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Global Positioning System: A Case Study Focused on Systems Engineering

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Abstract

A case study was conducted which describes the application of systems engineering during the concept validation, system design and development, and production phases of the GPS program. The case examines the applied systems engineering processes, as well as the interactions of the GPS Joint Program Office, the prime contractors, and the multitude of government agencies that were associated with the program's development and fielding. The systems engineering process is traced from the initiation of studies and the development of key technologies that established the vision of a satellite navigation system in the 1960s, through the multi-phase joint program that resulted in a full operational capability release in 1995. Numerous interviews were conducted with individuals who personally directed, managed and engineered the program, from which the systems engineering story, and the top four learning principles, emerged.

1. Background

GPS [1] is a space-based radio-positioning system nominally consisting of a 24 satellite constellation that provides navigation and timing information to military and civilian users worldwide. GPS satellites (shown in Figure 1), in one of six Earth orbits, circle the globe every 12-hours emitting continuous navigation signals on two different L-band frequencies. The system consists of two other major segments: a world-wide satellite control network and the GPS user equipment that is either man portable or integrated into host platforms such as ships, vehicles or aircraft.

The genesis of GPS occurred soon after the Russians launched Sputnik on October 4, 1957. While the satellite circled the Earth broadcasting its tone, an engineer at the Applied Physics Laboratory at Johns Hopkins University postulated that he could use the Doppler Effect from an orbiting satellite to actually compute where something was located on the Earth.

The Navy and the Air Force established separate programs to satisfy their unique service needs. Under these programs, key technologies such as precise atomic clocks, quartz oscillators, spread spectrum signals, precise ephemeris tracking and prediction, and reliable space systems were developed and demonstrated.

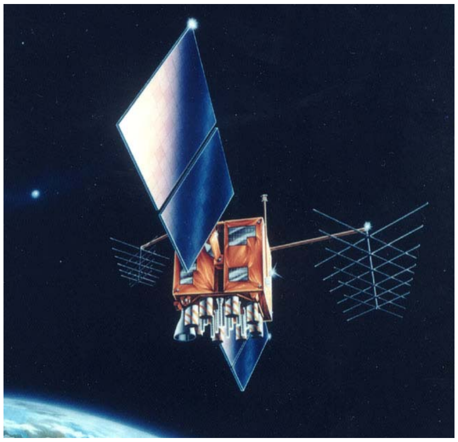

Figure 1. Block IIA GPS Satellite

Seeing the lack of coordination and cooperation, and in some cases duplication of similar efforts, in 1972 the Department of Defense proclaimed that navigation development for space would be accomplished using a single Joint Program Office (JPO). The purpose of the new space-based navigation system was to replace the plethora of land-based navigation aids such as LORAN, VOR, TACAN, VHF omni-directional ranging, and radio beacons. Further, the Air Force was assigned to lead the JPO to be located at the Air Force facility in El Segundo, California. The first program director was Air Force Colonel Brad Parkinson. The program was directed to develop a joint concept solution, through coordination with all services and the Coast Guard. Col. Parkinson assembled his staff, which included Air Force, Navy,

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Army, and Coast Guard personnel, and a true joint program evolved under his leadership. The long journey from early research, to program establishment to operation of GPS is captured in Table 1 milestones.

