For Want of a Nail: An Assessment of Global Positioning System Satellite Replenishment

A Monograph

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14. ABSTRACT
Despite its vital importance to the welfare and security of the nation, the Global Positioning System (GPS) constellation is populated with numerous satellites operating well beyond their design life. These aging satellites are more likely to malfunction, which can reduce service coverage, degrade accuracy, and in some cases, transmit dangerously inaccurate data. The Air Force currently subscribes to a launch to sustain (LTS) GPS satellite replenishment strategy. Under this strategy, new satellites are launched only after a satellite failure or just prior to a failure. The purpose of this monograph is to investigate whether the Air Force should forgo its LTS replenishment strategy in favor of a more aggressive launch to augment (LTA) strategy in order to proactively replace high-risk satellites and to accelerate modernization timelines. It will be shown that the explosive growth of GPS over the past fifteen years has outpaced the Air Force's strategy on satellite replenishment. The growing importance of GPS must be matched with a progressive replenishment strategy that sustains its reliability and improves its utility for military, civil, and commercial users. The LTS strategy has placed a disproportionate emphasis on operational efficiency at the expense of operational effectiveness and has impaired the timely insertion of critical new capabilities into the constellation. A LTA strategy would help to reverse this trend.

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ABSTRACT

FOR WANT OF A NAIL: AN ASSESSMENT OF GLOBAL POSITIONING SYSTEM SATELLITE REPLENISHMENT by Major David E. Hook, USAF, 98 pages.

The Global Positioning System (GPS) has become a vital component to both the military and civilian infrastructures. U.S. military forces have evolved from using its signal for routine navigation to depending on it for nearly every facet of combat operations. GPS is also seamlessly integrated into every major civil infrastructure, including transportation, communications, energy, commerce, banking, and emergency response services. In addition, the accuracy and worldwide availability of GPS has spawned a multi-billion dollar international market representing billions of dollars in annual tax revenue.

Despite its vital importance, the GPS constellation is populated with numerous satellites operating well beyond their design life. These aging satellites are more likely to malfunction, which can reduce service coverage, degrade accuracy, and in some cases, transmit dangerously inaccurate data. The constellation is in a frail state with multiple satellite failures predicted each year for the next several years.

The Air Force currently subscribes to the launch to sustain (LTS) satellite replenishment strategy. Under this strategy, new satellites are launched only after a satellite failure or just prior to a failure. The purpose of this monograph is to investigate whether the Air Force should forgo its current LTS replenishment strategy and adopt a more aggressive launch to augment (LTA) strategy in order to proactively eliminate high risk satellites and to accelerate modernization timelines.

It will be shown that the explosive growth of GPS over the past fifteen years has outpaced the Air Force's strategy on satellite replenishment. The growing importance of GPS must be matched with a progressive replenishment strategy that sustains the constellation's reliability and improves its utility for military, commercial, and international users. Instead, LTS has placed a premium on maximizing individual satellite life in order to reduce constellation life cycle costs. This has placed a disproportionate emphasis on operational efficiency at the expense of operational effectiveness. Extraordinary measures have been taken to sustain the aging satellites, sometimes at the expense of signal accuracy. These measures have successfully extended satellite life expectancy, but they have also concealed the declining state of health of the constellation. Consequently, the situation has not commanded the attention it merits from the DoD, and the funding for new launches has not received the priority it deserves. The LTS strategy has also impaired the timely insertion of critical new capabilities into the constellation. By permitting the failure rate of satellites to define the launch rate, the Air Force has deferred the replacement of older satellites with newer, more capable counterparts by several years.

The recommendations drawn by the author are focused on adopting a more aggressive Launch To Augment replenishment strategy in order to proactively replace fragile satellites before they fail and to accelerate satellite modernization timelines. The author also proposes integrating a precautionary risk assessment into the satellite replenishment deliberate planning process to ensure the extreme level of uncertainty inherent in satellite replenishment decisions is directly addressed.

TABLE OF CONTENTS

ILLUSTRATIONS

LIST OF TABLES

LIST OF ABBREVIATIONS

CSAT	Constellation Sustainment Assessment Team
DGPS	Differential Global Positioning System
DOP	Dilution of Precision
DoD	Department of Defense
FAA	Federal Aviation Administration
FOC	Full Operational Capability
GA	Ground Antenna
GPS	Global Positioning System
HMI	Hazardously Misleading Information
IOC	Initial Operational Capability
LTA	Launch to Augment
LTD	Launch to Deploy
LTS	Launch to Sustain
MCS	Master Control Station
MS	Monitor Station
OCS	Operational Control Segment
PDOP	Position Dilution of Precision
PNT	Position, Navigation and Timing
PVT	Position, Velocity and Timing
SIS	Signal In Space
SVN	Satellite Vehicle Number
UNE	User Navigation Error
URE	User Range Error

CHAPTER ONE: INTRODUCTION

For want of a nail the shoe is lost,
For want of a shoe the horse is lost,
For want of a horse the rider is lost,
For want of the rider the battle is lost,
For want of the battle the war is lost,
For want of the war the nation is lost,
All for the want of a horseshoe nail.
George Herbert

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Failing GPS Satellites Make Smart Weapons Dumb [1]

(Associated Press) OMAHA, Neb. -- Last week's tragic U.S. air strike that mistakenly killed a family of five and seriously injured three others in the Iraqi town of Khalis has been blamed on the failure of two navigation satellites, military officials confirmed today. There was an immediate backlash against the errant bombing when large crowds took to the streets of the mostly Sunni town to protest the killings. Town leaders have petitioned the Iraqi Governing Council to investigate the incident and to appeal to the U.S. government to turn over the airmen involved in the attack to face criminal charges.

The Pentagon has issued a written statement apologizing for the incident and has said the attack was based on intelligence reports that a high-profile terrorist leader was in the area. F-16 fighter jets patrolling the area targeted a 500-pound GPS-guided Joint Direct Attack Munition (JDAM) on the suspected safe house. Photos show the bomb missed its target by nearly 30 meters and struck a nearby residence instead. The suspected terrorist leader escaped injury. The Pentagon would not release the names of the pilots involved in the incident.

The two satellites are part of the military's Global Positioning System, a constellation of twenty-eight orbiting satellites that provide precise positioning service to millions of users worldwide. A spokesman from U.S. Strategic Command, the military organization responsible for the spacecraft, stated dual satellite failures have caused a loss of GPS navigation service for a twenty-minute period each day in the Baghdad region.

The first satellite to fail, satellite vehicle number 32 (SVN 32), malfunctioned over the central United States nearly three weeks ago. That failure was followed a week later by SVN 25 which malfunctioned while traversing over the Indian Ocean. The aging satellites are both well beyond their life expectancies and have been maintained on an Air Force Space Command "watch list" of high risk satellites for over a year.

The next launch to replenish the constellation has already been delayed five months due to several launch processing problems. The launch from Cape Canaveral Air Station aboard a Delta

[1] This is a fictitious news article. As a pre-mortem analysis, its purpose is to illustrate the potential military, political, and economic harm that can result from losing just two satellites in a fully populated GPS constellation. The civil consequences of the anomalies are a composite of actual user problems caused by previous satellite anomalies.

II launch vehicle is tentatively scheduled for late next month but officials have stated they "may look for ways to accelerate that launch, if possible."

The announcement today from U.S. Strategic Command comes on the heels of yesterday's revelation from the Coast Guard that navigation on the Mississippi River was temporarily disrupted three weeks ago after several U.S. Coast Guard Differential GPS sites along the river were "knocked off the air until they could be reset." The sites were unable to compensate for the erratic signals transmitted by the malfunctioning SVN 32 as it passed overhead. The differential sites transmit GPS correction signals used by ships to navigate the heavily congested river.

An official with the Federal Aviation Administration, speaking on condition of anonymity, also confirmed that "half a dozen" domestic commercial airliners experienced a complete loss of GPS navigation and had to switch to backup navigation aids. The departure of several international flights was delayed while controllers and pilots waited for GPS service to be restored.

The failing satellite also caused thousands of cell phone users in the central plains states to lose service for several hours. Several hundred cell phone towers in the region took erroneous "time hacks" from the satellite, causing a loss of synchronization between cell towers. The service disruption is expected to cost mobile communication providers millions of dollars.

Meanwhile, supporters of the £2 billion Galileo navigation constellation, Europe's version of GPS, contend the two recent satellite failures point to an ailing GPS constellation and one that does not have the necessary reliability that today's 25 million worldwide users expect. Europe has been keen to develop its own satellite positioning service to break what it calls a U.S. monopoly. "We have five million users in Europe today and that is set to rise to 250 million in the next 15 years," stated a European Space Agency official. "You can't rely on a single system belonging to one country. Galileo will insure uninterrupted service for not only European users, but for users worldwide." The thirty satellites that make up the Galileo constellation are scheduled to be operational in 2008.[2]

Central Command officials refused to comment on the likely impact the loss of GPS will have on operations in Iraq while they wait for a replacement satellite. However, there is evidence that soldiers' confidence in the system may be the first military casualty of the malfunctions.

"It's a very unfortunate situation," said a clearly frustrated battalion commander with the 173rd Airborne Brigade responsible for patrolling this small town located 35 miles north of Baghdad. "After many months of hard work, we were finally gaining the fragile trust and support of the local population. I thought we had turned the corner and were making real progress. But after an accident like this," he paused, "you have to go back to square one and start all over. There has been a definite spike in the number of attacks against my patrols since the accident."

"Usually GPS is dead-on accurate. I really don't know how we ever managed without it," shared a paratrooper. "With GPS, I know exactly where my unit is on the battlefield. I can call in long-range fires without fear of fratricide. But with the rumors about GPS no longer being reliable, I just hope I can count on it when I absolutely need it."

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[2] The information pertaining to the Galileo constellation was referenced from Ian Sample, "Europe to Back Satellite Positioning System," *NewScientist.com*, [Internet] (25 March 2002, accessed 6 January 2004); available from http://www.newscientist.com/.

Background

The designers of the Global Positioning System (GPS)[3] could never have anticipated the exponential growth of the position, navigation, and timing (PNT) system when it was first fielded over twenty-five years ago. What was originally intended to simply improve military worldwide en route navigation has now matured into the glue that binds the military's transformation efforts.[4] U.S. military forces have evolved from using GPS for routine operations to depending on it for nearly every aspect of combat operations. With new and innovative applications being discovered almost monthly,[5] the U.S. military is becoming increasingly dependent on this space service. In their paper "GPS at War: A Ten Year Retrospective," James M. Hasik and Michael Russell Rip discuss the "precision revolution" GPS has fostered while also exposing the potential vulnerabilities it brings to the joint force:

> It is doubtful that any technology since nuclear weaponry has had such a dramatic influence on military strategy [as GPS]. Today, GPS is the glue that binds together modern military operations, and its promises and pitfalls sits at the core of the question of military transformation. This is true because GPS' lethal combination of inexpensive precision, standoff range, adverse weather performance, and operational flexibility has prompted military forces the world over to adopt it with blinding speed.[6]

GPS has become so pervasive its loss could be catastrophic, hence making it a critical vulnerability to the Joint Force Commander.[7]

Civilian and commercial users of GPS have also come to depend on GPS' reliable and accurate navigation and timing signal. GPS is now seamlessly and invisibly integrated into every major civil infrastructure, including transportation, communications, energy, commerce, banking,

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[3] Readers may wish to reference Appendix A for a brief overview of the system.

[4] James M. Hasik and Michael Russell Rip, "GPS at War: A Ten-Year Retrospective," *ION GPS 2001*, 11-14 September 2001, Salt Lake City, UT, 2406.

[5] Michael Russell Rip and James M. Hasik, *The Precision Revolution: GPS and the Future of Aerial Warfare* (Annapolis, MD: Naval Institute Press, 2002), 232.

[6] Hasik and Rip, 2406.

[7] Michael McPherson, "GPS and the Joint Force Commander: Critical Asset, Critical Vulnerability." (Naval War College, 18 May 2001), 8-13.

and emergency response services.[8] These industries have quickly come to realize the untapped potential of GPS information to meet the growing requirements for improved productivity, efficiency, and safety. GPS truly has become an international utility in its own right.

Continued growth of GPS and its acceptance as the international standard are based on the assumption GPS will continue to provide the same unsurpassed global performance that it has for the past decade. Civil and commercial users expect the GPS signal to be reliable, stable, and predictable and one they can plan around, similar to the dependability of a wall outlet to deliver electricity.[9] These expectations are often well beyond what the original constellation was designed to support and beyond current funding levels. Nevertheless, this "expectation creep" has become the *de facto* performance standard.

In recognition of the growing importance of GPS to the emerging global information infrastructure, the Clinton Administration released a comprehensive national policy on the use and management of GPS. The presidential decision directive (PDD NSC-6) reaffirmed the Defense Department's responsibility to acquire, operate, and maintain the basic GPS service and to continue to provide the civil signal for "peaceful civil, commercial and scientific use on a continuous basis, free of direct users fees."[10] One of the most important tasks inherent in these stewardship responsibilities is the sustainment of a fully operational constellation of GPS satellites. The current constellation replenishment strategy is based on federal government policy, as stated in the *2001 Federal Radionavigation Plan*, to sustain no less than twenty-four

[8] L. Paul Bremer III and Edwin Meese III, *Defending the American Homeland* (Washington, D.C.: Heritage Foundation, 2002), 19.

[9] Scott Pace and others, *The Global Positioning System: Assessing National Policies* (Santa Monica, CA: RAND, 1995), 96.

[10] The White House, Office of Science and Technology Policy, National Security Council, "Fact Sheet: U.S. Global Positioning System Policy" [Internet] (29 March 1996, accessed 7 August 2003); available from http://www.ostp.gov/NSTC/html/pdd6.html.

operating satellites in the GPS constellation.[11] Today, the constellation consists of twenty-eight satellites, but with many satellites operating well beyond their life expectancies.

On the eve of Operation Iraqi Freedom (OIF), seventeen of the twenty-eight satellites were older than their design life of 7.5 years, fifteen satellites had lost redundancy in a critical subsystem and were one component away from complete satellite failure, and one satellite had completely failed and was awaiting disposal.[12] These aging satellites are more likely to malfunction, which can induce severe navigation and timing errors. In addition to design life being a probabilistic limiting factor, random hard failures can also cause unexpected mission failure. The randomness of component failures and the limited data on the statistically small number of satellites prevents the Air Force from precisely predicting when a satellite will fail or what components might break next. Moreover, the failure of a single satellite can have a significant impact on its users. Failures can reduce coverage, degrade accuracy, and in some cases, transmit dangerously inaccurate data.

To further compound the problem, reconstitution of the satellite fleet was impossible during the twelve months leading up to the war due to a series of complications with the Delta II launch vehicle, the only space launch vehicle capable of launching GPS satellites. This extended launch delay was not merely an isolated incident that can be easily written off to happenstance; this was the third launch incident in the past five years.[13] The launch vehicle problem was finally rectified with a successful launch in January 2003 prior to the start of ground operations in Iraq. Fortunately, the constellation weathered this critical period and performed flawlessly.[14]

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[11] Department of Defense and Department of Transportation, *2001 Federal Radionavigation Plan* (Springfield, VA: National Technical Information Service, 2001), 3-1.

[12] Capt Eddie Meidunas and Capt Mike Perz, *Navstar Global Positioning System CSAT* Presentation to CSAT at Vandenberg AFB, CA on 27 February 2003.

[13] Andrew Zolli, "Oh, Nooo! What If GPS Fails?," *Wired*, May 2003, 40.

[14] Bob Brewin, "Pentagon Tweaked GPS Accuracy to within Three Meters During Iraq War," *Computerworld*, [Internet] (24 June 2003, accessed 24 July 2003); available from http://www.computerworld.com/mobiletopics/mobile/story/0%2C10801%2C82464%2C00.html.; and

However, the fact that no satellites failed during the initial major combat operations is more accurately attributed to chance than to adept risk management.

Long satellite life and the length of time required to replace the entire constellation of twenty-four satellites has also obstructed the injection of new technology into the constellation.[15] Accordingly, modernization efforts to improve the security, accuracy, and integrity of the signal and to make it less susceptible to interference and enemy jamming have been slowed due to extended launch schedules. These extensions threaten the future of GPS as the world's navigation and timing standard because international users may lose confidence in the viability of the constellation and the willingness of the U.S. government to invest in its maintenance.[16]

The importance of these modernization enhancements was validated during Iraqi Freedom when Iraqi forces arrayed jammers around Baghdad in a vain attempt to disrupt coalition air attacks.[17] Although their effectiveness was questionable, the jammers send a clear and an unambiguous statement: our enemies understand the value of GPS to the "new American way of war" and will not hesitate to deny coalition forces access to the valuable signal.

Owen Wormser, the Pentagon's principal deputy for spectrum, space, sensors and command, control and communications, acknowledged the problem of the aging constellation in an interview in *Aviation Week and Space Technology* prior to the start of Iraqi Freedom. He stated the Defense Department was "increasingly concerned" that it would not be able to fix the "rapidly eroding" constellation problem on its own. Pentagon officials accepted some

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William B. Scott and Craig Covault, "High Ground over Iraq," *Aviation Week & Space Technology*, 9 June 2003.

[15] National Research Council, *The Global Positioning System: A Shared National Asset* (Washington D.C.: National Academy Press, 1995), 10.

[16] Clifford W. Kelley, Douglas Mortoccia, and Rex Pendley, "A Modernization Deployment Strategy to Meet Military and Civil Needs," *ION GPS 1999*, 14-17 September 1999, Nashville, TN, 1343.

[17] Jeremy Singer, "War in Iraq Boosts Case for More Jam Resistant GPS," *SpaceNews*, [Internet] (8 April 2003, accessed 1 April 2004); available from http://www.space.com/spacenews/archive03/gpsarch_040703.html.

responsibility for the “dire situation” because the “emerging crisis” had largely gone unnoticed by senior leaders until only recently.[18]

Problem Statement

Faced with a frail GPS constellation, a launch infrastructure of questionable responsiveness, a growing urgency to accelerate modernization timelines, and expanding performance expectations, it is time for the DoD to critically review its GPS satellite replenishment strategy. The increasing expectations and growing dependence on GPS suggests a more conservative acceptance of constellation risk. The Defense Department has an obligation to ensure the reliability of this important and valuable resource to domestic and international users, as well as to ensure its continued availability and security in harsh battlefield environments. An effective satellite replenishment strategy is essential to the continued viability of GPS.

The purpose of this paper is to qualitatively examine the risks of the current satellite replenishment strategy and to provide a new perspective in managing the problem. The paper will attempt to answer the research question, “Should the Air Force forgo its current launch to sustain (LTS) replenishment strategy and adopt a more aggressive launch to augment (LTA) strategy in order to proactively eliminate high risk satellites and to accelerate modernization deployment timelines?” It is not the objective of the paper to recommend a comprehensive solution to this complicated problem, but rather to provide a new perspective from which future replenishment decisions can be framed.

The GPS replenishment strategy is the plan to maintain the constellation to meet the satellite availability requirement. Satellite availability is documented in the “Global Positioning System Standard Positioning Service Performance Standard,” which defines the level of

[18] Robert Wall, "Eroding GPS Worries Pentagon," *Aviation Week & Space Technology*, 4 November 2002, 31.

performance the U.S. government is committed to provide civil GPS users. This standard mandates:

> …24 operational satellites must be available on orbit with 0.95 probability (averaged over any day). At least 21 satellites in the 24 nominal plane/slot positions must be set healthy and transmitting a navigation signal with 0.98 probability (yearly averaged).[19]

Satellite replenishment decisions are primarily driven by this requirement.

