ECE-GY 5213 INTRODUCTION TO SYSTEM ENGINEERING

Systems Engineering Project : Global Positioning Systems (GPS)

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Final Report

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Video Presentation Link : https://youtu.be/kS1R-AaK14E

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Background :

What is GPS ?

The Global Positioning System (GPS) is a radio navigation system and is satellite based. It provides users having receivers the ability to correctly determine 3-dimensional position, time and speed information on a global level. This system was developed to help United States of America and its Department of Defense with worldwide position, navigation, and timing functionalities to support military operations such as improved air, ground, sea warfare. However the main reason for which it was approved was due to its functionality to locate/detect and report nuclear detonations anywhere near/on earth, sea, atmosphere real time thus also making it a Nuclear Detection System (NDS). This system was made available to the civilians in 1983 by US President Ronald Reagan. Each of the GPS satellite continuously transmits precise signals at two L-band frequencies: L1 and L2, where L1 is ~1575.42 MHz and L2 is ~1227.6 MHz and L3 specific frequency for nuclear detonation (NUDET data) via Space Ground Subsystem on S-band. Trilateration method is used to determine the relative positions of the user. GPS consists of 3 major components:

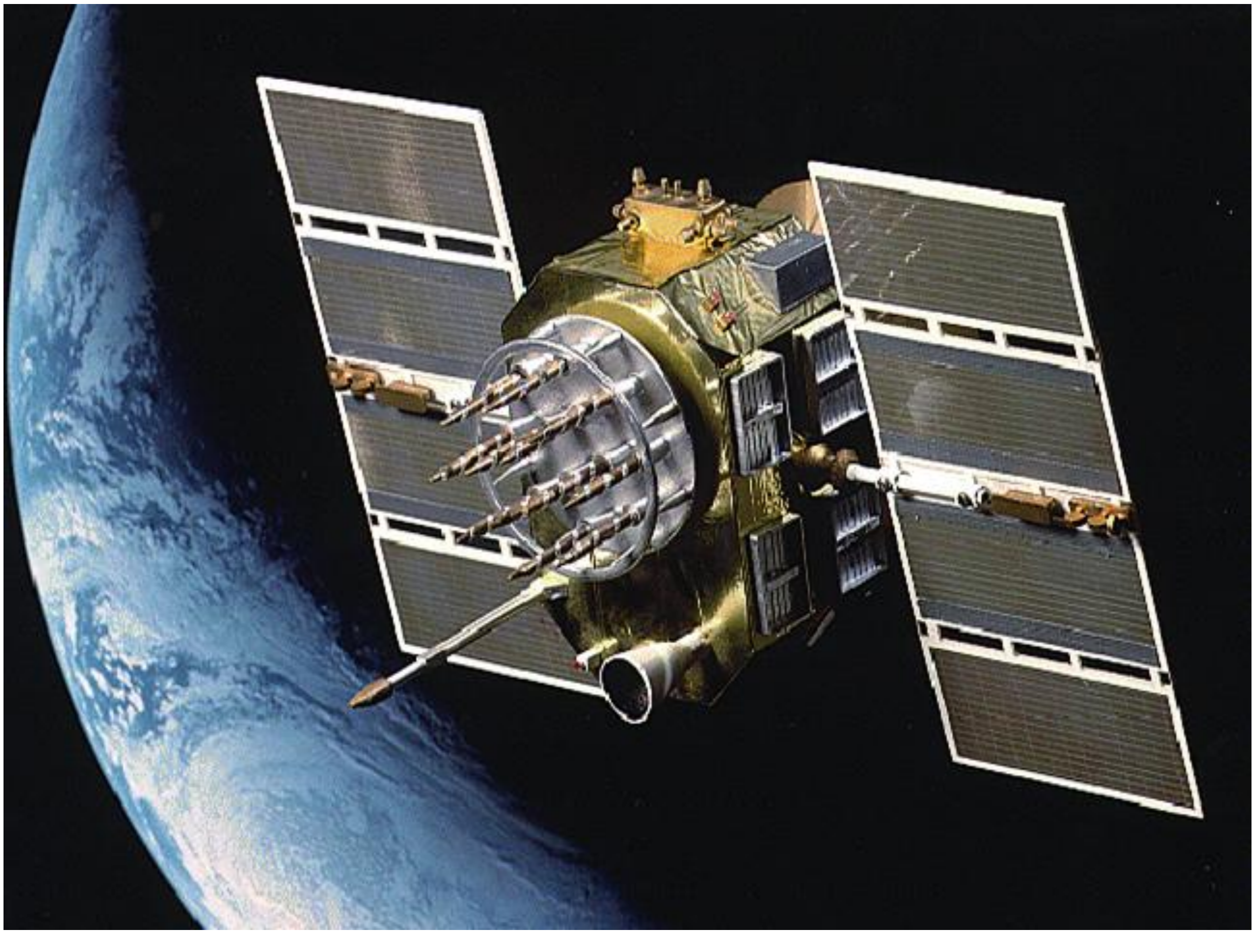


Figure 1 : Block IIA GPS Satellite

a) Space Vehicle : Consists of 24 satellites in space (including 3 spares). There is a constellation of 6 equally spaced orbits and each holding 4 satellites. The 3 spares are in each alternate orbital plane. Each of these 24 satellites have a 12hour orbit.

b) User Equipment : The user receiver compares, the time of a signal, sent by a satellite to the time it receives it. This time diff, combined with the location of the satellites, allows the receiver to determine the location of the receiver ie user. To determine a 3-dimensional position, signals from a min of 4 different satellites are essential. The user receiver generally has an antenna assembly, data processor, receiver, control unit, interface unit, display unit.

c) Control Station : The control segment sends commands, control and system data to the space vehicle. It also tracks the SV and monitors its health / condition. It consists of a Master Control Station and 5 remote monitor stations, 3 ground antennas and a Pre-Launch Compatibility station.

GPS : A Brief History

In the late 1950's, there were several efforts being put into space exploration / applications. After the Russian Sputnik launch in 1957, Drs. Geier and Weiffenbach at John Hopkins University conducted a research study on the signals generated by the Sputnik satellite. They found that the frequency of the signals sent by Sputnik increased as the it approached, and it decreased when the satellite moved away. This is in physics is the Doppler effect. This helped them to track the movement of satellite from earth. This idea was then extrapolated to see if track the movement of an object on earth from the satellite (ie position/distance from satellite) via same frequency shift and it was possible ! The Advanced Research Projects Agency (ARPA) used this to develop the initial and first GPS, TRANSIT. And thus the 1st satellite was launched in 1960.

