to satisfy US and Canadian requirements for area surveillance. RORSAT is operational but it is suggested to have only a short lifetime and target detection capabilities that are limited to large ships. This indicates that a capable RAR system could be available in the time horizon but it will be expensive. RAR will therefore remain as a feasible option

Synthetic Aperture Radar

SARs are not necessarily large, heavy payloads, and they require much less electrical power than RARs. For example, the SEASAT SAR payload required only 642 Watts of power and weighed about 223 kg, including the antenna.[8] However, with all five sensors and the other spacecraft support structure, SEASAT weighed 2290 kg. The future trend for space-based SAR appears to be for larger satellites with multi-frequency operation, although SEASAT demonstrated the capability of a relatively small payload.[9] Therefore, SAR sensors have the potential to operate from a small satellite platform in terms of weight,

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4 Derived from the extent of Canadian input to the SBR programme discussed in 'Outline of Canadian Space Based Radar Programme: Space Based Radar', *The Aries Association (Australasia) Symposium Proceedings*, Canberra, March 991.

5 Avrin, J., 'Space-Based Radar - Part 2', *Military Electronics / Countermeasures*, October 1981, p 95.

6 Peebles, C., *Guardians: Strategic Reconnaissance Satellites*, Presidio Press, Navato, 1987, pp 276-277.

7 Cantafio, L.J., *Space-Based Radar Handbook*, Artech House Inc, Norwood, 1989, p 36.

8 Cantafio, L.J., op cit, p 17.

9 Cantafio, L.J., op cit, pp 138 - 139.

but their power requirements are likely to be too high. SAR is therefore a feasible option but not for small satellites.

Laser Radar

Space-based laser radars have been actively researched for some years since they have considerable resolution advantages over microwave sensors, although the electro-optical wavelengths used can be severely affected by poor weather. These sensors have significant defence and civil applications, but there are many technological difficulties to be addressed for their use in wide area surveillance.

Electrical Power and Efficiency. High powered laser radars will require thousands of Watts of electrical power.[10] Small satellite platforms are therefore unsuitable for these sensors, and their power requirements are also approaching the limits of existing large satellite power sources. In addition, laser efficiency is low which implies that large quantities of waste heat will need to be radiated to space.

Lifetime. Lasers have limited lifetimes, in terms of the number of pulses the lasing material can generate. For example a carbon dioxide (CO_2) laser radar, based on year 2000 technology, is expected to have a life of about 10^9 pulses.[11] This equates to 3 years continuous operation at a pulse rate of 100 cycles per second, but continuous operation is not likely because of power efficiency limitations; however, a duty cycle of only 10% will give a lifetime in excess of 10 years. This implies that lasing material lifetime should not be a limiting factor until continuous operation is achievable, although payload consumables are needed to support laser operation and only limited quantities can be carried into space.

Feasibility. In addition to the power sourcing, efficiency and lifetime limitations, laser radars have narrow fields of view and will require accurate scanning optics to provide search and tracking functions for wide area surveillance. Technology advances from US Strategic Defense Initiative research may offer improvements for the long term use of these systems. However, a laser radar capability is not considered feasible for wide area surveillance applications in the time horizon.

Small Satellite Lifetime

Significant emphasis is being placed on small satellite development for US military tactical applications, to provide low cost and rapid restoration of capabilities lost in conflict situations. The mission lifetime being specified for the RESERVES small satellite program is only about one year;[12] although, other satellites are being designed for lifetimes of five to seven years. Satellites with less than five year lifetimes would not be eliminated, however, because their lower cost can offset the need to launch more satellites.

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10 Chen, H.S., *Space Remote Sensing Systems: An Introduction*, Academic Press, Orlando, 1985, p 181.

11 Kostiuk, T. and B. Clark, *Spaceborne Sensors (1983-2000 AD): A Forecast of Technology*, NASA Technical Memorandum 86083, April 1984, p 138.

12 Farrell, J., 'RESERVES: A Responsive Multi-Mission Tactical Satellite Architecture', *Fourth Annual AIAA/Utah State University Conference on Small Satellites*, 27 August - 30 August 1990, pp 9 - 10.

Feasible Set of Space-Based Surveillance System Options

After eliminating infeasible options, the following options remain:[13]

a. visible and near infrared multi-spectral sensor,

b. infrared sensor for hot body emission detection,

c. visible spectrum sensor on a small satellite platform,

d. infrared sensor on a small satellite,

e. synthetic aperture radar,

f. real aperture radar, and

g. the use of commercial satellite imagery[14].

Multi-spectral capabilities and multiple sensor packages would be incorporated on a satellite if size, weight and power limits can be satisfied. The cost effectiveness of using multiple sensor payloads has not been considered but these aspects will need to be addressed in future research.

Surveillance System Options

This section outlines basic technical and cost details of several typical satellite sensors and systems that are are considered to be viable in the time horizon. and can represent each of the surveillance system options.

Visible Spectrum Sensor

The current SPOT 2 commercial satellite, launched in 22 January 1990 and operated by the French SPOT Image Company, provides visible and infrared imagery and is used to illustrate the capability of a visible spectrum sensor on a large satellite. Imagery from this satellite is available from the Australian Centre for Remote Sensing (ACRES) in Canberra. Various products can be purchased, including multi-spectral, panchromatic and stereoscopic imagery. Table 6.1 summarises SPOT 2 technical data.

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13 The sensors are assumed to be on a large satellite unless stated otherwise.

14 The use of commercial remote sensing data is also examined since this option is already available.

Infrared Sensor

The Landsat 5 spacecraft, owned by the Earth Observation Satellite Company in the USA, is used to illustrate an infrared capability on a large spacecraft. Data from this satellite is also received and distributed through ACRES. Landsat 5 has a multi-spectral scanner (MSS) providing low resolution imagery in the visible and NIR bands, and a thematic mapper (TM) which provides higher resolution imagery in the visible, NIR, SWIR and LWIR bands. Table 6.2 provides a summary of the technical data, although only the infrared bands are of particular interest here.

Visible Spectrum Sensor on a Small Satellite[15,16]

This small satellite configuration is based on a visible spectrum, high resolution imaging satellite concept called the Tactical Imaging Demonstration and Experiment System (TIDES), which is under development by CTA Inc., and Globesat Inc., USA. TIDES is being considered by DARPA for their small satellite program. Table 6.3 summarises the data available. This satellite is part of a research and development program, although aspects such as the data compression component appear to be reasonably well advanced.

Infrared Sensor on a Small Satellite[17]

This capability is based on a multi-mission sensor design concept for small satellites, which was produced to meet US Air Force Tacsat requirements. The sensor proposed is for multi-spectral imagery for low earth and geostationary orbit missions. The technical feasibility of the concept is considered to be promising but further work is needed to demonstrate the capability. For the purposes of this study, the low Earth orbit MWIR mission capability of this satellite is used. Table 6.4 summarises the technical data available.

The satellite sensor system was designed to satisfy the following missions

a. topographical remote sensing,

b. infrared mapping of industrial installations, background mapping and locating 'hot' targets, and

c. oceanographic remote sensing of waves, the coastline and tides.

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15 'Lightsat Offers Near Real-Time Images', *Military Space*, 6 November 1989.
16 *TIDES Technical Data Summary*, Globesat Inc., 26 April 1991.
17 Utsch, T.F. et al, op cit, pp 1-13.

Table 6.1 SPOT 2 - Technical Parameters[18,19]

Spacecraft:		
	Weight	1750 kg at launch
	Power	1.3 kW
Sensor:		
	Type	Visible and Near IR imaging
	Spectral Channels:	
	panchromatic	0.51 - 0.73 μm
	multi-spectral	0.50 - 0.59 μm 0.61 - 0.68 μm 0.79 - 0.89 μm
	Field of View	4.13 degrees
	Numerical Aperture	f/3.3 (for focal length of 1.082 m)
	Detector Element IFOV	10 x 10 m panchromatic 20 x 20 m multispectral
	Detectors	4 x 6000 element CCD linear arrays
	Scan	pushbroom
	Pointing	27 degrees East or West of orbit plane, giving 850 km total FOV
	Swath Width	60 km (two instruments each with 60 km swath)
Orbit:		
	Altitude	832 km av. circular, sun-synchronous
	Inclination	98.7 degrees
	Revisit Time	26 days, (2.5 days average with pointing control and using both instruments to get a 120 km swath)
	Period	101.5 minutes
Communications:		
	Data	8 GHz (X Band) 25 Mbps for each of two channels
	Acquisition Range	About 2,500 km from ground station (ie. for satellite more than 5 degrees above the horizon)
Design Lifetime:		3 years, although SPOT 1 was still operational after 4 years.
Cost (1991 dollars)[20]:		\$A870 million satellite \$A65 million launch \$A22 million operation/year

18 *SPOT Data Sheet*, Australian Centre for Remote Sensing, Belconnen, ACT.
19 *SPOT User's Handbook*, Volume 1, CNES and SPOT Image Corporation, 1988.
20 SPOT cost estimates provided by P. Van Grunderbeeck, Managing Director, SPOT Imaging Services, Sydney.

Table 6.2 Landsat 5 - Technical Parameters[21]

Spacecraft[22]:		
	Weight	2000 kg at launch (based on Landsat 4)
	Power	2.2 kW (based on Landsat 4)
Sensor:		
	Type	Visible and IR imaging
	Thematic Mapper	0.45 - 0.52 μm visible blue
		0.52 - 0.60 μm visible green
		0.63 - 0.69 μm visible red
		0.76 - 0.90 μm NIR
		1.55 - 1.75 μm SWIR
		2.08 - 2.35 μm SWIR
		10.4 - 12.5 μm LWIR
	Multi-spectral Scanner	
		0.5 - 0.6 μm
		0.6 - 0.7 μm
		0.7 - 0.8 μm
		0.8 - 1.1 μm
	Detector Element IFOV	
		MSS 82 x 57 m
		TM 120 x 120 m thermal IR
		TM 30 x 30 m (all others)
	Scan	mechanical
	Swath Width	185 km
Orbit:		
	Altitude	705 km, circular, sun synchronous
	Inclination	98.22 degrees
	Revisit Time	16 days
	Orbits per day	14
	Period	98.9 minutes
Communications Data Rate:		15.06 Mbps
Lifetime:		5 years[23]
Cost (1991 dollars):		$A250 million based on Landsat 4 cost @7% since 1978.[24] Launch cost estimated at $A62 million.[25]

21 *The Landsat 5 Spacecraft*, ACRES Data Sheet, August 1989.
22 Velupillai, D., 'International Satellite Directory: Flight Data', *Flight International*, 14 May 1983, p 1330.
23 Current time Landsat 5 is expected to be in orbit before replacement by Landsat 6.
24 Velupillai, D., op cit, p 1330.
25 Launch cost estimate provided by P. Winch, Australian Launch Vehicles Pty Ltd, Technology Park, South Australia.

Table 6.3 TIDES Visible Spectrum Sensor - Technical Parameters[26,27]

Spacecraft:		
	Platform Size	0.91 X 0.91 m
	Power	40-70 W average daily
	Weight	204 kg
Sensor:		
	Type	Imaging visible spectrum
	Detector	CCD array
	Total FOV	53 degrees
	Detector El. IFOV	5 m
	Detector IFOV	60 km
	Swath Width	60 km
	Pointing	Within 700 km swath, due to 53 degree total sensor FOV.
Orbit:		
	Altitude	700 km, circular
	Period	98.8 minutes
Communications:		
	Data	X Band, 1.544 Mbps, BPSK
	Image Compression	Provides near real-time data
	Data Storage	200 Mbyte, storage for 60 x 960 km pass
	Image Downlink	8-14 images in 12 minute pass
Lifetime:		5 Years[28]
Cost (1991 dollars, including launch on Pegasus):		
	Initial Satellite	$A21.4 million
	Production	$A12.6 million

Synthetic Aperture Radar[29]

The Canadian RADARSAT SAR, scheduled for launch in 1994, is used to represent a potential SAR capability. This satellite is intended for scientific and operational use related to global ice surveillance, ocean surveillance and resources monitoring. RADARSAT's technical parameters are outlined in Table 6.5.

26 'Lightsat Offers Near Real-Time Images', op cit.

27 *TIDES Technical Data Summary*, op cit.

28 This system does not appear to have mechanical moving parts and the platform uses gravity gradient stabilisation,therefore a lifetime of 5 years should be a reasonable estimate.

