GPS/INS/STAR TRACKER NAVIGATION USING A SOFTWARE DEFINED RADIO

Alison Brown (NAVSYS Corporation, abrown@navsys.com)
Ben Mathews (NAVSYS Corporation, benm@navsys.com)
Dien Nguyen (NAVSYS Corporation, dienn@navsys.com)

ABSTRACT

NAVSYS Corporation and Microcosm, Inc., have jointly developed a design for a flexible, high-performance, miniaturized, space-based Software GPS Receiver (SSGR) based on a Software Defined Radio (SDR) architecture that optimally combines GPS, INS, and star-tracker inputs to provide a flexible, integrated precision navigation and attitude determination solution for space applications. The SSGR is suitable for supporting multiple space missions including GPS metric tracking during launch, orbit determination during transfer to geostationary orbits, and high accuracy navigation, attitude control and timing. The flexibility of the SSGR design allows it to be re-programmed for use in launch and orbit entry, station-keeping and autonomous orbit estimation applications.

In this paper we present a system design, analysis, and test results for the integrated SSGR navigation system. The filter design for the optimal integration of GPS, INS, and star-tracker measurements is presented along with simulation results that show predicted performance. In the design of a space-based GPS receiver, difficulty comes in testing, since the dynamics involved are radically different from anything achievable on the ground. Commercially available GPS simulators that are capable of simulating the space environment are very expensive, generally have high learning curves, and are limited in capability and flexibility. The multi-element Advanced GPS Hybrid Simulation (AGHS) capability available at NAVSYS addresses many of these concerns. As part of this effort, NAVSYS has modified its AGHS to support simulated star-tracker measurements for real-time receiver testing in space-based trajectories. Receiver test results using the AGHS are presented to validate performance predictions and demonstrate the benefits of the combined GPS, INS, and star-tracker approach.

INTRODUCTION

Navigation Challenges for Microsatellites

Microsatellites provide an affordable, near-term test platform for proving new spacecraft technologies. They can also provide a responsive capability for missions that necessitate quick launch. This technology is particularly relevant to rapid military responses in times of crisis. Although microsatellites offer substantial potential advantages in both cost and performance over traditional large satellites, current commercially available navigation and attitude determination components are designed for spacecraft that are an order of magnitude more massive than microsatellites and are too expensive and bulky for deployment on microsatellites.

Solving the problem of microsatellite navigation requires more than simply scaling down existing hardware; it must be designed and evaluated, not only as an individual subsystem, but also within the system level context of controlling a high precision microsatellite. Most dynamic characteristics of small satellites do not scale linearly with size. For example, the moments of inertia scale approximately as the 5th power of the linear dimensions, while the required control bandwidth decreases as the square of the linear dimensions. Consequently, microsatellites will be much more agile than their larger, more massive counterparts and will also require a much higher control bandwidth and will be more sensitive to disturbances. Thus, it is imperative that a microsatellite navigation and attitude determination components be designed with an understanding of expected accuracy and bandwidth requirements.

Developing low-cost components and systems specifically to meet the navigation and attitude determination needs of high performance microsatellites will enable low-cost testing of new space hardware, as well as making routinely available highly responsive and capable space systems. The goal of the effort described in this paper is to advance the state of the art with respect to navigation receivers capable of using components suitable for use on microsatellites.

Integrated Microsatellite Navigation Solution

To address the need for an integrated space-based navigation solution, NAVSYS has developed a space-based Software GPS Receiver (SSGR) design and prototype based on an SDR architecture that optimally combines inputs from a variety of sensors. The SSGR system provides a flexible, integrated precision navigation and attitude determination solution for space applications including Low Earth Orbit (LEO), highly eccentric orbit (HEO), and Geostationary Earth Orbit (GEO) missions. Advanced signal processing techniques give it the ability to track low power GPS satellites to extend the use of GPS for precision navigation and timing, particularly for high altitude space missions where the receiver is above the GPS satellite constellation and outside of the main beam of their radiation pattern. The SSGR is suitable for supporting multiple space missions, including GPS metric tracking during launch, orbit determination during transfer to geostationary orbits, and high accuracy navigation, attitude control and timing. The flexibility of the SSGR design allows it to be re-programmed for use in launch and orbit entry, station-keeping and autonomous orbit estimation applications.

To meet the specific needs of microsatellite navigation, NAVSYS Corporation and Microcosm, Inc., have teamed to develop a system that leverages the SSGR design combined with a miniature star tracker and a miniature inertial measurement unit (IMU) with Micro-Electro-Mechanical System (MEMS)-based accelerometers, and gyros, as shown in Figure 1. The low-cost, lightweight, integrated GPS, INS, and star-tracker solution provides a flexible, integrated precision navigation and attitude determination solution for space navigation applications.

