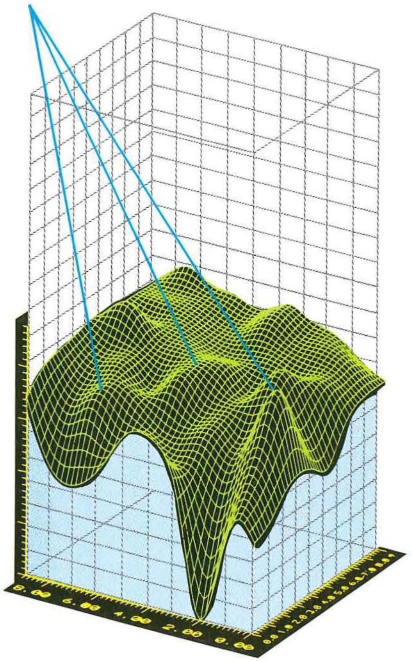

GPS Simulation

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Whether one refers to it as virtual reality, augmented reality, or simulation, today's testing facilities enable one to "experience" GPS under dynamic conditions while being in a controlled laboratory environment. The capability to perform repeatable, realistic testing representing varying user, space, and control segment conditions has resulted in significant efficiencies. Test facilities represent the only practical context for the evaluation of responses to many failure modalities. We will examine these facilities and other aspects of GPS simulation in this month's column. Our author is Marvin B. May, who is a senior navigation systems engineer for Naval Research and Development (NRaD) in Warminster, Pennsylvania. This is May's third article for "Innovation." His others, "Measuring Velocity Using GPS" and "Inertial Navigation and GPS," appeared in September 1992 and September 1993, respectively. The opinions and facts expressed in this article are solely those of the author and not of the Department of the Navy.

"Innovation" is a regular column in GPS World *featuring discussions on recent advances in GPS technology and its applications as well as on the fundamentals of GPS positioning. The column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, and we appreciate receiving your comments as well as suggestions of topics for future columns.*

The testing, evaluation, and certification of GPS receiver systems can be a difficult and expensive process. Due to the importance of GPS navigation for many commercial and military missions, as well as the costs involved in the purchase and integration of GPS navigation systems, many organizations must spend considerable time and effort in evaluating systems before they can make informed purchasing decisions. In this article, we discuss applications for GPS simulators, their categorization, modes of operation, generic capabilities, and future uses.

APPLICATIONS

The need to evaluate GPS receivers under the limited satellite constellation available during the early to mid-1980s spurred the development of satellite signal simulators. Operational field testing, when feasible, was limited to only a few hours of reasonable geometry. Out of this circumstance arose the realization that laboratory testing presents an alternative and complement to live satellite testing. Because the simulation defines the state of truth (true time and vehicle and satellite positions), tests can be conducted anywhere and can represent any time, past or future.

The following applications for simulators are particularly important:

- side-by-side competitive evaluations
- testing under jamming or spoofing conditions
- receiver characterization and troubleshooting where precise repeatability is required
- simulation of marginal signal conditions and outages
- determination of accuracies without the need for precise tracking ranges
- the evaluation of receiver responses to control and space segment anomalies.

The last application falls under the general category of *integrity monitoring,* the ability of the system to warn the user, in a timely manner, of an out-of-tolerance condition. With Department of Defense (DoD) declaration of GPS Initial Operational Capability on December 8, 1993, the intentional disruption of space segment signals for testing purposes is no longer permissible. Therefore, a simulation capability is required to address the safety implications of integrity monitoring.

MECHANIZATIONS

The detailed mechanization and performance specifications of GPS simulator equipment are vendor specific. The following descriptions are notional and not meant to represent a specific vendor's implementation. Although they are not universally accepted as definitions, one may distinguish among three levels of GPS simulation capability according to complexity: a satellite generator (SG), a satellite simulator system (SSS), and a user equipment test facility (UETF).

Satellite Generator. An SG produces signals similar to those of an actual GPS satellite, as depicted in Figure 1. It is the most elemental simulator and is principally used to test aspects of the radio-frequency (RF) front-end functionality of a GPS receiver by generating the broadcast signal of a single satellite with little or no flexibility in terms of the user dynamics being simulated or the satellite message content. The SG typically broadcasts only at one frequency, either L1 or L2. Overall receiver navigation performance cannot be evaluated with a single SG.

