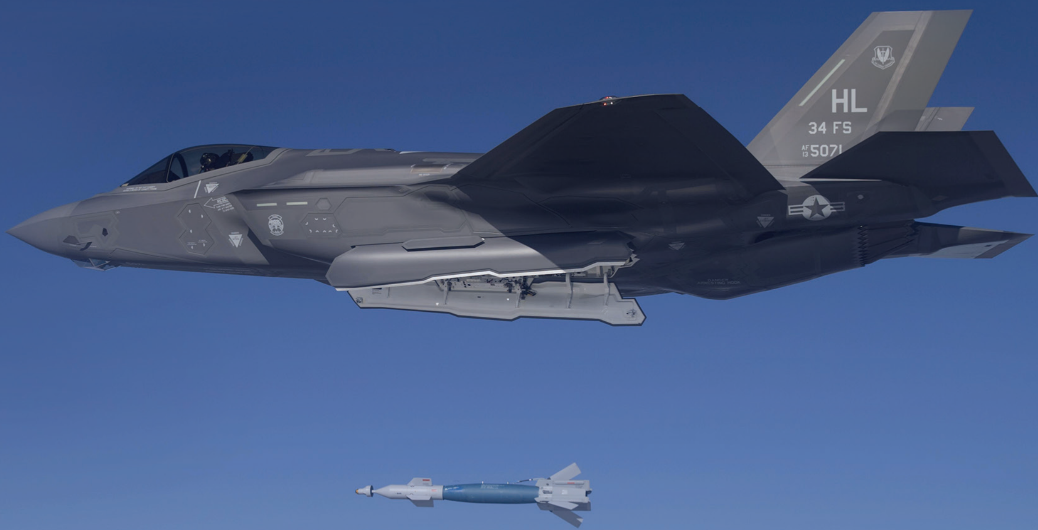
Dragon's Jaw

The Vietnam War target that paved the way to a modern precision air weapon



Michael Spencer

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The Vietnam War target that paved the way to a modern precision air weapon

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Cover Image

US F-35 flight-testing to certify the air delivery of a Laser Guided Bomb (LGB), an integrated air strike capability that is now in RAAF operational service; the first generation LGB was developed during the Vietnam War 1967 to 1972.

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Wing Commander Michael Spencer is an Officer Aviation (Maritime Patrol & Response), currently serving in the Air Power Development Centre, analysing potential risks and opportunities posed by technology change drivers and disruptions to the future employment of air and space power. He gained his operational flying experiences with No 10 Squadron as aircrew on the P-3C Orion long-range maritime patrol aircraft. He has been posted separately as both a student and instructor of the RAAF General Duties Weapons Systems Course at the RAAF School of Air Navigation. Additionally, he has also managed the development and acquisitions of air-launched guided weapons.

He is the first Australian graduate of the Royal Thai Air Force Air Command and Staff College, an Australian Institute of Project Management certified project manager, and an Associate Fellow of the American Institute of Aeronautics & Astronautics. He has completed postgraduate studies in aerospace systems, aircraft weapons systems and weaponeering, information technology, project management, space mission systems, and astrophysics. His APDC publications include:

- Pathfinder #147: Weapons in Space (2010)
- Beyond the Planned Air Force (2017)
- BPAF Series: Hypersonic Air Power (co-author, 2017)
- AFDN 1-19 Air-Space Integration (2018)
- MQ-4C Triton: A Fifth Generation Air Force Disruption of Maritime Surveillance (co-author, 2019)
- Pseudosatellites: Disrupting Air Power Impermanence (2019)

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Foreword

WGCDR Spencer has written this working paper to review a historical example of a disruption to the effectiveness of combat air missions that motivated the necessary pursuit of operational innovation and technical inventions to overcome adversity and to provide lessons that remain applicable today.

This paper looks at how the United States missions to destroy the Thanh Hoa Bridge in the Vietnam War forced their air combat planners to think more critically and systematically about new ways to attack the bridge with available resources. It also looks at how the combat aircrew had to innovate their mission plans to improve on their constant mission failures.

The paper uses these examples of new methods and innovations to demonstrate the evolution of tactical strike missions from a cockpit based individual efforts of aircrew to aim dumb bombs at a target, through team efforts of groups of weaponeers, engineers, targeteers, scientists, operations analysts and aircrew that led to successfully using precision guided munitions. It discusses how these smart teams used an adaptive and iteratively learning approach that was more efficient and economical to methods that are still prevalent today in modern air operations.

I would like to thank WGCDR Spencer for his efforts on this working paper and the prolific effort he has taken this year in producing a high number of quality products for the Air Power Development centre. I hope you enjoy reading this paper and find some lessons from the past that might make valuable contributions to future projects.

Andrew Gilbert
Group Captain
Director
Air Power Development Centre

August 2019

Contents

A Strike Pilot's Perspective

I began my RAAF career in the early 1980's flying F-111Cs and training to deliver "dumb" ballistic 500 lbs and 2000 lbs general purpose bombs. We did this using a variety of methods and sensors including manual visual bombing, using the lead computing optical sight, or computed radar deliveries, using the attack radar aiming system and a bomb/navigation computer. The most accurate deliveries were generally achieved at low level using manual visual bombing and the bomb/nav computer derived Continuously Computed Impact Point (CCIP).

