GPS RECEIVER
SELECTION AND TESTING
FOR LAUNCH AND ORBITAL VEHICLES

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ABSTRACT

NASA Marshall Space Flight Center's Bantam Robust Guidance Navigation & Control Project is investigating off the shelf navigation sensors that may be inexpensively combined into Kalman filters specifically tuned for launch and orbital vehicles. For this purpose, Marshall has purchased several GPS receivers and is evaluating them for these applications. The paper will discuss the receiver selection criteria and the test equipment used for evaluation. An overview of the analysis will be presented including the evaluation used to determine their success or failure. It will conclude with goals of the program and a recommendation for all GPS users.

KEY WORDS

Global Positioning System simulation, Differential Global Positioning System simulation, launch vehicle navigation testing, spacecraft GPS receivers.

INTRODUCTION

The paper will begin with a discussion of the project funding this work. Secondly it will discuss the methodology used in choosing a GPS receiver for space flight applications. Following this the paper will discuss the GPS constellation simulator test scenarios and a section on the hardware that will be utilized to conduct these tests. After this the paper will be summarized in a conclusion and recommendations section.

Part of the charter for the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center (MSFC) is to investigate new techniques to increase the safety and reduce the cost for launching payloads in to space. As such, both GPS receivers and Inertial Navigation Sensors (INSs) and Inertial Measuring Units (IMUs) are currently being evaluated at MSFC. These navigation sensors each have their own unique characteristics and abilities, and can complement one another if combined together properly. Kalman filters are a common algorithm used to integrate these two navigation sensors. The filters are designed with a specific trajectory type (dynamics) in mind, and achieve optimum navigation accuracy in this specific regime; for example, to navigate and air-to-ground missile or a ship-board helicopter. To investigate possible cost savings NASA Marshall has tasked its Avionics Department to develop the Robust Guidance, Navigation and Control (GN&C) program. The purpose is to be able to test Commercial and Military Off The Shelf (COTS, MOTS) navigation sensors that have been developed for terrestrial applications as candidates that could be integrated using a Kalman filter tuned specifically for computing launch vehicle navigation solutions.

Although the attitude capabilities of GPS have been proven, it was decided that initially this experiment would utilize INS/IMU information for attitude. However, part of the experiment is to design in flexibility for swapping out different sensors, as new technologies become available.

The GPS receivers used for this program will be subjected to various nominal and off-nominal tests, regardless of their intended mission. By exposing GPS receivers to varied test situations, key information about the receiver's operation will be learned, enabling the user to validate the appropriateness of the receiver. The INS and blended INS/GPS testing will only be discussed in this paper as they relate to the GPS testing. The intent of the Robust GN&C Program is to provide a Kalman filter and GPS and INS units capable of providing an accurate, continuos navigation solution for a launch vehicle, regardless of whether a nominal or off-nominal trajectory is followed. Ultimately the Kalman filter and chosen navigation sensors would be flown on launch or space vehicles.

GPS RECEIVER SELECTION METHODOLOGY

The authors' initial task for the Robust GN&C program was to pick the initial makes/models of GPS receivers to be evaluated as one of the navigation sensors for the Kalman filter development. The selection process of GPS receivers to consider for space flight began with a survey of what receivers had already flown. The initial compilation began with Munjal, Feess, and Ananada's paper as presented in the Institute Of Navigation's 1992 Proceedings (ref. 3). Through further research in additional ION proceedings, web searches, and vendor contacts, the database filled to a state such that receivers could intelligently be procured (ref. 4-9). It was difficult to find data on which receivers had actually flown in space; however an effort was made to determine the flight heritage of the receivers. Where information was available, occasional discrepancies arose that were resolved by majority voting of different references. Some of the database entries include receivers that have not flown, but were included because they were perceived to be likely candidates due to their COTS or MOTS applications.