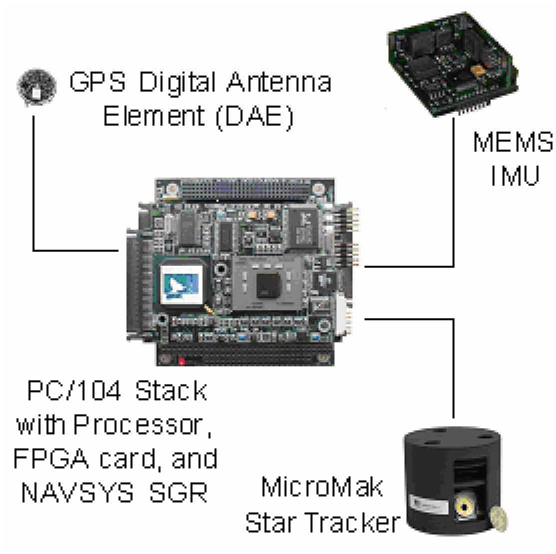

Figure 1 Integrated Space Navigation Receiver

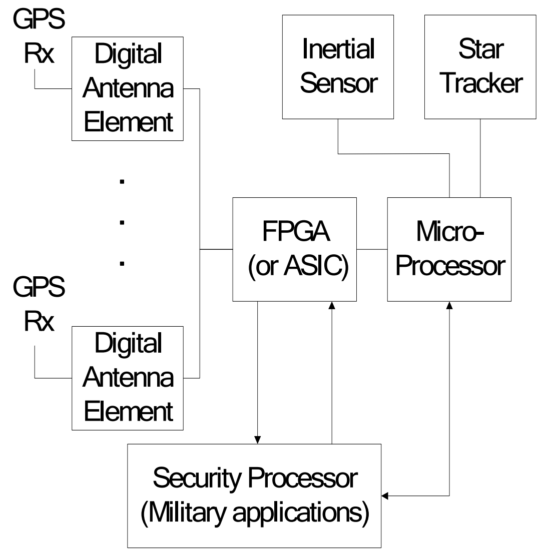

Figure 2 SSGR Architecture

SPACE SOFTWARE GPS RECEIVER

SSGR Testbed

Figure 2 shows the high-level core architecture of the NAVSYS PC-104-Based SGR/SDR. Multiple Digital Antenna Elements (DAE) RF front-ends are used to convert between analog radio signals and digital signals. An FPGA card provides high speed signal processing on the GPS data. A General Purpose Processor (GPP) running either Windows or Linux receives the processed GPS measurements, as well as inertial and star-tracker input, and provides higher level processing and user or application interface and control. In some applications, a GPS P(Y) code security processor is used for crypto functions. We have used this same architecture previously on PC and CompactPCI platforms [1,2,3].

The SSGR testbed has been used to develop the software and firmware to process the measurements from the various sensors, as well as to optimally combine them into an integrated navigation solution, as described in the following section.

PC/104-Plus Processor Card

The PC/104-Plus processor card stack is shown below in Figure 3, and has the following specifications:

- Standard PC-based architecture
- Pentium-M processors to 1.6GHz
- 1024 MB of SDRAM
- 10/100MBit Ethernet
- EIDE and USB ports
- Low Power ACPI compliant

- PC/104-Plus and PC/104 Expansion
- Available in Extended Temperature
- Standard 3.6in x 3.8in PC/104 form factor
- Total stack power consumption is 10-30W depending on hardware configuration, processor and application