A single frequency standard, either internally supplied or externally derived from a precise atomic standard, generates the frequencies and timing signals for message, codes, and carrier. The P (and Y for an anti-spoof-capable authorized simulator) and C/A digital pseudorandom noise (PRN) codes are generated at 10.23 megachips per second (Mcps) and 1.023 Mcps, respectively (each PRN code bit is called a *chip*). Each code is combined with the 50-Hz digital message by a modulo two binary addition. The two digital streams are each biphase modulated on 1575.42 MHz continuous-wave carrier signals that are out of phase with each other by 90 degrees. After nominal power level adjustments because the C/A component is twice as strong as the P(Y) component, the two components are summed to form the L1 satellite signal (see "Why Is the GPS Signal So Complex?" in the May/June 1990 issue of *GPS World* for further details on the structure of GPS signals).

The effect of vehicle-to-satellite motion, which induces a Doppler frequency shift in a received GPS signal, is illustrated by using a numerically controlled oscillator (NCO) to adjust the reference oscillator frequency. In a sense, the generation of signals in the actual GPS satellites is considerably simpler than in the simulated environment because the laws of physics naturally create, for all the components of the signal, the appropriate Doppler effects caused by relative satellite and user motions, relativistic effects, signal strength variations due to antenna gain patterns, and

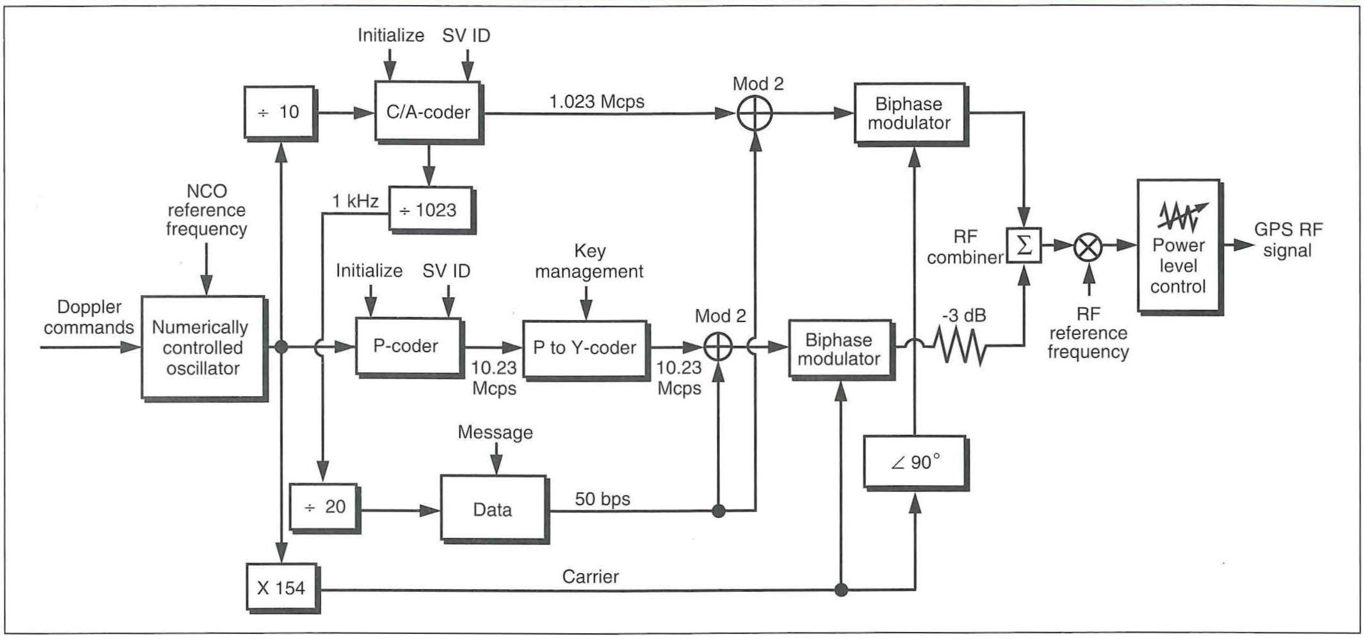

Figure 1. This figure is a simplified, conceptual portrayal of a single-channel GPS signal generator (SG). The SG produces a composite L1 signal, mimicking most aspects of a real signal from a satellite, including antispoofing.

environmental effects due to the atmosphere. The frequency of transmission in a satellite can be tightly tuned and filtered before code and data modulation, whereas in a simulated environment all components of the signal must have the dynamics superimposed.