The International Traffic in Arms Regulations (ITAR) prohibits domestic GPS manufacturers from selling receivers that can track at altitudes above 60,000 feet and/or at speeds greater than 1,000 knots. Since most projects at NASA Marshall exceed these limits, the most critical criteria used in selecting the receivers was to have the ITAR-imposed speed- and altitude- limits removed. Before the manufacturer can provide a receiver without these limits, a Non-Export Agreement and Intended-Use Form must be submitted to the manufacturer.

The units also had to acquire and track GPS signals while moving at high speed. Although these criteria sound very much alike, there are subtle and very important differences between them. Any GPS receiver may be manufactured with the ITAR speed and altitude software limits removed, but the receivers' tracking loops must be designed so they are physically capable of tracking as well as acquiring GPS signals with large Doppler shift offsets due to high host-vehicle velocities. To illustrate these subtleties, consider the following four scenarios. (1) A physics experiment carried aboard a helium weather balloon was carrying an untested GPS Receiver that stopped reporting GPS Position Data as soon as the altitude exceeded 60,000 feet. Follow-on testing with a GPS RF constellation simulator showed that ITAR software-limits were present. (2) A Launch Vehicle carrying a GPS Receiver for Range Safety tracking evaluation purposes provided GPS-based Navigation information during the launch and ascent phases, up to launch-plus-160-seconds (well beyond ITAR speed and altitude limits), after which no further GPS updates were received. Post flight data analysis revealed that at the time of GPS solution loss, the vehicle was traveling over 3000 meters per second at an altitude of over 400,000 feet. Consultation with the GPS receiver manufacturer revealed the receiver's physical signal bandwidth was insufficient to allow tracking of GPS signals with Doppler-induced frequency offsets above 3000 meters per second. (3) A GPS Receiver was fitted on a surface-to-air missile to provide Time Space Position Information (TSPI)[1] for post flight accuracy determination. The GPS receiver was providing accurate navigation solutions while on the launch pad. Immediately after launch, the GPS receiver lost lock and no further GPS TSPI was received. Post flight analysis using a GPS simulator showed the GPS receiver's tracking loops used a very narrow-bandwidth, which precluded the receiver from tracking during the high-accelerations of launch. (4) An All-In-View GPS receiver being tested as a candidate for long distance Range-Safety tracking was flown aboard a launch vehicle. The receiver provided excellent navigation data during the launch, ascent, and cruise phases of the mission at speeds and altitudes well in excess of ITAR Limits. Several thousand miles downrange however, the receiver's GPS navigation accuracy began to degrade rapidly, eventually resulting in no GPS navigation solution. Post flight analysis revealed that ITAR limits had been removed, physical signal bandwidths were sufficient for high-velocity tracking, and tracking-loop bandwidths were set properly for the acceleration environment. However, the receiver's satellite acquisition algorithm had not been designed for high speeds. It was not searching a wide enough Doppler range to acquire new satellite signals while traveling at high velocity. Thus, it launched and provided GPS navigation information while traveling downrange using the original set of GPS satellites it was locked onto from the launch site. As GPS satellites disappeared over the launch vehicle's horizon, the navigation accuracy degraded, until it finally had insufficient satellites to compute a navigation solution.

The next major criterion in selection was that the receivers have at least twelve parallel tracking channels to track the majority of satellites in view when in orbit. In Low Earth Orbit, depending on host vehicle altitude, attitude, antenna type(s) and antenna placement(s), as many as 16 GPS satellites may be visible. The level of navigation, Standard Positioning Service (SPS) or Precise Positioning Service (PPS) was dictated by mission accuracy requirements. For the ascent and on-orbit phases of most missions, SPS-level positioning accuracy is usually adequate rather than requiring PPS accuracy levels. However, some of NASA's uninhabited vehicle projects require higher precision than even PPS can deliver, and this accuracy is usually provided by some form of Differential GPS (DGPS), INS, or RADAR altimeter. The last criterion was that the receivers have the ability to output "raw" GPS data,

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[1] While GPS literature typically refers to GPS receiver navigation output as Position Velocity Time (PVT) data, Space Launch Range users are used to the nomenclature Time Space Position Information (TSPI).

such as pseudorange and carrier-phase measurements, for input into an external Kalman Filter algorithm. To ease the problem of interfacing these receivers, Original Equipment Manufacturer (OEM) boards with an integrator's kit were purchased. The challenge encountered working at the OEM level is that the interface is less of a plug and play solution than an integrated unit. Additional steps are typically required to transfer the data into a data analysis program.

