Lessons Learned from Two Years of On-Orbit Global Positioning System Experience on International Space Station

Susan F. Gomez , *NASA Johnson Space Center*
Michael L. Lammers , *NASA Johnson Space Center*

BIOGRAPHY

Susan F. Gomez received her B.S. from the University of Texas in 1992. She has been working at NASA-JSC on GPS and GPS attitude determination, including several GPS flight experiments, for the International Space Station (ISS) since 1993.

Michael L. Lammers received his B.S. from Iowa State University in 1996, and has been employed in mission operations at NASA-JSC since that time. He has been an Attitude Determination and Control Officer at Mission Control Center - Houston since 2001.

ABSTRACT

The International Space Station GPS receiver was activated in April 2002. Since that time, numerous software bugs surfaced that had to be worked around. Eventually, enough bugs surfaced that the three pieces of code included in the GPS unit have been upgraded.

The technical aspects of the problems are discussed, as well as the contractual problems that led to the delivery of a product that has had so many problems.

BACKGROUND

The US segment of ISS has been using GPS as its primary source of information for position, velocity, attitude, and time since April 2002 [Ref 1]**.** The GPS receiver for the ISS is a Trimble Force 19 embedded in a Honeywell Space Integrated GPS/Inertial Navigation System (SIGI). The SIGI was procured by NASA with the intent to provide a 'common' navigation sensor that would fulfill the Shuttle, ISS, and Crew Return Vehicle (CRV) requirements. In theory, a common navigation sensor would provide cost savings to NASA. For the Shuttle, SIGI was to replace the High Accuracy Inertial Navigation System (HAINS) and the Miniaturized Airborne GPS Receiver (MAGR). For ISS, SIGI is the navigation, attitude, and time sensor for the U.S. on-orbit segment. For Crew Return Vehicle, SIGI was to be the primary navigation and attitude sensor.

SIGI is based on the Embedded GPS/Inertial Navigation System architecture, which has been used very successfully in military aircraft, tactical missile and ground applications for the past 10 years.

Unfortunately the goal of developing a common navigation sensor was never fully realized. Shuttle SIGI uses a different GPS receiver than ISS/CRV SIGI and requires a completely different software interface due to the requirement to maintain transparency with the heritage Shuttle navigation system.

ISS and CRV SIGI are very similar in hardware, and the software interface was intended to accommodate both projects. In 2001, however, the software between the two programs diverged due to throughput issues in the Honeywell processor.

In the end the only thing common between the SIGIs for all three programs was the inertial hardware, which is currently unused by ISS.

Shuttle SIGI was cancelled after the SIGI phase 1 flight test and development program was completed [Ref 10]. CRV SIGI was cancelled when the CRV project was canceled.

This paper will focus on the ISS SIGI. Lessons learned from Shuttle SIGI and GPS on the Space Shuttle can be found in References 2-6.

For ISS, the SIGI's unfiltered GPS position and velocity solutions are used as updates to the flight software's orbit propagation, the SIGI's unfiltered GPS attitude solution's are used as inputs in the flight software's attitude filter, and the SIGI's time output is used to correct the on board clocks. Future releases of the ISS on board flight software include a filter for the GPS position and velocity outputs, and a filter for the SIGI's time output so that the time output can be used autonomously.

For the ISS SIGI, Trimble provided the GPS hardware and the navigation firmware. NASA provided the GPS attitude firmware that resides within the GPS receiver. Honeywell (HI) provided the integrated SIGI as well as the HI System Processor (SP) code that reads in the GPS receiver data and formats it for output over MIL-STD 1553. The HI SP code also includes the Kalman filter needed by CRV to blend the inertial and GPS measurements, and a GPS only filter intended for use on ISS. Figure 1A shows a block diagram of ISS SIGI and Figure 1B shows the ISS and the GPS Antenna Assemblies.

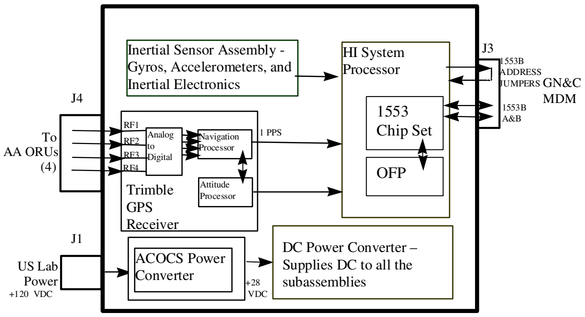

Figure 1A – Block Diagram of ISS SIGI

Figure 1B – ISS GPS Subsystem

After two years of on-orbit experience, the GPS continues to be used as the primary navigation, attitude, and time data source for ISS; however, some problems surfaced during operations that were not discovered during pre-flight testing. As a result, the firmware in the GPS attitude code was totally rewritten and new algorithms developed. In addition, the firmware that processes the time output from the GPS receiver was rewritten, while the GPS navigation code received minor revisions.

