Navigation at APL: A Historical Perspective and a Look Forward

Robert L. Henderson, William S. Devereux, and Thomas Thompson

The Space Department was founded in 1959 because of a seminal concept developed by APL engineers to solve a critical navigation problem for the U.S. Navy and the nation. The National Security Space Business Area, as well as several other business areas (notably Precision Engagement, Strategic Systems, InfoCentric Operations, and Civilian Space) at APL, continues to provide sponsors with innovative solutions to existing navigation problems and new ideas to counter future threats. This article will provide a historical perspective of APL's contributions to the science and engineering of global and theater navigation systems and will highlight some exciting new technologies and capabilities being developed today.

INTRODUCTION

An enemy aircraft, packed with explosives, bears down on a U.S. warship. It is March of 1944, and the kamikaze pilot is intent on unleashing his deadly cargo on the American vessel and its crew. But a mere 1000 yards from his goal, an anti-aircraft shell explodes so close to his plane that it breaks the aircraft apart, leaving its fragments to plummet harmlessly into the deep Pacific. Lives and a critically important asset are most assuredly saved.

The APL spacecraft Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED), launched in 2001, tirelessly circles Earth and uses remote sensing instruments to probe the upper atmosphere and its reactions to inputs from the Sun above and the inhabitants below. TIMED knows precisely and autonomously where it is and how fast it is going, critical parameters for the proper interpretation of its scientific data. The data collected by TIMED may soon help humankind better understand the consequences of our actions on the upper atmosphere and lead us to change our energy generation and consumption habits and approaches.

A Tomahawk cruise missile flies a low and circuitous route over enemy territory, eluding the attention of enemy radars. It follows a meticulously planned path away from detection yet toward its target: an antiaircraft missile system intent on shooting down soon-to-be-arriving piloted aircraft from the Nimitz-class USS *Enterprise*, at sea hundreds of miles away. The Tomahawk strikes within feet of its intended target, taking out the threatening installation. Two American pilots soon follow and safely carry out their mission.

The recently launched and state-of-the-art, yet lifeless, school-bus-sized spacecraft tumbles toward an unplanned and fiery encounter with Earth's atmosphere. Within its hold lurks a potentially deadly and toxic cargo: a 1000-lb block of unused hydrazine fuel. Although most dying spacecraft break apart and burn up harmlessly on reentry, some portion of this threatening mass is expected to survive. A sophisticated sea-launched interceptor chases down and destroys the spacecraft, breaking it into pieces small enough to melt away. Lives and property are very possibly saved, and an unwanted political fall-out is averted.

These are four seemingly unrelated events, yet they are tied together by APL's 65+ years of critically important contributions to the art and science of navigation and its practical application to both national security and scientific discovery. APL's scientists and engineers, from the Laboratory's very first days through today, have been at the forefront of discovery in this field, making what have proven to be seminal contributions along the way. This article will provide a historical perspective of APL's contributions to the science and engineering of global and theater navigation systems and will highlight some exciting new technologies and capabilities being developed today.

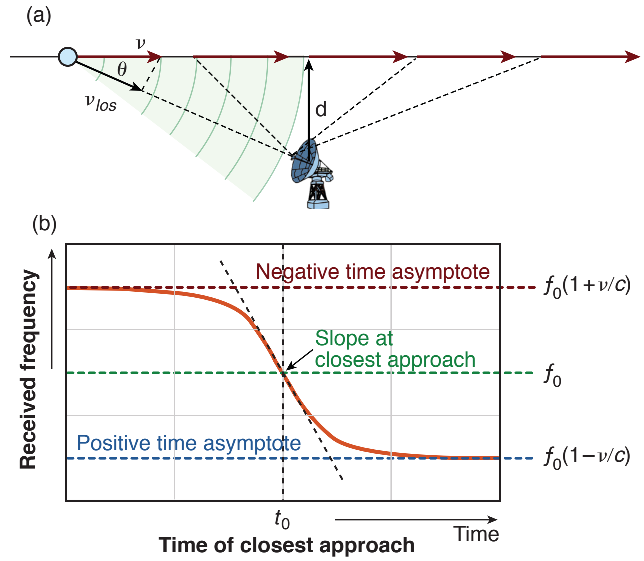

Figure 1. The Doppler effect on the received frequency from a transmitter in straight-line uniform motion allows determination of transmitter frequency and velocity and the time and distance of closest approach. (a) Transmitter/receiver geometry and relative motion. (b) Received frequency pattern and principal measurements. See Box 1 for a Doppler primer.

DOPPLER MEASUREMENT

It is probably not an accident that both the Laboratory as a whole and the Space Department in particular got their respective starts with a Doppler measurement. Doppler is a simple kind of measurement, as fundamental as the changing pitch of a police siren going by on the street, but one that has seen unending exploitation to meet critical needs. (See Box 1 and Fig. 1.)

The Variable Time Fuze

Let us go back to the beginning. In the Pacific theater of World War II, the U.S. Navy desperately needed a highly effective means to shoot down attacking (often kamikaze) enemy aircraft. Losses in lives and shipping were simply unsustainable. To shoot down an aircraft, one needs to aim a shell correctly and then cause it to detonate at precisely the right time. In the midst of the war, APL provided the solution to the timing problem, a solution that neither German nor Japanese scientific and engineering establishments were able to match, and turned the course of the war in the Pacific. This story is a cornerstone of APL's proud history and is described in detail in numerous other sources; see Ref. 1 for an example.