29 Ahmed, S. et al, 'The RADARSAT System, Remote Sensing: An Economic Tools for the Nineties', *1989 International Geoscience and Remote Sensing Symposium*, 12th Canadian Symposium on Remote Sensing, Institute of Electrical and Electronic Engineers, 10 -14 July 1989, Vancouver, p 213.

Table 6.4 Small Satellite Infrared Sensor - Technical Parameters[30]

Spacecraft:					
	Weight		145 kg		
Sensor:					
	Type		Visible and Infrared Imaging		
	Detectors		HgCdTe 50 μm and 100 μm square		
	8 x 4028, 8 x 2014				
			Si CCD 18 μm square, 2 x 7172		
	Total FOV		16 degrees		
	Detector FOV		3 x 0.5 degrees		
	Scan		Pushbroom (LEO mission) with scanning across a 16 degree swath at 4 degrees/sec for data and 10 degrees/sec return - 4 second update		
	Sensor Band	Element IFOV	Wavelength Band	Detector	
	MWIR	14.4 m	3.4-4.2 μm	50 μm	1 x 2554 pixels
	MWIR	14.4 m	4.6-4.8 μm	50 μm	1 x 2554 pixels
	LWIR	28.6 m	8.0-9.0 μm	100 μm	2 x 1277 pixels
	Integration Time		294 μsec for the above bands		
	Aperture Size		35 cm		
	Detector IFOV		36 km x 3 km		
	Scanned Swath		192 km		
Orbit:					
	Altitude		700 km, circular		
	Period		98.8 minutes		
Communications:					
	Data Rate		500 Mbps for 5.1 m IFOV 69.6 Mbps for 14.4 m IFOV 35.2 Mbps for 28.6 m IFOV		
Lifetime:	Assumed to be the same as TIDES				
Cost:	No data available - assumed to be the same as TIDES.				

Real Aperture Radar[31]

The RAR technical data in Table 6.6 was derived from a concept paper outlining research into a satellite based surveillance system for fleet and air defence of the United States. This research was performed under a contract to Lockheed Missiles and Space Company from US Naval Systems Command. A line or fence-type defence concept was proposed for surveillance coverage over longer ranges than existing sensors, in order to address the increasing threat of long range weapon systems such as cruise missiles. Near future technology considerations were used to determine a satellite configuration that could be

30 Utsch, T.F. et al, op cit.

31 Brookner, E. and T.F. Mahoney, 'Derivation of a Satellite Radar Architecture for Air Surveillance', *Microwave Journa* February 1986, pp 173 - 191.

realised by the year 2000. The specifications in Table 6.6 are brief but they provide an estimate of a RAR capability that may be achievable in the time horizon.

Use of Commercial Imagery

Commercial imagery is readily available and can be purchased to provide imagery of Australia's region of interest. ACRES receives imagery directly from Landsat and SPOT satellites via a ground station near Alice Springs. The cost of this imagery is dependent on the type of image product required, the size of the area imaged, availability of images and the time frame in which images are required. The collection range is about 2,500 km from Alice Springs, which means that images out some distance from the coast can be obtained. Imagery from outside this region is available from the SPOT Image Company through its network of ground stations, but it could take weeks to receive imagery that is already available.

Representative commercial imagery costs are provided in Table 6.7. This allows some comparison of costs for a single image from either SPOT 2 or Landsat 5. Commercial data will also be available from the ERS-1 SAR in the near future. For the analysis of the commercial imagery option, aspects such as coverage, revisit time and others that are satellite orbit and hardware dependent, are derived from appropriate SPOT and Landsat options.

Assessment Criteria

Specific criteria are used to judge the performance of each feasible option. The criteria are related to either political, technical, operational or economic factors. However, only those criteria that are considered most important have been included in order to limit the extent of the analysis. The systems approach used allows any additional criteria to be readily incorporated when and if required.

Performance judgments are based on either quantitative or qualitative considerations. For example, a criterion like *cost* can be quantified in dollar terms, but the value and importance of a criterion like *technical risk* can change for each individual making a judgement. The relative value and importance of subjective criteria are based on research and author judgment, but this work can be readily reviewed so that other values can be placed on the criteria.

Table 6.5 RADARSAT SAR Technical Parameters[32,33]

Spacecraft:		
	Weight	3152 kg
	Power	2.5 kW
Sensor:		
	Type	Multi-mode SAR
	Frequency	5.3 GHz, (C-Band)
	RF Bandwidth	11.6, 17.3 or 30 MHz
	Tx Pulse Length	42 μsec
	PRF	1270 - 1390 Hz
	Tx Peak Power	5 kW
	Tx Average Power	300 W (nominal)
	Availability	15 minutes continuous 28 minutes maximum per orbit
Antenna:		
	Aperture Size	15 x 1.6 m
	Scan	Electronic beam steering 29 degrees in elevation (primary)

SAR Modes:

Mode	Swath	Ground Cell Size	Incidence Angle
Standard	100 km	29 x 30 m	20 - 49 (4 looks)
High Resolution	55 km	8 x 8 m	20 - 49 (1 look)
Experimental	100 km	28 x 30 m	49 - 60
Scan SAR	500 km	100 x 100 m	20 - 49 (4 looks)

Orbit:		
	Altitude	792 km, circular, sun-synchronous
	Inclination	98.6 degrees
	Period	100.7 minutes
	Revisit Time	Daily coverage of the Arctic region 3 days for Canada coverage 16 days for Earth coverage
Communications:		8.215 - 8.4 GHz (X Band)
	Data	73.9 - 100.0 Mbps
Data Storage:		15 minutes at 85 Mbps
Ground Processing Rate:		0.25 real-time
Design Life:		5 years
Cost (1991 dollars):		$A508 million for satellite[34] $A69 million estimated for launch[35]

32 Shaw, E. and E.J. Langham, 'RADARSAT: Canada's Microwave Satellite', Remote Sensing: An Economic Tools for the Nineties, *1989 International Geoscience and Remote Sensing Symposium*, 12th Canadian Symposium on Remote Sensing, Institute of Electrical and Electronic Engineers, pp 197-199.

33 Ahmed, S. et al, op cit, pp 213 -217.

34 Lindsey, G. and G. Sharpe, *Surveillance Over Canada*, Canadian Institute for International Peace and Security, Working Paper 31, December 1990, p 64.

35 Launch cost estimate provided by P. Winch, Australian Launch Vehicles Pty Ltd, Technology Park, South Australia.

Table 6.6 Real Aperture Radar Technical Parameters[36]

Spacecraft:		
	Prime Power	10 - 30 kW
Sensor:		
	Type	Pulse Doppler Radar
	Frequency	1 - 2 GHz, (L-Band)
	Tx Average Power	1 - 6 kW
	Minimum Detectable Velocity	150 km/hr
	Footprint Size (nominal)	280km x 55km (@ L Band and 25° grazing angle)
Antenna[37]:		
	Aperture Size	5 x 15 m to 10 x 30 m
	Scanning	2D electronic beam steering (horizon to horizon)
	Radiating Elements	5,000-15,000
Orbit:		
	Altitude	1100 to 2800 km
	Period	107.3 to 145.8 minutes
	Qty Satellites	2 - 14 for Earth coverage constellation
Communications:		
	Data rate	50 - 150 Mbps (ground processing) (on-board processing will reduce this)
Cost (1991 dollars):		$A1,200 million for satellite[38] $A75 million estimated for launch to 1100 km altitude[39]

Criteria Definitions and Importance Measures

A definition of each criterion is required to precisely indicate the characteristics being examined and to describe the measures being used. These definitions are used specifically for this analysis and may not correspond directly to more generic descriptions given in previous chapters.

Instantaneous Field of View (IFOV)

The size of the footprint that a sensor detector element makes in the target area. IFOV is dependent on detector element size, sensor optics and range to the target. The target size detectable and therefore spatial resolution is dependent on the IFOV.

36 Brookner, E. and T.F. Mahoney, op cit, pp 173 - 191.

37 *Used the lower range of the parameters aperture size and number of radiating elements, suggested by Brookner, when estimating performance.*

38 Estimate obtained during discussions with Canadian Space Briefing Team, Space Familiarisation Course, Canberra, 11-14 March 1991.

39 Derived from launch cost data provided by P. Winch, Australian Launch Vehicles Pty Ltd, Technology Park, South Australia.

Table 6.7 SPOT and Landsat Commercial Imagery[40]

An assumption is made that imagery processed to systematic geocoded level would be purchased in order to allow overlays of other sensor data. This corresponds to ACRES Level 8 data in computer tape format 6250 bpi.[41]

Image Cost:	
Landsat	$1,680 Landsat TM, 1:100,000
SPOT	$1,380 SPOT Panchromatic, 1: 50,000
Priority Orders:[42]	3.5 times quoted price for average turnaround of 2 days and 2 times quoted price for average turnaround time of 5 days.
SPOT Programming:	Programmed pointing of SPOT can be ordered at an additional cost.
Licence to Receive Imagery:[43]	$2.5 million per year for both SPOT and Landsat data licence.

When detailed intelligence is required a small IFOV is needed. However, while specific IFOV values are needed to detect targets of certain size, this is only directly relevant to imaging sensors. Non-imaging sensors such as pulse Doppler RARs that only provide moving target information do not necessarily require a small IFOV. In addition, some sensors exploit other than dimensional characteristics of targets. Therefore, IFOV is of reasonable importance but its value is dependent on the target information required.

<u>Area Coverage</u>

The total area per day that a sensor can view and obtain valid data, expressed as a percentage of the total area of the region of interest. Area coverage is a function of sensor field of view, orbit altitude and inclination. Environmental factors such as poor weather and illumination conditions can also severely affect the effective coverage of sensors that operate in the visible and infrared spectrum.

40 ACRES Price List, July 1991.

41 ACRES Data Sheet on Mapper Products and processing options, August 1989.

42 Discussions with ACRES staff indicate that delivery and processing could be reduced to less than 24 hours if a special imagery tape delivery flight from Alice Springs to Canberra could be made.

43 Personal conversation with Mr. P. Wise, Director of Applications, Australian Centre for Remote Sensing (ACRES), 17 October 1991.

Revisit Time

The time taken for a sensor to return to and re-view a given target area. Sensor pointing can significantly improve revisit time without improving the area coverage capability although revisit time is proportional to the area coverage of a sensor.

Target Information

The ability of a sensor to determine the characteristics of a target. This capability is a function of the sensor type. For example, pulse Doppler radar can be used to rapidly detect moving targets from background clutter in a large FOV. Staring infrared arrays can also provide detection and tracking functions, but different target characteristics are being exploited. Sensors that produce static images, on the other hand, generally require considerable analysis to identify targets.

Timeliness of Data.

The total time taken to get surveillance data from a satellite to the user. This criterion depends on ground station positioning, data transmission rate, ground processing, data analysis and distribution time, and the method of distribution. Many of these aspects can only be estimated without detailed information on ground segments or the use of specific surveillance scenarios, and these are left to later studies. Data analysis time varies dramatically from sensor to sensor, but in principle imaging sensor outputs can take many hours to analyse but RAR and some IR sensors can provide near real-time detection and tracking of targets.

Effect of Environment.

The ability of sensors to operate effectively in a range of atmospheric, weather and illumination conditions. This criterion is important for Australia's surveillance system, particularly since the critical Northern approaches can be severely affected by cloud cover and poor weather.

System Control.

The degree to which satellite system ownership offers a guarantee of data availability. Data from a system that is owned and controlled by allies or foreign commercial suppliers cannot be assured, although agreements are often negotiated to obtain some confidence in the provision of services. However, system control is of concern and financial commitment to a space-based capability appears to be necessary to ensure timely access to data. Future small satellite capabilities may be well within Australia's budget, but the problem could then be one of reliance on foreign industry to produce equipment. Consequently the need for indigenous development is an issue that will need to be addressed in the long term, given that Australia is now and is likely to remain a significant user of space-based resources.

Technical Risk.

The degree of risk associated with implementation of a sensor option, as a consequence of the technical maturity of the option. Technical risk is dependent on the level of development or production of that system. This means that any system based only on a concept is technically risky, but the risk decreases if significant research and development have been completed.

Technical risk must always be considered but it is not unusual to purchase equipment that is state-of-the-art or still in the late stages of research and development. This situation occurs regularly with purchases of high technology equipment such as military fighter aircraft. Therefore, a high technical risk may be acceptable for development of a satellite based surveillance system.

Capital Investment.

