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Overcoming Challenges to Transformational Space Programs: The Global Positioning System (GPS)

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NORTHROP GRUMMAN

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Preface

Transformational space programs are at the front and center of debates between the current Administration and the Congress regarding the future of U.S. national security space activities and programs. They offer potentially revolutionary capabilities to provide critically needed information for decision-making through persistent imagery of targets and areas of interest to policy-makers and military planners, expanded accuracy and timeliness of information to meet dynamic operational requirements, and new concepts of operations that integrate multiple phenomenologies and platforms. Consequently, successful acquisition and deployment of these capabilities will greatly enhance U.S. national security objectives, support U.S. and coalition military operations, and strengthen the contribution of intelligence to the on-going global war on terrorism.

However, these programs face not only technological challenges but also acquisition, operational, organizational, and policy challenges along the path to deployment and operation. Developing these programs and sustaining them politically and financially over the long term can be a daunting effort. An approach offering potentially useful insights for such efforts is to assess earlier space programs that experienced similar challenges. The most notable example is the Global Positioning System (GPS), a space-based constellation of satellites providing positioning, navigation, and timing for worldwide utility. GPS is a tremendous and critical success, not only as a military system but also for numerous civil, commercial, economic, and global applications unforeseen when the program was initiated. A review of GPS' history, as described in this paper, reveals the hurdles that GPS had to overcome to emerge as a leading example of what today would be considered as a transformational space program. Examining these hurdles as they developed in the program's early history should offer important insights for those decision-makers pursuing transformational space programs today.

This paper should be of interest to policymakers concerned with national security space program development, acquisition, and operations, and to those persons with a general interest in U.S. national space policy, strategy, and programs.

Executive Summary

The NAVSTAR Global Positioning System, or GPS as it is more commonly known, has become one of the world's "global utilities." The signals each satellite provides are critical for positioning, navigation, and timing (PNT) of innumerable activities, ranging from banking and secure funds transactions and precise timing for network security protocols, to precision bombing operations. GPS is a U.S. military developed, owned, and operated satellite constellation. Yet its uses by the civil and commercial sectors far outweigh its original military purposes, and services continue to grow. GPS was conceived as a generic navigational tool, but has evolved into a predictable, reliable, and ubiquitous capability of "information on demand" that users employ for wide-ranging purposes and requirements. In every sense, it is a transformational system that has dramatically shaped our society, economy, and national security. Indeed, it would be difficult, if not impossible, to envision going back to a world without GPS.

This enormous success of a transformational space-based system does not imply, however, that GPS has had smooth sailing since its inception and growth into the current, productive satellite constellation and PNT-related applications. Rather, uncertainties associated with estimates of its potential military utility, coupled with technology and funding issues and pressures to preserve legacy systems and capabilities resulted in major challenges that threatened the program's survival. A review of GPS' early history, specifically the operational, organizational, technological, and political challenges faced in bringing the GPS to fruition, may highlight the existence of similar challenges facing other transformational space programs today that act to stifle their development and deployment.

Operational Challenges

Neither its providers nor its operational users understood the scope of GPS' full transformational potential at the program's onset in the early 1960s. At the time, military space systems were primarily viewed as intelligence or strategic deterrence assets, so a satellite system offering ubiquitous, continuous, predictable, and reliable PNT was novel and somewhat suspect. Potential users were uncomfortable with the idea of transitioning from existing terrestrial navigation systems to relying on an unproven, space-based system out of their operational control. To address this issue, and to avoid having to continuously satisfy unforeseen and ill-defined requirements, the GPS program developed clear, stable, and open interfaces that were platform independent. This approach allowed users to adapt GPS to their own needs, and encouraged the widespread development of GPS applications for civil and commercial use as well as for national security. Furthermore, the introduction of GPS into U.S. military forces not only reduced the need for other precision targeting capabilities, but also introduced dramatic changes in targeting doctrine, tactics, training, and procedures (TTP), and the enabling of new missions using PNT.

Organizational Challenges

In the late 1950s and early 1960s, each military service developed its own space-based PNT effort to meet its needs and explore prototype technologies. To eliminate redundancy, the Department of Defense (DoD) initiated the GPS program as a consolidation of the best attributes of its predecessors into a single system providing critical navigational capabilities to the warfighter and eliminating service duplication. GPS was organized as a joint program, with the Air Force as lead acquisition agency. While theoretically this approach was appropriate given the system's wide range of users, and the services supported the idea of a single navigation system, no one service wanted to bear the burden of funding and other resources for a requirement outside its core missions and program priorities. The Air Force's unenthusiastic support for GPS reflected its view that GPS was a DoD system supporting a wide range of users beyond the Air Force. This increased the pressures on the Joint Program Office (JPO) to "sell" the program's merits to other potential users.

Acquisition and Technology Challenges

DoD's primary objectives in GPS acquisition were: (a) furthering precision weapons delivery; and (b) consolidating competing efforts by the services for navigation systems. Thus, GPS was viewed by both its acquirers and its potential users as a weapon systems enabler, not a weapon system. Furthermore, unlike weapon systems, GPS lacked a clear mission and a well-defined concept of operations.

While maintained, owned, and operated by the DoD, GPS' utility to widespread civil and commercial users ultimately benefited the DoD as well. The Air Force employed innovative acquisition approaches, including performance-based requirements and best commercial practices, such as block buys and phased competitions. These innovations, however, were hampered by technical, schedule, cost, and risk issues and underestimated program costs. In the Congress, consistent Senate support for GPS and the Air Force acquisition approach was countered by House concerns over schedule slips and potential wartime jamming vulnerabilities. The House zeroed GPS funding in the early 1980s, but the DoD responded by reprogramming funds from lower priority programs to keep the program going.

Policy Challenges

GPS' dual-use nature means that policy issues cut across traditional boundaries between military and civilian interests and uses. While GPS' core role lies in supporting military operations, early in the program the Air Force made a concerted effort to provide a level playing field for commercial GPS applications development while preserving military equities. However, at the national level, until the first GPS Presidential policy in 1996, national PNT policy lagged behind the expansion of GPS roles, missions, uses, and technologies. The Clinton GPS policy acknowledged GPS' importance as a dual-use system, providing critical operational support to military forces and becoming an integral part of the emerging Global Information Infrastructure. In 2004, the Bush Administration revisited the Clinton era GPS policy and issued a new PNT policy reflecting changes in interagency management and international developments since 1996. The explosion of opportunities in the commercial GPS applications market, coupled with the operational dependence by U.S. and allied military forces and emerging threats by adversaries, warranted a new management structure and executive oversight of the GPS system. Policy challenges requiring a balance between national security interests and economic opportunities will continue to evolve and affect the GPS program for the foreseeable future.