The replenishment strategy also "prescribes the satellite positions that compose the system and the manner in which those satellite positions will be replenished."[20] It is similar to a maintenance strategy in that it "initializes the system and keeps it in operation a high percentage of time (hopefully) by regular 'part' replacement knowing that failures will occur eventually."[21] This paper will focus exclusively on that portion of the strategy that applies to the timing of replenishment launches and will leave the discussion of optimal satellite positioning for others.

The Air Force currently prescribes to the Launch to Sustain (LTS) replenishment strategy.[22] Under this strategy, launches are scheduled to replace satellites "nearing the end of their useful life, predicted to fail, or that fail abruptly."[23] The inability to accurately predict satellite and component failures and the lack of a consensus on what constitutes satellite "useful life" tends to make this a reactive approach to satellite failure.

The other viable alternative for a mature constellation is the Launch to Augment (LTA) strategy.[24] This strategy allows for "increased operational capability above the designed standard

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[19] Assistant Secretary of Defense for Command, Control, Communications, and Intelligence, *Global Positioning System Standard Positioning Service Performance Standard,* October 2001, 13.

[20] J.M. Womack, *GAP Users Guide: Instructions for Use of the GAP (Preliminary)* (Los Angeles Air Force Base, CA: Space and Missile Systems Center, Air Force Materiel Command, 1995), 27.

[21] Ibid.

[22] Air Force Space Command, *Air Force Space Command Concept of Operations for the Global Positioning System*, 28 December 2001, 3-18.

[23] Air Force Space Command, *Air Force Space Command Instruction 10-1213 Spacelift Launch Strategy and Scheduling Procedures,* 2 October 2000, 2.

[24] A third strategy, Launch to Deploy, is only used for initial satellite system deployment and for research and development systems. It is therefore not discussed here.

in response to war, crisis, contingency, or theater need."[25] This strategy uses accelerated time lines, subject to operational constraints, to rapidly build enhanced capabilities.

Although the nation is not in imminent danger of a major catastrophic failure of the constellation,[26] one should not be complacent about the possibility of satellite failures causing localized outages or degraded service. These outages are technically feasible; it is only the probability of it happening that is uncertain. Also uncertain is the likelihood of a GPS failure to induce cascading failures across interdependent civilian and military infrastructures. As political economist Thomas Schelling has pointed out, "There is a tendency in our planning to confuse the unfamiliar with the improbable. The contingency we have not considered looks strange; what looks strange is thought improbable; what is improbable need not be considered seriously."[27] The Space Commission Report completes this line of thought by stating, "Surprise is most often not a lack of warning, but the result of a tendency to dismiss as reckless what we consider improbable."[28] The aim of this paper is to illuminate some the "improbable" and "unfamiliar" consequences that can arise due to a fragile GPS constellation. It is hoped that by doing so, we shall heed the ready warnings and take the necessary precautions to prevent an unfortunate surprise.

[25] Air Force Space Command, *Launch Strategy and Scheduling Procedures*, 2-3.
[26] Zolli, 40.
[27] *Commission to Assess United States National Security Space Management and Organization,* by Hon. Donald H. Rumsfeld, chairman (Washington DC, 2001), 25.
[28] Ibid.

CHAPTER TWO: AN EMERGING CRISIS?

> Failure does not strike like a bolt from the blue; it develops gradually according to its own logic.…complicated situations seem to elicit habits of thought that set failure in motion from the beginning. From that point, the continuing complexity of the task and the growing apprehension of failure encourage methods of decision making that make failure even more likely and then inevitable.
>
> Dietrich Dorner, *The Logic of Failure*[29]

> It has been through talented operators and ingenious work-arounds that GPS continues to provide outstanding performance.
>
> U.S. Strategic Command, *GPS III Concept of Operations*[30]

The problem of satellite replenishment is deceptively complex. The production of boosters and satellites is a very expensive endeavor requiring long lead times.[31] Replace a satellite too early and scarce military dollars are needlessly diverted from more pressing defense needs. Wait too long and one risks satellite failures disrupting military operations or threatening civilian safety-of-life applications. However, the timing of when to replace a satellite and how many to acquire is clouded in uncertainty. The decision to acquire new satellites must be made years in advance, sometimes before their predecessors have even reached orbit. Due to the random nature of component failures and limited on-orbit reliability data, senior leaders do not have the precise failure predictions needed to guide their launch decisions. Without a clear need to launch, but with undeniable and unambiguous budgetary pressures, the "prudent" decision gradually becomes a "wait and see" approach. All the while, the constellation continues to age with few warning signs of an impending failure. Increasing reliance, and then outright

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[29] Dietrich Dorner, *The Logic of Failure*, trans. Rita and Robert Kimber (New York: Metropolitan Books, 1996), 10.

[30] U.S. Strategic Command, *Global Positioning System III Concept of Operations,* 28 February 2003, 2.

[31] Amy Butler, "GPS Spacecraft Lasting Longer Than Expected, Prompting Possible IIF Delay," *Defense Daily*, 2 December 2003.; It costs approximately $100 million to acquire a GPS satellite and place it in orbit. It should be noted, however, that the tax revenue generated from the sale of GPS products in the U.S. more than covers the cost of the system. Assuming a conservative tax rate of 25 percent on the $17 billion annual U.S. GPS market, the tax income for 2003 alone would top $4.25 billion. This is more than the $3-4 billion cost of maintaining and operating GPS for ten years.

dependency, is placed on ingenious work-arounds and software patches to keep the system functional. What emerges is a paradigm that places greater value on extending individual satellite life than limiting overall constellation risk.

Edward Tenner calls this paradigm the "rearranging effect."[32] Rearranging effects are the result of misguided efforts to manage acute risks. The acute risks, however, are never actually eliminated but are instead distributed or rearranged differently. They are broadened and shifted toward the future. These gradual, accumulated risks are sometimes more hazardous than the acute risks they replaced.[33] In attempting to maximize the life of individual satellites, the Air Force has inadvertently exposed itself to a more elusive and chronic problem of constellation degradation. Rather than dealing with satellite degradation proactively, it has permitted the fleet to age beyond its optimal design life. This has allowed constellation risk to accumulate while shifting greater liability to the future. The hallmark of a system with rearranged risks is a need for constant vigilance, monitoring, and adjustment in order to manage and mitigate those escalating risks.[34] This is precisely the situation we face today.

As Peter Senge points out in *The Fifth Discipline*, slow, gradual processes pose the greatest threats to organizations because humans are conditioned to focus on sudden events which pose a threat to our survival. We are maladapted to recognize the "longer-term patterns of change" which commonly threaten our systems.[35] Our fixation on the immediate threat instinctively focuses our attention on the troublesome satellite *du jour*, but we fail to recognize the underlying pattern of escalating trouble across the constellation.

[32] Edward Tenner, *Why Things Bite Back* (New York: Alfred A. Knopf, Inc., 1996), 8.
[33] Ibid., 48-58.
[34] Ibid., 72, 104, 277.
[35] Peter M. Senge, *The Fifth Discipline: The Art and Practice of the Learning Organization* (New York: Currency Doubleday, 1990), 21-23.

Dietrich Dorner echoes these sentiments in his book, *The Logic of Failure,* in which he documents common errors of logic which can lead to catastrophe. "In solving problems that involve complex dynamic realities," he writes, "…we must think about problems we may not have at the moment but that may emerge as side effects of our actions….[W]e neglect them because we don't have those problems at the moment and therefore are not suffering from their ill effects. In short, we are captives of the moment."[36] Dorner asserts our preoccupation with the pressing problems of the day is one of the major mistakes we make in dealing with complex systems. It is the gradual deterioration of the constellation that has caused the "emerging crisis" to go unnoticed by senior Pentagon leadership until only recently.

This chapter will trace the history of the constellation deployment and prior replenishment decisions in order to understand the context of the current situation. Armed with the advantage of historical perspective, it is possible to identify the long-term trends and the rearranging of risk that has led to today's chronic problem of multiple fragile, ailing satellites. The chapter will conclude by examining the constellation's current status and the near-term outlook for constellation health.

A Short History: How Did We Get Here?

The chronology of the GPS program can be traced through the three major blocks, or versions, of satellites that have been fielded. The block I satellites were developmental satellites designed to provide the proof of system concept. After this concept was successfully demonstrated, the DoD elected to construct the operational constellation with improved block II satellites. Since 1997, these aging satellites have been gradually replaced by the block IIR (replenishment) satellites. A modernized version of the block IIR with enhanced capabilities, the IIR-M, and the block IIF (follow-on) satellites are being built and are waiting their turn for launch

[36] Dorner, 190.

in 2004.[37] A radically new generation of satellite, the block III, is currently under development with projected deployment starting in 2012.[38] The modernized birds will be discussed in greater detail in Chapter Three.

The block I satellites were research and development satellites designed and built by Rockwell International to test and refine the capability of the system. The Rockwell team designed, tested, and launched the first GPS satellite in less than four years.[39] The first GPS block I satellite was launched on 22 February 1978, and within the calendar year, four satellites were in orbit. Over the course of the next seven and a half years, a total of eleven satellites were launched using a launch-on-schedule strategy, with one satellite lost due to a booster failure.[40]

The block I satellites exceeded all expectations and demonstrated remarkable longevity and robustness despite being developmental satellites. The average life of the block I satellites reaching orbit was 8.9 years, twice the mean mission duration of four years.[41] Four satellites even managed to survive beyond their ten-year anniversaries, thus doubling their five-year design life.[42] Eventually the developmental satellites would fail due to the deterioration of their atomic clocks or malfunctions of the attitude control system, but not before they convincingly demonstrated the concept of the system. Perhaps the greatest legacy of the block I satellites was the precedent it set for operational longevity and for exceeding performance standards. With the GPS technology successfully proven, the system was now prepared to advance from a developmental program to an operational capability.

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[37] Col. Rick Reaser, *GPS Program Update* (Brussels, Belgium: NATO C3 Board Subcommittee 8), Presentation, 7.

[38] Ibid., 10.

[39] Dennis M. Galvin, "History of the GPS Space Segment from Block I to the New Millennium," *ION GPS 1999*, 14-17 September 1999, Nashville, TN, 1844.

[40] Air Education and Training Command, 534 TRS/DOBM, "Payload System Operator Course Student Study Guide: Block II GPS Navigation Theory," 1 May 1998, 2.

[41] Galvin, 1851.

[42] Air Force Materiel Command, Global Positioning System Joint Program Office, "Sust-Plan-001, Navstar Global Positioning System Maintenance Plan for the Space and Control Segments (Draft)," (Peterson Air Force Base, CO: Detachment 11, Space and Missile Systems Center, 15 December 2000), 4.

The path toward a fully operational system, however, was not smooth. The acquisition program for the production satellites, dubbed the block II, had to be significantly restructured in 1979 due to severe funding cuts. The system's forecasted budget for 1981 to 1986 was slashed by nearly 30 percent.[43] Two major factors contributed to the lack of financial support for GPS. First, GPS was categorized as a support system as opposed to a weapon system. Because it did not have a history of well-defined operational concepts, its military utility to the armed services was not as obvious as other well-established weapons systems. No one could have predicted twenty-five years ago the revolutionary changes GPS would spawn. The untried navigation combat support system, although promising, lost out to seemingly more pressing warfighting needs. Secondly, the constellation's status as a joint program retarded strong financial support from any single service. The services were not eager to spend their own scarce resources on a program that would benefit everyone. Without a strong sponsor to shepherd it through the sometimes-cutthroat budgeting process, the system was zeroed out during budget negotiations in 1980, 1981, and 1982. The program was rescued only after the Office of the Secretary of Defense directed that its funding be restored.[44]

With funding in place for the time being, Rockwell was awarded the contract in September 1983 to build and launch twenty-eight block II satellites. The block II satellites incorporate significant improvements over the block I, including enhanced radiation hardening to improve reliability and survivability. These enhancements helped to increase the specification design life from 6 years to 7.5 years.[45] In March of 1984, it was decided to make further modifications to the configuration of the tenth and all subsequent block II satellites. These

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[43] Peter Grier, "The Sensational Signal," *Air Force Magazine*, February 2003, 68-69.
[44] Ibid.
[45] *SS-GPS-300E, System Specification for the Navstar Global Positioning System*, 30 January 1995, 13.

satellites, designated the block IIA, have enhanced payload survivability capabilities and incorporate improved sensors into the nuclear detonation detection payload.[46]

The initial deployment of the block II was further delayed in 1986 as a result of the Space Shuttle *Challenger* accident. The DoD had earlier designated the Space Shuttle as the principal launch vehicle for all Air Force space missions.[47] As the only planned launch vehicle for GPS satellites at that time, the loss of the shuttle caused a twenty-four month delay in the scheduled launch of the block IIs. During the moratorium on shuttle launches, it was decided to modify the new satellites to make them compatible with the Delta II launch vehicle.[48] The first block II satellite, satellite vehicle number 14 (SVN 14), was eventually launched aboard a Delta II in February 1989 and was available for operational use two months later.

Following the successful launch of SVN 14, the Air Force adopted an aggressive Launch To Deploy (LTD) strategy with launches scheduled approximately every two to three months to rapidly constitute the new constellation. Within less than two years of SVN 14 reaching orbit, a flurry of GPS launches from Cape Canaveral brought nine more satellites into service.[49]

By early August 1990 as Iraqi armored divisions were rolling into Kuwait, the constellation was still an experimental system with only thirteen satellites available, including six of the older block I satellites. The Air Force, however, possessed no satellite production or launch surge capability to accelerate the buildup of the constellation. Consequently, the war had little impact on the launch schedule.[50] During the seven-month period of Operations Desert

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[46] Galvin, 1844.; Pace and others, 244. Block IIA satellites have the capability to operate for 180 days without control segment intervention. The block I and II satellites required intervention at least every 3.5 days.

[47] Pace and others, 243.

[48] Ibid.

[49] Joint Program Office, *Navstar GPS User Equipment Introduction* (September 1996), 1-21.

[50] Rip and Hasik, 132.

Shield and Desert Storm, the U.S. launched three previously-scheduled satellites and placed them in orbital positions to provide optimal GPS coverage over the region.[51]

In late 1990 two serious satellite problems were discovered which threatened the entire fleet. The first problem was an attitude control anomaly that posed a threat to all previously launched block II satellites. The other problem was a design deficiency in the electrical power system of the new block IIA satellites, which were just being delivered into the launch sequence. A decision was made to delay launches until these two issues could be resolved. The deployment of new satellites was interrupted for approximately fifteen months while a solution was sought.

After both of these issues were resolved in early 1992, the launch schedule resumed with new vigor. A string of thirteen satellites, over half the constellation, was successfully placed into service within twenty-six months. A full compliment of twenty-four satellites was finally achieved, and Initial Operational Capability (IOC) was announced for the system in December 1993. The IOC notification signified GPS was capable of sustaining the civil GPS service at the required performance levels on a continuous, worldwide basis.[52] Because the system still contained some of the older and less capable block I satellites, the launch rate continued unabated until March 1994 when the twenty-fourth block II/IIA completed the constellation. Seventeen months later, Air Force Space Command formally declared Full Operational Capability (FOC) for GPS, meaning the constellation had reached full military functionality.[53]

Just as the constellation was in a state of transition from an experimental system to a fully operational one, so, too, was the launch strategy in flux. Immediately following the declaration of FOC, the launch rate immediately tapered off, with no launches for the next two years. With a full set of satellites on orbit, the launch strategy shifted from Launch To Deploy (LTD) to Launch

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[51] Ibid.
[52] Pace and others, 265.
[53] Ibid., 246.

To Sustain (LTS). LTS is a strategy to replace satellites predicted to fail or that fail abruptly.[54] LTS may be implemented in one of two ways: launches may be proactively scheduled based on predicted satellite failure (launch-on-schedule) or they may be scheduled in response to an abrupt satellite failure (launch-on-failure).

The original plan called for a launch-on-schedule strategy with replacement satellites launched about every three months.[55] It was thought that this routine would ensure twenty-four healthy satellites most of the time, with the constellation very rarely dipping to the minimum twenty-one satellites. The strategy of routine, regularly scheduled launches, however, was never implemented. Instead, a greater acceptance of operational risk prevailed because ensuing circumstances encouraged a policy of maximizing individual satellite life.

By 1996 it had been seven years since the first block II satellites had been launched, and they were already approaching their 7.5-year design life. The first two block II satellites failed in 1996, bringing the satellite count to twenty-five, and several satellites experienced attitude control component failures.[56] There was "great concern" the armada of satellites would drop below the mandated level of twenty-four satellites within three to six years, based on sustainment studies which assumed the satellites would fail (on average) at the same rate they were launched.[57] The predicted spike in failures was a reflection of the twenty-two satellites launched during constellation deployment in 1989-90 and 1992-93. The minutes from a 1996 Constellation Sustainment Assessment Team (CSAT), a quarterly forum to evaluate the condition of the constellation and to make launch recommendations, read: "Even if every current launch

[54] Air Force Space Command, *Concept of Operations*, 3-18.

[55] Colonel G.B. Green, "The GPS 21 Primary Satellite Constellation," *NAVIGATION: Journal of The Institute of Navigation* 36, no. 1 (1989): 10.

[56] Capt McDowell, "Point Paper on GPS Constellation Status Assessment Team (CSAT) Minutes," (2 SOPS/DOUAS, 18 June 1996). memo.

[57] Steven C. Fisher and Kamran Ghassemi, "GPS IIF-the Next Generation," *Proceedings of the IEEE* 87, no. 1 (1999): 25.

opportunity is used, there is still a 50% probability of dropping below 24 satellites and a 10% chance of dropping below 21 satellites in the 1999 to 2003 timeframe based on a [life expectancy] of 7.5 years."[58] The most expedient way to solve this dilemma was to sustain the on-orbit satellites as long as possible. In short, the emerging replenishment strategy was to string out launches so satellites would be available to fill the predicted satellite gap. Several launches were cancelled or delayed in the 1998-2001 time frame, even though in one case the probability of maintaining twenty-four satellites dropped below eighty percent and in another instance it dropped to sixty percent.[59]

By January 1997 the next generation of satellite, the block IIR (replenishment), was prepared to launch. This replenishment program has been started in 1988 while the block II satellites were still in production. Martin Marietta was awarded the contract the following year to build twenty-one satellites.[60] These satellites incorporated several enhancements over the earlier satellite versions, including more accurate atomic clocks, on-orbit software reprogrammability, extended survivability, and reduced operations support requirements.[61] The first launch ended just seconds after liftoff in a fiery explosion that destroyed the satellite. The next launch attempt six months later successfully placed SVN 43 into orbit. The newest spacecraft underwent extensive testing which unearthed some abnormalities with its time keeping system, its extended survivability capabilities, and it nuclear detonation detection payload. This halted IIR launches for twenty-eight months while a fix could be designed and tested.

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[58] McDowell. memo.

[59] Col. Henry W. Poburka, Jr., "Global Positioning System (GPS) Constellation Sustainment Assessment Team (CSAT) Report," 23 March 1998, Vandenberg AFB, CA, memo.; and Joint Program Office, *JPO CSAT*. Presentation to CSAT at Vandenberg AFB, CA, April 2001.

[60] Lt Col C. McGinn, Capt S. Rajotte, and D. Latterman, "Global Positioning System (GPS) Modernization," *32nd Annual Precise Time and Time Interval (PTTI) Meeting*, 28-30 November 2000, Reston, VA, 403.

[61] Willard Marquis, "Increased Navigation Performance from GPS Block IIR," *ION GPS 2002*, 24-27 September 2002, Portland, OR, 1230-1232.

