Inertial Navigation and GPS

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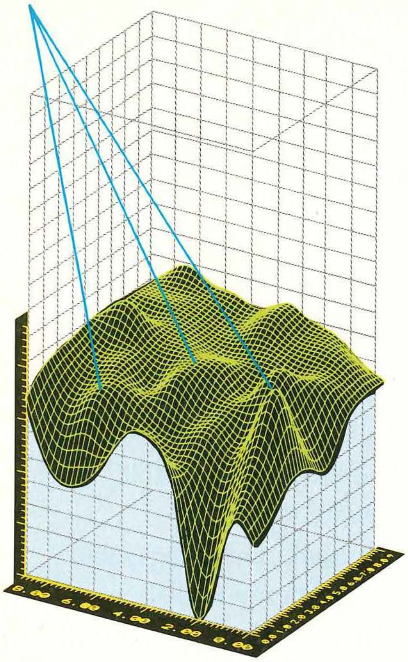


The Global Positioning System (GPS) and inertial navigation systems (INSs), both of which can be considered discrete systems providing position and velocity information, were once regarded as potentially competing technologies. In this article, we explore the currently more prevalent viewpoint that the complementary or synergistic relationship between GPS and INSs could yield a marriage made in navigation heaven. Our author is Marvin B. May, who is a senior navigation systems engineer for the Naval Command and Control Ocean Surveillance Center (Naval Research and Development — NRaD); Research, Development, and Technology Division; in Warminster, Pennsylvania. This is May's second article for "Innovation." His first — "Measuring Velocity Using GPS" — appeared in the September 1992 issue of GPS World. *The opinions and facts expressed in this article are solely those of the author and not of the Navy Department.*

"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 Surveying Engineering at the University of New Brunswick, and we appreciate receiving your comments as well as suggestions of topics for future columns.*

Consider the attributes of an ideal navigation system: high relative and absolute accuracy; complete global coverage; efficient real-time response in the presence of high user dynamics; capable of providing three-dimensional position, velocity, and attitude; unaffected by the environment; resistant to intentional and unintentional electronic jamming or spoofing; deniable to an enemy; wide user applicability; autonomous timely failure detection and correction; high reliability; compatibility with avionics suite requirements; and affordability.

The Global Positioning System, although eminently successful toward its original goal of replacing and reducing the proliferation of other radionavigation systems, has limited dynamic velocity and attitude capabilities, is susceptible to electronic warfare countermeasures, and can be affected by the environment and signal obscurations (shading, foliage, building blockages). Moreover, it has marginal capability with the present space and control segment configuration to achieve the high-probability levels of timely failure detection and identification necessary for sole-means navigation. Inertial navigation, sometimes referred to as "astronomy in a closet" because of its total autonomy subsequent to initialization, can uniquely abate these limitations, creating a navigation suite approaching the aforementioned ideal characteristics. Before addressing the specific benefits of integrating an INS with GPS, we will briefly review the theory, history, mechanization, and error propagation characteristics of inertial navigators.

INERTIAL NAVIGATION OPERATION

Inertial navigators are autonomous devices that provide three-dimensional position, velocity, and attitude information based on onboard measurements of specific force (force per unit mass) and angular deviations relative to a fixed, nonrotating coordinate system referred to as the *inertial coordinate frame.* The specific force sensors, commonly referred to as *accelerometers,* measure the reaction force due to vehicle translational accelerations plus gravitational force. Given knowledge of the gravitational force based on the computed position of the vehicle, the inertial navigator's electronics and computer can accumulate (that is, mathematically integrate) the accelerometer outputs to produce velocity and, with a subsequent level of accumulation, to produce position outputs relative to an inertial frame. These accumulations depend on the orientation of the accelerometers relative to inertial space.

The task of maintaining knowledge of the orientation of the inertial platform, upon which the orthogonal triad of accelerometers resides, is accomplished by the angular deviation sensors, commonly called *gyroscopes,* which are also rigidly attached to the platform in a precisely known orientation relative to the accelerometers.

The cluster of accelerometers, gyroscopes, platform, and associated sensor electronics is referred to as the *inertial sensor assembly (ISA),* the *inertial measurement unit (IMU),* or the *inertial reference unit (IRU).* The gyroscopes measure angular rates, angular increments, or total angular displacement from an initial known orientation relative to inertial space. This information enables the inertial navigator's computer to appropriately resolve the accelerometers' outputs.

The additional knowledge of the initial three-dimensional position, velocity, and orientation of the platform, along with knowledge of inertial earth rotation and parameters of the reference ellipsoid, allows the inertial navigator's computer to derive and output the geographic quantities of latitude, longitude, and height above the reference ellipsoid; north, east, and vertical velocity; roll, pitch, and heading; as well as other parameters of interest such as attitude rates and track angles (azimuths of aircraft ground-speed vectors). The processes associated with starting up an inertial navigator are referred to as *initialization* and *alignment.*

HISTORY OF INERTIAL NAVIGATION

The initial development of inertial navigation theory goes back to the pioneering work of Maximilian Schuler and Hermann Anschütz-Kaempfe in Germany, circa 1908. Modern inertial navigators have evolved from stable platforms and attitude heading devices developed in the 1920s and 1930s. These used similar sensors, but without the necessary accuracies to support the long-term accumulations inherent in inertial navigation.