Both of these radar aimed and visual bombing methods had significant limitations and required pilots to achieve and hold specific and strict performance parameters, for height and speed, in order to successfully deliver the weapon where you were aiming and even then the achieved accuracy was generally poor (unless you were a "gun" pilot or navigator). With the advent of modern defences, this would also place you well inside the engagement envelope for most short range air defence (SHORAD) systems whilst you were required to fly straight and level for a period of time during the weapons releases.

Prior to my second flying tour on the mighty pig, the F-111 weapon/navigation system had been upgraded with the Pave Tack targeting pod. The new Pave Tack system provided a much more accurate electro-optic acquisition and aiming system and, with the laser targeting system, enabled the use of the new Paveway series of weapons, GBU-10 (2000lbs) and GBU-12 (500lb) laser guided bombs. Instead of flying constrained to hold specific parameters, the Pave Tack system with the Paveway weapons gave the pilot more freedom to manoeuvre the aircraft in the attack run; I now only had to deliver the weapons into the acquisition "bucket" so that the Paveway system on the weapon could itself acquire the reflected laser energy and "ride the beam" to the target.

Paveway was not only more accurate but allowed the aircrew to manoeuvre the aircraft or remain at high altitude whilst still achieving the necessary parameters for assuring accurate weapon deliveries. From a pilot's perspective, putting us outside of the air defence systems, or making us a much more difficult target for SHORAD systems– is a much better option!

AVM (retd) Mark 'Skates' Skidmore AM
RAAF RF/F-111C and Test Pilot

A Strike/Recce Navigator's Perspective

As a RAAF veteran navigator assigned to fly RF/F-111C in the reconnaissance and strike roles it was immediately obvious the advantage that Laser Guided Bombs and the PAVETACK laser designation system gave to strike operations.

When flying into harm's way, great effort was made to ingress undetected, and strike and depart threat envelopes before being detected or engaged. The concept of having to re-attack, and re-attack again was a nightmare scenario, eroding both chance of success, and chance of survival.

The art of weaponeering was advanced and the Joint Effectiveness Munitions Manuals provided probabilities of success in attacks based on the weapon's effect (blast and fragmentation damage) against a miss distance. Simply put, the further you missed the target by, the less the likelihood of damaging it.

The capability to accurately deliver a weapon within metres of the aimpoint—as opposed to tens of metres—took military aviation and strike missions from requiring multiple aircraft, sorties or munitions, to 'one bomb, one target'. Further refinement, with GPS precision guided weapons, allow us to plan one airframe to carry multiple weapons and engage multiple discrete targets.

Apart from the obvious self-interest, the mantra of 'fly fast; get the job done; get out. Bring you, your mate and your machine home' had an attractiveness to military planners, in that as the strike aircraft became more complex and more expensive, fleet sizes became smaller. It was barely sustainable for RAF No 460 SQN to lose five Lancaster bombers and RAAF crews in a single night in December 1943, and again in May 1944. The total losses from these two World War II missions equated to about half the RAAF F-111C fleet; truly unsustainable.

The development of precision guided munitions has allowed us to dominate the battlespace when unopposed. Indeed, it also allowed us to achieve greater effects whilst minimising harm to civilian populations.

Continuing self-analysis and innovation are essential to allow us to continue to influence the battlespace and be successful in future operations. The evolution of 'smart' weapons was not an accidental discovery, it was the work of enormous operational analysis and the application of concepts from scientific discoveries. I commend this book for its exploration of what was one of the great air power breakthroughs in the strike role.

David 'Doc' Millar
RAAF RF/F-111C Navigator

A Legal Officer's Perspective

The development and integration of smart cockpits, the smart team and smart weapons, not only enhanced operational effectiveness, but also increased the capacity to avoid or at least reduce the unintended incidental effects that flow from inaccurate munition delivery (actual or prospective in the case, for instance, of using larger munitions to account for expected inaccuracy). In this context, these developments during the Vietnam War and, most particularly, the transition of PGMs from a niche and very limited capability into a more ubiquitous element of the inventory, has had significant legal consequences.

As part of international law, the law of armed conflict (LOAC) regulates the methods and means of warfare. With respect to targeting, LOAC prescribes the precautions to be taken to avoid causing death and injury to protected persons (including civilians) and protected objects (e.g. civilian objects). Under LOAC, it is through the lens of 'precautions in attack' that the developments in Australian targeting capabilities are viewed.

LOAC requires those controlling an attack to 'take all feasible precautions in the choice of means and methods of attack with a view to avoiding, and in any event to minimizing, incidental loss of civilian life, injury to civilians and damage to civilian objects' (Article 57(2)(a)(ii) of Additional Protocol I of 1977, reflecting the underlying law applicable to all nations, including during the Vietnam War). The developments in targeting technology and methodology are obviously relevant to the application of this test. Most importantly, if you possess a capability that when used could reduce the incidental effects, the question arises whether it is a 'feasible precaution' you are legally obliged to take.