In 1998 Vice President Gore announced a major initiative that promoted "enhancements to the Global Positioning System that will benefit civilian users worldwide."[62] The service enhancements included broadcasting a second and third civil GPS signal, adding new military codes, and increasing signal strength. These upgrades will provide much needed civil signal redundancy, improved positioning accuracy, and increased resistance to interference.[63] The Air Force planned to retrofit up to twelve IIR satellites with the new capabilities. [64] The final number of modernized satellites, designated block IIR-M, would depend on the IIR launch rate. The slower the launch rate, the greater the number of block IIR satellites available for the modernization retrofit. Although the Air Force stated constellation sustainment was the first priority, there was an undeniable institutional incentive to delay launches in an effort to modernize as many satellites as possible.

Also contributing to the delayed launch schedule were declining acquisition budgets which put a tight squeeze on national security space programs. According to a report authored by the Defense Science Board and the Air Force Scientific Advisory Board, the budgetary environment during the 1990s created a space acquisition culture which emphasized cost rather than mission success as the primary objective. The result of this cultural bias was increased acceptance of risk to mission.[65] Although the report specifically studied the acquisition of new space programs and did not address their sustainment directly, the organization responsible for acquiring Air Force space programs, the Space and Missile Systems Center, is also responsible for their sustainment. The constrained funding environment was not singularly limited to the

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[62] McGinn, Rajotte, and Latterman, 404.

[63] Michael Shaw, Kanwaljit Sandhoo, and David Turner, "Modernization of the Global Positioning System," *32nd Annual Precise Time and Time Interval (PTTI) Meeting*, 28-30 November 2000, Reston, VA, 18.

[64] McGinn, Rajotte, and Latterman, 403.

[65] *Report of the Defense Science Board /Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs* (Washington, D.C.: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, 2003), 10.

acquisition phase; sustainment was also effected. Moreover, the issues of acquisition and sustainment funding were tightly coupled, especially in regard to the block IIR modernization program. It is reasonable to assume the same funding pressures that produced a culture of risk taking during the acquisition of new capabilities was also at work for the less glamorous sustainment phase of GPS.

Another significant factor encouraging the acceptance of risk during satellite sustainment is the "peculiar aspects associated with space system development and production."[66] Space programs have a different funding curve than most typical weapon systems. A space system spends most of its budget early in its life cycle during development and well before deployment. Consequently the sustainment phase of a space system accounts for a much smaller percentage of the system's life cycle costs than do most other systems.[67] Moreover, the sustainment costs for an on-orbit satellite are based on relatively fixed overhead infrastructure and personnel costs. The operations and maintenance (O&M) costs for the control segment and the expenses for sustaining the satellite operators and contractor engineering support remain fixed regardless of constellation size or health. Because these costs remain stable throughout a satellite's life, there is no direct economic incentive to proactively replace an ailing satellite before it fails.

Now contrast satellites with an aging fleet of aircraft. Older aircraft need extensive periodic inspections and depot-level maintenance to maintain aircraft operational rates. Rising O&M costs impose escalating economic pressure to replace aircraft before they become prohibitively expensive. The optimal replacement interval for an aircraft shortens as the growth

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[66] Elizabeth Rees, "Air Force, GAO Officials Wrangle over New Space Acquisition Policy," *Inside the Air Force* (21 November 2003) in [e-mail newsletter] *CGSC Space News (*Ft Leavenworth, KS: Command and General Staff College, 25 November 2003).

[67] SSgt Melanie Streeter, "Space-Acquisitions Policy Changes," *Air Force Print News* (20 November 2003) in [e-mail newsletter] *CGSC Space News (*Ft Leavenworth, KS: Command and General Staff College, 25 November 2003).

rate of O&M costs increases.[68] Consequently, economic pressure helps to curb the overall operational risk of an aging aircraft. Periodic inspections also provide the added benefit of giving decision makers an unambiguous source of information on the health of the aircraft, thereby further making the case for proactive replacement. In contrast, the inaccessibility of satellites limits the knowledge of satellite health to a thin stream of telemetry data. Latent satellite deficiencies remain hidden and uncertain, and operational risk is permitted to accumulate.

The most significant reason replenishment launches in the late 1990s and the new millenium were delayed was simply because the block II/IIA satellites were continuing to outperform their accuracy and availability requirements and were far outliving their original design lives of 7.5 years. The average life expectancy for a block II/IIA satellite in late 1999 had grown to over 8.5 years and the number of on-orbit satellites had ballooned to twenty-eight.[69] The remarkable success of GPS over the past decade had helped to disguise the underlying cracks in the system. Ironically, this success may have planted the seeds for possible future failure.

With satellites living longer, there was mounting pressure to reduce the number of replenishment launches due to limitations in the control segment.[70] The ground control segment can command and control a maximum of thirty on-orbit satellites.[71] Once that ceiling is reached, launches must be postponed until either a satellite fails or one is proactively disposed. It became increasingly difficult to justify replenishment launches while there were "excess" satellites on orbit, especially if it meant a satellite had to be disposed prior to launch. At face value this seemed wasteful and illogical. An emphasis on extending satellite life became the prime

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[68] Victoria A. Greenfield and David M. Persselin, *An Economic Framework for Evaluating Military Aircraft Replacement* (Santa Monica, CA: RAND, 2002), xi.

[69] 1Lt John J. Losinski, "Operational Response to an Aging Global Positioning System Constellation," *ION GPS 2000*, 19-22 September 2000, Salt Lake City, UT, 2543.; and Major Mike Mason, *GPS Mean Mission Durations*. Presentation to HQ AFSPC/XOS, 30 October 2003, 12.

[70] Losinski, 2543.

[71] Ibid.

directive, sometimes even at the expense of navigation accuracy.[72] While the practice of retiring functional aircraft is well established within the Air Force,[73] the idea of replacing an operational satellite, no matter how old or crippled, is still considered wasteful and is not well accepted.[74]

At this juncture, numerous orbital planes had at least one satellite beyond its design life operating on a redundant, backup system. A common technique was to buttress an aging, fragile satellite with a new satellite in order to mitigate the impact of a satellite failure.[75] With so many weak satellites, however, there were not enough backups available to cover them all. The difficulty was no longer determining whether a launch was needed, but which satellite should be replaced first. Without a clear prediction of which satellite would fail next, the Air Force cancelled launches in 2000 and 2001 because of "no operational need" despite the fact there was a forty percent chance three satellites would fail within the next twelve months.[76] There was growing concern a satellite might be launched into the "wrong" orbital plane and be unavailable to replace a failed satellite in an unexpected plane. As a result, a launch-on-failure satellite replenishment strategy prevailed.

Current Constellation Status

All the while constellation risk continued to mount. The tradeoff for delaying launches through 2001 was greater reliance on launches in later years. Conservative estimates in 2002

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[72] Capt Michael Violet and others, "Navigation Accuracy or Satellite Health? Controlling Momentum on Aging GPS Satellites," *ION GPS '99*, 14-17 September 1999, Nashville, TN, 2273.

[73] The Aerospace Maintenance and Regeneration Center at Davis Monthan Air Force Base in Tucson, AZ is a testament to the long standing practice of retiring aircraft before they become an operational risk or technologically obsolete. Better known as the "boneyard," it is home to 4,500 aircraft.

[74] Losinski, 2543.; and Air Force Materiel Command, "Aerospace Maintenance and Regeneration Center" [Internet] (2003, accessed 1 March 2004); available from http://www.dm.af.mil/AMARC/history.html.

[75] Capt Jim Smith and Lt Brian McFarland, *GPS Constellation Sustainment.* Presentation to CSAT at Vandenberg AFB, CA, May 2002, 3.

[76] Losinski, 2544.;Maj Gen William R. Looney III, "Results of GPS Constellation Sustainment Assessment Team (CSAT)," (2001) memo.; GPS Joint Program Office, *GPS JPO CSAT Recommendation - May 2002 Launch.* Presentation to CSAT at Vandenberg AFB, CA, May 2002; and Capt Donald A.

predicted eighteen satellite failures by the end of 2006, but there were only sixteen launches scheduled during the same period.[77] However the exact failure distribution was unpredictable and likely uneven. While few failures were predicted in 2002 and 2003, it was possible for a spike in failures in later years to exceed the nominal maximum rate of four launches per year.[78] Moreover, launches generally cannot occur on demand because there is significant competition for launch pad availability. Assuming a launch pad and satellite are readily available for launch, it nominally takes 140 days from the receipt of the launch order to have a satellite on orbit broadcasting a usable signal.[79] Consequently, launches need to occur before actual failures, and additional satellites should be incorporated into the constellation to increase its robustness against unforeseen failures.

Today the constellation is the largest and oldest it has ever been. As of November 2003, the twenty-eight operational satellites have an average age of 8.4 years, far exceeding their design life of 7.5 years. Twelve satellites are operating on a redundant, backup component and are a single component failure away from a complete loss of the navigation mission. In addition, eight satellites are only one component failure from a complete loss of the spacecraft bus.[80]

There are signs the block II satellites may be reaching the end of their life expectancy. The average life expectancy each block of satellite, officially termed the mean mission duration (MMD), is updated semi-annually based on the previous six-month's performance and component failures. Component failures in 2003 shortened the average life expectancy of block

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Daugherty memo to COMAFSPACE, "GPS Constellation Sustainment and Assessment Team (CSAT) Minutes," (Vandenberg AFB CA: n.d.).

[77] Smith and McFarland, 2.

[78] Major David E. Hook, *OCS Launch Process.* Presentation to CSAT at Vandenberg AFB, CA, 18 January 2002, 5, 9; and Smith and McFarland, 2.

[79] Hook, 5, 9.

[80] Capt Patrick Long and Capt Daniel Lid, *Navstar Global Positioning System CSAT*. Presentation to CSAT at Vandenberg AFB, CA, 19 November 2003.

II satellites from a peak of 9.90 years in November 2002 to 9.65 years in October 2003. Block IIA satellites had a similar drop from 10.82 years to 10.32 years. The MMD and the launch schedule are input into a Monte Carlo analysis to generate a forecast of the probability of maintaining twenty-four operational satellites. This forecast forms the basis for scheduling replenishment launches.[81]

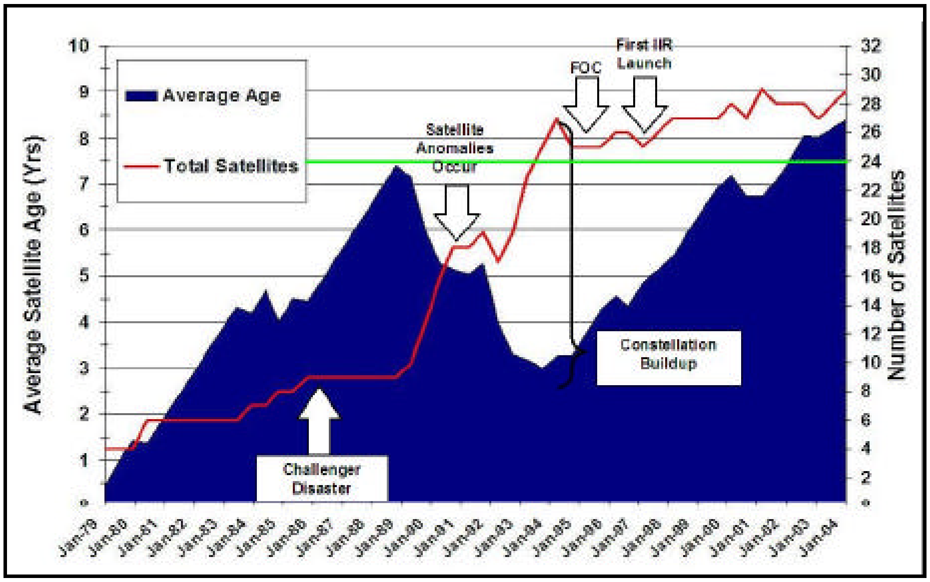

Figure 1. Constellation Status 1979-2004

The decrease in life expectancy in the block II and IIA satellites by a mere three and six months, respectively, had a significant impact on sustainment predictions. Figure 2 shows the probability of maintaining twenty-four satellites drops to 65 percent in fiscal year 2007, thereby violating the 95 percent satellite availability requirement. The strategy of maximizing satellite life by postponing launches has reduced the available “slack” in the system, thereby making the constellation very sensitive to changes in MMD predictions. It is similarly susceptible to unforeseen “frictions” such as a launch failure or a significant satellite design error which imposes an unexpected launch delay while a resolution is worked. Although this satellite availability deficiency will likely be resolved by shifting launches a few months earlier, it should

[81] Mason, 16, 23.

nevertheless send a clear warning signal to decision makers that the constellation is in a very precarious condition.

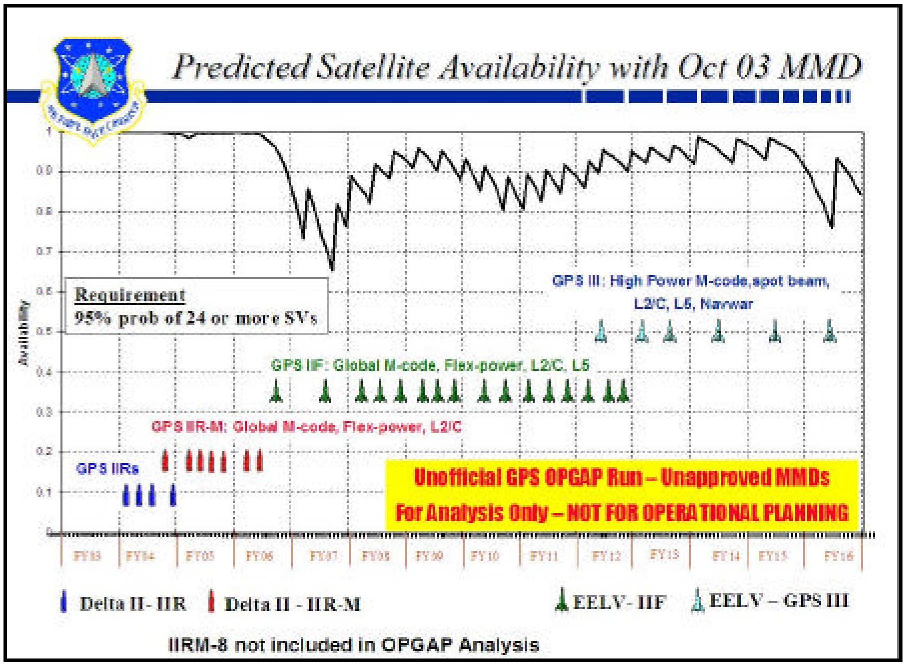

Figure 2. Predicted Satellite Availability from November 2003[82]

Perhaps more startling is the probability of multiple satellite failures within the next twelve months. Figure 3 on the next page shows a twenty-nine percent chance of five satellite failures within the next twelve months, and a fifty-five percent chance of four failures. There is simply no margin for canceling future satellite launches. While a single satellite failure within a fully populated constellation is manageable, the interaction of multiple satellite failures can degrade GPS service availability and reduce positioning accuracy for limited geographic areas. The potential user impacts caused by a satellite failure will be investigated in the next chapter. The history of the GPS space segment can be characterized as one of incredible achievement. No less amazing has been the remarkable efforts of the dedicated space operators and engineers

[82] Ibid., 4. This analysis is based on the official launch schedule and the proposed October 2003 MMDs. At the time of the analysis, the proposed MMDs had not yet been approved and were therefore unofficial.

tasked to keep the constellation flying. The GPS community has come to expect-- and rely on-- these remarkable efforts to maintain uninterrupted service that far exceeds the standard. Today one finds a constellation populated with fragile satellites operating with software patches and operational work-arounds. Each satellite has its own unique hardware and software configuration requiring tailored support requirements and specific handling instructions. Each satellite, in effect, has become its own engineering project. These half measures belie the importance of a global utility of GPS' stature.

Probability of Multiple GPS Failures

November 2003 (April 2003 Reliability)

(Includes mission success for IIR-10 and IIR-11. SVN-22 Out-of-Service)

	Probability of ≥ X Failures			
X	In Next 6 Months	In Next 12 Months	In Next 24 Months	In Next 36 Months
1	92%	100%	100%	100%
2	63%	96%	100%	100%
3	30%	81%	100%	100%
4	11%	55%	98%	100%
5	3%	29%	94%	100%

Figure 3. Probability of Multiple Failures from November 2003[83]

The very success of GPS has helped to conceal the emerging crisis which looms on the horizon. This "failure of success"[84] has severely reduced the margins from the current launch schedule and has inadvertently led to a chronic constellation problem of ailing spacecraft of questionable reliability. In addition, history demonstrates that numerous little "frictions" in the form of insufficient and unstable funding, programmatic scheduling delays, catastrophic launch failures, unforeseen launch slippage, and unexpected satellite anomalies are an ever-present

[83] Capt Mike Perz, *Navstar Global Positioning System CSAT.* Presentation to CSAT at Vandenberg AFB, CA, 19 November 2003, 8.

[84] Tenner, 48-49.

element of constellation management. The inability to precisely predict satellite failures coupled with the long lead times needed to build replacement satellites further complicates the problem. Sustainment plans must contain adequate slack and robustness to recover from these inevitable frictions and uncertainties. At the heart of satellite replenishment decisions lies the level of risk that must be deemed acceptable to mission assurance. The next chapter will investigate the risks to military and civil users at both the satellite and system level and the opportunity costs that have been borne due to delayed modernization schedules.

CHAPTER THREE: VULNERABILITIES AND COSTS

> In the old days, the tools of farming, manufacture, business management, and communication were simple. Breakdowns were frequent, but repairs could be made without calling the plumber, the electrician, the computer scientist--or the accountants and the investment advisors. Failure in one area seldom had direct impact on another. Today, the tools we use are complex, and breakdowns can be catastrophic, with far reaching consequences. We must be constantly aware of the likelihood of malfunctions and errors.
>
> Peter L. Bernstein, *Against The Odds: The Remarkable Story of Risk*[85]

> We are loath to let others do unto us what we happily do to ourselves.
>
> Chauncey Starr, *Perspectives on Benefit-Risk Decision Making*[86]

Since GPS made its military debut in the Gulf War, it has been imbedded into nearly every U.S. military platform and has come to perform a central, integrating role for most of the nation's critical civilian infrastructure. One simple measure of the growing importance of GPS to U.S. military operations is the number of GPS receivers in the inventory. Prior to the start of Desert Shield, the U.S. Army had only a few hundred handheld military GPS receivers.[87] In contrast, the U.S. Air Force and the Navy expect to have about 7,000 GPS-equipped platforms in service by 2006, with the U.S. Army deploying about 30,000 units. By then the three services will have fielded a total of more than 500,000 weapons using some form of GPS for guidance.[88] The loss of GPS could have a devastating effect on the combat power of these platforms and on joint operations in general.[89]

Critical civilian infrastructure, seeking the increased efficiencies made possible by GPS, has also developed a reliance on GPS that can lead to serious consequences if the service is

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[85] Peter L. Bernstein, *Against the Odds: The Remarkable Story of Risk* (New York: John Wiley & Sons, Inc., 1998), 2.

[86] Chauncey Starr, *Perspectives on Benefit-Risk Decision Making* (Washington, D.C.: National Academy of Engineering, 1972), 30.

[87] Rip and Hasik, 135.

[88] David Foxwell and Mark Hewish, "GPS: Is It Lulling the Military into a False Sense of Security?," *Jane's International Defense Review*, September 1998, 33.

[89] John G. Roos, "High Stakes Contract 'Winner Takes All' Outcome Unlikely from Air Force's GPS Satellite Plan," *Armed Forces Journal International*, October 1995, 64.

disrupted and the applications are not prepared with mitigating equipment and procedures.[90] As the "…essential services that underpin our society,"[91] critical infrastructures are vital to the nation's security, economy, and survival. A reliable GPS timing signal is essential to the efficient operation of geographically distributed infrastructures such as telecommunications and electrical power systems.

