GPS Receiver Testing Issues and Techniques

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BIOGRAPHY

Kenea Maraffio received her BS in Electrical Engineering from Arizona State University in 1990. Employed by NAWCWPNS, China Lake, in 1991, she worked on development of phased-array antenna control software and radome compensation algorithms. In 1993, she developed software for real-time remote control of the Stanford Telecom 7200 GPS satellite simulator. Kenea is currently manager of the Navigation Laboratory, which is part of the Navigation and Data Link Section, NAWCWPNS, China Lake, Calif.

ABSTRACT

Characterization and system integration of GPS receivers requires the use of complex hardware-in-the-loop test environments running satellite signal simulators and other dynamic simulations. These test environments are expensive to purchase and maintain. NAWCWPNS has developed a distributed processing methodology using computer networking to reduce the expense of GPS receiver characterization and integration. NAWCWPNS customers now have the option of performing tests on-site or at a local site separate from the Navigation Laboratory.

This paper begins with an overview of the types of GPS receiver tests and the issues associated with those tests. Then, descriptions of the Navigation Laboratory and the techniques it incorporates to resolve these issues are given as a case study of the distributive processing test environment. Laboratory enhancements being developed in response to broadening customer needs is also included. The paper concludes with a summary of GPS satellite simulator lessons learned.

INTRODUCTION

In the late 1960s and early 1970s the Navigation and Data Link Section (then the Inertial Development Branch) funded research and development of new technology for inertial guidance sensors and systems. The focus was development of software and ring laser gyros for advanced navigation systems on Navy attack aircraft.

The group was first introduced to Navigation System with Timing and Ranging (NAVSTAR) Global Position System (GPS) in the mid-1980s while providing navigation system engineering support for the Standoff Land Attack Missile (SLAM) program. In the early 1990's, the section procured a GPS satellite simulator in anticipation of future missile programs integrating GPS receivers into their navigation systems.

In 1993, F/A-18 funded an effort to use the group's GPS satellite simulator to perform distributed integration testing of the Miniature Airborne GPS Receiver (MAGR) in conjunction with the Weapons Software Support Activity's (WSSA) hardware-in-the-loop (HWIL) simulation. Completion of this effort in 1994 now allows the F/A-18 WSSA, located approximately 5 miles away, to use the GPS satellite simulator in their HWIL as though it were collocated within their facility.

The Navigation Laboratory (NavLab) continues to enhance its capabilities to meet new customer needs and broadening test requirements of current customers. Knowledge about receiver testing issues and methods gained from these and continuing efforts, is presented in this paper.

TYPES OF GPS RECEIVER TESTING

A variety of GPS receivers is available for a multitude of applications. They range from C/A-code carrier phase receivers for precise surveying to Y-code receivers for military use. However, for testing purposes, GPS receivers fall into two broad operational categories: stand-alone and integrated. Stand-alone receivers operate without the benefit of external aiding from ancillary navigation sensors. Integrated GPS receivers act as intelligent sensors, integral to a closed-loop navigation subsystem. For stand-alone receiver operation, knowledge of receiver characteristics is desired. When used as part of an integrated navigation system, how the receiver operates as part of the entire system is the concern. Descriptions of these testing categories follow.

GPS Receiver Characterization Testing

GPS receiver characterization is the detailed examination of a receiver's performance in a stand-alone, controlled test environment. The rest of the host platform's system is not part of the test environment. Receiver characterization is normally conducted in real time but not closed loop. The usual reasons for receiver characterization are to verify compliance with its specifications or to determine the margins of compliance. Only the receiver's specifications are considered. Typically, the receiver is given extreme input stimulus while noting performance degradation or failure.

GPS Receiver Integration Testing

How the GPS receiver operates as part of the navigator in conjunction with the host platform is of paramount importance. Receiver integration testing considers how the receiver performs as an integral part of a total navigation system. A typical HWIL setup for receiver integration testing is shown in Figure 1.

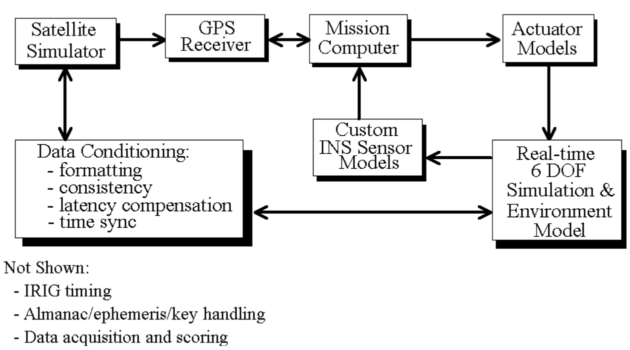

Figure 1. GPS Receiver Integration Test Set-Up

Two important aspects of receiver integration testing are real-time stimulation and closed-loop operation. These two aspects allow examination of the subtle intricacies of subsystem interactions and estimation of entire system performance.

Real time means stimulating the system under test at its defined operating speed. This stimulation allows normal system execution so that timing between components can be verified.