The re-written code has been delivered to the ISS program and is expected to be uploaded in the SIGIs in October of 2004.

The requirements for the ISS are as follows:

1. Semi major axis requirement of 100 feet 3 sigma
2. Attitude accuracy of 0.5 degrees 3 sigma
3. Time accuracy of 100 microseconds

GPS alone can meet the semi major axis and time requirements, but GPS alone can not meet the attitude accuracy requirements. The multipath environment on ISS is such that the unfiltered GPS attitude solutions can not meet the 0.5 degree requirement. The unfiltered GPS attitude solutions are used as an input in the ISS's on board software attitude filter.

PROBLEMS ENCOUNTERED THAT REQUIRE OPERATOR/MISSON CONTROL INTERVENTION

This section discusses the problems that were found with the code and their impacts. Some of these problems were found during the SIGI's functional and qualification tests and some were found in flight experiment on the Space Shuttle. The SIGI code was put through extensive ground testing which included 4 months of simulations, as well as 2 Shuttle flight experiments where the SIGI was configured to use all 4 GPS antennas so that GPS attitude solutions could be characterized (STS-101 and STS-106), and 2 Shuttle flight experiments where SIGI was connected to the Shuttle's GPS antennas and was not outputting GPS attitude solutions (STS-100 and STS-108) [Ref 1].

Time Outputs Were Incorrect

After SIGI had been delivered to the ISS program, numerous time problems were uncovered. These problems were found in flight experiments for CRV and in the data from the SIGI after it was operational on the ISS. There were several different types of time anomalies.

In one case, the time output from the SIGI would not jump back to the correct time following long periods of tracking fewer than 4 satellites. It generally took periods as long as 19 hours for the problem to surface. It was discovered that logic put in place in the HI SP to accommodate the time intervals when the HI SP was not receiving a time message from the GPS receiver caused problems following long outages. The GPS receiver did not output the time message due to the particular implementation of the integer resolution algorithm. Once HI's SP clock and Trimble's clock had drifted apart by more than 3.5 seconds, the HI SP code didn't think the time output it later received from the Trimble was accurate, even though it was. The integer resolution algorithm is a search technique. During the time that the software is searching thru the integers, all interrupts are disabled, which also means that no messages, including the time message, are output. The time output from the GPS receiver could cease for as long as 10 seconds, which the HI SP code perceived as time jumps. The bug in the HI code was a result of the HI SP code attempting to accommodate these perceived time jumps.

In another case, the SIGI's time was observed to jump by entire GPS epochs. This was traced to code in the SIGI that was attempting to use GPS leap seconds to determine how many GPS rollovers had occurred.

In other instances, the SIGI time was observed to jump by seconds. The cause of this particular problem was never fully understood; however, the time code was totally re-written and the problem has not recurred.

Figure 2 shows some of the time data from the SIGI on the ISS. SIGI's time is compared to the time stamp placed on the telemetered data by the Orbital Data Reduction Complex (ODRC). Notice the jump of 1024 weeks near the beginning of the plot.

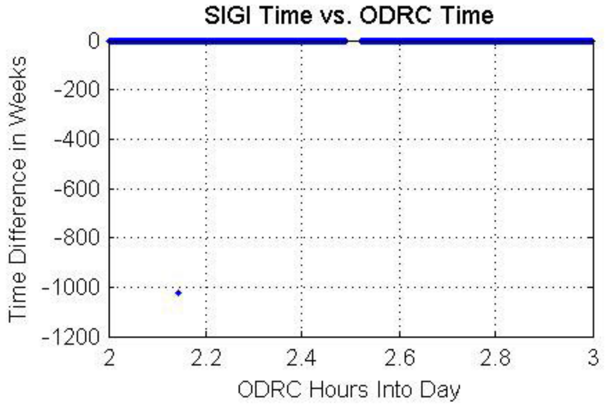

Figure 2 – SIGI Time Compared to ODRC Time

The data file for this plot contains the following:

ODRC Time	SIGI Seconds
2002_142:02:08:38.296	706068511
2002_142:02:08:39.296	706068512
2002_142:02:08:40.296	706068513
2002_142:02:08:41.296	706068514
2002_142:02:08:42.296	706068515
2002_142:02:08:43.296	706068516
2002_142:02:08:44.296	86753317
2002_142:02:08:45.296	706068518
2002_142:02:08:46.296	706068519
2002_142:02:08:47.296	706068520
2002_142:02:08:48.296	706068521
2002_142:02:08:49.296	706068522
2002_142:02:08:50.296	706068523

Notice the time output at 2002_142:02:08:44.296 in which the SIGI time jumps back in time 1024 weeks, but recovers on the subsequent output.