Utilizing the above criteria, four different relatively low-cost GPS receivers have been purchased for the initial investigations. The first is a twelve channel, L1/L2[2], PPS-capable receiver with Receiver Autonomous Integrity Monitoring (RAIM), utilizing a GPS Receiver Application Module Modified Standard Electronics Module (GRAM-SEM) interface that is upgradeable to the Selective Availability Anti Spoofing Module (SAASM). This receiver was chosen for its PPS capability, high dynamics, and use of new interface standards. The second unit is a twelve-channel, L1 C/A-code receiver designed for high dynamic (20g) tracking applications. The third unit purchased is a dual-frequency SPS GPS receiver, to investigate the potential benefits of having dual-frequency SPS measurements available to the Kalman Filter. The fourth unit chosen is a twelve-channel SPS receiver with integrated Wide Area Augmentation System (WAAS) receive-capability.

TEST METHODOLOGY AND EVALUATION

The Mars Polar Lander and Climate Orbiter accident investigation report (ref. 10) has suggestions applicable to NASA, as well as all technical projects. Some of them include the need to validate test equipment against an absolute truth, to perform extensive component and complete system testing and to know, understand and document the risks being taken. This work is intended to provide the means to ensure mission success first.

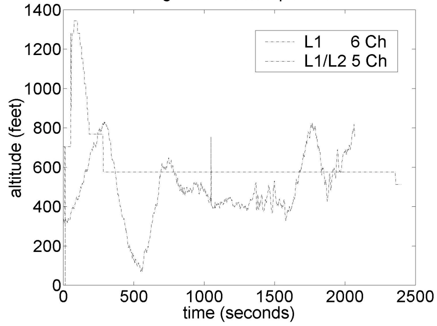
The initial tests of a GPS receiver, once a reliable, predictable interface has been established, are static position tests using an outdoor antenna. Not only does static testing give a feel for the performance capabilities of the receiver, it's a good warm-up for data processing with a particular receiver. If the test is performed using a surveyed in antenna or over a surveyed point, there is an absolute truth source available. Otherwise a mean of all the data points can be used as truth – reference point. The error can be shown as the difference from the chosen reference point or from statistical function such as the standard deviation of the data. The receiver should have a position difference caused only by the GPS error budget.

Figure 1 shows the results of a static live sky test (with Selective Availability activated). It compares the vertical changes of an L1 only receiver and an L1/L2 receiver over 20 minutes. The figure illustrates the accuracy improvement the L2 carrier and code provides for a similar technology generation of receivers. The tests utilized the same antenna, with RF amplifiers and attenuators to provide a nominal (-130 dBm) signal level to the RF input of each receiver. With the satellites at 20,200-km the geometry of calculating a position from four or more satellites geometrically constrains the possible position solutions to a narrower range in the local horizontal plane then in the local vertical plane. This explains

[2] GPS User-Segment signals are currently transmitted on what is commonly referred to as L1, which is nominally centered at 1575.42 MHz, and L2, nominally centered 1227.6 MHz.

why GPS accuracy, regardless of GPS receiver type or architecture is more accurate horizontally than vertically.

Fig. 1 L1/L2 Comparison



After completing the outdoors static test, a GPS constellation simulator test works well for validation of the simulator. Next a known static scenario is run for comparison against other receivers for direct, repeatable receiver comparison. The same receiver, position, time and almanac as the previously run outdoor test are used. By taking data from a predefined course with a GPS receiver, and importing it in to the simulator another useful scenario can be generated. This scenario may point out some of the low dynamic satellite switching logic used by the receiver. Results obtained with the GPS receivers connected to a GPS simulator should possess the same accuracy, phase and frequency characteristics as the data collected with live GPS signals

Since many projects at NASA Marshall exceed the ITAR limits it is critical to be able to test that a receiver will track beyond them. As ITAR limit removal is an unusual request for the manufacturers, it sometimes gets overlooked. This is why pre-flight testing of a given GPS receiver is necessary.