The first operating inertial system is generally attributed to the Peenemunde group in Germany and was employed on the V-2 rockets of late World War II. Post–World War II development of inertial navigators proceeded at an extraordinary pace with the Massachusetts Institute of Technology Instrumentation Laboratory (later to become the Charles Stark Draper Laboratory) spearheading the development efforts of U.S. companies such as North American Aviation (currently Rockwell Autonetics Division), Sperry Gyroscope (currently Sperry Marine and Paramax), Northrop, Honeywell, Singer-Kearfott, and Litton, among others.

By the late 1960s, most high-value military aircraft, ships, and missiles with precision autonomous navigation requirements were equipped with INSs. For the most sophisticated systems aboard submarines and long-endurance aircraft, instrumentation was refined to the point where position accuracies approached "port-to-port" capabilities and velocity errors were dominated by uncertainties in the gravitational force. The electronic miniaturization and computational advances of the 1970s and 1980s, along with the development of solid-state accelerometers and optical gyroscopes, provided the size, cost, and reliability impetuses for further proliferation of inertial navigators.

Today, most large commercial airplanes have complements of INSs, and military usage has expanded to even relatively low-cost vehicles. INSs have historically been physically separated from, and loosely integrated with, the avionics systems they support and the aiding devices that bound their error growth. In the past few years, systems have been developed in which the inertial navigators are physically embedded and tightly integrated with GPS and other avionics.

INERTIAL NAVIGATION MECHANICS

There are two generic implementations of inertial navigation: gimballed and "gimballess" (commonly called *strapdown*). In the gimballed systems, the inertial sensor assembly is isolated from most of the vehicle's attitude motions by a mechanical assembly of concentric rings called gimbals. In the strapdown systems, the ISA is mounted directly ("strapped down") to the vehicle. Strapdown systems have higher dynamic instrument scale factor requirements (the scale factor relates the output of an accelerometer to the component of the applied specific force it senses), increased computational load, and reduced calibration flexibility relative to gimballed systems; however, their mechanical simplicity, smaller volume and weight, and lower costs have made them the dominant mechanization for aircraft.

Figure 1 is a simplified block diagram of a pure inertial strapdown system. Vehicle angular increments and changes in specific force with respect to inertial space are obtained from the ISA at typical rates of several hundred Hertz. The navigation computer utilizes the angular increments, along with the computed angular rates due to vehicle translational motion and earth rotation, to maintain an estimate of the platform's attitude that is used to convert the accelerometer outputs to a geographic (two horizontal or level axes, and one vertical) frame of reference. Subsequent to compensation for gravitation, earth rotation, and curvilinear motion effects, the computer can accumulate changes in velocity to obtain total north, east, and vertical velocities, with a following accumulation to obtain geographic positions. The latter two computations are typically accomplished at about 100- and 50-Hz iteration rates, respectively.

INS ERRORS

Errors in inertial navigators arise from an interaction of vehicle inertial motion with

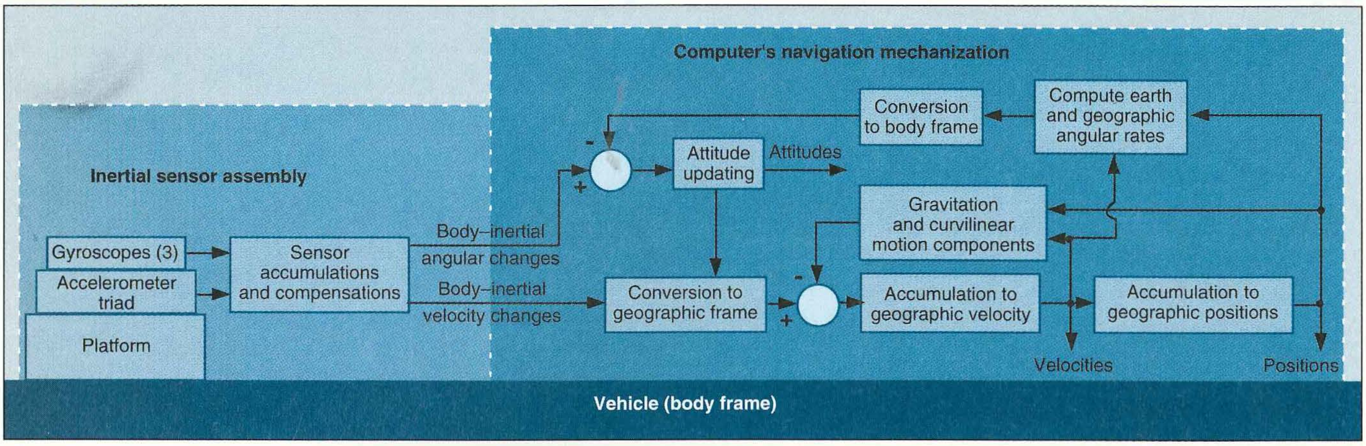
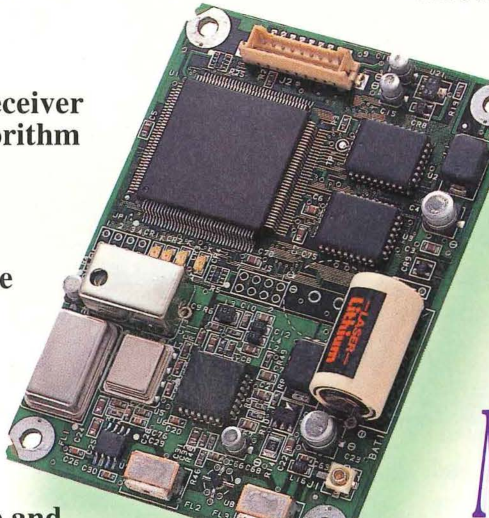