The approach was to equip each shell with an RF transmit/receive device. As the shell closed in on an attacking aircraft, the reflected signal, offset in frequency by the Doppler effect, would beat against the transmitted signal and set up an audio frequency (less than a few thousand hertz) fluctuation in the transceiver electronics. Amplified and filtered, this fluctuation, when it reached the frequency and amplitude indicating that the shell was within its blast radius of the intended target, would initiate fuzing. Detonation of the shell could thus be timed (hence, the "variable time," or VT, fuze) for maximum effect. (The challenge of course was to do this with 1940s technology—vacuum tubes in an artillery shell!) Here was a technology innovation that saved untold numbers of lives, based on something as simple in principle as the Doppler shift of a returned radio signal. Of a version adapted to explode artillery shells at predetermined heights above ground, and employed to great effect in the Battle of the Bulge, General Patton wrote (29 December 1944):

> *The new shell with the funny fuze is devastating. . . . I think that when all armies get this shell we will have to devise some new method of warfare. I am glad that you all thought of it first. It is really a wonderful achievement.*
>
> –Quoted by Baldwin on p. xxxi of Ref. 1.

BOX 1. A DOPPLER PRIMER

The Doppler shift of frequency from a moving object is a familiar everyday experience for acoustic signals: for instance, the apparent pitch change of a train's whistle as it speeds by. The same basic effect applies to electromagnetic radiation: the frequency of an approaching source appears higher than the raw transmitted frequency (that is, the frequency from the source at rest) and the frequency appears lower for a source that recedes. The amount of shift is determined by the component of source velocity along the line of sight between receiver and source. The Doppler component is

$$f_D = -f_0 \frac{\dot{r}}{c},$$

where f_0 is the transmitted frequency and $\dot{r}$ is the velocity in the line of sight relative to the receiver. The minus sign ensures that for an approaching transmitter ($\dot{r} < 0$) the observed frequency is increased. Here c is the speed of light; the form neglects relativistic corrections of order v^2/c^2; and the transmission is one way, as, for instance, in a user-passive satellite navigation system (Global Positioning System, or GPS); for radar returns, as in the case of the VT fuze, or returns for spacecraft navigation, the transmission is two way and the calculation requires an extra factor of 2.

For the space navigation cases discussed in this article, this frequency change provides a measure of the line-of-sight velocity of a spacecraft relative to an Earth-based receiver. [Direct measurement can be complicated by signal return times that may be minutes or even hours (for deep space missions), during which time the spacecraft moves, Earth moves and rotates, and we may even be receiving on a different receiving antenna.] With proper accounting for the motion of the Earth-based receiver and the spacecraft ($\dot{r}$ combines the motion of both), such measurements form input into estimators for the spacecraft trajectory.

In the case of the VT fuze, the objective was to sense the target and detonate within a preset radius of the target. The test was fundamentally on the amplitude of the interference pattern between the transmitted signal and the Doppler-shifted return. This amplitude would increase as the strength of the Doppler return increased, effectively yielding a range measurement. The parameters had to be adjusted depending on the target type, e.g., metal skin of an attacking aircraft for anti-aircraft or ground return for an artillery shell (see, for example, the discussion on pp. 20–21 of Ref. 1).

Of interest for Doppler location is the shape of the Doppler curve as a transmitter (or reflector) passes by a receiver (basically, from negative to positive "far away"—the train-whistle case). Figure 1 illustrates a transmitter that moves with constant speed v (assumed positive) along a straight line and passes within a distance d of a receiver (*rec*). The line-of-sight velocity goes with the cosine of the angle θ ($\dot{r} = -v\cos\theta$, Fig. 1a), so that the received frequency is

$$f_{rec}(\tau) = f_0\left(1 + \frac{v}{c}\cos\theta(\tau)\right).$$

Here τ is time measured from the point of closest approach (negative for times ahead of closest approach). As θ varies due to the motion, the Doppler component changes, so that the overall received frequency takes a form like that shown in Fig. 1b. Suppose we detect such a signal. What can be learned?

In this simple model the received Doppler provides direct measurement of the frequency of the source, the speed of the source, and the time and distance of closest approach. From the cosine extremes (±1), the asymptotes of the frequency are $f_0(1 \pm v/c)$, so that the average of the asymptotes gives f_0 and the difference between them gives v. The time at which the received frequency crosses f_0 is the time of closest approach, and given f_0 and v, the slope of the curve at that point yields the distance of closest approach. (The train-whistle Doppler shift from high to low occurs a lot faster for a listener standing right beside the tracks than for one standing a mile away.)

For determining the Sputnik orbit, this basic picture applies but with some complication. It might seem that analysis of a single pass would not be sufficient to determine the motion. Indeed, the basic Doppler measurement as described above has no sensitivity to the direction of the motion, only to the fact that the signal source "passes by." In fact, though, the Earth's rotation under the inertially fixed plane of the satellite orbit creates an asymmetry that allows for significant observability on a single pass over an Earth-fixed receiver. For spacecraft for which good orbit precision is required, e.g., navigation satellites, full orbit determination is based on a number of such measurements from different pass geometries, stirred together with the math of orbital dynamics, to converge on a solution.