Figures 2 and 3 show a modified Apollo 11 trajectory, which are far above the ITAR limits, for two different receivers. The trajectory was generated using Satellite Tool Kit with information from the book "Apollo By The Numbers" (ref. 11). The light lines represent the truth trajectory while the dark lines show the GPS receiver solution. Figure two is an older six-channel receiver and figure three is a current twelve-channel receiver. Both receivers are designed for high dynamics and were run through the same simulation five times with similar results. It can be seen that both were able to exceed the ITAR altitude limit but weren't able to make orbit. Looking back at the Apollo tests shows the first level of examination; did the receiver provide mission success from a navigation standpoint? This test demonstrates what would have been two failed missions if these units had been used on a real flight.

Fig. 2 Six Ch. Orbital

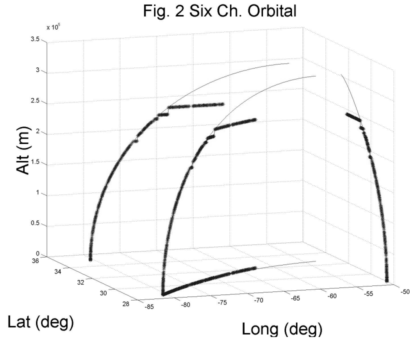
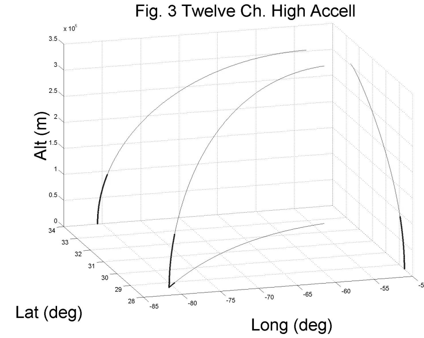


Fig. 3 Twelve Ch. High Accell



Assuming previous testing was successful, the next test is typically a simulation of the nominal trajectory. If it must navigate its way to a pre-determined point such as landing on a runway threshold centerline, the plot of errors to that point will show how far it is in error. In other words the difference between where it is and where it should be makes accuracy analysis straightforward The errors may be presented as time history plots of the along-track, cross-track and down-track errors.. For another type of mission, such as relative GPS positioning between two dynamic vehicles, or for scenarios in which the start time, date, or trajectory may vary, a statistical mean of the difference between truth and the receiver's output may be desirable.

A critical trade study to perform is what effort it will take for a terrestrial GPS receiver to be usable in an orbital environment. The two major factors to be considered are environmental (thermal, vacuum, vibration, etc.) and operational (ITAR limits removed, satellite selection algorithms, etc.) On the operational side, one of the more important parameters to consider is the Doppler window bandwidth the receiver looks at to acquire/track GPS satellites. It is possible that a receiver designed for the high initial Doppler shifts of a missile may work well for the orbital environment. However, missiles require extremely high accelerations and jerks, but over a relatively short duration, whereas an orbital receiver operates continuously in a high Doppler environment with minute accelerations once in its final orbit. Thus it is equally possible that a receiver designed for missile applications may not be a good candidate for spaceflight without operational/environmental modifications.

One idea for testing to better understand the operation of a receiver is to subject it to a completely different environment than the intended mission. The thinking behind this idea is to investigate navigation solutions based on dynamic inputs as pursuing a fault tree investigation, not how does it work nominally, but rather, is it known what happens in anomalous situations. For example spacecraft simulations have high speeds but relatively slow maneuvers. Testing a spacecraft receiver on a fighter's air combat maneuvering flight may point out possible problems for an improper orbital insertion.