The total capital expenditure required to purchase and launch a space-based surveillance sensor capability. Costs are always of critical importance and systems require close scrutiny to ensure that they offer cost effective performance. For example, any proposed additions to Australia's future wide area surveillance capability must be examined in conjunction with JORN's performance expectations to ensure that the capabilities complement each other.

Image Cost.

The total cost in dollars of obtaining an effective scene image, measured in dollars per square kilometre of area, taken over a projected system lifetime of five years This criterion assists in evaluating the cost effectiveness of commercial imagery in comparison to purchasing the satellite capability. Imagery purchases from commercial imagery sources, based only on scene cost, are expected to cost much less since the capital investment is lower. In addition, commercial visible and IR sensor imagery that is cloud affected will not be purchased, but the system will collect many unusable images over its lifetime. Therefore, using commercial imagery is likely to be more cost efficient but the inability to control the commercial system and the lack of response time should offset this apparent benefit.

Criteria Priority Ordering and Weighting

Establishing the relative importance of criteria is difficult where those aspects being compared are significantly different. Criterion importance is based on surveillance system objectives and the author's interpretation of those requirements. Table 6.8 uses a tabular method to determine a priority order by allowing a systematic judgment of the perceived value of one criterion against another. Tactical surveillance requirements are more demanding and are generally given higher priority.

Obtaining an authoritative judgement on criteria importance could be the subject of considerable discussion, particularly within Defence; however, this judgement has not been sought in this first order analysis. The factors and considerations used in comparing criteria have not been described in detail. These aspects are left for an analysis that focuses more closely on those higher priority options being considered for implementation.

Mechanics of Criteria Comparison

Each criterion in the left hand column of Table 6.8 is compared in turn with those in the other columns, and a symbol is provided to indicate how much more or less important the one in the left hand column is. Point scores are allocated to each symbol and they are summed across the table to get a total number value for each criterion. These number values are divided by the lowest total points score in the column to obtain a relative importance score. The criteria are then assigned to importance groups, based on closely scoring criteria, and each group is given the lowest weighting value of the group. Importance weightings for each criterion are used as multipliers to scale the performance result of each sensor option, at the end of the analysis.

In Table 6.8 the criteria form two importance groups. This provides a simplified measure of importance, and allows the preference chart structure to be used later if a more detailed examination of criterion importance is attempted.

Desirability of Sensor System Performance

In order evaluate sensor system performance, a rating scheme or system utility function has been created in Table 6.9. It specifies, in either quantitative and qualitative performance terms, a range of performances from barely acceptable to exceptional that would be anticipated in the surveillance role. The characteristics needed in a wide area surveillance system directly influence the performance scales used, but it is difficult to satisfy all the surveillance needs in such a brief table structure. An expansion of this table would be expected in a subsequent analysis of the most preferred options.

The rating scales values are based on research and author judgement of the surveillance system characteristics documented earlier, and the anticipated performance of the sensor options. The intention is to provide a consistent performance basis for judging options against each criterion. Comments are also provided to support most criteria assessments in Table 6.9 but many entries are self explanatory and representative of anticipated performances.

Options performances were expected to vary widely since most of the systems are optimised for missions other than wide area surveillance. Therefore, the comparison may be superficial for some criteria but it provides a basic comparison between common sensor types. Table 6.9 also attempts to show the maximum desired performance while allowing a range of relative performance assessments to be made.

Orbit for Comparison

An orbital inclination of at least 45 degrees is required to conduct surveillance of all the area of interest specified. Therefore, a 45 degree orbit inclination is used for sensor comparison, except for the commercial satellite option where the actual orbital parameters are used.

Area Coverage

The surface area viewable by a satellite sensor is dependent on altitude, inclination, field of view, weather, illumination and the type of sensor being used. To achieve the maximum performance in Table 6.9 a constellation of low Earth orbit satellites would be required. However, satellite constellations are not examined here but Table 6.9 provides an assessment scale for a range of coverage capabilities.

Area of Interest. The region of interest is simplified for computational purposes by assuming that it extends from 110° to 157° East longitude, and 45° South latitude to the equator. This region is about 5,200 km East to West at the equator and 5,000 km North to South, an area of about 26 million square kilometres.

Maximum Area Viewable. The Earth's surface area viewable from low Earth orbit satellites is fundamentally limited by line-of-sight to the horizon for visible and IR sensors. Viewing targets in the atmosphere above the horizon is also possible, although atmospheric effects such as airglow limit the extent of viewing. Pulse Doppler microwave radar sensors have a viewing limit from a few degrees less than the grazing angle to about 15 degrees from nadir.

At a nominal 700 km altitude, the maximum area viewable is about 18 million and 17 million square kilometres for visible/IR and microwave radars respectively. In theory, this means that about 65% of the area of interest may be viewable in one pass. However, even if imaging sensors were available that could view all of this region in one pass, the data transmission rate required to down-link the data would be enormous. In addition, the slant viewing of objects at the extremities would limit imagery usefulness. However, slant viewing is necessary for Doppler radars to ensure that targets are moving toward or away from the sensor.

Table 6.8 Criteria Preference Chart

Criteria	IFOV	Area Coverage	Revisit Time	Target Information	Technical Risk	Capital Investment	Timeliness of Data	Effects of Environment	System Control	Image Cost	Number Value	Importance Grouping	Weight
IFOV		=	=	=	>	<	=	=	>	>	20	V. Important	2
Area Coverage	=		=	=	>	=	=	=	>	>	21	V. *Important*	2
Revisit Time	=	=		=	>	=	=	=	>	>	21	V. Important	2
Target Information	=	=	=		>	=	=	=	>	>	21	V. Important	2
Technical Risk	<	<	<	<		<	<	<	=	=	11	Important	1
Captial Investment	>	=	=	=	>		=	=	>	>	22	V. Important	2
Timeliness of Data	=	=	=	=	>	=		=	>	>	21	V. Important	2
Effects of Environment	=	=	=	=	>	=	=		>	>	21	V. Important	2
System Control	<	<	<	<	=	<	<	<		=	11	Important	1
Image Cost	<	<	<	<	=	<	<	<	=		11	Important	1

Symbol	**Meaning**	**Points**
> >	Much More	4
>	More	3
=	Equal	2
<	*Less*	1
< <	Much Less	0

Revisit Time

For tactical surveillance, once a target is detected there is a need to return to the area within a short enough time to detect the target again before it moves out of the area. Strategic surveillance is less time critical. The scale in Table 6.9 is compressed to include both surveillance time scales, and provide a desirability function that can illustrate the relative performance of all the systems.

Ratings are based on the revisit times needed to track fast aircraft, slow aircraft, war ships, small ships and fishing vessels, using a sensor with a swath width of about 500 km. This swath width is considered to be reasonable in the 15 year time horizon.[44] The target is assumed to be in the centre of the swath at the time of first detection and travelling tangentially to the ground track. In the case of a fast aircraft travelling at about 900 km/hr, a revisit time of 15 minutes would be required.

Sensor Pointing. A sensor pointing ability can significantly improve revisit time performance over that of fixed sensor viewing. The SPOT, TIDES and RAR systems are able to point their sensors. This capability improves revisit time but area coverage performance remains the same; the area viewed is determined by detector FOV, not by sensor FOV. The detector FOV images only a small part of the total sensor FOV at any one time, thereby sacrificing the surveillance of some other area in order to deliberately point at a target. However, this level of control requires active pre-programming of the satellite sensor during its mission.

Capital Investment

The capital investment figures are indicative costs for the purchase and launch of a satellite sensor capability. Ground infrastructure, insurance, management and operations costs are common to all systems and are not included. However, these other costs are typically a large component of the overall cost and would be needed in a more detailed analysis. To illustrate the possible impact of these additional costs, Figure 6.1 shows a cost breakdown for a two satellite communications system, costed over a five year period. This indicates that the actual satellite cost is less than about 25% of the total cost of the system.

Target Information

This criterion considers the range of target information available from the sensors. Since the priority is for tactical surveillance of moving targets such as aircraft and ships, those sensors that can provide moving target detection and rapid response score better. However, some of the sensors provide fundamentally different information, consequently multiple entry descriptions are used. It is difficult to determine an equivalent importance scale between these sensors; therefore, additional research is needed but it can only be easily done when comparing like sensors.

44 Table 6.5 illustrates that RADARSAT will provide this swath width but with only a 100 x 100m resolution.

Table 6.9 System Utility Function - Performance Desirability

	Rating	0 1	2 3	4 5	6 7	8 9
Weight	Criteria	Barely Acceptable	Below Average	Average	Above Average	Exceptional
2	Capital Investment	$2 Billion	$1 Billion	$300 Million	$100 Million	$50 Million
	Effect of Environment	Daytime Only. Clear Weather.	Daytime Only. Cloud Cover.	Day & Night. Clear Weather.	Day & Night Heavy Cloud Cover	Day & Night. Heavy Cloud Cover. Heavy Rain & Fog.
	Area Coverage	10% Region	25% Region	50% Region	75% region	90% Region
	Revisit Time	2 Days	1 Day	12 Hours	6 Hours	15 Minutes
	Timeliness of Data	5 Days	2 Days	24 Hours	One Hour	Near Real Time
	Target Information	Image Stationary Target s Only. Low resolution	Detect Slow Moving Tgts	Detect and Track Slow Moving Tgts. Image Lge Ship Size Tgts.	Rapid Report of Fast Moving Targets. Image Small Tgts.	Rapid Report of Moving Targets. Fast and Slow Targets
	IFOV	50 metres	30 metres	10 metres	5 metres	1metre
1	System Control	Foreign Owned. Use Agreement.	Ally Owned Use by Agreement.	Joint Venture	Australian Owned and Controlled.	Develop capability In Country.
	Technical Risk	Concept Only	Under R&D Programme.	Pre-Production Development.	In Production. New Capability.	Existing Capability. Proven Technology.
	Image Cost	$120	$30	$1	$0.20	$0.02

The highest performance score is expected from a RAR using Doppler processing, which should provide near real-time detection and reporting of some moving targets. Imaging sensors are able to detect fast and slow moving targets, but these detections cannot be rapidly reported because image analysis is a time intensive and mainly manual process.

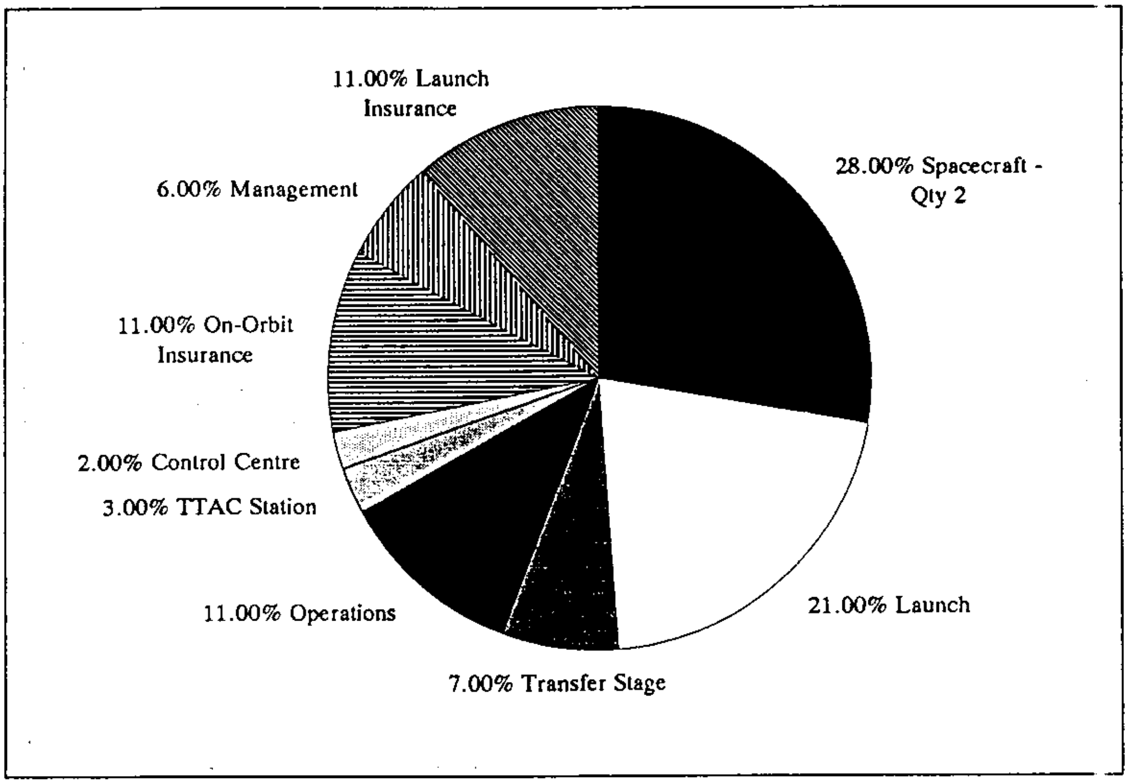

Figure 6.1 Cost Breakdown of a Satellite Space Segment[45]

Simulation of Sensor Performance

In this section the performances of all sensor system options are simulated for each criterion in turn, and the results are rated in terms of the performance scales in Table 6.9. Each simulation is summarised in a separate table along with supporting comments. A confidence level is provided to illustrate how well the expected performance is considered to reflect the true situation. Comments are also made on all simulations except *Technical Risk* which is self explanatory. These comments indicate the accuracy, validity and the improvements that may be sought in future simulations.