GPS has also spawned a multi-billion dollar international economic market representing billions of dollars in annual tax revenue.[92] The synergistic combination of shrinking receiver size, declining receiver prices, and improved constellation performance has created a diverse, dynamic, and rapidly expanding commercial market for GPS applications.[93] The Commerce Department reported global sales for GPS receivers were $867 million in 1994.[94] A recent report forecasts the world market for GPS equipment in 2008 will grow to either $34 billion as a moderate figure or to a more optimistic $41 billion, depending on the world economic recovery.[95] Similarly, the number of commercial users in the United States has exploded from more than 500,000 in 1995 to over 20 million in 2002.[96] GPS is on par with the Internet as one of the most successful dual-use technologies in history.[97]

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[90] John A. Volpe National Transportation Systems Center, *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System* (Office of the Assistant Secretary for Transportation Policy, U.S. Department of Transportation, 2001), 5.

[91] Theresa Brown, "Assessing Infrastructure Interdependencies: The Challenge of Risk Analysis for Complex Adaptive Systems," *A Workshop on Mitigating the Vulnerability of Critical Infrastructure to Catastrophic Failures*, 10-11 September 2001, Alexandria, VA, 1.

[92] Bruce D. Nordwall, "GNSS at a Crossroads," *Aviation & Space Technology*, 8 September 2003, 59.

[93] *The Global Positioning System: Charting the Future Summary Report* (National Academy of Public Administration and National Research Council, 1995), 9.

[94] John C. Dailey, "Space and Oceans: Can They Be Controlled?," in *Strategic Assessment 1999: Priorities for a Turbulent World* (Washington D.C.: National Defense University, 1999), 302.

[95] Allied Business Intelligence Research, "GPS World Markets: Opportunities for Equipment and IC Suppliers" [Internet] (accessed 31 December 2003) available from http://www.abiresearch.com/reports/GPS.html.

[96] Dailey, 302.; and Brad Parkinson, "GPtS, INtS and Critical Infrastructure," *ION National Technical Meeting 2003*, 22-24 January 2003, Anaheim, CA, 3.

[97] A dual use technology is one which benefits both military and civilian applications.

The dynamic and rapidly expanding nature of GPS makes its management that much more difficult. Constellation management policies must keep pace with GPS' exploding user base and its growing importance to the functioning and security of the nation. William Lowrance in his book, *Of Acceptable Risk*, warns that risk acceptance may simply be a passive continuance of "historical momentum" which persists because no alternatives are seen or the level of risk may not be fully understood or appreciated.[98] As the penetration of GPS into the military and civil infrastructure continues unabated, it is imperative the effects of a GPS disruption on the military and civil infrastructure and the national economy be fully appreciated. When considering satellite replenishment policy, one must account for all relevant costs and risks involved, not simply those direct costs associated with purchasing and launching a new satellite. Additional costs include the potential catastrophic consequences resulting from a loss or degradation in GPS service as well as the enhanced capabilities that have been foregone in favor of delaying launches.

While it is beyond the scope of this paper to quantify the risks and the associated costs of a GPS degradation, this chapter will attempt to illuminate some of the possible consequences and vulnerabilities involved with the aging GPS constellation.

The Limits Of Graceful Degradation

Despite the fragile condition of the constellation, there is little chance for a failure of the entire system. According to Owen Wormser, the Assistant Secretary of Defense responsible for overseeing space communications issues, GPS can withstand the loss of several satellites before completely collapsing. "If it ever came to it, the system would degrade slightly, rather than seize up," he says.[99] The ability of a system to fail gradually, as opposed to catastrophically, is the concept of graceful degradation.

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[98] William W. Lowrance, *Of Acceptable Risk* (Los Altos, CA: William Kaufmann, Inc., 1976), 78.
[99] Zolli, 40.

Graceful degradation is fundamental to the design of the GPS constellation. The placement of satellites within each orbital plane is designed to improve the constellation's overall robustness. Robustness is the ability of a satellite constellation to provide continued coverage and service availability during satellite failures.[100] Coverage is defined as the terrestrial service volume and the space service volume in which GPS service is provided. Service availability is the percentage of time the required GPS position accuracy is provided within a defined coverage volume.[101] The twenty-four satellites in the baseline constellation are positioned so a single satellite failure will not significantly degrade global availability or reduce global coverage.[102]

However, graceful degradation does not preclude localized service from being effected by one or two satellite anomalies. For the baseline twenty-four satellite constellation, there are some locations that can experience up to thirty-nine minutes of time when positioning service is lost entirely for the worst-case two-satellite out combination.[103] In this twenty-two satellite constellation, thirteen percent of the world would experience a daily loss of GPS service with the average loss of service reaching seven minutes in duration.[104] While seven minutes may not seem severe, the loss of GPS service during the final moments of an aircraft landing under low visibility conditions could be catastrophic. So while its true the constellation will not collapse entirely from one or two satellite failures, one should take little comfort in this fact. Users are still susceptible to potentially catastrophic effects due to multiple satellite failures even while global performance metrics continue to far exceed requirements. In summary, graceful degradation is a concept that only ensures continued performance at the constellation and global level, but it is not intended to protect navigation and timing users in limited geographical areas.

[100] N.W. Rhodus and P.D. Massatt, "GPS Baseline Constellation Update," (1991), 18.
[101] Air Force Space Command and Air Combat Command, *Operational Requirements Document (ORD) AFSPC/ACC 003-92-I/II/III Global Positioning System (GPS)*, 18 February 2000, 33.
[102] *SS-GPS-300E*, 12.
[103] Assistant Secretary of Defense for Command, Control, Communications, Intelligence, A-16.
[104] Ibid.

Appendix B contains two case studies of past satellite anomalies. Both anomalies impacted large geographical areas and clearly depict the inadequacy of graceful degradation in preventing potentially catastrophic results to users. In both cases, the anomalies had unexpected consequences on military, civil, and commercial applications, including safety-of-life aviation and maritime transportation augmentation systems. The growing pervasiveness of GPS has exposed numerous civil and military systems to new vulnerabilities.

Growing Civil Vulnerabilities

Over the past fifteen years GPS has become fully integrated into the Global Information Infrastructure.[105] The growth of the Global Information Infrastructure, to include GPS, has played a key role in dramatically changing how the nation's infrastructure and military operate. In the recent past, the many components of the nation's infrastructure operated independently of one another. The stand-alone nature of the various sectors and systems of the infrastructure were inefficient, but a failure in one system remained isolated to that system. Today, diverse sectors ranging from banking and finance to wastewater treatment and emergency services have become inextricably linked through the power, telecommunications, and information systems infrastructures. The networking and automation of assets have improved efficiencies, lowered costs, and expanded available capacity.[106] This has, in turn, increased competition among utilities, motivated them to reduce costs, and placed greater demands on an already strained infrastructure weakened by years of neglect.[107] These pressures have further fueled the trend to seek additional efficiencies in automation and networking.

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[105] The White House, (accessed).

[106] Miriam Heller, "Interdependencies in Civil Infrastructure Systems," *The Bridge*, [Internet] (Winter 2001, accessed 4 December 2003); available from http://www.nae.edu/nae/naehome.nsf/weblinks/KGRG-573PLA?OpenDocument.

[107] Ibid. (accessed).

These improvements and efficiencies have not been achieved without a sizable cost. The networking of infrastructures and the sharing of information across systems creates dependencies and vulnerabilities that never before existed. Because of the widespread use of information technology, a disturbance within one system of a sector, such as a GPS satellite outage, may be transferred to another system in an entirely different sector. The new system of large-scale, complex systems has created an emerging meta-infrastructure system.[108] A system failure within the meta-infrastructure can create complex, vertical interactions within and between systems as well as horizontal interplay between sectors. However, the distributed nature of most infrastructures, the enormous number of elements involved, and their complex interdependencies prevents one from knowing *a priori* the vulnerabilities of a system and how a disturbance will propagate through an infrastructure and possibly effect other related infrastructures.[109]

While there have been numerous studies related to civil GPS use, no consistent or objective method for assessing its cost, benefits, and risks have been established.[110] Part of the problem involves the multifarious nature of GPS applications and the interdependent, complex character of meta-infrastructures. The tighter interdependencies between systems and sectors and their increasing automation has raised new problems with analyzing a system's risks and vulnerabilities. Accordingly, there is currently no single, best method for scientifically assessing the potential consequences of meta-infrastructure disruptions.[111] Dr. Brown of Sandia National Laboratory's Infrastructure Interdependencies Program succinctly explains the difficulty of evaluating the risks to the nation's infrastructure. She writes:

> Direct dependencies are generally easy to recognize, describe and evaluate and past responses to outages may provide an indication of potential consequences of outages.

[108] Ibid. (accessed).
[109] Brown, 1.
[110] Brian B. Mahoney and Yacov Y. Haimes, "Quantitative Risk Analysis of GPS as a Critical Infrastructure for Civilian Transportation Applications," *ION GPS 2001*, 11-14 September 2001, Salt Lake City, UT, 58.
[111] Heller, (accessed).

> However, as the interdependencies increase the complexity and alter system responses, the secondary effects and feedback mechanisms may generate unforeseen consequences or reduce the magnitude of what appear to be considerable risks. Events that caused isolated faults in the past could now result in widespread disruptions. Additionally, and perhaps even more significantly, disruptions considered minor or acceptable at the scale of an infrastructure may now cause significant outages in a single operation or process critical to another infrastructure.[112]

In short, the very characteristics that make meta-infrastructures difficult to analyze are the same ones that can also cause a seemingly trivial component failure to quickly spread throughout the system. An incident that might seem inconsequential can ultimately have catastrophic effects.[113] Meta-infrastructures that are complex and highly interdependent are more vulnerable to "unavoidable system accidents."[114]

In recognition of the new vulnerabilities of the nation's infrastructure to disruption, President Clinton issued an infrastructure protection directive known as PDD-63. This policy identifies twelve infrastructures as "essential to the minimum operations of the economy and government" and deemed them as "critical infrastructure."[115] These systems have been singled out because of their central role in the welfare, security, and survival of the nation. They include, but are not limited to, information and communications, banking and finance, water supply, transportation, emergency law enforcement, emergency fire service, electric power, oil and gas production and storage, foreign intelligence, and national defense.[116] The twelve critical infrastructures and their relationships to GPS are listed in Table 1. The directive specifies, "Any interruptions or manipulations of these critical functions must be brief, infrequent, manageable,

[112] Brown, 2.

[113] Charles Parrow, *Normal Failures: Living with High Risk Technologies* (Princeton NJ: Princeton University Press, 1999), 92.

[114] Ibid., 72.

[115] "White Paper on the Clinton Administration's Policy on Critical Infrastructure Protection: Presidential Decision Directive 63," [Internet] (22 May 1998, accessed 3 February 2004); available from http://www.fas.org?irp/offdo cs/paper598.htm.

[116] Ibid. (accessed).

geographically isolated and minimally detrimental to the welfare of the United States."[117] Although this policy is chiefly aimed at the need to defend against physical and cyber attacks, it nonetheless clearly articulates the importance of protecting these systems from disruption and stresses their inherent vulnerability to cascading effects. Whether these cascading effects are initiated via attack on the GPS constellation or by satellite malfunction is largely irrelevant if the resulting disruption is identical.

Conspicuously absent from the twelve critical infrastructures is GPS itself. In the wake of the terrorist attacks on the World Trade Center and the Pentagon, the Heritage Foundation Homeland Security Task Force was established to recommend priorities for preventing future attacks and to limit their effects should one occur. In their report, "Defending the American Homeland," the Task Force sought to correct this oversight. The report's number two priority for protecting the nation's infrastructure is to designate the GPS constellation as a critical national infrastructure because of the vital role it plays in national security and as an enabler for the other critical infrastructures.[118] This recommendation clearly emphasizes the central importance of a functioning GPS constellation to homeland security, national defense, and the economy and places it on equal footing with the other critical systems.

Despite the clarity with which many doomsday scenarios seem to foretell, our true understanding of the consequences of a loss or degradation of GPS service on civil and military applications is limited and shrouded in uncertainty and ignorance. Without a clear understanding of the risks and vulnerabilities the aging GPS constellation poses to the nation's infrastructures and military operations, it is impossible to optimize the costs and benefits of the satellite replenishment strategy. In such a scenario, it is likely for risk acceptance (and satellite

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[117] Ibid. (accessed).
[118] Bremer and Meese, 2.

replenishment strategy) to reflect "historical momentum" and not be based on what the situation truly warrants.

Critical Infrastructure	GPS Dependencies
Information and Communications	GPS central to network synchronization, encryption, positioning and time transfer
Banking and Finance	GPS timing used for encryption, legal time traceability, and internet timing
Water Supply	No apparent direct involvement
Transportation	GPS used in virtually every mode of transportation; many include safety of life
Emergency Services	GPS critical to location of downed aircraft, car accidents, and maritime rescue. Also used in the dispatch and control of public safety vehicles.
Public Health Services	GPS timing for telemedicine
Electric Power	GPS timing synchronizes electric power grid; detects and precisely locates grid faults
Oil and Gas Production and Storage	GPS critical for monitoring large oil tankers in narrow waterways
Internal Defense[119]	GPS timing and positioning for Enhanced 911, precise incident location and reporting, emergency dispatch, encrypted communications, tracking of aircraft and ships
Foreign Intelligence[120]	GPS positioning and timing used in spacecraft attitude control systems, geolocation, and mission planning.
National Defense	GPS timing and positioning central to network centric warfare

Table 1. GPS Dependencies[121]

The following sections will examine GPS' contribution to four critical infrastructures. These four have been selected based on their criticality. Of the twelve critical infrastructures identified in PDD-63, Willis Ware argues that the power, telecommunications and information

[119] Dr. L. Jocic and others, "Space Overlay for Homeland Security Communications and Navigation," *National Technical Meeting*, 22-24 January 2003, Anaheim, CA, 741-744.

[120] Patrick W. Binning, Alan S. Hope, and Mark T. Soyka, "Orbit Determination and Prediction Concept for NEMO, the Naval Earthmap Observer Program," *ION GPS 1999*, 14-17 September 1999, Nashville, TN, 837. The Naval EarthMap Observer (NEMO), an unclassified remote sensing, hyperspectral imaging spacecraft prototype, uses GPS for accurate image geolocation and autonomous image planning and execution.

[121] Parkinson, 8.; and "White Paper on the Clinton Administration's Policy on Critical Infrastructure Protection: Presidential Decision Directive 63, (accessed).

systems are the most critical systems in the nation's infrastructure.[122] There is nearly universal dependence on telecommunications to operate all other infrastructure components. Information systems, linked together by telecommunications systems, must also function for most other aspects of the infrastructure to operate. Energy is necessary for facilities and equipment used by telecommunications and information systems. Consequently, these three systems are the most critical and are tightly coupled with one another.[123] In addition to these three systems, the chapter will also address the transportation sector because its "present or potential vulnerability to degradation or loss of GPS will have catastrophic consequences to either human life or economic and environmental damage."[124]

The author readily admits that by studying these infrastructures in isolation, one risks the chance of missing important cross-sector and multi-sector vulnerabilities. Lost in this review are the millions of dollars in indirect costs arising from a GPS satellite failure due to lost credit card sales, missed market trades, failed bank machines, delayed overnight deliveries, tardy just-in-time manufacturing, and the inability to contact emergency medical services. As Dorner warns, "To deal with a system as if it were a bundle of unrelated individual systems is, on the one hand, the method that saves the most cognitive energy. On the other hand, it is the method that guarantees neglect of side effects and repercussions and therefore guarantees failure. If we have no idea how the variables of the system influence one another, we cannot take these influences into account."[125] Regardless, this limited review of the role of GPS and its contributions to the nation hints at the possible expense and cascading consequences that can result from a regional degradation of GPS.

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[122] Willis H. Ware, *The Cyber-Posture of the National Information Infrastructure* (Santa Monica, CA: RAND, 1998), 17.

[123] Ibid.

[124] John A. Volpe Center, 5.

[125] Dorner, 88.

Transportation

The best-known civil use of GPS is in aviation, maritime, and surface transportation navigation. The transportation industry has rapidly embraced GPS technology because of its worldwide coverage, improved accuracy, and rapidly decreasing user equipment costs.[126] The widespread adoption of GPS promises to improve safety, increase operational effectiveness, and lower transportation costs. However, as GPS becomes more fully integrated into the transportation sector, legacy systems such as ground based surveillance radar will be eliminated and the dependence on GPS will continue to grow. Consequently, the loss of the GPS signal to the transportation sector could be severe.[127]

The aviation industry has set the groundwork for the use of GPS in nearly every phase of flight. The FAA has certified GPS as a primary means for navigation during oceanic operations and as a supplemental navigation system for domestic enroute, terminal, and non-precision approach phases of flight.[128] GPS and its augmentations are being further integrated into the aviation infrastructure to support aviation modernization programs to reduce aircraft separation distances for en route operations and to provide more efficient routing of commercial air traffic. These improvements promise to reduce flight times, save fuel, and cut costs. The continuing acceptance of GPS will reduce the number of costly ground navigation aids and the suite of cockpit avionics needed, thus further increasing the transportation industry's dependence on GPS.

The growing reliance on GPS has some concerned about the ability of the aviation industry to safely operate in case of a GPS failure. Langhorne Bond, former administrator of the Federal Aviation Administration (FAA), has stated, "GPS positioning and/or timing [has] crept into all three elements of the NAS [National Airspace System]--communications, navigation, and

[126] John A. Volpe Center, 1.
[127] Ibid., 43-48.
[128] Ibid., 7.

surveillance. Now we have a common failure mode that could bring down the entire ATC [air traffic control] system."[129] A severe outage of GPS would effect aviation safety if extensive vectoring of aircraft around the outage were necessary. The grounding of aircraft until the disturbance subsided would cause an "enormous" economic impact.[130]

The Department of Transportation (DOT) has investigated the potential impact of a short or long term GPS outage on the national transportation infrastructure. The DOT study, titled "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System," found the "civil transportation infrastructure … is developing a reliance on GPS that can lead to serious consequences if the service is disrupted, and the applications are not prepared with mitigating equipment and operational procedures."[131] The study further concluded a loss of GPS service could disrupt transportation service resulting in economic damage, property damage, serious injury or fatality, loss of confidence in a transportation mode, and liability to the service provider.[132]

Maritime operations are similarly becoming more dependent on GPS for both navigation and communication. The International Maritime Organization (IMO) has mandated that the estimated 20,000 ships internationally registered in 1999 be equipped with a GPS-based tracking system by 2007.[133] The system transmits automated tracking reports containing ship identification, position, heading, and velocity from ship-to-ship and ship-to-shore. In addition to the improved situational awareness it provides, the pinpoint accuracy GPS delivers in all weather conditions enhances the efficiency of shipping within restricted and heavily congested waterways

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[129] Charlotte Adams, "GPS: How Vulnerable Is GPS?," *Avionics Magazine*, [Internet] (2001, accessed 16 January 2004); available from http://www.defensedaily.com/reports/vulnerable_gps.htm.

[130] John A. Volpe Center, 41, 43-44. A severe outage is one that lasts days over wide areas or a series of moderate length outages over a wide area.

[131] Ibid., ES1.

[132] Ibid., 2.