Aerospace Corporation was holding studies for space-based concepts. One of these studies, Project 57, envisioned the use of satellites for enhancing navigation for fast-moving vehicles (automobiles) in 3 dimensions. It was from this study that the concept for GPS was born. This project eventually became Air Force Project 621B in 1963 to evolve TRANSIT into current day GPS.

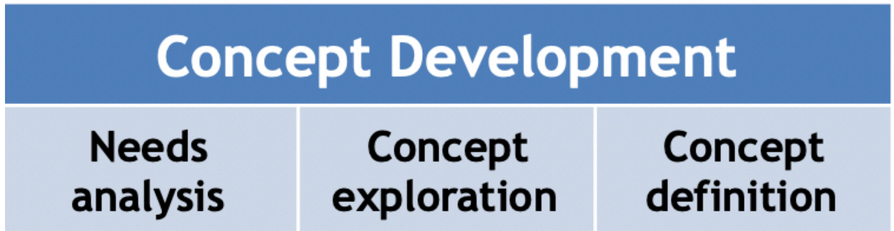


Figure 2 : Concept Development Stage Subparts

Concept Development Stage:

This stage questions and answers the need for a new / replacement system. It involves analyzing and planning the new / improved system, and its feasibility. And thus this requires to take into consideration various factors such as stockholders needs, practical feasibility, budget cost, scalability etc. Since this is an initial stage of the System Engineering / development life cycle, it is very different from the rest of the stages. Systems engineering helps in converting operational needs into a economically and technically viable solution.

It can be classified into 3 sub-stages:

a) Need Analysis

b) Concept exploration

c) Concept definition

We will see how this crucial stage of software engineering was carried out while developing the GPS. The concept development stage of the GPS will provide some crucial information needed to carry out the subsequent two parts of the software engineering system life cycle. Below figure highlights how the Concept development stage fits in the entire system life cycle.

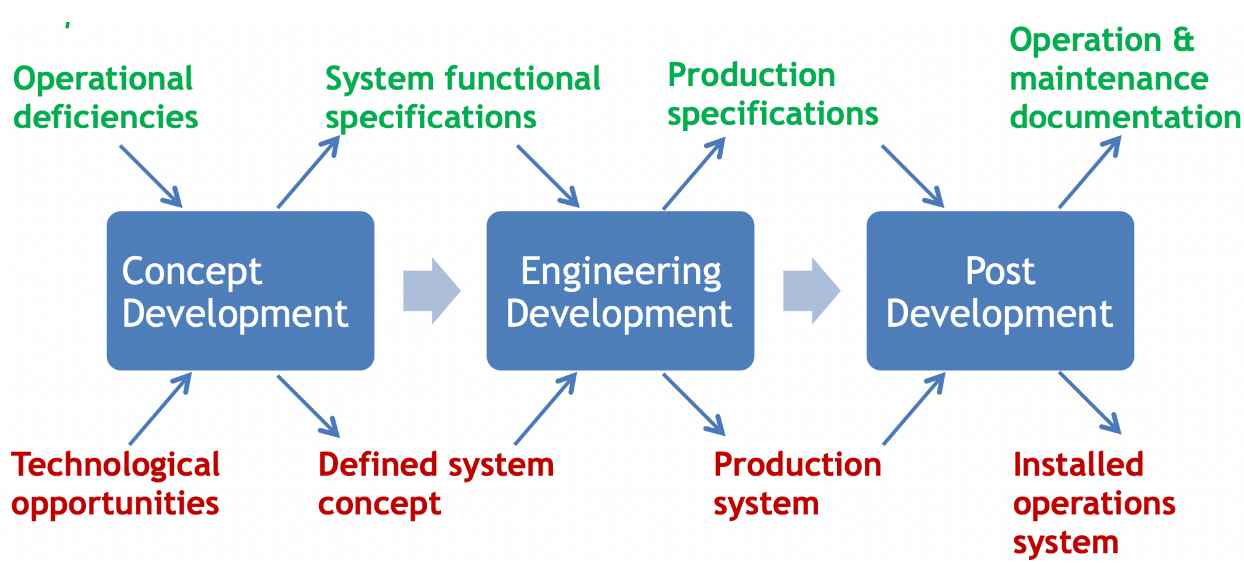


Figure 3 : System Engineering Life Cycle

a) Need Analysis:

The primary objective of Need analysis is to show that there is valid operational need, a strong market for GPS. We need to see if developing this system really brings any value to its predecessors and if it can be fully developed within an affordable budget and level of risk. Since GPS development used US taxpayers money, it was all the more essential to prove to the stockholders the value it brings in for both military and non military (civilian, commercial) use.

A system can be classified into 2 types :

a) **Need driven system** : Focuses on replacing a system that has evident deficiencies
b) **Technology driven system** : Focuses on developing a new system that is better than existing ones.

The 1960's saw the United States Navy conducting experiments to track submarines carrying nuclear missiles using satellite navigation, TRANSIT. 5 satellites were orbiting the poles and with this it was possible to observe the satellite changes in Doppler and find the location of submarine every 1 hour. However this system was not very robust and stable and was slow considering the advancements in the military and civilian automobile industry was thriving with faced paced vehicles . Thus the development of a more robust and and stable satellite system was seen as a **Need and Technology driven** effort. There were other similar systems developed during a similar timeframe such as the TIMATION satellite in 1967 which used clocks accurately in space. Also OMEGA navigation system which was a ground based system based on comparison, in phases, of signal transmission from pairs of stations. However due to scalability and accuracy limitations in all these systems and with advancements in the military and civilian automobile industry there was need of a equalling solutions which was more accurate and universal.

There was another need based aspect behind GPS. Around this time ie post WW2, there was a Cold War between US and USSR and its allies and this led to a arms race. The USSR was already a nuclear power and this posed a threat to the United States. The GPS could also be used to detect nuclear activity near the surface of the earth and this was the main reason that convinced the US congress to spend Billions of dollars of US taxpayer money.