The methodology for accurately simulating these factors, which occur naturally for the real satellites, necessitates departures from the simplified representation of Figure 1. These would include the utilization of multiple intermediate frequencies to reduce phase noise resulting from frequency multiplication of the Doppler frequency up to the RF frequency and the incorporation of separate NCOs for the code and carrier to implement the ionosphere's retarding effect on the code phase and advancing of the carrier phase. Other effects are generally created utilizing RF attenuators and/or control of the NCOs. Typical functions of an SG usually include the ability to simulate any one of the 37 satellite slots as specified by the Interface Control Document "Navstar GPS Space Segment/Navigation User Interfaces" (ICD-GPS-200B), simulation of simple Doppler frequency profiles, and power level control.

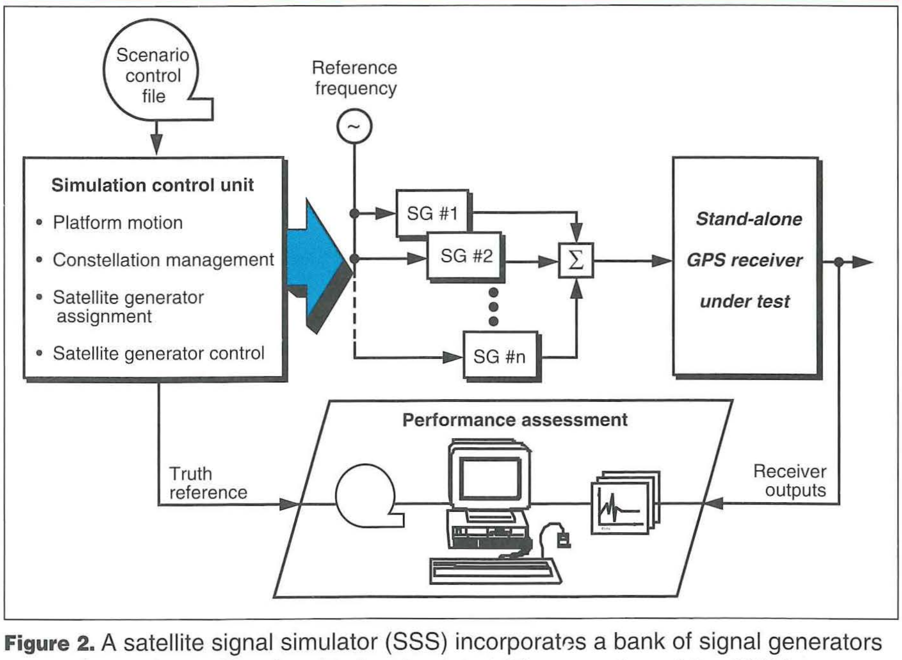

Figure 2. A satellite signal simulator (SSS) incorporates a bank of signal generators — one for each satellite signal to be simulated. The operation of the SSS is controlled by a simulation control unit.

Satellite Simulator System. An SSS generates the RF signals from a number of satellites simultaneously and self-consistently. (*Self-consistently* means that all signals from all of the satellites are generated with a phase relationship representing a single point user.) The signals represent some subset of an entire constellation. Ideally, the signals would represent at least those signals used for the navigation solution within a GPS receiver. An SSS can be used to test all the normal navigation functions of a stand-alone GPS receiver. As shown in Figure 2, an SSS for commercial receivers may consist of a bank of L1 SGs, RF combiners to create a composite RF signal, and a simulation control unit (SCU) to perform overall scenario control and coordination among the SGs. The SCU software computes the satellite positions and higher-order derivatives from orbital element descriptions provided as an input file; these may intentionally be made to result in different satellite positions than those computed from the ephemeris or almanac orbital elements contained in the satellite message, in order to simulate space and/or control segment errors. A description of vehicle motion may be supplied from an input file, in real time from another external computer, or from canned scenarios running within the SCU. Knowing the satellite and vehicle trajectories, the SCU determines which available satellites will be simulated and assigns SGs.

