INTEGRATED GPS/INS/STAR TRACKER SPACE NAVIGATION SYSTEM USING A SOFTWARE DEFINED RADIO

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ABSTRACT

NAVSYS Corporation has developed a design and prototype of 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 including LEO, HEO and GEO missions. Working jointly with Microcosm, Inc., we have prototyped and tested this capability with a miniaturized star-tracker developed specifically for microsatellite 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 are presented along with simulation results that show predicted performance. As part of the test and simulation effort, the NAVSYS Advanced GPS Hybrid Simulation (AGHS) capability was used to simulate the space environment. Receiver test results using the AGHS will be presented to validate performance predictions and demonstrate the benefits of the combined GPS, INS, and star-tracker approach.

1. INTRODUCTION

1.1. 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 time of crisis. Although they 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. Neither the attitude properties nor attitude motion scales 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.

1.2. 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 will be 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 will allow it to be reprogrammed 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.

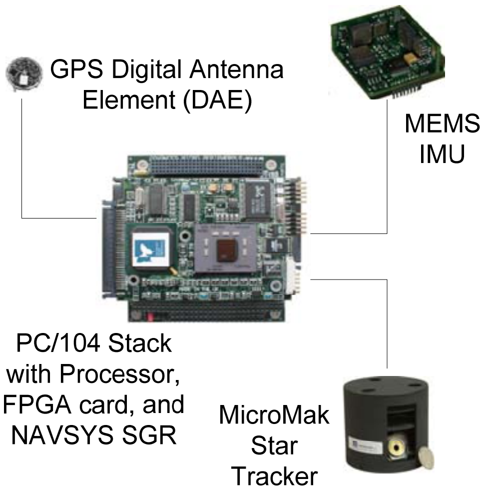


Figure 1 Integrated Space Navigation Receiver

2. SPACE SOFTWARE GPS RECEIVER

2.1. SSGR Testbed

Figure 2 shows the high-level core architecture of the NAVSYS 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) receives the processed GPS measurements, as well as inertial and star-tracker input, and provides higher level processing and user or application interface control. In some applications, a security processor is used for crypto functions. We have used this same architecture previously on PC and CompactPCI platforms[1,2,3]. We are now using it on PC/104 platforms

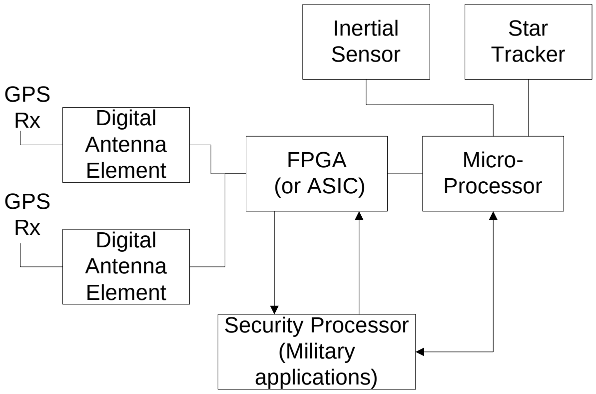


Figure 2 SSGR Architecture

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.

2.2. PC/104-Plus Processor Card

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

- 100% PC-AT compatible
- 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

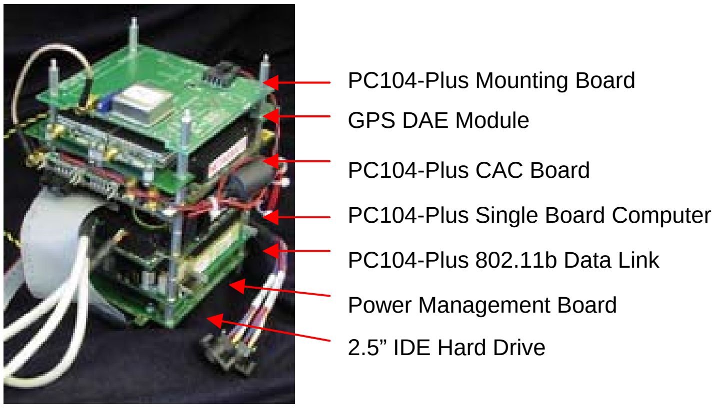


Figure 3 PC/104-Plus SSGR System

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.

2.3. 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.

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.

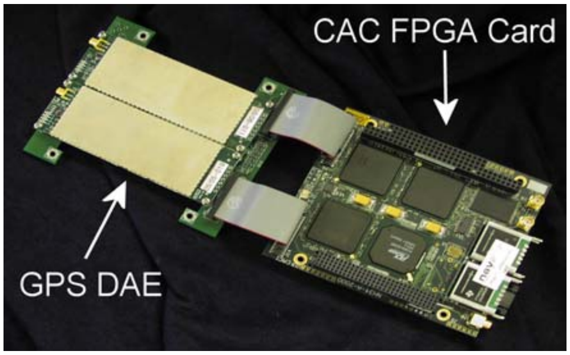


Figure 4 GPS Digital Antenna Element and Correlator Accelerator Card

2.4. 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 DMAed to the host processor for analysis. This buffer has been used for FFT-based satellite acquisition.