Closed-loop testing feeds generated outputs back so that they can be used to modify future inputs. An example will help to clarify the necessity of closed-loop simulation. If a precision guided missile's navigation system is to be tested, the following method might be used. A predefined course trajectory is loaded into the mission computer. Initial course parameters and sensor inputs are given to the 6-degree-of-freedom (DOF) trajectory generator. During simulation, the 6-DOF generator feeds trajectory information to the inertial navigation system (INS) sensor models and the satellite simulator's data condition computer. The satellite simulator receives the trajectory data and generates the appropriate signals for the GPS receiver. The mission computer obtains location and velocity information from the GPS receiver and INS models. The mission computer compares this information with the desired course trajectory. If a course correction is required, the mission computer updates the fin actuator model. The output from the actuator and environmental models are fed back to the 6-DOF causing a modification to the course trajectory. A predefined 6-DOF trajectory that does not compensate for sensor input (i.e., open-loop simulation) prevents the platform under test from responding to its own calculated guidance commands. Closed-loop simulation provides the feedback necessary for more complete system testing.

GPS Receiver Distributed Integration Testing

Distributed integration testing with GPS receivers is the same as normal receiver integration testing, except that all parts of the HWIL are not collocated. Simulation processing is distributed throughout the HWIL and synchronized via a common clock reference. For example, the GPS satellite simulator may be located at one test facility while the mission computer, 6-DOF generator, and system models are positioned at a remote site. Distributed integration testing increases HWIL programming complexity, but duplication of facilities is eliminated.

GPS RECEIVER TESTING ISSUES

Each type of GPS receiver testing has technical and operational issues that must be addressed. Some of these issues and viable solutions follow.

General Testing Issues

The following issues are common to GPS receiver characterization, integration and distributed integration testing.

GPS Satellite Simulator. Almost any type of GPS receiver testing requires the use of a GPS satellite simulator. These simulators replicate transmitted RF signals from satellites visible at a receiver's location. Typically, GPS satellite simulators are delivered equipped to do receiver characterization testing. They usually have some form of a trajectory profile generator, data collection, analysis capability, and an operator interface that allows modification of power levels, the navigation data message, antenna gain patterns, body masking, etc. If INS models are provided with the satellite simulator, a custom interface with the receiver under test will be required to use them.

If the simulator is to be used for integration testing, an external control computer must be interfaced to it. This computer will perform the functions shown in the data conditioning block of Figure 1. The simulator manufacturer should supply an interface control document (ICD), describing the physical interface, protocol, and data formats necessary for external control.

As of June 1996, the more affordable, 10- to 12-satellite, Y-code-capable satellite simulators are selling for approximately $300,000. The initial capital outlay for a simulator is perhaps the smallest cost associated with owning it. Simulators are complex and require detailed technical knowledge of the simulator, GPS signal structure, GPS navigation data message, and testing methods to ensure proper use. Custom interfaces must be developed or purchased if more than receiver characterization is desired. Characterized GPS receivers and associated monitoring equipment are necessary for quality control.

RF Radiation and Receiver Antenna. Normally the signal is fed via cable to the receiver's RF front end during test, bypassing the antenna. Signals cannot be broadcast because of the possibility of affecting equipment other than the receiver under test. Hence, the antenna is not exercised in the simulation. Commonly, the antenna is modeled instead by antenna gain patterns and body-masking compensation. A shielded anechoic chamber is required for RF radiation if the antenna is to be included in the test. The resulting tests are complex and costly, since chamber time tends to be expensive.

Data Consistency. When driving simulators with trajectory data generated from 6-DOF models, creating scenarios that defy the laws of physics is possible. Some examples of physically impossible scenarios are “teleportation” and “fast hovering.” Teleportation allows a platform to instantaneously appear anywhere without regard to its previous location or current velocity, acceleration, etc.; fast hovering occurs when location does not change, yet the platform has a non-zero horizontal or vertical velocity.

Inconsistent data may cause erroneous output from the simulator. The dilemma is which input parameter is taken as truth: jerk, acceleration, velocity, or position? Some simulators take input acceleration or jerk, and integrate several times to obtain velocity and position. These may be employed to validate user input. If the current input data are not consistent with the derived data, they may be ignored. Other simulators may take position as truth and attempt to perform teleportations by moving to that position as quickly as possible. However, since some finite amount of time is required to do so, output RF data will not be correct. Also, the pseudorange errors may be large, since the difference in computed system position and actual system position may be substantial.

Anticipating these problems, China Lake developed a filtering algorithm to ensure that input user data forms a self-consistent set. A detailed analysis of this algorithm with source code is given in China Lake Technical Memorandum 7762.[1]

Validation. Validation is the establishment of quality-control methods to provide quality assurance of the laboratory. Validation is required to *consistently* yield test data with minimal error. The complexity of GPS satellite simulators and the low power levels of the spread-spectrum GPS signals make this a very problematic issue. Still, several things can be done to ensure integrity of the test.

First, when developing test capabilities, build validation into the design process. Emphasize and make provisions for monitoring system parameters. Some parameters of particular interest are satellite simulator pseudorange error estimates and status flags.