For the Transit navigation system, the orbits of the transmitting Transit satellites are extremely well known and the objective is to locate the position of a receiver on Earth. For a receiver of known altitude (e.g., a ship at sea or a stationary land surveyed point), a single pass by a single satellite, in fact only a short portion of such a pass, suffices to determine receiver position. To see how, consider that once the receiving station determines the time of closest approach, the spacecraft position (latitude/longitude) at that time is known from the satellite trajectory information. Because the Transit satellites are in polar orbit (straight north–south) the receiver latitude at that time is thus the same as that of the spacecraft. Furthermore, with the receiver altitude known, the Doppler slope at closest approach gives the difference in longitude between the receiver and the spacecraft. (The remaining east–west ambiguity, i.e., same difference in longitude, is usually easily resolved.) In practice, the solution involves intersection of multiple hyperbolas, of constant Doppler, on Earth's surface. This "single-pass" feature was critical to Transit concept and operation. (But note that multiple passes of a stationary point could provide extremely precise positioning. Indeed, Transit surveys provided the original determination of site locations for the GPS tracking stations.)

Sputnik Orbit Determination

Fast-forward 14 years, to 1957. APL is an established institution. The Soviet Union launches Sputnik (4 October 1957) and the space race is on. But the United States faces other problems besides beating the Russians to space, and one of them is the U.S. Navy's problem of precisely locating its nuclear fleet to provide the required accuracy for surface and subsurface missile launches. A chain of inventions at APL, starting from a Sputnik observation, led to the solution of the Navy's problem and the creation of a space-faring capability within APL, again based on exploitation of the Doppler effect.

The Sputnik satellite transmitted a continuous 20.001-MHz tone. The Soviets had chosen this frequency so that anyone with a 20-MHz reference could pick up the difference signal as an audible tone, varying roughly between 500 and 1500 Hz (from about C above middle C to G an octave and a half higher). The variation, of course, was Doppler. Using a ground-based receiver, APL engineers W. H. Guier and G. C. Weiffenbach captured and processed this signal. (Among all those monitoring Sputnik in its early days, these two were the only ones focusing on its Doppler.) From the pattern of the Doppler shift, the time of a spacecraft's closest approach to the receiver could be determined, and with some refinement, Guier and Weiffenbach were quickly achieving better orbit knowledge (measured by ability to predict subsequent passes) than anyone else. (For a very readable discussion, and yet another reminder that science does not always proceed in straight lines, see the story of this effort by Guier and Weiffenbach themselves.[2])

TRANSIT

It was the next step, however, that turned this observation from an interesting exercise into a major system development for APL and the U.S. Navy. It was Frank McClure at APL who spotted it.[2] The step was to realize that this process could be inverted: if a satellite orbit was well known by other means, then the location of a ground-based receiver could be accurately determined, by that receiver, from observations of the Doppler shift of the satellite signals. With this recognition the Navy's Transit navigation system was born. The issue was accurate at-sea navigation for the Navy's fleet, particularly its missile launchers, because at the time, targeting of a missile could certainly be no better than the knowledge of its launch point.

Basically what was needed was "Sputnik in reverse," but a single satellite in low-Earth orbit is visible to any one ground location only a small portion of the time. What was needed for an operational capability was a full constellation. To that end, APL proposed, designed, built, and then helped operate the Transit system. The system eventually consisted of four to eight (typically six) operational spacecraft in polar orbit. In addition to designing the satellites, APL developed the prototype ground station (one of which is still at APL and is used for other missions) and developed ship-based radio receivers used for detecting and processing the Transit signals. APL designed the algorithms and software used to reduce the Doppler measurements from the Transit satellites to a complete navigation fix. These accomplishments were all transitioned to industry during the lifetime of the Transit system. The resulting Transit system met the navigational needs of the U.S. Navy for some 40 years, demonstrated the absolute utility of satellite-based navigation, and paved the way for its modern replacement, the GPS.[3]

The Transit system stands as one of APL's greatest achievements. The space segment alone cataloged an impressive list of firsts[3–5] that included the first nuclear-powered spacecraft, the first spacecraft to be magnetically stabilized, and the first gravity-gradient-stabilized spacecraft, not to mention simply the first space mission to require a constellation.[5] A more extensive list of such achievements (note the dates!) is shown in Table 1. The system would never have achieved the desired accuracy without the development of the dual-frequency approach to ionospheric compensation (for the beginnings, see, for example, Ref. 6), which is still the baseline in GPS today, or the detailed tropospheric models developed by APL scientist Helen Hopfield, models that bear her name.[7] Also, and not very fortunately, Earth is not a perfect sphere, and work at APL, eventually coupled into the work of many others, was critical in mapping and representing Earth's gravitational field in a way that orbits could be predicted with high accuracy and resonance effects avoided or compensated.[8] Even today, several Transit satellites are still in orbit and are used as atmospheric "sounders" for continuing research.

And, of course, along the way the APL Space Department was born.

TIME MEASUREMENT

With such intense focus on precise navigation, it is no surprise that APL, and particularly the Space Department, has developed world-class timekeeping capabilities. As anyone who has read Dava Sovel's *Longitude*[9] knows, precise timekeeping is essential to accurate navigation. In the world of John Harrison and his chronometer (the subject of *Longitude*), this meant at sea. In today's world, this means anywhere on Earth, in near and deep space, and on Earth while using space-based assets.