In this context, it would be wrong to say that the development of targeting capabilities, particularly PGMs, changed the law: the test under the law was ready to account for such developments and will continue to account for future developments. Nor did such developments make it 'easier' to comply with the law: the strict legal burden expands and contracts to cover whatever 'feasible precautions' are available.

The law, however, requires that decision-makers consider their extant technical capability to reduce certain unintended effects, as a factor when choosing if, how and when to launch an attack. Accounting for such capability as a factor is, however, different to assuming that as matter of legal obligation a capability must be used in every case.

In short, non-PGMs have not been outlawed and the existence of PGMs in an inventory does not mean that they must always be used, even in circumstances where non-PGMs may cause collateral effects. Weapon choice remains a command decision, with that choice guided by the application of the LOAC principles of military necessity, the avoidance of unnecessary suffering and proportionality. Nevertheless, nations understand that any targeting activity must be explicable through the frame of 'feasible precautions' and this will include accounting for the choice of weapon, if not the application of other targeting technologies and capabilities. Moreover, as a matter of policy a nation may choose to limit its actions, including choice of weapons, beyond that which is required by the law.

The development of smart weapon systems such as Paveway/Pave-Tack also provides greater flexibility (over a 'dumb' bomb) with respect to aircraft altitude and manoeuvring while still maintaining the accuracy of the munition's delivery. Whether delivering smart or dumb munitions, the security of the attacking force is a factor that is relevant in the assessment of the 'feasible precautions' required in a particular case. Nevertheless, it is worth emphasising that these kinds of developments provide additional scope to preserve the force, if not achieve other kinds of legitimate military advantage, while still complying with the obligation to take 'feasible precautions'.

So, when considering new capabilities that were developed and employed by the US to strike the Thanh Hóa bridge more effectively, it is worth recalling the wider ramifications of those capabilities, including in the legal sphere. The advent of smart munitions and other capabilities did not change the law, but potentially caused a significant change in how militaries – Air Forces' in particular – were able to operate and comply with the law.

AIRCDRE (retd) Chris Hanna CSC and Bar
RAAF Legal Officer

KNEEPAD EXECUTIVE SUMMARY

Early in the Vietnam War, the US identified 27 infrastructure targets as critical to North Vietnamese efforts to support its warfighting in South Vietnam. Using visually delivered ballistic bombs, the first US strike aircraft missions successfully destroyed 26 of these 27 nominated targets.

The 27th target was the Thanh Hóa bridge (aka "Dragon's Jaw"), an over-engineered bridge that continued to challenge US air power whilst the North Vietnamese continued to repair and use this vital infrastructure link to sustain its warfighting.

This well-defended bridge would continue to challenge mission planners, aircrew, and weapons designers to evolve their strike mission systems over the war years from 1967 until a strike mission finally collapsed the bridge in 1972.

The mission objective that was the Dragon's Jaw drove innovative changes in US strike mission systems. Air strikes began with the integration of smart cockpits and dumb bombs, stepped through an evolution of integrated smart cockpits with new smart precision guided munitions.

The final evolution that successfully dropped the Dragon's Jaw was the integration of a smart team using statistics-based weaponeering and mission planning, smart cockpit, and smart weapons: the beginning of a longstanding approach for strike mission planning that continues to be used today.

"At long last, after seven years, 871 sorties, tremendous expenditure in lives, 11 lost aircraft, and a bewildering array of expended munitions, the Dragon's Jaw was finally broken."

W Boyne, Historian and veteran
USAF combat pilot[1]