Figure 1. Simplified block diagram of a strapdown inertial navigator.

instrument noise, instrument and platform misalignments, initial position and velocity errors, and gravitational disturbances. Figure 2 depicts radial (horizontal) position errors from an ensemble of tests on a typical aircraft inertial navigator operating without external aiding. Note that although the INS errors are significantly larger than those of GPS, they oscillate or drift at low and somewhat predictable frequencies and have negligible high-frequency errors or latency. In addition to INS autonomy, it is this contrast with the small, high-frequency errors characteristic of GPS that makes the two systems so complementary.

For many applications, the principal natural frequencies of error oscillation are at the Schuler frequency with a period of about 84 minutes and at the diurnal frequency with a period of 24 hours. These oscillations can be variously set off by the aforementioned error sources and can grow unbounded even when the error inputs are bounded. Conventionally, for aircraft missions of less than about four hours' duration, the horizontal position error growth of an INS is statistically characterized by the slope of a straight line statistical (least



squares) fit to the ensemble of test runs, as shown in Figure 2. This line, called the *circular error probable (CEP)* rate, represents, at a 50 percent probability level, the average slope of the horizontal position error growth — typically in units of nautical miles per hour = 1.852 kilometers per hour — over the mission duration and is primarily applicable to relatively short aircraft missions (see "The Mathematics of GPS" in the July/August 1991 issue of *GPS World* for a discussion of the assessment of GPS position error). The velocity error specification — typically in units of feet per second = 0.3048 meters per second — of an inertial navigator is a measure of the instantaneous rate of change (slope) of the position error and represents the ability to estimate the instantaneous speed and flight path direction of the vehicle. Due principally to the Schuler oscillations, the position error growth specification and velocity error specifications are unequal. Table 1 provides representative error characteristics of a medium-to-high quality unaided aircraft inertial navigator.

Table 1. INS performance error characteristics (assuming a 4–8-minute ground alignment)

Position	0.8 nmi/h (CEP)
Velocity	2.5 ft/s (rms)
Heading	0.1 deg (rms)
Pitch and roll	0.05 deg (rms)
Angular rate	0.04 deg/s (rms)

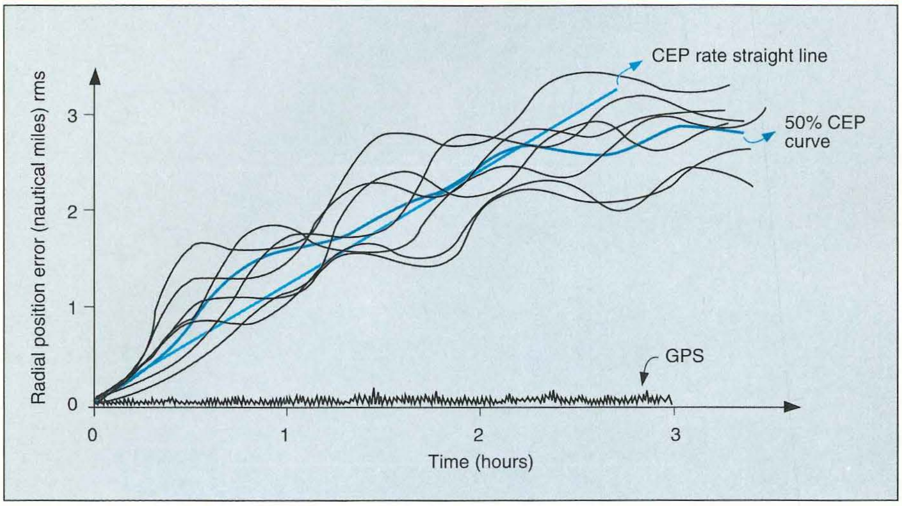


Figure 2. Sample ensemble of INS position errors.

GPS–INS INTEGRATION

Practically since the inception of GPS, it was apparent to military inertial system vendors and system integrators that GPS, either by necessity due to the planned elimination of other aiding sources or by virtue of its superior performance, would supersede or de-emphasize the utilization of earlier INS aiding sources, such as Doppler radar, barometric altimeter, air speed sensors, Loran-C, Transit, and Omega. The choice of a methodology for accomplishing the integration of GPS and INS on a particular vehicle depends on the existing avionics, data bus structure, mission requirements, and logistical and security considerations. Two general approaches, commonly called *loosely coupled* and *tightly coupled,* are shown in Figure 3.

