Testing of Ultra-Tightly-Coupled GPS Operation using a Precision GPS/Inertial Simulator

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BIOGRAPHY

Alison Brown is the President and Chief Executive Officer of NAVSYS Corporation. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge University. In 1986, she founded NAVSYS Corporation. She was a member of the GPS-3 Independent Review Team and the Interagency GPS Executive Board Independent Advisory Team, and is an Editor of GPS World Magazine. She is an ION Fellow and an Honorary Fellow of Sidney Sussex College, Cambridge.

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ABSTRACT

Next generation high anti-jam GPS receivers will take advantage of Ultra-Tightly-Coupled (UTC) GPS/inertial signal processing to improve their anti-jam robustness. UTC signal processing uses the inertial observations to aid the GPS receiver correlation channels and extend the period over which the coherent correlator outputs can be accumulated. For UTC tracking to operate, the residual carrier error from the inertial aiding must be maintained within a fraction of a cycle. Maintaining the carrier coherence of a GPS signal to within a few centimeters of the inertial aiding observations places some new and challenging constraints on GPS RF and inertial simulators. This paper describes the design of a high fidelity simulator suitable for GPS/inertial UTC testing that has been developed by NAVSYS.

INTRODUCTION

Simulation and testing of high accuracy, integrated GPS/inertial applications, requires tight control of the simulated GPS and inertial observations. One example of a system that requires next generation GPS simulation technology is the Shipboard Relative GPS Joint Precision Approach and Landing System (SRGPS JPALS). To simulate the SRGPS JPALS performance, synchronous simulation to millimeter accuracy of the GPS signals on both the aircraft and on the ground (shipboard) reference systems are required. As shown in Figure 1 and Figure 2, both of these subsystems also include GPS and inertial components requiring similar levels of accuracy in the simulation to model the inertial measurements that would be generated in the real-time system[1]. Since the SRGPS also has high anti-jam requirements, the GPS/inertial simulator must also be able to model the GPS signal wavefront arriving at a Controlled Reception Pattern Antenna (CRPA). Two example CRPA arrays used for SRGPS testing are shown in Figure 4 and Figure 5[2]. This again requires precise synchronization with the position and attitude observations generated from the inertial simulator. Perhaps the most challenging requirement for a simulator arises when testing high anti-jam Ultra-Tightly-Coupled (UTC) GPS/inertial receivers such as the NAVSYS' High-Gain Advanced GPS Receiver (HAGR-A) shown in Figure 6. This has the capability of using the input inertial data to aid the correlation channels, allowing the I/Q data from the correlators to be integrated over extended periods, improving the signal/noise ratio. Test data collected using the HAGR-A with live satellites (Figure 7 and Figure 8) shows that the GPS and inertial data must be aligned to within a fraction of a cycle on the L1 and L2 signals to accurately represent the live signal environment.