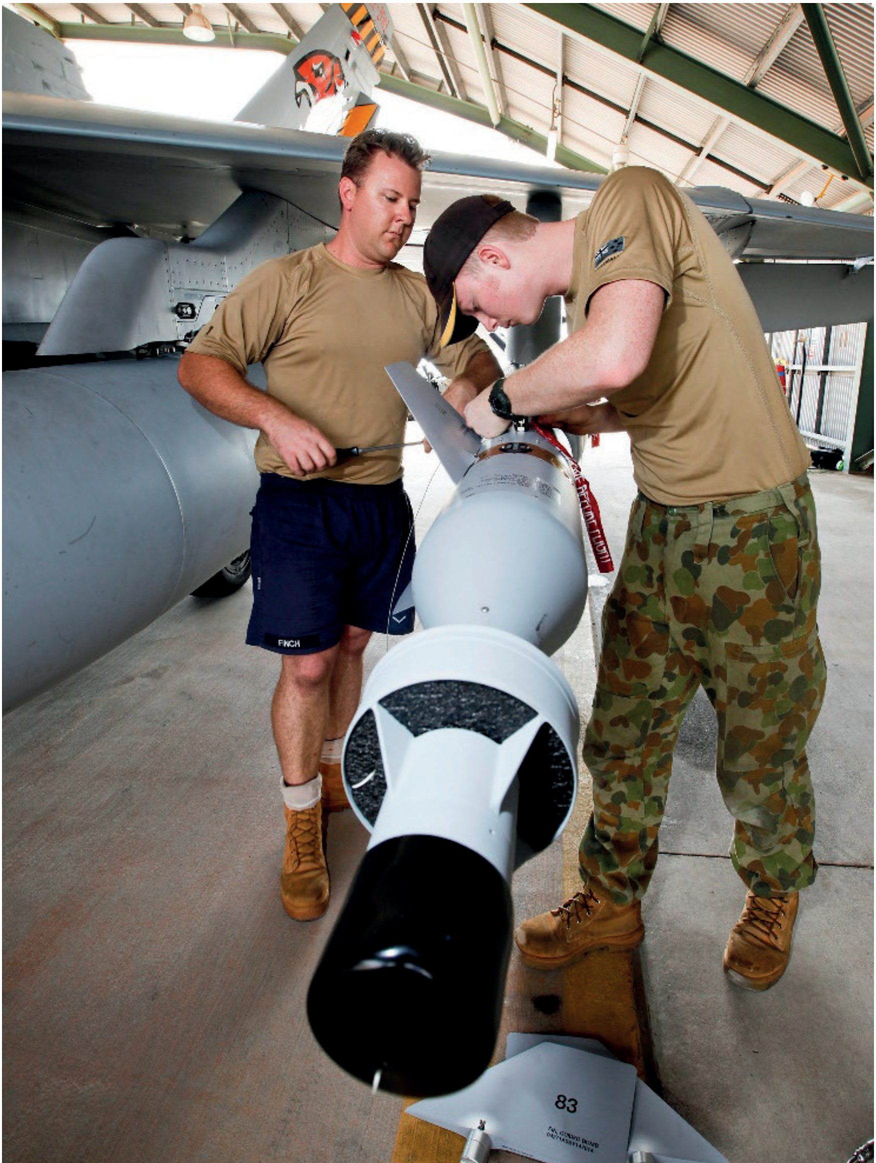

Figure 1. Armament Fitters configure a Paveway IV GBU-54 Laser JDAM[2] on a RAAF F/A-18 Hornet; Paveway I was first developed for use against the "Dragons' Jaw", a key strategic infrastructure target in the Vietnam War.

Introduction

The Air Force air weapons inventory includes the GBU-54 Laser JDAM. The GBU-54 is a Mk 82-series General Purpose 500 lbs bomb configured as a Paveway IV with a dual-mode, Laser JDAM GPS/INS precision guidance and control kit, that enables the munition to be autonomously (GPS) or semi-autonomously (laser) guided more accurately along its freefall trajectory to its designated surface target. The Paveway family of laser guidance and control fin kits has its origins in the Vietnam War, when US Air Force and Navy aircrew, tactics and weapons were failing to bring down one well-engineered and heavily defended bridge that was identified as a key strategic road and rail infrastructure target, and nicknamed the "Dragon's Jaw."

The bridge was a prominent target in the US strategy to interdict the North Vietnamese lines of communication for moving men and war materiel to the battlefields in South Vietnam. The Dragon's Jaw challenged tacticians, weapons designers, mission planners, and aircrew during 1967 to 1972. The mission objective to destroy the Dragon's Jaw would become an operational requirement to drive the rapid development of innovative new ways for US aircrew to conduct effective air strike missions against well-defended and hardened targets.

The "Dragon's Jaw"

The Thanh Hóa Railroad and Highway Bridge, built over the Song Ma river near the geographical centre of North Vietnam, was nicknamed by North Vietnamese as "Hàm Rong"—which translates to "Dragon's Jaw"—since its massive steel and concrete construction gave the appearance of a row of sturdy teeth set in the mouth of a deadly dragon.[3] The French built the first bridge during the colonial era and, in 1945, Viet Minh guerrillas destroyed it by detonating two TNT-laden locomotives together at the midpoint of the bridge. Vietnamese engineering and labour replaced the bridge in 1964 with a 540-foot long span, 56-foot width, and 50-foot height, and it was officially opened by Ho Chi Minh.[4] Fortuitously, it was over over-architected and over-engineered for the war that came.

Figure 2. The Thanh Hóa Bridge was strategically significant for the North Vietnamese movements of men and war material to their operations in South Vietnam.[5]

US strategists identified the Dragon's Jaw as a vital infrastructure link that enabled road and rail traffic access to different regions of North Vietnam and became strategically significant for assuring supplies, communications, and reinforcements for Viet Cong operations in South Vietnam. It was a funnel for sending men and war materiel to the battlefields in South Vietnam, and probably analogous to a dragon's powerful bite into the enemy it was facing towards in the south. Throughout history, there have been targets that have been notably reluctant to fall. The Thanh Hóa Bridge is prominent in air war history because it proved to be one of the most challenging targets to successfully withstand the might of US air combat power for most of the Vietnam War.

Over-designed and over-engineered in its construction, it was well-defended by a concentration of accurately operated air defence systems with anti-aircraft artillery, surface-to-air missiles, and MiG-17 fighter interceptors. The US military strategists drove a mission requirement to strike the Thanh Hóa Bridge with air-delivered weapons, using enough ordnance to collapse the Dragon's Jaw, to keep it out of service permanently and interdict the north-south supply and communications line.