Time and Frequency Laboratory

The first requirement of timekeeping is a reliable, easily disseminated timescale. A timescale is a measuring standard by which events can be coordinated in

Table 1. Transit firsts.

Satellite	Date	Firsts
Transit 1A	17 Sept 1959	• Yo-yo de-spin mechanism • Dual-frequency ionospheric corrections • Doppler trajectory determination
Transit 1B	13 Apr 1960	• Magnetic attitude control system
Transit 2A	22 June 1960	• Dual-payload launch • Satellite geodetic survey capability • Measurements of long-term satellite drag effects
Transit 3B	21 Feb 1961	• Satellite electronic memory • Navigation message and time synchronization capability
Transit 4A	29 June 1961	• Triple-payload launch • Operational navigation transmissions • Satellite nuclear power supply
Transit 5A-1	19 Dec 1962	• Operational configuration with deployable solar arrays • Satellite uplink authentication system
Transit 5A-3	16 June 1963	• Gravity-gradient-stabilized satellite • Automatic thermal control
TRIAD	2 Sept 1972	• Disturbance compensation system (three-axis) • Single-frequency (group/phase delay) ionosphere error correction
TIP-II	12 Oct 1975	• Drift-corrected crystal oscillator • Pulsed plasma microthrusters • Worldwide time synchronization to 40 ns

Derived from Ref. 5.

time by using universally accepted intervals generated by a precise clock. For centuries (or most of humankind's existence), the clock represented simply by the rotation of Earth drove the timescale, and the timescale interval was known as the day. But with today's requirements, where, for instance, position is calculated by multiplying accurate times by the speed of light, Earth itself proves a rather ever-changing clock for the world's timescale. Its pole wanders, the rotation rate varies, and the overall average length of day is steadily increasing because of the action of tides.

APL has been an important player since 1978 in determining and contributing to the key international timescale, Universal Time, Coordinated, or UTC. This is a synthesized, worldwide universal timekeeping standard that is derived from the performance of an ensemble of atomic clocks located in laboratories on several continents. The APL master clock, located in the Time and Frequency Laboratory (TFL) shown in Fig. 2, is a contributor to the UTC ensemble and is given the designation UTC(APL).[10] The TFL maintains a timekeeping ensemble consisting of three high-performance cesium and three hydrogen masers. These six precision frequency standards are referenced to UTC(APL), which is the output of an extremely accurate frequency synthesizer (microphase stepper) driven by one of the TFL's cesium atomic frequency standards. The ensemble measurements thereby monitor the variations in the UTC(APL) master clock as it is steered to UTC. As a safeguard monitor, daily GPS common-view time transfer data are compared between the U.S. Naval Observatory and the National Institute of Standards and Technology to alert of imminent inaccuracy. Adjustments to the microphase stepper are based on monthly reports from the Bureau International des Poids et Mesures that give the time error difference, UTC – UTC(APL).

Ultrastable Oscillator

The second requirement is to keep the precise local master clock in various applications well synchronized to its relevant timescale. Accurate synchronization over time depends mostly on how stable the master clock is when it is running free. Clock (or time) stability and its associated derivative (frequency stability) are critical factors in precision performance of a host of modern systems, from navigation, communication, and tracking, to medical imaging and many others.

Modern clocks determine time by counting cycles from a frequency reference (actually, so does the pendulum grandfather clock in the living room), so that the critical measure of clock performance is the frequency stability of its reference. The standard method for measuring frequency stability for precision frequency references is the Allan deviation,[11] represented in Fig. 3. Roughly speaking, the Allan deviation is a measure of the random error that will be introduced by a given frequency reference (or oscillator type) as a function of the time interval being measured. The common "bathtub" shape of these curves indicates the dominance of different noise sources over different time intervals.

APL has developed, and flown on multiple spacecraft, the ultrastable oscillator (USO), shown in Fig. 4. As is evident in the Allan deviation results shown in Fig. 3, this package provides frequency stability that fills the performance gap between atomic clocks, when aver-

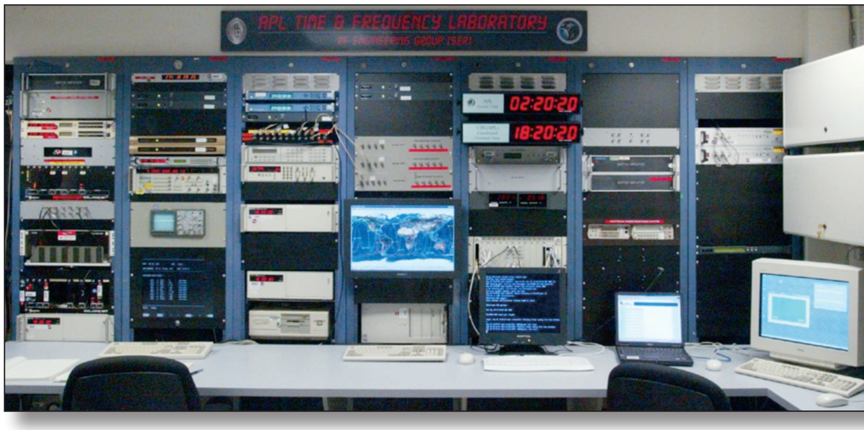

Figure 2. APL's TFL (building 4, third floor) is a member of the international ensemble responsible for UTC.

aged over long time periods, and ordinary oscillators, which maintain their stability only for short periods. Ongoing efforts in disciplining (or "steering") the APL USO to compensate for long-term drift are achieving performance that begins to approach that of the atomic references.