Overcoming Challenges to Transformational Space Programs

A number of lessons identified from the GPS program offers useful insights for other transformational space programs:

- A transformational space program's full potential from its onset is likely to be unknowable. Increased user familiarity with system capabilities leads to new roles, missions, and opportunities.
- Developing a space system with clear, stable, and open platform-independent interfaces encourages user-adapted and -developed applications.
- Programs involving new, experimental, or revolutionary capabilities are likely to experience technological difficulties and short-term technical obstacles in system concept development, prototyping, and other early phases.
- A stable resource stream, backed by a political commitment, is needed. Block buys are important for reducing potential acquisition costs and for demonstrating political support.
- Institutional reluctance to accept new space systems offering potentially dramatic improvements in capabilities and/or changing doctrine, tactics, techniques, and procedures (TTP), or force structure will create organizational and cultural barriers to system acquisition and operation. One approach to reducing these barriers is to increase operational familiarity with the system by potential users through "real world" experience, exercises, and training.
- For interagency transformational space programs, agreement and cooperation regarding mission, operational, and system requirements are required as early as possible. Changing or adding requirements, acquisition processes, or system "ownership" in midstream may result in technical problems, schedule delays, higher costs, and increased political scrutiny of the program.

Introduction

The NAVSTAR Global Positioning System, or GPS as it is more commonly known, has become one of the world's "global utilities." The signals each satellite provides are critical for positioning, navigation, and timing (PNT) of a myriad of activities, ranging from banking and secure funds transactions, and precise timing for network security protocols, to precision bombing operations.[1] GPS is a U.S. military developed, owned, and operated satellite constellation. Yet its uses by the civil and commercial sectors far outweigh its original military purposes, and services continue to grow. GPS was conceived of as a generic navigational tool, but has evolved into a predictable, reliable, and ubiquitous capability of "information on demand"[2] that users employ for wide-ranging purposes and requirements. In every sense, it is a transformational system[3] that has dramatically shaped the conduct of economic, social, scientific, and military transactions. Indeed, it would be difficult, if not impossible, to envision going back to a world without GPS.

This enormous success of a transformational space-based system does not imply, however, that GPS has had smooth sailing since its inception and growth into the current, productive satellite constellation and PNT-related applications. Rather, uncertainties associated with estimates of its potential military utility, coupled with technology and funding issues and pressures to preserve legacy systems and capabilities, resulted in major challenges that threatened the program's survival. For example, in 1979 the program was restructured following funding cuts by the Office of the Secretary of Defense (OSD). From 1980-1982 the Air Force zeroed the program budget only to have OSD reinstate the funds.[4] Additionally, the program experienced periodic critical reviews by the General Accounting Office (GAO) and the Congressional Budget Office (CBO) on behalf of the Congress.

This paper describes and explains the operational, organizational, technological, and political challenges faced in bringing the GPS to fruition. The paper details GPS' early history, explains the rationale and context for institutional support as well as opposition, and documents the difficulties of introducing such a transformational system into the inventory of U.S. national security space capabilities. As a case study, the methodology used in this paper suggests the existence of similar challenges facing other transformational space programs today that act to stifle their development and deployment. A brief technical description of the GPS constellation is found in the appendix.

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[1] For more detailed discussions of GPS utility, see: Scott Pace and James E. Wilson, *Global Positioning System: Market Projections and Trends in the Newest Global Information Utility*, The International Trade Administration, Office of Telecommunications, U.S. Department of Commerce (Washington, D.C.: September 1998); Defense Science Board Task Force, *The Future of the Global Positioning System*, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (Washington, D.C.: October 2005); and Scott Pace, Gerald Frost, Irving Lachow, David Frelinger, Donna Fossum, Donald K. Wassem, and Monica Pinto, *The Global Positioning System: Assessing National Policies*, RAND MR-614-OSTP (Santa Monica, CA: RAND, 1995).

[2] Joan O'C. Hamilton, "Where on Earth?" *Stanford Magazine*, May/June 2000, p. 6, found at: http://www.stanfordalumni.org/news/magazine/2000/mayjun/articles/gps.html.

[3] "Transformational" is a term currently applied to a number of weapon and support systems, although it is intended to be more than that. It is defined as:

> *A process that shapes the changing nature of military competition and cooperation through new combinations of concepts, capabilities, people, and organizations that exploit our nation's advantages and protect against our asymmetric vulnerabilities to sustain our strategic position, which helps underpin peace and stability in the world.*

See: Donald Rumsfeld, Secretary of Defense, *Transformation Planning Guidance* (April 2003), quoted in Office of Force Transformation, Office of the Secretary of Defense, *Elements of Defense Transformation*, October 2004, p. 2. A more recent discussion of transformation is found in "An Interview with Acting Director, DoD Office of Force Transformation Terry J. Pudas," *Joint Force Quarterly*, Issue 42, 3rd Quarter 2006, pp. 32-35, as well as several other articles in the same issue.

[4] Pace, et. al., *The Global Positioning System: Assessing National Policies*, op. cit., p. 243.

Operational Challenges

Today's GPS operational concept builds on the legacy of technologies and operational experience of several earlier navigation satellites developed and deployed by the military services, often in competition with each other. These earlier systems included the Navy's Transit and Timation programs, the Air Force's Project 621B, and the Army's SECOR (Sequential Correlation of Range) program.