In the loosely coupled mechanization, the GPS receiver and the INS maintain separate position and velocity solutions utilizing separate Kalman filters. GPS geographic positions and velocities are sent to the INS's Kalman filter for error bounding and instrument calibration. INS positions and velocities may also be sent to the GPS receiver, where they are resolved into satellite-to-user

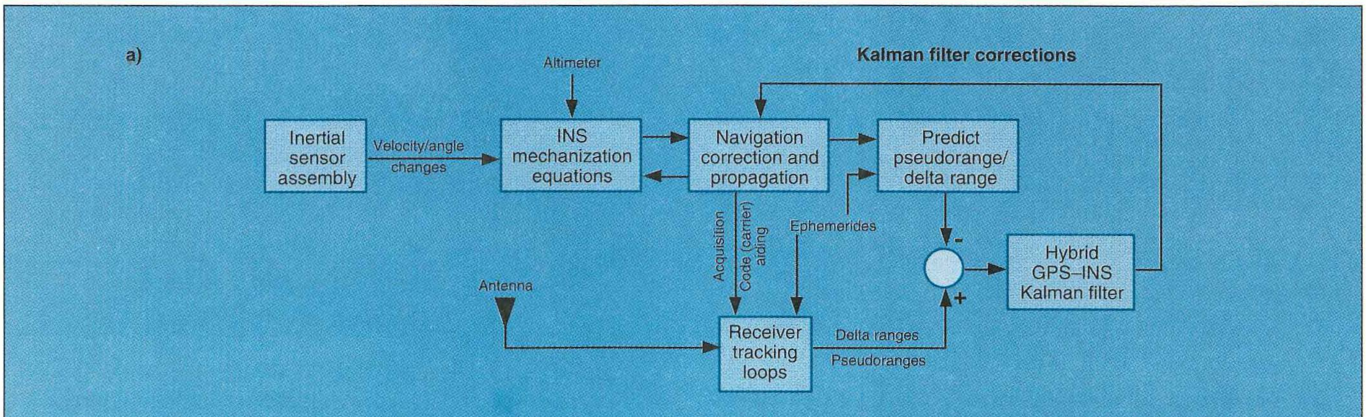


Figure 3. a. Tightly coupled mechanization. **b.** Loosely coupled mechanization.

line-of-sight ranges and range rates (and higher derivatives) for code loop aiding and acquisition.

In the tightly coupled mechanization, measurements of GPS pseudorange and delta range (the change in range over some time interval), along with satellite ephemerides, are provided to a single navigation processor that mechanizes the INS navigation equations and collectively estimates all observable system errors.

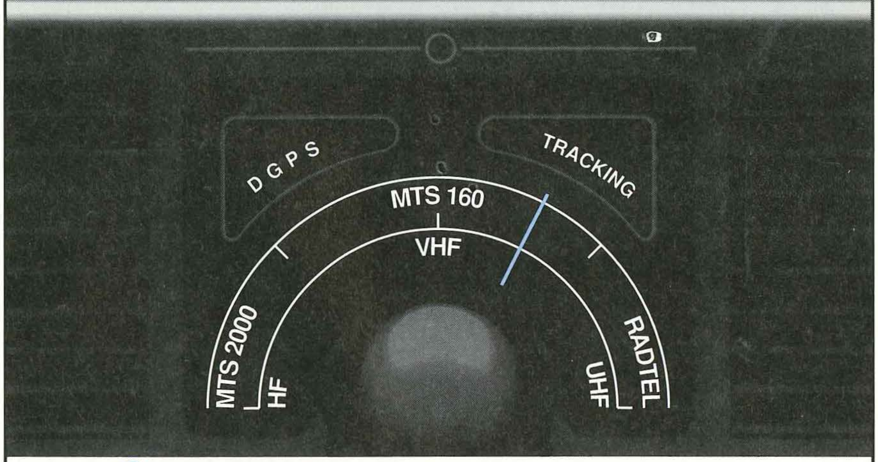
The navigation processor forms a nominal solution based on the ISA data that follows the high-frequency motions of the vehicle very accurately. The processor then implements a single Kalman filter using the GPS pseudorange and delta range measurements to estimate the errors in the INS nominal position and velocity solution, INS misalignments, gyroscope and accelerometer errors, and GPS receiver clock biases and drifts, in addition to possible external sensor errors such as barometric altimeter biases.

The Kalman filter is external to the high-iteration rate loops associated with the accumulations of the ISA's outputs to create the nominal velocities and positions; instead, the dynamic upon which the filter is based is the low-frequency (Schuler 84-minute dominant) INS error propagation.

The INS-related Kalman filter estimates are fed back to the INS mechanization equations, creating the "optimal" hybrid GPS – INS solution. Corrected INS positions and velocities are provided to the GPS receiver microprocessor, and in some mechanizations, carrier tracking loops, for acquisition and aiding.