[133] Pace and others, 36.; and John A. Volpe Center, 10-11.

such as harbors and channels and reduces the risk of collision and oil tanker spillage. The loss of GPS by itself would probably be manageable, but when combined with poor weather or a mechanical failure, the consequences could be serious. An off-course vessel in a constricted waterway is often only seconds away from grounding or colliding with another nearby ship. The loss of GPS navigation could leave a ship's captain blind and only seconds from trouble. The environmental and economic loss from such an accident would be significant.[134]

Telecommunications and Information Systems

Not only is GPS positioning data a tremendous asset to transportation systems, its timing signal is becoming deeply imbedded into the global information infrastructure used for both wireless and fiber voice, data, and video networks. Precise timing has become an enabler for the proliferation of geographically distributed computing. A U.S. Space Command report has even stated that the timing signal is now more commercially important than the positioning services it provides.[135] The value of GPS timing to the national telecommunication and information systems and its contributions to the nation's economic strength and military prowess is immeasurable.

Solitary computers working in isolation have been replaced by distributed servers and workstations connected to local area networks. Local area networks have, in turn, been connected to larger, global networks. The emerging system of networks require stable clocks accurate to the millisecond to synchronize shared databases, time stamp transactions, and coordinate distributed applications.[136] However, most workstations operate with inexpensive, internal crystal oscillators for their timing source which can lose up to 10 seconds per day.[137] In

[134] John A. Volpe Center, 45.
[135] Dailey, 303.
[136] Paul Skoog, "The Importance of Network Time Synchronization" [Internet] (n.d., accessed 16 January 2004); available from http://www.truetime.net/pdf/imp_netsync.pdf.
[137] Richard E. Schmidt, "GPS Times the Internet," *GPS World*, February 2000, 44.

order for thousands of computers to efficiently and reliably exchange information across thousands of miles, it is crucial their timing be in unison.

Not long ago, network timing originated from a limited number of hyper-accurate external timing sources. The timing signals from these sources were passed along sequentially throughout the system and were used to discipline the less accurate crystal oscillators.[138] The most common external timing sources were highly stable but expensive cesium atomic clocks. These clocks cost as much as $55,000 a piece and were difficult to operate and maintain.[139] The superior performance of GPS as a timing source and the ability to economically install inexpensive GPS receivers throughout a network has revolutionized the way synchronization is accomplished today. GPS has become the most widely used timing source for distributing dependable and accurate timing signals to the Internet as well as to smaller local area networks.[140]

Several additional trends have led to the widespread adoption of GPS as the timing standard of choice. First, the ever growing demand for greater throughput capacity, speed, and cost efficiency has driven the telecommunication industry to incorporate digital lines and servers into their communication architecture. Digital communications, however, are more complex and are more susceptible to timing errors than their analog counterparts.[141] In a digital network, information is broken down into tiny, discrete packets. Each of these packets is encoded with a time stamp before being transmitted across the network. After the data packets reach their destination, computers must reassemble them according to their time stamps. Failure to keep the source and receiver clocks in lock step will cause information to be dropped, misread, or

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[138] Jeremy Kintzel, "Timing Is Everything," *Wireless Review*, [Internet] (1 September 2001, accessed 3 May 2004); available from http://www.wirelessreview.com/microsites/magazinearticle.asp.

[139] Chris Bucholtz, "Timing from a Higher Source GPS Could Help Put All Networks in Sync," *Telephony Online*, [Internet] (17 June 1996, accessed 29 October 2003); available from http://telephonyonline.com/ar/telecom_timing_higher_source/index.htm.; and Ed Butterline and Sally L. Frodge, "GPS: Synchronizing Our Telecommunications Networks," *ION GPS 1999*, 14-17 September 1999, Nashville, TN, 602.

[140] Schmidt, 42.

[141] Butterline and Frodge, 598.

repeated. Synchronization is the means of keeping these elements operating at the same rate and is essential for reliable operation.[142] As GPS timing continues to improve, synchronization can be made more precise by reducing the spacing between digital data packets. As a result, more data can be "squeezed" into the same space, thereby improving the efficiency and speed of digital applications and maximizing the utilization of the available bandwidth.[143]

The proliferation of long distance carriers and cell phones have also increased the need for synchronization. One long distance phone call may transit a network by using several different carriers before it reaches its final destination. Each carrier must synchronize its network to the networks of other carriers to whom it is connected to ensure a clean and efficient handover of data. In a similar fashion, as a cell phone user transits through her cell, the wireless network must know where the caller is located with respect to its towers and cleanly handover the caller from one tower to the next. These multiple interfaces must be properly managed to achieve a seamless communication infrastructure. If carriers or towers use timing sources that are not consistent with one another, there may be timing mismatches. Depending on the severity of a timing mismatch, it may be merely a nuisance or a drag on the efficient use of bandwidth. In more severe cases, the mismatch can cause a fault to promulgate throughout the network, causing ever greater problems as it progresses. In the extreme case, a geographic telecommunications blackout can occur.[144]

The impact of even a trivial timing error on communications networks is hard to predict. Take for instance a brief GPS satellite anomaly that occurred in 1997. During routine navigation payload commanding by satellite operators, erroneous timing data was uploaded to a single

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[142] Symmetricom, "Synchronizing Telecommunications Networks: Basic Concepts" [Internet] (n.d., accessed 8 September 2003); available from http://www.symmetricom.com/media/pdf/app_notes/an-stnbc.pdf;.

[143] Butterline and Frodge, 599.

[144] Kintzel, (accessed).; and Butterline and Frodge, 599.

satellite. The satellite broadcast a thirty-second timing error for a mere six-second period before it automatically removed itself from service. This was, however, long enough for numerous timing users in the eastern United States to take an erroneous time hack from the satellite. Cellular telephone networks were especially hit hard. Out of 800 cellular sites in that region of the country, 110 sites failed. Thousands of cell phone customers were left without service for several hours, causing millions of dollars in damage.[145]

A loss or degradation of GPS timing can be visible to customers in a number of ways depending on the application. As already mentioned, a complete loss of GPS timing can bring down an entire digital network.[146] Fortunately, there is redundant timing and failsafe measures built into many systems to prevent a widespread blackout. Less sensitive analog applications can continue to "coast" along using their less accurate, internal clocks for a week to one month.[147] However, without an accurate external clock reference, the timing of the various elements of the system will slowly drift until call control can no longer function.[148] Less serious timing faults can manifest themselves in a number of ways, depending on the application. Temporary timing errors in an analog voice signal will result in cross-talk or static, faxes will lose portions of their image, and video teleconferencing and telemedicine will experience frozen frames. A mistimed digital signal can cause jitter, a phenomena where the signal is briefly but completely cut out. More severe timing anomalies can cause blocks, lost handoffs between cell phone towers, or failed call setups.[149] In addition, many encryption schemes are very sensitive to timing errors and will cause a secure connection to fail. The attempts to re-establish the secure connection will further reduce

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[145] Simon P. Worden and John E. Shaw, *Whither Space Power? Forging a Strategy for the New Century* (Maxwell Air Force Base, AL: Air University Press, September 2002), 92.; and Dailey, 303.
[146] Kintzel, (accessed).
[147] Butterline and Frodge, 601.
[148] Kintzel, (accessed).
[149] Ibid. (accessed).

data rates and will expose the encryption keys to compromise.[150] Pagers, ATMs, e-commerce, banking, market trading, and the Internet could all be disrupted. All of these failures can range from mere annoyances and inconvenience to inefficiencies, fiscal losses, or loss of life.

Power Generation and Distribution

GPS is also ideal for economically distributing a precise, common time reference throughout the large geographical areas that electrical power systems occupy. Precise timing is essential for electrical power generation control, system monitoring, analysis, and fault detection and location. GPS is replacing older timing sources in many areas because it offers improved accuracy, reliability, and economy.[151]

The nation's electrical power infrastructure consists of four massive power grids which span most of the continent. Each grid is subdivided into several utility service areas which contain numerous power generators. The utility service areas and power grids are interconnected to permit efficient and economical power sharing and load leveling.[152] The electric power grid is a very dynamic system requiring constant balancing of power generation with shifting loads. Since electricity cannot be stored for later use, power generation must exactly match the rate it is used. This requires constant real-time monitoring and sophisticated controls to dynamically restore system stability by adjusting generator output and shedding of loads.[153] The output from each generator must also be carefully controlled to ensure it meets stringent standards to permit the seamless transfer and sharing of power across utility boundaries. For instance, the alternating current (AC) power generated in Tennessee must be consistent with the AC power in Arizona in terms of frequency, phase angle, and voltage magnitude. GPS provides a common, accurate

[150] Butterline and Frodge, 599.
[151] Kenneth Martin, "GPS Timing in Electric Power Systems," *ION GPS 1999*, 14-17 September 1999, Nashville, TN, 1057.
[152] Ibid. 1058.
[153] Ibid. 1063.

timing reference that can be used by all utilities across North America to synchronize their power generation.[154]

GPS timing is also used by automated monitoring and recording equipment to detect local and system-wide disturbances. A generator failure or a transmission line outage can cause a damaging disturbance to ripple throughout the system. These failures must be quickly detected and isolated to protect interconnected generators and to prevent the needless isolation of a utility service area from the remainder of the grid. Fault location equipment located at substations and transmission line towers can pinpoint a failure to within three hundred meters by triangulating the differences in the time of arrival of the disturbance as it propagates throughout the system.[155] Rapid fault location can significantly reduce the time needed to restore electrical service.

For many of these applications, only GPS can deliver the required timing accuracy at a cost that permits it to be widely used throughout the system. Consequently, GPS is becoming more tightly integrated within the nation's power infrastructure. A reliable GPS signal is essential for the power system's safe and reliable operation.[156]

Military Vulnerabilities

Just as civil infrastructure has become more reliant on the GPS signal, so, too, has the U.S. military. Since the Gulf War, joint military operations have become increasingly dependent on information superiority and the ability to collect, process, and distribute relevant information through a network of widely dispersed sensors and shooters.[157] The primary mechanism to achieve the vision of information superiority is through the concept of network centric warfare (NCW). GPS is a fundamental element to achieving the technological vision of NCW. For its

[154] Ibid. 1058-1061.
[155] Ibid. 1060.
[156] Ibid. 1063.
[157] Chairman of the Joint Chiefs of Staff, *Joint Vision 2020* (Washington, D.C.: US Government Printing Office, 2000), 6-7.

proponents, NCW represents an "emerging theory of war" which recognizes that combat power is no longer derived from the Industrial Age concept of mass. Rather, combat power in the Information Age is generated from the timely access to quality information which leads to improved battlespace awareness.[158] Heightened battlespace awareness enables dispersed forces to self-synchronize themselves to the commander's intent thereby achieving greater speed of command, increased operations tempo, enhanced lethality, and improved survivability.[159] In theory, networked forces have access not only to their own resident capabilities but also to the capabilities distributed across the entire network. A commander can use the power of the network to reach across the theater to select the most appropriate munition based on the target, the risk of collateral damage, the required responsiveness, and the desired probability of damage. Networking ultimately has the potential to exponentially increase the combat power of small, dispersed forces by improving their speed, precision, and reach. Once this is achieved, it is believed a networked commander will be able to mass effects without massing forces.[160]

The military infrastructure of NCW harnesses the power of geographically dispersed sensors and shooters by linking them together into networks that allow for the extremely rapid, high-volume transmission of digitized data to decision makers. Technologically, the concept of NCW relies on three tightly interconnected grids: the sensor, the shooter, and the information grids.[161] Each of these grids is highly dependent on GPS positioning and timing to achieve discriminate precision effects.

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[158] Fred P. Stein, "Observations on the Emergence of Network Centric Warfare" [Internet] (n.d., accessed 19 January 2004); available from http://www.dodccrp.org/steinncw.htm.

[159] Ibid. (accessed).; Vice Admiral Arthur K. Cebrowski and John J. Garstka, "Network-Centric Warfare: Its Origin and Future," *Proceedings of the U.S. Naval Institute*, [Internet] (January 1998, accessed 19 January 2004); available from http://www.usni.org/Proceedings/Articles98/PROcebrowski.htm.; and Force Transformation Director, Office of the Secretary of Defense, *Creating a Decisive Warfighting Advantage* (Washington, DC: Department of Defense, Winter 2003), 3.

[160] Cebrowski and Garstka, (accessed).

[161] Ibid. (accessed).

Information Grid

GPS timing plays a similarly important role in integrating the dispersed network of diverse battlefield sensors and munitions as it does in synchronizing distributed civilian infrastructures. The information grid is the backbone that lashes the sensors, shooters, and decision makers together. The information grid provides "the means to receive, process, transport, store, and protect information for the Joint and combined forces….This grid provides the necessary infrastructure to permit the 'plug and play' of the sensors and shooters."[162]

Most fundamentally, in order for the sensors, platforms, and systems spread across an area of operation to work cooperatively, they must be referenced to a common time and space standard. The absolute common time scale used throughout the DoD is Universal Coordinated Time as maintained by the U.S. Naval Observatory UTC(USNO), and the common positioning reference has become the World Geodetic System 84 (WGS-84).[163] GPS is the primary means for distributing UTC(USNO) timing to military users worldwide, and its positioning solutions are referenced to the WGS-84 common grid.[164] Quite simply, GPS is fundamental to the NCW architecture for enabling interoperability of all its disparate elements.

The complex NCW architecture also requires a high degree of synchronization across its various elements in order to seamlessly collect and exchange billions of bits of data and fuse them into a common battlefield picture. GPS is the primary means for synchronizing this architecture.[165] A disruption in GPS timing could adversely effect each grid individually or it could induce rippling regional effects across the grids. This could leave the U.S. military temporarily blind, confused, and de-fanged. At the very least, military forces may worry about

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[162] Stein, (accessed).

[163] R.L. Beard and J.D. White, "Common Time Reference Technology for Systems Inter-Operability," *32nd Annual Precise Time and Time Interval (PTTI)*, 28-30 November 2000, Reston, VA, 369.

[164] Staff, CJCSI 6130.01c, A-1.

[165] Air Force Space Command and Air Combat Command, 4.

data quality and lose confidence in the system. The fog and friction of war would be increased, and command and control would suffer.[166] In a worst case scenario, a degraded GPS signal could interrupt the command and control system and isolate the Joint Force Commander from his fielded forces or his reachback capabilities.[167] It logically follows that a combat force dependent on an information-rich network must be supplied with a robust and reliable information grid that is not susceptible to such failure.

Sensor Grid

The sensor grid consists of a myriad of permanent and mission-specific sensors which provide the joint force with precise and persistent situational awareness over the area of interest to enable superior decision making. These sensors may reside on a multitude of platforms, including unmanned aerial vehicles (UAVs), patriot missile defense systems, attack helicopters, individual aircraft, troops in ground vehicles, special operations forces on horseback, and intelligence satellites, to name just a few.

GPS not only helps to navigate the sensor platforms and to synchronize them with maneuver units in time and space, but its timing signal also aids in accurately locating targets with respect to the WGS-84 common reference grid. Sensors require an accurate reference time to time stamp observations of platform position or sensor measurements for geo-referencing. Radar and laser sensors, among others, use precise timing to accurately range their targets by multiplying the time difference of arrival of an observation by the speed of light.[168] The more precise the time stamp of each measurement, the more accurate the range to the target. Once the data is collected, it must again be time tagged before being transmitted to the network for processing and for later distribution to the rest of the net.

[166] Bucholtz, (accessed).
[167] McPherson, 12-13.
[168] Beard and White, 376.

For instance, Airborne Warning and Control (AWACS) aircraft can provide real-time direction to attacking forces by referencing themselves, their targets, and their allies to within meters by the use of GPS.[169] The RC-135 Rivet Joint aircraft and the U-2R Dragon Lady both use precise GPS timing to accurately locate targets from the signals and images they collect.[170] The Predator medium endurance unmanned aerial vehicle (UAV) uses GPS to reconnoiter hostile enemy territory at low altitudes without the fear of losing a pilot to enemy fire. With knowledge of its own position and the range and angle offsets of its high resolution video and still photography sensors, the Predator can transmit the location of dynamic targets to another platform for engagement and can conduct post-strike combat assessments to assist in re-attack recommendations.[171]

Another GPS-based sensor of significance is the Force XXI Battle Command Brigade and Below (FBCB2), also known as "blue force tracker." It allows soldiers to differentiate between enemy (red) and friendly (blue) forces. The system uses GPS transmitters mounted in military vehicles and aircraft to monitor their precise location. That information is combined with terrain maps and intelligence on enemy positions to create a battlefield picture that can be shared over commercial satellite networks. The use of blue force trackers during Iraqi Freedom allowed commanders in the theater and in the United States to have a "precise sense of the location, capacity and capability of the battlefield."[172] It also improved joint situational awareness and was credited with reducing incidents of fratricide and collateral damage.[173] The three brigades of the Army's 3rd Infantry Division were stretched out over 300 miles but were still

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[169] Rip and Hasik, 230.
[170] Ibid.
[171] Ibid.
[172] Megan Scully, "Iraq War Proves Power of Net-Centric Vision," *Defense News*, 26 January 2004, 2.
[173] William B. Scott, "Military Space Engineers Explore Broad Spectrum of Technologies," *Aviation Week and Space Technology* (28 January 2004) in [e-mail newsletter] *CGSC Space News (*Ft. Leavenworth KS: Command and General Staff College, 28 January 2004).

able to monitor each other's activities and those of the Marines on their flank, which was key to rapidly reaching Baghdad.[174] Furthermore, it helped to more fully integrate air and ground operations since pilots had a much clearer picture of where coalition troops were located.[175]

Shooter Grid

The shooter grid exploits the improved situational awareness made possible by the sensor grid by precisely and discriminately engaging targets. The extended standoff range and precision of today's munitions offer the joint force commander an expanded range of options for rapidly engaging targets while limiting the exposure of U.S. troops to enemy fire. GPS is the DoD standard for position, navigation, and timing data and is required on all U.S. weapon platforms.[176]

The accuracy once common to only expensive cruise missiles is now being incorporated into virtually every future munition, including artillery and mortars. The number of GPS-aided weapons capable of being plugged into the network will continue to grow, as will our vulnerability to a GPS failure if mitigating procedures and backup systems are not in place. Adding GPS to conventional guidance systems can trigger "cascading value enhancements" and greatly increase the military utility of the weapon system.[177] An example is the Army Tactical Missile System (ATACMS). In the Gulf War, ATACMS used an inertial guidance system for navigation and was strictly limited to area targets. Following the war, GPS was added to the system. The increased accuracy improved its lethality to the point where the number of bomblets carried in the warhead was reduced from 950 to 300. This reduced the warhead's weight which, in turn, increased its range from 160 to 300 kilometers, placing a greater number of enemy targets

[174] Scully, 2.
[175] Scott, "Military Space Engineers Explore Broad Spectrum of Technologies,"
[176] Staff, CJCSI 6130.01c, C-1.; and Linda de France, "GPS Upgrades Raise Protection Issues," *Aerospace Daily*, [Internet] (6 June 2001, accessed 15 October 2003); available from http://www.aviationnow.com/avnow/news/channel/news/;.
[177] J.R. Wilson, "Precision Strike: Weapons Getting Smarter All the Time," *Armed Forces Journal*, February 2004, 34.

at risk. During Iraqi Freedom, a new warhead was married to the system which was very successful against point targets with minimal risk of collateral damage.[178] Hence the mere inclusion of an inexpensive GPS receiver improved lethality, increased effective engagement range, reduced logistical requirements, and expanded missions. The loss of GPS would result in a reversal of these fortunes by causing unexpected "cascading failures" across the myriad of systems that now use GPS.

Real world military experience and past military exercises have demonstrated the potential confusion and loss of combat power a degraded GPS could cause. During the Gulf War when the constellation was not yet fully operational, GPS service was lost for two hours each day over the Gulf region.[179] During these periods, U.S. and allied maneuver units often became lost in the featureless desert. General Patrick Cordingley, Commander of the British Seventh Armored Brigade, later recalled his reliance on GPS for navigation during the Gulf War: "First thing in the morning, and then just after dark, the satellites that provided the signals would go out of range. As a result every morning and evening for about fifteen minutes we would get lost."[180] Military exercises that have simulated the loss of GPS have significantly confused command and control functions and complicated planning. In one case, a GPS disruption caused a convoy of helicopters to ignore obvious visual cues and fly off in the direction indicated by an inaccurate GPS receiver.[181] It is likely coalition forces have become more reliant on GPS since the Gulf War and are even more susceptible to limited disruptions in navigation data. As GPS is more fully integrated into the NCW infrastructure, problems arising from the loss or disruption of GPS will be more severe.