The principal characteristic of the APL USO is its extremely low noise. In fact, an industry driver for very low-noise oscillators actually derives from the atomic clocks themselves, in which such oscillators act as a "flywheel" to enable the lock-in amplifiers to find and hold the extremely narrow ($Q \sim 10^9$) atomic frequency line. The principal thrust of APL's effort has been toward precise frequency references for space instruments and space science missions.[12] Indeed, APL USOs have come to dominate in this arena. An APL USO enabled the mapping of the cosmic background radiation by the Cosmic Background Explorer (COBE), revolutionizing our understanding of cosmology. An APL USO on Cassini enables the radio science that has produced the detailed mapping of Saturn's ring structure. For their ability to maintain precise synchronization between two independent spacecraft in lunar orbit, USOs are currently being delivered to the Gravity Recovery and Interior Laboratory (GRAIL) lunar mission.

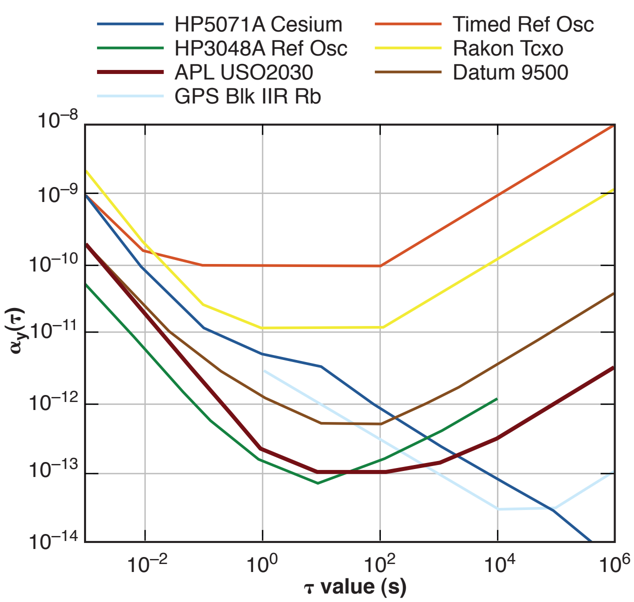

Figure 3. Allan deviation results for atomic, high-precision quartz and the APL USO oscillators. (We are indebted to Dr. Dennis Duven, APL Space Department, for granting us permission to use his MATLAB compilation of system performance.)

APL AND THE GPS

As is widely known, a GPS receiver determines its position by measuring the signal travel time from multiple spacecraft, whose orbits are precisely known, to a receiver and then multiplying by the speed of light to obtain a "pseudo-range." This pseudo-range is not usable for navigation until the receiver clock can be synchronized accurately with the clocks in the GPS constellation. So of the classic triad Doppler, time, and range, GPS is fundamentally a range- and time-based system. (See Box 2 and Fig. 5.)

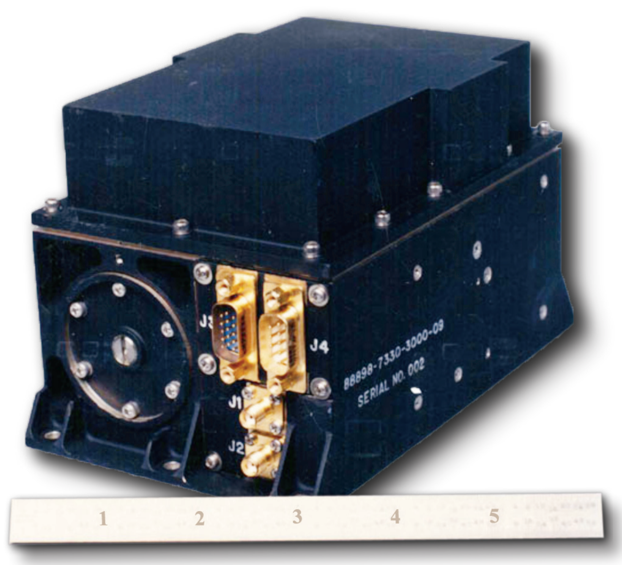

Figure 4. The APL USO.

BOX 2. A GPS PRIMER

A GPS receiver works out its position basically from a set of range measurements. Figure 5a indicates a GPS receiver with ranges to multiple GPS spacecraft shown. If these ranges can be measured, and if the locations of the spacecraft are known, the position of the receiver can be determined, basically as the intersection of a number of spheres whose only common point is the receiver position. But of course, nothing is ever that simple. . . .

How are these ranges measured? The underlying principle is shown in Fig. 5a. Each GPS satellite transmits a ranging code and the receiver locks to these codes and measures code delays. The system is a Code Division Multiple Access system, in the sense that the codes from different satellites when correlated against each other are orthogonal—the correlations give (nearly) zero. Further, each of the codes, when correlated against shifted versions of itself, gives a strong match only when the code and its replica are precisely aligned. Each GPS satellite transmits its code according to a sequence that moves in synch with an absolute time standard. In the receiver, replica codes are generated according to the same prescription and then shifted in time to find alignment with the signal received. The resulting time shift ("code delay") is effectively a measure of the transit time of the received signal from GPS satellite to GPS receiver.