The loosely coupled approach will, when other factors are equal, be less robust under conditions of multiple satellite obscurations and when high dynamics occur during periods of jamming. This approach is therefore primarily applicable when physically discrete GPS and/or INS equipment already exists in the aircraft's avionics suite, often interfaced through relatively slow mission computer data busses. Under these circumstances, logistical factors and cost considerations associated with existing component modifications often dictate a loosely coupled system.

The benefits of tight coupling are most practically realized when the GPS receiver and the INS are embedded in a single box that minimizes data bus traffic and latency and, for systems employing the GPS Precise Positioning Service (PPS), confines data transfers of encrypted quantities. The concomitant benefits of reduced size, weight, power, and under many circumstances,



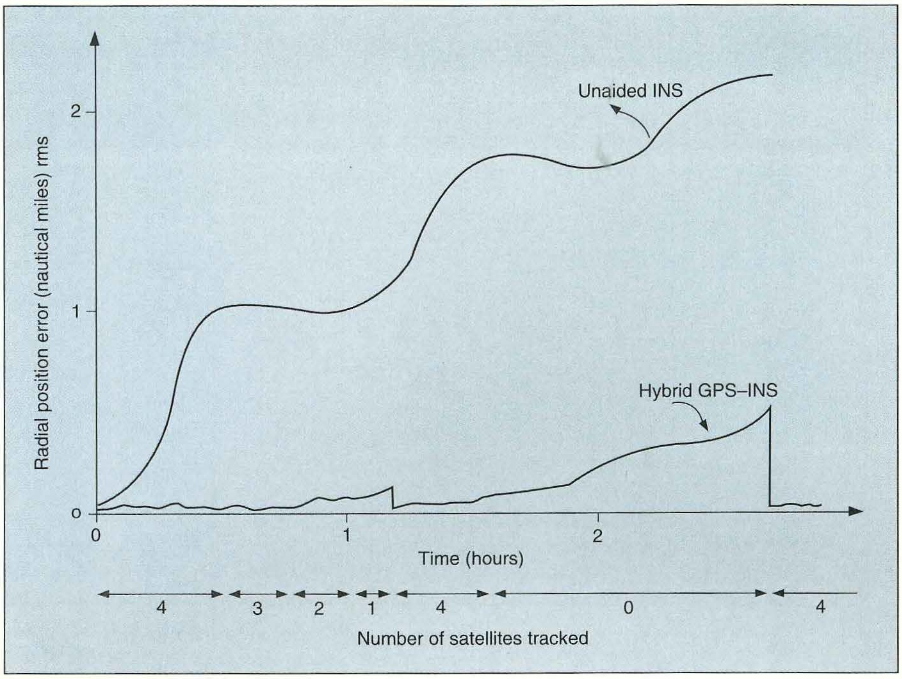


Figure 4. Typical variation in hybrid GPS–INS position error with number of satellites tracked.

cost, make embedded systems particularly attractive.

Numerous variations of the aforementioned coupling strategies have been implemented or studied, including so-called intimately coupled systems where the total vehicle dynamics are estimated using the raw ISA outputs along with the receiver's code and phase detector outputs using a high-iteration rate Kalman filter. Although these implementations may theoretically improve performance by statistically adjusting bandwidths, their marginal incremental benefits do not currently justify the significantly increased processing load, complexity, and single point of failure limitations.

GPS BENEFITS TO INS

Initialization of the INS requires knowledge of three-dimensional position, velocity, and level and azimuth orientations. During a stationary ground alignment, a GPS receiver provides the position information, while the angular alignment is accomplished independently by the inertial navigator simultaneously seeking a level orientation and nulling the difference between the sensed and computed easterly component of earth rotation — a procedure called *gyrocompassing.*

For dynamic in-air alignments, GPS can, in addition, provide the initializing velocities. INS level misalignments propagate into INS velocities over time through the action of gravity and vertical accelerations. Although GPS cannot directly measure attitude (excluding unconventional multiantenna interferometric systems) and thereby provide instantaneous alignment data, a comparison of INS velocities with GPS velocities over time enables the estimation of level misalignments. Horizontal accelerations of the aircraft significantly increase the observability of azimuth misalignments, thereby potentially enabling an in-air alignment using precise GPS velocities to be accomplished more quickly than a stationary alignment.

Calibration. Subsequent to initialization, and when there is sufficient satellite availability, the hybrid GPS–INS filter will essentially follow the GPS positions with a somewhat reduced level of high-frequency noise. During these times, underlying sources of INS error propagation, primarily those due to residual accelerometer and gyroscope instrument biases, can be estimated.

As a result of these calibrations, during subsequent periods of reduced satellite availability or complete unavailability of GPS, the calibrated performance of the INS will be superior to its nominal performance characteristics. Figure 4 depicts the performance of a hybrid GPS–INS filter under varying conditions of satellite availability in comparison with an unaided INS. Following 20 minutes of full GPS availability, a 1-nautical-mile-per-hour INS would typically drift at the reduced rate of 0.5 nautical miles per hour for up to an hour after total loss of GPS. In this respect, GPS can be regarded as a cost enhancement for the INS, potentially allowing the utilization of less accurate, less costly gyroscopes (the principal cost and accuracy driver) for selected applications.