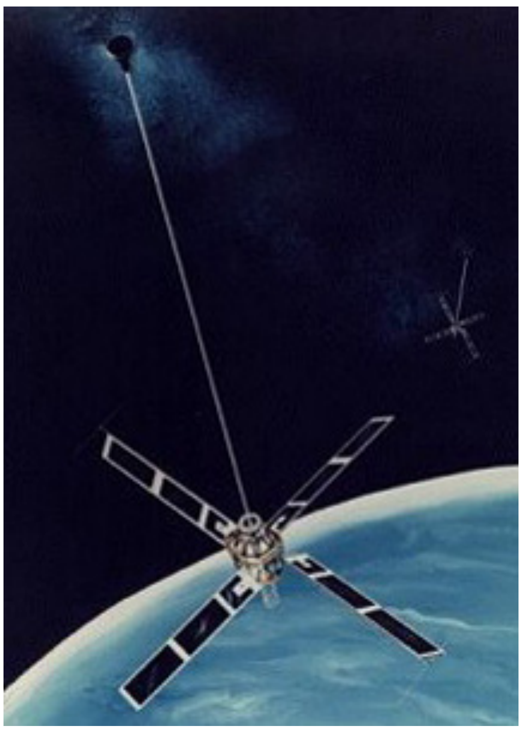


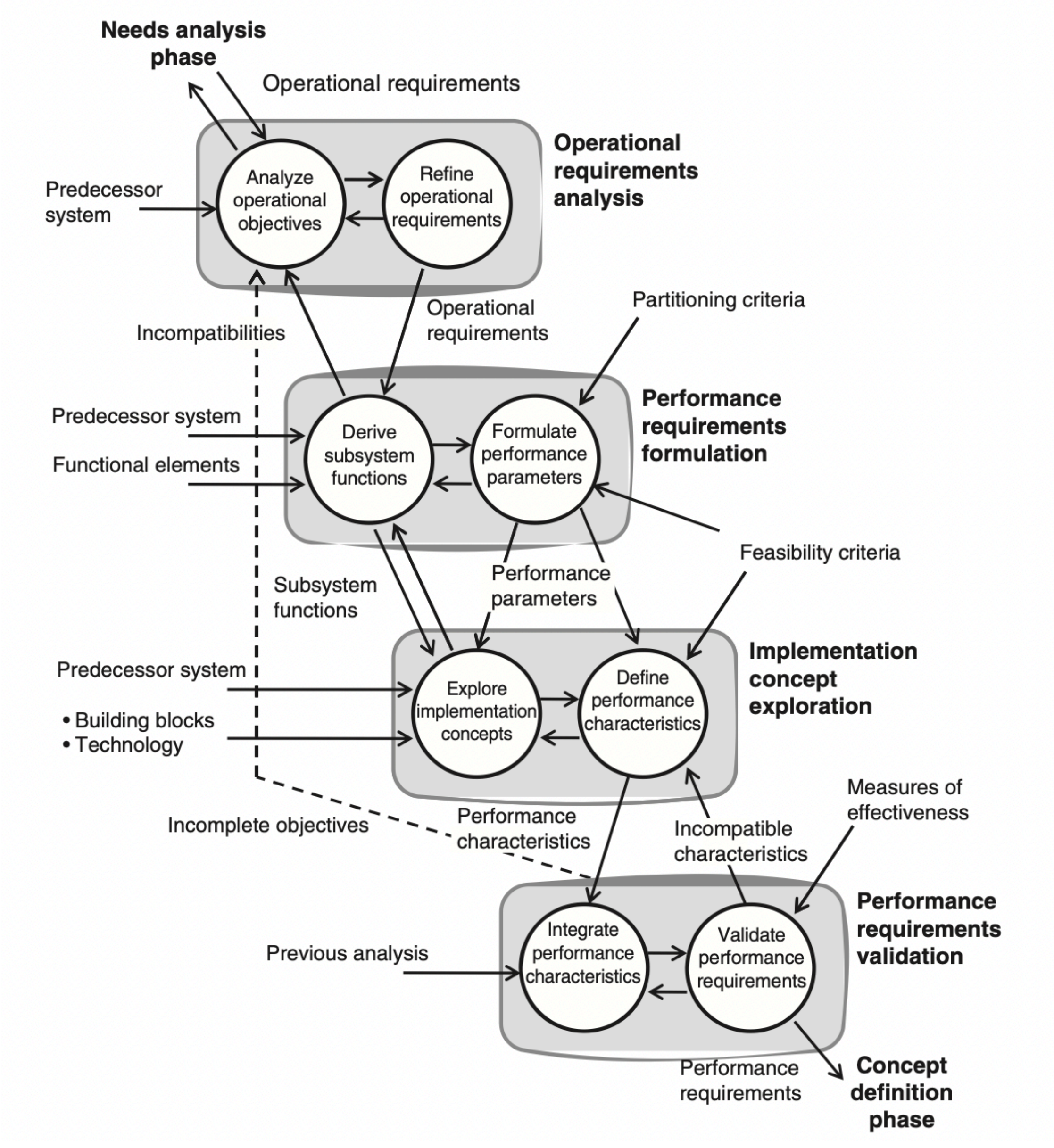
Figure 4 : TRANSIT satellite

Figure 5: Omega Transmitter

b) **Concept exploration:**

Concept exploration sub phase uses the output from “Need Analysis” sub phase and builds on top of it. It converts the operational view point of system to an engineering viewpoint required in all systems engineering phases. This means to provide a measurable basis for selecting a system concept that can be evolved into a physical model of the system. Here the various requirements such as operational, performance requirements are analyzed and a new system/model is selected. Needs driven system development is conducted by the customer itself with maybe the guidance of a systems engineer employed with the customer. Whereas technology drivers system is developed by a system developer skilled in that particular technology. In short, produce a set of achievable perf requirements that are capable to create a system that can satisfy valid operational need. The below chart explains this step graphically.

Figure 6: Concept Exploration Stages



- Operational Requirements Analysis : Involves analyzing the the operational requirements of the system in terms of objectives and then refining them.
- Performance Requirements Formulation : Translates operation requirements into sub-system functions and formulates perf parameters.
- Implementation of Concept Exploration : Involves researching all the implementations possible of technology and also defines the perf characteristics.
- Performance Requirement Validation : After above all steps are done, lastly as part of the concept exploration phase integrates and validated the perf characteristics defined in last stage.

1) The first objective even before analyzing the operational requirements was to determine the preferred User Equipment designs and validate life cycle cost models for the design to cost process. 6 classes of designs were analyzed with aim in mind to have the highest degree of similarity between these designs. This was done as part of the requirements analysis since each design catered different requirements such as Accuracies : High, Medium accuracies, Dynamics of user : High, low, medium, Immunity levels to jamming : High, Low, Usage entity : Airforce, Navy, Army.
2) After this operational requirements were analyzed by testing of operational utilities. Demonstrations of co-ordinated bombing, terminal navigation, landing approaches, army land operations, airborne fueling, anti-jamming margins, satellite hardening, long-term

stability of rubidium frequency standards, navigation signals compatible between technology and development satellites were done.