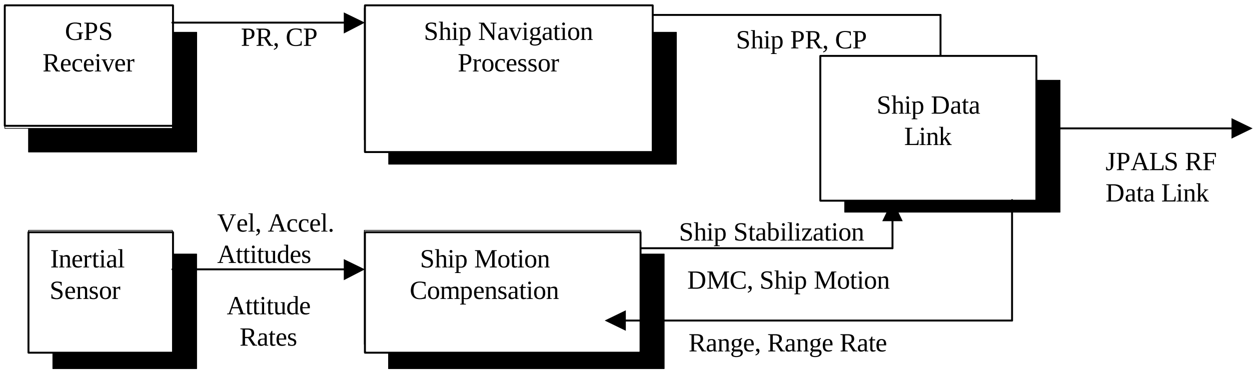


Figure 1 Aircraft JPALS functions

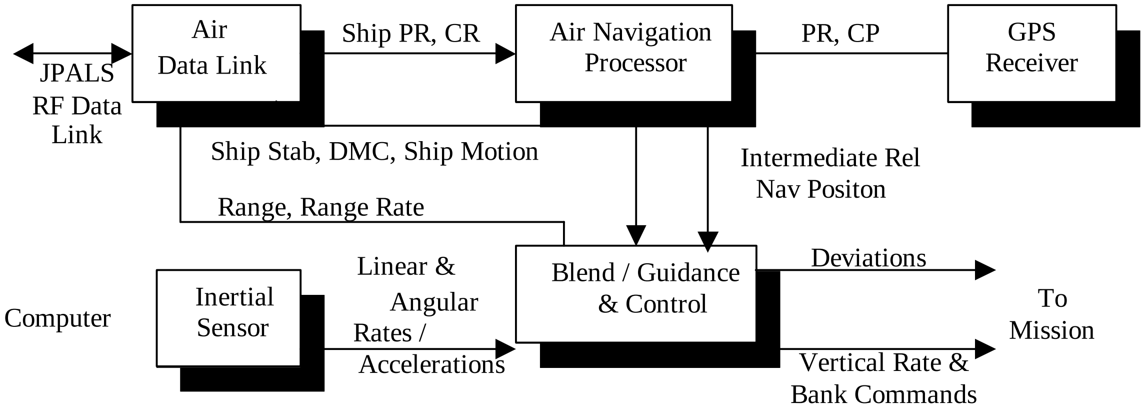


Figure 2 Shipboard JPALS Functions

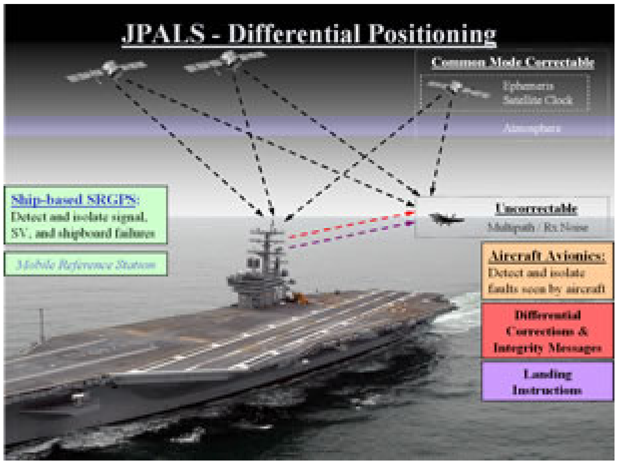


Figure 3 SRGPS JPALS Differential Positioning[3]

Figure 4 CRPA on the Carrier Flight Deck

Figure 5 NAVSYS Prototype 3D 7-Element Antenna Array

Figure 6 HAGR-A Digital Beam Forming UTC GPS/Inertial Receiver

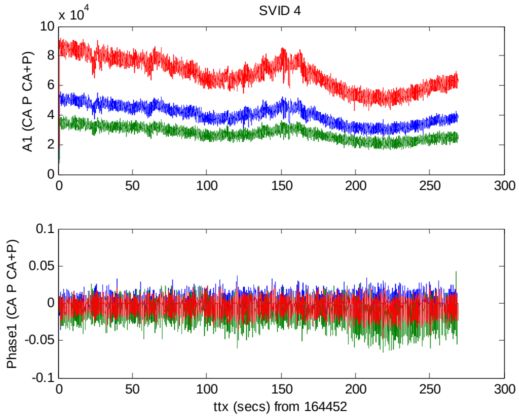


Figure 7 UTC-Aided C/A & P1 Amplitude and Phase (SV 4)