Table 1. Milestones

1941-43	Long Range Navigation (LORAN) developed and operational
1957	Satellite ephemeris by measuring Doppler shift - Applied Research Lab
1960	First navigation satellite TRANSIT launched by US Navy
1963	US Air Force establishes Project 621B
1963	First operational TRANSIT launched
1964	TIMATION begins development at Naval Research Lab
1967	First TIMATION satellite launched. TIMATION fully operational
1968	Navigation Satellite Executive Group (NAVSEG) established in DoD
1971	DoD lists US Naval Observatory for establishing, coordinating and maintaining time and time interval
Jun 1972	Defense Navigation Satellite System Program established (later became GPS)
Dec 1973	Approval to proceed with GPS
Jul 1974	Navigation Technology Satellite launched with atomic clocks (Rubidium)
Aug 1974	Block I Satellite Contract Award (Rockwell International)
Sep 1974	Block I User Equipments/Ground Station Contract Award to General Dynamics
Feb 1978	First Block I Navigation Development Satellite (NDS) is launched
Jun 1979	Approval to proceed into Full Scale Development (FSD)
Fall 1979	Decision to cut constellation from 24 to 18 due to DoD funding cutback
Apr 1980	First GPS satellite to carry the Integrated Operational Nuclear Detection System (IONDS) launched
Sep 1983	President Reagan directs GPS become available to civilian community at no-cost
May 1983	Block II satellite contract award to Rockwell International
Apr 1985	GPS user equipment production contract
Oct 1985	Seventh and last Block I satellite launched
Jan 1986	Space Shuttle Challenger accident
Jun 1986	Block II approved - proceed into production
Feb 1989	First Block II production satellite launched
Jun 1989	Block IIR Satellite contract award to GE Aerospace Division
Nov 1990	Selective Availability activated
Dec 1993	NAVSTAR GPS Initial Operation Capability (IOC) declared with a constellation of Block I/II/IIA satellites
Apr 1995	Air Force Space Command declares GPS fully operational with Block II/IIA satellites
Mar 1996	Presidential Policy on GPS – discontinue Selective Availability within a decade
Dec 1996	Navy terminates TRANSIT operations
Nov 1997	Last block IIA satellite launched
Jul 1997	First successful Block IIR satellite launch
May 2000	Selective Availability function discontinued

The fundamental systems engineering approach was to first construct the system specification, which is now known as the "functional baseline." The strategy of the program office was to manage the performance-level requirements, as well as manage all interfaces between the interrelated segments of the satellite constellation, ground stations, and user equipment. The program office was staffed with technically oriented military officers and civilians, and augmented by the technical, scientific, and engineering staff from the Aerospace Corporation. The Government oversaw and managed the Interface Control Working Groups (ICWG) and retained ownership of the functional baseline. Figure 2 shows the first phase segmentation.

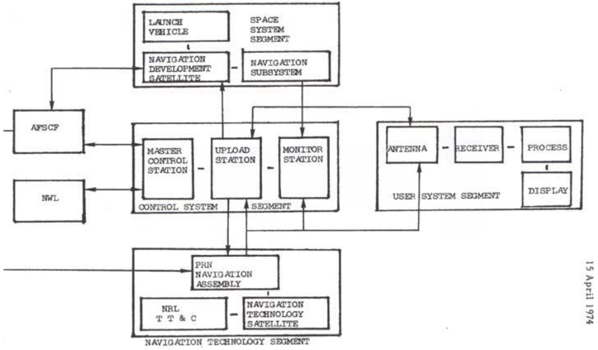

Figure 2. System Segments and Interfaces

If the systems engineering process highlighted areas of the specification that were causing cost, schedule, or performance risks, the combined program office and industry teams quickly derived alternatives and presented them to the decision-making body. Decisions were made quickly because of the close-knit, integrated, and focused efforts of the combined team. Managing the interfaces, achieving insight over the technical development, leading the systems engineering trade studies, and retaining control of the system specification were essential and critically important to strategies for the JPO. Basic system performance requirements are provided in Table 2.

Table 2. GPS Performance Requirements

Characteristic	Performance
Accuracy (relative and repeatable)	5-20m (1 sigma)
Accuracy (predictable)	15-30m (1 sigma)
Dimensions	3-D + time, 3-D velocity
Time to acquire a fix	Real Time (for stated accuracies)
Fix Availability	Continuous
Coverage	Global

In addition to this performance, the system was to have the following additional characteristics:

- Passive operations for all users
- Be deniable to enemy
- No saturation limit
- Resistance to countermeasures, nuclear radiation and natural phenomenon
- Common coordinate reference
- Available for common use by all services and allies
- Accuracy not degraded by changes in user altitudes

2. GPS Analysis Approach Learning Principles

The Friedman-Sage Framework[2] was used to examine the GPS program and served as the context of the learning principles derived including their effect on the program. This construct and its associated matrix of nine Concept Domains and three Responsibility Domains give the SE practitioner a powerful tool to examine any program from an SE perspective and identify areas of risk. Table 3 shows the Friedman Sage Matrix with the areas that most represent the associated learning principles supported by the GPS case study.