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[178] Ibid.
[179] Rip and Hasik, 133.
[180] McPherson, 15.
[181] John A. Volpe Center, 32.

As the concept of NCW comes to fruition, military power will no longer primarily reside within the platforms. Instead, true combat power will be derived from the network itself and the ability to contribute to the commander's intent via the network.[182] Consequently, the importance of a robust and fully functional network, enabled by GPS, can not be overestimated. Robert Leonhard notes that the correct way to assess the value of a system is, "focusing not on a weapon's lethality, but rather on its complementary effects on other friendly weapons."[183] In this regard, although GPS is not lethal and has been categorized as a support system, it can profoundly affect the lethality and survivability of nearly every other weapon system. The proper functioning of each grid within the NCW construct depends on a viable and robust GPS constellation. There are few military systems that can claim the same level of military utility as GPS. Nor are there many systems which could have similar widespread and devastating impact on the joint scheme of maneuver as an ailing GPS constellation.

Deferred Modernization

The previous sections have explored the vulnerabilities of various civil and military applications to a satellite failure with the aim of illustrating the potential indirect costs that could be incurred by a failing constellation. This last section will discuss another "cost" of the LTS replenishment strategy: the postponement of critical enhancements to the constellation. By permitting the failure rate of satellites to define the launch rate, Air Force Space Command has deferred the replacement of older satellites with newer, more capable counterparts by several years. Figure 4 on the next page is a graphical depiction of the 1995 satellite replenishment plan. The 1995 plan forecasted the constellation in 2004 to consist of eighteen block IIR satellites and

[182] William B. Scott and David Hughes, "Nascent Net-Centric War Gains Pentagon Toehold," *Aviation Week & Space Technology*, [Internet] (26 January 2003, accessed 20 January 2004); available from http://www.aviationnow.com/avnow/news/.

[183] Robert R. Leonhard, *The Principles of War for the Information Age* (Novato, CA: Presidio Press, 1998), 221.

six IIF satellites; all block II/IIA satellites were to have been decommissioned by 2003. Accordingly, the infusion of new technology has been retarded by at least five years.[184] More significantly, by continuing to subscribe to the LTS strategy, Air Force Space Command risks additional future delays. Owen Wormser, the Assistant Secretary of Defense responsible for overseeing space communications issues, has succinctly stated, “the longer we continue to support the current system, the worse we will be in the long run.”[185] The significant capabilities these modernization programs will bring to the joint warfighter are the subject of the remainder of this chapter. The capabilities that have been deferred in favor of postponing launches must be considered an “opportunity cost” of the current LTS strategy.

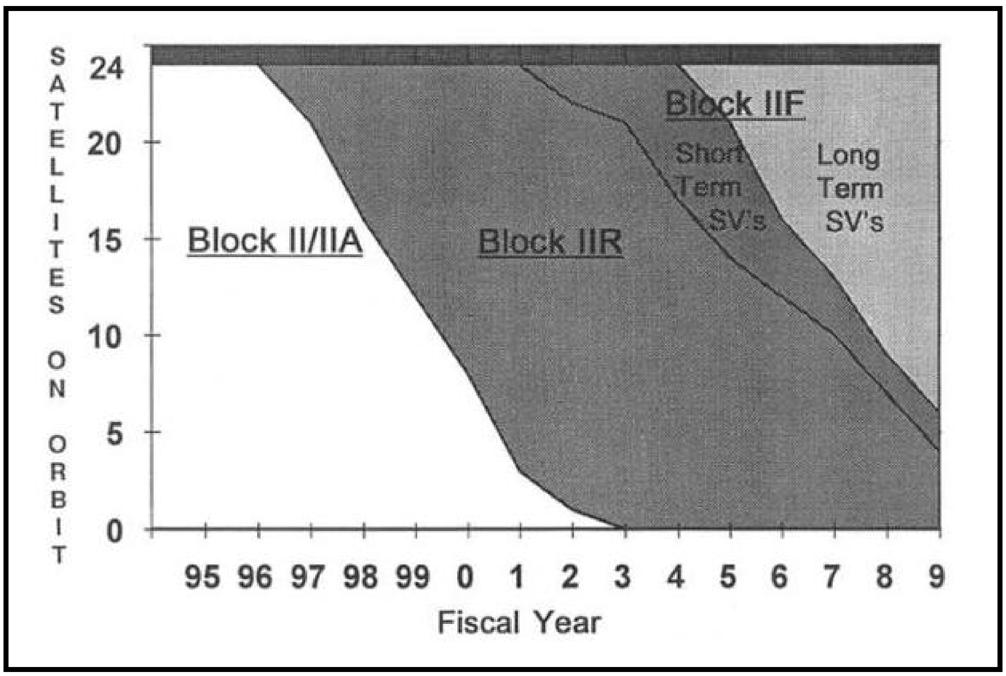

Figure 4. 1995 Satellite Replenishment Plan[186]

[184] Michael Sirak, "Holding the Higher Ground," *Jane's Defence Weekly*, [Internet] (8 October 2003, accessed 8 October 2003); available from http://ebird.afis.osd.mil/ebfiles/s20031008222886.html. The 1995 plan called for the first launch of IIF in 2001. Current plans place the first IIF launch in late 2006.

[185] Zolli, 40.

[186] National Research Council, 11.

Why Modernize?

Despite the incredible utility of GPS, the current system has several limitations. The first and most significant of these limitations is its susceptibility to intentional jamming and unintentional signal interference.[187] Malicious disruptions can range from limited denial of GPS service caused by a low power, localized jammer to more catastrophic incidents that could result in the denial of GPS service over large geographic areas and for extended periods of time.

During Operation Iraqi Freedom, the U.S. saw the first salvos fired in the struggle to control space when Iraqi forces attempted to jam the GPS signal around Baghdad.[188] Although the U.S. was able to quickly eliminate the jamming threat, the struggle for control of the GPS signal will increase in intensity for three reasons. First, as the U.S. military becomes more dependent on its signal, GPS will become a more enticing target for our adversaries. Secondly, the very low power of the GPS signal makes it very easy to jam; neither large amounts of power nor sophisticated technology is needed to overcome the weak signals.[189] For instance, Russia is actively marketing a handheld jamming system slightly larger than a cigarette pack that is capable of denying GPS service over a 120-mile radius.[190] Lastly, U.S. officials expect our adversaries to improve their sophistication and effectiveness in denying our use of GPS. "We know potential adversaries are increasing their skills," said Adm James Ellis, Commander of US Strategic Command. "We must be ready."[191]

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[187] For a discussion on GPS interference, see John A. Volpe Center, 25-34, 63-78.; *Commission to Assess Space Management and Organization*, 19-20.; *GPS Risk Assessment Study - Final Report* (Johns Hopkins University Applied Physics Laboratory, 1999) 5-1 to 5-10, I-1 to I-11.; and Adams, (accessed).

[188] Capt. Chris Watt, "Space Superiority Essential to Warfighters in Global War on Terror," *USAFE News Service* (13 April 2004) in [e-mail newsletter] *Space News (*Ft Leavenworth, KS: US Army Command and General Staff College, 20 April 2004).

[189] U.S. Space Command, *Global Positioning System Joint Concept of Operations*, 24 November 1999, A-3.

[190] *Commission to Assess Space Management and Organization, 20;* and Bremer and Meese, 19-20.

[191] Sirak, (accessed).

The Heritage Foundation Homeland Security Task Force in their report, "Defending the American Homeland," recognized GPS' susceptibility to jamming. It recommended the Department of Defense:

> …accelerate modification of GPS satellites currently in production to include more robust signals. It should begin launching these satellites at an increased rate to augment the fragile constellation currently in operation…Additional satellites with stronger, better designed signals would increase availability and ensure operations by providing a more robust signal structure that is considerably less vulnerable to jamming….Immediate planning is necessary to begin acquiring additional satellites to sustain the larger constellation.[192]

The Air Force is also looking to improve GPS accuracy for both military and civil users. The service is gradually enhancing accuracy from two meters to less than one meter. The eventual goal is to refine the signal to the twenty- to fifty-centimeter range to allow a bomb to be dropped to within one-meter of its target.[193] This improved level of accuracy is needed to minimize the risk of collateral damage and to guide smaller munitions to their targets while maintaining the same probability of damage.[194]

Many civil users, such as the aviation industry, are also seeking improved real-time accuracy for dynamic applications. The primary source of civil GPS error is ionospheric delays, which can normally add up to seven meters of error.[195] Military users are able to correct for this error by comparing the ranging solution from the L1 and L2 frequency bands. Because civil users currently have access to only the L1 frequency, they are unable to correct for this error. It is

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[192] Bremer and Meese, 21.

[193] Robert Wall, "USAF Renews GPS III Focus," *Aviation Week & Space Technology*, 20 May 2002, 57.

[194] There is a trend toward smaller munitions. The large 2,000-pound Joint Direct Attack Munition (JDAM) is being augmented by a 500-pound JDAM variant. When placed into service in 2004, this smaller weapon will increase the B-2 stealth bomber's capacity to deliver GPS-guided weapons by a factor of five. The B-2 will be able to independently strike up to 80 separate targets on a single bombing mission or can destroy an enemy airfield in a single pass. A 250-pound small diameter bomb is also under development.

[195] Shaw, Sandhoo, and Turner, 21-22.

government policy to add two new civil frequencies by 2005 to enable civil users to eliminate this source of error.[196]

Lastly, the U.S. has a policy to deny the enemy's use of GPS while protecting its use by allied military forces and preserving it for civilian users. This capability, called NAVWAR, will be a significant force protection measure as our adversaries begin to exploit the GPS signal against us by integrating the technology into their own cruise and ballistic missiles. In order to selectively and locally deny GPS signals, the military signal must be spectrally separated from the civil signals. New military codes, known as M-codes, will be added to the signal structure to prevent enemy use while limiting the "bleed over" effects to civilians outside of the area of operation.

Modernization Programs

These challenges are being met by three new versions of satellites. The first satellite to bring enhanced capabilities to the constellation is the modernized block IIR, also known as the IIR-M. Presently, the Air Force plans to modernize eight of the remaining IIR satellites. The first IIR-M launch was originally scheduled for March 2003,[197] but that has now slipped to July 2004. The IIR-M will significantly reduce the susceptibility of the civil signal to unintentional interference by doubling the power of the signal and modulating the new civil signal on L2 (referred to as L2C).[198] The L2C has the added benefit of improving civil accuracy by allowing users to directly correct for the ionospheric delay error.

The IIR-M will benefit military users by adding a new military signal (M-code) onto the existing L1 and L2 frequencies. The M-code will be a key component of NAVWAR and will

[196] Ibid. 18.

[197] Dee Ann Divis, "Washington View," *GPS World*, (13 June 2002, accessed 3 January 2004); available from http://www.gpsworld.com/gpsworld/article/articleDetails.jsp?id=21892.

[198] John A. Volpe Center, 79.

enhance signal security and will enable military users to directly acquire the encrypted signal without having to first acquire the easily jammed civil code.[199] The IIR-M will also have a flex power upgrade to defeat low level enemy jamming. Flex power will allow operators to boost the power to either of the military codes (M-code or the encrypted precision P-code) by a factor of ten.[200] These improvements will provide the U.S. military with a limited anti-jam capability.

The block IIF is the follow-on satellite for constellation sustainment. The launch of the first IIF satellite has slipped three years to late 2006.[201] In addition to the enhanced IIR-M capabilities, the block IIF will also add a third civil frequency known as L5. The L5 is specifically designed to meet the needs of safety-of-life services, such as civil aviation and maritime transportation. The L5 is located within a protected portion of the electromagnetic spectrum reserved for aviation safety-of-life applications. This measure should protect the signal from unintentional interference and ensure its continual availability for critical applications. The new civil frequency will provide signal redundancy, improve positioning accuracy, enhance signal availability, increase resistance to interference, and provide system integrity.[202]

GPS III will follow the IIF satellites and represents a quantum leap in capability. GPS III will look at the entire GPS architecture to find areas for improvement to ensure the system meets the nation's PNT needs for the next thirty years. It will feature stronger, jam-resistant signals, more precision, and greater reliability. In 2001, the launch of the first GPS III satellite was estimated to be in the 2009 timeframe.[203] However, in what has been called the "single most incomprehensible move since the Cold War,"[204] the Air Force cut funding for GPS III in 2002 to

[199] Kelley, Mortoccia, and Pendley, 1344.; and Shaw, Sandhoo, and Turner, 19.
[200] Wall, "USAF Renews GPS III Focus," 57.
[201] Sirak, (accessed).; and Kelley, Mortoccia, and Pendley, 1344.
[202] Shaw, Sandhoo, and Turner, 18.
[203] de France, (accessed).
[204] Divis, "Washington View," (accessed).

divert monies to other troubled space programs facing cost overruns. The cuts forced a restructuring of the program and pushed the projected first GPS III launch out to 2012.[205]

GPS III is looking to fix the jamming problem "once and for all" [206] by increasing signal power by 100 to 300 times over the signal strength of the current constellation. In addition, GPS III spacecraft will have a spot beam that can focus the power and signal strength within a specified area of operations to overcome attempts at jamming.[207] The increased signal power will improve its reception and availability in virtually all terrain and atmospheric conditions. The signals will penetrate thick, triple canopy jungles and will be available in downtown "urban canyons" where high-rise buildings often obscure the signal. The signal may even be usable inside enclosed steel and concrete structures and underground facilities.

GPS III will also significantly improve navigation and timing accuracy. Today the nominal positioning accuracy is 1.5 to 2 meters and 5 to 8 nanoseconds of clock error. GPS III will drive positioning errors to less than one meter and timing errors to hundreds of picoseconds (trillionths of a second).[208]

These modernization programs represent significant improvements in GPS capabilities for the joint warfighter and the civil user. Both civil and military users can expect to see improvements in accuracy, security, reliability, integrity, and signal availability. Unfortunately, the expanded capabilities afforded by the modernized satellites have been delayed for the sake of maximizing on-orbit satellite life. While we wait for obsolete technology to step aside for the next-generation of satellites, these enhanced capabilities remain firmly grounded.

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[205] Ibid. (accessed).; and Mason, 4.
[206] Wall, "USAF Renews GPS III Focus," 57.
[207] Ibid.
[208] Command, 10.; and Dee Ann Divis, "GPS III, Modernization Face Budget Cuts," *GPS World*, September 2002, 10.

CHAPTER FOUR: PRECAUTIONARY RISK ASSESSMENT

> …the science of risk management sometimes creates new risks even as it brings old risks under control. Our faith in risk management encourages us to take risks we would not otherwise take. On most counts, that is beneficial, but we must be wary of adding to the amount of risk in the system.
>
> Peter L. Bernstein, *Against The Gods: The Remarkable Story of Risk*[209]

> When safety limits are set … the goal typically is also to ensure "reasonable certainty of no harm." But when current uses create vested economic interests in the status quo, risk assessments may readily be biased toward declaring practice "safe." Quite often, in cases of this nature, the standard practice is not "reasonable certainty of no harm," but rather "lack of certainty of harm," which is not the same thing at all.
>
> Dr. Edward Groth III, *Science, Precaution and Food Safety: How Can We Do Better?*[210]

The essence of decision-making is making tradeoffs among different objectives that are often in conflict with one another. Satellite replenishment decisions are difficult because there is an inherent tension between maximizing operational efficiency and mission effectiveness. Complicating this tradeoff is a significant degree of risk, uncertainty, and ignorance.

Satellite replenishment decisions have several sources of risk, uncertainty, and ignorance. We have seen in previous chapters that our ability to predict when a satellite will fail or which component will eventually falter is very limited. The more accurate a prediction, the less precise it is, and vice versa. Also, the long lead times needed to build and launch replacement satellites require satellite acquisition decisions to be made "in the blind" before all the necessary evidence is on hand to accurately calculate satellite longevity. This uncertainty limits our ability to strike a balance between operational effectiveness (defined as successful mission accomplishment) and efficiency (optimal and economical use of resources). Additionally, our understanding of how a satellite failure will ultimately impact users is even less well understood. Our ignorance in this

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[209] Bernstein, 335.

[210] Edward Groth III, "Science, Precaution and Food Safety: How Can We Do Better? [Discussion Paper for the US Codex Delegation] (February 2000, accessed 5 January 2004); available from http://www.biotech-info.net/precautionary_groth.pdf.

regard is easily appreciated when one considers the multitude of GPS receivers built to varying degrees of sophistication and quality, the dizzying array of GPS applications in sheer number and diversity, and the complex interdependencies among applications and meta-infrastructures. Lastly, our knowledge of the current state of each satellite is restricted to a stream of telemetry due to their remote inaccessibility.

When the probabilities and outcomes of a course of action are known, numerous statistical tools and methods such as cost-benefit analysis and expected value theory can assist risk-based decisions. These tools can provide leaders with valuable insights which can improve the quality of decisions. These assessments have traditionally been perceived as scientific and objective evaluations based on the best available facts. However, in cases where uncertainty or ignorance is high, these tools may no longer be appropriate.[211] Dr. Groth, the senior scientist at the Consumers Union, explains the limitations of this conventional wisdom: "quantitative risk assessment ordinarily, almost by definition, can be done only for comparatively well-understood risks on which good data exist. Less adequately understood risks may be heavily discounted, even if they are possibly more serious than the risks for which we have good data."[212]

Another limitation to the current art of risk assessment is the analysis tends to be reductionist in nature, problems are simplified, and relationships are treated linearly.[213] However, complex adaptive systems have a myriad of dynamic and interdependent relationships fueled by feedback loops which cannot be treated linearly. For instance, research into the vulnerabilities of our nation's infrastructure can indicate the vulnerabilities of GPS to attack, but we are largely ignorant of how an anomaly in the GPS constellation may propagate across the power and telecommunication infrastructures to pose a hazard to the finance or transportation sectors. These

[211] Ibid. (accessed).
[212] Ibid. (accessed).
[213] Ibid. (accessed).

more complex issues of determining the risks of cascading effects across meta-infrastructures is just now starting to be addressed.[214]

Under these conditions, the traditional approach to assessing risk may be inadequate and more subjective than once thought. Specifically, traditional assessments rely only on available and quantifiable evidence and fail to explicitly consider the absence of evidence or evidence which cannot be quantified. In "Late Lessons From Early Warnings," its authors state, "Such complex reality demands better science, characterized by more humility and less hubris, with a focus on 'what we don't know' as well as on 'what we do know'."[215]

The Precautionary Principle

One method that has gained attention in recent years for explicitly dealing with uncertainty and ignorance is the precautionary principle. The precautionary principle is "an overarching framework of thinking that governs the use of foresight in situations characterized by uncertainty and ignorance and where there are potentially large costs to both regulatory action and inaction."[216] Fundamental to the concept is the idea of taking prudent action when the possible consequences may be catastrophic, even in the absence of conclusive scientific proof.

The principle has its origins in the German concept of *Vorsorgeprinzip*, or foresight planning with wise care and stewardship.[217] During the 1970s and 80s, environmentalists and public health advocates modified the concept as a mechanism for anticipating the adverse side effects of new technologies in order to minimize the collateral damage caused by their use before they could be regulated. The predominant regulatory paradigm requires conclusive scientific

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[214] Mahoney and Haimes, 57-58.