- *Transit:* Based on their pioneering orbital analysis using radio signals, Applied Physics Laboratory (APL) scientists developed the Transit space-based navigation system in 1958. The first prototype satellite was launched in April 1960; Transit became operational in 1964. Its original purpose was to provide accurate, reliable, all-weather, global navigation for the U.S. submarine fleet, but evolved to include other public and commercial uses, such as commercial marine navigation and recreational boating. The Navy launched a total of 28 Transit satellites, and the system remained operational until being phased out on December 31, 1996.[5]
- *Timation:* An experimental concept developed in 1964 by the Naval Research Laboratory (NRL), Timation consisted of time (or range) measurements between a satellite and a user that were based on spaceflight-qualified atomic clocks.[6] Such timing signals were believed to be more accurate and would provide more precise navigation than Transit could provide. Three Timation satellites were launched, with the third being renamed the Navigation Technology Satellite (NTS). It flew the first atomic clock in space in 1974. NTS-2 was launched in 1977 with the first cesium clock in space. These clocks were then used in what became the GPS program.[7]
- *Project 621B:* Based on earlier analyses in efforts such as Project Forecast,[8] and studies initiated by the Aerospace Corporation in 1963, the Air Force pursued a spacecraft design called Project 621B to provide continuous three-dimensional (latitude, longitude, and altitude) navigation. Project 621B also led to a new satellite ranging signal based on pseudorandom noise (PRN) whose characteristics were less vulnerable to jamming than other techniques.
- *SECOR:* Built for the U.S. Army, SECOR consisted of a small geodetic satellite and four ground stations with known coordinates used to determine precise locations on the Earth's surface from space. First launched in 1964, SECOR satellite launches continued until 1969. One of its significant successes was to determine previously uncertain positions of Pacific islands by bringing them within the same geodetic global grid.[9]

Each program was developed to meet specific military needs or to explore or develop certain technologies required to perform navigation from space. However, given their technical and operational limitations, they were not widely used beyond their initial design purposes. Each program's constellation size was insufficient to attain the accuracies required for widespread employment by military forces. Nevertheless, the satellites' operational value lay in their exploration and testing of the technological building blocks necessary for a future PNT capability.

[5] Pace, et. al., ibid., p. 238; Committee on the Navy's Needs in Space for Providing Future Capabilities, Naval Studies Board, Division on Engineering and Physical Sciences, *Navy's Needs in Space for Providing Future Capabilities*, National Research Council (Washington, D.C.: The National Academies Press, 2005), pp. 130-131.

[6] Ibid., p. 131.

[7] Ibid.

[8] Dr. Francis X. "Duke" Kane (Colonel, USAF, ret.), Schriever Institute, San Antonio, TX, oral history, available at http://www.salsa.net/medialab/dr-kane.htm, accessed 6/2/2006.

[9] See: Joshua Boehm, System Planning Corporation, with Craig Baker, Space Commission Staff, Stanley Chan and Mel Sakazaki, System Planning Corporation, *A History of United States National Security Space Management and Organization*, prepared for the Commission to Assess United States National Security Space Management and Organization, 2000, p. 30; "SECOR," *Astronautix*, http://www.astronautix.com/craft/secor.htm, accessed 7/17/2006.

During the Cold War, most space systems were developed to meet critical strategic requirements such as missile warning, strategic communications, surveillance, reconnaissance, and environmental monitoring. Some observers recognized a nascent space-based navigation capability had the potential to add dramatic improvements in precision, scale, and speed to existing accepted navigation methods. That confidence in space-based navigation ran counter to a more prevailing view of operational unfamiliarity and an unwillingness to rely on an unknown, out-of-sight space system for highly precise, time-critical aircraft flight operations, for position location and situational awareness by the foot soldier, and for location of ships and potential threat emitters at sea. As a result, reliance on space-based navigation had to wait for the deployment of a large satellite constellation to yield the accuracies necessary for full-scale operational employment.

Acceptance of GPS as a critical enabler of military missions was enormously accelerated by its performance during the first Gulf War in 1991 when GPS transformed warfare in ways unimaginable to its early supporters. GPS became the most highlighted military space contribution to the war effort. For example, the widespread military use of commercially available precision lightweight GPS receivers (PLGRs) in Operations Desert Shield and Storm (ODS) in 1990-1991 vastly increased public familiarity with GPS and had secondary effects of pressuring DoD to drop restrictions on nonmilitary access to the GPS signal. The ability to maneuver land forces with unprecedented speed and precision during ODS was a direct consequence of the fielding of GPS and other transformational technologies. Army forces were able to fight as they did because of their ability to see the battlefield, particularly by knowing precisely where their own forces were. ODS's land battles involved moving thousands of vehicles and helicopters across hundreds of kilometers of trackless desert, at night or in bad weather.[10] While only 16 satellites of the full 24-satellite constellation were deployed by 1990, a squadron of F-16s, many KC-135s and B-52s, most Marine helicopters, some Navy ships, and the Army's divisions deployed to Saudi Arabia were equipped with GPS receivers.[11] These forces are far too small in numbers, however, to be indicative of widespread operational acceptance and reliance on GPS as the primary military space-based PNT capability at that time.

[10] Richard J. Dunn, III, *McNair Paper No. 13: From Gettysburg to the Gulf and Beyond: Coping with Revolutionary Technological Change in Land Warfare* (Washington, D.C.: National Defense University Institute for National Strategic Studies, 1992), pp 90-91.

[11] James A. Winnefeld, Preston Niblack, and Dana J. Johnson, *A League of Airmen: U.S. Air Power in the Gulf War*, MR-343-AF (Santa Monica, California: RAND, 1994), pp. 203-204.

Organizational Challenges

By the late 1960s, the various service navigation programs were competing for missions and resources. DoD established a joint tri-service steering committee, the NAVSEG (Navigation Satellite Executive Group), in 1968 to determine the constellation size, altitudes, signal codes, modulation techniques, and the costs of a space-based navigation system. Intense debates occurred within the NAVSEG over several years concerning competing efforts by the Navy and the Air Force to expand Timation and Project 621B. Including Transit, none of the concepts were considered capable of evolving into a future DoD space-based navigation system.[12] In 1973, Deputy Secretary of Defense William P. Clements forwarded a memorandum to the service secretaries directing a joint development program to test satellite-based navigation systems for potential future acquisition.[13] The Air Force was designated the lead agency for developing a single comprehensive Defense Navigation Satellite System (DNSS). Air Force Chief of Staff General John D. Ryan directed that a Joint Program Office (JPO) be established at the Air Force Space and Missile Systems Organization (SAMSO) in Los Angeles, with joint participation.[14]

Subsequently, the program went through a Defense System Acquisition and Review Council (DSARC) in August 1973, but was rejected because of concerns that it was not sufficiently joint. At the time, only the Navy had the practical experience of spaceflight-qualified atomic clocks required for a future system. Following the DSARC decision, a small team from the JPO met over the Labor Day weekend 1973 to develop a concept that incorporated the best technologies and system concepts from the earlier separate service programs. The result was a compromise system that included Project 621B's signal structure and frequencies and Timation's satellite orbits—albeit higher in altitude (12-hour periods rather than 8).[15] Army support for the program was bolstered by choosing the Yuma Proving Grounds for testing of GPS "pseudolites," i.e., ground-based "pseudo satellites" used for testing the ground segment and receiver equipment.