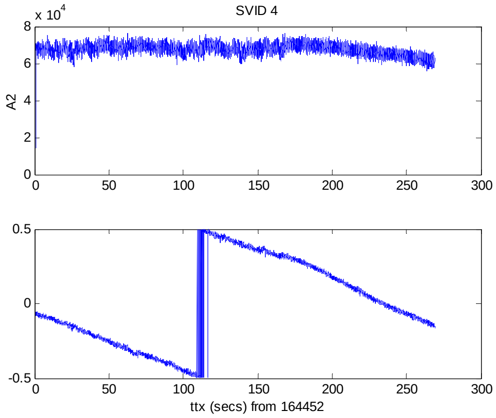


Figure 8 UTC-Aided P2 Amplitude and Phase (SV 4)

INERTIAL MEASUREMENT DATA

An inertial system consists of an instrument assembly and electronics providing the raw inertial measurements from the instruments. A typical inertial system will include three gyroscopes and three accelerometers providing the angular rate (Δθ) and acceleration (ΔV) at the electronics sample rate (e.g. 100 Hz). A major difficulty in aligning the simulated GPS and simulated inertial data to an input trajectory in real time is that highly non-linear equations are involved to solve for the angular rate (Δθ) and acceleration (ΔV) to match the input trajectory. NAVSYS has developed a software package, INSSIM, that performs this non-linear solution generation in real time allowing matched inertial instrument observations to be provided to a GPS/inertial system under test.

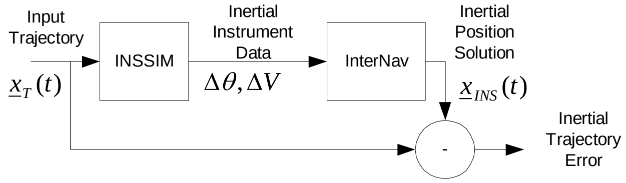


Figure 9 Measuring the Inertial Solution Fidelity

To demonstrate the accuracy to which INSSIM solves for the inertial instrument data, the test case shown in Figure 9 was run. An input aircraft trajectory was provided to INSSIM (Figure 10 to Figure 12) and the instrument outputs assuming ideal observations were used to compute an inertial-only solution using our InterNav inertial navigation software[4]. The difference between the inertial derived navigation solution and the input trajectory was plotted in Figure 13 and Figure 14. This testing showed that the simulated inertial observations provided a solution that matched the input trajectory to within 1 cm and 0.1 mm/sec at all times.