[215] European Environmental Agency, "Late Lessons from Early Warnings: The Precautionary Principle 1896-2000" [Internet] (2002, accessed 13 March 2004); available from http://reports.eea.eu.int/environmental_issue_report_2001_22/en/Issue_Report_No_22.pdf.

[216] Ibid. (accessed).

[217] Tim O'Riordan and James Cameron, "Interpreting the Precautionary Principle" [Internet] (Earthscan Publications Ltd., 1994, accessed 5 January 2004); available from http://dieoff.org/page31.htm.

evidence that harm is occurring before steps can be taken to protect public health or the environment.[218] New products and technologies are presumed safe until proven harmful. The dilemma for environmental science is that it may take several years, if ever, to collect enough scientific evidence to firmly establish stringent cause and effect relationships between an offending technology and its negative consequences. By that time, irreversible or widespread damage may already be done. The precautionary principle holds the potential to resolve this dilemma by "provid[ing] a rationale for taking action against a practice…in the absence of scientific certainty rather than continuing the suspected practice while it is under study, or without study."[219] In essence, the precautionary principle shifts the burden of proof away from those advocating caution to those who are undertaking the potentially hazardous course of action.

The application of the precautionary principle is appropriate if the situation under consideration meets three criteria.[220] First, the potential hazard must represent a serious or irreversible harm to society. Previous chapters have shown the pervasiveness of GPS throughout the civilian infrastructure and its tight coupling with safety-of-life applications which could lead to catastrophic regional consequences in case of a failure. The potential harm to national security should GPS fail during a conflict could be disastrous as well. Second, the situation must contain significant uncertainty or ignorance. GPS uncertainty and ignorance exists at both the satellite and the meta-infrastructure level. Lastly, there is a compelling need to reduce the potential hazard before one can establish a strong causal linkage between the hazard and its suspected consequences. In such cases, the time needed to gather more information to reduce epistemic

[218] Joel Tickner, Carolyn Raffensperger, and Nancy Myers, "The Precautionary Principle in Action: A Handbook" [Internet] (n.d., accessed 5 January 2004); available from http://www.biotech-info.net/handbook.pdf.; O'Riordan and Cameron, (accessed).; and Edward Groth III, "Towards a More Precautionary and More Scientific Approach to Risk Management," *World Conference on Medicine and Health*, [Internet] (12 August 2000, accessed 1 March 2004); available from http://www.biotech-info.net/towards_precaution.pdf.

[219] Tickner, Raffensperger, and Myers, (accessed).

[220] The first criteria are from Ibid. (accessed).; European Environmental Agency, (accessed). expanded the litmus test for applying the precautionary principle by adding the final criterion.

uncertainty may seriously jeopardize public safety. In our case, we will expand this criterion to include jeopardizing mission accomplishment. A review of the criteria indicates GPS satellite replenishment is a valid candidate for adopting the precautionary principle. Adopting a precautionary risk assessment approach cannot eliminate uncertainties or avoid the consequences of ignorance altogether, but it does offer a better chance for anticipating both real and opportunity costs and ultimately for achieving a better balance between operational effectiveness and efficiency.

One of the difficulties in applying the precautionary principle to satellite replenishment decisions is there is no universally accepted definition for the principle. The concept has been encapsulated in many international agreements and treaties and has now moved beyond environmental protection and into the fields of biotechnology, pharmaceutical safety, food safety, occupational safety, and consumer protection.[221] Nevertheless, the most common definitions are written with public safety or environmental protection in mind and are often too broad to guide practical decision making processes. There are, however, a number of common elements that can be distilled from these numerous definitions and modified for our purposes. Eliminating those elements that deal exclusively with environmental stewardship and retaining those concepts most salient to satellite replenishment strategy, one is left with four tenets.[222]

The first tenet is a reframing of the traditional decision making approach so the burden of proof is shifted away from those advocating protection toward those proposing a course of action that may be harmful. Sometimes referred to as "duty of care,"[223] this tenet suggests a more conservative decision making process. It offers the opportunity to break the chain of "logic of failure" decisions that ultimately lead to poor decisions with potentially catastrophic results. This

[221] Groth, "Science, Precaution and Food Safety: How Can We Do Better?" (accessed). ; Tickner, Raffensperger, and Myers, (accessed).

[222] O'Riordan and Cameron, (accessed).

[223] Ibid. (accessed).

tenet changes the replenishment question facing decision makers from “Prove we need to launch” to “Prove we don’t need to launch.” Under this new construct, the burden of proof is shifted away from those who advocate a conservative stance (i.e. adhere to the approved launch schedule) to those who are recommending a riskier approach (i.e. postpone launch). This tenet harnesses the power of the inherent uncertainty involved in the decision to help ensure that if an error in judgment is to be made, it should be made to the benefit of mission effectiveness.

The second tenet is termed “preventive anticipation.” Preventive anticipation is “a willingness to take action in advance of scientific proof of evidence of the need for the proposed action on the grounds that further delay will prove ultimately costly to society.”[224] Unfortunately, unambiguous evidence of an impending satellite failure is not always forthcoming. An unwillingness to proactively replace an ailing satellite before it fails permits risk to accumulate within the constellation, increases the probability of multiple satellite failures, and ultimately places users at risk. Decision makers must also accept that current launch technology prevents the rapid and timely replacement of a failed satellite. Users may be exposed to degraded GPS performance for months while a replenishment launch is prepared. Accordingly, the decision to launch a replenishment satellite must come before a failure; otherwise the cost to society can be enormous.

The next tenet obligates decision makers to safeguard margins of safety. Margins of safety and confidence levels should be sacrosanct and not be approached, let alone breached. This requires the decision maker to deliberately constrain one’s choices and to adopt a conservative perspective. In the past, replenishment decisions have permitted the probability of maintaining twenty-four satellites to dip below the ninety-five percent boundary. These measures erode the robustness and vitality of the constellation. In the future, leaders may be tempted to

[224] Ibid. (accessed).

again violate the mandated level of certainty as it becomes more challenging to maintain. The precautionary principle helps guard against such a temptation by making the ninety-five percent probability boundary inviolate. Decision makers are encouraged to take proactive measures to build sufficient "slack" into the system to guard against inevitable frictions such as unforeseen launch delays and unpredicted satellite failures which can quickly consume planning margins and management reserves.

The final tenet is "proportionality of response." This tenet requires decision makers to consider the cost-effectiveness of the margins of safety to show that the selected degree of restraint and conservativeness is not unduly costly. This introduces a bias to conventional cost-benefit analysis to include a "weighting function of ignorance" and to consider the costs of possible second and third order cascading effects due to implementing a selected course of action. One must consider not only the direct expense of a replenishment satellite, but also the relevant indirect costs that would be incurred if a malfunctioning satellite were to disrupt military operations or place safety-of-life applications in jeopardy.

There are two basic forms of the precautionary principle: the strict and active forms. [225] The strict form of the precautionary principle requires inaction when action might pose a risk.[226] If sufficient proof of safety is unavailable for the proposed course of action, then it should be rejected. In contrast, the active form calls for choosing less risky alternatives when they are available, and for taking responsibility for potential risks. This form calls for more action, not

[225] Chris Phoenix and Mike Treder, "Applying the Precautionary Principle to Nanotechnology" [Internet] (January 2003, accessed 9 March 2004); available from http://www.crnano.org/precautionary.htm.

[226] An example of the strict form of the precautionary principle is reflected in how Air Force Space Command's eastern and western launch range safety offices approach risk assessment. The range safety office is responsible for ensuring the safe conduct of all launches. When a launch provider wants to launch a new or significantly redesigned booster, it is the launch provider's responsibility to first demonstrate the booster meets exacting safety standards before it is certified for launch. Inability to adequately demonstrate the booster's safety results in it not being approved for launch. Significantly, it is not the responsibility of the safety office to prove the booster is unsafe. In other words, the onus of proof rests squarely with the actor proposing the potentially dangerous action: the launch provider.

less, to find an appropriate mechanism to mitigate the risk. It is the active form that best applies to satellite replenishment.

Under the active form of the precautionary principle, the satellite replenishment decision is reframed so the default replenishment decision is to launch to replace satellites that have exceeded their mean mission duration and are showing signs of approaching their end-of-life. In the absence of convincing contradictory evidence, the recommendation is to launch. The party advocating that a launch be delayed or cancelled, for whatever reason, has the responsibility for "proving" the constellation will not drop below its minimum performance standards within the mid-term (defined as the next six years) and modernization capability milestones will not be effected. Failure to provide such convincing evidence results in the selection of the default decision: a recommendation to launch.

Before precautionary risk assessments can be applied to satellite replenishment decisions, more work must be done to "operationalize" the principle for everyday use. The principle must be rigorous, disciplined, and defensible against challengers. Moreover, the commander's estimate of the current state of the constellation, the commander's intent toward constellation sustainment, and his willingness to accept risk must also be incorporated into the precautionary risk assessment.

In the meantime, the precautionary principle's greatest value is simply helping to illuminate the biases in the current framework that work against a decision to launch and to encourage decision makers to consider the possible second- and third-order consequences of a decision not to launch. By putting proper emphasis on what we don't know, we can put what we do know into proper perspective. A thorough analysis of the uncertainties and sensitivities of our risk assessments and assumptions is essential. However, over precaution can be expensive in terms of lost opportunities and under investment in other pressing defense needs. The precautionary principle provides a framework to balance the uncertainties inherently involved with satellite replacement decisions while ensuring investments in the constellation are justified.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

> More and more it is not the single catastrophic event that disturb society the most. Whereas the old disasters were spectacular, the new disasters are diffuse, silent processes that continue almost invisibly and usually too late. Several years can separate cause from its eventual effect. Often the cause is no longer a singular event, but is the cumulative effect of many small events. Whereas the old disasters were localized and sudden, the new ones may be global and gradual.
>
> Edward Tenner, *Why Things Bite Back*[227]

Conclusions

The world is developing a growing dependency on GPS services. Its highly accurate, globally available signal coupled with declining receiver prices has encouraged diverse industries to fully integrate it into their processes. Within the United States, GPS is imbedded into nearly every critical civilian infrastructure. The proper functioning of these critical infrastructures, such as power and telecommunications systems, is essential to the country's welfare and security. Safety-of-life applications, such as the 50,000 aircraft that fly within the national airspace everyday,[228] count on a reliable and accurate GPS signal. In addition, GPS has spawned a $17 billion annual domestic receiver market.[229] A failure or degradation in GPS could significantly impact the economic growth, trade, and productivity of the United States.

The U.S. has also come to embrace GPS has a means for delivering shorter, more decisive, and less destructive military victories with fewer casualties for all. As a "battlefield utility," the GPS signal is essential to the functioning of the emerging network centric sensor, shooter, and information grids. The loss of GPS could have disastrous and widespread effects across the battlefield as dispersed units are desynchronized from the operational plan and forced

[227] Tenner, 25.

[228] Federal Aviation Administration, "Air Traffic Control System Command Center" [Internet] (accessed 2 April 2004); available from http://www.fly.faa.gov/Products/Information/information.html.

[229] Butler.

to operate with degraded command and control, diminished situational awareness, and without the support of long-range precision fires.

The explosive growth of GPS over the past fifteen years has outpaced the Air Force's management policy on satellite replenishment. The growing importance of GPS must be matched with a replenishment strategy that improves its utility for military, commercial, and international users. However, the Launch to Sustain (LTS) replenishment strategy, which launches satellites only after a failure or just prior to failure, has led to two problems. First, LTS has placed a premium on maximizing individual satellite life in order to reduce constellation life cycle costs. Extraordinary measures have been taken to sustain aging satellites, sometimes even at the expense of signal accuracy and reliability. These extraordinary measures have led to unsurpassed global performance, but it has temporarily hidden the declining state of health of the constellation. Consequently, the situation has not commanded the attention it merits from the DoD, and the funding for new launches has not received the priority it deserves. As a result, the constellation is populated with numerous aging satellites, causing overall risk to accumulate within the constellation. This "rearranging effect" of risk has led to a more elusive and chronic problem of a fragile constellation prone to multiple satellite failures. The risk of multiple satellite failures impeding military operations or degrading critical civilian infrastructure is a very real possibility.

The LTS strategy has also impaired the timely introduction of critical new capabilities to the constellation. By permitting the failure rate of satellites to define the launch rate, the Air Force has deferred the replacement of older satellites with newer, more capable counterparts by several years. Modernization efforts to increase the signal's resistance to interference and jamming, to improve accuracy to the sub-meter level, and to selectively prevent our adversary's use of GPS are all critical to the future success of U.S. forces on the battlefield. In addition, the new satellites will incorporate redundant civil signals and improved integrity monitoring for safety-of-life applications. These improvements will likely generate entirely new GPS markets and will help ensure GPS remains the universal standard for navigation and timing services. The following recommendations are made to improve the satellite replenishment process.

Recommendations

First Recommendation. Instead of viewing satellite replenishment as primarily an engineering optimization problem, it should be perceived as an operational issue with a central focus on the commander's acceptance of risk to the joint warfighter and the civil and commercial user. The commander of U.S. Strategic Command should communicate his level of risk acceptance to the Constellation Sustainment and Assessment Team (CSAT) through a commander's intent statement. Moreover, leadership should consider an effective satellite replenishment strategy as the first and most fundamental step in achieving and maintaining space superiority. The ability of a space force to operate "without prohibitive interference" starts with capable and reliable on-orbit space assets and the trained space crews to operate them. Few adversaries today possess the counterspace capability to neutralize five medium earth orbit satellites. However, the current LTS strategy has accomplished something our adversaries can not do: it has placed five GPS satellites at risk for failure over the course of the next twelve months.[230] In addition, the LTS strategy has successfully denied worldwide users access to the expanded capabilities of the IIR-M satellite due to the low launch rate. Adopting a warfighter perspective will assist in restoring some art and warfighter judgment to the science of satellite replenishment.

Second Recommendation. Air Force Space Command should replace the Launch to Sustain (LTS) replenishment strategy with a Launch to Augment (LTA) strategy. The LTA strategy will accelerate the deployment of "increased operational capability above the designed standard in

[230] Perz, 8.

response to war, crisis, contingency, or theater need,"[231] and will proactively replace ailing satellites before they can place users at risk. Under the LTA strategy, replenishment launches should be executed at the rate of three to four per year to accelerate the infusion of new capabilities. This rate should continue until Full Operational Capability (FOC) is achieved for the new safety-of-life L5. Functioning satellites that are proactively replaced can either be disposed or maintained in a "mothball" configuration as a quick reaction spare in case of an unexpected failure. The timely improvement in system performance and the reduced chance for degraded GPS service is adequate justification for the additional cost of accelerating the launch schedule.

GPS is vital to national military and economic infrastructures. Funding levels and stability should be commensurate with its national importance as a critical infrastructure. The $100 million price tag to procure and launch a new satellite is expensive, but it also promises a significant return on investment in terms of improved efficiency, global commerce, enhanced safety, and improved capability for the warfighter. In at least two studies it was found the added costs incurred from a fixed launch schedule are partially mitigated by cost reductions through multiyear procurements, lower satellite storage costs, and reduced contractor "standing army" expenses. The LTA strategy allows new technology to be rapidly fielded, and it sustains a well-defined, steady funding profile. [232]

Third Recommendation. A precautionary-based risk management approach should be integrated into the deliberate satellite replenishment planning process. A precautionary risk assessment reframes the launch decision to place the burden of proof on those advocating a launch delay, as opposed to those recommending a launch. A precautionary risk assessment approach, in

[231] Air Force Space Command, *Launch Strategy and Scheduling Procedures,* 2-3.
[232] Kelley, Mortoccia, and Pendley, 1345.; and *White Paper on Future Global Positioning System (GPS) Acquisition Policy and Impacts* (KPMG Peat Marwick LLP, 1996), 13-14.

conjunction with the LTA strategy, will ensure the inherent biases associated with extreme uncertainty will not work to delay future launches. This will help restore a proper balance between operational effectiveness and operational efficiency. Furthermore, risk assessments and reliability predictions must explicitly communicate the uncertainty involved in them and their sensitivity to changing assumptions and conditions. The use of sensitivity analysis and scenarios to explore the implications of different assumptions will aid decision makers in recognizing the limits of our understanding of the risks involved and the possible consequences of degraded GPS service.

Fourth Recommendation. The military services should incorporate scenarios simulating the loss and degradation of GPS services into military training, wargames, and exercises. As the Space Commission Report points out, "military commanders have had relatively little experience in learning to cope with the loss or temporary interruption of key space capabilities, such as GPS, satellite communications, remote sensing or missile warning information. Space capabilities should be embedded in military exercises."[233] These scenarios should exercise backup navigation and command and control systems and contingency procedures. In addition, the services should develop models and simulations to identify key military capabilities that are vulnerable to a loss or degradation of GPS service. This will assist combatant commanders in developing necessary contingency plans for a loss of GPS. The exercises and models will also help identify acquisition requirements for supplemental theater navigation and timing systems and validate more stringent theater GPS availability and security requirements.

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[233] *Commission to Assess Space Management and Organization*, 77.

Fifth Recommendation. The Department of Homeland Security, in collaboration with the Departments of Defense, Justice, Transportation, Energy, and Commerce (among others), should develop modeling and simulation tools that quantify the effects of a loss or degradation of GPS on the nation's critical infrastructures. The tool could also be integrated into homeland defense exercises, experiments, and wargames to simulate the potential second- and third-order cascading effects arising from a terrorist attack on vulnerable infrastructure systems and to assist in developing contingency response plans. The main goal is for the integration of sectoral results and the modeling of interdisciplinary systems to gain an understanding of the interdependencies among GPS, its augmentation systems, critical end-user applications, and the meta-infrastructure.

Sixth Recommendation: The Defense Advanced Research Projects Agency (DARPA) and the Naval Research Laboratory (NRL) should conduct research into developing satellite prognosis equipment that continually monitors critical satellite components for early signs of failure and alerts operators of a predicted malfunction. Satellite operators can use the alert to conduct additional analysis to verify the need to command the satellite to a redundant, backup system in advance of the component failing. The prognosis equipment would support a more proactive approach to satellite maintenance and help reduce the costly, unscheduled downtime needed for anomaly resolution and reduce the risks to users and the satellite arising from a component failure. Research effort should first focus on prognosis equipment for the atomic frequency standards since these components are the most likely to fail and can cause the greatest harm to users when they do fail.

APPENDIX A: GPS DESCRIPTION

The mission of GPS is to provide reliable worldwide, high accuracy, three dimensional, position, velocity, and time (PVT) information to military forces across the full spectrum of combat as well as to civil, commercial, and scientific users for peaceful purposes.[234] It accomplishes this mission through its space, control, and user segments.