INS BENEFITS TO GPS

During initial satellite signal acquisition or reacquisition after total signal loss of lock, a GPS receiver must search over a region of pseudorandom noise code uncertainty while simultaneously assuming that the Doppler-shifted signal frequency is within a certain frequency bin.

For a selected code uncertainty region, the receiver will search over different frequency bins until an indication of satisfactory signal correlation is achieved. Under dynamic vehicle conditions, a major part of the frequency uncertainty is due to the Doppler shift contribution caused by velocity uncertainty.

Under conditions of total signal loss of lock followed by a high-dynamic maneuver, the frequency uncertainty can be so large for an unaided receiver that it precludes the timely signal reacquisition. With INS velocity-aiding data, the frequency uncertainty can usually be reduced such that only one frequency bin needs to be utilized, thus increasing the probability of a timely reacquisition.

Jamming. The navigation accuracy of a mission under hostile jamming conditions can be enhanced if the GPS receiver can at least provide accurate pseudoranges for as long as possible as the vehicle approaches the area of increased jamming power. To make pseudorange measurements under dynamic conditions, the receiver must employ a code tracking loop with a bandwidth wide enough to account for code phase changes due to line-of-sight dynamics primarily induced by vehicle maneuvers. However, the bandwidth must be narrow enough to limit the level of jamming noise seen by the phase detector. During times when the carrier tracking loop can maintain lock, range rate aiding to the code loop can be provided by the carrier loop, thereby reducing the effective level of dynamics seen by the code loop.

Once carrier loop tracking is lost, INS aiding must be employed to maintain code loop tracking. Bandwidth reductions are possible by using the INS velocities, thereby eliminating the need for the tracking loop to follow signal variations due to vehicle maneuvers. For a tightly coupled system, the incremental benefit of an INS under high-dynamic conditions relative to an unaided system results in an increased jamming margin of about 15 dB for pseudorange measurements. Each 6 dB increase in jamming margin represents a halving of the distance at which a jammer of a given power could disable availability of GPS.

Once tracking of the code loop becomes impossible due to jamming, the calibrated INS allows for graceful degradation of the vehicle s navigation capability. The incremental high-dynamic antijam benefits of INS aiding apply to all types of jamming signals and are equally, if not more, effective for Standard Positioning Service receivers using the C/A-code, although the overall jamming margins achievable will be approximately 6 dB less.

Several military tightly coupled systems also implement direct INS aiding of the carrier-phase tracking loop. This extends the jamming margins available for data demodulation, carrier-phase positioning, and GPS velocities using delta ranges. The technical difficulty with direct carrier-phase aiding using an INS is that any effective INS velocity error as resolved into the line-of-sight aiding signal must not induce a cycle slip. This means that accumulated velocity errors over a time interval commensurate with the tracking loop bandwidth must be less than several centimeters, root-mean-square (rms). This implies that extreme care must be utilized when accounting for senescence, latency, flexure, and lever arm effects (the *lever arm* is the physical displacement of the GPS antenna phase center from the IMU location; *flexure* refers to variations in this displacement). Incremental benefits of INS aiding for maintaining delta range measurements and data demodulation are estimated to be about 7 dB.

Velocity. The accuracy of GPS stand-alone velocities for accurate high-dynamic, real-time applications can be marginal due to data senescence, delta range interval averaging effects, and tracking loop bandwidth limitations. These effects are largely overcome when the INS assumes the task of providing the high-frequency information. GPS—INS velocity instrument accuracies of about 3 centimeters per second (rms) per axis under dynamic conditions are expected.

Attitude. GPS—INS instrument attitude accuracies of about 0.002 degrees (rms) in the level (horizontal) axes and 0.01 degrees (rms) in azimuth are expected under dynamic conditions with attitude changes of up to several hundred degrees per second. Accurate attitude is necessary for targeting and seeking applications, to further improve antijam margins utilizing nulling or beam steering antennas, and for accurate lever arm compensations. Multiantenna separation limitations, antenna phase center variations, processing delays, and multipath errors appear to preclude commensurate performance from a GPS stand-alone attitude determination system.

Integrity Monitoring. Integrity monitoring refers to the timely detection and isolation of an unhealthy satellite or invalid data in a satellite navigation message before their manifestation beyond a threshold level of navigation error (see Synergistic Integration of GPS and INS for Civil Aviation in the May 1991 issue of *GPS World*). A stand-alone GPS or GPS-altimeter—aided system with the present space and control segment configuration will probably not meet anticipated requirements for availability of integrity monitoring for sole-means navigation conditions.

Although further definition of requirements and research is needed in this area, the autonomy and rapid response characteristics of even a relatively low-cost INS should enable detection and isolation of many classes of signal-in-space failures that could not otherwise be corrected in a timely fashion by the control segment, receiver autonomous integrity monitoring (RAIM), or other receiver algorithmic modifications. In a similar manner, GPS—INS integration should be useful in combatting potential GPS signal spoofers. Spoofing can deny, degrade, or deceive the GPS receiver s outputs by generating a GPS-like signal capable of passing the C/A-code correlator stage of the receiver without spreading, thereby utilizing less power than a conventional jammer would.