The SCU initially commands the SGs to set up their coder registers and carrier phases consistent with the satellite-to-vehicle ranges. Actually, a GPS receiver, at the time of reception, replicates the code existing at the satellite at the time of transmission of the signal. Therefore, the simulator, unlike a real satellite, must appropriately account for the user-to-satellite range, as well as earth rotation and user motion during the signal travel time. Having established the initial code register and carrier-phase values for all the satellites, the SCU sends Doppler commands, computed from the relative satellite-to-vehicle range rates, to the code and carrier NCOs, which maintain the signal phases during the simulation. Additional software in the SCU handles delays caused by tropospheric, relativistic, and ionospheric effects (which require delays of the opposite sign for carrier and code) and user-specified errors.

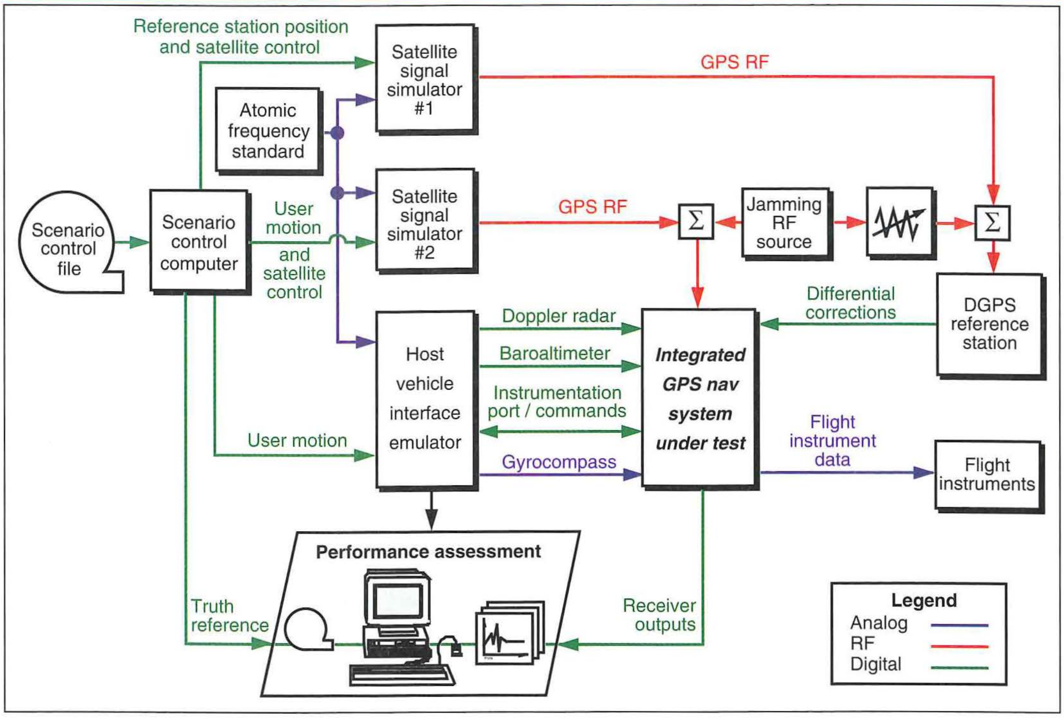

Figure 3. A user equipment test facility (UETF) is employed for testing GPS receivers and sensors that operate as part of an integrated navigation system. The UETF illustrated in this block diagram features two SSSs — one for the DGPS reference station and one for the GPS receiver in the simulated vehicle.

Additional functions performed in an SCU or an external computer, modifiable by scenario control files configured by the user, often include vehicle dynamics profile generators, navigation message control, multipath error generation, signal amplitude control representing antenna gain or shading effects, and orbital perturbation insertion. The SCU along with the SGs are able to simulate vehicle dynamics at least equal to those of a high-dynamic aircraft with a signal fidelity, in terms of pseudorange and delta range errors, better than normally specified for receiver performance.