The central clock for the US segment is the clock of the Primary Command and Control (C&C) computer, which is an Intel 386 based machine that broadcasts time to all other US segment computers and other devices via the MIL-STD 1553 network. The clock of the C&C is not terribly precise, and can have a clock drift of up to one second per day uncorrected. The C&C code was designed to be synched to SIGI and automatically track GPS time output, thus negating the need for a precision clock within the C&C itself. However, because the time outputs from SIGI are so erratic, the C&C clock has never been synched to SIGI to avoid large time errors from being accepted. Such errors would immediately impact onboard Guidance, Navigation, and Control (GNC), including possible loss of attitude control and communications antenna pointing.

Instead, flight controllers leave the C&C clock in local mode (where the local clock is allowed to drift and is not reset by the time output from SIGI). The drift can be coarsely metered in a positive or negative direction through daily manual adjustment commanded by the ground. Flight controllers compute onboard time error by comparing timestamps on downlink telemetry to the Mission Control Center central timing system and adjusting the clock metering rate daily. Using this workaround, the C&C clock is kept to within +/- 2 seconds of GPS system time. The error is acceptable, but is outside design specifications.

These time problems were all traced back to coding deficiencies in the HI SP. The problems with the code were corrected and the new HI SP code has been tested in all of the scenarios that caused the problems noted above. Unfortunately, one new problem has been uncovered that will occur when there are 15 leap seconds and will manifest itself as time jumping entire GPS epochs. This problem will have to be corrected prior to the leap seconds reaching 15.

The original time design did meet the requirements when the GPS receiver was doing position fixes, and therefore it passed the initial tests, which were designed strictly to test the requirements. Subsequent tests have been designed that test the SIGI under conditions that are more strenuous and therefore more likely to uncover problems. The new time design has been thoughtfully crafted so that even when the GPS is tracking less than 4 satellites, time propagates at the rate of the error in the last output drift rate. Previously, HI propagated time using their clock, which wasn't nearly as accurate as the GPS clock. Under the new design, the time drifts at a lower rate than the drift rate of the GPS oscillator since that last measured drift rate is compensated for. Figures 3 and 4 show the time error for the new SIGI code compared to a True Time GPS card. Figure 3 is for a time period when the SIGI is tracking at least 4 satellites, and Figure 4 includes a period when the Radio Frequency (RF) port was disconnected so that SIGI was not tracking satellites.

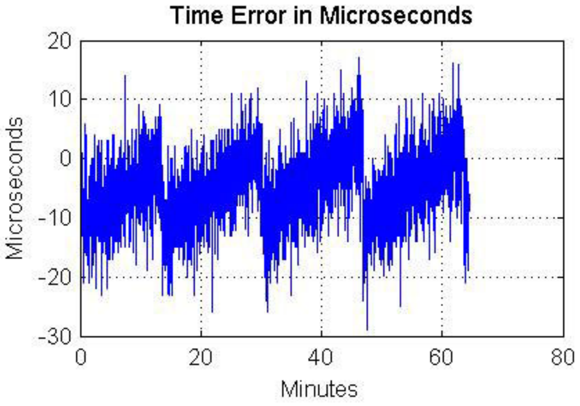

Figure 3 – Time Error in Microseconds When Tracking at Least 4 Satellites

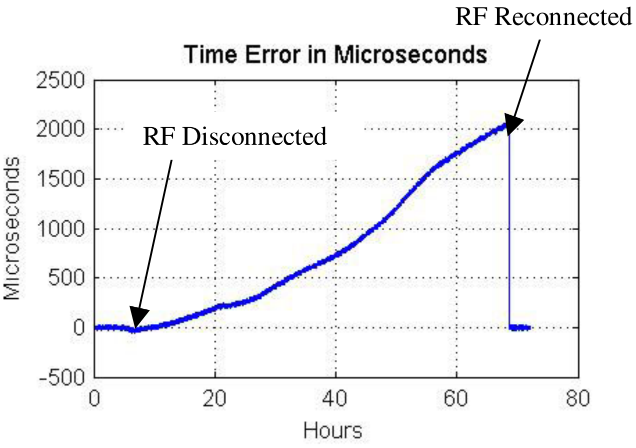

Figure 4 – Time Error in Microseconds: SIGI RF Port Disconnected for Weekend

GPS Attitude Determination Problems

There were numerous problems with the attitude determination code that required ground operator intervention. One problem required a code modification to the ISS flight software, but all the others required power cycles. Power cycles are not inherently an issue, but they do contribute to the overall system being operator intensive.