This code acquisition process is actually a search both in code delay and in Doppler frequency, because the observed frequency at the receiver is altered by Doppler shift due to motion of both the transmitting spacecraft and the receiver itself. A correlation search (Fig. 5b) across delay/Doppler space encounters the peak shown and identifies the proper delay. Note that once lock is achieved, the receiver can actually phase lock to the GPS signal and achieve measures of relative motion on the order of fractions of the GPS wavelength of 19 cm.

As described, the approach appears to rely on precise synchronization of the clock in the receiver to the clocks in the GPS satellites (any offset in the receiver clock adds directly to the delay required to achieve code alignment, so that "ranges" measured by this process are usually called pseudoranges). In fact, however, the error introduced by receiver clock offset is a common mode error, i.e., applies equally to the delay measurements from all satellites in view. The clock offset can thus be found as part of the navigation solution, as long as at least four satellites (for three position variables and one time variable) are tracked. Indeed, this latter feature has made GPS an effective worldwide standard for time synchronization. Note that part of the challenge in high-attenuation cases is that there can be long periods when not even four satellites can be tracked. Other techniques must be applied, as in the case of GPS at the Moon described in this article.

Other features to note, relative to topics addressed in this article:

1. **Signal strength and integration time:** As received in an unobstructed environment on the surface of Earth, the GPS signal lies well below receiver noise at room temperature in its full acquisition bandwidth. How far below depends on the signal being tracked: The civilian CA signal, for a typical antenna and receiver noise characteristic, sits ~22 dB below the receiver noise; the military codes, being weaker signals with 10 times the bandwidth, sit some 35–38 dB down. In this situation, it is the correlation process noted above that pulls the signal from the noise. When the local code is properly aligned with the received signal, the many thousands of bits in the correlation sum all point in the same direction and the peak emerges. The gain in such processing typically goes with the ratio of the signal bandwidths before and after the integration step. Typical sums greater than ~4 ms result in postprocessing signal to noise ratios of order 17 dB for the civilian codes, 11–14 dB for the military codes. When the GPS signal is heavily attenuated (e.g., for indoor operations), APL weak-signal technologies described in this article directly address means to significantly increase this integration time.

2. **GPS/Inertial Navigation System (INS) navigation:** An extremely powerful combination for navigation of many systems is to combine results from a GPS system and an INS in a single navigation Kalman filter. As discussed in the *APL NAVSIL* section, the performance of each system complements the other.

GPS Genesis

In the late 1960s and early 1970s, APL participated with several other organizations in studies conducted to evaluate constellation and navigation signal alternatives for a future satellite navigation system. The various studies from this activity contributed to establishing the concept that would eventually become GPS. Indeed, at the time, APL was the only organization anywhere in the world with experience in defining, building, fielding, and operating a satellite-based globally capable navigation system. APL studies focused on the potential for a low-Earth-orbit-based constellation solution, constructed as extensions to the basic Transit concept [i.e., establishing a low-Earth-orbit constellation to give two (up to four) in view and incorporating ranging as well as Doppler signal structures that could provide 3-D continuous navigation capability while continuing to support the existing Transit users]. Such APL participation provided critical inputs to the overall process of determining a system solution. Eventually, though, the proposed GPS concept was limited to a blend of the medium- and high-altitude constellation concepts of the earlier studies and the APL concept was not realized.

Although not a direct participant in the GPS space segment development, APL has been a heavy participant in critical developments within the GPS user segment