Smart Cockpit & Dumb Weapons

Air strikes flown by USAF single-seat fighter aircraft were the preferred option against the bridge, over high-altitude strategic bombardment. Small US fighters, like the F-105 "Thud" Thunderchiefs and F-4 Phantoms, were tasked to speedily fight their way through the enemy ground-based air defences and MiG-17 fighter interceptors to infiltrate the target. It was at this point that they could visually deliver their freefalling unguided bombs and manually steered short-range Bullpup air-to-ground missiles.

The baseline inventory of air-delivered weapons that were available at the start of this air weapons innovation trail, commenced with the following weapons:

1. Mk 82 (500 lbs), M-117 (750 lbs), and Mk 84 (2000 lbs) conventional unguided ballistic freefall General Purpose (GP) bombs.
2. AGM-12C Bullpup short-range air-to-ground missile. A rocket that propelled a 250 lbs explosive warhead. The pilot controlled the missile trajectory by observing a flare ignited in the rear of the missile and manually operating a joystick to send radio commands for steering corrections (ie Manual Command to Line-of-Sight), while steering the aircraft.

With the types of USAF air weapons technology that were available, hindsight could be used to describe the mission system as being comprised of a "smart cockpit & dumb weapons". This description highlights that the main 'smart' effort and workload in acquiring and attacking the target is performed by the pilot in the cockpit. The pilot needed to succeed in flying the weapons delivery aircraft through the enemy air defences, find and acquire the target, and then calculate and perform the necessary actions to deliver the 'dumb' weapon onto a trajectory that impacts the target. These baseline weapons are regarded as being 'dumb' because they are totally dependent on the aircrew to determine the target, calculate the release point and trajectory, and where possible, manually determine and execute corrections to trajectory errors.

The USAF planned Operation ROLLING THUNDER to conduct air strikes against targets in North Vietnam.[6] The first swipe at the Dragon's Jaw was conducted in April 1965 by a US strike package comprised of 79 strike aircraft accompanied by 21 fighter escorts, two reconnaissance aircraft, and ten air-to-air refuelling aircraft. The strike package elements that made it to the target, collectively delivered 32 Bullpup missiles and 120 M-117 bombs, resulting in numerous hits against the bridge. The US strike package suffered many aircraft losses with a number of downed aircrew ending up as Prisoners-of-War for the remainder of the war.[7]

The USAF post-mission analysis of this first attack showed that the strike mission did not succeed in bringing down the bridge, and that it had survived and continued to be used as a key supply line by North Vietnamese forces. US mission planners ordered that a second strike be conducted on the next day, with strike reports indicating that the aircraft had successfully delivered over 300 individual munitions onto the bridge target. However, the post-mission battle damage assessment showed that the Dragon's Jaw remained standing and continued to be usable.[8] The air weapon effort planning team on the US headquarters staff were disappointed and disturbed that the bridge had not fallen; the bridge had been architecturally overbuilt[9]. By May 1967, a total of 27 North Vietnamese bridges had been attacked by US forces and 26 had been successfully destroyed – only the Dragon's Jaw remained standing and it had taken its toll of US aircrew using their 750 lbs GP bombs and 250 lbs Bullpup missiles.[10] The combination of rugged physical structure, and an accurately firing integrated air defence weapons system situated on the surrounding hills, made it obvious that a new, more survivable, and far more powerful kinetic effect was needed.

Mission elements needed new and innovative solutions to deliver a greater kinetic effect with a better economy of effort, survivability, and probability of mission success. A journey of innovation eventually developed a capability to modify an existing inventory weapon into a cost-effective precision guided munition The eventual realisation of the Paveway I laser guided bomb modification kit would coincide with the introduction of more effective weapon effort planning and calculation methods to better quantify mission requirement for the delivery of precision kinetic effects.

The manual delivery of the unguided GP bombs by pilots simultaneously contending with the ground-based air defences and the MiG interceptors, led to a high stress workload in the cockpit that resulted in unexpected aircraft attrition and poor attack results. The USAF/USN operationalised the Bullpup missile as their first tactical guided air-to-surface missile in their air weapons inventory, to provide some standoff from the ground-based air defences and improve the accuracy of the weapon impact. However, the standoff range was too short against the enemy air defences and, once again, the demands of the manually operated missile when under fire, would have resulted in a high stress workload on the single pilot, degrading the mission survivability and attack effectiveness. Additionally, the single unitary 250 lbs warhead was inadequate to inflict the necessary damage at the target.

After repeated air missions had failed to achieve the desired damage, a new innovative approach to using tactical air power against the Dragon's Jaw was sought by US air mission planners. One approach to remediate the mission effectiveness was to address the inadequacy of the warhead size and explosive quantities in the air-delivered ordnance. Since the air weapons available in the inventory did not have a large enough explosive warhead, deemed necessary for the desired damage, US Air Force sought research into new options for delivering a significantly larger unitary warhead to a unitary hardened target.