3) 2 key performance requirements were established :

A. Dropping 5 bombs in the same hole : This parameter helped to confirm the integration of receivers on platforms and the ability to transmit exact space based timing and navigation data. The demonstration of this provided strong data to gain support for the military use of the system. People experienced in the relevant and appropriate fields were required to observe the experiment and assess/review the data for this experiment to gain considerable value.

B. User Equipment (receiver) for less than 10k$: The US government apart from seeing it only as a system useful to detect nuclear armory and use by the military, for-saw its use for the civilian community. Also by involving the civilian community it hoped that the commercial market would become competitive which could benefit the DOD with cost of this equipment going down which would be beneficial for the military. Another benefit would with the vested interests of the civilian community came the much needed political to keep the program going.

4) The top level requirements were "negotiable" for the JPO. And this turned out to be a huge benefit since it allowed the requirements and thus in turn the system to improve with evolving / advancing technology.

Trade Study	Selection
Satellite Memory Loading	Resolve the method for uploading user-required data and verifying accuracy after SV has received it. S-band uplink and L-band downlink, verified at SV
Satellite Orbit	Resulted in a 2/2/0 configuration
Monitor Station Sites	Selection: Hawaii, VAFB, Elmendorf AFB & TBD; VAFB to be MCS and Upload Station
Control Segment Computers	Evaluation criteria established
User Segment Computer	Interim findings only…did not consider on Phases II/III
User Cost/Performance	Low fidelity study, some cost/performance data; no selection
User Ionosphere Model	Identified important features: user storage, satellite transmission & technique accuracy
User Ephemeris Model	Kepler functional model, functional ephemeris
Ephemeris Determination	

5) Requirements were communicated to the stockholders eg DOD, operational users and by doing this help optimize the operational concept, risk, cost, schedule, perf / design.

c) **<u>Concept Defination</u>**:

This phase involves choosing from a number of alternative/candidate system concepts discussed in "Concept Exploration", a system that will form the basis of the next stages of development and engineering. This phase actually marks the start of effort for the functional, physical characteristics of the new system to be defined. The system development phase will use this to actually develop the new system. To make a final selection a number of trade studies need to be conducted amongst all the options to assess the relatively "better" option based on :

a) Operational performance and compatibility

b) Program cost

c) Program schedule

d) Risks

- General dynamics in July 1974 performed a series of trade studies on various important requirements listed in the previous phase and selected the relatively best alternative from all available for each requirement. Some of them include are listed above.

- Constellation Development : Before 1974 the constellation development POC had 6 block I satellites in 2 planes and build upto 24 Block 2 satellites in 3 planes. However there was a consensus that a trade study should be conducted to reduce the number of satellites required by determining a higher SV orbit. JPO in association with Aerospace corporation conducted various analyses and trade studies on working constellation concepts that resulted in a baseline configuration of 8 satellites, each in 3 circular rings with 63-degree inclinations with considerations to satellite replacement issues, location of remote sites, global coverage.

- PRN signal structure : It is one of the most important technologies that has enabled GPS. It too resulted from extensive analysis and trade studies based on system engineering concepts. The structure is based on the ability to communicate accurate timing and navigation data to each of the segments. Substantial trade studies in signal and communications message development were performed to come to this phase from its predecessor Project 621B by Aerospace Corporation and Magnavox.

  - Risks Mitigations : GPS concept was based on a highly reliable Atomic Frequency Standards (AFSs). It was one of the key technologies in making GPS viable. The atomic clocks in the GPS satellites were important in providing GPS users accurate velocity, position, and time values. However the ability to test the AFS / clocks, performing correctly in a space like environment and outputting precise timing to the user receiver equipment was a huge risk.

Figure 7: Cesium Atomic Clock

Engineering Development Stage:

The Engineering Development Stage is the 2nd major phase and comes after the Concept Development stage. It involves working on top of needs which were analyzed and finalized in the previous concept development stage. In this stage we will put together the engineering design / develop the system by first creating a prototype for the system and followed by rigorous testing until it is deemed perfect for use (ie production). This stage can be divided into 3 major sub components:

a) Advance development

b) Engineering Design

c) Integration and Evaluation

We will be going through each of these sub-components in detail below and how they contributed to the development of the highly complex and successful System - GPS.

Figure 8 : Engineering Development Stage

The GPS engineering development stage aimed to develop the Space Vehicles (SV's), finish the IOT&E ie Initial operational Test & Evaluation of the UE ie user equipment, and to also begin production of low cost UE, and to establish a 2 dimensional limited operational capability.

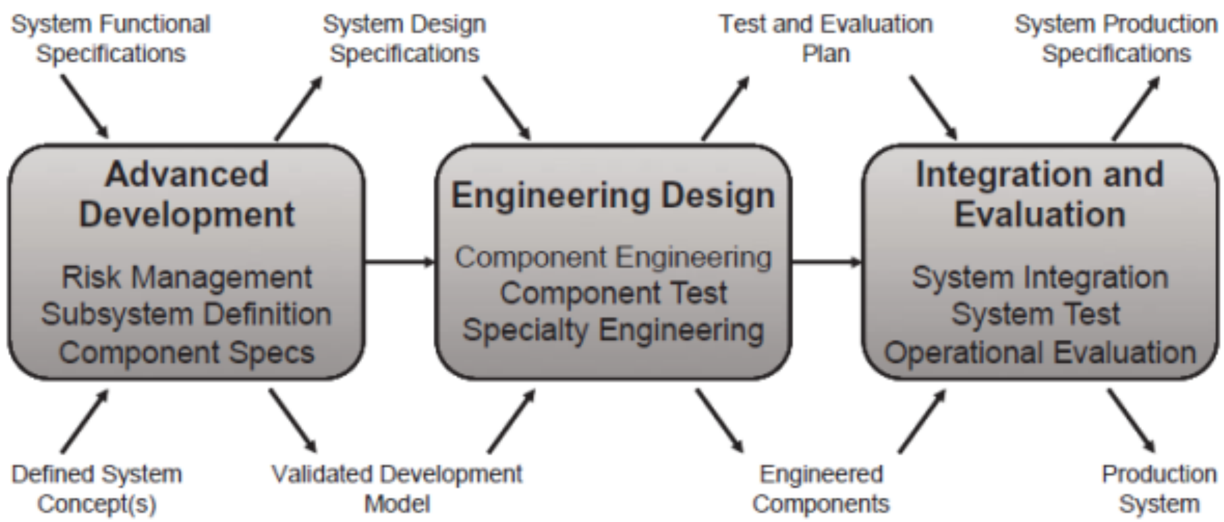


Figure 9: Complete Engineering Development Stage

a) Advanced Development

This sub stage aims to solve the risks associated with the system which were analyzed in the previous stage by performing analysis, development and validation of the system design which forms the basis for full scale engineering process. The result of this sub stage is validated system design specification and development model. The need for this sub system is mainly for systems which have unproven concepts , in order to discuss and either prove them or remove them.