Selling Air Force leadership on the program, however, was difficult owing to funding concerns. At this juncture the support of Dr. Malcolm Currie, the new director, Defense Research and Engineering (DDR&E), was instrumental. While he chose to fail the program at the DSARC, Dr. Currie reiterated his support for the concept of a space-based navigation system, provided it reflected joint support and requirements.[16]

Another key supporter at this time was Dr. John L. McLucas, Secretary of the Air Force from 1973 to 1975, and Undersecretary of the Air Force and Director of the National Reconnaissance Office (NRO) from 1969 to 1973, all crucial periods in GPS concept development. Dr. McLucas wrote in 1998 that "Since 1974, having been the Air Force Secretary at the time of the GPS go-ahead, I have become almost a GPS 'junkie.' As the FAA Administrator in the 1970s, I could not get the FAA interested in GPS….[Since then,] FAA has in fact speeded up its actions to adopt GPS as a primary if not *the* primary aerial navigation system…."[17]

[12] Boehm, ibid., p. 31.

[13] Major Dennis L. Alford, USAF, *History of the NAVSTAR Global Positioning System (1963-1985)*, Student Report Number 86-0050 (Maxwell AFB: Air Command and Staff College, Air University, April 1986), p. 5. Unclassified report; distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 16 APR 1986. Other requests shall be referred to Air Command Staff College, Attn: EDCC, Maxwell AFB, AL 36112-5542. Document partially illegible.

[14] The Services participating included staff from the Army, Navy, Marine Corps, Defense Mapping Agency, Coast Guard, Air Logistics Command, and NATO. The Aerospace Corporation also provided technical support. See: Scott Pace, et. al., op. cit., p. 240; and Bradford W. Parkinson, "Origins, Evolution, and Future of Satellite Navigation," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 1 (January-February 1997), p. 14.

[15] Pace, et. al., ibid., pp. 240-241. Choice of 12-hour orbits was also dictated by the requirement to minimize overseas ground stations, and the selection of orbital planes was shaped by replenishment considerations.

[16] Parkinson, "Origins, Evolution, and Future of Satellite Navigation," op. cit., pp. 14-15.

[17] John L. McLucas, "The U.S. Space Program Since 1961: A Personal Assessment," in R. Cargill Hall and Jacob Neufeld, eds., *The U.S. Air Force in Space: 1945 to the 21st Century; Proceedings of the Air Force Historical Foundation Symposium, Andrews AFB, Maryland, September 21-22, 1995* (Washington, D.C.: USAF History and Museums Program, United States Air Force, 1998), pp. 93-94, italics in the original.

Acquisition and Technology Challenges

After the JPO staff made the rounds of internal Pentagon briefings to gain support, another DSARC was convened in December 1973. DoD decision-makers gave the JPO its approval to proceed with a three-part program:[18]

- *Phase 1:* design, develop, and deploy four navigation satellites, and develop, test, and evaluate receivers, hardware, and computer programs
- *Phase 2:* test and evaluate prototype system, launch additional satellites, and operate limited system
- *Phase 3:* deploy remaining satellites and receivers[19]

In May 1974, HQ USAF issued the Program Management Directive, renaming the program the Global Positioning System[20] and dividing it into three segments: a space segment, a control segment, and a user equipment segment to respond to the diverse range of service and operational missions. The GPS concept included a constellation of 24 satellites placed in 12-hour inclined semi-synchronous orbits, and NRL continued further development of the Timation clocks under the JPO's direction. Phase 1 included four satellites (including a refurbished Timation satellite), launch vehicles (initially refurbished Atlas-F ICBMs, followed by Delta*) three varieties of user equipment, a satellite control facility, and a detailed test program. The first user equipment included sequential and parallel military receivers, as well as a civil type for use by the military.[21] The second Timation satellite was renamed NTS-11 and launched in June 1977 as the first satellite launched in the GPS program.

In 1975 the JPO advocated increasing the number of satellites in the early phase of the program from four to six, largely to allow 3-dimensional navigation and to reduce overall program risk from a potential launch failure. In parallel, the Navy made the case to upgrade certain Transit satellites to use a PRN code similar to that used by GPS in order to provide accurate tracking of the Trident booster during test firings. Dr. Robert Cooper of DDR&E initiated a set of reviews examining whether GPS could perform the Transit navigation mission. The reviews proved that GPS could perform the mission,[22] and so Dr. Cooper transferred $60M from the Navy's Transit program to the Air Force for GPS.[23]

Prior to the demonstration stage, the JPO considered accelerating the program schedule to achieve initial operational capability (IOC) in 1982 or 1983, and to reap significant cost savings by eliminating a planned pause between the second and third phases of the system's evolution. Key to this acceleration was the developmental progress in accuracy and stability of the spaceflight-qualified clocks.[24] In late 1976, however, the program

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[18] Parkinson, "Origins, Evolution, and Future of Satellite Navigation," ibid., pp. 15, 18. See also Boehm, op. cit., p. 31.

[19] Alford, op. cit., pp. 6-7.

[20] Ibid., p. 7.

* In 1979, the Space Shuttle became the means by which all GPS satellites were to be launched. However, the loss of *Challenger* in 1986 forced a revisit of the policy, with the outcome that GPS satellites are now launched on Delta rockets.

[21] Bradford W. Parkinson, "Chapter 1: Introduction and Heritage of NAVSTAR, the Global Positioning System," op. cit., pp. 8-9. Also, to keep the program focused, the JPO adopted a motto:

"The mission of this Program is to:

1. Drop 5 bombs in the same hole, and
2. Build a cheap set that navigates (<$10,000),
   and don't you forget it!"

[22] Provided two additional satellites were procured to provide 3-4 satellites within view of Atlantic or Pacific instrumentation. See: Barry Miller, "Defense Navstar Program Progressing," *Aviation Week & Space Technology*, January 12, 1976, p. 45.