Smart Cockpit & Smart Weapons

Military researchers pursued innovative options and technology to provide some relief to the aircrew workload in the cockpit, and used technology to transfer some of the work effort needed to manage a weapon attack, from the cockpit to the weapon. Technology options were sought to relieve the pilot and mechanically perform some of the functions in the execution of the attack (eg accurately delivering the warhead to the target, guidance to a target vulnerability, sensing target proximity, and fuze functioning for detonating the warhead, etc). This was the beginning of "smart weapons" that were designed to interact with the target and function independently, to the relief of aircrew managing the mixed cockpit priorities of wanting to survive against enemy air defences whilst assuring the success of their mission.

The US Air Force Armament Laboratory considered this problem and proposed seeking an innovative large high-explosive solution. The fundamental design premise was to deliver a 4000 lbs high-explosive unitary warhead, scientifically calculated as necessary for a single weapon to deliver the knockout blow with enough punch to break the Dragon's Jaw. In order to relieve the aircrew from needing to fly close to the target to deliver the munition, it would be air-dropped into the river, at a position upstream from the target, and use the river current to float to the target. The munition was designed with a "smart" sensor to itself determine when it was passing beneath the bridge structure and automatically initiate the warhead.

Under Operation CAROLINA MOON, the Air Force research team devised a floating magnetic mine to attack the bridge. A 4000 lbs unitary warhead was configured as a focused-warhead or self-forging fragment that would concentrate the explosive effect to travel in an upward direction from a floating base. The 5000 lbs floating mine would be deployed upriver from the bridge and use magnetic (primary) and infrared optical (secondary) sensors to detonate the warhead when they detected they were passing beneath the metal bridge structure. The only aircraft available and capable of delivering the 5000 lbs floating mine was the C-130 Hercules, using a low-altitude parachute extraction technique.[11]

In May 1966, a USAF C-130 Hercules conducted its airdrop missions at night and at low-altitude, with fighter escorts, to deliver the bridge-busting floating mines developed under Operation CAROLINA MOON.

In the first mission, the C-130 successfully deployed its load of five floating mines and they functioned correctly under the bridge. However, post-attack reconnaissance photos did not show any significant damage to the bridge.

The US air mission planners immediately ordered another floating mine attack on the next day and told the crew to release the remaining bombs closer to the bridge. However, flying closer to the Dragon's Jaw also meant flying inside the effective engagement ranges of the enemy anti-aircraft guns and missiles, after they had been alerted and seen the air tactics in the previous day's attack. The North Vietnamese shot down the C-130 and the deployed floating mine failed to function correctly.[12] It was an innovative approach, to increase the quantity of high-explosive delivered to a single point on the target, but the innovation in weapon design led to a failure in the tactics to deploy a large and slow aircraft against an alerted enemy air defence system. The bridge was not significantly damaged by the attack; USAF cancelled Operation CAROLINA MOON.

The Dragon's Jaw remained on the strike targets list. The US needed a new direction in innovative weapons design to improve the standoff range, precision accuracy, and damage mechanism to succeed against the over-architected and well-defended bridge. The standoff range and warhead size of the USAF/USN inventory AGM-12C Bullpup had proven to be unsuitable for the stress burden placed on the pilots to guide the weapon whilst they were exposed and vulnerable to the enemy's short-range air defence systems. A new operational requirement for better standoff and survivability led to the development of the AGM-62 Walleye family of TV-guided glide bombs for USAF and USN strike aircrew.

1. **AGM-62 Walleye I** was an electro-optical TV-guided glide bomb configured with a 250 lbs warhead.
2. **AGM-62 Walleye II** was a follow-on development to improve Walleye with a 1900 lbs warhead and a longer glide trajectory for aircrew to standoff further from enemy air defences.

The aircrew received seeker imagery via datalink system in order to define and lock the aimpoint feature on the TV view of the target; the munition automatically made flight controls to optimise its glide trajectory to the target. Although Walleye could achieve good mission results in good weather conditions, the performance of the electro-optical seeker was degraded in tropical weather and night conditions, as the reduced contrast made it difficult for operators to discriminate the target. Walleye I was eventually deemed by the aircrew to be too costly, and the warhead too small, to be effective against a hardened target like the bridge.

US Air Force and Navy aircrew persisted with strike missions against the Dragon's Jaws, using available precision guided munitions, albeit without success. US strike munitions against the bridge ceased in 1968 when the US government agreed to halt air strikes against North Vietnam sites in order to facilitate discussions with North Vietnam for peace negotiations.[13] Although there was a pause in US strike operations, US weapons engineers continued to innovate new designs with emerging technology to improve weapons delivery techniques, aircrew workload and survivability, weapons effects, and mission success. This operational pause in US bombing operations ceased in 1972 when peace negotiations had failed and the US decided to resume the air strike campaign under Operation LINEBACKER.

Smart Team & Smart Weapons

Also occurring in the background, behind the air mission planning teams, was the maturation of the operational art of weaponeering to exploit scientific-based analyses and mathematics in weapon effort planning or weaponeering – defined by the US DoD as *"the process of determining the specific means required to create a desired effect on a given target".*[14] This initiative was to provide a robust scientific basis to improve the quality of mission planning by using analyses of target vulnerabilities and matching them to the measurable effects from available weapons, and statistically determine a recommended size of a force, including the numbers of weapons, needed to achieve different levels and types of damage at the target.[15]

US Defense established the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) to manage a number working groups to focus on different subject areas: Target Vulnerability, Chemical and Biological, and the original Air-to-Surface (JMEM/AS) Group. By 1967, the JTCG/ME was concerned not only with deriving or validating data by tests, experiments, and mathematical models, but also from direct inputs of data from the battlefield.[16] The introduction of JMEM/AS planning guidance significantly enhanced the quality of force estimations, mission viability testing, and mission planning and continue to be in use today.