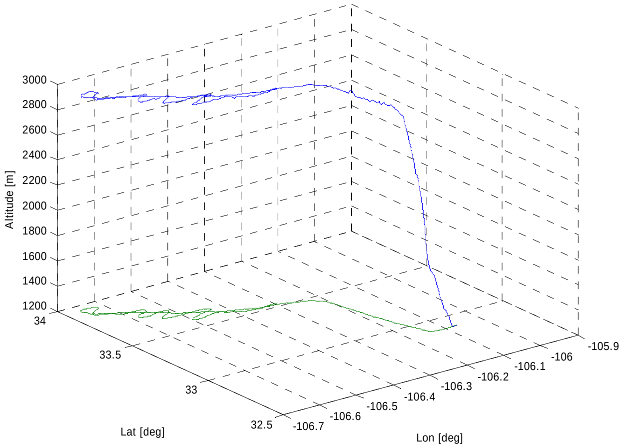


Figure 10 3D Position Trajectory

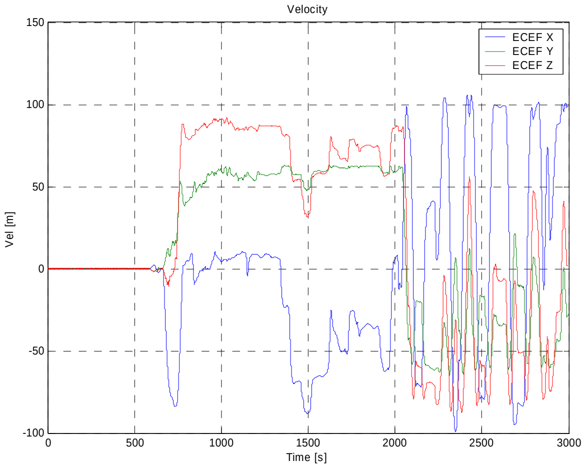


Figure 11 Velocity Trajectory

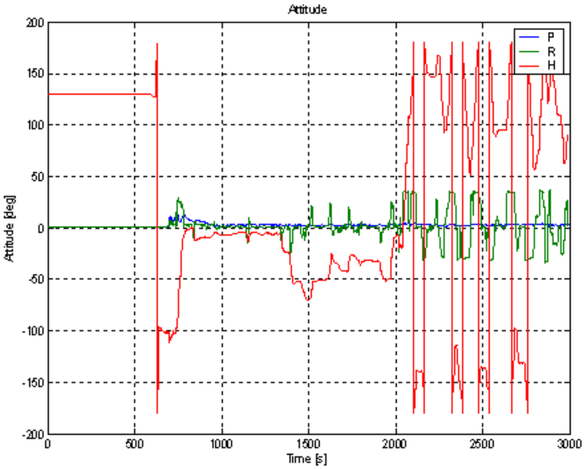


Figure 12 Attitude Trajectory

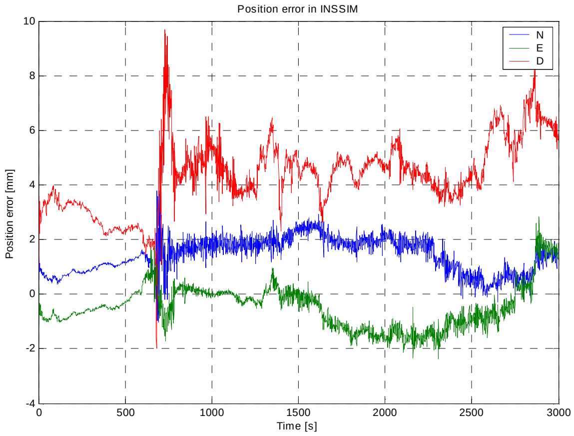


Figure 13 Inertial Position Error

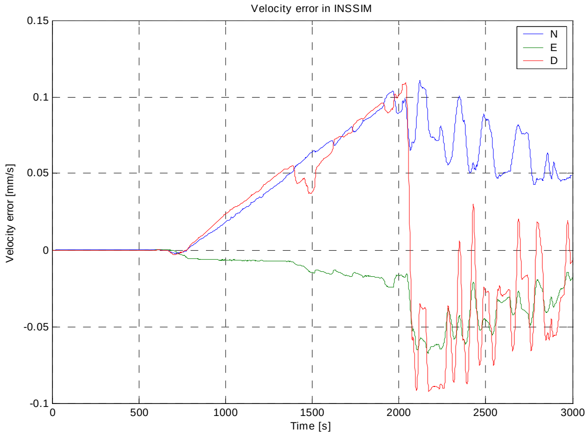


Figure 14 Inertial Velocity Error

AGHS ARCHITECTURE

The precision GPS/inertial simulation capability has been added to our Advanced GPS Hybrid Simulator (AGHS) product. The AGHS 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 15 is capable of simulating 12 GPS satellites simultaneously, and can model any antenna array with up to 8 elements (L1 and L2).

The AGHS hybrid RF/digital simulator approach has the following advantages.

- High and low level software satellite signal generator control using NAVSYS' MATLAB®/Simulink® satellite and signal generation tool box[5]
- Open architecture to allow user access for low level simulation customization
- High speed digital signal generation using a re-programmable logic card for real-time operation

- Software interface for insertion of future GPS signals or simulated jammer waveforms onto composite digital satellite signal profile.
- Digital data storage for exact reconstruction and playback of signal simulation profiles
- Digital output from the simulator of pre-recorded or real-time simulated signals
- High fidelity, phase coherent RF re-modulation of digital signals for output to a GPS receiver
- Wavefront simulation to model 2D and 3D antenna arrays
- IMU simulator outputs for inertial aided navigation systems.

The AGHS software architecture is designed to run under Windows and allows for networked connectivity with external trajectory generation sources, such as Microsoft Flight Simulator. The low-level, time critical functions have been implemented using the RTX real-time-extension to windows using a 1 kHz master clock signal generated by the AGHS firmware as the reference. This reference is generated from either an internal or external 10 MHz reference oscillator, allowing multiple AGHS units to operate together each generating synchronized signals and aiding data.