2.5. MEMS IMU

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

2.6. 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.

Figure 6: MicroMak with three fields of view through a common aperture

3. NAVIGATION FILTER

The NAVSYS InterNav software is used on the SSGR to calculate 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 and Earth sensors.

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.

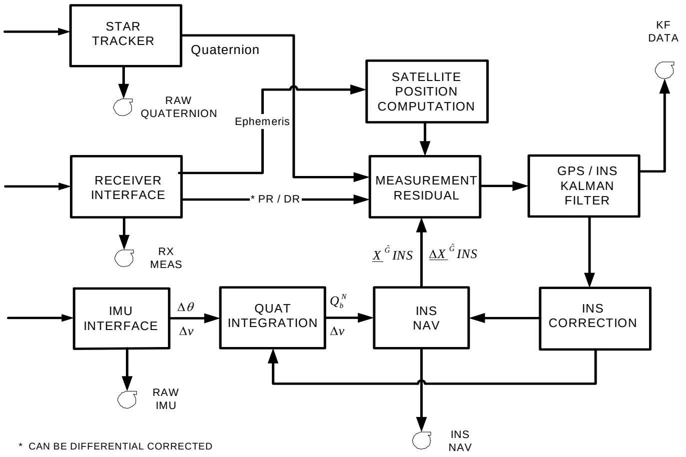


Figure 7 NAVSYS GPS/Inertial Filter Software

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 will be applied before the navigation solution quality is affected by IMU drift.

4. SIMULATION RESULTS

Using a simulated LEO trajectory, simulated GPS, INS, and star tracker data were generated using NAVSYS' GPS Toolbox for Matlab. 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.

Using the toolbox simulated pseudorange, inertial, and quaternion update data was generated. 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 9, 9, and 10. 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 11 attitude estimation errors are plotted using the 10-Hz star tracker updates. With the filter updates, attitude estimation errors are on the order of tenths of microradians, a significant improvement over attitude estimation using GPS, INS, and 1-Hz star tracker measurements.