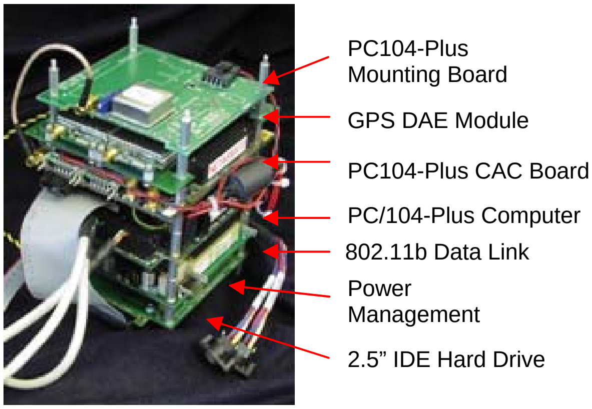

Figure 3 PC/104-Plus Space Software GPS Receiver System

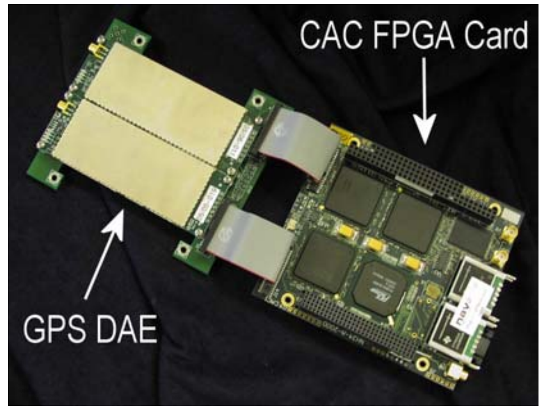

Figure 4 GPS Digital Antenna Element and Correlator Accelerator Card

The processor card can support multiple operating systems. For the purposes of this effort, Windows XP running VentureCom's Real-Time Extensions (RTX) was chosen in order to support real-time data transfer with direct memory access (DMA), and to provide sub-10μs interrupt latencies for reading in inertial data. Other NAVSYS programs have used this same board with the FSMLabs RT Linux product.

Digital Antenna Element (DAE)

The DAE provides some useful features for SGR and SDR applications:

- L1 (1575.42 MHz) and L2 (1227MHz) RF frequency range
- 40 MHz sampling rate (20 MHz bandwidth) at 8 bits per sample
- Small size; approximately 3" diameter/square.
- Low power consumption.
- Simplified RF interface. Abstracts analog domain from processing components.
- Uses LVDS (low-voltage differential signaling) over standard category-5 twisted pair cable. USB and IEEE 1394 Firewire available for future DAEs.
- LVDS interface provides ability to develop diverse range of antenna elements for different bandwidths/frequencies with a common interface to FPGA card.
- Sampling rate controllable via far end. Clock can be provided through LVDS pairs for phase-coherent operation, and reduces noise and power introduced by an on-board oscillator.
- Converts analog RF signal to digital domain close to antenna. Minimize cable interference.
- Supports active or passive antenna arrangements. SMA connector available.
- Individual units can be combined to support phased array processing for tracking low-power signals and mitigating multipath and jamming

The GPS DAE, depicted in upper left part of Figure 4, down-converts and samples GPS RF signals and provides a serial digital output to the SGR FPGA card which performs the GPS code generation and correlation. It is capable of receiving both L1 and L2 GPS signals.

PC/104 Correlator/Accelerator Card

The NAVSYS PC/104 Correlator/Accelerator Card (CAC) is shown in lower right part of Figure 4. This card contains three Xilinx Spartan-3 FPGAs used to perform high-speed correlations and firmware-based signal processing. LVDS connections are used for receiving data from the GPS DAE.

The CAC contains a PCI bus chip to provide high speed interfacing between the FPGAs and the processor card over the PC/104-Plus PCI bus. The PCI bus chip also provides interrupt and DMA capabilities. We have measured a sustained data rate of 72 megabytes per second with our current FPGA card using DMA data transfer (the theoretical maximum bandwidth is 33 MHz by 32 bits or 133 Mbytes/sec). For use in capturing snapshots, the CAC also contains an SRAM buffer, which can be sent via Direct Memory Access (DMA) transfers to the host processor for analysis. This buffer has been used for FFT-based satellite acquisition in conjunction with external processing components..

MEMS Inertial Measurement Unit

The MEMS IMU used in this effort is the Crista IMU produced by Cloud Cap Technology, shown in Figure 5. This is built using a triad of Analog Devices accelerometers [4] and gyroscopes [5]. The instruments used by the Crista IMU, while significantly smaller, lower cost and lower power, are perform several orders of magnitude more poorly than current state-of-the-art Ring Laser Gyro IMUs [6]. While future MEMS technologies promise to provide improved performance levels, approaching those of the HG1700 instruments, the challenge today for low cost navigation applications is to design an integrated system that can perform inertial navigation using these existing low grade MEMS instruments.

Figure 5 Cloud Cap Crista IMU

Figure 6: MicroMak with three fields of view

through a common aperture

MicroMak Star-Tracker

The MicroMak device, shown in Figure 6, is a new, high-precision, very compact star sensor weighing less than 100 grams, with three independent 4-degree square fields of view [7]. The MicroMak consists of three individual optical systems which share a common aperture, and features a Maksutov collection telescope design that incorporates three telescopes into a single sensor head. The sensor is designed for star identification and spacecraft attitude determination with a device that offers unprecedented low cost, volume and mass. While star trackers have achieved sub-arcsecond accuracy by utilizing sophisticated algorithms and complex hardware, the MicroMak sensor relies on efficient algorithms that utilize data from only the image sensor.