On two occasions, the code output an IEEE 754 Not-A-Number (0x7FFF 0xFFFF). This caused both the primary and backup ISS Guidance, Navigation, and Control (GNC) computers to stop processing. Attitude control was handed off from the Control Moment Gyroscope (CMG)-based system on the US segment to the thrusters-based system on the Russian segment, resulting in loss of micro-gravity and use of propellant supplies for control. Flight controllers manually pointed the high rate S-band used for core system commanding, telemetry, and voice in an intense effort to maintain communications with the crew, while Ku-band communications for payload data, operations plans, and video were lost. The entire event cost a day of on-orbit operations.

This problem could not be worked around and the SIGI was left unpowered for several months to protect the vehicle from a recurrence of the problem. Although the SIGI continues to occasionally output a Not-A-Number, a modification was made to the GNC flight code to handle the Not-A-Number output so that the US GNC flight computer no longer stops functioning. The root cause of the Not-A-Number output from the SIGI was never determined; however, all the code that could have generated it has been re-written.

The attitude determination code also resets itself under certain circumstances which were not seen in ground testing or in any of the Shuttle flight experiments. When the code resets itself, it erases certain parameters of its memory and needs re-initialization. This problem was fairly easy to work around, although flight controllers are having to perform many power cycles.

Additionally, the integer resolution scheme is a search method originally designed for use in aircraft. The method used is described in [Ref 7]. This method requires an initial attitude estimate, which implies operational constraints. For many of the ISS maneuvers, it is not worth the time required to re-initialize the GPS receiver with an attitude estimate. Also, since the attitude input has to be an East, North, Up attitude, when the ISS is in an inertial hold, the attitude update would have to be constantly updated. Instead, for certain maneuvers, it is accepted that the GPS will not be outputting attitude solutions. For the inertial attitudes, the attitude estimate is input as the attitude of the ISS at orbit noon, where there is the best GPS coverage. However, for the rest of the orbit, any attitudes that are output are all incorrect since the attitude estimate is incorrect. This search method requires that all interrupts be stopped during the search time, meaning that no position or velocity information is output during these times.

Since the integer resolution scheme mentioned above was not well suited for ISS, the attitude code was reformulated using a new integer resolution method as part of the re-code effort. This new method simply accumulates measurements over a user-settable interval and performs a batch solution for the attitude and the integers. The new method assumes that the ISS is in either an inertial hold or a Local Vertical Local Horizontal Hold (LVLH), which are the only types of attitudes the ISS flies in. See reference 8 for more information on the new integer resolution algorithm.

The coverage statistics for the original and new attitude algorithm for an inertial hold 4 day simulation are given in Table 1. Coverage is defined as the percentage of time that a fresh attitude or position solution is output. Notice the higher position and attitude coverage for the new method. The increased position coverage is due to the new integer resolution algorithm not obstructing data from being output.

	Original Method	New Method
Position	23%	48%
Attitude	15%	31%

Figures 5 and 6 show the attitude error during a 12 hour LVLH simulation for the old and new attitude algorithm with the simulated multipath environment of the ISS.

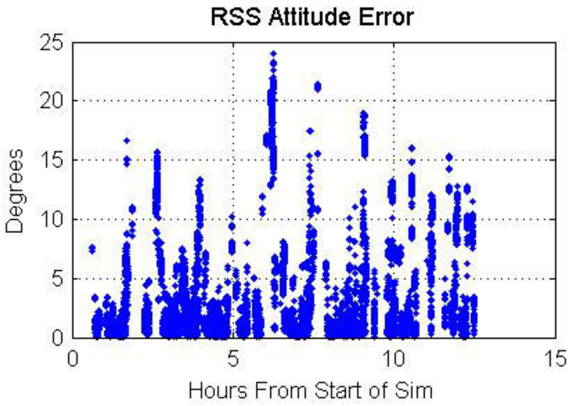

Figure 5 – Attitude Error in Degrees for Orbit Simulation with ISS Multipath Environment – New SIGI Firmware