Second, use quality components when implementing the design. Examples of things to consider are low-loss cables, high-caliber signal generators, and high-fidelity receivers.

Third, verify design implementation. This verification should be done at the component and system level. Test the components before integrating them into the system. System validation can be accomplished by supplying known scenarios and assessing end-to-end results.

Finally, enforce validation in daily operation. Have procedures and check lists in place to ensure correct operational steps are taken. For example, did the rubidium oscillator have enough time to warm up? Do observable system parameters fall within specified bounds?

Data Collection and Analysis. Data collection is typically used for three functions: troubleshooting, validation, and analysis of test results. Correlation of data is necessary for all three functions. Correlation requires identifying, time-stamping, and logging (formatting and recording) all data entering and leaving every portion of the test configuration. This procedure permits time-tracking data, commands, and results throughout the system. When troubleshooting, this procedure is crucial for locating timing and performance problems. Validation is concerned with monitoring test system observables that may indicate operational problems. Some parameters that may indicate degraded test system performance are simulator output power; pseudorange; delta pseudorange; C/A-, P-, or Y-code mode indication; and jammer output power levels. Collecting test data for analysis depends on parameters under investigation. However, some of the common types of data collected are test run identifier, trajectory truth data, receiver position, receiver velocity, receiver status, INS position, and INS velocity. In all data collection functions, formatting the data so that it is readable by commercial analysis packages such as MATLAB[TM] is desirable. This formatting eliminates in-house development of plotting and analysis tools and enables wider dissemination of data.

GPS Receiver Integration Testing Issues

Issues of concern for GPS receiver integration and distributed integration testing follow.

GPS Satellite Simulator Interface and Data Formatting. Using trajectory generators external to the GPS satellite simulator means that an interface to the simulator must be developed. Software must be developed to convert control commands and 6-DOF data from the external trajectory generator to the required format delivered via the protocol specified in the simulator's ICD.

Time Synchronization. Some GPS satellite simulators require new data be sent to them at specified update intervals. Often a small window of time exists in which the simulator can receive these data. Dispatching the data too early or late, or skipping an update can cause degraded accuracy or force the simulator to stop. A few of the newer simulators require an update only when the user's trajectory changes. Still, the data cannot be fed at a rate greater than that specified by the manufacturer.

Certain simulators require the data they receive to contain a time stamp. This time stamp tells the simulator when the data are to be used in the simulation. Since in real-time operation a late answer is a wrong answer, if the data's time stamp is behind the current simulation time, the simulator may discard it. Thus, the data must be synchronized with the simulation time dictated by the satellite simulator.

A satellite simulator requires a high-precision oscillator (e.g., rubidium, cesium) just like the real NAVSTAR satellites. Simulation time generated by the simulator is referenced to this oscillator. Because of its high-precision and stability, the oscillator is an excellent synchronization standard for collocated equipment. However, an external standard must be provided for equipment not located near the satellite simulator. The external standard must have enough precision to prevent time slippage with respect to the GPS satellite simulator.

Laboratories at China Lake commonly synchronize systems by using Inter-Range Instrumentation Group (IRIG) receivers and time code generators that supply an IRIG-B time-stamp. Current IRIG generators are typically GPS timing receivers that output time in IRIG format. Since the GPS frequency accuracy of an IRIG generator is 10^{-9} parts per million (PPM) and rubidium oscillators have a frequency accuracy of 10^{-11} PPM, maintaining synchronization with these two standards is not an issue. A simulation could run for well over a year without any detectable drift between simulation segments synchronized to a rubidium oscillator and those synchronized with IRIG (i.e., GPS) time.

Data Latency Compensation. Some delay always occurs between the time data or a control command is fed to a system and when an output response is detected. When performing real-time simulations, compensation must be made for this data latency. Otherwise, the correct data will not be applied at the appropriate time to subsequent systems. Two different methods can be used to approach this problem: slow down other portions of the simulation to match the longest latency or use the latency time to predict output ahead of time.

Slowing down other portions of the simulation to wait for the data may be computationally more accurate, but does not reflect real-time operation of the system. The waiting time will vary somewhat during the simulation as a result of imprecise clocks, different processing times for various portions of code, etc. Adjusting the delay during simulation can be difficult.

Prediction may not be as accurate as waiting, but fidelity can be improved with fast, sophisticated algorithms. Prediction works by forecasting the output by the amount of latency incurred. Thus, when new input data are applied, the output appears to instantaneously reflect this change in input. Time-stamped data in a synchronized

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simulation will allow real-time determination of latencies and adjustment of the amount of prediction required.

Custom Receiver Interface for Inertial Aiding. Since the method of supplying INS aiding data varies from receiver to receiver, a custom interface is usually required to get those data to the receiver. Also, correct timing must be ensured so that the 6-DOF data given to the INS sensor models generate aiding output correlated to the RF output from the satellite simulator.

GPS Receiver Distributed Integration Testing Issues

Issues that are unique to GPS receiver distributed integration testing are discussed below.