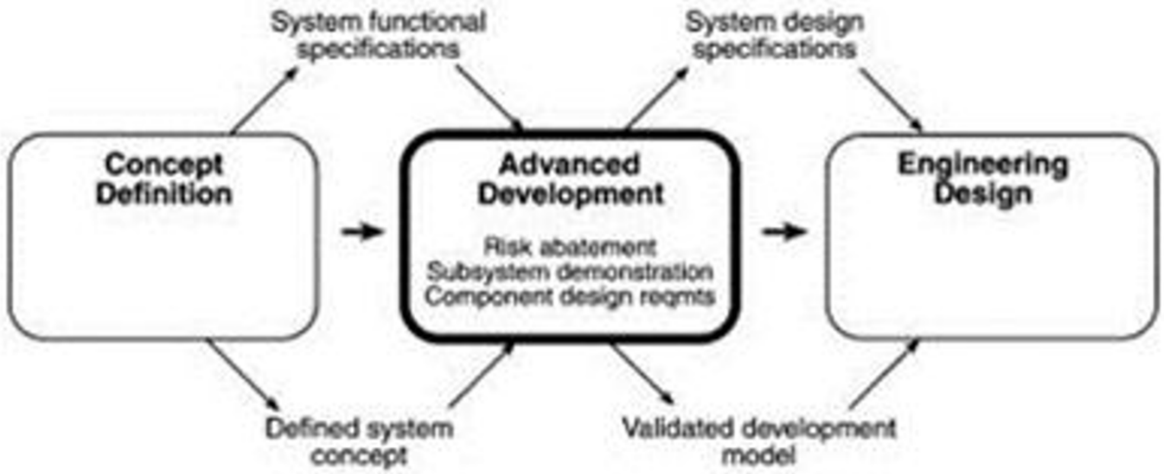


Figure 10 : Advanced Development Phase

Requirements Analysis :

A) Interface Requirements : When the ICS ie Interim Control Segment was being developed, there was an interface issue wrt the telephone communications with the sites remotely located. The government and the contractors did not anticipate the issue with the relatively small telephone companies on the West Coast of USA establishing unique out requirements/ procedures that influenced the efforts to try and determine communications links among the remote stations / master control and test facilities. They required huge workarounds and time intensive solutions.

B) Performance requirements : Rockwell International was a parallel organization to the JPO (one which was mainly en-tasked with the development of the GPS) and it worked on the top-level performance requirements such as SV ie Space Vehicle life, error budgeting, signal generation and some other interface requirements. These Interface and Design requirements sometimes drove system-level requirements. Design studies were conducted to establish the best way to implement such decisions. Solutions were formulated such that its implementation would minimize the cost and schedule impact.

C) IONDS requirement : Interface between IONDS and the SV ie Space Vehicle which required the development of firstly, the L3 signal which was odd to the IONDS data transmission and secondly, the establishment of the ICD and MOA with the Department of Energy (DOE), specifically Sandia National Laboratories and Los Alamos Laboratory was done to resolve issues.

<u>Prototyping :</u>

A) Prototype receivers : Build and Validate prototype receivers (User Equipment) which could precisely predict location using time and navigational signals. Performance limits under dynamic conditions in a severe environment were also established. It was essential to perform this in order to ensure that the instruments being developed were actually going to work with the satellites. Using 4 ground-based scrutinized transmitters and the prototype receiver, a test plan was devised and conducted to test the compatibility with the receivers, signal-wise. Azimuth and angular errors were scrutinized . This was an essential test for the Phase1 satellites.

<u>Risk Mitigation</u> :

A) Ability to test the AFS / clocks which were of utmost importance in the functioning of the GPS, performing correctly in a space like environment and outputting precise timing to the user receiver equipment was a huge risk.Testing for this feature was done using the Navy TIMATION satellites which has atomic clocks onboard and incorporating predecessor Project 621B code generators. The objectives of this NTS concept development tests were to test the techniques for high resolution satellite orbit prediction, behavior of accurate clocks in space, the distribution of precise time data worldwide, and the signal propagation characteristics.

<u>Testing Efforts :</u>

A) UE (User Equipment) Development Testing : A threat assessment study was conducted by Aerospace Corp. for the UE receivers and using the results of which the JPO conducted its own assessment of the 2 types of antennas used in the receivers : 1) FRPA ie Fixed Reception Pattern Antenna, 2) CRPA ie Controlled Reception Pattern Antenna to understand how a common antenna can satisfy all the requirements of the user and at the same time be cost effective by procuring larger amounts of units. After this analysis, FRPA was selected .

Figure 11: Rockwell Collins Manpack

Functional Analysis :

A) The GPS project funding became a cause for major concern during the 1970-1980's. System Engineering development principals were used to reduce the number of satellites needed from 21 to 18 which in turn reduced costs. Following the systems engineering process, trade studies were conducted on the SV ie Space Vehicle constellation to establish the minimum number of satellites required. The result of these efforts was the decision to have a 18 satellite constellation which would provide continuous global coverage.

b) **Engineering Design**

Building on the prototype model derived from the previous "Advanced Engineering" stage, this stage aims to create a more engineered prototype with well defined test requirements. In other words any unknowns arisen from the previous stage prototype model are solved in this stage. The figure below explains this diagrammatically.

