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CHAPTER NINE

Overcoming Challenges to Transformational Space Programs:

A Case Study of the Early History of the Global Positioning System (GPS)[1]

By Dana J. Johnson

My experience of studying with Dr. William Van Cleave began at USC in 1983. At the time I was employed by Rockwell International in Seal Beach, California, analyzing space systems' contributions to U.S. national security, and was perhaps one of a very few Ph.D. students working in the aerospace industry among all his students. I remember a conversation Bill and I had that first semester when he expressed a point of view that space systems were not survivable. To the contrary, I told him, a certain space system called the Global Positioning System, or GPS, that Rockwell was developing for the Air Force was survivable because of its constellation size and orbital parameters, its characteristic of "graceful degradation," and other survivability measures incorporated into the satellite design. I also mentioned I knew several individuals at Rockwell who would be most happy to help change his mind with detailed briefings on GPS. I doubt he believed me, and so I spent a good part of the five years of my academic studies at USC trying to change his viewpoint–but without much success, or so I thought. To have seen some of the important studies on space and missile defense policy that Bill has led since then makes me think that perhaps I did have some impact on expanding his understanding of space. But I certainly benefited from the experience, particularly in learning how to relate complex technical matters to broader national security concepts and policies. This chapter on GPS' early history brings that experience full circle, and I am honored to contribute it to this book.

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.[2] 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"[3] that users employ for wide-ranging purposes and requirements. In every sense, it is a transformational system that has radically changed 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. For example, in 1979 the program was restructured following funding cuts by the Office of the Secretary of Defense (OSD), and in the period 1980-1982 the program budget was zeroed out by the Air Force, only to be reinstated by OSD.[4]

The purpose of this chapter is to describe and explain the operational, organizational, technological, and political challenges faced in bringing the GPS to fruition. The chapter describes GPS and its early history, explains the rationale and context for institutional support as well as opposition, and documents the difficulties related to introducing such a transformational system into the inventory of U.S. national security space capabilities. As a case study, the methodology used herein suggests the existence of similar challenges facing other transformational space programs today that act to stifle their development and deployment.

What Is GPS?

The NAVSTAR GPS 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.[5] 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.[6] 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.[7] 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.[8]

While the application of GPS capabilities was primarily intended for national security missions and operations, 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."[9]

GPS Block I satellites were launched between 1978 and 1985; they 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.[10]

Beyond PNT, 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.[11] Provided by the Department of Energy through the Sandia and Los Alamos national laboratories, the NUDET sensors are designed to detect nuclear weapons explosions, assess nuclear attack, assist in evaluating strike damage, and perform treaty monitoring.[12]

Operational Challenges

Today's GPS 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. Neither its providers nor its operational users fully understood the scope of GPS' full transformational potential at the program's onset in the early 1960s. The earlier navigation systems that provided the core elements and technologies of the current GPS were developed for discrete purposes and included the Navy's Transit and Timation programs, the Air Force's Project 621B, and the Army's SECOR (Sequential Correlation of Range) program. First launched in 1960 and operational from 1964 to 1996, Transit was intended to provide accurate, reliable, all-weather, global navigation for the U.S. submarine fleet, but evolved to include other public and commercial use, such as commercial marine navigation and recreational boating.[13] Timation consisted of time (or range) measurements between a satellite and a user that were based on spaceflight-qualified atomic clocks.[14] Project 621B emphasized the development of spacecraft design to provide continuous three-dimensional navigation, and a satellite ranging signal less vulnerable to jamming. 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.[15]

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.

During the Cold War, most space systems were viewed as intelligence or strategic deterrence assets, and developed to meet critical strategic requirements such as missile warning, strategic communications, surveillance, reconnaissance, and environmental monitoring. As a consequence, a satellite system offering ubiquitous, continuous, predictable, and reliable PNT was novel and somewhat suspect. 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. Consequently, 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. 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. ODS's land battles involved moving thousands of vehicles and helicopters across hundreds of kilometers of trackless desert–at night or in bad weather–without fratricide.[16] 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.[17] 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.

Organizational Challenges

In the late 1950s and early 1960s, as described earlier, 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.

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 to evolve into a future DoD space-based navigation system.[18] 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.[19] The Air Force was designated the lead agency for developing a single comprehensive Defense Navigation Satellite System (DNSS), and a Joint Program Office (JPO) was stood up at the Air Force Space and Missile Organization (SAMSO) in Los Angeles.[20]

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).[21] 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.