Network Data Latencies. Depending on the client's distance from the test facility, network data latencies could become a significant factor. Latency compensation methods become crucial. If the slowing down method is used, the wait time can become excessive. If the prediction method is used, the amount of time predicted ahead is increased, causing decreased fidelity in the output. A case-by-case analysis should be performed to determine if the data path latencies are acceptable.

Collocation of Receiver Near GPS Satellite Simulator. The receiver under test must reside near the satellite simulator because of the effect of signal loss through the RF cable on the already small GPS signal. For the remote user, this means a receiver interface must be developed for access from their location. This requirement can be problematic, if INS aiding is to be provided to the receiver. If the client provides the INS aiding data, then he or she must ensure the correct timing of the data to correspond with the appropriate RF output. Thus, the client must implement one of the two latency compensation methods mentioned. Otherwise, a shared receiver interface must be devised to allow local INS aiding and remote receiver access.

Security. Jamming characteristics of a Y-code receiver is of great concern to the military community. As such, any information associated with this type of testing cannot be sent across the communication link without protection. The most reasonable solution is the use of a network encryptor. However, delays will be introduced by the encryption process. Again, data latency compensation methods must be adjusted to account for these latencies.

Another approach would be to download an entire scenario to the laboratory via the communication channel. The client then disconnects and allows the simulation to be run completely within the laboratory. The results can then be shipped back to the client by any approved secure method. However, receiver characterization instead of integration testing is now being performed since real-time, feed-back control is no longer available.

CASE STUDY: NAVIGATION LABORATORY

The NAWCWPNS NavLab illustrates some working solutions to the issues presented. This multifaceted laboratory, located in a secure facility, has three interrelated sections: (1) Inertial Navigation, (2) Differential GPS, and (3) GPS Receiver Characterization and Integration Test. Aspects of each section are discussed in the following paragraphs.

Inertial Navigation Section

The Inertial Navigation Section supports INS performance analysis and characterization. These characterizations may form the basis of INS software models used in GPS receiver tests and other end-to-end simulations. The Inertial Navigation Section has a three-axis Contraves environmental rate table, two single-axis Contraves environmental chambers (a horizontal and a vertical), granite blocks for measuring gyro drift, and a Faraday shielded shake table for vibration effects.

Differential GPS Section

The Differential GPS Section, which supports navigation performance analysis, operates several differential GPS reference stations (DGPSRS). An Allen Osborne Associates (AOA) high-precision carrier-phase receiver is used as one of the base stations. This receiver is the lowest noise one on the market. Accuracy of test results is almost totally dependent upon the user's equipment. The AOA is mainly used for high-dynamic time-space-position-information (TSPI) applications. However, the receiver, which can also be used to validate the GPS satellite simulator, allows access to pseudorange and delta pseudorange measurements for each satellite. Thus, each channel of the satellite simulator can be monitored in real time by this high-fidelity receiver.

Another DGPSRS operates as a Satellite Reference Station in the Holloman Test Support Network (TSN). This network provides TSPI truth reference data in support of test programs throughout the continental U.S., supporting tests within a 375-mile radius. The Differential GPS Section has a Rockwell Collins five-channel code-phase 3A receiver. This receiver tracks satellites, computes pseudorange and delta pseudorange corrections, and stores those corrections as well as raw data to disk. These data are post-processed to yield an accuracy of 2 to 3 meters.

GPS Receiver Test Section

The GPS Receiver Test Section is unique in that distributed integration testing of GPS receivers can be performed via ethernet. The potential cost savings for customers exercising this test option are substantial, since they do not bear the burden of purchasing and maintaining costly test equipment or the associated technical expertise.

The GPS Receiver Test Section has a PC-based client/server, distributed processing architecture. This modular design eases integration of new test equipment. All real-time server software is window driven, MS-DOS™ based, C and C++ code. Servers that are not real time are written in LabView™ operating under Windows NT™.

As can be seen from Figure 2, jamming is accommodated via the Jammer Subsystem. However, since the NavLab does not currently have a network encryptor, distributed integration testing using jamming is not available; but general Y-code distributed integration testing is certified at the facility. Signals of the GPS satellite simulator and Jammer Subsystem are accessible through a patch panel, which allows a high degree of observability and rapid reconfiguration of system parameters for varying customer needs.

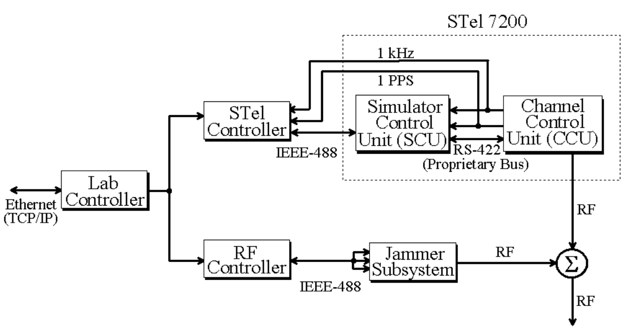

Figure 2. GPS Receiver Test Section Functional Block Diagram

Components of the GPS Receiver Test Section. Functional descriptions of GPS Receiver Test Section components follow.