User Equipment Test Facility. A UETF enables testing of GPS receivers and sensors that operate as part of a larger system and therefore are integrated with other equipment. Figure 3 represents a UETF configured to test a vehicle that is employing differential GPS (DGPS) in conjunction with an aircraft barometric altimeter, Doppler radar system, and gyrocompass. Two SSSs, utilizing the same reference time and GPS constellation, are needed for the DGPS reference station and vehicle. The sensor simulation computer implements models of the auxiliary navigation sensor errors and adds these to the true vehicle motion parameters, which then get transmitted to the receiver through the host vehicle interface emulator (HVIE). The HVIE sends data to the GPS receiver over typical avionics interfaces such as EIA RS-422-A/RS-449, MIL-STD-1553B, and NMEA 0183. Also shown included in the UETF are data evaluation capabilities and jamming and spoofing sources.

MODES OF OPERATION

Three modes of generating the scenario to be used in a simulation, based on the degree of real-time control required, have been employed. In the *off-line mode,* a scenario control file that typically defines the vehicle waypoints and velocities, in addition to the constellation configuration, is created and used as an input to an off-line (non-real-time) program, which in turn generates a file of commands. Later, this file of commands is buffered into the SSS, which executes the real-time commands to create the simulated satellite RF signals. In the *pseudo-real-time mode,* a similar scenario control file is defined, but the inputs to the SSS are developed in real time.

The *true real-time mode* occurs when the output of the GPS receiver influences the subsequent maneuvers of the vehicle or platform carrying the receiver. For example, consider a full-up simulation of an aircraft instrument landing approach system using GPS. As the aircraft is making its final approach fix, an integrity-warning algorithm within the GPS receiver issues alerts as a result of a simulated failing satellite. These alerts activate either manual or automatic missed-approach procedures. These missed-approach procedures manage simulated aircraft control systems, which in turn dictate the trajectory of the aircraft, thereby influencing the SSSs. In this mode, the simulation's output or the operator must be able to modify the scenario control file.

SA AND AS

Selective availability (SA) is the intentional degradation of the GPS signal with the objective of denying full position and velocity accuracy to unauthorized users. SA is part of the Precise Positioning Service (PPS), which was formally implemented on March 25, 1990. To implement SA, two different methods are used: manipulation of the navigation message orbit data, also referred to as the *epsilon process;* and manipulation of the satellite clock frequency, also referred to as the *delta process, dither process,* or simply *clock dither.*

Manipulation of the navigation message orbit data degrades the accuracy of the receiver's calculated satellite positions and results in slowly varying user position errors. Note that the actual satellite orbits are not affected; only the parameters describing the satellite orbits are corrupted.

Clock dither, in contrast, involves the manipulation of the satellite clock itself. Because the underlying satellite clock is dithered, clock dither affects both the C/A-code and the P-code, as well as the carrier-phase measurements.

For a simulator to reproduce the exact selective availability effects that the real satellites broadcast, it requires the cryptographic algorithms and keys that are managed by the National Security Agency and the GPS Joint Program Office. With such a capability, these systems become classified. The exact equipment boundary where the classification applies is implementation specific: some implementations may have all the cryptographic functions within the SG's firmware, whereas others implement portions within the software of the SCU. PPS is considered an upgrade capability by two of the major simulator manufacturers. It is the Joint Program Office's stated policy to strictly limit the availability of simulators with PPS capabilities, and few systems currently have a demonstrated capability.

SA effects may also be simulated in a statistical sense by modeling (using models available in the literature, for example) the nominal stationary variations induced by SA as a random process, and by implementing perturbations in the navigation message orbit data and satellite clocks. This modeling approach would not reproduce the exact SA pattern of the satellites for a given time and is not classified.

Antispoofing (AS) is another feature of the PPS that applies encryption to the P-code on L1 and L2 to create the Y-code. The production of the Y-code requires an Auxiliary Output Chip (or equivalent), which requires an input derived from the classified key, for each channel of L1 Y-code and each channel of L2 Y-code to be simulated. PPS-capable simulators should have the capability to independently control the presence of SA and AS on each channel, as well as the level of SA.