[23] Parkinson, "Chapter 1: Introduction and Heritage of NAVSTAR, the Global Positioning System," op. cit., pp. 9-10.

[24] Miller, op. cit.

experienced developmental and financial problems resulting in cost growth, schedule slips, and Air Force restructuring of the program.[25]

Changing GPS requirements also slowed acquisition. The JPO originally planned for GPS to provide limited, two-dimensional capabilities by the end of Phase 1 (development), requiring the deployment of 1,000 user receivers and nine satellites. However, the Strategic Air Command (SAC) opted not to procure 600 receivers for installation in their aircraft. This decision was influenced by a number of factors, including the 1977 B-1 cancellation decision, the reduction in the number of long-range SAC bombers by more than 1,300 aircraft in the 1970s,[26] an emphasis on Air Force air superiority doctrine, training, and operational experience, and a general disinterest in funding precision guided weapons (PGMs). As a result, the Air Force postponed procurement of all GPS receiver sets, and procured only three of the planned nine satellites, thus eliminating plans for a limited operational capability by the end of Phase 1.[27] Furthermore, it cancelled plans for any satellite launches in Phase 2, putting all the remaining satellite launches into Phase 3.[28]

The Congress was also troubled by the program's problems. The General Accounting Office (GAO) reviewed the program at Congressional request, pointed out launch and user equipment slippages and cost growth, and expressed concern over the reduced time for testing prior to the next DSARC for Phase 2.[29] Senior DoD officials attempted to assuage Congressional concerns by testifying that GPS would make existing weapons delivery systems "up to four times more effective against certain targets" than existing systems using less accurate external radio navigation systems.[30] Lieutenant General Richard C. Henry, USAF, commander of SAMSO, stated, "The implications [of NAVSTAR] are so staggering that the strategic and tactical doctrine of our fighting forces will be rewritten. We are becoming dependent on the high ground of space for future military operations."[31]

Despite these views of GPS as a transformational system, in December 1979 cuts in the defense budget led OSD to reduce funds across the board for research, development, construction, and procurement. The resulting cut of $512 million over five years led the Air Force to reduce the GPS constellation size from 24 to 18 satellites, thus resulting in a loss of navigational accuracy.[32] Rather than seeking to remedy the problem, the Air Force budget offered reductions so severe they essentially terminated development and acquisition of GPS.[33] However, OSD restored the full program funding to $259.3 million.[34] Support also came from the Senate. Recommending the addition of $41 million for a total of $168.9 million in FY 1981, the FY 1981 Senate Authorization Report noted GPS' importance and the urgency of maintaining program funding:

> …The military implications of this system are very significant in terms of improved conventional bombing accuracy, assault helicopter operations and many other military activities. It may be difficult to understand the full potential until the system is deployed and the vast number of potential users are able to see what it will do for them.

[25] These problems consisted of: unanticipated technical changes in the Atlas launch vehicle reliability improvement program; Rockwell's financial obligation to buy two replenishment satellites that came earlier than the JPO expected; digital software development-related problems with General Dynamics/Electronics' ground control element and user equipment element; and a shortage of JPO personnel to conduct and monitor testing. See "NavStar Development to be Restructured," *Aviation Week & Space Technology*, February 28, 1977, p. 28.

[26] Michael E. Brown, *Flying Blind: The Politics of the U.S. Strategic Bomber Program* (Ithaca, New York: Cornell University Press, 1992), p. 268. The B-1B program was restarted in 1981 by President Reagan, and was followed by the B-2 bomber program.

[27] Alford, op. cit., pp. 13-14.

[28] Ibid., p. 15.

[29] "GAO Cites NavStar Slippage," *Aviation Week & Space Technology*, March 14, 1977, p. 22. See appendix for additional details.

[30] Testimony of Vice Admiral William H. Rowden, USN, before the Senate Armed Services Committee, March 15, 1977.

[31] George C. Wilson, "Pentagon Plans Revolutionary Navigation System," *Washington Post*, May 28, 1979, p. A3.

[32] Pace, et. al., op. cit., p. 263; Alford, op. cit., pp. 17-18.

[33] In June 1980, to comply with DoD budget cuts, the Air Force Program Objective Memorandum (POM) requested $16.3 million in FY 1982 instead of the JPO's stated requirement of $234.5 million.

[34] Ibid., pp. 18-19.

> The committee is concerned with recent program and budget decisions which have had the effect of reducing the capability of the system and stretching out completion of the program. Witnesses have testified that it has truly revolutionary implications for improving navigation and effectiveness of both military and civilian vehicles. However, if for short-term budget limitations its potential is compromised or deployment delayed, it will be difficult for potential users to plan for and rely on the availability of what could be a major step forward in weapon system effectiveness….The committee urges the Department of Defense to preserve the integrity of this program and not delay it.[35]

Further development of GPS technologies led to an increasingly complex but more capable system. While Block I (experimental) satellites were designed to validate the GPS concept, Block II GPS satellites had more advanced operational capabilities such as increased clock reliability and nuclear hardening, the nuclear detection payload Integrated Operational Nuclear Detonation Detection System (IONDS),[36] and selective availability measures.[37] These capabilities made them heavier and more complex than Block I spacecraft. Furthermore, the large numbers of Block II spacecraft necessary for an operational constellation made them attractive for an alternative procurement approach.

The Air Force's innovative acquisition approach – the "block buy" – for the Block II satellite procurement was proposed to HQ Air Force Systems Command (AFSC) and HQ USAF in March 1981, and to DoD officials in May 1981 who approved it. In contrast, Congressional support was mixed. The Senate voted to fund the complete Presidential budget request and to consider a multi-year procurement of the constellation as a means of achieving cost savings. However, the House voted to eliminate all funding for the program, because of concerns that GPS' overall price was "far too high for the additional capability it would ultimately provide if it performed as planned" and for the system's uncertain wartime survivability.[38]

The result in conference committee was $200 million in R&D funds but no production of Block II spacecraft. The Congress allowed satellite production if the DoD reprogrammed funding from lower priority programs.[39] DoD agreed and reprogrammed $20 million to begin the block buy, and also sent a block buy strategy to Congress which the latter approved in July 1982. As part of the block buy acquisition strategy, the Air Force then awarded a long lead contract for 28 Block II satellites to Rockwell International in September 1982, costing $1.2 billion.[40] The block buy of GPS satellites was the first time this approach was applied to a multi-satellite system acquisition.