Stanford Telecom Model 7200 GPS Satellite Signal Simulator (SSS). The STel SSS, core of the GPS Receiver Test Section, consists of the Simulator Control Unit (SCU) and the two Channel Control Units (CCUs). The CCUs are the RF chassis of the SSS capable of transmitting C/A-, P-, and Y-code signals from up to 10 satellites[2].

The SCU is a PC-based system that uses a Vertex™ real-time operating system. The main function of this system is to provide an interface to the simulator. The two different ways of interfacing to the SCU are local and remote. Local control is effected by the man-machine interface and keyboard use. A complete description of local capabilities can be found in the user's manual[3]. Remote control is accomplished via IEEE-488 with the SCU acting as bus master[4]. In either control case, the two main modes of operation are Test and Trajectory.

In Test Mode, the user is burdened with satellite parameter computations. Some of the parameters the user must supply for each satellite are range rate, acceleration, jerk, ionospheric delay rate, and output power level.

In Trajectory Mode, the simulator computes all of the necessary satellite parameters (e.g., geometries, power levels, pseudoranges) based on the platform's trajectory data. If antenna effects are desired, then body masking, antenna gain pattern, attitude direction cosines, and so forth are also required. Using antenna modeling in Trajectory Mode limits the maximum data update rate to the SCU to 100 ms (i.e., 10 Hz). However, the data must be submitted 2.5 update intervals before they are to be applied. Thus, the data latency of the simulator is 250 ms.

STel Controller. This server handles all of the issues shown in the data-conditioning block of Figure 1. The STel Controller interfaces to the SSS via the SCU using the IEEE-488 interface. A problem was encountered with the National Instruments' IEEE-488 interface card when the server would not accept interrupts while operating as a bus slave. Thus, arrival of asynchronous messages from the SCU could not be noted via interrupts. To resolve this issue, the IEEE-488 port is checked for data before sending messages to the SCU and when time permits. A driver could be written for the NI-488 card that would enable interrupts while operating as a slave.

Currently, trajectory data can be submitted to the STel Controller at a maximum rate of 20 Hz. Since the SSS is used in Trajectory Mode with antenna modeling, its maximum data-update rate is 10 Hz. Thus, some trajectory data are not given to the SSS.

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Even though some data may not be sent to the SSS, the data-consistency filter is applied to all trajectory data received by the STel Controller. This procedure enables a more accurate prediction, since it limits the trajectory to realistic values based on historical input.

The STel Controller performs prediction to compensate for data latencies in the system. This procedure frees the client from the programming burden associated with slowing his or her system down to wait for data. The STel Controller is synchronized to the simulator via the 1-KHz output derived from the 5-MHz rubidium oscillator in the CCU. This signal increments a counter every 1 ms until the specified update interval of 100 ms is reached. At that time the last filtered data set received is predicted, formatted, and sent to the SSS via IEEE-488. The 1-pulse-per-second (PPS) output signal from the CCU disciplines the oscillator of an IRIG card in the STel Controller. The output from this card is used for data time-stamping and prediction time estimation. The amount of time compensated for in the prediction is computed as

Tpred = (current simulation time - time when data were generated) + SSS latency time.

NOTE: Current simulation time minus the time when the data were created compensates for path delays from the client through the SSS. However, latencies from the receiver back to the client must be compensated either by the client or an estimate of latency given to the STel Controller for inclusion in the prediction time equation.

Jammer Subsystem. This subsystem gives the NavLab a full spectrum of GPS jamming techniques. The following jamming configurations are available:

1. Narrow-Band (NB). NB jamming is generated from a pseudorandom noise sequence of 2-MHz bandwidth centered on the desired L1 or L2 frequency.
2. Wide-Band (WB). WB jamming is generated from a pseudorandom noise sequence of 20-MHz bandwidth centered on the desired L1 or L2 frequency.
3. Continuous Waveform (CW).
4. *Pulsed NB, WB, and CW*. Each of the previously described jamming signals can be pulsed at a maximum pulse repetition frequency (PRF) of 50 KHz.
5. FM Swept. FM swept jamming can be implemented, if a function generator is added to act as the frequency sweeper.

Additionally, any of the above jammer configurations allow offset of the L1 or L2 center frequency by a maximum of +/- 10 MHz.

As shown in Figure 3, the Jammer Subsystem consists of two RF signal generators and an arbitrary waveform generator (AWG). These generators can be controlled manually from their respective front panels or remotely via IEEE-488. The two-channel AWG has the ability to create the IF jamming signal in either the time or frequency domain. The IF signal is used to modulate the L1 and L2 carriers from the RF signal generators.