CURRENT USES

Over the last 10 years or so, the DoD has sponsored UETF development for preliminary qualification testing at receiver equipment manufacturer sites and for government laboratory qualification testing. The genesis of most of the currently available commercial simulators stems from these efforts. Government laboratory qualification testing includes both Precise and Standard Positioning Service testing under different user dynamics ranging from those of a foot soldier to those of a fighter aircraft. Typical government laboratory testing includes evaluation of pseudorange and delta range accuracy; acquisition and reacquisition operation; multipath rejection; jamming susceptibility; and overall position–velocity–time performance for unaided, INS (inertial navigation system)-aided, and Doppler-aided configurations. Technical sample unit testing at government laboratories has also been important in recent side-by-side "nondevelopment item" competitive procurements for the Precision Lightweight GPS Receiver (PLGR), GPS Inertial Navigation Assembly (GINA), Embedded GPS Inertial (EGI) System, and the U.S. Coast Guard's reference station receivers.

The Federal Aviation Administration (FAA) within its Technical Standard Order C-129 for nonprecision approaches, implicitly requires some level of UETF testing for its certification of the nonprecision approach integrity function of receivers. The tests described in this document apply to GPS receivers that employ "snapshot" receiver autonomous integrity monitoring (RAIM) augmented by a barometric altimeter. The tests call for the UETF to simulate a nominal constellation, with an aircraft performing a circular trajectory about a fixed location, and to create simple error ramps for specific satellite ranges and for the baroaltimeter. These signals created by the UETF are sent to the receiver under test, whose integrity algorithms would be expected to provide an alarm within 10 seconds of exceeding a horizontal position error of 555 meters (0.3 nautical miles), while maintaining an acceptable false alarm rate under normal conditions. Clearly more extensive and realistic testing using UETFs will be forthcoming from the FAA as GPS use increases and integrity requirements for all phases of flight are formalized. In particular, system-in-space failures due to momentum dumps, nonstandard codes, bit hits, clock malfunctions, and bad uploads may be phenomena that will be tested in future laboratory simulations.

Also under FAA leadership is the Differential Global Navigation Satellite System (DGNSS) Instrument Approach System to support precision approaches. (A *precision approach* is a standard instrument approach procedure in which a glideslope/glidepath is provided.) This system will initially be a local area differential GPS implementation for Special Category I (SCAT-I) precision approaches. Within the SCAT-I Minimum Aviation System Performance Standards (MASPS) are numerous tests for both the reference receiver and the airborne receiver, which require the use of an SSS.

For the airborne-receiver testing, principal emphasis is placed on exercising the cautions and warnings related to the aircraft crossing the containment surface boundaries associated with the precision approach tunnel concept. (The tunnel concept assigns a flight path to each phase of flight. Surrounding this flight path is an aircraft containment surface, which forms a tunnel within which the aircraft should stay to maintain a standard separation from the terrain, ground obstacles, or other aircraft.)

The ground-station testing assesses the accuracy and timeliness of the transmitted differential corrections, as well as the ground station's ability to perform integrity monitoring. The SSS is employed to induce alarm conditions by programming it for unacceptable satellite geometries, outages, and/or status conditions. Although the SCAT-I bench testing represents the most extensive official use of an SSS at the time this article was written, it still does not include simultaneous, self-consistent testing of the airborne and ground systems, testing under SA and AS conditions, and possibly important space and control segment failure modalities.

OUTLOOK

As has often been the case in the brief history of GPS, the test community lags behind the requirements and equipment development communities. The availability of adequate UETFs to meet the needs for testing new integrated GPS systems is questionable. Examples of newly fielded or proposed systems that currently cannot be adequately tested are embedded GPS–INS systems, wide area differential GPS systems, combined GPS–GLONASS systems, and pseudolite-augmented systems.