An example of how multiple units could be connected, for example in simulating an SRGPS JPALS scenario, is shown in Figure 16. Here, two AGHS units are used, one to simulate the signals received at the ship-board units and provide the simulated inertial data provided by the ship's systems into the SRGPS Reference Receiver, and the second unit to simulate the signals received onboard the aircraft and to provide the simulated aircraft inertial data. The SRGPS Reference Receiver can compute the DGPS corrections in real-time and pass these up to the aircraft's receiver where they are applied. The AGHS units and HAGR receivers are also designed to interface in real-time with Simulink through the Ethernet network connection. This allows real-time insertion of modeled errors and also real-time collection and display of performance data throughout the test.

Figure 15 NAVSYS Advanced GPS Hybrid Simulator (AGHS)

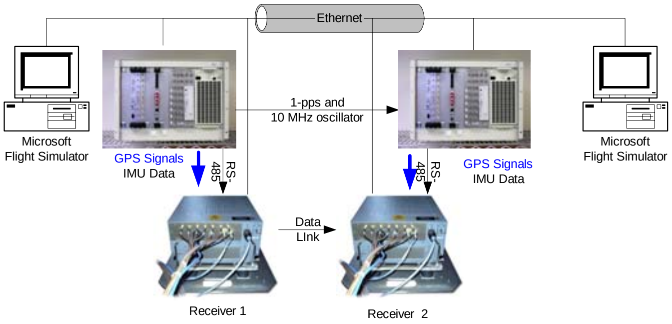


Figure 16 Example Test Configuration with Multiple AGHS Simulators

AGHS INERTIAL SIMULATION CAPABILITY

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. The design was developed to meet the desired capabilities of IGI testing as laid out by STANAG 4572 - Open System Architecture Interface To Enable Simulator Laboratory Test of Integrated Global Positioning System/Inertial Navigation Equipment[6]. This STANAG for an OSA provides a means of substituting simulated IMU data for the actual IMU data in the IGI under test and therefore a method to test all modes of operation of IGIs that is common to allied equipments.

From the error free IMU data, different grades of IMU can be simulated by setting the parameters of the IMU instrument error model (see STANAG 4572 Appendix 2 [6]). There are 98 error parameters under user control, which simulates the accelerometer and gyro behavior induced by bias, scale factor, misalignment, asymmetry, g-sensitivity and mass effect. There are also parameters to simulate the white and correlated noise on the accelerometers and gyros.

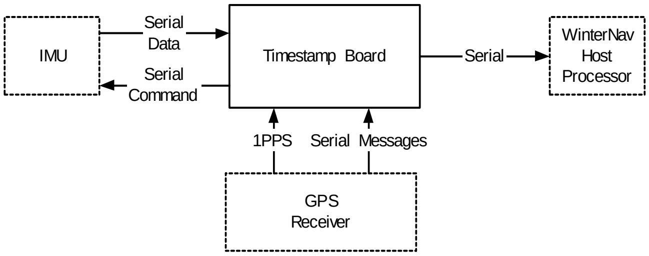


Figure 17 NAVSYS Timestamp Card and IMU Interfaces[7]