Sensor configurations are evaluated from the technical and performance data provided in this Chapter, with the exception of the area coverage and revisit time criteria.

45 Elbert, B.R., *Introduction to Space Communications*, Artech House, Norwood, 1987, p 301.

These criteria are constrained in orbital inclination for all but the commercial satellite option. An inclination of 45 degrees was selected because it permits total coverage of the area of interest and also allows a direct comparison of all sensor performances. Area coverage and revisit times are calculated by a computer program that processes the results from satellite ground track latitude and longitude coordinates. Detailed consideration of other orbits is left to future work.

Some satellite sensors are difficult to compare when the measures used are not relevant to the mode of operation of all sensors. Approximations and judgement are used to ensure that the overall results are not biased on the basis of partially inadequate assessment criteria. Bias may also occur when the effect of a particular characteristic is accounted for more than once in the overall study. For example, cloud cover attenuates EM radiation in the visible and infrared bands and this aspect could be included in the *Effect of Environment*, *Area Coverage*, *Revisit Time* and *Image Cost* criteria. Including cloud cover aspects in all these would produce a cumulative bias in the overall result, consequently care is taken to prevent duplication.

Satellite Lifetime

Satellite lifetime has not been used as a criterion but it has an impact on the cost effectiveness of individual options. It could be included separately or used to modify the results of other criterion; however, an examination of the lifetimes of each option indicates that five years is a reasonable estimate for each system. Therefore, no adjustments have been made to the relative merit of criteria due to lifetime. This aspect would require closer examination for a specific system implementation.

Effect of Environment

The sensors options that operate in different parts of the EM spectrum will have fundamentally different performances. As previously discussed, visible and infrared sensors are affected by cloud cover and illumination conditions, but microwave radars do not require external sources of illumination, and depending on the frequency of operation they may be unaffected by weather conditions. Table 6.10 summarises sensor option performances in this criterion.

Daytime Illumination. The number of daylight hours varies throughout the year and between latitudes. This variation is accounted for by assuming that there are 12 hours of daylight each day. The assumption is reasonable at the equator, but some inaccuracies occur at other latitudes since the number of daylight hours can significantly increase in summer and decrease in winter, for latitudes North or South of the equator.[46]

Cloud Cover. Cloud cover in tropical regions to the North can be high, particularly during the monsoon season. For visible and IR sensors, the requirement is for

46 Granger, K., *A Very Different Place: Australia's North-West Frontier*, Centre for Resource and Environmental Studies, Australian National University, Canberra, February 1990, p 26.

clear line-of-sight viewing; therefore, images from these sensors are likely to be severely limited due to cloud cover. However, it is difficult to predict just how effective these sensors will be during these periods, since there is general lack of line-of-sight viewing prediction data for the high priority areas of interest.

The most readily available remote area cloud cover statistics are derived from single site ground observations, and these are typically based on human eye estimates of the percentage of the sky that is cloud covered. These observations are made on a daily basis around the country and the data is extrapolated to estimate cloud cover over the ocean. The validity of extrapolating this land or coastal data to estimate open ocean or in-land cloud cover is questionable.

Cloud cover assessments made in this way are based on poor initial estimates since the human observer is not looking vertically through the cloud cover for all the region being examined. At some distance from the observation point clouds may appear much larger than they actually are, due to the oblique viewing aspect. Therefore, these observations will generally over-estimate the actual cloud cover. Consequently, they are unreliable for determining the probability of clear line-of-sight viewing through clouds, for other than at the observation point. Therefore, further research is required to evaluate the probability of line-of-sight viewing through cloud cover across the region of interest.

An average value of 50% cloud free line-of-sight is used as a representative average across the region of interest.[47] This estimates, therefore, that visible and IR sensors can provide effective images only half of the viewing time available.

<u>Comparison.</u> The microwave radar options provide the best performance in various lighting and weather conditions; however, this would not always be the case, particularly if frequencies much more than an order of magnitude higher than L-Band (1-2 GHz) are used. The performance of visible and IR spectrum sensors will depend on obtaining clear line-of-sight viewing during the daytime, although sensors using longer IR wavelengths are useable in clear weather at night. Under worst case conditions the overall probability of obtaining effective images with visible and Near IR sensors under these environmental conditions is 0.25 and it is 0.5 for thermal IR sensors.

<u>Area Coverage</u>

There are fundamental viewing restrictions from low Earth orbit. For instance, unless a sensor has a pointing capability, it cannot observe any region North or South of the inclination latitude that is outside its field of view along the ground track. In addition, line-of-sight viewing to the horizon restricts area coverage. The need for cloud free line-of-sight with visible and IR sensors and the lack of solar illumination at night also requires consideration, but the impact of illumination and cloud cover have been included in the *Effect of Environment* criterion.

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47 Representative for tropical Pacific region according to Clark, A.S., *On the Probability of Obtaining Clear Sight Lines Through Clouds*, WRE-TN-1227 (AP), Weapons Research Establishment, Salisbury, December 1974, pp 6-7.

Table 6.10 Effect of Environment

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
	Visible/ Near IR Sensors	Daytime only	VC	1. Clouds highly reflective in visible/NIR spectrum. 2. Rain, fog & pollutant attenuation effects can be high.
Effect of Environment (weather, atmosphere)	MWIR & thermal IR sensors	Day & night & in clear weather	VC	1. Cloud & atmospheric effects similar to visible & NIR 2. Thermal emission from natural & man made objects may be detectable day & night
	Synthetic Aperture Radar (SAR)	Day & night & in all weather conditions	VC	1. Low atmospheric attenuation in C Band 2. Cloud cover transparent
	Real Aperture Radar	Day & night & in all weather conditions	VC	1. Low atmospheric attenuation in L Band 2. Cloud cover transparent

VC = Very Confident
C = Confident
LC = Low Confidence
NC = No Confidence

Simulation. Table 6.11 illustrates area coverage simulation performance. These values are obtained from a computation based on the average time a satellite spends over the area of interest, satellite ground speed and sensor swath width.

The results of area coverage performance computations show that for other than polar orbits, a satellite spends a significant portion of its time nearly above the latitude equal to its inclination. Figure 6.2 illustrates that satellite with a 45° inclination spends nearly 18% of its time within 10° of either the 45° North or South latitude and 12% of the time within five degrees of the maximum latitudes. Polar orbiting satellites, by comparison, spend about the same time over each latitude, or about 5% of the time within each 10 degree latitude band. Therefore, the 45° inclined orbits will provide a marginally higher area coverage at latitudes near the inclination latitude. However, this non-linear area coverage performance has not been factored into the results here but it has been included in the revisit time computations. This aspect could be worthwhile examining in detail in the future for optimum satellite constellation performance.

Comparison. The RAR sensor out-performs the other sensors by far due to its horizon to horizon scanning capability. This sensor appears to provide the capability to scan a region equivalent to about seven times the area of interest per day, which is more than 50 times the coverage of the next best sensor. All the imaging sensors have less than 15% area coverage per day. However, this computation gives an equivalent area covered per day but it does not account for duplication of coverage on successive passes, or show how successive satellite passes relate to each other. Therefore, some inaccuracies in absolute coverage are evident but they occur in each option and do not detract from a relative comparison. Software could be developed to correct this limitation for future analyses.

Revisit Time

The time for a satellite sensor to revisit a target area is fundamentally constrained by the satellite orbital period and sensor field of view from a given altitude Moving targets also complicate revisit time performance since a target may move out of the viewing area during the orbital period of a low earth orbit satellite, even if the sensor is able to view the same area on the following pass.

Chapter Two identified the need to revisit within about 90 minutes for limited tactical surveillance across much of the North coast. Satisfying this requirement with a single satellite is difficult unless the target is near the equator, in which case the revisit time would be about 100 minutes for a low Earth orbit satellite. This indicates that satellite constellations need to be considered although only single satellites are used here to evaluate the minimum performance achievable from typical satellite sensor types.

Simulation. Revisit time estimates are derived using a target that is stationary on the equator, in order to gain a first order performance estimate. The simulation used two computer programs: one to generate satellite ground track latitude and longitude values and the other to calculate the time taken for the satellite sensor to re-view the target region. Sensor field of view pointing control has also been simulated, although this assumes that maximum control of the sensor is available to achieve the best possible revisit time. Active sensor pointing will disrupt normal surveillance coverage but can achieve significant improvements in revisit times. For example, the near polar orbiting SPOT 2 satellite revisit time improves from 26 days to 2.5 days with pointing control. The revisit time improvement is not as dramatic for lower inclination satellites.

Comparison. Table 6.12 shows that the options are unable to meet the revisit time requirements for tactical surveillance of aircraft, as was expected; however, the time scales of the best performer are nearly adequate for surveillance of maritime vessels. This indicates that a small constellation of satellites should satisfy the revisit time requirement for ship surveillance; depending on the latitude of the region being examined, sensors used and the satellite inclination selected and subject to weather conditions. Additional simulation would be needed to draw any definite conclusions about constellation performances or to examine a range of moving targets in the region of interest.

Table 6.11 Area Coverage

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
	SPOT Visible/NIR Sensor	8.8 %	VC	Percentage of defined area viewable/day. All are limited in the maximum by line-of-sight viewing to horizon, but RAR is the only sensor that can view to the horizon anyway.
	Landsat Thermal IR sensor	27.5 %	VC	At 45 degree inclination as for SPOT above.
Area Coverage (% area of interest per day)	Small Satellite Visible/NIR	8.8 %	C	Appears realisable without significant technology advances.
	Small Satellite Infrared Sensor	28.6 %	LC	May be technology limited at 500 Mbps data rate, although it is possible with data compression of say 10:1, as proposed in the TIDES system.
	Synthetic Aperture Radar (SAR)	14.4 %	VC	Using 100 km swath for adequate resolution of 30 m.
	Real Aperture Radar (RAR)	761 %	LC	Has horizon-to-horizon scan, therefore large area coverage using 1100 km orbit. Suggested to be realisable with existing technology.
	Commercial Satellites	4.4 %	VC	Based on SPOT. Landsat provides 3.5%/day. Low due to near polar orbit.

Target Information

For tactical surveillance of targets such as ships and aircraft, target detection, tracking and identification may be required. Identification, classification and technical description are generally needed for military intelligence purposes. Civil activities such as monitoring illegal fishing and smuggling also need to positively identify targets, to support civil police action. High resolution imagery is required for precise target identification, but lower resolution may be adequate to just detect targets. Sensors may also be selected to exploit specific spectral characteristics of targets. Table 6.13 documents the range of target information available from each sensor option.