Table 3. Friedman-Sage Framework with 4 GPS Learning Principles

Concept Domain	Responsibility Domain		
	Contractor	Shared	Gov't
Requirements Definition Mgt			LP3
Systems Arch Conceptual Design			
System/ Subsystem Detailed Design & Implementation			
System Integration & Interface			LP2
Validation and Verification			
Deployment & Post Deployment			
Life Cycle Support			
Risk Assessment and Management		LP4	
System & Program Management		LP1	

By any measure, the GPS program has been hugely successful. The factors that significantly influenced the successful outcome of the program are captured in the learning principles summarized below. Important concepts pertaining to the principals were coupled with further activities, decisions and events to emphasize why they were chosen.

2.1. Learning Principle 1 - Programs must strive to staff key positions with domain experts.

From program management to systems engineering, to design, to the manufacturing and operations teams, the people on the program were well-versed in their disciplines, and all possessed a systems view of the program. While communications, working relationships, and organization were important, it was the ability of the whole team throughout all levels to understand the implications of their work on the system that was vital. Their knowledge-based approach for decision making had the effect of shortening the decision cycle, because both the information was understood and the base and alternative solutions were accurately presented.

2.2 Learning Principle 2 - The systems integrator must rigorously maintain program baselines.

The JPO retained the role of managing and controlling the system specification and, therefore, the functional baseline. The JPO had derived and constructed a mutually agreed-to set of system requirements that became the program baseline in 1973. While conducting the development program, the GPS team was able to make performance/risk/cost trade analysis against the functional baseline to control both risk and cost. The JPO was fully cognizant of the implications of the functional requirements on the allocated baseline because they managed the Interface Control Working Group process. Managing that process gave them first-hand knowledge and insight into the risks at the lowest level.

The Program Office owned the technical data associated with the performance baseline. Although management of this data was often cumbersome, the program manager decided the benefits of technical ownership far outweighed the resource commitments. For a new program seeking major technological breakthroughs, the JPO's approach of controlling the baselines gave them unprecedented understanding regarding performance, cost, and schedule.

It should be noted that in today's environment of reduced government manning, it may not always be possible for the DoD to be the systems integrator. Whoever has this role, be it government or contractor, they must rigorously maintain the system specification and functional baseline. When a prime contractor is the systems integrator, there must be appropriate sharing of management and technical responsibilities between them and their government counterparts to ensure success especially on complex programs with advanced, unprecedented technology.

2.3 Learning Principle 3 - Achieving consistent and continuous high-level support and advocacy helps funding stability, which impacts SE stability.

Consistent, continuous high-level support provided requirements and funding stability. In this role, the OSD provided advocacy and sourced the funding at critical times in the program, promoted coordination among the various services, and reviewed and approved the GPS JPO system requirements. OSD played the central role in the establishment and survivability of the program. The GPS JPO had clear support from the Director of Defense Development, Research and Engineering (DDR&E), Dr. Malcolm Currie, and program support from the Deputy Secretary of Defense, Dr. David Packard. Clearly, the services – particularly the Navy and the Air Force early on, and later the Army – were the primary users and the eventual customers. However, each service had initial needs for their individual programs, or for the then-current operational navigation systems. Additionally, the Secretary of the Air Force provided programmatic support to supply manpower and facilities.

2.4 Learning Principle 4 - Disciplined and appropriate risk management must be applied throughout the lifecycle.

The GPS program was structured to address risk in several different ways throughout the multiphase program. Where key risks were known up front, the contractor and/or government utilized a classic risk management approach to identify and analyze risk, and developed and tracked mitigation actions. These design (or manufacturing/launch) risks were managed by the office who owned the risks. Identified technical risks were often tracked by Technical Performance Measures (TPMs), (e.g. satellite weight and Software Lines Of Codes (SLOC)), and addressed at weekly chief engineer's meetings.

The JPO, serving in the clear role of program integrator, sponsored risk trade studies at the top level. The Program Office would issue study requests for proposals to several bidders for developing concepts and/or preliminary designs. Then, one contractor would be down-selected to continue. This approach not only provided innovative solutions through competition, but also helped in defining a lower risk and more clearly defined development program for the fixed-price contracts approach that was being used for development and production.

The Program Office was closely involved with the technical development as the system integrator. To identify unforeseeable unique technical challenges, the Program Office would fund studies to determine the optimal approaches to new issues. For example, there were schedule risks associated with the scheduled first launch due to unforeseen Block II issues with respect to the space vehicle and control segments (software development). Although a catastrophic event, the Challenger accident actually provided much needed schedule relief. Using decision analysis methodology led the JPO to an alternative approach to develop the expendable launch vehicle for the Block II satellites.