Embedded GPS–INS systems will probably dominate future military procurements and high-value commercial systems. To best exercise these systems in a laboratory under arbitrary dynamic conditions, raw inertial sensor assembly outputs must be simulated in a manner consistent with the satellite signal. These simulated inertial sensor assembly outputs, commonly referred to as "delta-thetas" and "delta-vees," represent high-rate incremental angular rotations and specific velocities, respectively, of the system's body axes relative to inertial space (see "Inertial Navigation and GPS" in the September 1993 issue of *GPS World* for further details). The simulated delta-thetas and delta-vees must be injected into the embedded system emulating the real inertial sensor outputs.

Three recent embedded GPS–INS DoD procurements — GINA, EGI, and the GPS Guidance Package (GGP) — all have a similar specification requiring an interface to enable these laboratory tests. The Simulated Inertial GPS Navigation Laboratory (SIGNaL) is a DoD-sponsored effort to modify existing UETFs for this capability. With the SIGNaL capability, all characteristics of an embedded GPS–INS can be exercised by a UETF with the exception of certain physical phenomena, such as true inertial sensor reactions to actual specific forces or angular rates, receiver oscillator acceleration sensitivity effects, and some high-rate inertial sensor compensation firmware.

Although still in the study phase at this time, the FAA has plans for the Wide Area Augmentation System. This system would provide integrity monitoring and additional ranging signals to augment the standard GPS signals. The system will likely include as many as 30 ground reference stations and leasing capacity on three or four commercial geosynchronous satellites. The service, which may also include differential corrections, will improve the availability and continuity of service as well as its integrity for suitably equipped aircraft in U.S. airspace. For a UETF to have a high-fidelity simulation capability of this system, it should be able to simultaneously generate the satellite signals seen at the applicable reference stations and user location; simulate the communications and integrity monitoring among the reference stations, geosynchronous satellites, and user; and, if employed, simulate the additional ranging signals emitted by the geosynchronous satellites. The development of more capable UETFs has been hampered by the lack of common standards for government-provided GPS augmentation services. The proliferation of differential services imposes a corresponding expansion in testing complexity, which would be significantly alleviated should standards on data formats and transmissions be adopted. The role of GLONASS and pseudolite-based local area differential systems will also affect future UETF designs.

CONCLUSION

Laboratory simulations of satellite navigation and related equipment are available for a broad range of applications. These capabilities have proven to be cost-effective for receiver development, characterization, and competitive selection. Their use may be required, for all practical purposes, for verification of integrity-monitoring capabilities and for testing at the envelopes of user dynamics. As the GPS receiver evolves as a sensor integrated into distributed applications, the overall demands on a test facility become more complex. This should stimulate further efforts toward ensuring that "testability" is a factor in system design. ■

For product information, turn to page 62 and see Manufacturers. *For reprints (250 minimum), contact Mary Clark, Marketing Services, (503) 343-1200.*

CALENDAR

OCTOBER 19–21

The 85th AEEC General Session
Algarve, Portugal. This meeting of the Airlines Electronic Engineering Committee (AEEC) will be preceded by the Users' Administrative Session on October 18. Contact: Denise Earley, Director's Assistant, 2551 Riva Road, Annapolis, MD 21401, USA, (410) 266-4110, fax (410) 266-2047.

OCTOBER 23–27

GIS/LIS '94 Conference and Exposition
Phoenix, Arizona. Sponsored by the American Association of Geographers and others, this multidisciplinary meeting is for those interested in the design and use of geographic information systems, land information systems, and related specialties and technologies. Contact: Susan Aucock, AM/FM International, Communications Coordinator, 14456 East Evans Avenue, Aurora, CO 80014, USA, (303) 337-0513, fax (303) 337-1001.

OCTOBER 24–26

Intelligent Vehicles Symposium '94
Paris, France. The symposium will feature demonstrations of test vehicles, as well as paper presentations. Contact: Ichiro Masaki, Room E40-159, Massachusetts Institute of Technology, Cambridge, MA 02139, USA, (617) 253-8532, fax (617) 258-7334, e-mail masaki@mit.edu.

NOVEMBER 1–4

The 23d Annual Technical Symposium of the Wild Goose Association
Newport, Rhode Island. This conference on "The Role of Loran in a Global Navigation World" is for the radionavigation community, including global navigation–system policy-makers, providers, manufacturers, and users. Contact: Sheila Markey, Synetics Corporation, 540 Edgewater Drive, Wakefield, MA 01880, USA, (617) 245-9090, fax (617) 245-6311.