Another challenge for GPS receivers is to test how well they perform when they are released on orbit with no initialization data or incorrect initialization data. This would occur, for instance, in a situation where estimated orbital-insertion parameters were inaccurate, or where a GPS receiver is power-cycled multiple times while on-orbit, to save power. Also, how a receiver stores satellites that aren't in view is critical. The GPS satellites are in an approximately twelve hour orbit with a circularized velocity of 3875 m/s. If the earth occludes a satellite, a stationary, terrestrial receiver may have up to six hours before it has to consider that satellite. A spacecraft in a 200 km., circular orbit has a period of 88 minutes, with a velocity of 7800 m/s. Therefore over the horizon satellites may be visible again in minutes instead of hours. This emphasizes the importance of understanding the receiver's satellite selection algorithms.

It is always best to perform a high fidelity test of the GPS receiver at least once to know how it will track the C/A and P(Y) code that will be present in the real world. It is informative to run through the combinations of C/A, P and P(Y) codes to see how the receiver will process the different codes. It would be wise to include tests that have Selective Availability turned back to previous levels. If it were to be turned on, the mission may not be able to be re-scheduled and it would be important to know what performance to expect from the GPS receiver. The authors have no knowledge of such an event happening, but do suggest this for a contingency.

Finally, it is critical to characterize the effects, if any, that other nearby transmitters will have on the unit. The flight test community typically uses C-band radar beacons, L- or S- band telemetry transmitters and UHF Flight Termination System (FTS) receivers. Although the usual guard band requested around the GPS L1 and L2 frequencies is 75 MHz, it is possible that emissions from these relatively high-powered, nearby RF sources could adversely affect the GPS receiver. A critical piece of information required for the design of the GPS system is the isolation between the GPS antennas and the other transmitting antennas on the vehicle. This number can only be realistically determined by a measurement on an antenna range using actual antennas. The test data will most likely differ from the real vehicle results, but is far closer to reality than just a theoretical analysis can provide. The antenna range data can be used to make sure the interfering signal level is well below the interference level for the receiver. It is critical that RF interference scenarios be analyzed and tested before a given mission.

TEST EQUIPMENT FOR GPS RECEIVER EVALUATION

In a number of discussions with the authors there have been research Principal Investigators who did some surfing, purchased a GPS receiver, then surprisingly concluded they had taken care of their navigation system. There is simply no substitute for laboratory testing and evaluation of hardware being considered for a mission. The most expensive tools for these types of tests in the Robust GN&C lab are a three-axis rate table for inertial testing and a GPS constellation simulator. Also, for live sky and stationary receiver testing, a Micro Pulse 12300-survey quality antenna has been installed. The choke ring L1/L2 antenna provides a nominal 53 dB of gain at both frequencies (ref. 12). The antenna position has been surveyed in by the Army Corps of Engineers in WGS-84 and NAD-27, and -83. As mentioned in the test scenario section, it’s critical to have a surveyed antenna position so that it may be used as an absolute truth source.

The GPS constellation simulator is a Global Simulation Systems Incorporated (GSSI) 4760. With one chassis the 4760 is capable of simulating either thirty-two L1 channels or sixteen L1 and sixteen L2 channels. Most earth surface receivers will only have eight to nine satellites visible, while on orbit there may be as many as sixteen visible GPS satellites. Real time trajectories are input via an IEEE 488 interface. The system is also capable of simulating PPS, P(Y) code on both L1 and L2. The GPS simulation capability also includes the ability to mix up to six different interfering RF signals that can be associated with a geographic location in a simulation scenario or staged according to elapsed time in the scenario. The GSSI 4760 system is capable of providing WAAS and European Geostationary Navigation Overlay System (EGNOS) RF signals, as well as DGPS correction messages (RTCM SC-104 2.1) via RS-232. Future testing will incorporate these features into orbital simulations.