NAVIGATION FILTER

The NAVSYS InterNav navigation filter is used on the SSGR to calculate the combined GPS/Inertial/Star-tracker navigation solutions. This includes the software functions illustrated in Figure 7. The InterNav software includes several software modules. The receiver interface module handles the interface to the GPS receiver, which receives and formats the GPS pseudo-range and carrier phase observations for processing in the Kalman Filter. The IMU interface module performs a similar function, formatting the IMU angle rate and acceleration observation for the inertial navigation solution. The inertial navigation solution is based on a quaternion integration algorithm to compute the body-to-navigation transformation direction cosine matrix and integrate the acceleration to propagate position and velocity. The integrated GPS/inertial solution can also be precisely time aligned with other sensors, including star trackers, Earth sensors, and other navigation signals.

The receiver interface module handles the interface to the SSGR tracking software, which provides the GPS pseudo-range and carrier observations for processing in the Kalman Filter. The IMU interface module formats the IMU delta-theta and delta-V observation for the inertial navigation solution. The inertial navigation solution is based on a quaternion integration algorithm to compute the body-to-navigation transformation direction cosine matrix and integrate the acceleration to propagate position and velocity in a wander-azimuth navigation frame.

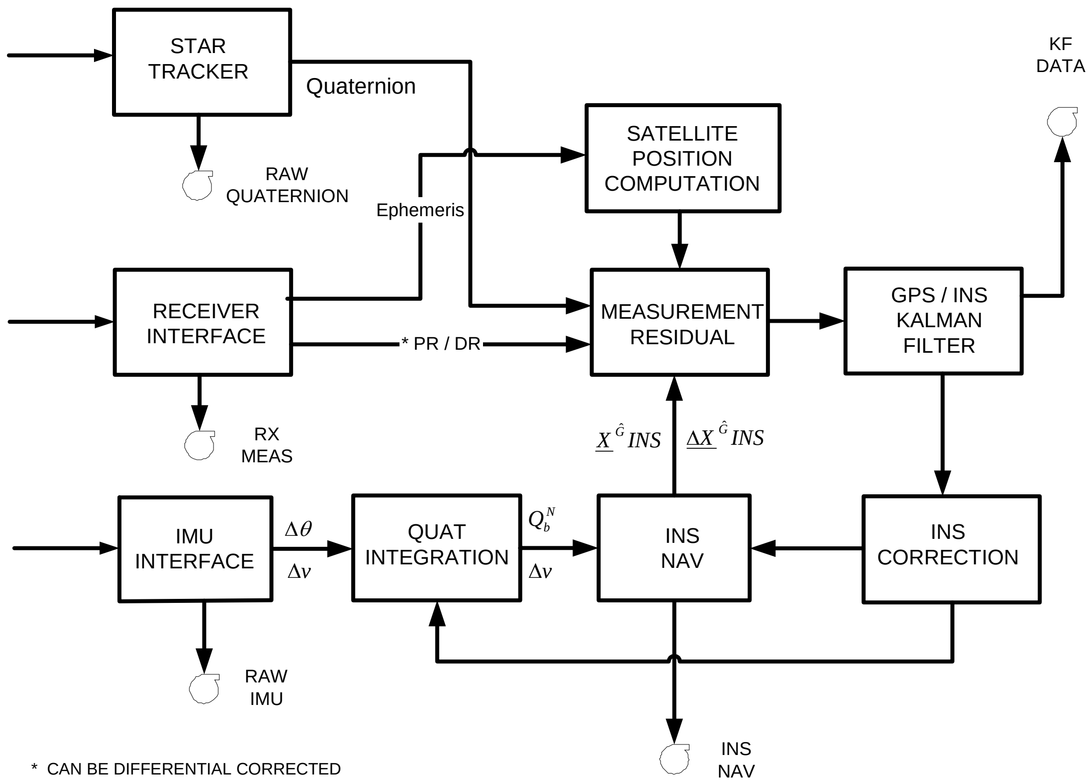

Figure 7 NAVSYS GPS/Inertial Filter Software

A major focus of this effort was adapting the InterNav filter to process the quaternion updates from the star-tracker. The Star tracker provides up to 10-Hz attitude measurements to the Kalman filter, where it is used to augment inertial measurements and to provide updates to corrections to the inertial navigation functions. By incorporating quaternion updates into the integrated navigation solution, a much lower quality IMU may be used since regular corrections from the star-tracker are applied before the navigation solution quality is affected by IMU drift.