Acquisition innovation also extended to the GPS program's user equipment segment. The Air Force used a two-phased procurement approach: two contractors for prototype development, down-selected to one for user equipment production. The Air Force also emphasized modularity of receiver design based on users' needs, from those requiring high accuracy/high anti-jam capabilities, to surface vehicles, manpacks, submarines, and missiles.[41] This approach encouraged competition, leading to improved criteria for selecting production hardware.[42] Complicating this acquisition approach, however, was SAC's decision (described earlier) to reduce the number of operational sets acquired for bomber aircraft.[43] Subsequently, in the second phase of development, software problems experienced during equipment testing led to delays and decisions to postpone production in the early 1980s.[44]

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[35] *FY 1981 Senate Authorization Report*, p. 107.

[36] See appendix.

[37] Alford, op. cit., p. 21. See appendix for a discussion of "selective availability."

[38] *FY 1982 Authorization Conference Report*, p. 90.

[39] As stated in the *FY 1982 Authorization Report* (p. 90), "…The conferees are aware that the GPS has, at times, not enjoyed high priority within the services. The conferees wish to inform the Department of Defense that continuing Congressional support for this program will be contingent upon the nature of the Department of Defense priority assigned in the development and fielding of this system and that any further slippage in the currently planned Initial Operational Capability (IOC) date may result in program termination."

[40] Alford, op. cit., pp. 21-22, 23.

[41] Barry Miller, "Defense Navstar Program Progressing," *Aviation Week & Space Technology*, January 12, 1976, p. 45.

[42] Alford, op. cit., p. 46. Five-channel X receivers were intended for high-performance aircraft for very precise navigation and rapid uploading of information; two-channel Z receivers served low-performance aircraft and surface vessels; and wheeled and tracked vehicles and foot soldiers employed one-channel Y receivers. These receivers had to be compatible with the equipment associated with the ground control segment (i.e., the monitoring stations).

[43] Ibid., pp. 37-38.

[44] Ibid., pp. 41-43.

Policy Challenges

Further shaping GPS' operational, organizational, and acquisition and technology challenges were policy choices, which, as usual, lagged behind technical development and deployment. A review of national space policy from the Ford to Clinton administrations showed that PNT-specific policy tended to lag behind decisions made in the early acquisition phases of GPS and its predecessors. Where national space policy did have an effect on GPS was in mandating the space transportation system (STS) as the primary space launch system for all U.S. government payloads and for government spacecraft "to be designed to take advantage of the unique capabilities of the STS."[45] Nevertheless, early in the program a conscious effort was made by the Air Force to preserve military equities in a dual-use system and maintain a level playing field for commercial applications development.

In parallel with acceptance of GPS as a critical enabler of military missions was acceptance of GPS as a critical element in civilian applications. Two policy decisions had a critical bearing on this acceptance: (1) the downing of Korean Air flight 007 on 16 September 1983[46] and the resulting Reagan Administration policy decision to make the system available to international civil use once GPS became operational; and, (2) the 1984 Federal Geodetic Data Committee recommendation to use GPS for the commercial survey market, later expanded in 1992 to encompass national policy toward full and open access to U.S. Government-generated geographic data by government users and the general public.[47]

Because of the latter decision, the market for developing commercial GPS surveying equipment received a boost even before the GPS system was declared operational. It also spurred R&D investment in GPS technologies by U.S. manufacturers, opening the door for other markets such as aviation.[48]

Not until the early 1990s when the wider implications of GPS' dual-use nature were becoming evident did the White House acknowledge the need to define a national PNT policy. Key questions raised in the comprehensive studies[49] leading up to the promulgation of a national GPS policy were:

- How should the United States integrate its economic and national security objectives into GPS policy decisions?
- How should the Department of Defense respond to the existence of widely available, highly accurate time and spatial data?
- What approach should the U.S. take toward international cooperation and competition in global satellite navigation systems?
- How should GPS and associated augmentations be governed in the future?[50]

The RAND and the NAPA/NRC studies addressed these questions by assessing alternative policies, governance structures, and issues associated with GPS, including providing GPS signals free of direct user charges and applying selective availability to protect militarily significant signal accuracies.[51] The conclusions emerging from these studies laid the foundation for the issuance of the Clinton Administration's GPS policy in 1996.[52]

[45] White House, National Security Decision Directive Number 42, *National Space Policy*, July 4, 1982.

[46] See http://en.wikipedia.org/wiki/Korean_Air_Flight_KAL-007 and Irene Gorin, George Wiggers, and Kenneth Lamm, Chapter 6, "Civilian GPS Planning and Policy Making in the Federal Government," in Commission on Engineering and Technical Systems, *The Global Positioning System for the Geosciences: Summary and Proceedings of a Workshop on Improving the GPS Reference Station Infrastructure for Earth, Oceanic, and Atmospheric Science Applications* (Washington, D.C.: National Academies Press, 1997), for background information.

[47] Pace, et. al., op. cit., pp. 248-249. See also http://www.ngs.noaa.gov/FGCS/ for documentation.

[48] Pace, et. al., ibid., p. 249.

[49] See Pace, et. al., op. cit.; and National Academy of Public Administration (NAPA) and National Research Council (NRC), *The Global Positioning System: Charting the Future* (May 1995).

[50] Pace, et. al., op. cit., pp. xv-xvi.

[51] Pace, et. al., op. cit., pp. xv-xvi.

[52] White House, *Fact Sheet, PDD/NSTC-6, U.S. Global Positioning System Policy*, March 29, 1996.