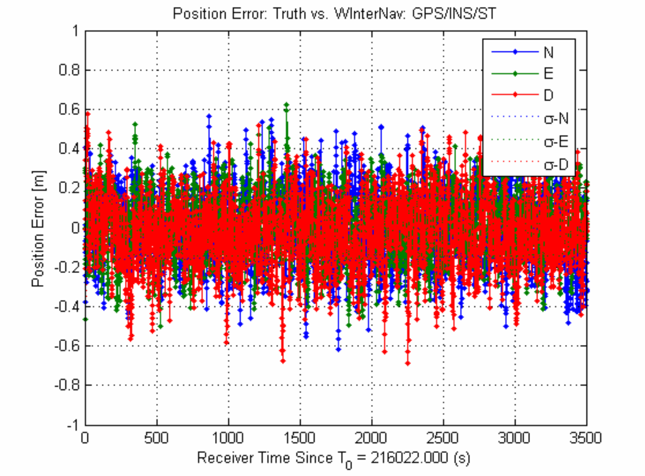


Figure 8 GPS/INS/ST Position Estimation Error

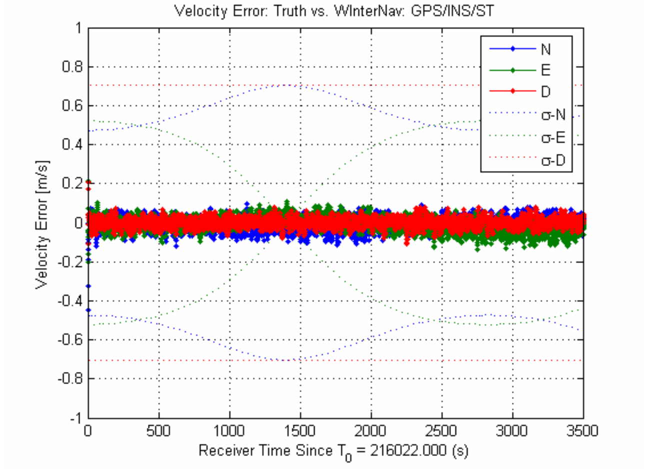


Figure 9 GPS/INS/ST Velocity Estimation Error

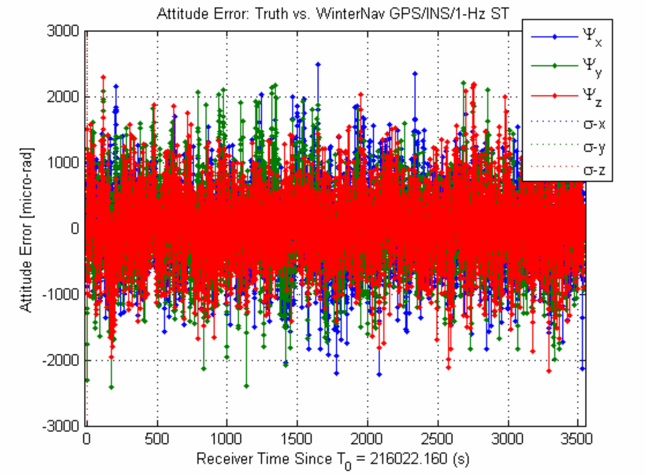


Figure 10 GPS/INS/1-Hz ST Attitude Estimation Error

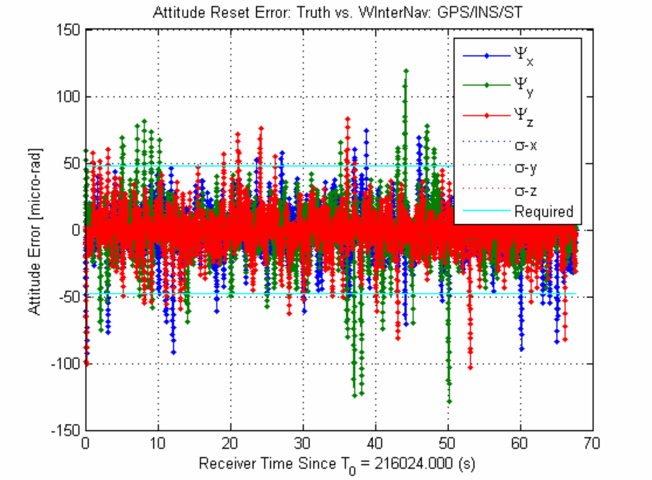


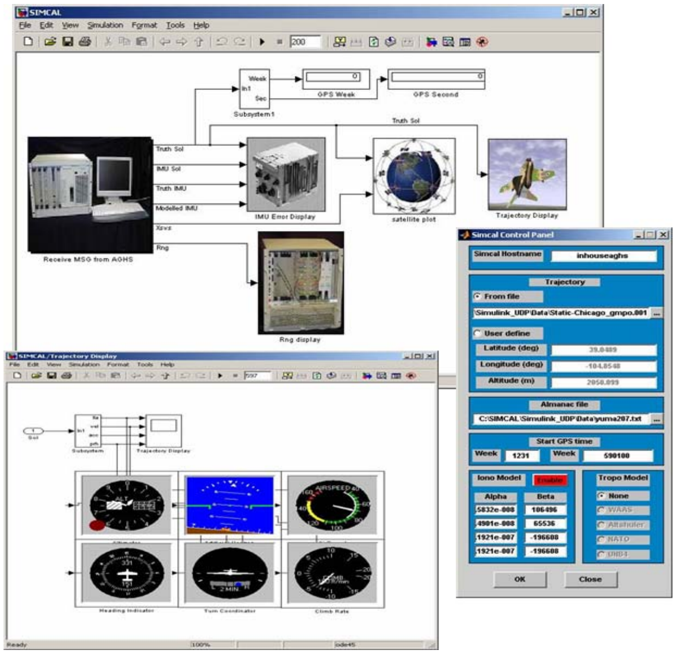
Figure 11 GPS/INS/10-Hz ST Attitude Estimation Error

5. ADVANCED GPS HYBRID SIMULATOR TEST SET-UP

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 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 12 is capable of simulating 12 GPS satellites simultaneously, and can model any antenna array with up to 8 elements (L1 and L2).

Figure 12 NAVSYS Advanced GPS Hybrid Simulator

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 generate to 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 13.



Simcal Hostname: inhouseaghs

Trajectory

● From file: \Simulink_UDP\Data\Static-Chicago_gmpo.001

○ User define

Latitude (deg): 39.0489

Longitude (deg): -104.8548

Altitude (m): 2050.899

Almanac file: C:\SIMCAL\Simulink_UDP\Data\yuma207.txt

Start GPS time: Week 1231 Week 590100

Iono Model: Enable

Alpha	Beta
5832e-008	106496
4901e-008	65536
1921e-007	-196608
1921e-007	-196608

Tropo Model: ● None ○ WAAS ○ Altshuler ○ NATO ○ UNB3

Figure 13 Simulink Control Software

The next step in this effort is simulation of the SSGR using the AGHS test set-up described in this section. Results from these tests will be presented in a future paper.

6. 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 microsatellites. 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 acceptable 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. In the next stage of testing, RF signals and simulated inertial and star-tracker data will be injected into the SSGR in order to test the overall system performance. To aid in testing of this space qualified receiver, the NAVSYS GPS Toolbox, and AGHS products have been augmented to include tools to allow simulation of GPS, INS, and star-tracker data in a space environment. Results from these tests will be presented in a future paper.

7. REFERENCES

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[7] U.S. Patent #6,060,072