ADVANCED GPS HYBRID SIMULATOR TESTING

To support testing with live RF data for this effort, the NAVSYS Advanced GPS Hybrid Simulator (AGHS) was used. The AGHS is a hybrid software, digital and radio frequency (RF) GPS and INS simulator. It was developed using a software defined radio architecture to allow for detailed real-time software control of the waveforms and signals being generated. The AGHS can be configured to support different numbers of simulated satellite, platform and antenna configurations. The model shown in Figure 8 is capable of simulating 12 GPS satellites simultaneously, and can model any antenna array with up to 8 elements (L1 and L2).

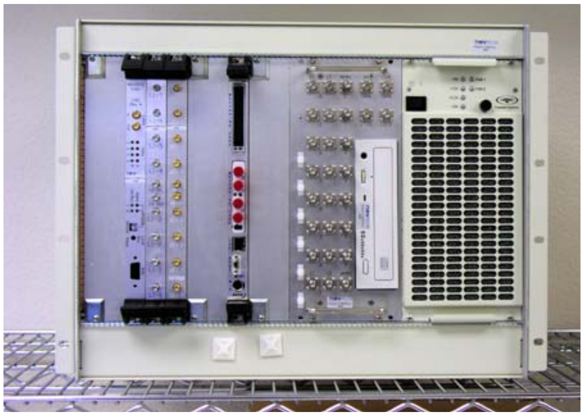

Figure 8 NAVSYS AGHS Simulator

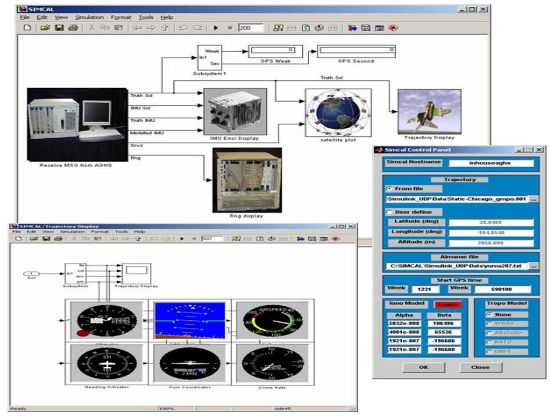

Figure 9 Simulink Control Software

In addition to GPS signal simulation, the AGHS simulator is designed to generate precisely synchronized simulated inertial data to allow testing of tightly integrated GPS/inertial (IGI) systems and ultra-tightly coupled (UTC) GPS/inertial signal tracking. As part of this effort, the AGHS was easily extended to also support simulated star tracker-generated quaternion updates for space trajectories. This was facilitated by the use of the Simulink-based AGHS control and analysis interface, shown in Figure 9.

The goal of the AGHS testing was to validate the interface compatibility of the hardware components, the tracking capability of the software GPS receiver, as well as the attitude and navigation processing capability of the InterNav Kalman Filter that resides in the host controller/flight computer. When used with the MicroMak star-tracker model, the AGHS HWIL testing architecture, shown in Figure 12, provided the SSGR test-bed with star-tracker, inertial, and GPS RF data in the same way it would be received on an operational satellite, which provided the ability to perform HWIL testing on most aspects of the hardware and software interfaces and algorithms of interest.
Using this test set-up, the ability to acquire and track GPS was tested, and the ability to perform the integrated navigation functions was successfully tested. Using a simulated LEO trajectory, the SSGR was run off of AGHS to verify tracking ability in a space environment. Figure 10 shows the number of satellites tracked over the course of the trajectory, and Figure 11 shows a sample satellite geometry for a point in the trajectory.