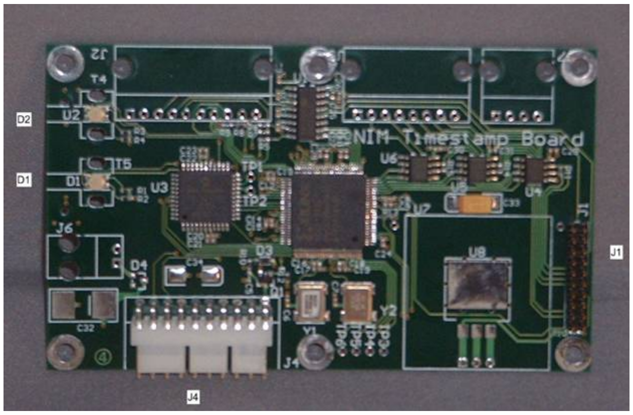


Figure 18 NAVSYS Timestamp and IMU Interface Card

The precise real-time control of the simulator, combined with the sophisticated non-linear INSSIM IMU measurement estimation algorithm, allows the AGHS simulator to match the inertial aided output to an input truth trajectory in real-time. The serial output can easily be modified to emulate different IMU interfaces. NAVSYS has developed a Timestamp board (Figure 17 and Figure 18) designed to interface with different IMUs, add a precise timestamp to their data, and pass the IMU data into the Host Processor through the serial interface using a common message format (see Table 1). Firmware loads have been already developed for this Timestamp board to allow it to operate with the LN-200, HG1700 and NG2000, and MAE MIMU IMUs. The serial interface to the Host Processor includes, in addition to the raw inertial data specified by STANAG 4572, the precise time-tag of the inertial data for coupling into the UTC tracking loops and a checksum. We elected to use this message format instead of the STANAG 4572 definition since it included the precise timetag. Any receiver that is able to interpret this message format could also be integrated and tested with the IMUs supported by the Timestamp board as well as with the AGHS INS simulator.

Table 1 STANAG and Time Stamped IMU Message Definitions

	STANAG Message	**NAVSYS Message**	**Units**
Time Stamp		PacketCount	Count
		TimestampStatus	Status
		1PPS_TimerCount	LSB = 20 micoseconds
		EventTimerCount	LSB = 20 micoseconds
		GPSIntegerSecond	Seconds
IMU Data	X1_GYRO_SIMDTH	X1_GYRO_SIMDTH	LSB = X Radians
	Y1_GYRO_SIMDTH	Y1_GYRO_SIMDTH	LSB = X Radians
	Z1_GYRO_SIMDTH	Z1_GYRO_SIMDTH	LSB = X Radians
	X1_ACCEL_SIMVEL	X1_ACCEL_SIMVEL	LSB = Y m/s
	Y1_ACCEL_SIMVEL	Y1_ACCEL_SIMVEL	LSB = Y m/s
	Z1_ACCEL_SIMVEL	Z1_ACCEL_SIMVEL	LSB = Y m/s
CheckSum	SDLC Error correction	Checksum	

AGHS SIMULINK USER INTERFACE

The AGHS is designed to use Simulink and MATLAB for the user interface, simulated error generation and also to perform real-time analysis on the GPS receiver under test through an Ethernet UDP interface. The simulated trajectory and satellite ephemeris data is passed down to the AGHS simulator in real-time through Simulink allowing flexibility for the user in specifying both the constellation, trajectory and the error models used to perform the simulation. Advantages of using this system to control satellite error generation are as follows:

Adaptability: The user can easily modify the trajectory and error models used to specify the GPS performance

Expandability: Since each error model can be modularized and plugged into the tool on the fly, the satellite error model library can be easily expanded to include additional errors, including satellite trajectory, atmospheric and multipath errors.

Ease of Use: Users can enable and disable single or multiple satellite errors on any satellite that is in view during the simulation, then observe the effect of the error(s) on the navigation solution in real-time.

The satellite error failure module, which resides in Simulink, contains several different types of error models, including step error and ramp error. Users can select and enable different types of satellite errors in real time from Simulink. This input data is transferred to the real-time AGHS simulator box in the format of error messages which are used to generate RF signals containing the range and range rate errors to be inserted onto the satellites. The AGHS Simulink user interface and example plots are shown below.