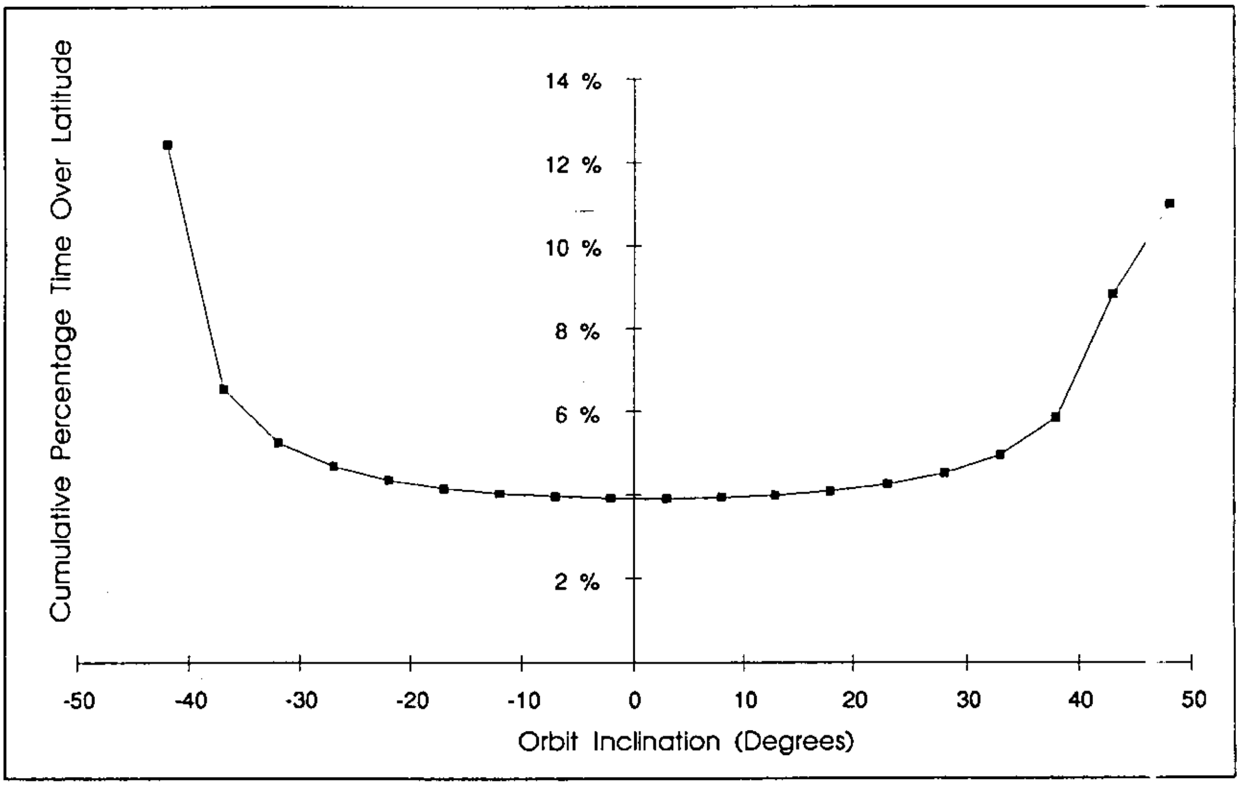

Figure 6.2 Percentage of Time Over Latitude

Sensors that are able to detect and track moving targets are assessed as most useful. Identification is considered to be less important for tactical surveillance but this is dependent on user requirements. Target detection is a function of sensor type and capability from the chosen altitude, but tracking of targets is difficult to achieve with single low Earth orbit satellites, even if they have some form of on-board tracking antenna. In addition most of the sensors here are imaging types, consequently significant electronic and manual processing of images are needed to detect targets.

Infrared Emission Detection. The performance of infrared emission sensors in detecting hot objects like aircraft engines is of particular interest, since this capability may be possible with a small low cost satellite. Consequently, the infrared sensor capability is examined in more detail.

Emission characteristics of aircraft are difficult to obtain from unclassified sources, as would be expected. The B-52 bomber emission profile in Figure 6.3 was obtained from recent research into a conceptual aircraft detection system using IR sensors. A representative small jet aircraft IR emission characteristic has also been used.[48,49] Estimates are made to determine if the small satellite IR sensor is able to detect emissions from these aircraft engine sources. This sensor is the only IR option with a detector in the relevant IR

48 Farrell, J., op cit, pp 10-13.

49 During a personal discussion with G. Poropat, Defence Science and Technology Organisation, the infrared emission figure quoted was indicated to be representative of a small jet aircraft engine tail-pipe emission.

band. Annex A lists the computation method used to determine the detection performance of this sensor.[50]

Figure 6.3 illustrates that the B-52 engine emission is most intense in line with the longitudinal axis of the aircraft. However, this maximum intensity view is unlikely to occur at minimum range while using a space-based sensor since targets will generally be travelling nearly parallel to the satellite path at nadir, and emission in this direction is almost zero. Therefore, Annex A computes detection performance with an off-nadir viewing angle.

IR Simulation Result. While the analysis at Annex A is not rigorous, it does indicate that detection of both the large and small jet aircraft appear to be possible from an altitude of 700 km, but the small aircraft must be viewed from nadir to be detected. The B-52 engine emission appears to be detectable with an order of magnitude increase in range. Therefore, this IR sensor capability appears to be worthwhile investigating in further detail but it is evident that this sensor wavelength band will only be useful for very intense IR emissions. A range of other targets require examination to determine the full potential of this sensor option.

Table 6.12 Revisit Time

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
	SPOT Visible/NIR Sensor	1 day	C	Has pointing control of 27 degrees East or West of track.
Revisit Time	Landsat Thermal IR sensor	1.5 days	C	No pointing control but has a large swath.
	Small Satellite Visible/NIR	1.5 days	C	Pointing control within 53 degree FOV.
	Small Satellite Infrared Sensor	1.5 days	C	Wide swath but no pointing.
	Synthetic Aperture Radar (SAR)	2.2 days	C	100km swath of RADARSAT simulated at 45° inclination.
	Real Aperture Radar (RAR)	11.6 hours	C	Horizon to horizon scanning capability.
	Commercial Satellites	2.5 days	C	Based on SPOT with pointing control, is 26 days without it.

50 Computation method uses a Mathcad computer software implementation of equations from remote sensing Course notes Evans, H.E., *Electro-Optical Space Systems Technology Course*, PHYS 6.21, USAF Institute of Technology, Dayton, Ohio, 1988.

Table 6.13 Target Information

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
Target Information	SPOT Visible/NIR Sensor	Imaging	VC	a. Existing capability b. narrow field of view c. visible/NIR sensor
	Landsat Thermal IR sensor	Imaging and IR source mapping	VC	a. Existing capability. b. Spectrum bands unsuited for detection of hot aircraft engine type emissions.
	Small Satellite Visible/NIR	Imaging	C	a. Narrow field of view b. Visible/NIR sensor
	Small Satellite Infrared Sensor	Imaging & IR source mapping	LC	a. Narrow field of view b. Able to detect emissions from small aircraft engines ie. night capable, but not in FOV for long enough to track c. Concept development req'd
	Synthetic Aperture Radar (SAR)	Imaging Detect stationary & slow moving targets	VC	a. Under development b. Ship wakes detectable
	Real Aperture Radar (RAR)	Detect & track fast moving targets	LC	a. Doppler for moving target detection, 150 km/hr minimum speed b. Large radar cross section targets may be detectable c. Concept system only
	Commercial Satellites	Imaging only IR mapping on Landsat	VC	Existing SPOT and Landsat systems

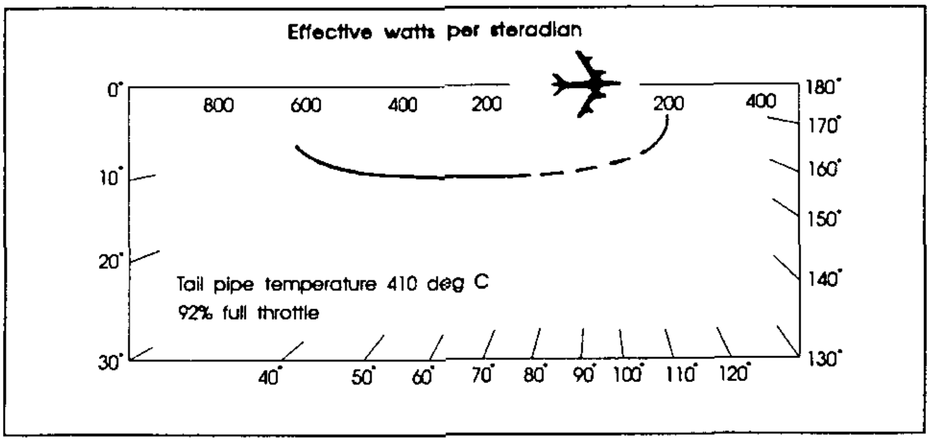

Figure 6.3 Radiation Pattern of a B-52[51]

Capital Investment

Table 6.15 illustrates the capital investment to purchase and launch the satellite options.[52] As previously indicated, there are many other costs associated with a full system implementation, but the intention is to give a relative comparison of surveillance sensors, rather than detail on both the space and ground segments. A detailed cost comparison of the range of options examined would form a substantial study in its own right, and is therefore left to future research.

Comparision. The projected costs for small satellites are more than an order of magnitude lower than the other options. Therefore, a constellation of these small satellites appears to be affordable in terms of Australia's national or defence budget. The RAR option is very costly when it is considered that the ground infrastructure will also need to be developed.

51 Lawder, T.J., *Specification of an Infrared Satellite Surveillance System for the Detection of Aircraft*, Thesis, USAF Institute of Technology, AFIT/GSO/ENP/87D-1, Dayton, Ohio, 1987, p 18.

52 Launch costs estimates were obtained from information provided by P. Winch, Australian Launch Vehicles Pty Ltd, South Australia.

Table 6.14 Technical Risk

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
Technical Risk	SPOT Visible/NIR Sensor	Existing Technology	VC	Existing satellite capability
	Landsat Thermal IR sensor	Existing Technology	VC	Existing satellite capability
	Small Satellite Visible/NIR	Concept under R&D	C	Early stage of concept development
	Small Satellite Infrared Sensor	Concept Only	C	Early stage of concept development
	Synthetic Aperture Radar (SAR)	New capability under development	VC	Development in progress Due for launch in 1994 Building on existing technology
	Real Aperture Radar (RAR)	New capability in early R&D stage	C	Space based radar R&D started in Canada in late 1980s. Capability possible in early 2000s.
	Commercial Satellites	Existing technology	VC	Existing systems

<u>Image Cost</u>

This criteria attempts to include the utility of commercial satellite surveillance when compared with a satellite system purchase option. The image costs in Table 6.16 are evaluated using both the area coverage and capital cost estimates from Tables 6.11 and 6.15. However, the costs here are only approximate relative values for each option. Inaccuracies occur because not all costs have been included, consequently an under-estimation of about 40% is expected for the options in which satellite systems are being purchased.

Table 6.16 represents the cost to provide imagery coverage of all the area of interest. However, the regular purchase of all this commercial imagery from a satellite like SPOT would not occur. Imagery may be purchased once so that a database of the entire region can be established for a geographic information system, but further purchases would just update the high priority regions.

Table 6.15 Capital Investment[53]

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
	SPOT Visible/NIR Sensor	$935 million	C	Estimates from SPOT Imaging Services, Sydney
	Landsat Thermal IR sensor	$312 million	C	Estimated from Landsat 4 cost in 1978.
Capital Investment ($ A)	Small Satellite Visible/NIR	$21.4 million	C	Design estimate for concept is based on initial satellite development costs. Production version estimated to cost $12.6 million.
	Small Satellite Infrared Sensor	$21.4 million	LC	Assumed to be the same as for above small satellite.
	Synthetic Aperture Radar (SAR)	$577 million	C	Contracted cost.
	Real Aperture Radar (RAR)	$1,275 million	LC	Value estimated by Canadian Space briefing team & from Canadian SBR development budget as % of financial commitment agreed between USA and Canada.
	Commercial Satellites	$2.5 million/year	VC	Annual cost of licence for access to SPOT & Landsat. Imagery charged on a per scene cost.

Costs are based on area coverage, which is dependent on sensor swath width and this in turn is sensitive to spatial resolution: higher spatial resolution means a smaller swath width and therefore a higher image cost. This appears to unfavourably bias this criterion in favour of low resolution sensors but no minimum resolution need has been specified, since high spatial resolution it is not a useful measure for all sensors. An improved comparison could be achieved by comparing like sensors only, but this would suggest the need for another measurement criteria.

Comparison. Table 6.16 shows that commercial user only imagery costs are orders of magnitude cheaper than the user purchased system, as would be expected.

53 Estimated 1991 prices including launch costs.

Consequently the under-estimation of satellite purchase option costs or biases in favour of low resolution sensors are not significant. The small satellite options are also significantly cheaper than larger satellites as they are able to provide a similar imagery capability at a much lower capital cost. Table 6.17 supports this a relative cost analysis by providing a cost comparison of imagery from space assets and aircraft systems, based only on the commercial cost of imagery. It shows the low cost of spacecraft for area surveillance, although the capital cost has been neglected in all cases.