In 1968, the US Air Force conducted testing and evaluation of the newly developed Texas Instruments BOLT-117 (ie BOmb, Laser Terminal) based on using a "bolt on" kit to transform a conventional GP bomb into the world's first Laser Guided Bomb (LGB). The design philosophy behind this newly innovated munition was based on keeping the project cost low by recycling parts, where possible, from other inventory weapons, except for the new laser seeker head.[17]

- **Laser Guided Bomb**. The Texas Instruments BOLT-117 kit (later redesignated by USAF as GBU-1) used the KMU-342 laser guidance and control unit; the warhead was a standard M-117 750 lbs GP bomb; the guidance system and control fins were adapted from the AGM-45 Shrike missile.

- **Laser Target Designator.** The original concept was to deploy the LGBs and laser designator in different aircraft with the first aircraft releasing the LGB, one at a time, to automatically guide itself to the target that was manually illuminated by the laser operator in the second aircraft.
- **Weapon Delivery Aircraft.** F-4 Phantoms crewed with a pilot and Weapons System Operator (WSO) seated in the rear cockpit.

The prototype laser illuminator, designed for a WSO to manually sight and steer the laser beam, was an innovation of local USAF engineers. The engineers adapted a hand-operated laser designator and mounted it inside the left canopy rail of the rear cockpit of the F-4 Phantom. The laser illuminator was fondly nicknamed the "Zot" for "the sound effect for the lightning-fast thrust of the anteater's tongue in the comic strip 'B.C.'"[18]. During flight trials and evaluations, WSOs experienced problems in keeping the hand-pointed laser steady on the target continuously and for long enough, whilst the aircraft was manoeuvring in the attack, in order to assure adequate illumination for the LGB laser seeker to lock on.

Before operationalising the new F-4 precision strike capability, USAF engineers responded to the problems experienced by the WSOs and developed "PAVE KNIFE".[19] PAVE KNIFE was a laser designator installed into a wing-mounted pod, to replace the Zot. The pod laser was mounted on a gyro-stabilised gimbal that automatically swivelled to keep the laser pointing at the selected ground target. The WSO was relieved of the burden of manually pointing the laser through the port side of the cockpit and the aircraft no longer was constrained to fly orbits to keep the cockpit-mounted laser pointing at the target, which made the designating aircraft vulnerable to enemy air defences during the attack.

When the US air strike campaign was resumed under Operation LINEBACKER, The first LGB attack was conducted against the Dragon's Jaw in April 1972, using both Walleye II and PAVE KNIFE-guided GBU-1s. Adverse weather conditions disrupted the electro-optical guidance and the laser designation at the target. The Walleye missiles did some damage but, once again, the air strike had failed to achieve the mission objective. The air mission planners recommended a re-attack mission.

Figure 3. LGB strikes a target on the range during early US flight trials.[20]

The delay in planning the follow-on mission would have enabled some robust weapon effort planning and force estimations using the newly developed JMEM/AS data and methodologies to estimate appropriate force sizes and weapons numbers, and recommend an appropriate aimpoint on the bridge structure. The weapon effort planning results would have helped to support the recommendation to replace the GBU-1, and its 750 lbs warhead, and modify Mk 84 2000 lbs bombs into GBU-10 LGBs, a capability still commonly in use today by many air forces around the world.

The re-attack mission was planned in May 1972 with 14 USAF F-4 Phantoms configured with Pave Knife and 2,000 lbs and 3,000 lbs LGBs. The strike aircraft struck the bridge multiple times and rendered it unusable. The F-4s aircrew had successfully attacked the bridge with 26 air-delivered LGBs and the Dragon's Jaw was finally toppled. USN carrierborne aircraft continued with strike missions throughout 1972 in order to delay any bridge repair efforts and movements by North Vietnamese forces.

The Dragon's Jaws stayed collapsed until after the cessation of the war in 1973.

Conclusion

Air missions conducted in conflict and war are proving grounds for validating the effectiveness of mission plans, aircrew, technology and tactics. The anticipation and the experience of failures drives a necessary process of review and remediation in observed shortfalls in capabilities. The weapons innovation trails depicted here for the development and realisation of the Paveway I capabilities provide a useful historical account of change drivers and change management in the development, adaption, adoption, and operationalisation of the first LGB.

The new team combination approach of adapting and integrating the "smarts" from deliberate weapon effort planning, "smart cockpit" operations expanded by the pilot and WSO combination, and the development of "smart" munitions had finally delivered a mission to overwhelm the Thanh Hóa Bridge – a long-time benchmark that tested the effectiveness of previous US air strike capabilities to their failures.