Good communications, facilitated by cooperative working relationships, was a significant positive intangible factor, whether it was between the contractors and government (JPO or other agencies) or contractors to sub-contractors. A true team environment also played a significant role in reducing risk, especially considering the plethora of government agencies and contractors that were involved in the effort.

For today's program offices, the primary take-away is that a disciplined and documented risk management approach is essential to program success. While oftentimes risks are transferred to the contractor, the government still needs insight/oversight into their risk management strategies. Accordingly, all program risks should be handled in accordance with the organization's documented risk management processes.

3. Comparative Systems Analysis

Several other case studies examining the historical practice of systems engineering have recently been conducted [3]. These cases (predominantly on Department of Defense systems) include such successful systems as the Hubble Space Telescope, Theater Battle Management Core Systems, the C-5 Galaxy, the F-111, the B-2 Spirit, the Joint Air-to-Surface Standoff Missile, and the A-10 Thunderbolt. Others studies under way are the Peacekeeper Missile System and the International Space Station.

Many important learning principles can be drawn from the studies; one that transcends this body of work is that systems engineering and analysis exist as a continuum across the life cycle [4]. Mission and systems analyses start well before program initiation and must be part of the entire systems engineering continuum. To ensure a continuous and strong set of integrated systems engineering activities, it is necessary to apply rigorous processes and tools early, from the conceptual solutions throughout system developmental and operational life.

These other cases point out how this thread can break at many points for many different reasons, and show that there are no shortcuts. In particular, the case studies often highlight disconnects at the seams in the continuum, as roles and responsibilities transition between requirements (user), acquisition, and developer (contractor) communities. The successful GPS program offers several insights to maintain appropriate systems engineering throughout a lifecycle.

4. Summary

The GPS program was presented challenges in various areas such as technology, customers, organization, cost, and schedule for a very complex navigation system. This system has become a beacon to military and civilian navigation and other unique applications. As best put by Ivan Getting, GPS provides “a constellation of lighthouses in the sky.”

Several precepts or foundations of the Global Positioning Satellite program are the reasons for its success. These foundations are instructional for today’s programs because they are thought-provoking to those who always seek insight into the program’s progress under scrutiny. These foundations of past programs are not a complete set of necessary and sufficient conditions. For the practitioner, the successful application of different systems engineering processes is required throughout the continuum of a program, from the concept idea to the usage and eventual disposal of the system. Experienced people applying sound systems engineering principles, practices, processes, and tools are necessary every step of the way. Mr. Rob Conley, formerly of the GPS JPO, provided these words: “Systems engineering is hard work. It requires knowledgeable people who have a vision of the program combined with an eye for detail.”

Systems engineering played a major role in the success of this program. The challenges of integrating new technologies, identifying system requirements, incorporating a system of systems approach, interfacing with a plethora of government and industry agencies, and dealing with the lack of an operational user early in the program formation required a strong, efficient systems engineering process. The GPS program imbedded systems engineering in their knowledge-base, vision, and day-to-day practice to ensure proper identification of system requirements. It also ensured the allocation of those requirements to the almost-autonomous segment developments and beyond to the subcontractor/vendor level, the assessments of new requirements, innovative test methods to verify design performance to the requirements, a solid concept of operations/mission analysis, a cost-benefit analysis to defend the need for the program, and a strong system integration process to identify and control the “hydra” of interfaces that the program encountered. The program was able to avoid major risks by their acquisition strategy, the use of trade studies, early testing of concept designs, a detailed knowledge of the subject matter, and the vision of the program on both the government and contractor side.

The case study revealed that key DoD personnel maintained a clear and consistent *vision* for this unprecedented, space-based navigation capability. The case study also revealed that good *fortune* was enjoyed by the JPO as somewhat-independent, critical space technologies matured in a timely manner. Although the system required a large degree of *integration*, both within the system and external amongst a multitude of agencies and contractors, efforts were taken to directly address it. Lastly, GPS had and continues to have a huge *effect* on the military and commercial industry. A system originally designed to help “drop 5 bombs in one hole” has increasingly grown in use and now impacts our everyday lives.

10. References

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