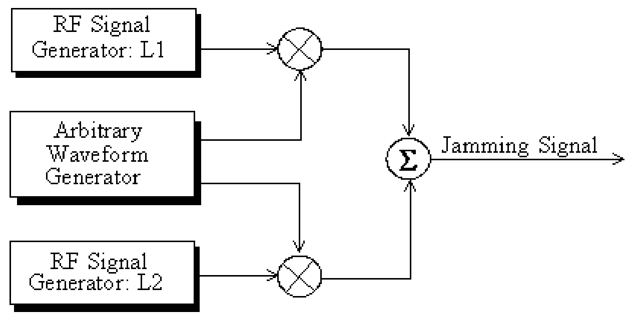

Figure 3. Jammer Subsystem Functional Block Diagram

RF Controller. As shown in Figure 2, this LabView-based server provides an interface to and enhances the capabilities of the Jammer Subsystem. Trajectory data and control commands are received from the Lab Controller via ethernet. These commands are used to control the RF signal generators and AWG using IEEE-488. How the data are used depends on the jamming mode of operation.

In Mode 1, the user specifies the desired jam-to-signal ratio (J/S) at the receiver's input. The RF Controller performs all the calculations necessary to keep the J/S level constant throughout the simulation. The following parameters must be defined for each jammer bandwidth:

1. Jamming Type. Jamming choices are CW, NB, and WB.
2. Pulsed Jamming. The user must indicate if pulsed jamming is desired.
3. PRF. If pulse jamming was specified, then the required PRF must be given. The maximum PRF is 50 KHz.
4. Center Frequency Offset. A maximum offset of +/- 10 MHz from the L1 or L2 center frequency may be specified.
5. J/S Level. The maximum J/S level is 120 dB.

In Mode 2, the J/S level at the receiver input varies according to parameters controlled by the client. In addition to parameters 1 through 4 given in Mode 1, the user must define the following for each jammer bandwidth:

1. Number of Jammers. A maximum of four jammers per bandwidth may be specified.
2. Jammer Output Power. The maximum output power that can be specified is 100 KW.
3. Jammer Location. Earth-centered earth-fixed coordinates must be specified for each jammer.

The RF Controller has a very flexible design that allows it to be commanded to any mode at a 1-Hz rate. This design allows the user to simulate dynamic jammers with a variety of different characteristics or let the controller take care of all computations to provide a desired J/S. Also, all capabilities associated with remote control are available locally via the LabView interface.

Lab Controller. As can be seen from Figure 2, the Lab Controller is the central server where clients login. The client establishes a Transmission Control Protocol/Internet Protocol (TCP/IP) connection, identifies himself or herself, and requests specific laboratory configuration parameters be set. (TCP/IP is a point-to-point protocol that ensures all data transmitted will be received). The Lab Controller verifies that the client is a valid user, configures the laboratory as requested, returns a status message, and enters an idle state awaiting input from the client. After the laboratory is configured, the client is free to start the simulation. Once the simulation has started, the client must send trajectory data at a rate no greater than 20 Hz. During simulation, the client may asynchronously request status, manipulate the jammers, or send a stop simulation message. A complete description of the laboratory interface is contained in the NavLab's ICD[5].

In addition to being the central server for clients connecting to the laboratory, the Lab Controller itself is a client to the STel and RF Controllers. During configuration, the Lab Controller establishes TCP/IP connections to each server controller as well as a broadcast User Datagram Protocol (UDP) connection. (The UDP protocol has limited handshaking and does not guarantee that all data sent will arrive.) The TCP/IP connection is used for sending messages whose delivery must be guaranteed (e.g., control commands and status messages). The UDP connection is used for broadcasting trajectory data during simulation.

The Lab Controller may also run in a local configuration. In this mode, the Lab Controller can parse trajectory files and send the data to the STel and RF Controllers at a 20-Hz rate.

Other Components Not Shown. The following items are not shown in Figure 2 but are necessary components of the GPS Receiver Test Section.

1. Validation Receivers. A VR2 GPS Timing Receiver from JCT Consulting monitors SSS calibration. A characterized Precision Lightweight GPS Receiver (PLGR) with a LabView interface to the instrumentation port (IP) monitors SSS output before the mixer that adds the jamming signal. Monitoring SSS output at this point allows simulator data logging even when the receiver under test loses lock as a result of jamming input. The Allen Osborne Associates receiver can be used to measure individual channel data when it is not being used for differential base-station activities.
2. Data Collection and Analysis. Troubleshooting data are collected by each controller via time-stamping and local logging of all incoming and outgoing data. Software has been developed that pieces the data together sequentially in time. Validation and analysis data are collected from the following: (1) a high-quality RF spectrum analyzer that is monitoring the Jammer Subsystem, (2) a characterized PLGR receiver collecting ICD-GPS-153 data, and (3) a characterized Trimble TANS C/A-code receiver collecting almanacs, ephemeris data, and navigation solutions.
3. Trajectory Profile Generators. The NavLab has two trajectory profile generators capable of creating data to drive the STel simulator: PROFGEN and the STel User Motion Generator (UMG). PROFGEN generates position, velocity, acceleration, attitude and attitude rate over an ellipsoidal earth. PROFGEN is capable of generating four types of maneuvers: vertical turn, horizontal turn, sinusoidal heading change, and straight flight.[6] The UMG can generate platform position, speed, altitude, bank angles, turn radii, Coriolis force, specific force, gravity and earth rotation in the WGS-84 reference frame. However, the UMG cannot generate trajectories that involve inverting the vehicle.[7]