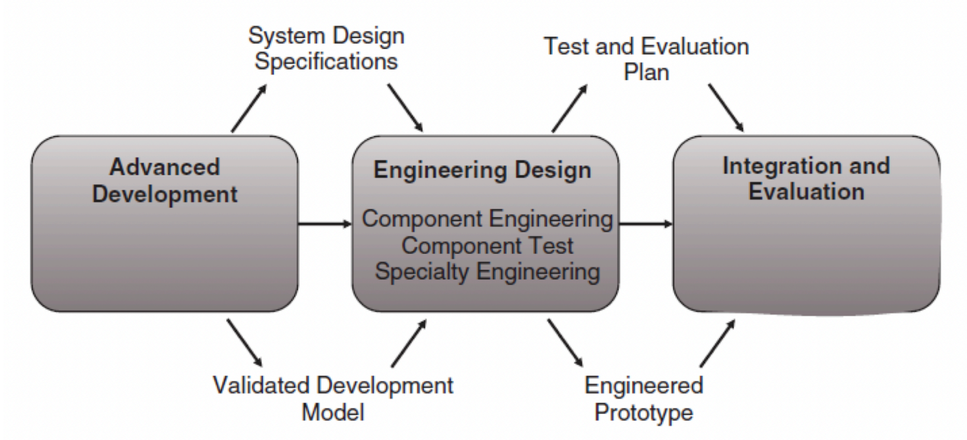


Figure 12 : Engineering Design Stage

Rockwell, which was the organization parallel to the main JPO, was also working on designing and developing the GPS system. Focus was kept on keeping the design simple so that manufacturing becomes easier and also in case of high risk components, addressing the functionality becomes simpler.

4 high risk items were designed. (1)Navigation payload (2)Atomic Clocks (3)Antenna lastly (4)High Power Amplifier / RF chain. Design, fabrication, testing of these components was done prior to contract award so that the risk was reduced and feasibility was demonstrable. The goal for GPS team, during the design and development phases, was to "construct what was the resultant design of the proposal phase." This policy made sure that the final product quality kept improving during the short factory to launch pad schedule.

The triumphant GPS satellite design was the consequence of the below engineering concepts:

1) Focus was put on the design of the environmentally significant component, which were the atomic clocks, and this made all other component considerations secondary.

2) Design of of the GPS system was kept as simple as possible and that made the satellite highly reliable, cost effective, more producible and compatible without any constraints. This simplicity in complexity was extended to the launch and on orbit operations.

3) Sub system designs and trade studies also contributed to the simplistic and reliable design of the GPS satellite system. Cases of these include:

   A. Solar array's with 1(Single) degree of freedom drives were utilized whereas for the 2(second) degree of solar array freedom, yawing was utilized.

   B. The less expensive TWT ie Travel Wave TubeSolid was pitted against the state HPAs for improved life, removal of high voltage power supplies and effective power consumption.

   C. On board systems controlling the navigation functions was no longer required.

   D. Passive thermal control system which were developed for the temperature-sensitive clocks, were helpful in reducing power consumption were utilized.

   E. SSR ie Spread-spectrum-ranging and DDSR ie data-stream-signal-structures were optimized in order to meet the link requirements, and strict adherence to the limitations of the national / international regulations concerning EM ie electromagnetic radiations was ensured.

F. Single SV ie Space Vehicle broadcast coverage was capitalized by constructing the 12 array antenna which was helix phased . This not only decreased power consumption but also from the SVs' line of sight a more analogous radiation pattern was provided to the earth's surface.

G. Magnetic momentum dumping of the ACS ie active control system reaction wheels to ensure longer spacecraft orbital life was implemented.

c) **Integration and Evaluation**

Post the engineering design phase, comes the integration and evaluation stage which is also the final sub phase of the engineering development phase. A System engineer in this stage, works to determine how closely the system match its intended design and use cases. The results from this stage are weighed up against the operational requirements which were initially defined in the needs analysis stage. This stage can be skipped if all components in the system are flawlessly engineered and their designs were perfectly implemented which would make their evaluation and integration effortless. However if not skipped this stage can be a lengthy process. But however throughly the components were tested there always occur some unforeseen issues that only arise when the entire system is brought together. The JPO ie organization which mainly managed the development of the GPS made sure none of the partner organizations received the responsibility of the system integration. One of the most important aspects in terms of system integration was the control of the interfaces. By taking care of this it would ensure that the inputs, technical requirements, system testing, constraints associated with all the stakeholders such as contractor's, US government etc were considered equally and in a orderly manner, and at the same time establish a means of communication amongst them.