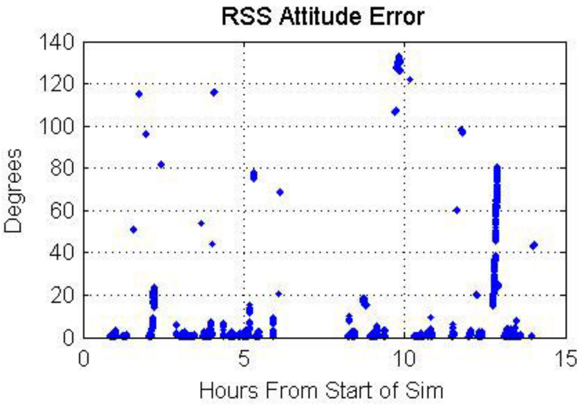

Figure 6 - Attitude Error in Degrees for Orbit Simulation with ISS Multipath Environment – Original SIGI Firmware

The new SIGI firmware is computing an attitude with no initial attitude estimate. The original firmware has an initial estimate for the roll and pitch of the ISS. The new firmware has more coverage and better standard deviation statistics: 26 degrees root mean square for the original method and 4 degree root mean square for the new firmware.

Navigation Problems

There were also problems encountered with the navigation solution. These have been traced to various root causes, but the symptom was very similar in each case. The symptom is that the position and velocity solutions are incorrect, and slowly 'walk off.' The ISS error checking tends to accept the 'walk offs' as valid since the GPS receiver output slowly walked off from the correct answer, rather than just outputting a single anomalous solution. Figure 7 shows a sample of such a walk off in the semimajor axis. Semimajor axis combines the position and velocity outputs into a single number. For ISS, the semimajor axis, when compensated for J2, is a fairly constant number.

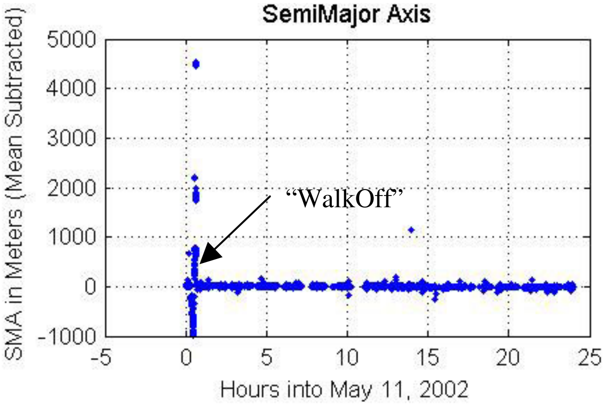

Figure 7 – Semimajor Axis For May 11, 2002

The walk-offs were tracked to several sources. One source was the receiver tracking satellites thru the Earth's atmosphere, which caused severe distortion of the pseudorange signal. Another factor was the health message which was output in a separate message from the navigation solution, but was occasionally being incorrectly associated with the previous navigation solution rather than the current navigation solution.

Velocity Noise Due To Ionospheric Scintillation

Velocity noise has also been observed in ISS GPS measurements. Reference 9 contains an analysis of both ISS and Shuttle measurements that show this phenomenon. It appears to be related to high ionospheric activity. Figure 8 shows the SIGI's velocity noise as compared to a ground filter (SPOT).

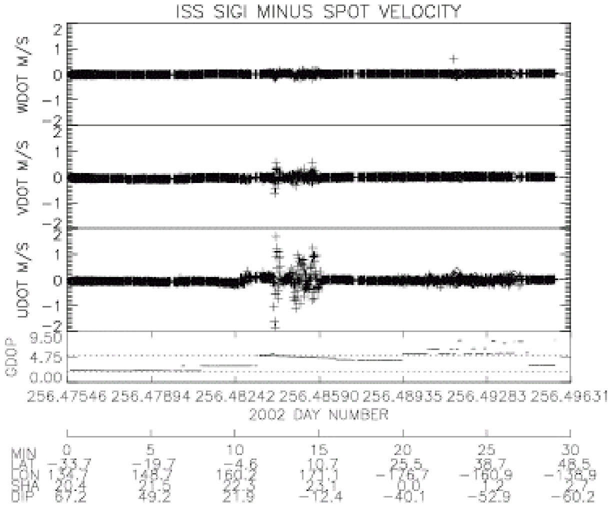

Figure 8 – SIGI Velocity Noise as Compared to Ground Filter

Figure 9 shows the latitude and longitude of the GPS solution when the velocity was output with an error that exceeded 0.5 meters/second. These noisy outputs appeared to be clustered in similar patterns as described in [Ref 12].