4. INS Models. Currently, all NavLab HWIL customers prefer to use their own INS models for GPS receiver aiding. However, the NavLab does have a validated strapdown INS model in which the gyro and accelerometer sensor errors can be easily modified. This model can be integrated into the GPS Receiver Characterization and Integration Test Section, if desired.
5. Almanac Availability. Since GPS receivers and satellite simulators require almanac data during testing, the Navigation and Data Link Section maintains a receiver that logs these data every hour. Current and archived almanacs can be accessed via the section's home page on the World Wide Web (http://sirius.chinalake.navy.mil). Also located there is a satellite prediction program, an internet mirror of Holloman's GPS bulletin board, and links of interest to GPS users.

GPS Receiver Testing Techniques. All types of GPS receiver testing can be performed with the flexible design of the GPS Receiver Test Section.

GPS Receiver Characterization Testing. Receiver characterization testing requires collocating the GPS receiver in the NavLab as shown in Figure 4. Not shown in the figure is the receiver's IP interface for data collection. The SSS can be controlled manually using the interactive man-machine interface on the SCU. Trajectory profiles may be supplied to the SSS by three methods. The first method is to use profiles generated by the UMG. UMG files can be read directly by the SCU. The second method is to use profiles generated by PROFGEN. The Lab Controller can parse a PROFGEN trajectory file and send the data to the SCU in real time. The third method involves downloading entire scenarios from the client to the Lab Controller's hard disk. The Lab Controller can then parse the file and send the data to the SCU in real time.

Three different methods are available for including jamming in receiver characterization testing. The first method is to use the Jammer Subsystem manually via front panel controls of the individual generators. The second method is to use the RF Controller's LabView interface to access all the jamming capabilities of the Jammer Subsystem. The third way is for the client to include jammer control commands for the RF Controller when downloading the scenario to the Lab Controller.

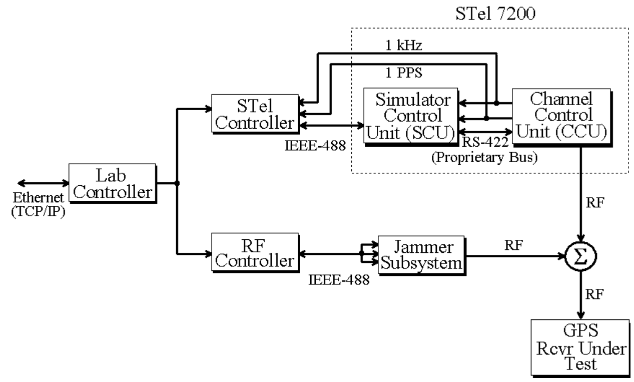

Figure 4. GPS Receiver Characterization Test Functional Block Diagram

GPS Receiver Integration Testing. Integration testing requires the customer's portion of the HWIL to be collocated within the NavLab as shown in Figure 5. The client accesses GPS Receiver Test Section equipment via the Lab Controller. GPS receiver integration testing uses the SSS, STel Controller, and Lab Controller. If jamming scenarios are desired, then the RF Controller and Jammer Subsystem must be also used. Testing with jammers is permitted since all HWIL components are located in the NavLab. Collocation eliminates security concerns with sending sensitive data across the network. Also, network data latency is minimized because of the proximity of all HWIL components.

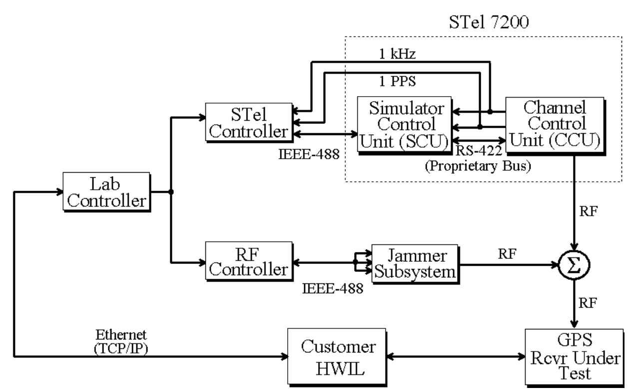

Figure 5. GPS Receiver Integration Test Functional Block Diagram

GPS Receiver Distributed Integration Testing. Distributed integration testing is very similar to normal integration testing. One difference is that only the customer's GPS receiver and Receiver/Ethernet Interface Computer must be collocated in the NavLab as shown in Figure 6. The remote client still accesses the GPS Receiver Test Section's SSS via the Lab Controller. However, the client must now access the GPS receiver via the Receiver/Ethernet Interface Computer. Another exception is that distributed testing involving jammer scenarios is not permitted, since a secure communication channel is unavailable for data transmission.