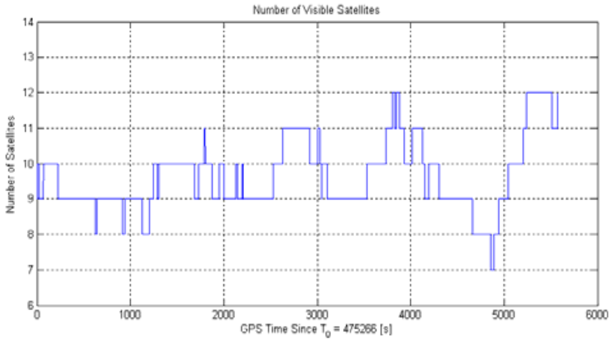

Figure 10 Number of Satellites Tracked

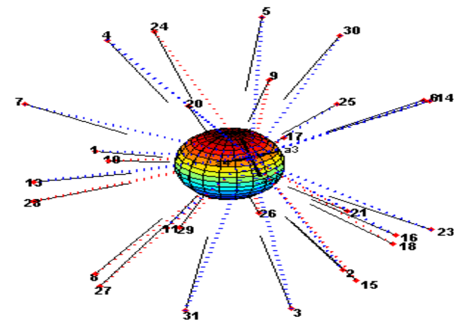

Figure 11 Satellite Visibility

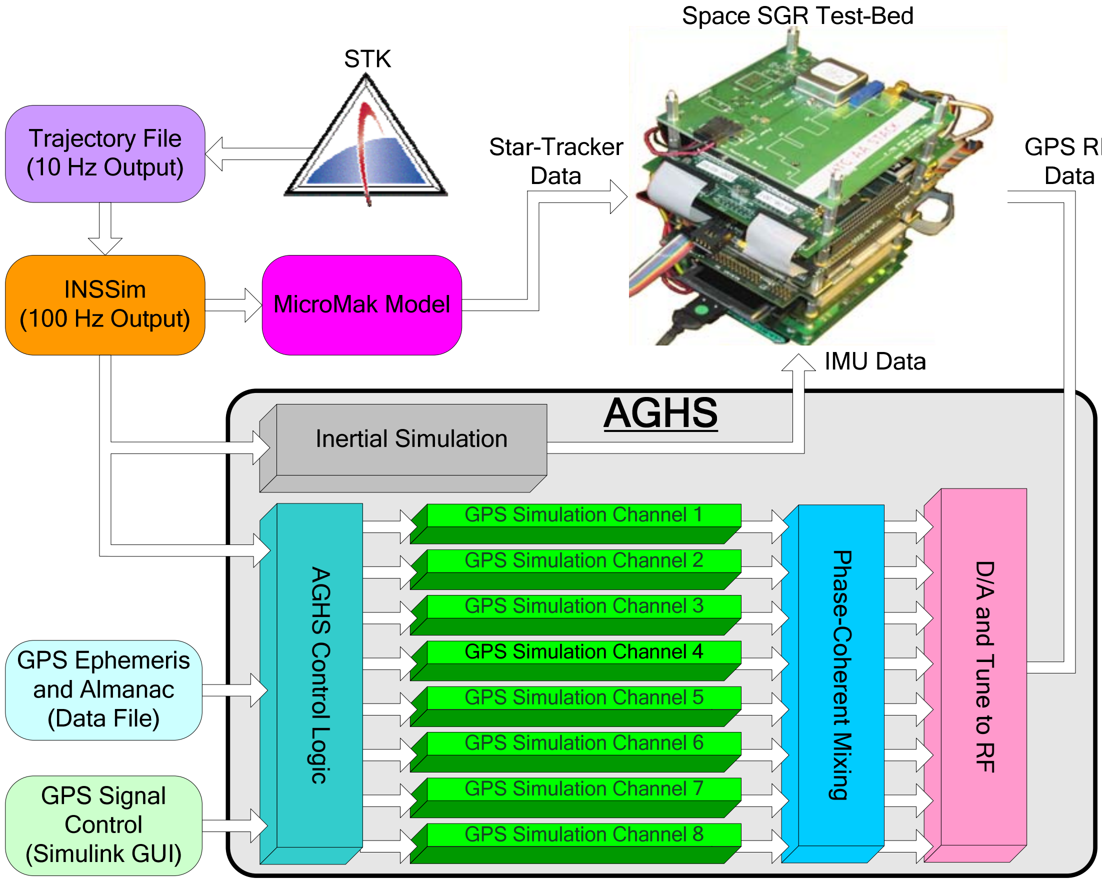

Figure 12 SSGR HWIL Test Functional Block Diagram

Using a simulated LEO trajectory, simulated GPS, INS, and star tracker data were generated using NAVSYS' GPS Toolbox for Matlab, using known error models for the INS and star tracker, and adding zero mean pseudorange noise to the GPS measurements. The GPS Toolbox is a complete set of GPS signal simulation, test, and analysis tools. The Matlab signal simulation tool simulates the complete GPS signal, as generated by the GPS satellites, including effects such as signal interference or atmospheric signal degradation (e.g. ionosphere). The Toolbox's geographic tools facilitate the transformation of data between the various coordinate systems commonly used in GPS research, such as latitude-longitude-altitude, WGS-84 ECEF, North-East-Down, and body reference frames. It also provides tools to read GPS almanacs and ephemeredes and compute ECEF and line-of-sight vectors to GPS satellites as a function of user position and time.

Simulated pseudorange, inertial, and quaternion update data was generated and fed into the SSGR. In order to simulate realistic conditions, the inertial data was generated using a model of the Crista Cloud Cap IMU. The GPS receiver model has 0.5-meter range noise for space environment. The quaternion update data was generated using a model of the MicroMak star tracker of 48 micro-radian measurement noise. Attitude, position, velocity, and attitude errors are shown in Figure 13, Figure 14, and Figure 15. Position errors are on the order of 0.7 meter, and velocity errors are on the order of 0.1 m/s. Attitude errors are in the order of 2 miliradians using 1-Hz attitude update.