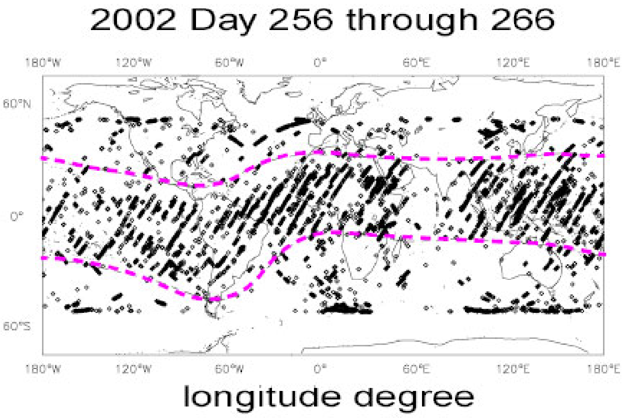

Figure 9 – Latitude And Longitude for Noisy SIGI Velocity Output

Robotic Arm Interference

The ISS GPS antenna array consists of four antennas in a 3 meter by 1.5 meter rectangle on the S0 element of the ISS main truss. The array center is slightly to the port side (4 meters) of the vehicle centerline, as shown in Figure 10.

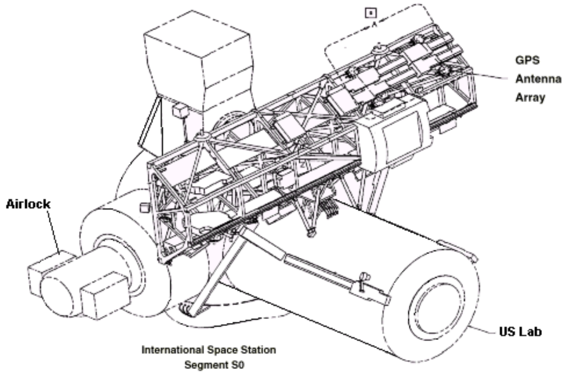

Figure 10 - GPS Antenna Array.

The Space Station Remote Manipulator System (SSRMS) robotic arm is often positioned near this area in order to support spacewalks, both for physically moving crew members from place to place, and also to utilize the cameras on the arm to observe the crew working. Figure 11 shows the position the SSRMS was parked at from May 26 - July 22, 2004 for viewing a spacewalk that was performed on the truss.

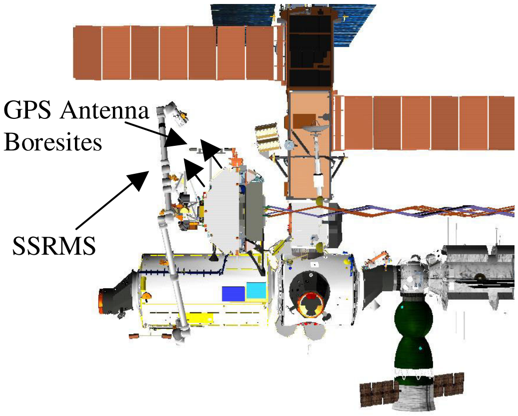

Figure 11 - SSRMS Parked Over GPS Antenna Array.

When the SSRMS is parked over the array, interference results in lower attitude coverage from SIGI. This is primarily an impact when ISS is flying inertial attitudes, since SIGI attitude coverage in these attitudes is already low. In some cases, the coverage has been reduced enough that the attitude filters within the US GNC flight software could not remain reliably converged using the attitude data from SIGI.

While the obvious solution appears to be avoiding the area of the antenna array, it is often operationally impossible to do so. Additionally, the complexity of activating and physically moving the SSRMS (which requires several hours of crew time, a carefully managed commodity on orbit) often results with the SSRMS being parked over the array for weeks at a time, instead of being repositioned immediately after spacewalks.

Instead, flight controllers work around the problem by reconfiguring the software to utilize attitude data from the Russian Segment GNC system, which is available to the US GNC flight software as a backup to GPS.

SIGI Impacts On Mission Control State Vector Ground Processing

Although there were no requirements on the SIGI to support state vector ground processing, once SIGI was operational on ISS, the benefits of such a filter became apparent. However, although the position and velocity accuracy requirements for SIGI are sufficient to support antenna pointing for TDRS communications, they are not sufficient to support maneuver planning, long-term orbital prediction and debris avoidance activities performed by Mission Control. A Mission Control based Kalman ground filter was developed to process SIGI state vectors and provide more precise orbit determination using high fidelity environment modeling.