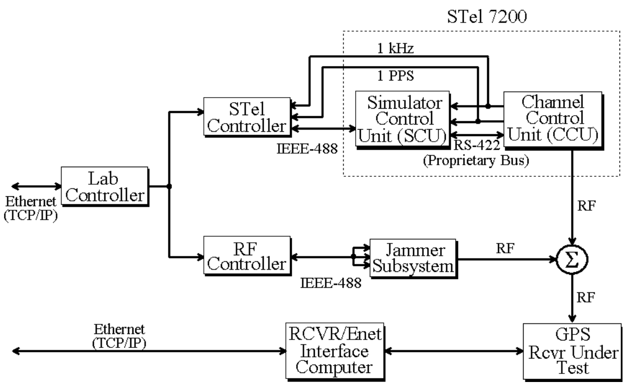

Figure 6. GPS Receiver Distributed Integration Test Functional Block Diagram

Planned Laboratory Upgrades. The following NavLab enhancements will be made in the 1996 fiscal year:

1. *Interstate Electronics Corporation (IEC) SCS 2400 Satellite Simulator*. The GPS Receiver Characterization and Integration Test Section will obtain a new IEC SCS 2400 satellite simulator. This simulator will reduce simulator latency to 10 ms or less, increasing simulation accuracy. With dual RF outputs, platforms with multiple GPS antenna systems can be exercised. Differential GPS simulation will also be possible. Digital Terrain Elevation Database (DTED) data can be used to model the effects of terrain masking. INS models with configurable sensor characteristics will also be available. However, interfaces to the receivers must still be developed to use the models.
2. *Allen Osborne Associates Receiver Upgrade*. The Differential GPS Section's AOA receiver is currently being upgraded to 12 channels. This upgrade will allow the receiver to track all satellites in view. Thus, data dropout attributed to the test platform collecting data from satellites not tracked by the base station should be eliminated.

The following enhancements are being considered for the GPS Receiver Test Section in fiscal year 1997:

1. *Encrypted Ethernet Link*. To resolve the security issues associated with distributed operation, an encrypted ethernet link to the laboratory will be installed. Induced data latency attributable to encryption and decryption is unknown.
2. *Allen Osborne Associates Receiver*. With the capability of obtaining pseudoranges and delta pseudoranges for each satellite, this receiver will provide a high-level quality-control check for the satellite simulator.
3. *Fast Ethernet*. A 10-fold increase in bandwidth will be available with the installation of this high-speed ethernet.
4. *Porting Real-Time Software to VxWorks™ Operating System*. To take advantage of the low latency time of IEC SCS 2400, time-critical controllers will have their software ported to the VxWorks real-time operating system.

GPS SIMULATOR LESSONS LEARNED

Following are some suggested guidelines when using GPS satellite simulators to ensure proper operation and utilization.

Form a good working relationship with the simulator vendor and user community. The vendor is the primary source of information for the simulator. Another excellent source for simulator information is the Satellite Simulator Control Working Group (SSCWG) sponsored by the GPS Joint Program Office (JPO). This group defines certification standards for new simulators entering the market sporting increased capabilities.

Develop an in-depth knowledge of the simulator. Know what type of status information can be obtained during different modes of operation (i.e., idle, running, calibration, etc.). Understand how the satellite parameters are computed. For instance, how are ephemeris parameters generated if only an almanac has been loaded? Or, how does the simulator compute the next output when an update cycle has been missed? For Y-code simulators, a thorough understanding of how the simulator uses cryptographic keys is essential.

Do not ignore simulator RF output. When in an idle state, some simulators may generate undefined output. During simulation, verify that the RF output power levels

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are appropriate. Too much power may confuse the receiver, while too little power may cause the receiver to think it is being jammed.

Always assume that the simulator output is suspect. Constant monitoring with a characterized GPS receiver provides a good operational check. Also watch simulator status flags and pseudorange error estimates. Status flags sometimes indicate hardware errors. Large pseudorange error estimates can indicate that the simulator is receiving inconsistent data or is missing data updates. Pseudorange errors may also be caused by not updating the simulator with platform dynamics data at the appropriate time. Propagating almanacs many weeks forward or backward in time will cause degraded accuracy. Rubidium oscillators that have not been given at least 20 minutes to warm up may cause problems. Lower precision oscillators may drift over long simulation runs, giving erroneous but somewhat predictable results. Restarting a simulation without resetting the receiver time (i.e., going backward in time) may cause the receiver to go into continuous search.

Develop or acquire system analysis tools. When debugging, time stamp all data flowing through the system. This procedure will help to determine if timing problems exist in the configuration. Generate repeatable test scenarios with known results. This baseline can help determine if problems are operator-induced or are the result of simulator hardware/software problems. Use of analysis and visualization tools, such as MATLAB, are invaluable for post-simulation data analysis.

Realize that the satellite simulator is only a small part of the task when performing integration testing. The 6-DOF data must be synchronized to the simulator's computed simulation time. Otherwise, missed update cycles may occur. Compensation for data latency between the 6-DOF and simulator output must be performed. Otherwise, erroneous results will occur. Consistent 6-DOF data must be ensured, which means that position, velocity, acceleration, and jerk must form a self-consistent set.

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