Testing the characteristics of an Inertial Measurement Unit (IMU) or an Inertial Navigation System (INS) requires a table that can be commanded to concurrently rotate about all three axes. Between two of the groups within the Avionics Department there are six rate tables of varying capabilities. The one to be utilized for this experiment was modified in 1983 to allow full rotation about all three axes to allow testing of the image motion compensation system for the Astro missions (two shuttle flights). Some of the other missions these have been utilized for include the (canceled) Aeroassist Flight Experiment and the redundancy management studies for the shuttle's IMUs, and the solid rocket booster's rate gyro requalification program. In the table's Precision Rate Mode: the angular range is zero to ±200 deg/sec, except for the outer axis which is limited to ±100 deg/sec for safety reasons. The table's command resolution is 0.0001 deg/sec. Its stability, over a 360 degree average, is 0.002% and over a 10 degree average its stability is 0.01%, with a 5 degree interval. The repeatability is 0.00005% from revolution to revolution. This is assuming use of the local control by the 30H MPACS controller (ref. 13). Absolute testing of the INS/IMU will include such items as angular resolution, angular rate, 1 g in the room (rotate box on six sides for ±xyz), and three axes testing on the table.

A rack-mount, multi-processor Silicon Graphics Origin 2000, functions as the key computer for the initial build up. It is the controlling/interface computer for the rate table, host for the vehicle simulation generating a real time trajectory to feed to the GPS simulator, Kalman filter processor, matlab processor, and bus controller for the INS/IMU remote terminal. Two SGI O2 workstations and two PC's provide additional computing power. It is planned to utilize a GPS time sourced, IRIG G time synchronization card for synchronizing signals and computer system clocks. IRIG-B is up to 1 milli-second resolution, while Inter Range Instrumentation Group (IRIG)-G is up to 10-microsecond resolution (ref. 14). For discussing classified PPS related issues with other organizations, there is a Secure Telephone Equipment (STE) phone in the lab. The set up of the lab is currently awaiting integration of computers, which includes such things as IRIG time synchronization, and the porting of real time controller interface to the GPS simulator. Until the lab computers are integrated together, data may be recorded separately for the IMU/INS's and GPS receivers for play back in to the Kalman filter development system.

Labs that are set up and operational at MSFC the Marshall Avionics System Testbed (MAST) and the Flight Robotics Lab (FRL). Both are equipped for real-time, closed loop, HardWare in The Loop (HWIL) GPS simulations. The MAST lab is used extensively for systems level simulation and testing of integrated avionics. Two primary capabilities of the FRL is the 3800 sq. ft. Flat Floor Facility (FFF) and the Dynamic Overhead Target Simulator (DOTS). The FFF is used to evaluate guidance, navigation and control subsystems by using self-contained test vehicles that move on air bearings. DOTS is an 8 DOF electronic robot that is used to simulate relative motion with respect to a fixed target. DOTS was used in the design, development and testing of the Video Guidance Sensor (ref. 15) typically associated with the AR&C program discussed earlier.

For proper testing with the GPS constellation simulator a RF vector network analyzer and spectrum analyzer are required. Acceptance testing of new receivers using a simulator requires that the ICD-200C (ref. 16) level of –130 dBm for L1 C/A is present at the RF input to the antenna. Lab cabling almost always is different than that which may have shipped with a receiver and antenna, assuming the receiver had matched cabling and antenna at all. The RF group has an HP 8753C network analyzer with a corresponding 85047A S parameter test set which work together to cover from 300 kHz to 6 GHz, and several different spectrum analyzers. A recently purchased network analyzer will increase the upper frequency limit to 40 GHz. For proper interference and antenna pattern testing, access to an anechoic chamber and antenna measurement range is required. Table 1 summarizes the capabilities of the chamber and two ranges at MSFC.