A serious challenge faced by filter developers was lengthy SIGI state vector outages during integer ambiguity resolution for attitude determination, which lengthened the time required for the filter to converge on a solution. Numerous telemetry issues also affected data quality. Extensive analysis of SIGI data and lengthy development of filter data pre-processor code was required to overcome SIGI and ISS telemetry deficiencies.

Impacts of Poor State Vector Coverage Following Reboost

ISS reboosts are performed several times a year to counter atmospheric decay and to support phasing requirements for visiting vehicle rendezvous. In order to perform a reboost, attitude control of the vehicle is handed over from US segment CMG control to Russian segment thrusters control, and the Russian segment performs the reboost itself, normally by utilizing axial thrusters on a disposable Progress resupply vehicle docked to the rear port of ISS.

Because there are currently no inertial measurement units in either the US or Russian GNC systems, reboosts are performed open loop. Onboard state vectors in the US system are continuously updated through the burn by applying ground predicted accelerations and (when available) GPS sensed state vectors. The accuracy of the onboard state vector after the burn must remain within 60 kilometers of truth in order to accurately point the ISS ku-band communications system.

Experience has shown performance variability in Russian reboost burns. For example, a reboost on Februrary 11, 2003 was targeted for 6.0 meters/second, but problems with the Progress propulsion system resulted in an actual burn that was later calculated at 4.1 meters/second.

At the time, both Russian and US flight controllers were aware that there had been a problem with the Progress, but were unable to establish the exact post-burnout state vector of ISS because of the lack of sensed acceleration data, poor state vector coverage from SIGI in the post-burnout inertial attitude, and the time delay required to process ground radar data.

The onboard state vector (which was updated with accelerations assuming a nominal predicted 6.0 meter/second burn) eventually achieved an error of 165 kilometers before enough GPS and tracking data had been taken to establish the actual orbit of the vehicle and true reboost magnitude, nearly 10 hours after burnout.

Following this event, flight controllers modified the reboost sequence to fly a higher SIGI performance LVLH attitude for up to an orbit following burnout to increase the likelihood of achieving post reboost state vectors. Flight controllers also began using accelerometers within the ISS payload system to provide an estimate of reboost performance. Unfortunately, these accelerometers were originally designed to monitor microgravity performance, not core system GNC performance, and are not always available to flight controllers in real time.

Additionally, modifications have been made to SIGI firmware and US GNC flight software to incorporate the currently unused inertial data from the SIGI into the US GNC system by the end of 2005.

LESSONS LEARNED

The factors that contributed to the delivery of a GPS receiver for use on ISS that requires extensive operator intervention to function are discussed.

Inadequate Software Quality Processes

As a general rule, purchasing a Commercial Off the Shelf (COTS) product when the vendor and NASA do not have adequate hardware and software processes in place will lead to significant operational problems. Both HI and Trimble had processes in place to ensure the quality of their hardware, and, as a result, the SIGI hardware has not had any problems. However, of the three pieces of software code in the ISS/CRV SIGI, only the Trimble code was developed using a recognized coding standard to ensure the quality of the code. HI put their code standards in place *after* the ISS/CRV SIGI development, and NASA did not follow any code standards during the development of the attitude determination software. By comparison the Trimble code that was developed using a recognized coding standard had on the order of 10 discrepancies reported, whereas both the NASA and HI code had discrepancies on the order of 100.

Extensive Testing Doesn't Overcome an Inadequate Design

One of the major lessons learned from this experience was that no amount of testing will overcome an inadequate or ill adapted box design. The prevailing philosophy was to procure a product that was as close to the vendor's Commercial Off the Shelf (COTS) product as possible. One result of this philosophy was that NASA had very limited insight into the hardware and software design of the SIGI. NASA's extensive testing uncovered numerous anomalies (> 200). In retrospect, it appears that the whole software process and design needed re-working. Extensive testing can not solve inherent design deficiencies.

Firm, Fixed Price Contract Was Not Appropriate for This Procurement

Relatively early into the contract it was realized that the vendor was not going to be able to deliver the SIGI product for their firm, fixed price bid. Unforeseen development issues arose which inevitably led to schedule and requirements issues. In retrospect, this is easy to understand: the SIGI product had never been demonstrated in a space environment; therefore, its final development faced a significant degree of uncertainty and risk. Consequently, using a firm, fixed price contracting mechanism resulted in an inflexible contracting situation when technical problems and other unforeseen difficulties arose.