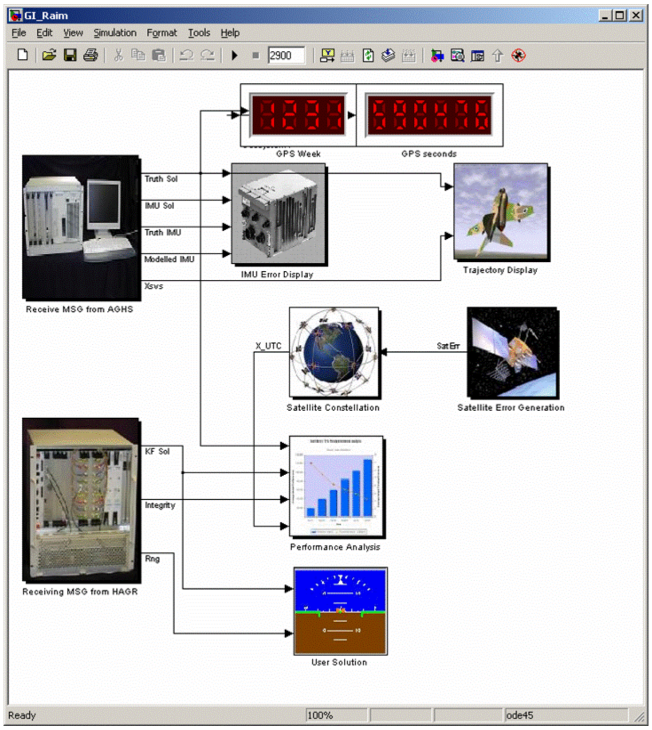


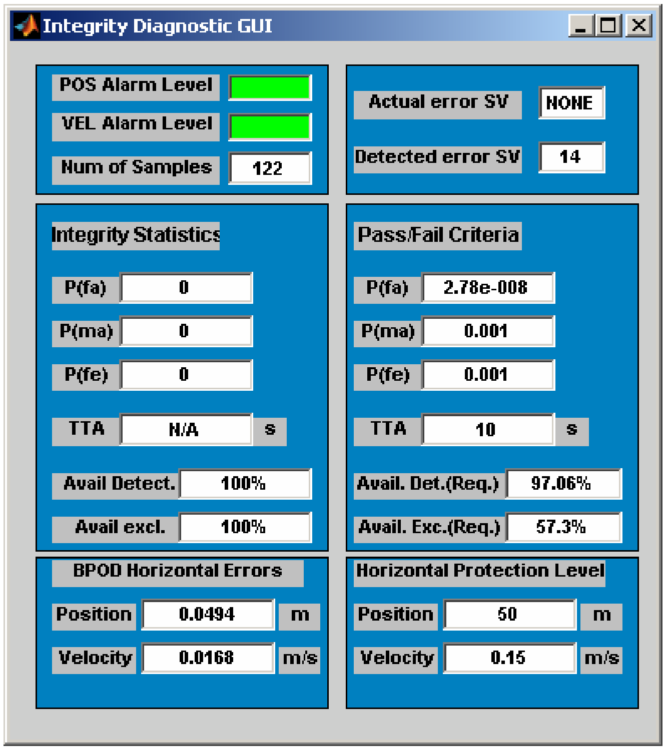
Figure 19 AGHS Simulink User Interface

TEST RESULTS

The AGHS GPS/inertial simulator was used to test the precision of the coherent GPS and inertial simulated data with the HAGR UTC GPS/inertial receiver shown in Figure 6. The RTCA SC-159 GPS/inertial working group developed a set of representative failure mechanisms for testing GPS/inertial integrated integrity performance. Table 2 lists the predicted failure types, the predicted probability, assigned test range and assigned probability from the GPS MOPS[8]. Using a precision GPS/inertial Fault Detection and Exclusion (FDE) algorithm, we have demonstrated with the AGHS GPS/inertial simulator that small range rate errors as low as 0.01 m/sec can be detected and excluded before they can corrupt the integrated GPS/inertial solution. This high precision simulation was needed to allow this remarkable capability to be demonstrated. Figure 20 shows the real-time simulation diagnostics where SV 14 has been identified and rejected as soon as the 1 cm/sec range rate error was added. Figure 21 shows GPS/INS navigation errors from the final solution when compared with the simulator truth trajectory.

Table 2 Summary of Failure Type Probabilities

Predicted MI Failure Type, meters/second (m/s)	Predicted MI Failure Probability in units of 10^{-7}/ hour/satellite	Assigned Test Range	Assigned MI Failure Probability in units of 10^{-5}/ hour/satellite
Ramp 0.01 m/s	2	Ramp 0.01-0.05 m/s	2/29
Ramp 0.1 m/s	1	Ramp 0.05-0.25 m/s	1/29
Ramp 0.5 m/s	3	Ramp 0.25-0.75 m/s	3/29
Ramp 1.0 m/s	10	Ramp 0.75-2.5 m/s	10/29
Ramp 5.0 m/s	12	Ramp 2.5-5.0 m/s	12/29
Step 300 meters	1	Step 300-700 meters	1/29
Step 3000 meters	34	Step 700-3000 meters	N/A



POS Alarm Level 🟩

VEL Alarm Level 🟩

Num of Samples 122

Actual error SV NONE

Detected error SV 14

Integrity Statistics

P(fa)	0	
P(ma)	0	
P(fe)	0	
TTA	N/A	s
Avail Detect.	100%	
Avail excl.	100%	

Pass/Fail Criteria

P(fa)	2.78e-008	
P(ma)	0.001	
P(fe)	0.001	
TTA	10	s
Avail. Det.(Req.)	97.06%	
Avail. Exc.(Req.)	57.3%	