The first USAF air strikes were conducted in 1965 and were unsuccessful in dropping the bridge span. US air forces continued to conduct air strikes with evolving weapons and tactics, and finally destroyed the bridge in 1972.

Annex: PAVEWAY Generations

LASER GUIDED BOMBS

The modular designed LGB kit is a low-cost approach to modify an existing inventory air-delivered unguided general-purpose bomb into a precision guided munition guided by a semi-active laser seeker, with flight controlled by pneumatically driven canard fins, and warhead actuated by a programmable fuze.

HISTORICAL PAVEWAY

Original "PAVEWAY" was used to describe the following new guided weapons:

- **PAVEWAY 1** was the first laser-guided bomb.
- **PAVEWAY 2** was an electro-optical (TV) guided munition HOBO (ie "Homing Bomb") that was operationalised and used in combat by US air forces.
- **PAVEWAY 3** was an infrared homing seeker (not operationalised).

MODERN PAVEWAY

The modernisation of the LGB development programs resulted in the following revised nomenclature for Paveway LGBs:

- **PAVEWAY I** LGBs used a semi-active laser seeker and pneumatically controlled canards to guide the Mk 82 500 lbs GP bomb or M-117 GP bomb; bombs were configured with a bolt-on tail section with fixed fins. The canard fins operated with "bang-bang" movements (eg hard up or hard down) in response to any error corrections needed by the guidance and control unit.
- **PAVEWAY II** LGBs feature an enhanced but also simpler and cheaper seeker head. Configured for use with Mk 80-series GP bombs, BLU-109 penetrator; bombs were configured with folding pop-out fins to improve the weapon's glide characteristics and make it easier to fit to the launch

aircraft. The canard fins moved in proportional response to any error corrections needed by the guidance and control unit.

- **Enhanced PAVEWAY II** features a GPS-aided Inertial Navigation System and a laser guidance system for employment in all weather conditions.
- **PAVEWAY II Enhanced Laser Guided Training Round** (ELGTR). ELGTR is an air-delivered laser guided training round used to train aircrew to employ GBU-10/12/16 LGBs.
- **PAVEWAY II Plus** is a lightweight LGB kit capable of guiding the Mk 82 (500 lbs), Mk 83 (1000 lbs), Mk 84 (2000 lbs) and BLU-109 (2000 lbs penetrator) warheads for both training and tactical applications.

- **PAVEWAY III** Low Level LGB (LLLGB) is an enhanced development of PAVEWAY II and designed for low altitude toss and off-axis delivery, improved standoff capability, and midcourse guidance that allows for delayed laser-designating and trajectory shaping.
- **PAVEWAY IV** a dual mode GPS/INS and laser-guided bomb.

LASER TARGET DESIGNATORS

The gyro-stabilised laser target designators are installed into aerodynamic wing-mounted or bomb-bay pods, that are bore-sighted to be aligned and steered by other onboard TV and/or infrared sensor systems operated by the navigator or weapons systems operator in the cockpit or a Joint Terminal Attack Controller in a ground location with line-of-sight to the target and communications with the strike aircraft.

- **PAVE KNIFE** pod, developed during the Vietnam War is a small daytime-use only laser designator.
- **PAVE SPIKE** pod flown on F-4s at the very end of the Vietnam War, and later the much more capable, day and night capable version.
- **PAVE TACK** pod, was first used on USAF F-4 Phantoms and also configured into a semi-recessed design of the RAAF F-111 internal bomb-bay.

Glossary

AGM	Air-to-Ground Missile
BOLT	Bomb, Laser Terminal
BPAF	Beyond the Planned Air Force
ELGTR	Enhanced Laser Guided Training Round
GBU	Guided Bomb Unit
GPS	Global Positioning System
HOBO	Homing Bomb
INS	Inertial Navigation System
JDAM	Joint Direct Attack Munition
JMEM/AS	US Joint Munitions Effectiveness Manual/Air-to-Surface
JTAC	Joint Terminal Attack Controller
JTCG/ME	US Joint Technical Coordinating Group for Munitions Effectiveness
LGB	Laser Guided Bomb
LGTR	Laser Guided Training Round
LLLGB	Low-Level Laser Guided Bomb
PAVE	Precision Avionics Vectoring Equipment
USAF	US Air Force
USN	US Navy

Endnotes

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Dragon's Jaw is the Vietnamese nickname for the Thanh Hóa bridge. During the Vietnam War, American intelligence analysts identified it as one of a number of critical infrastructure targets nominated for US air power to disrupt since it provided Vietnamese logistics support to its war efforts in South Vietnam. Over-engineered when built before the war, and surrounded by tactical air defence systems, the Vietnamese successfully defended this one bridge against multiple US air strikes using ballistic bombs, thereby denying US air power the success it had achieved with other targets on the critical infrastructure list.

As a consequence, US air power needed to innovate and find a new way to regain the combat advantage. Trials with new combat techniques and weapons ultimately led to the development of the Pave Way laser-guided bomb. Pave Way would relieve the aircrew of some of the stresses of target acquisition, weapon delivery, and survivability under fire to become an enduring legacy design for modern air power.

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