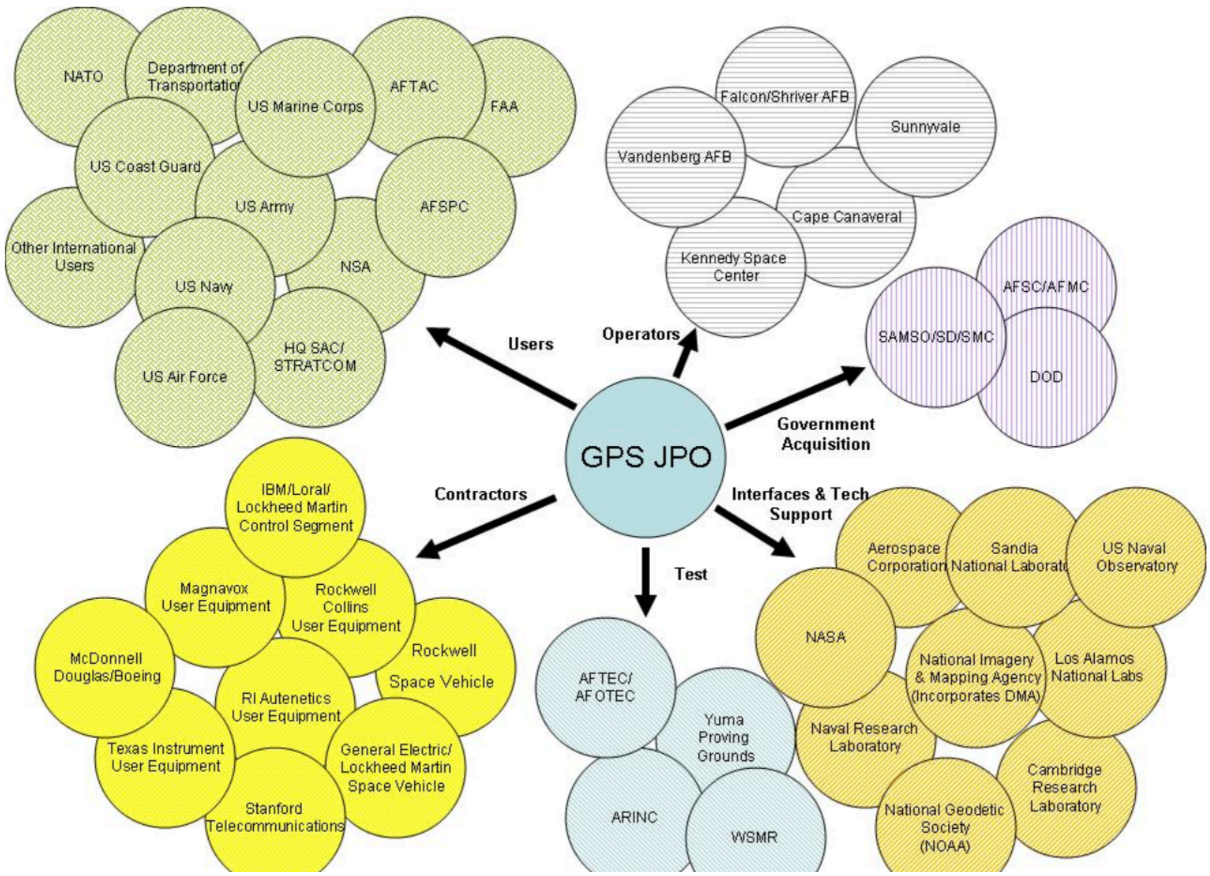


Figure 13: GPS JPO Agency/Contractor Interfaces

The integration role required communication between multiple US govt and industry contractor companies. This phase involved a lot of fluidity among the different organizations shown above and the actual design concepts. The program was divided into 3 separate contracts, 1 corresponding to each of the 3 major segments: a) SV ie Space Vehicle, b) CS ie Control Segment c) UE ie User Equipment.

Post Development Stage:

Final stage of the system life cycle. This stage commences after the all the engineering development, validation of the new system is completed. The system engineer performs a crucial role in this stage as many components of the system may demand frequent changes, upgrades or maintenance even after development. This stage can broken up into 2 main components: a) Production, b) Operation/Support.

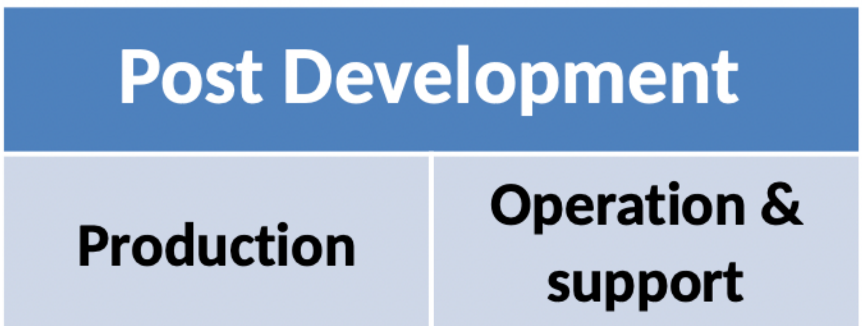


Figure 14: Post Development Stage

D) **Production**:

The 1st sub-phase of the post development stage is the production phase. It aims to incorporate the design and engineering from the previous engineering development stage into real components.This is usually done using a combination of HW(hardware) and SW(software) implementations. In this stage the system engineer needs to ensure that the system to be produced needs to successfully transition from development to production phases and at the same time meets the requirements for safety, reliability and affordability.

The objectives of this stage for the GPS software engineering team was to “fine-tune loose ends” of the previous development stage while issuing production contracts for the 28 SVs ie Space Vehicles. An initial analysis of the operational capability was performed for a mix of Block-I and Block-II satellites alongside full operational capability for all Block-II satellites and it was concluded that the SVs ie Space Vehicles were to be launched from the Space Shuttle.

1) **Space Vehicle Acquisition Strategy for Production**: JPO, the organization mainly entasked with the GPS development, procured the SVs ie Space Vehicles like an aircraft system, which was a new approach for the space community. The concept of this strategy was to buy a lot of the SVs as not only was it cost effective, but also a technique that minimalized the approval cycles through the US Air Force since it was a simultaneous effort in both developing the system and including them into the production contract. The Air Force also gave a fixed price contract to the aircraft manufactures, McDonnell Douglas to purchase the 28 boosters required for the upper stage, called PAM-DII ie (Payload Assist Modules).
2) **Nuclear Detection System** : The NDS helped to provide a earth-wide functionality to detect and report nuclear detonations of any kind that had happened in the atmosphere of the earth or in near earth space in near real time. The GPS was thus the best system to carry this capability, as the GPS baseline (functional) also demanded world wide coverage for navigation purposes. The NDS sensors were developed by Sandia National Laboratories/Los

Alamos National Laboratory and provided GFE to Rockwell. After the 1st deployment, the systems engineering process saw a technical risk of integrating one of the sensors and then the Air force established a requirement to scale up to the IONDS system.

1) **Control Segment** : Based on the CS ie Control Segment functional requirements study done in the earlier phases, 5 bidders were award contracts to perform concept design studies before 1 was selected to actually produce the CS. Multiple rounds of these contractual effort not only helped down size the bidder size but helped further develop and refine the concepts and functional requirements resulting in a pre-SDR functional baseline stage . IBM was the final winner of the contract. Although IBM did not have previous experience working in space related projects but had pretty strong systems engineering processes. IBM approached the production with parallel paths : a) program management, b) tech group reporting to the director of the program. Originally the estimate of the size (LOC) of the CS software was 300K-400K however the final size was 1.1 million. Early software releases of the CS allowed the operation-ability to be achieved by 1985. 1986-1989 saw a period of software improvements and fault resolution.
2) **User Equipment** : Lates 80s and 90s saw the improvement of the huge and importable User Receiver instruments into more portable and simple to use designs ie commercial designs made by companies of these instruments started being incorporated. The Army purchased commercial SLGR ie Small Lightweight GPS Receiver for demonstration only and over time after a series of trade offs agreed to incorporate these (GPS enabled

receivers) as parts of its manpacks. The reason for these changes was to obtain a system, more like an off the shelf item, that would meet minimum yet critical requirements, be available in the near future, be cost effective, easy to operate. It was established that the commercial products might not match the performance of the top notch AN / PSN-8 manpack but nonetheless it was a viable solution and it worked.