BPOD Horizontal Errors

Position	0.0494	m
Velocity	0.0168	m/s

Horizontal Protection Level

Position	50	m
Velocity	0.15	m/s

Figure 20: Integrity Diagnostic Display showing Detection of SV 14 with 1 cm/sec error

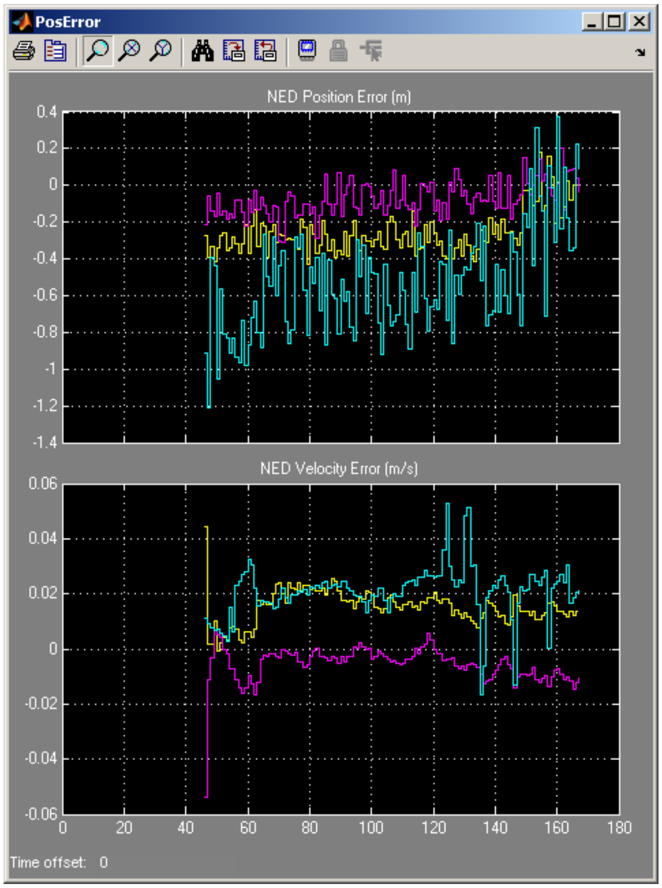


Figure 21: GPS/INS Position/Velocity Errors

CONCLUSION

The integrated GPS/inertial Advanced GPS Hybrid Simulator described in this paper has been demonstrated to have the high fidelity observations needed for precision GPS/inertial applications. This includes Ultra-Tightly-Coupled GPS/inertial testing and kinematic GPS/inertial positioning for applications such as SRGPS JPALS. In addition, the AGHS will provide precision GPS wavefront and jammer simulation for anti-jam testing. The networked architecture developed allows multiple GPS simulators and receivers to be simultaneously operated. When integrated with our AGHS Simulink real-time user interface, real-time diagnostics and testing can be performed. The level of automation provided by Simulink facilitates setting up detailed test scenarios and running and analyzing data for multiple test cases, such as is required for RTCA DO-229C certification of GPS/inertial systems[8].

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REFERENCES

[1] P. Bruner, R. Breslau, "Use of Inertial Reference Data to Support Differential GPS For Carrier Landing," Proceedings of ION 57th Annual Meeting 2001, Albuquerque, New Mexico, June 2001
[2] A. Brown and B. Mathews, "GPS Multipath Mitigation Using a Three Dimensional Phased Array:, Proceedings of ION GNSS 2005, Long Beach, California, September 2005
[3] http://waas.stanford.edu/research/jpals.htm
[4] InterNav Modular GPS/Inertial Software
[5] http://www.mathworks.com/
[6] STANAG 4572 – Open System Architecture Interface to Enable Simulator Laboratory Test of Integrated Global Positioning System/Inertial Navigation Equipment, Version G
[7] NAVSYS NIM Timestamp Board Specification and ICD, NAVSYS Document No. Timestamp Board-04-001, Rev 6, January 30, 2005
[8] "Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment," RTCA/DO-229C, November 28, 2001.