NOVEMBER 8–10

NAV '94 Conference
London, United Kingdom. The 11th annual international conference in the series organized by the Royal Institute of Navigation will focus on "Transport 2000 — Navigation, Command, and Information Systems for the 21st Century." The conference will address navigation, command, control, communications, and information systems involved in the transportation of people and material. Contact: Royal Institute of Navigation, 1 Kensington Gore, London SW7 2AT, United Kingdom, +44 (71) 589 5021, fax +44 (71) 823 8671.

ADVERTISERS INDEX

MANUFACTURERS

Page 20. *Etched in Stone: Recovering Native American Rock Art.*
The Southwest GIS Center operates a Pathfinder Community Base Station from **Trimble Navigation** (Sunnyvale, California). **Differential Corrections, Inc.** (Cupertino, California) provided the real-time correction subscription in Albuquerque. A Trimble Professional GPS and two identical Trimble Basic Plus units were used (both using software version 5.4) to receive the real-time corrections. Both sets of point files were downloaded into the Trimble Pathfinder Professional software (version 2.31*03). Two GIS software packages are being used during this project. A public domain software, GRASS–Geographical Resources Analysis Support System version 4.1, was developed by the **U.S. Corps of Engineers Research Lab**, Champaign, Illinois; the other, EPPL–Environmental Planning and Programming Language, version 7, was developed by the **University of Minnesota** in Minneapolis.

Page 32. *On Top of the World: GPS Surveys Mount Everest.*
Five System 200 GPS sets from **Leica AG** (Heerbrugg, Switzerland) were used in the remeasurement of Mount Everest. The Italian party of the Everest expedition used the Kern ME5000 distance meter and a WILD T3000 theodolite, both from Leica AG. The backup distance meter was the WILD DI3000 distance meter. The Chinese surveyors measured with a K&E distance meter and a WILD T2 theodolite. The astronomical coordinates were determined with a WILD T1600 theodolite connected to a time-digitizing unit made by the **ETH** (Zurich, Switzerland) and the geodetic coordinates with a **Trimble Navigation** (Sunnyvale, California) 4000SST GPS receiver. **Micros** (Treviso, Italy) built the special sensor to measure temperature and pressure.

Page 46. *Losing Ground: Mapping Louisiana's Disappearing Coastline.*
The Laser Walkabout system is marketed by **Laser Technology Inc.** (Englewood, Colorado). The system includes Laser Technology's Criterion 400 survey laser, data-logging and postprocessing software from **ConTerra Systems Inc.** (San Francisco, California), and a field data collection unit. In the Louisiana field project, LSU used an MC-5 data collector from **Corvallis Microtechnology Inc.** (Corvallis, Oregon). **Trimble Navigation** (Sunnyvale, California) Pathfinder Professional systems served as both the GPS rover and base station units. LSU researchers use **Intergraph**'s (Huntsville, Alabama) Modeler GIS Environment (MGE), Microstation, and Modeler MGE software for database development, surface modeling, and change analysis.

Page 51. *GPS Simulation.*
DoD has used GPS simulator equipment manufactured by **Northern Telecom Europe Ltd.** (Schaumburg, Illinois) and **Stanford Telecommunications, Inc.** (Sunnyvale, California). The Precision Lightweight GPS Receiver is being manufactured by **Rockwell International Corporation's Collins Avionics and Communications Division** (Cedar Rapids, Iowa). The Navy's GPS Inertial Navigation Assembly is being provided by **Litton Industries's Guidance and Control Systems Division** (Woodland Hills, California). Litton, for the inertial system, and Rockwell Collins, for the embedded GPS receiver, form the contractor team for the Advanced Research Project Agency's GPS Guidance Package Phase One. **Honeywell Military Avionics** (St. Petersburg, Florida) has been selected as the contractor for the Embedded GPS Inertial System.

Correction

On page 74 of the September issue, under *Manufacturers,* the location of **Clearwater Instrumentation Inc.** should have been listed as Wellesley, Massachusetts.