Table 6.16 Image Cost

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
	SPOT Visible/NIR Sensor	$1635	C	Visible & IR costs are based on effective images available which must account 50% loss of images due to cloud cover and a 50% loss due to lack of solar illumination.
	Landsat Thermal IR sensor	$176	C	However, cloud covered images from commercial sources would not be purchased; therefore,
Image Cost (scene cost per km^2 for an effective coverage day)	Small Satellite Visible/NIR	$36	C	get price is based only on purchased images.
	Small Satellite Infrared Sensor	$11	LC	High data rate 500 Mbps is required for coverage.
	Synthetic Aperture Radar (SAR)	$154	C	Using medium resolution mode 100 x 100 km scene.
	Real Aperture Radar (RAR)	$6	LC	Early Concept design.
	Commercial Satellites	SPOT 1. $0.38 user only 2. $2 total (Landsat figures) 3. $0.05 user only 4. $0.6 total	VC	(1) Based on SPOT capability @ $1380 per 60 x 60km scene for panchromatic image. Cloud covered images are not purchased. The 'User Only' costs are used in the simulation.

Table 6.17 Remote Sensing Imagery Cost Comparison[54]

Sensor	Working Scale	Scene Cost	Cost/km	Scene Coverage (km)	Spatial Resolution	Frequency
NOAA-AVHRR	1:1,500,000	$125 (CCT)	-	2700 x 5000	1 km	8 hours
LANDSAT-HSS	1:100,000 - 1:250,00	$960 (CCT) $420 (print)	$0.03 $0.01	185 x 185	80 m	16 days
LANDSAT-TM	1:50,000 - 1:100,000	$4,500 (CCT) $700 (print)	$0.13 $0.02	185 x 185	30 m	16 days
SPOT-XS	1:50,000 - 1:100,000	$3,100 (CCT) $2,980 (print)	$0.86 $0.83	60 x 60	20 m	1 - 5 days
SPOT-PA	1:25,000 - 1:50,000	$3,815(CCT) $3,295 (orint)	$1.06 $0.92	60 x 60	10 m	1 - 5 days
AERIAL PHOTO	1:50,000	$20 (print)	$0.20	10 x 10	50 cm	5 - 10 years
AERIAL PHOTO	1:25,000	$20 (print)	$0.80	5 x 5	25 cm	5 -10 years
AIRCRAFT SCANNER	1:1,000 - 1:50,000	Dependent on location approx $200,000 -	$69	variable depends on flying height	1 - 20 m	when req'd

NOAA-AVRR	Advanced Very High Resolution Radiometer
LANDSAT-HSS	Multi-spectral Scanner
LANDSAT-TM	Thematic Mapper
SPOT-XS	Multi-spectral Scanner
SPOT-PA	Panchromatic
CCT	Computer Compatible Tape

54 Costs in 1990 prices, table data provided by Mr T. Millane, Army Scientific Advisor, Department of Defence, Canberra.

Timeliness of Data

Table 6.18 estimates the time for data to be collected by a satellite sensor and distributed to users in a processed form. Once a sensor is able to view the target area, a communication method must be available to transmit data in real-time or provide storage until transmission is possible. Received data will then be processed and analysed to meet user requirements. The times proposed are representative of the best that can be achieved by the system options; however, future analysis using particular surveillance scenarios could provide a greater focus for operational situations.

Ground station positioning is important to ensure that data can be collected at the extremities of the area of interest and transmitted directly to a processing facility, to achieve the shortest possible response time is required. If stations are placed across Australia's North coast, it should be possible to receive data from a low Earth orbit satellite that is directly to the North and over the equator. The most significant time delay is for signal and data processing of imagery, consequently direct linking of satellite data to the user provides the best response time. However, processing overheads can be high and may preclude direct linking for some sensor types.

The mode of data transmission will depend on the response time required Remote ground stations data communications bandwidth requirements may be costly if electronic transmission of high resolution imagery is required, but manual delivery is an option if the delay can be justified. A manual delivery method is used at ACRES, where tapes of the received imagery is transported by a Courier service from the receiving station near Alice Springs to the ACRES Office in Canberra for processing. Therefore premium prices will be paid for fast access to surveillance data from remote sites.

System Control

Options for system control range from total reliance on a commercial service to having an indigenous capability to design, develop, launch and operate a space-based capability. Without adequate system control the overall effectiveness of a surveillance capability can be compromised. The possible control options are illustrated in Table 6.19.

In the case of using foreign commercial satellite data, the user pays little in capital expenditure but this must be weighed against the long term likelihood of actually obtaining data when needed, particularly for military applications. At some time in the future, all data collected by foreign satellites is likely to be remoted by data relay satellites to the owner's ground station. This may exclude less affluent users who have gained access to data by building a ground station and processing facilities for a foreign owned remote sensing network, and are perhaps paying licence or access fees to distribute data.

Data access can generally only be guaranteed by joint or total ownership of a capability. For example, the mutually agreed use of allied surveillance systems, particularly military systems, would provide reasonable confidence of access to surveillance data. However, without financial, technical or other contributions to such a capability, the long term provision of services that are focused to Australia's needs should not be anticipated. An indigenous satellite development, launch and operations infrastructure may appear to be costly at the outset but the long term advantages must outweigh any disadvantages. This option would provide the highest level control over space capabilities and systems can be introduced to satisfy Australia's needs. Cost offsets could be achieved by marketing the surveillance services internationally.

A significant space-based wide area surveillance capability for Australia probably has a system control structure somewhere between commercial use and indigenous development. There will be the need for a range of satellites and sensor types in a comprehensive wide area surveillance system, consequently an indigenous capability could be developed while co-operating with allies to develop the more costly system options.

Instantaneous Field of View

Analysis of this criterion involves a comparison of dissimilar sensors with a criterion that is not totally suited for the task. For example, not all the figures in Table 6.20 represent actual IFOVs. The SAR entry is actually the resolution of the sensor and RAR IFOV means little for imaging of small targets. However, an order of merit is obtained since performances are judged against the values in Table 6.9, which accounts to some extent for a range of sensors even if they are not strictly comparable. In a more detailed analysis a comparison of performances based on like sensors could address this shortfall. However, an overall judgement of sensors that do not operate in the same way, or have similar outputs, is still required.

Table 6.18 Timeliness of Data[55]

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
	SPOT Visible/NIR	16 hours	C	ACRES staff indicated that a dedicated facility could Sensor process imagery in about 2 hours. Imagery collection & delivery estimat d at about 4 hours from a remote location. Analysis time is target specific an is difficult to estimate (used 10 hours)
Timeliness of Data	Landsat Thermal IR sensor	12 hours	C	Lower resolution imagery processing time likely to be marginally decreased.
	Small Satellite Visible/NIR	4 hours	LC	Assumed performance for tactical applications with data linking direct to users. Analysis would be target specific & therefore completed in a shorter time.
	Small Satellite Infrared Sensor	4 hours	LC	As above for small satellite
	Synthetic Aperture Radar (SAR)	18 hours	C	Improved SAR processing at 0.25 real-time expected to provide priority users data in this time[56]. Complex processing need dedicated facility.
	Real Aperture Radar (RAR)	Near real-time (10 minutes)	LC	RAR provides moving target detection on single pass with little ground processing. Data direct to usei .
	Commercial Satellites	48 hours	VC	ACRES costing data sheets indicate a 2 day turnaround for priorit commercial sales products. A cost premium of 3.5 times nominal cost is levied. For 5 days it is 2 times cost.

55 This assumes that the satellite sensor is in position to view the area of interest.
56 Ahmed, S. et al, op cit, p 213.

Table 6.19 System Control

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
	SPOT Visible/NIR Sensor	Foreign owned capability	VC	Existing capability.
	Landsat Thermal IR sensor	Foreign owned capability (ally)	VC	Existing capability.
System Control	Small Satellite Visible/NIR	Joint venture possible or indigenous capability in future	C	System cost relatively low & could be simple entry into space capability development in Australia.
	Small Satellite Infrared Sensor	Joint venture possible or indigenous capability in future	C	As above.
	Synthetic Aperture Radar (SAR)	Foreign owned capability (ally)	VC	System for launch in 1994.
	Real Aperture Radar (RAR)	Foreign owned (ally) Maybe minor partner in venture possible	C	Cost appears too high for Australia alone. Power limited satellite with small operating time in orbit, therefore sharing of allied ystem may not be possible.
	Commercial Satellites	Foreign owned capability	VC	Commercial source ground station in Australia.

Table 6.20 Instantaneous Field of View

Criterion	Alternative	Expected Performance	Confidence Level	Supporting Data
Instantaneous Field Of View IFOV	SPOT Visible/NIR Sensor	10 x 10 metres	VC	SPOT data sheet. Existing capability.
	Landsat Thermal IR sensor	120 x 120 metres	VC	Landsat data sheet. Existing capability.
	Small Satellite Visible/NIR	5 x 5 metres	C	R&D detail to be undertaken.
	Small Satellite Infrared Sensor	14.4 x 14.4 metres	C	MWIR band. Concept design only.
	Synthetic Aperture Radar (SAR)	8 x 8 metres	VC	In production for launch in 1994. This is ground resolution cell size since IFOV is of no value for comparison.
	Real Aperture Radar (RAR)	280 x 55 kilometres	C	Concept paper studies. FOV realistic with proposed antenna size.
	Commercial Satellites	10 x 10 metres	VC	Existing capability - SPOT

Overall Evaluation of Surveillance System Options

The system analysis approach brings together all the data compiled above into the one evaluation matrix, shown in Table 6.21. This table illustrates, based on criteria simulations, the relative performance and confidence in sensor system options. There is, however, some measure of bias in the results from both the criteria used and the author's subjective performance estimates. Therefore, care is required in interpreting and adopting the numerical results. In the situation where scores are high and confidence is low, or scores are nearly the same, there is probably a need for further investigation. Additional criteria may be needed to focus on these particular issues. However, further iterations of the analysis are not proposed here. Overall conclusions and recommendations are made in Chapters Seven and Eight.

Compilation of the Evaluation Matrix

Details on the mechanics of Table 6.21 are provided to allow the matrix to be readily interpreted or re-compiled if required. Each term in the matrix is described along with the method used to derive the numerical values.

Criteria Importance Weighting. This represents the relative value of each criterion and is derived from the Criteria Preference Chart, Table 6.8.

Relative Rating (R). This is a measure of the performance of each option in terms of the values in the System Utility Function at Table 6.9.

Confidence Level (C). Confidence is a subjective estimate of the likelihood that the system utility score reflects the actual value over the planning horizon, and is provided by each simulation table.

System Utility (U). This is a measure of the contribution of each criterion to overall system utility. The score is the mathematical product of the Criteria Importance Weighting and the Relative Rating value.

Discounted Utility (D). This is a scaled value of the System Utility, adjusted by the Confidence Level, which is determined by multiplying the System Utility value by the Confidence Level.

Total Value. Total Value estimates the overall value of an option and is the sum of System Utility values for each option.

Discounted Value. This measures the value of each system option, adjusted by the Confidence Level of that option, and is therefore the sum of Discounted Utility values.

Overall Confidence. This measures the accuracy or confidence of the overall rating of each system option. It is determined by dividing the Discounted Value by the Total Value and expressing the number as a percentage.

Preferred Surveillance Sensor

The selection of a preferred satellite sensor is conceptually difficult because the types of sensors being compared have significantly different performance characteristics, and user needs for surveillance products also vary dramatically. Conclusions are provided in the next Chapter but a brief summary of the implications of the results in Table 6.21 is given here.