This policy acknowledged the role of GPS as a dual-use system – "enhancing the effectiveness of U.S. and allied military forces…[and] becoming an integral component of the emerging Global Information Infrastructure, with applications ranging from mapping and surveying to international air traffic management and global change research."[53] The policy's guidelines stressed:

- Providing GPS for peaceful civil, commercial, and scientific use on a continuous, worldwide basis, free of direct user fees
- Cooperating internationally to balance user needs and security interests
- Advocating GPS as an international standard
- "To the fullest extent feasible," purchasing commercially available GPS products and services for U.S. government use.[54]

In 2004, the Bush Administration revisited the Clinton GPS policy and issued a new PNT policy reflecting changes in interagency management and international developments.[55] The new policy pointed out that GPS-derived information and applications are now "an engine for economic growth, enhancing economic development, and improving safety of life, and the system is a key component of multiple sectors of U.S. critical infrastructure."[56] Consequently, this poses opportunities, risks, and threats to U.S. national, homeland, and economic security: dependence on GPS by military, civil, and commercial systems and infrastructures makes them vulnerable to potential disruptions in PNT services. The policy acknowledged that protection against signal use or disruption by adversaries is a critical requirement to ensure GPS continuity. Emerging international PNT capabilities can also serve to both enhance and complicate GPS' role as a global standard. Recognizing these imperatives, the policy initiated extensive structural changes to existing inter-governmental management approaches for GPS to encourage greater agency cooperation and achievement of national PNT goals. These actions should lead to a more unified and balanced government approach to protecting the GPS system, increasing interoperability with emerging foreign navigation systems, and protecting GPS in international spectrum allocation decisions. However, policy challenges will continue to evolve and affect the GPS program for the foreseeable future.

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[53] Ibid.

[54] Ibid.

[55] White House, *Fact Sheet: U.S. Space-Based Positioning, Navigation, and Timing Policy*, December 15, 2004.

[56] Ibid.

Overcoming Challenges to Transformational Space Programs

What does all this mean for transformational space programs today? Several insights from the early experiences of the GPS program are applicable:

- A transformational space program's full potential from its onset is likely to be unknowable. New roles, missions, and opportunities will emerge as users become increasingly familiar with the system's capabilities.
- Developing a space system with clear, stable, and open interfaces that are platform independent encourages users to adapt and develop their own applications, rather than requiring the space system meet all users' needs.
- Programs involving new, experimental, or revolutionary capabilities are likely to experience technological difficulties and potential short-term technical obstacles in system concept development, prototyping, and other early phases.
- A stable resource stream, backed by a political commitment, is needed. Block buys, especially of space systems involving more than one or two individual satellite buys, are important for reducing potential acquisition costs and for demonstrating political support.
- Institutional reluctance to accept new space systems offering potentially dramatic improvements in capabilities and/or changing doctrine, TTP, or force structure will create organizational and cultural barriers to system acquisition and operation. One approach to reducing these barriers is to increase operational familiarity with the system by potential users through "real world" experience, exercises, and training.[57]
- For transformational space programs involving more than one "provider" community (i.e., interagency programs), agreement and cooperation regarding mission, operational, and system requirements are required as early as possible in the development process. Changing or adding requirements, acquisition processes, or system "ownership" in midstream may result in technical problems, schedule delays, higher costs, and increased political scrutiny of the program.

In summary, GPS has become indispensable to U.S. national security and critical economic and societal infrastructure, and is truly a success story, despite its rocky early history. Its successes have made it the global standard against which other PNT systems are measured. Furthermore, the evolution of GPS services and applications has borne out GPS' dual-use nature of providing critical contributions to economic security as well as national security. Examining its history from operational, organizational, acquisition/technological, and policy perspectives has helped identify lessons relevant to today's transformational space programs. Those leading such transformational space programs should profit from this brief case study of the challenges they will face, and must overcome.

[57] A leading example was the commercial buys of the precision lightweight GPS receivers (PLGRs) by soldiers' relatives in Operations Desert Shield and Storm in 1990-1991.

Appendix: Description of GPS

Background

The use of navigation aids of one form or another has been present for thousands of years. The word "navigation" is derived from the Sanskrit word "navgatih" and links to the development of the art of navigation in India's Indus River valley six thousand years ago.[58] Early approaches to navigation included celestial navigation (tracking movement of sun, moon, stars, and sometimes planets), stick charts (used by the peoples of the Marshall Islands to navigate over the Pacific Ocean), pilotage (using visible natural and man-made features), dead reckoning (estimating one's position by nautical experience, compass, and log), waypoint navigation, position fixing, and collision avoidance.[59] More recently, techniques such as radionavigation, e.g., LORAN (Long Range Aid to Navigation) a "terrestrial navigation system using low frequency radio transmitters that use the time interval between radio signals received from three or more stations to determine the position of a ship or aircraft,"[60] allowed for semi-automated equipment to locate geographic positions to less than half a mile. LORAN-C remains in extensive use today, despite being affected by weather, atmospheric changes, and magnetic storms.

What Is GPS?

The NAVSTAR GPS[61] is a constellation of 24 or more satellites at semi-synchronous altitudes (10,900 nautical miles), with a minimum of 4 satellites in each of six orbital planes inclined at 55 degrees. The GPS system includes a number of worldwide ground monitoring stations, with the Master Control Station located at Schriever AFB, Colorado. The satellites use a time-difference-of-arrival concept using precise satellite position and on-board atomic clocks to continuously generate navigation messages that can be received by users anywhere on Earth.[62] GPS services include extremely accurate, three-dimensional location information (latitude, longitude, and altitude), velocity and precise time provided passively and continuously through all-weather, 24/7 operations.[63] Position location and navigation are made by triangulating signals from four or more satellites using, in many cases, hand-held GPS receivers, enabling position determination within a few meters and time accuracy to within a few nanoseconds.[64] System time is maintained on each satellite according to Cesium and Rubidium atomic frequency standards accurate to within a few nanoseconds of global coordinated time (UTC) produced by the Master Clock at the U.S. Naval Observatory in Washington, D.C.[65] Figures 1 and 2 illustrate the GPS concept of operation.

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[58] "Navigation," *Wikipedia*, found at http://en.wikipedia.org/wiki/Navigation, accessed 6/21/2006.

[59] Early navigation devices included the diptych, compass rose, the navigator's rutter (diary), magnetic compass, astrolabe, sextant, and mechanical chronometer. Ibid.

[60] "LORAN," *Wikipedia*, found at: http://en.wikipedia.org/wiki/LORAN, accessed 6/21/2006.