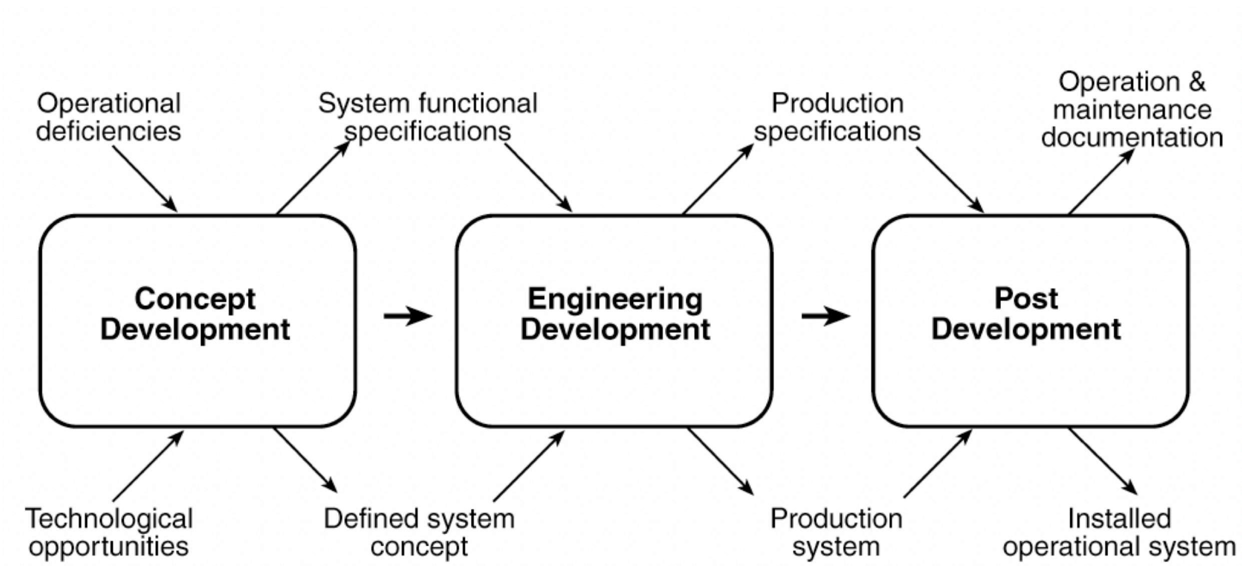


Figure 15: Post Development Stage

B) **<u>Operation And Support</u>**

The 2nd component of the Post development stage and the final component of the entire Systems Engineering system life cycle is the Operation and Support phase, and marks the end of the role of the systems engineer. The aim this sub phase is to provide support and maintenance to the system post its deployment in the field, in order to sustain the life cycle of the product. To do this there should be a well structured plan for the maintenance, timely upgrades and repairs if any of the system that is expected on any product as it wears over time.

The Global Positioning System aka GPS project, was envisioned and started out as a vague new idea post the launch of Sputnik I, when it was realized that space frontier can be used for many exciting opportunities. Navigation studies and technology attempts caused a baseline (functional) being setup around 1973 to have a more stable, accurate and reliable means of worldwide navigation. On 17 April 1995, nearly 20 years later on, the US Air Force Space Command declared the GPS fully operational. This accomplished US DoD's major goals of uniting suites of various military navigation systems.

As part of the fully operational capability, the system was ,triumphantly tested in battle in the Persian Gulf War years before the IOC ie Initial Operational Capability which proved it operational capability worthy to the visionaries of the program from the late 1960s .
The JPO which was instrumental in the development of the GPS was able to successfully establish themselves as system integrators and controller of the functional baseline. Furthermore

with the assistance of the Aerospace Corporation,JPO was able to conduct required system trade studies in order to optimize the functional baseline from which increased requirements were identified resulting in changes in future budgets. Baselined structured signal was used as the vital interface, to create a specification tree which was based upon the alliance of the signals associated with the three major components of the GPS which allowed to manage all the system integration and segment specifications . Domain prowess existed on all levels with the others contractor and supporting government agencies, which allowed visibility into the system vision and thus the systems engineering process a success. Communications was seen as a vital ingredient that was encouraged throughout the GPS development.

Challenges:

1) **Rockwell GPS Block I Satellites Clock**: One of the major challenges was during the development of the Block I satellites by Rockwell which involved developing a space-qualified clock based upon the research data and lessons learned from previous TIMATION and NTS programs. The original plan for the Block I was that each satellite would contain 2 Rubidium (Rb) and 1 Cesium (Cs) atomic clocks after SVN 3. However, 3 Rb clocks were flown on SVN 1, 2, and 3, and 2 Rb and one second-generation preproduction model Cs clock was incorporated after SVN 3. The Cs clock was referred to as a Pre Production Model and was derived from the NTS-2 Cs clock. The high level requirements were clock stability and a service design life requirement of 5 years. Embedded in the service life requirement

was the ability to withstand the space environment, especially thermal and radiation effects. NRL had adequately addressed the radiation effects on the clocks in the early phase of this program.

2) **Rockwell GPS Block I Satellites Lamp :** The challenge for Rockwell during developing the atomic clocks was also the Rb lamp, which was a high risk effort. Rockwell got technical expertise from Aerospace Corporation to resolve issues with the lamp. Diligent testing with actual hardware was conducted to verify radiation, thermal and life cycle requirements.

<u>Summary / Session Learnt</u> :

During the development of the GPS, the team faced interesting challenges in a bunch of domains - stakeholder expectations, organization, technology, budgets, and scheduling for the very complex navigation system. However the results paid off as this system, to the civilian, military and other related unique applications, has become a beacon. A constellation of lighthouses in the sky can be the best analogy for it.

An amalgamation of varied principles / fundamentals followed by the GPS ie Global Positioning Satellite program is one of the reasons for its success. And these principles/foundations are educational for contemporary programs because they provoke thought in those who wish to scrutinize the programs. That being said these foundations aren't of-course a complete set of necessary/sufficient conditions. For the implementer, the successful and consistent application of all the systems engineering processes discussed above are required throughout the program/ project execution, starting from conceptualizing the idea to its usage right to eventual disposal of the system. Highly experienced and skilled system engineers applying the correct systems engineering processes, principles and tools are essential in every step/stage of the process. Systems engineering is strenuous work. It requires skilled and well learned engineers/managers who have a forward looking vision of the program, with an eye for detail.

As we saw throughout this case study, we can conclude by saying that systems engineering played a vital role in the program's success. The challenges of identifying requirements, building and using a system of systems approach, amalgamating new technologies, dealing with a abundance of government/industry agencies, and most importantly dealing with the absence of an available working user in the nascent stages of the program were achievable due to a advanced, powerful, coherent established systems engineering process. The GPS program embedded the systems engineering concepts in their goal, data base and generally in their day to day practice to make sure that continual and proper system requirements are indentified. Allotment of those requirements to the completely autonomous segment developments and furthermore to the subcontractor or vendor level, the continuous assessment based improvements of new requirements, unconventional test methods to check the actual design performance against the requirements, operations or mission analysis, a budget analysis to support the need for the program, and a powerful system integration process. The program was thus able to completely abstain from major risks due to the acquisition strategy, trade studies usage, premature testing of the concept designs, subject matter expertise, and a holistic perception of the program from both the contractor and government ends.

Figure 16: NAVSTAR GPS

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