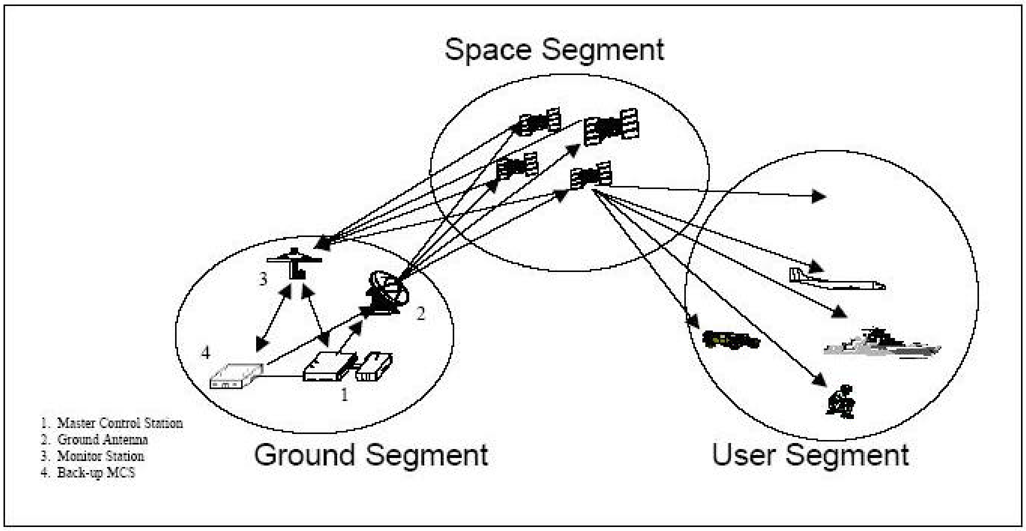

Figure 5. The Global Positioning System[235]

Space Segment

The space segment consists of at least twenty-four satellites positioned in semi-synchronous, circular orbits located 10,898 nautical miles above the earth's surface. The satellites are arranged in six orbital planes with four satellites in each plane. Each of the six orbital planes are inclined 55 degrees relative to the earth's equator. The satellites are strategically positioned within each orbital plane so at least four satellites, the minimum number generally needed to calculate a user's three-dimensional position, are observable at any point on

[234] The White House, (accessed).
[235] Air Force Space Command, *Concept of Operations*, 3-1.

the earth's surface. Six to ten satellites are typically visible to a user in an unobstructed, benign environment.[236] The twenty-four satellite constellation configuration is pseudo-optimized to minimize the impact on global coverage in the event of a single satellite failure.[237]

Each satellite transmits an L1 (1575.42 MHz) and L2 (1227.6 MHz) carrier radio signal for the navigation and timing missions of GPS. Two levels of GPS service are superimposed on these signals: the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). Currently, SPS is available to the worldwide user community free of charge and is transmitted on the L1 frequency. Future modernization programs will also modulate the SPS onto the L2 frequency and will add a new L5 frequency for civil safety-of-life applications. The PPS is encrypted on both the L1 and L2 frequencies and is only available to authorized users with cryptographic keys.[238] PPS is intended for U.S. military forces, authorized government users, and select allies.

Control Segment

The control segment is made up of the resources on the ground that operate, maintain, and manage the space segment. Collectively referred to as the Operational Control Segment (OCS), it consists of the Master Control Station (MCS), located at Schriever Air Force Base, and five ground antennas and six monitor stations strategically located around the world. The Master Control Station is the focal point for GPS command and control operations. From the MCS, satellite operators from 2d Space Operations Squadron (2 SOPS) continually monitor the health and status of the satellites to verify the spacecraft subsystems are operating nominally and to ensure navigation performance remains within acceptable limits. Satellite telemetry is received by the remote ground antennas and displayed in the MCS for satellite operators to monitor and

[236] Assistant Secretary of Defense for Command, Control, Communications, Intelligence, A-18.
[237] SS-GPS-300E, 12.
[238] Joint Program Office, *Navstar GPS User Equipment Introduction*, 1-3.

evaluate the health of the satellite. Satellite operators conduct periodic maintenance, troubleshooting, and anomaly resolution of the satellites by transmitting commands via the ground antennas.

In addition to maintaining the health of the satellites, the OCS also monitors and evaluates the performance of the navigation signals. The six unmanned monitor stations passively receive the L-band navigation signals of overhead satellites, calculate satellite-ranging data, and pass that information to the MCS. The MCS uses the near real-time data to continuously fine-tune its sophisticated computer models which are used to predict the orbit (ephemeris) and clock behavior of each satellite. At least once a day, each payload is uploaded with the most current model prediction for the satellite. As the model ages, it gradually becomes less accurate, causing the navigation signal to degrade. If navigation performance degrades to the point where it exceeds standards, a new navigation message is uploaded to the restore normal accuracy. By monitoring the navigation signal of each satellite nearly continuously, the OCS is able to ensure satellite navigation performance remains within tolerance and errant signals are quickly reigned in before they can endanger users.

User Segment

The user segment consists of the millions of users and applications which use the navigation and timing signals broadcast by GPS to calculate position, velocity, and timing measurements. There are currently over twenty million civil user sets in use with more than four hundred thousand civil sets sold each month.[239]

[239] Parkinson, 3.

APPENDIX B: SATELLITE ANOMALY CASE STUDIES

The following two cases have been selected to illustrate the potential for satellite failures to cause potentially catastrophic consequences and to uncover the limitations of graceful degradation from a user's perspective. While these cases may not be representative of most satellite anomalies, they nonetheless depict the possibility for hazardous consequences. At a time when multiple satellite failures are expected each year for the foreseeable future, these hazards should be clearly understood and their consequences incorporated into the cost side of the satellite replenishment ledger.

Case One: SVN 22 Clock Failure[240]

The most common failure mechanism on GPS satellites is the atomic frequency standard (AFS).[241] The AFS generates a highly precise timing signal which is fundamental to all payload operations since a timing deviation as small as one billionth of a second results in a one foot ranging error.[242] Although usually very precise, these atomic clocks are extremely sensitive to even the minutest environmental changes and require constant monitoring by the satellite operators. As the clocks age, they become more susceptible to failure. A clock failure may manifest itself as either a gradual and graceful deterioration in performance or it can be instantaneous and catastrophic with little or no advanced warning. In the latter case, satellite operators must rapidly identify the problem and move quickly to protect users from the hazardous signals. From the time an anomaly is first detected, it normally takes satellite operators up to one hour to transmit a payload safing command. The safing command protects users by earmarking

[240] Unless otherwise noted, this case study relies on unpublished material from Lt Col Daniel P. Jordan memo to 50 OG/CC, "Operations Review Board (ORB) 01-003," (Schriever AFB CO, 10 August 2001).; and Air Force Space Command, "Global Positioning System (GPS) Satellite Vehicle Number (SVN) 22 Anomaly Review" (Peterson AFB CO, 2001).

[241] Air Education and Training Command, 47.

[242] Office, *Navstar GPS User Equipment Introduction*, 1-2.

the signal as “unhealthy,” which prevents it from being used by GPS receivers. In the meantime, users can be exposed to navigation errors of several hundred, sometimes even thousands, of meters.

On 28 July 2001, satellite vehicle number 22 (SVN 22) experienced a severe navigation payload anomaly as it traveled in a northeasterly direction over the southeast Pacific Ocean toward Central America and the United States. Unfortunately the clock failure occurred in an area where a known “blind spot” exists in the GPS monitoring network. When the satellite re-entered monitor station visibility, its initial performance data available to the satellite operators was inconclusive. As a result, the satellite broadcast faulty data undetected for eighty-three minutes. The subsequent safing command to protect users was not issued until nearly two hours after the anomaly had first started. During that time, the ranging errors reached between 300 kilometers to 550 kilometers. This single satellite failure effected navigation and timing users throughout the Western Hemisphere to varying degrees of severity. This anomaly demonstrates the potential widespread consequences a single satellite failure can have on users, even in a fully populated constellation of twenty-eight satellites.

Post-analysis discovered the satellite anomaly had a significant impact on national transportation systems. The Federal Aviation Administration’s Wide Area Augmentation System (WAAS), a nationwide system of ground reference stations and geostationary satellites designed to improve the accuracy, availability, and integrity of GPS signals, was especially hit hard. The computer workstation clocks at the master reference stations in both Los Angeles and Washington D.C. lost synchronization with GPS time, causing the entire WAAS network to fail for thirty minutes. Fortunately, the network was still undergoing testing at the time and was not yet fully operational.[243] Had the system been in use for airport approaches and landings, the consequences could have been catastrophic to any one of the four thousand to six thousand aircraft normally operating within the national airspace during peak flight times.[244] During the course of the anomaly, eight different aircraft in the North Atlantic notified air traffic controllers that they were experiencing “severe GPS outages in their navigation systems.”[245] Had the outage been prolonged, multiple Trans-Atlantic flights would have been required to return to the U.S. According to an FAA controller, “Depending upon the flow of traffic, a few RTB’s (return to base) could have a terrible impact on the oceanic operation.”[246]

The U.S. Coast Guard Differential GPS (DGPS) network also malfunctioned, which effectively shut down the entire network within the contiguous United States for several minutes. This nationwide network of sixty reference stations is used by sailors to navigate the restricted and congested waterways of harbors, inlets, and rivers and along the coast. The very network designed to protect shipping from hazardous GPS signals was itself crippled by a single GPS anomaly.

Testing also showed the military could have been severely impacted by this anomaly. A common military receiver used in many military airborne platforms was found to have processed errors as large as 550 kilometers. In another case, a freight train near Philadelphia had its GPS receiver report it was in the vicinity of Lansing, Michigan before it was no longer able to track the malfunctioning satellite.[247] Fortunately the train was not using GPS for positive train control

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[243] Col Rick Reaser email to Lt Col Norman R. Albert, "Re: E-SSS (DR Info) GPS SVN 22 Anomaly - Additional Information," (7 August 2001).; and Col Douglas R. Loverro email to Lt Col Norman R. Albert, "FAA SPS Incident and Fall Out," (3 August 2001).

[244] Federal Aviation Administration, (accessed).

[245] Pete Hruz email to Michael Pumphrey, "GPS Unreliability on 7/28/01," (28 July 2001). ; Canadian Space Geodesy Forum and A B Kristinsson, "Was There a GPS Outage?" [Internet] (2 August 2001, accessed 15 December 2003); available from http://listserv.unb.ca/bin/wa?A2=ind0108&L=canspace&D=0&P=1120.

[246] Hruz, email.

[247] Capt Liz Roper, *GPS SVN 22 Anomaly*. Presentation, HQ AFSPC/DOOS, 7 September 2001, 9.

at the time so there was no safety hazard. Ironically the huge magnitude of the timing and navigation error induced by this anomaly may have prevented it from being worse than it actually was; many receivers were simply unable to track the erratic signal.

Case Two: SVN 14 and 16 Failures

In the early part of 2000, both SVN 14 and 16 were operating well beyond their 7.5-year design lives. SVN 14 was the first block II satellite to be launched and had celebrated its eleventh anniversary in February of that year. SVN 16 was the third oldest spacecraft in the constellation, having also been launched in 1989. Both were beginning to show their age and were operating on redundant backup components in several subsystems. They were both running on the third of four frequency standards, and each was operating with a failed reaction wheel, the primary means for maintaining attitude control. Their crippled state required extraordinary measures and precautions to keep them operating.[248]

On 19 February, the SVN 16 experienced a brief atomic clock anomaly which caused a sharp rise in navigation and timing errors. Ranging errors from the satellite spiked to more than 450 meters within ninety minutes.[249] Satellite operators quickly responded to the anomaly by commanding the satellite's signal to an "unhealthy" setting to protect users from the worst of the errors. Of particular concern was the Space Shuttle *Endeavor* which was conducting a $142

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[248] Captain Michael H. Rivers, "2 SOPS Anomaly Resolution on an Aging Constellation," *ION GPS 2000*, 19-22 September 2000, Salt Lake City, UT, 2547-2548.; and Gary L. Dieter, "GPS Block II Operations Reach a Ten Year Benchmark: Managing a Mature Constellation," *ION GPS 1999*, 14-17 September 1999, Nashville, TN, 2262. Each satellite has four reaction wheels. A reaction wheel is a heavy rotating disc which generates momentum by changing the rate of its rotational speed. By spinning the correct combination of reaction wheels, the spacecraft can impart the precise momentum needed to counter a destabilizing momentum along the roll, pitch, and yaw axes. A stable platform is an essential prerequisite for delivering a highly accurate navigation signal. The reaction wheels on early block II satellites are susceptible to wheel seizure due to insufficient lubrication. In early 2000, five satellites were operating with a failed reaction wheel and one, SVN 20, had previously been disposed because of its failed reaction wheels.

[249] Rivers, 2549.

million Shuttle Radar Topography Mission (SRTM) at the time.[250] The SRTM had very stringent GPS timing requirements, and SVN 16's erratic timing errors threatened to affect the mission's success. Satellite engineers devised an ingenious method to manually command the satellite untrackable for the next two days as the shuttle came in and out of view of the ailing satellite.[251] This "on-the-fly" measure successfully preserved the SRTM, which ultimately generated the most complete, near-global, high-resolution database of the earth's topography to date.[252]

After ninety minutes SVN 16's clock recovered, errors returned to normal, and service was restored within two days. Two weeks later the same frequency standard had a catastrophic failure; this time errors climbed to 1,300 meters within 90 minutes. With two major anomalies in two weeks, the clock was shut down, and its last remaining clock was powered on. This last clock failed to properly stabilize over the course of the next three weeks. Satellite operators and engineers struggled to resurrect a previously failed clock in a last bid to restore the satellite's mission capability.

With SVN 16 out of service for the time being, navigation accuracy in the Gulf of Mexico and the central United States unexpectedly deteriorated. The dilution of precision (DOP) in the region was periodically rising above twenty in the region.[253] The DOP is a unitless multiplier to navigation accuracy based on the geometric position of the satellites relative to a user's location. The lower the DOP value, the better the possible navigation accuracy. The elevated DOP was causing positioning errors to be more than eight times their norm. [254] The

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[250] NASA, "SRTM Mission Statistics" [Internet] (14 March 2000, accessed 31 March 2004); available from http://www2.jpl.nasa.gov/srtm/statistics.html.

[251] GPS Support Center, "2000 Archived Advisories" [Internet] (2000, accessed 30 March 2004); available from http://www.schriever.af.mil/GpsSupportCenter/archive/advisory/2000_archived_advisories.htm.

[252] NASA, "SRTM Mission" [Internet] (4 December 2003, accessed 31 March 2004); available from http://www2.jpl.nasa.gov/srtm/mission.htm.

[253] Lt Col William K. Kaneshiro, "DGPS Problem in Gulf of Mex," (2000). email.

[254] Capt Mike Rivers and SSgt Roger Gallardo, *GPS User Briefing for 2 SOPS.* Presentation to 2 SOPS at Schriever AFB, CO, 12 December 2001, 50. To gain a sense of comparison, the average daily

large DOP values were wreaking havoc on the Coast Guard's DGPS augmentation network in and around the Gulf. The reference stations were malfunctioning whenever positional DOP exceeded a value of eight.[255]

While operators struggled to bring another SVN 16 atomic clock on-line, SVN 14 experienced a second reaction wheel failure. Each spacecraft has four reaction wheels which are its primary means of maintaining a stable, earth-pointing platform. The attitude control subsystem can maintain control in the event of a single reaction wheel failure, but the loss of a second reaction wheel renders the satellite inoperable. As the satellite slowly tumbled out of control, it lost electrical power and autonomously shutdown the payload and other non life-essential equipment to conserve power. Through some delicate commanding, a team of satellite operators and support engineers were able to regain satellite control by enabling its backup thrusters. However, the unpredictable thruster firings perturbed the satellite's orbit which induced large navigation ranging errors. Without a stable platform to support the navigation payload, the satellite had to be disposed.

With SVN 14 and 16 simultaneously off the air, a gap in GPS coverage opened up over the central United States. Fewer than four satellites were visible over portions of Oklahoma, Kansas, Nebraska, and Texas resulting in a complete loss of GPS service for approximately thirty minutes each day (see Figure 4 on the next page).[256] In addition, the loss of both satellites exacerbated the ongoing DOP problem in the western United States. The average maximum position DOP routinely reached between 200 to 300, resulting in a positioning error of 500 to 1,000 meters.[257] In one area, the maximum position DOP spiked to over 888 for short periods.[258]

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global position DOP is 2.40. Assuming all other variables remain constant, accuracy is degraded by a factor of 8.33.

[255] Kaneshiro. e-mail

[256] Rivers, "2 SOPS Anomaly Resolution on an Aging Constellation," 2550.

[257] Stephen Hillman, interview with author by telephone, 23 April 2004.

Aircraft were warned of the navigation gap. For a period of time, the large navigation errors threatened to disrupt operations at the Dallas-Fort Worth Airport which was near the coverage gap and the DOP spikes. These anomalies also caused the Coast Guard's DGPS augmentation network along the Mississippi River to repeatedly malfunction.[259]

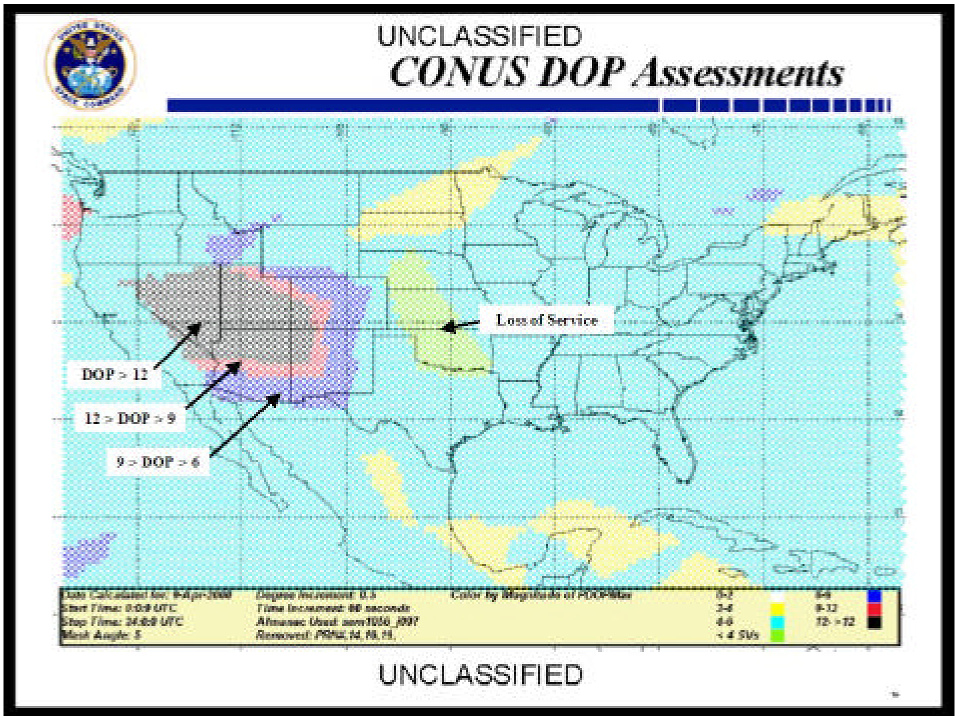

Figure 6. CONUS DOP Assessment[260]

The situation was partially resolved on 9 April, seven weeks after it started, when SVN 19 was maneuvered to cover the hole opened by the failures. But SVN 19 was operating on

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[258] Rivers, "2 SOPS Anomaly Resolution on an Aging Constellation," 2550.; and Hillman telephone interview.

[259] Capt Donald A. Daugherty memo to AFSPACE/A33, "Emergency GPS Constellation Sustainment and Assessment Team (CSAT) Minutes," (Vandenberg AFB CA: 2000).

[260] GPS Support Center, "CONUS DOP Assessment (Unclassified)" [Internet] (9 April 2000, accessed 4 March 2004); available from http://www.schriever.af.mil/GpsSupportCenter/archive/advisory/uclas_conus_dop.gif.

its last atomic clock and was not expected to survive much longer.[261] It was feared that an SVN 19 failure would reopen the coverage gap. Consequently, a previously scheduled launch was redirected to permanently replace SVN 14. Service was finally restored to normal on 1 June when the new satellite was in place and fully operational.[262]

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[261] Lt Col J. Kevin McLaughlin memo to 50 OG/CC, "Commander's Monthly Status Report (CMSR) - October 1999," (Schriever AFB CO: 1999).; and Rivers, "2 SOPS Anomaly Resolution on an Aging Constellation," 2550.

[262] GPS Support Center, "2000 Archived Advisories" (accessed).; and Losinski, 2544.

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