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Table 6.21 Evaluation Matrix

Criteria	SPOT Visible / NIR Sensor				LANDSAT Infrared Sensor				Small Satellite Visible / NIR Sensor				Small Satellite Infrared Sensor				Synthetic Aperture Radar				Real Aperture Radar				Commercial Satellites			
Very Important (Weight = 2.0)	R	C	U	D	R	C	U	D	R	C	U	D	R	C	U	D	R	C	U	D	R	C	U	D	R	C	U	D
Capital Investment	3.0	C	6	3.6	5.0	C	10	6	10.0	C	20	12	10.0	LC	20	6	4.0	C	8	4.8	2.0	LC	4	1.2	10.0	VC	20	18
Effect of Environment	3.0	VC	6	5.4	6.0	VC	12	10.8	3.0	VC	6	5.4	6.0	VC	12	10.8	10.0	VC	20	18	10.0	VC	20	18	4.0	VC	8	7.2
Area Coverage	1.0	VC	2	1.8	2.0	VC	4	3.6	1.0	C	2	1.2	2.0	LC	4	1.2	2.0	VC	4	3.6	10.0	LC	20	6	1.0	VC	2	1.8
Revisit Time	3.0	C	6	3.6	2.0	C	4	2.4	2.0	C	4	2.4	2.0	C	4	2.4	1.0	C	2	1.2	5.0	C	10	6	0.0	C	0	0
Timeliness of Data	5.5	C	11	6.6	6.0	C	12	7.2	6.5	LC	13	3.9	6.5	LC	13	3.9	5.5	C	11	6.6	9.0	LC	18	5.4	3.0	VC	6	5.4
Target Information	6.0	VC	12	10.8	4.0	VC	8	7.2	6.0	C	12	7.2	6.0	LC	12	3.6	5.0	VC	10	9	8.0	LC	16	4.8	6.0	VC	12	10.8
IFOV	5.0	VC	10	9	0.0	VC	0	0	7.0	C	14	8.4	4.0	C	8	4.8	6.0	VC	12	10.8	0	C	0	0	5.0	VC	10	9
Important (Weight = 1.0)																												
System Control	1	VC	1	0.9	3	VC	3	2.7	6	C	6	3.6	6	C	6	3.6	3	VC	3	2.7	3	C	3	1.8	1	VC	1	0.9
Technical Risk	10	VC	10	9	10	VC	10	9	2	C	2	1.2	1	C	1	0.6	7	VC	7	6.3	1	C	1	0.6	10	VC	10	9
Image Cost	0	C	0	0	0	C	0	0	3	C	3	1.8	4	LC	4	1.2	1	C	1	0.6	4	LC	4	1.2	6.5	VC	6.5	5.85
Total Value			64				63				82				84				78				96				75.5	
Discounted Value				50.7				48.9				47.1				38.1				63.6				45				67.95
Overall Confidence			79.2%				77.6%				57.4%				45.4%				81.5%				46.9%				90.0%	

Legend

R = Relative Rating U = System Utility
C = Confidence Level D = Discounted Utility

Confidence Ratings

Very Confident	VC	0.9
Confident	C	0.6
Low Confidence	LC	0.3
No Confidence	NC	0.1

The real aperture radar sensor has scored the highest total value, but little confidence can be placed in this capability because of its early stage of development and the anticipated cost is high. However, it can support the long term need for a system to detect and track moving targets over a wide area, even though JORN should provide some of this capability in the future. The next best sensor scores are from the SAR and the two small satellite options that use visible and infrared sensors. These small satellites have a higher system utility score than the SAR option but they have a lower confidence level due to the limited extent of small satellite technology development. The future of small satellite capabilities is promising, however, and the significant difference in performance between these and existing large-satellite visible and infrared sensors illustrates the dramatic changes in satellite and sensor technology. SAR technology is maturing and the option has scored accordingly. In addition, SAR all weather capability is highly desirable for surveillance in the North

Commercial imagery has scored reasonably well because there are a range of sensors products to choose from, but in reality this option offers totally inadequate control capability and would be eliminated for other than strategic surveillance use. The value of commercial imagery could be further explored however since it was apparently use extensively in the recent Gulf conflict.[57] The larger satellite electro-optical sensors have scored poorly in relation to the small satellite options but this study has not considered the utility of having multi-sensor and multi-spectral capabilities on a larger platform.

Overall the results indicate that the close scoring group of sensors, including SAR and the small satellites, require further investigation to compare them in specific surveillance scenarios. However, the real limitation for SAR is cost but its 24 hour, all weather capability will remain highly desirable.

Simulation Improvements and Follow-On Research

This study has used a number of estimations and simplifications to examine the use of space-based sensors in the surveillance role. Fringe options can be eliminated to allow follow-on research to concentrate on specific options. The following items highlight where future investigations could be directed to either improve these simulations or expand the study scope.

Effect of Environment. The assessment of environmental effects on sensor performance can be improved by:

a. conducting detailed cloud coverage analysis and categorisation by geographic area and time of the year,

b. developing a model for estimating cloud free line-of-sight viewing in the region of interest, and

57 A contract for $US4.7 million was awarded to SPOT Image by USAF Tactical Air Command in 1990 for imagery according to Roos, J., 'SPOT Images Helped Allies Hit Downtown Bagdad', *Armed Forces Journal International*, May 1991, p 54.

c. including solar illumination time variations throughout the year and at various latitudes.

Comprehensive data on the probability of clear line-of-sight viewing through clouds over Australia's area of interest is not immediately available. However, the Bureau of Meteorology has a satellite imagery database that could provide the statistical data needed for a model.

Area Coverage. The analysis of area coverage could be improved by:

a. analysing of area coverage for a range of satellite inclinations and altitudes to determine optimum coverage for priority areas,

b. determining the extent to which ground locations get repeated coverage depending on satellite orbital parameters and the latitude of interest, and

c. accounting for the convergence of tracks toward the Poles.

Orbit inclination has been constrained here but comments have been made as to the impact of using other inclinations. Detailed area coverage simulations would be required to support decisions on area surveillance applications for the Northern coastal approaches. Considering the potentially low cost of small satellites, it would also be useful to examine the area coverage performance of various satellite constellations.

Revisit Time. Many aspects can be changed to examine revisit time in more detail, including: satellite altitude and inclination, moving targets at different velocities and latitudes, and also satellite constellation performance. The scenario worth investigating in detail is a low inclination orbit or constellation focusing surveillance on Australia's North.

Target Information. Further analysis of target detection performance of all sensor options is required, using operational scenarios to provide specific performance data.

Capital Investment. A comprehensive evaluation of the space and ground segment implementation and operation costs is required.

Ground Stations. The position and quantity of satellite ground stations requires examination for surveillance scenarion and a range of sensors.

Integration With other Surveillance Assets. A detailed analysis of surveillance system integration is required to identify current and future system capabilities and the potential integration problems and solutions.

Additional Criteria

There are many issues that can impact on the decision to implement a specific surveillance system. This study has only addressed some of the principal technical, financial and operational criteria. The analysis can be readily expanded to include other criteria and investigate the existing criteria in more detail. The following items may also be considered in an expanded analysis:

a. contribution to regional security,

b. cost to Australia of undetected drug trafficking and illegal immigration,

c. potential for Australian owned surveillance assets to provide surveillance for regional neighbours as a commercial service or as foreign aid, and

d. Australian industrial technology growth if a substantial indigenous space industry capability was developed.

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CHAPTER 7

CONCLUSIONS

Providing cost effective surveillance of Australia's vast and generally sparsely populated mainland, off-shore territories, coastal resource zones and the further reaches of strategic interest is problematic. Conventional platforms are unable to cost effectively provide surveillance of even the coastal approaches. Defence, security and economic needs should dictate that these surveillance coverage shortfalls be addressed. JORN will provide a substantial capability for surveillance of the Northern approaches from the early 2000s but this system will have limitations that need to be addressed by other surveillance capabilities. With a costly program like JORN in progress any proposed future area surveillance system should complement JORN's capabilities by addressing its shortfalls while minimising coverage duplication. Space-based sensors have an inherent ability to overfly and observe any part of the Earth with impunity; therefore, they offer the potential to support JORN with a range of wide area surveillance capabilities in the future.

Australia's surveillance requirements were separated here into military and civilian applications, although considerable overlap is evident. The requirements are both strategic and tactical in nature, although tactical issues such as the need for near real-time surveillance of coastal regions and resources zones should be a high priority.

Space-based sensors are unlikely to offer a complete wide area surveillance solution in the time frame examined here, but a number of sensors have the potential to cost effectively address some shortfalls and provide a path for growth of future capabilities. An extensive surveillance system will be costly to provide in the future, with or without satellites; however, they are likely to be the means by which long term wide area surveillance capabilities are achieved. Reliance on allies may be necessary initially but it is expected that space systems development in Australia will ultimately be justifiable for economic reasons. Small satellites can provide a low cost entry into an indigenous space systems development program.

This book examined a number of typical existing and planned satellite surveillance sensors, based on small and large satellite platforms, to determine their suitability for wide area surveillance of Australia in the next 15 years. In addition, a framework has been provided within which future studies can be progressed. Conclusions are drawn on the surveillance potential of the sensors examined and additional research topics have been identified to expand on the analysis.

Real Aperture Radar

Real aperture radar has the potential to rapidly detect and track fast moving aircraft size targets and some ships, 24 hours a day and in all weather. A single side looking RAR in an equatorial low Earth orbit may be able to detect and track targets as far South as the coast of Australia, and provide a revisit time of about 100 minutes. However, for a more rapid revisit time additional satellites are required but at a cost of about $A1,200 million per satellite, the cost for even a small constellation of three satellites and the ground infrastructure to operate for about five years would be about $A4,000 million. In addition, a significant RAR capability is only in the early stages of concept development and initial satellite production is likely to be more than 10 years away.

A RAR capability would also duplicate the fast moving target detection capability of JORN, rather than complement it. Both JORN and the RAR appear to have a minimum target speed threshold due to the Doppler processing used, which limits their ability to detection of slow moving targets. JORN, however, appears to have a lower target speed detection threshold. Targets with large radar cross-sections may be detectable, depending on the processing method used. A detailed performance comparison is difficult with the limited technical data available, but this apparent duplication of capabilities and shortfalls is not acceptable. Therefore, RAR development is not justifiable in the time frame, but in the long term, allied cooperation for RAR development would be valuable, particular since its performance will be less affected by ionospheric changes. In addition, involvement in an allied program may provide guaranteed access to a global surveillance resource in the future.

Imaging Sensors

Most imaging sensors are capable of detecting fast moving targets but considerable manual analysis is required to just locate small targets. This time delay prevents these sensors from providing a target tracking function, consequently they are generally used for strategic surveillance and reconnaissance to obtain fixed 'snap-shots' of targets scenes. However, SARs can identify the movement of ships by imaging their wakes and some infrared sensors can detect and track specific 'hot' targets, as long as the revisit time is short enough. Therefore, other surveillance assets such as JORN and AEW&C aircraft will be needed in conjunction with most imaging sensor types to provide the continuity to track and identify targets after they are detected.

Synthetic Aperture Radar

SAR can provide medium resolution surveillance imagery, 24 hours a day and in all weather, which is vital for operations in the North. The technology is maturing and imagery resolutions of eight metres or better are possible. However, the high data transmission, signal and data processing overheads are limitations that will remain for some time. SAR rated well in performance estimates against other sensors, although the cost of about $500,000 per satellite suggests that they are unlikely to be launched in quantity. This high cost may be significantly reduced if only a SAR payload was launched, although the inclusion of multi-spectral sensors may make a more versatile and cost effective implementation. A space-based SAR system could also complement JORN's capabilities by providing medium resolution imagery and a slow ship detection and tracking capability, as well as the all weather capability.

Small Satellites

Traditionally, satellite systems have been expensive to develop, launch and maintain. However, the recent trend toward development of small, low cost satellites is addressing this problem. These satellites have the potential to provide low cost surveillance capabilities for Australia. The projected performance for cost outlay of the small satellite sensors examined is much higher than that of established large satellite sensors and the costs are typically an order of magnitude lower. However, the possible sensor types are expected to be limited to visible and infrared sensors and both sensor types have degraded performance in poor weather. In addition, imaging sensors have limited value in the real-time response wide area surveillance role therefore a constellation of these satellites would be required for wide area coverage applications.

Visible Spectrum Sensors

These sensors provide the highest resolution imaging of all the sensors examined consequently they are the preferred sensors for target identification. The technology is mature and can be achieved on a small satellite platform. However, in achieving this high resolution, swath width and therefore area coverage capabilities are sacrificed. But, some of these electro-optical sensors have a steering capability that can be used to collect imagery from a larger overall sensor field of view. If this capability is used with a constellation of low inclination orbiting small satellites, a tactical imaging capability for identification of targets of interest may be possible. Nevertheless, other sensors are needed to initially detect targets and provide direction to the area in which higher resolution sensors are to be employed. For adequate response time a rapid image analysis capability would also be required. Therefore, a constellation of small satellites with visible spectrum sensors may be cost effective support for JORN and AEW&C aircraft in the near future by providing a target identification capability for strategic and tactical applications.

Infrared Sensors

Infrared sensors provide lower resolutions than visible spectrum sensors but they have the ability to detect temperature differences in the field of view. This means that specific targets may be detectable from their infrared emissions. Low Earth orbit infrared sensors have the potential to detect hot body emissions from targets like aircraft and ship engines and exhausts. However, there is doubt in the sensor performance for detecting targets like these. The simulation of typical target emission profiles indicate that sensors will be range limited in the spectrum of interest other than intense target emission. Nevertheless, the inherent ability to detect specific targets from the background is worthwhile exploiting, particularly since it appears possible to implement on a small satellite platform.