In Figure 16 the attitude estimation errors are plotted using the 10-Hz star tracker updates. With the filter updates, attitude estimation errors are on the order of tens of microradians, a significant improvement over attitude estimation using GPS, INS, and 1-Hz star tracker measurements.

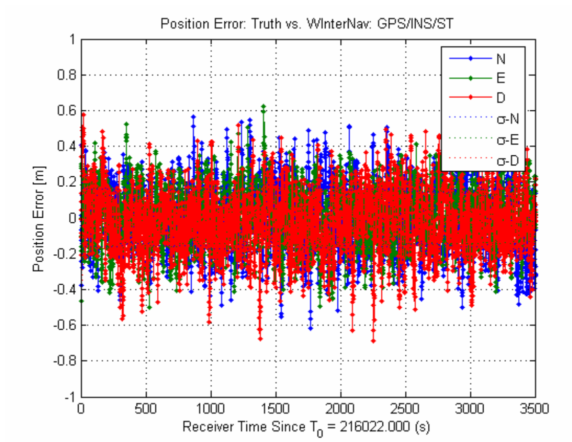

Figure 13 GPS/INS/ST Position Estimation Error

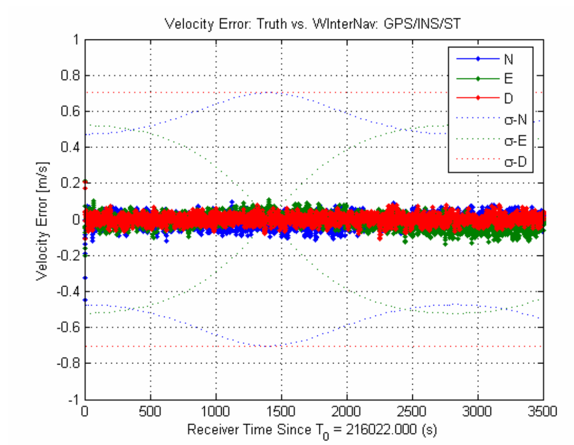

Figure 14 GPS/INS/ST Velocity Estimation Error

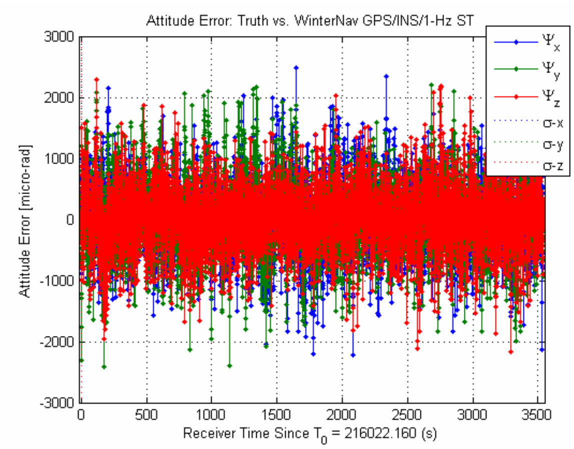

Figure 15 GPS/INS/1-Hz ST Attitude Error Without Attitude Reset

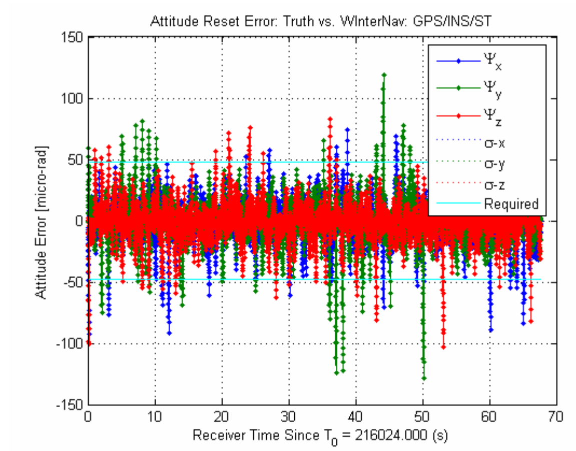

Figure 16 GPS/INS/10-Hz ST Attitude Error With Attitude Reset

The benefits of such an integrated approach can be seen be observing the effects when star-tracker input is not available. A test scenario was generated and run where the filter was allowed to operate for a period of time with all available measurements in order to initialize, and then the star-tracker input was removed. In Figure 17 and Figure 18 the velocity errors for the two scenarios are shown, and in Figure 19 and Figure 20 the attitude errors for the two scenarios are shown (positioning was unaffected by star-tracker drop-out). The drift in velocity and attitude can clearly be seen. Updates from GPS measurements alone to the inertial measurements are not able to offer the same level of performance as the integrated GPS / star-tracker measurements.