Unrealistic Schedules

The original philosophy behind COTS procurements was that the development costs had already been absorbed and the item's adaptation for use in the space program would be both faster and cheaper. Unfortunately, in the case of the SIGI, this was not quite true and it led to very optimistic project schedules.

Ultimately, unrealistically optimistic schedules only lead to a poor quality product that will probably still be delivered late. The original ISS/CRV SIGI development schedule allowed six months for the delivery of the development units. The hardware arrived about one month late, but the software was not completed for another two years (and it still had all of the problems discussed in this paper).

Even though NASA was dubious of meeting the project schedules, there were two reasons to think the schedules might be met: 1) GPS attitude had been demonstrated on flight experiments, and 2) the SIGI was as close to the vendor's COTS product as possible. However, it requires a significant amount of time and effort to take a technology from flight experiment demonstration to accepted Criticality 1 hardware. Also, just because a product appears to work for an existing application doesn't mean it is free of errors or will work well in a different environment (i.e. taking a technology from a terrestrial application to a space application is an extensive amount of work).

The unrealistic schedule impacted the quality of the SIGI product because rather than create a realistic schedule that included time for testing of the COTS software, time to put in place coding standards, and time to create a well planned software design, the vendors worked long hours until they ultimately produced a system that functioned, if only marginally.

Ownership

Additionally, it is unrealistic to expect a gyro manufacturer to take ownership of a box that is being used solely as a GPS receiver. Integrated navigation system vendors that do not manufacture GPS receivers may not devote enough attention, personnel resources, budget and schedule to resolving GPS receiver issues. Thus, when dealing with multi-component boxes that must be integrated, the ownership and responsibility for each component must be established early on.

CONCLUSIONS

Implementing GPS on ISS required that many technical and contractual hurdles be overcome. The technical problems included software bugs as well as physical phenomena that were not well understood. The software bugs were traced to inadequate software processes. The contracting problems included an inappropriate contract type and unrealistic schedules.

ACKNOWLEDGMENTS

Thanks to David Saley and John Goodman for their valuable comments in drafts of this paper.

REFERENCES

[1]Gomez, Susan F. "Flying High – GPS on International Space Station and Crew Return Vehicle," GPS World, June 2002.

[2]Goodman, J. L., "GPS In Earth Orbit – Experiences From The Space Shuttle, International Space Station And Crew Return Vehicle Programs," Proceedings of the 2002 Core Technologies for Space Systems Conference, Colorado Springs, CO, November 19-21, 2002. See http://www.spacecoretech.org/, Technology Maturation, Transfer, and Utilization Session. Accessed in July, 2004.

[3]Goodman, J. L., "Lessons Learned From Flights of "Off the Shelf" Aviation Navigation Units on the Space Shuttle," Joint Navigation Conference, Orlando, Florida, May 6-9, 2002. See also Lesson #1370 on the NASA Public Lessons Learned System Database website:http://llis.nasa.gov/llis/plls/index.html. Accessed in July, 2004.

[4]Goodman, J. L., "The Space Shuttle and GPS – A Safety-Critical Navigation Upgrade," COTS-Based Software Systems, edited by H. Erdogmus and T. Weng, Springer-Verlag Lecture Notes in Computer Science Volume 2580, Springer-Verlag, Berlin, Germany, 2003, pp. 92-100.

[5]Goodman, J. L., "A Software Perspective On GNSS Receiver Integration and Operation," Satellite Navigation Systems: Policy, Commercial and Technical Interaction, edited by M. Rycroft, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2003, pp. 119-126.

[6]Goodman, John L., "A GPS Receiver Upgrade For The Space Shuttle – Rationale And Considerations," Paper AIAA-2004-3911, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, FL, July 11-14, 2004

[7] Knight, Don, US Patent Number 5,296,861 issued March 22, 1994.

[8] Gomez, Susan, F. "New GPS Attitude Algorithms for Use in International Space Station (ISS) Space Integrated Global Positioning System/Inertial Navigation System (SIGI)," August 2004.

[9]Kramer, Leonard, and John L. Goodman, "Ionospheric Instability Observed in Low Earth Orbit Using GPS," AIAA Journal of Spacecraft and Rockets, AIAA, Reston, VA, to be published.

[10]Goodman, J. L., "Space Shuttle Navigation in the GPS Era," Proceedings of the Institute of Navigation National Technical Meeting, Institute of Navigation, Fairfax, VA, 2001.]

[11] Knight, Mark Frederick, "Ionospheric Scintillation Effects on Global Positioning System Receivers," Doctoral Thesis submitted to The University Of Adelaide, December 2000.