Precise Positioning. INSs may be valuable for kinematic carrier-phase differential GPS operations such as precision aircraft approach applications, where the real-time detection of cycle slips is critical. The INS velocities can be used as a check on invalid changes in cycle counts over an interval, particularly for single-frequency operations, and can aid in reducing the integer search region for short-duration carrier signal losses of lock.

STATUS

The U.S. Department of Defense (DoD) has several embedded GPS—INS systems under development or in procurement. The Navy program, designated GPS Inertial Navigation Assembly (GINA), is initially targeted for the McDonnell Douglas/British Aerospace T-45

jet trainer — the first DoD aircraft scheduled to have a production embedded GPS–INS system. A contract was let in April 1993 with initial preproduction units for integration testing expected for delivery in late 1993 and production deliveries scheduled to start in March 1996. The system, which has a PPS five-channel embedded GPS receiver, should generally meet the unaided INS performance parameters of Table 1 within a physical 7 inches wide by 7 inches high by 11 inches deep envelope (1 inch = 2.54 centimeters). Nominal weight and power requirements are 23 pounds (1 pound ≈ 454 grams) and 42 watts at 28 volts DC.

The GINA requirements incorporate two interesting features that should enhance its overall flexibility and utility. The first is the continuous maintenance of a GPS only (in addition to the hybrid GPS–INS) solution that can also accept aiding of its code tracking loop from an external INS or Doppler navigation system. This may be desirable in the event of an inertial component failure within the embedded IMU. The second feature calls for the ability to input from an external simulation device some level of dynamic simulated IMU data during laboratory testing using a GPS satellite signal generator. The satellite signal generator and external IMU simulator would be programmed to exercise the same user dynamics simultaneously. This could provide some system-level testing alternatives to expensive flight testing on an instrumented range.

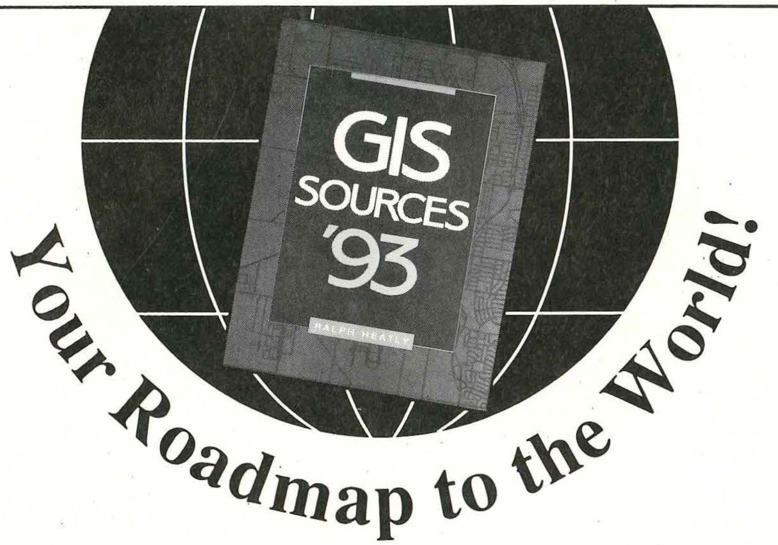
The GPS Guidance Package (GGP), sponsored by the Advanced Research Project Agency (ARPA), will be a low-cost, miniature 10-channel PPS, tightly coupled embedded system aimed at a variety of DoD manned and unmanned platforms. The GGP will exploit technologies for monolithic microwave integrated circuits, fiber-optic gyros (FOGs), solid-state accelerometers, and integrated optical circuits. The Phase I GGP, one of the first embedded systems truly designed from the start as a totally integrated package, is scheduled for completion in late 1994. It will have a volume of 295 cubic inches and a weight of 14.9 pounds. The Phase II GGP, scheduled for completion in 1998, will aim for a 100-cubic inch and 7-pound package.

The Air Force's Aeronautical Systems Center at Wright-Patterson Air Force Base, operating under a broad directive to be the lead service for acquisition of advanced GPS–INS embedded systems, has issued draft Requests for Proposals for the Embedded GPS Inertial (EGI) System. Preliminary schedules call for large-scale procurements beginning in late 1995.

OUTLOOK

Commercial GPS–INS integrations are still in a relatively early stage of development as exemplified by the appearance, only within the last two years, of commercially available embedded systems. Their attributes appear so compelling for many applications that expansion into new market areas is inevitable. Recent advances in inertial component and GPS circuit technology, including lower-cost FOGs, solid-state multisensor ISAs, and single-chip GPS receivers, will provide the miniaturization and cost reductions currently limiting this expansion. ■

For product information, turn to page 74 and see Manufacturers. *For reprints (250 minimum), contact Marketing Services, (503) 343-1200.*



CALENDAR

SEPTEMBER 19-22

63rd Annual Meeting of the U.S. Institute of Transportation Engineers

The Hague, The Netherlands. Contact: U.S. Institute of Transportation Engineers, (202) 554-8050, fax (202) 863-5486.