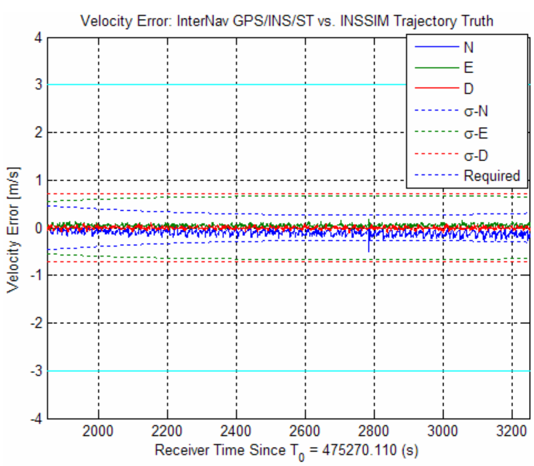

Figure 17 Velocity Error With Star-Tracker Input

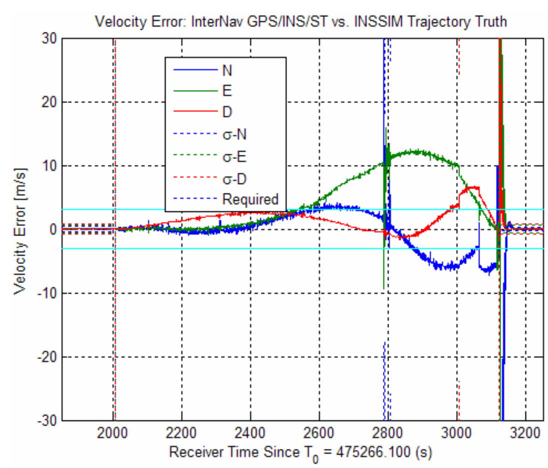

Figure 18 Velocity Error Without Star-Tracker Input

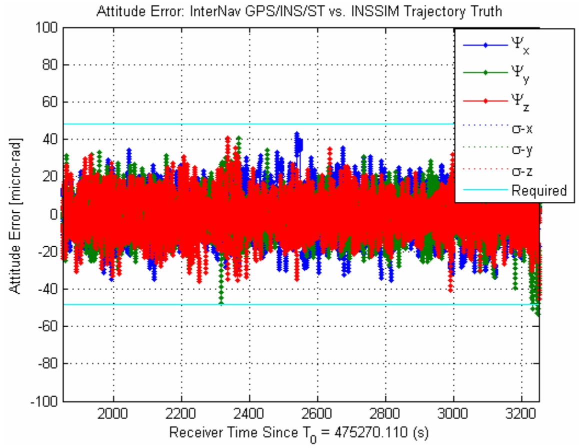

Figure 19 Attitude Error With Star-Tracker Input

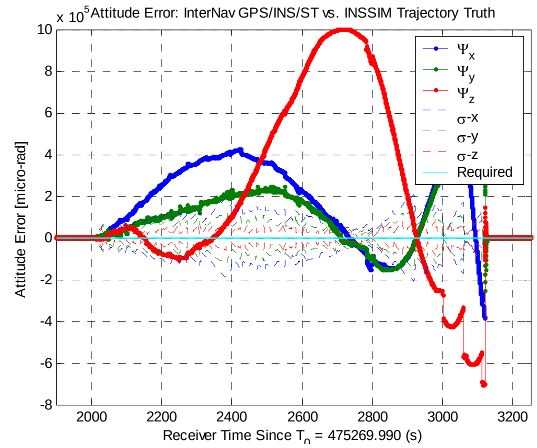

Figure 20 Attitude Error Without Star-Tracker Input

CONCLUSIONS

The SSGR units with integrated GPS/INS/Star-Tracker navigation capability are being developed to provide a robust navigation and attitude determination capability that is suitable for deployment on small satellites. Low cost, weight, and power make this a viable and affordable option for use on near-term test platforms for proving new spacecraft technologies. Use of advanced signal processing and filtering techniques allow the SSGR to utilize cheap, inexpensive, and light weight components whose performance otherwise would not be suitable for use in an integrated navigation solution.

The test data presented in this paper has shown that the SSGR filter architecture offers a means of improving the attitude measurement accuracy for precision space applications such as rendezvous, docking or formation flying. The use of a software-defined radio architecture made possible the rapid development and prototyping of this capability. By using a set of flexible GPS/INS testing tools, realistic test scenarios were able to be generated and used with a minimum of effort.

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