Table 1. MSFC Anechoic Chamber and Antenna Measurement Range Capabilities

	ANECHOIC CHAMBER:	400 FOOT RANGE:	1/2 MILE RANGE:
Frequency Range	200 MHz to 40 GHz	100 MHz to 60 GHz	2 to 60 GHz
Features:	Chamber is covered with RF absorber	Fully adjustable for optimum test conditions	Tower height of 90-ft
	Simulates a free space environment for RF tests	Instrumentation allows measurement of spherical antenna pattern	Elevators are available on each tower for raising equipment

CONCLUSION AND RECOMMENDATIONS

The task agreement between the Avionics Division and the Advanced Space Transportation Program states that at the end of the task, two deliverables will be provided. One is a final report stating the outcome of the experiment. The other is a brassboard circuit (with associated software) which captures the final design of a spacecraft-oriented, Kalman filter that has the flexibility to drop in new navigation sensors as they become available. The report and brassboard design and software should be available to licensees through the MSFC Technology Transfer Office.

Just before the submission date for this paper, Selective Availability was reduced to zero. This has profound effects on the accuracy of SPS GPS receivers, and will constitute volumes of papers by itself. The elimination of Selective Availability is almost an order of magnitude increase in GPS accuracy

It is the feelings of the authors that all GPS receivers should be thoroughly tested by a staff familiar with their GPS constellation simulator and test equipment, and that are experienced with many different GPS receivers. The receivers should be tested in nominal and off nominal conditions. Testing and analysis will lead to system changes that will need to be tested and analyzed again. If limitations arise, it will be important to provide these mission constraints to project operations.

In summary, GPS is now even more accurate. It will now be more tempting, yet equally inappropriate, not to properly test a receiver, since it will be assumed that it will be 'good enough'. The experimenters may have to give simple GO/NO-GO answers to managers, but they should understand the receiver and the test data so they are confident that they will achieve mission success.

REFERENCES

1. Interview with Jim Lomas, Aerospace Engineer, Marshall Space Flight Center, TD-54, Vehicle Flight Mechanics Group (Branch), Vehicles and Systems Development Department (Division), Space Transportation Directorate.

2. Deaton, A.W., Lomas, J.J. and Mullins, L.D., “A Plan for Spacecraft Automated Rendezvous” , NASA TM-108385 , October 1992.

3. Munjal, Dr. Prem, Feess, William and Ananada, Dr. Mohan , "A Review of Spaceborne Applications of GPS," Session 5D, paper 1, 5th International Technical Meeting of the Satellite Division of the Institute of Navigation, Albuquerque, New Mexico, September 16-18 1992 proceedings,.

4. http://gauss.gge.unb.ca/grads/sunil/receiver.htm

5. http://gauss.gge.unb.ca/grads/sunil/mission.htm

6. http://www.ee.surrey.ac.uk/SSC/SSHP/list_gps.html

7. http://rogueweb.jpl.nasa.gov/RogueWeb/MiscWebImages/Family%20Tree.GIF

8. Osterhoudt, Michele, Assistant Editor "GPS World Receiver Survey" GPS World Eugene, OR, Volume 9, Number 1, January 1998, pages 46-59.

9. Phillips 2000 GPS Directory, 15th Edition, Phillips Business Information Inc., Potomac, MD, 1999.

10. Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA", March 13, 2000, available from ftp://ftp.hq.nasa.gov/pub/pao/reports/2000/MCO_MIB_Report.pdf

11. Orloff, Richard W., "Apollo By The Numbers", 1996. Retrieved from http://www.floridatoday.com/space/explore/manspace/apollo/orloff.htm

12. http://www.micropulse.com

13. Interview with John Calhoun, Electronics Engineer, Marshall Space Flight Center, ED-12, Instrumentation and Control Group (Branch), Avionics Division, Engineering Directorate.

14. Range Commander's Council, "IRIG Serial Time Code Formats", IRIG Standard 200-98, May 1998.

15. Interview with Linda Brewster, Computer Engineer, Marshall Space Flight Center, Orbital Simulation Team Lead, ED-19, Instrumentation and Control Group (Branch), Avionics Division, Engineering Directorate.

16. Arinc Research Corporation, "Navstar GPS Space Segment / Navigation User Interfaces", GPS Navstar JPO, El Segundo, CA, October 1993. Available from: ftp://ftp.navcen.uscg.mil/policy/icd200/icd200c.pdf