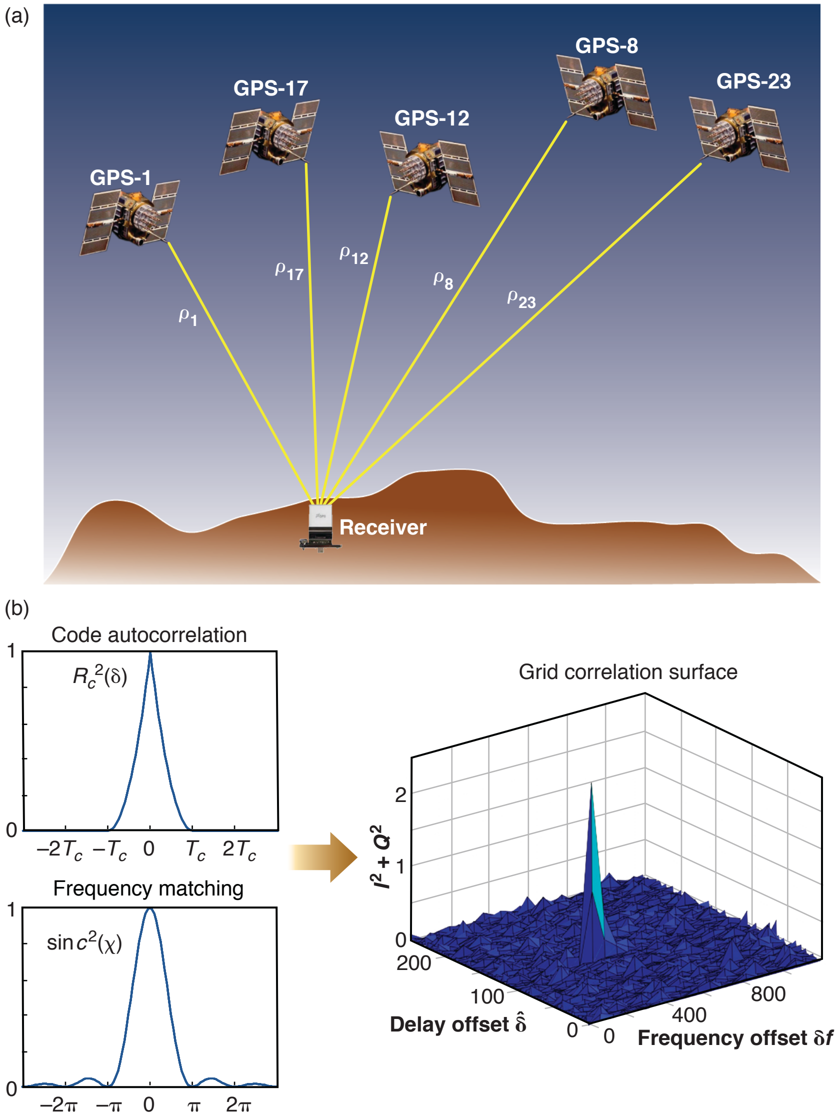

Figure 5. (a) Measured ranges to multiple GPS satellites permit determination of the position of the GPS receiver. (b) GPS signal acquisition identifies the correlation peak at matched frequency and delay. See Box 2 for a GPS primer.

from the very beginning. In fact, as will be described in the *SATRACK* section of this article, a Navy system designed by APL was the first committed user of GPS. The critical Navy capability was first demonstrated using a modified Transit spacecraft called Transat[13] (launched in 1977), giving APL the capability to test the proposed system as soon as the first GPS spacecraft was available. The first Navy missile test of the system was conducted in 1978 using ground-based pseudo-satellites in conjunction with the two available GPS satellites.

SATRACK

An APL-designed system was indeed the first committed user of GPS. Transition of the Navy's Fleet Ballistic Missile system from Poseidon to Trident included acceptance of a requirement for more demanding targeting accuracy. The issue confronted by the U.S. Navy was how to demonstrate in a testing program that this accuracy requirement was met—specifically, not only that it was met on selected test trajectories, but also that it would be met in practice on the varying tactical trajectories flown in a real engagement. For the earlier systems, success in meeting the targeting requirements could be demonstrated by simply evaluating the miss statistics from a flight test program. Uncertainties related to differences between test and tactical trajectories were small enough, relative to the requirement, that test flight miss statistics sufficed. For the Trident system it was clear that this situation no longer applied and that to properly validate the system against its accuracy requirement required significant change and improvement in the evaluation methodology, instrumentation, and testing for this weapon system.

In a study presented in 1971, APL proposed an approach that involved a major shift in the emphasis of the test program and required the application of satellite-based measurements to carry it out. The basic concept was to use a satellite system to provide independent measurements of a test article trajectory, and then to combine these measurements with the measurements from the test article's guidance set to extract a test-based model of the guidance set performance. As the accuracy and completeness of this model grew during a test program, it could be applied with increasing confidence to the evaluation of expected system performance across a wide range of tactical (versus test) trajectories. In the end, very high confidence prediction for trajectories never even flown could be achieved at a much reduced cost in actual number of test flights performed. It was a sound idea and was so well received that the Navy was even considering developing a specialized satellite constellation to meet the need. But then in 1973, the GPS concept was presented and it was clear that GPS could provide the space segment that was needed. Three APL engineers (Thomas Thompson, Larry Levy, and Ed Westerfield) conceived this system, for which they sub-

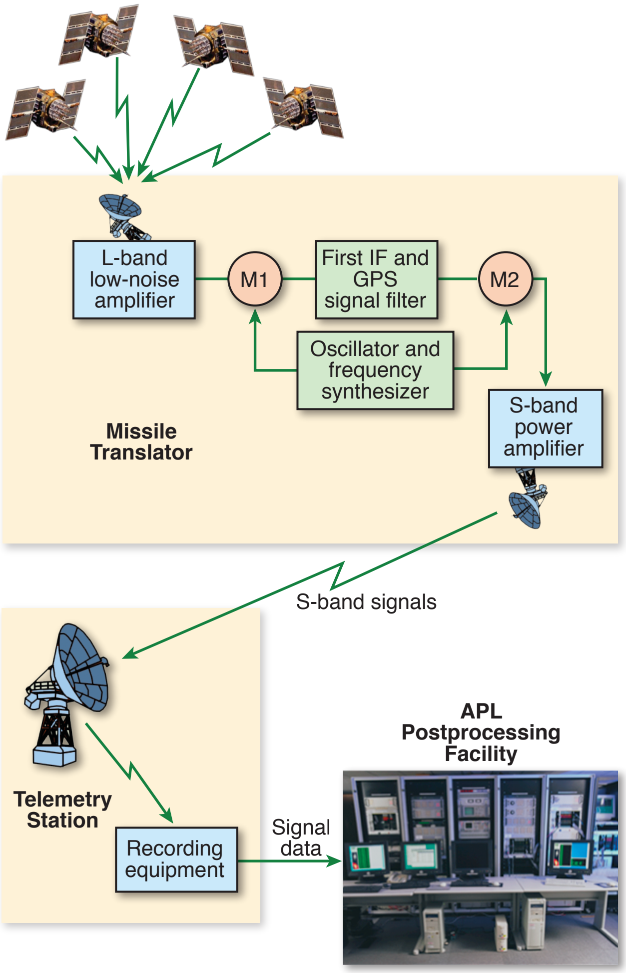

Figure 6. SATRACK processing laboratory and system concept. M1 and M2 denote the mixers used to downconvert the incoming L-band signal to an intermediate frequency and then upconvert to S-band for the telemetry downlink.

sequently received a Fleet Ballistic Missile Achievement Award from the Navy's Strategic Systems Program.