Satellite Constellations

Most of the sensors examined have some fundamental need to operate from low altitudes and at these altitudes sensor coverage capabilities are limited. This indicates that a constellation of low Earth orbit satellites is needed to achieve the area coverage and revisit times required for tactical surveillance, and small satellites are the only likely option for Australia to implement in a constellation. For example, it has been demonstrated that the cost of a three satellite constellation would be about $A60m. In low inclination orbits a small constellation could provide significant coverage of North coastal region in reasonable weather.

Commercial Imagery

A commercial service option is inadequate for tactical surveillance since it cannot provide the data response required, but it can be useful for some strategic applications. ACRES imagery sales data suggests that the ADF purchases very little commercial imagery. By contrast, the US DoD is a major purchaser of global commercial imagery, even with all the surveillance and reconnaissance assets they have in their inventory.

Preferred Sensor Option

The space-based real aperture radar is the only sensor option that can conceptually provide wide area surveillance with adequate response for tactical applications, but implementation of this option will be costly and it is also not likely to be achievable for some time. However, staring infrared sensors may be able to provide these capabilities if sensor technology is adequate to detect emissions from the range of targets involved. Most of the other sensors are imaging types and for the most part they have inherent difficulties in rapidly detecting and tracking targets. These sensors have small fields of view and swath widths which limit their coverage capability. But, the small satellite visible and infrared options can provide low cost capabilities to address shortfalls in existing and planned surveillance capabilities.

Real aperture radar would need substantial allied support and it would duplicate much of JORN's capabilities anyway. Synthetic aperture radar can supplement JORN with a reasonable resolution imagery capability and the ability to detect slow moving ships, but at a cost of about $500,000 per satellite SAR is not likely to be adopted for use in constellation quantities. However, SAR would be useful in the long term with its all weather, day and night capability, particularly if costs can be reduced. Visible and infrared sensors in a constellation of small satellites appear to be capable of providing a limited but cost effective tactical and strategic imaging capability in support of JORN and other surveillance assets.

Overall this study indicates that wide area surveillance using satellites is not likely to be achievable for Australia in the 15 year time frame, but their long term potential is apparent. However, a low cost small satellite using a visible or infrared sensor option options can be justified and will provide a migration path to future sensors systems. A visible spectrum sensor is proposed as the first space-based surveillance capability for Australia because it offers a low risk and low cost option, and can directly support both civil and military requirements. Migration to a satellite constellation and a mix of sensors is needed in the longer term to allow all target characteristics to be exploited. This would include SAR, visible and infrared and multi-spectral sensors on a range of platforms.

Fusion

These conclusions indicate that there will always be a requirement for a range of assets to satisfy particular surveillance needs, and to provide the redundancy that is vital for systems used in key defence and security activities. In order to optimise the use of costly surveillance assets, it is vital to fuse sensor data into a comprehensive picture of Australia's threat environment. Surveillance data from JORN, AEW&C aircraft, P3C aircraft, Coastwatch operations, ground based assets and satellite sensors all need to be fused. Collaborative information from sources such as commercial remote sensing sensors, intelligence agencies, civil aircraft flight plans, shipping schedules, and personal visual observations would also be used. Command and control of forces can then be exercised based on a more complete surveillance scenario.

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CHAPTER 8

RECOMMENDATIONS

Surveillance is vital for Australia's long term security requirements, and space is recognised as the ideal location from which to observe all of Australia's vast area of interest. While a space-based capability is not likely to provide an entire surveillance solution, satellites are a cost effective way of providing some elements of the surveillance system. In the long term, space assets have the potential to be the dominate capability for wide area surveillance.

The following recommendations are offered in support of future space-based surveillance system development:

a. In the short term, the Government should pursue a co-operative program to develop a small satellite surveillance capability using a visible spectrum sensor, and this should be followed by infrared and multi-spectral sensor payloads.

b. In the long term, an indigenous small satellite development, production and launch capability is needed to support future surveillance and remote sensing needs, and it could also support future long distance communications needs.

c. Further research is recommended into potential applications of small satellites with visible and infrared sensors, to provide strategic and tactical information for civil and military use.

d. Research and modelling of line-of-sight visibility through clouds is required, for areas across the ADMI, to support investigations into surveillance using satellite-based electro-optical spectrum sensors.

e. Investigation of optimum satellite altitude, inclination and constellation configuration is needed to evaluate area coverage and revisit times for detection and tracking of targets in high priority areas of the ADMI.

f. Further research is required to confirm the capability of near-term infrared sensors for the detection and tracking of infrared emissions from aircraft and other targets of interest.

g. A short to medium term program is needed to develop the capability to fuse appropriate data from existing and planned surveillance sensors, and other collaborative data sources, to maintain a comprehensive picture of the sea, air and land threat environments.

h. A long-term program is required to develop and launch a space-based synthetic aperture radar capability for surveillance of Australia either by indigenous development or by co-operative effort with allied nations.

i. Commitment is required to maintain a watch on space-based real aperture radar developments, and to establish a long term program involving Australian scientists and engineers when the capability is being actively pursued by an allied nation.

j. The ADF should make increased use of commercial imagery available from existing commercial satellites.

ANNEX A

DETECTION OF INFRARED EMISSIONS FROM AIRCRAFT

This Annex estimates if infrared emissions from an aircraft engine are likely to be detected by a satellite sensor against background emissions from solar energy reflections and Earth infrared emissions.

Emission Characteristics:

1. Assume engine tailpipe at about 410 degrees C (B-52).
2. IR emission characteristic 320 W/ster @ 30 degree from longitudinal axis (B-52) - goes to about zero at 90 degrees.
3. IR emission of 10 W/ster for small jet aircraft engine.

MAXIMUM EMISSION WAVELENGTH

$T := 410 + 273$ Tailpipe temperature in Degrees Kelvin

$$L_{max} := \frac{2897.8}{T}$$

$L_{max} = 4.243$ um

** This lies mostly in the 3.4 - 4.2 um atmospheric transmission window **

Small satellite IR sensor has band pass from 3.4 - 4.2 um with HgCdTe detector which may provide detection capability

Assumptions

1. IFOV of sensor = 14.4m, therefore assume targets are point source emission wrt IFOV of sensor.
2. Assume IR emission from targets is constant in frequency band.

Background Energy Sources

1. Mainly diffuse reflections of sunlight moonlight/starlight.
2. Earth surface emission from body at about 30 degrees Celsius

REFLECTION OF DAYTIME SOLAR RADIATION: In the 3.4 - 4.2 um band

Ms = Exitance or power leaving sun in wavelength band

$T_s := 5800$ Approx. peak temperature of sun in degrees Kelvin

$$F_s(\lambda) := \exp\left[1.44 \cdot \frac{10^4}{\lambda \cdot T_s}\right]$$

$$M_s := \int_{3.4}^{4.2} 3.74 \cdot \frac{10^8}{\lambda^5 \cdot [F_s(\lambda) - 1]} d\lambda$$ in m
M in Watts/m^2 m

$$M_s = 4.223 \cdot 10^5$$

Irradiance at earth range from solar energy = Es

$R_s := 6.9 \cdot 10^8$ mean surface area of sun

$R_{eo} := 1.5 \cdot 10^{11}$ surface area of sphere with radius of 1AU in m^2

$$E_s := M_s \cdot 4 \cdot \pi \cdot \frac{{R_s}^2}{4 \cdot \pi \cdot {R_{eo}}^2}$$

$E_s = 8.935$ Watts/m^2 m

(Assume atmospheric reflectivity =0.6
due to clouds with Es incident on earth)

Reflected radiance - worst case reflected EM energy in window is at 3.4um.

$\rho := 0.6$

$$L_s := E_s \cdot \frac{\rho}{\pi}$$ diffuse reflection

$L_s = 1.706$ Watts/m^2 ster m

INFRARED EMISSION FROM EARTH SURFACE

Me = exitance of earth at temperature Te

$\varepsilon := 1$ Worst case emissivity

$T_e := 300$ Approx. average maximum temperature of earth in degrees Kelvin.

$$F_e(\lambda) := \exp\left[1.44 \cdot \frac{10^4}{\lambda \cdot T_e}\right]$$

$$M_e := \int_{3.4}^{4.2} 3.74 \cdot \frac{10^8}{\lambda^5 \cdot [F_e(\lambda) - 1]} d\lambda$$ in m
M in Watts/m^2 m

$M_e = 1.319$ Watts/m^2 m

Le = Radiance from earth by diffuse emission from surface.

$$L_e := \frac{M_e}{\pi}$$

$L_e = 0.42$ Watts/m^2 ster m

EMISSION FROM TARGET

$I := 320$ W/ster — Radiant Intensity @ 30 degree aspect from tail

$I := 10$ W/ster — For small jet aircraft

THERMAL DETECTOR COLLECTION OF INCIDENT ENERGY

Field of view of single detector in array

$x := 60$ — pointing angle from nadir to detect target

$\theta := x \cdot \frac{(2 \cdot \pi)}{360}$ — pointing angle in radians

$ALT := 700 \cdot 10^3$ — metres - altitude of satellite

$ANGLE_{fov} := \frac{14.4}{ALT}$ — radians

$IFOV := ALT \cdot \frac{ANGLE_{fov}}{\cos(\theta)}$ — IFOV at slant range to target

$AREA := IFOV^2$ — Area in FOV of single pixel @ slant range

$r := \frac{ALT}{\cos(\theta)}$ — Slant range to target from 700km @ 30 degrees from longitudinal axis

$\Omega := \frac{AREA}{r^2}$ — Sensor solid angle field of view in steradians

$\Omega = 4.232 \cdot 10^{-10}$ — Ster

Sensor output current - due to target

Constants:

$e := 1.6 \cdot 10^{-19}$ — coulombs - electron charge

$h := 6.63 \cdot 10^{-34}$ — joule sec

$c := 3 \cdot 10^{14}$ — um/s - speed of light

$S_a := 0.096$ — square metres sensor aperture area

$\tau := 0.4$ atmospheric transmission - worst case due to haze, pollutants etc

$\tau_o := 0.9$ transmission of optics

$\eta := 0.4$ detector efficiency of conversion photons to electrons

$$I_t := \left[\frac{e}{h \cdot c}\right] \cdot \frac{S_a}{r^2} \cdot \int_{3.4}^{4.2} I \cdot \tau \cdot \tau_o \cdot \eta \cdot \lambda \, d\lambda$$

$I_t = 5.519 \cdot 10^{-12}$ amps - current from detector

Sensor output current due to background

$\tau := 1.0$ worst case atmospheric transmission

$$I_b := \Omega \cdot \left[\frac{e}{h \cdot c}\right] \cdot S_a \cdot \int_{3.4}^{4.2} \left[L_e + L_s\right] \cdot \tau \cdot \tau_o \cdot \eta \cdot \lambda \, d\lambda$$

$I_b = 7.605 \cdot 10^{-11}$ amps - current from detector

SIGNAL TO NOISE RATIO CONSIDERATIONS

Assume: Backgound noise limited

Assume: Shot noise dominant

$I_{mean} := I_b$

$T_d := 294 \cdot 10^{-6}$ seconds - integration time for detector

$$I_{shot} := \left[e \cdot \frac{I_{mean}}{T_d}\right]^{.5}$$

$I_{shot} = 2.034 \cdot 10^{-13}$ amps

Total noise current

$$I_{rms} := \left[I_b^2 + I_{shot}^2 - I_{mean}^2\right]^{0.5}$$

$I_{rms} = 2.034 \cdot 10^{-13}$ amps

Signal to Noise Ratio

$$SNR := \frac{I_t}{I_{rms}}$$

Therefore: $SNR = 27.13$ for 320 W/ster target

$SNR = 3.4$ for 10W/ster target - nadir pointing

CONCLUSION

1. These estimates indicate that the B-52 intensity emissions should be easily detectable at 700 km and another iteration not shown indicates that it may be possible to detect this intensity emission out to about 5500 km altitude. This corresponds to a maximum range of 11,000 km in this example due to the need to be pointing less that 30 degrees off the longitudinal axis of the aircraft (or 60 degrees from nadir), at the tailpipe source.

2. The small aircraft emissions should be detectable at only 700 km altitude when viewed at nadir.

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