[61] There is some ambiguity over the origins of the names "NAVSTAR" and "Global Positioning System." References exist to the names Navigation Satellite Timing and Ranging (see: Committee on the Navy's Needs in Space for Providing Future Capabilities, op. cit., p. 131) and NAVigation System Timing And Ranging. However, Dr. Bradford W. Parkinson, the first Air Force colonel in charge of the GPS Joint Program Office (JPO), states that the term "NAVSTAR" was never an acronym but rather, was suggested by John Walsh, an Associate Director of Defense Development, Research, and Engineering (DDR&E), as a "nice sounding name." Dr. Parkinson also states that "Global Positioning System" was suggested by Major General Henry B. "Hank" Stelling, USAF, then Director of Space for Air Force Deputy Chief of Staff for Research and Development in the Pentagon. General Stelling thought that "navigation" was an inadequate descriptor and recommended "Global Positioning System" as a better name. Since the program enjoyed support from both General Stelling and Mr. Walsh, the names were adopted. See: Bradford W. Parkinson, "Chapter 1: Introduction and Heritage of NAVSTAR, the Global Positioning System," in Bradford W. Parkinson and James J. Spilker, Jr., eds., *Global Positioning System: Theory and Applications, Volume I*, American Institute of Aeronautics and Astronautics, Washington, D.C., 1996, pp. 6-7.

[62] Defense Science Board Task Force, *The Future of the Global Positioning System*, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., October 2005, p. 26.

[63] U.S. Air Force *Fact Sheet: Global Positioning System*, undated.

[64] Ibid.

[65] Defense Science Board Task Force. op. cit., p. 27.

Figure 1. GPS Operational Constellation

Source: Defense Science Board Task Force, *The Future of the Global Positioning System*, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., October 2005, p. 28.

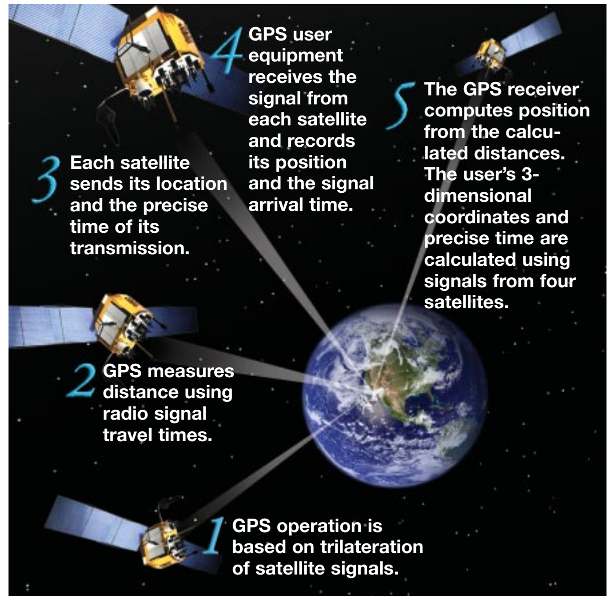

Figure 2. GPS Operational Concept

Source: Defense Science Board Task Force, *The Future of the Global Positioning System*, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., October 2005, p. 26.

While the application of GPS capabilities was primarily intended for national security missions and operations, the DoD officials recognized early in the program that GPS applications would likely have dual-use capability beyond the national security community. However, the requirement to protect its military role led to the initiation of a code structure approach that segregated GPS signals into two modulations: a precise code for military use, and the second, less accurate, code for civilian use. Intentional degradation of the GPS signal was called "selective availability."[66]

GPS Block I satellites were launched between 1978 and 1985 and were followed by Block II satellites that included a civilian signal. These were followed by the Block IIA series and led to the declaration by Air Force Space Command of full operational capability on April 27, 1995. GPS modernization efforts are underway and are planned to include a new military code and a second civil signal. Additional measures will reduce vulnerability to interference and will improve accuracy, availability, integrity, and reliability.[67]

GPS satellites carry an additional payload: nuclear detection (NUDET) sensors. The placement of NUDET sensors on GPS platforms occurred in the mid-1970s as a result of the opportunities afforded by GPS to provide accurate location determination for all nuclear events.[68] Provided by the Department of Energy through the Sandia and Los Alamos national laboratories,

[66] The codes are as follows: (1) The "P or Precise Code," that could be encrypted; its use is called the Precise Positioning Service (PPS) and encryption prevented spoofing of the signal; when encrypted, the P code becomes the Y code; and (2) the "C/A or Clear Acquisition Code," that is the principal civilian ranging signal; its use is called the Standard Positioning Service (SPS). The accuracy of the C/A code could be degraded by intentionally desynchronizing the satellite clock or by introducing small errors into the broadcast ephemeris – this intentional degradation is called Selective Availability (S/A). Differential GPS was commercially developed as an approach to overcome S/A. In May 2000 President Clinton reversed U.S. policy by discontinuing S/A in order to make GPS "more responsive to civil and commercial users worldwide….This increase in accuracy will allow new GPS applications to emerge and continue to enhance the lives of people around the world." See: "President Clinton: Improving the Civilian Global Positioning System (GPS), May 1, 2000," found at: http://www.ostp.gov/html/0053_4.html, accessed 5/19/2006. The Bush Administration further acknowledged the expanded contributions of GPS as a global utility whose multi-use service are integral to U.S. national security, economic growth, transportation safety, and homeland security, and as an essential element of the global economic infrastructure. See: National Space-Based Positioning, Navigation, and Timing Executive Committee, "Fact Sheet: U.S. Space-Based Positioning, Navigation, and Timing Policy," December 15, 2004, found at: http://pnt.gov/policy/, accessed 5/19/2006. However, concerns remained that the GPS signal could be arbitrarily degraded to meet the military's operational needs, thus adversely affecting civil and other users and casting doubt on GPS's professed worldwide availability. This became part of the motivation behind the European push for an independent space-based navigation system, known as Galileo, in the 1990s.

[67] Joe Davidson, "Air Force Space Command Continues GPS Modernization," *Transformation United States Department of Defense*, August 18, 2005, found at: http://www.defenselink.mil/transformation/articles/2005-08/ta081805a.html, accessed 5/31/2006.

[68] *Department of Energy National Security Research and Development Portfolio, Volume 3 of 4*, "Chapter 4: Monitoring Nuclear Treaties and Agreements" (Washington, D.C.: Department of Energy, February 2000), p. 80.

the NUDET sensors are designed to detect nuclear weapons explosions, assess nuclear attack, assist in evaluating strike damage, and perform treaty monitoring.[69] The first sensor launched on a Block I GPS satellite in 1980 was called the Integrated Operational Nuclear Detonation Detection System (IONDS); subsequent improved NUDET sensors carried on later satellites were called the Nuclear Detonation Detection System (NDS).[70]

[69] Pace, et. al., op. cit., pp. 241-242.

[70] Ibid.

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