Acquisition and Technology Challenges

DoD's primary objectives in GPS acquisition were: (1) furthering precision weapons delivery; and (2) 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. 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,[22] 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 the program's Phase 1.[23] Furthermore, it cancelled plans for any satellite launches in Phase 2, putting all the remaining satellite launches into Phase 3.[24]

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 General Accounting Office (GAO) reviewed the program at the Hill's 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.[25] 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.[26] 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."[27]

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.[28] Rather than seeking to remedy the problem, the Air Force budget offered reductions so severe that they essentially terminated development and acquisition of GPS.[29] However, OSD restored the full program funding to $259.3 million.[30]

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, and selective availability measures.[31] 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.[32]

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.[33] 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 $1.210 billion.[34] The block buy of GPS satellites was the first time that this approach was applied to a multi-satellite system acquisition. Acquisition innovation also extended to the GPS program's user equipment segment and included a two-phased procurement approach based on receiver design modularity. This approach encouraged competition among different industry providers, leading to improved criteria for selecting production hardware.[35]

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. At the White House level, two decisions influenced the civilian applications of GPS: (1) the downing of Korean Air Flight 007 on 16 September 1983[36] 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.[37] 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.

The 1996 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 GPS. 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 the protection of GPS in international spectrum allocation decisions. 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

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

- Understanding a transformational space program's full potential from the onset of the program 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 that 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 advisable. Block buys, especially of space systems involving more than one or two individual satellite buys, are important for reducing potential acquisition costs and demonstrating political support. Acquisition approaches such as spiral development can help keep costs under control while introducing technological improvements.
- Institutional reluctance to accept new space systems offering potentially dramatic improvements in capabilities and/or changing doctrine, Tactics, Techniques and Procedures (TT&P), 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.[38]
- 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 process, 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 and 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.

ENDNOTES

1 This chapter appeared earlier as a Northrop Grumman Corporation Analysis Center publication by the same author, titled *Overcoming Challenges to Transformational Space Programs: The Global Positioning System (GPS)* (Arlington, VA: Northrop Grumman Corporation Analysis Center, 2006) at: http://www.analysiscenter.northropgrumman.com/index.html. The author wishes to acknowledge and thank Richard Chamblin, Adam Cushing, Gayle Berry, and Karin Ward for their important contributions and research support to this paper. The author benefited greatly from the insights shared by Charles Trimble, founder of Trimble Navigation, and Ann Ciganer, Vice President of Strategic Policy, Trimble Navigation. In addition, the author is grateful to Jeff Grant, Darryl Fraser, Bob Haffa, Rich Dunn, Harrison Freer, Michael Isherwood, and David Negron for their reviews, and to Dr. Harry N. Waldron, Historian, Air Force Space and Missile Systems Center, for his help in researching early GPS history. Nevertheless, any errors or omissions are those of the author alone.

2 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.: Department of Commerce, 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.: Department of Defense, 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: Rand, 1995).

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

4 Scott Pace, et. al., *The Global Positioning System: Assessing National Policies*, Rand MR-614-OSTP (Santa Monica: Rand, 1995), 243.

5 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, 26.

6 U.S. Air Force, *Fact Sheet: Global Positioning System*, undated.

7 Ibid.

8 Ibid., 27.

9 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," 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 services 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, 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.

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

11 *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), 80.

12 Pace, et. al., *The Global Positioning System*, 241-242. 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).

13 Ibid., 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*, (Washington, D.C.: National Research Council, The National Academies Press, 2005), 130-131.

14 Ibid., 131.

15 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, 30; "SECOR," *Astronautix,* at: http://www.astronautix.com/craft/secor.htm, accessed 17 July 2006.

16 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), 90-91.

17 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: Rand, 1994), 203-204.

18 Boehm, *A History of United States National Security Space Management and Organization*, 31.

19 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), 5.

20 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 Pace, et. al., *The Global Positioning System*, 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), 14.

21 Pace, et. al., *The Global Positioning System*, 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.

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

23 Alford, *History of the NAVSTAR Global Positioning System (1963-1985)*, 13-14.

24 Ibid., 15.

25 "GAO Cites NavStar Slippage," *Aviation Week & Space Technology*, March 14, 1977, 22.

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

27 George C. Wilson, "Pentagon Plans Revolutionary Navigation System," *Washington Post*, May 28, 1979, A3.

28 Pace, et. al., *The Global Positioning System,* 263; Alford, *History of the NAVSTAR Global Positioning System (1963-1985)*, 17-18.

29 In June 1980, to comply with DoD budget cuts, the Air Force Program Objective Memorandum (POM) requested $16.3 million in FY82 instead of the JPO's stated requirement of $234.5 million.

30 Alford, *History of the NAVSTAR Global Positioning System (1963-1985)*, 18-19.

31 Ibid., 21.

32 *FY 1982 Authorization Conference Report*, 90.

33 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."

34 Alford, *History of the NAVSTAR Global Positioning System (1963-1985)*, 21-22, 23.

35 Ibid., 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).

36 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 Policymaking 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.

37 Pace, et. al., *The Global Positioning System*, 248-249. See also http://www.ngs.noaa.gov/FGCS/ for documentation.

38 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.