SEPTEMBER 20-21

Civil GPS Service Interface Committee Meeting

Salt Lake City, Utah. The 22nd meeting of the Civil GPS Service Interface Committee (CGSIC) is organized by the U.S. Coast Guard. Contact: Lt. Luann Barndt, USCG ONSCEN (GPSIC), 7323 Telegraph Road, Alexandria, VA 22310, USA, (703) 313-5862, fax (703) 313-5920.

SEPTEMBER 20-21

ION GPS-93 Tutorials

Salt Lake City, Utah. Contact: Navtech Seminars, 2775 South Quincy Street, Suite 610, Arlington, VA 22206-2204, USA, (800) NAV-0885, fax (703) 931-0503.

SEPTEMBER 22-24

The Satellite Division of the Institute of Navigation's Sixth International Technical Meeting

Salt Lake City, Utah. Contact: Phillip W. Ward, Navward GPS Consulting, 9629 Covemeadow Drive, Dallas, TX 75238-1819, USA, (214) 348-9446, fax (214) 348-9447.

SEPTEMBER 30-OCTOBER 1

Mobile Satellite Users Expo '93

Arlington, Virginia. The third annual Mobile Satellite Users Expo is hosted by COMSAT Corporation. The expo will include panel discussions, exhibits, and demonstrations of mobile satellite technology. Contact: Christine Kramer, COMSAT Mobile Communications, (202) 863-6809, fax (202) 863-7418.

OCTOBER 12-14

INMARSAT Conference

Paris, France. Mobile satellite communications affecting governments, regulators, manufacturers, suppliers, and end users. Contact: Tania Starley, IBC Technical Services Ltd., Gilmoora House, 57-46 Mortimer Street, London W1N 7TD, United Kingdom, +44 (71) 637 4383, fax +44 (71) 631 3214.

OCTOBER 12-15

VNIS '93: IVHS Toward 2000

Ottowa, Ontario, Canada. IEE/IEEE international conference on vehicle navigation and information systems. Contact: VNIS '93 Registration, Conference Coll Inc., 1138 Sherman Drive, Ottawa, Ontario, Canada K2C 2M4, (613) 224-1741, fax (613) 224-9685.

OCTOBER 19-21

83rd Airlines Electronic Engineering Committee (AEEC) General Session

Tulsa, Oklahoma. Contact: ARINC, Inc., 2551 Riva Road, Annapolis, MD 21401-7465, USA, (410) 266-4110, fax (410) 266-4040.

NOVEMBER 2-4

NAV 93: Practical Navigation — The Application of Advanced Systems

London, United Kingdom. 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. *The Bottom Line: DGPS Speeds Offshore Oil Pipeline Project.*
The SkyFix DGPS reference station was backed up by HyperFix, a portable 2-MHz radio positioning system, and MicroFix, a mobile 5-GHz terrestrial positioning system. SkyTrac, a GPS-based system, was used for remote tracking of targets operating in the pseudorange domain. All of the aforementioned services are from **Racal Survey Ltd.,** New Malden, Surrey, United Kingdom. Model 4000 RL GPS receivers from **Trimble Navigation,** Sunnyvale, California, were used at the SkyFix reference station and 4000 DL on board the vessels.

Page 28. *Getting the Bugs Out: GPS-guided Aerial Spraying.*
For the GPS evaluation, USDA used the AirStar system from **Satloc,** Casa Grande, Arizona; **Custom Farm Service,** Stanfield, Arizona, markets the system. Both the AirStar and the base station utilized the GPSCard 911R 10-channel receiver from **NovAtel Communications,** Calgary, Alberta, Canada. The datalink is a proprietary forward error-correcting unit developed by Satloc. The onboard computer was a Little Monster II unit from **Zykronix,** Englewood, Colorado. In addition to the GPS receiver and 900-MHz radiolinks, the base station was equipped with a 286 computer with 1Mb of memory, a monitor, and a keyboard, all from **SIIG,** Fremont, California. Before the spray operation, fieldwork was done with Pathfinder Basic handheld receivers from **Trimble.**

Page 36. *On Shifting Ground: GPS Control Networks in California.*
The dual-frequency, P-code receiver used for field observations was a Geodesist II P receiver from **Trimble Navigation,** Sunnyvale, California. The Jena Ni002 and Wild NA2002 units by **Leica Wild,** Deerfield, Illinois, recorded digital/barcode levels. **National Geodetic Survey (NGS),** Rockville, Maryland, developed the OMNI and ADJUST software programs for final data reduction and adjustments.

Page 56. *Inertial Navigation and GPS.*
The Navy's GPS Inertial Navigation Assembly is being provided by **Litton Industries,** Arlington, Virginia. The embedded GPS receiver is manufactured by Cedar Rapids, Iowa–based **Rockwell Collins.** Litton, for the inertial, and Rockwell Collins, for the embedded GPS, also form the contractor team for ARPA's GGP.

Manufacturer credits reflect the products used for the applications, as reported by the authors, at the time the articles were written.