The basic functions of SATRACK are illustrated in Fig. 6. The measurement component uses a GPS signal translator, a device that receives the GPS signals from the missile antenna, "translates" the combined signal to a frequency in the telemetry band, and retransmits it to a ground tracking station. The embedded GPS signals are not tracked either in the missile or at the ground station. Instead, wideband recording of the signal received at the ground station captures the signal for subsequent analysis. This recorded signal (digitally sampled) is sent to APL, where a special postflight tracking system tracks all the available satellite signals.

The heart of the posttracking processing system is a large-scale Kalman filter that combines measurements from the GPS signals and the missile system's guidance set to produce both a best-estimated trajectory and estimates of all the associated guidance system errors. These guidance system errors, e.g., gyro/accelerometer errors, are fundamental to the guidance set itself and are not specific to any particular flight trajectory. To be more precise, it should be noted that exactly which error sources are adequately excited for observation can depend on the details of any given flight test, so that development of the full model requires careful architecting of the flight test program and an ensemble-level analysis of the results. The result over multiple tests is a system error model that supports application to trajectories not actually executed in the flight program, i.e., validation that the weapon system meets its accuracy requirements for its intended tactical trajectories, and provides the ability to triage error sources in the missile guidance set for targeting subsequent improvement programs.

A striking feature of this approach, now in use for more than 30 years, is that it still employs a signal translator as the onboard element. Certainly an original motivation for building a translator was that it was basically the only thing that would fit; a GPS receiver in the early 1970s was a full rack of electronics. Yet, with all that modern electronics can do, the use of the translator has proven so valuable that the approach has never been abandoned; the reason: by providing access in the laboratory to the full, raw, GPS signal, the translator approach enables processing after flight that could never be achieved in real time. The signal data can be replayed any number of times, aiding can be provided from postflight inertial measurements, and after-the-fact GPS message data can be used to extend integration times of the signal correlators (without knowledge of message bits, the correlation interval is restricted to the bit length of 20 ms). Furthermore, the postflight processing can take advantage of after-the-fact satellite ephemerides that most accurately describe the GPS orbits and clocks during the flight test period.

SATRACK was actually conceived as an outgrowth of the "Two in View" Transit work. The system development was led by the Space Department with strong support from the Strategic Systems Department, which is now part of the Global Engagement Department, where maintenance and operations of the SATRACK system continue. The evaluation system has expanded to include similar support for the Air Force Minuteman, AEGIS, Ground-Based Midcourse Defense (GMD), and Terminal High Altitude Area Defense (THAAD) programs. The system has also been applied outside its original domain of flight test tracking. For instance, recent analysis of SATRACK-received data has supported a Space Department study of GPS radio occultation events for atmospheric sounding. (For a good review of the history and implementation of SATRACK, written by the inventors, see Ref. 13.)

APL NAVSIL

In contrast to the SATRACK effort, in which GPS is employed as a calibration/test tool that is purposefully kept separate from and independent of the target system's primary navigation equipment, a whole series of modern weapons use either GPS or GPS in conjunction with an INS as the primary navigation system. APL has played a central role in the evaluation of GPS/INS systems for such weapons, with much of this effort carried out in APL's Navigation and Guidance System Integration Laboratory (NAVSIL), summarized in Fig. 7.

To understand NAVSIL, consider the operation of a precision-guided weapon such as a Tomahawk cruise missile or Joint Direct Attack Munition (JDAM). These systems operate with a combined GPS/INS guidance system in which the two principal elements are complementary: the INS provides extremely accurate measurement of short-duration motion and the GPS is employed to correct for long-term drift, perhaps to support initial INS alignment, and to calibrate the inertial-set error sources. At the start of a precision weapon mission, the inertial set must be initiated and properly aligned, and the GPS receiver must acquire and lock to the accessible GPS satellite signals. As the weapon flies and approaches its target, these systems may be subjected to high-dynamic maneuvers, which can disturb the GPS tracking. The weapons system may encounter enemy jamming or spoofing of the GPS signal, which can appear in the target area, en route, and, for the short-range weapons, perhaps even in the launch area. Such jamming can make signal acquisition difficult or cause the GPS system to lose its lock before the target is reached, degrading the performance of the combined system. Key navigation performance measures are the success of GPS tracking and the accuracy of navigation. Issues in the performance of these GPS/INS guidance units for such systems include

- GPS acquisition time, especially for weapons of short mission duration (Joint Direct Attack Munition, Standard Missile);
- High-dynamic environments and the ability of the GPS system to stay locked through such maneuvers;
- Jamming susceptibility in terms of type and placement of jammers employed as well as mission scenario; and
- Achievable navigation accuracy as a function of the mission scenario.

The APL NAVSIL provides a unique capability for thorough evaluation of these issues for GPS/INS navigation systems without expensive flight testing. The test article in a NAVSIL exercise is often a contractor-provided guidance set for the weapon under consideration. NAVSIL commonly is configured with a set of

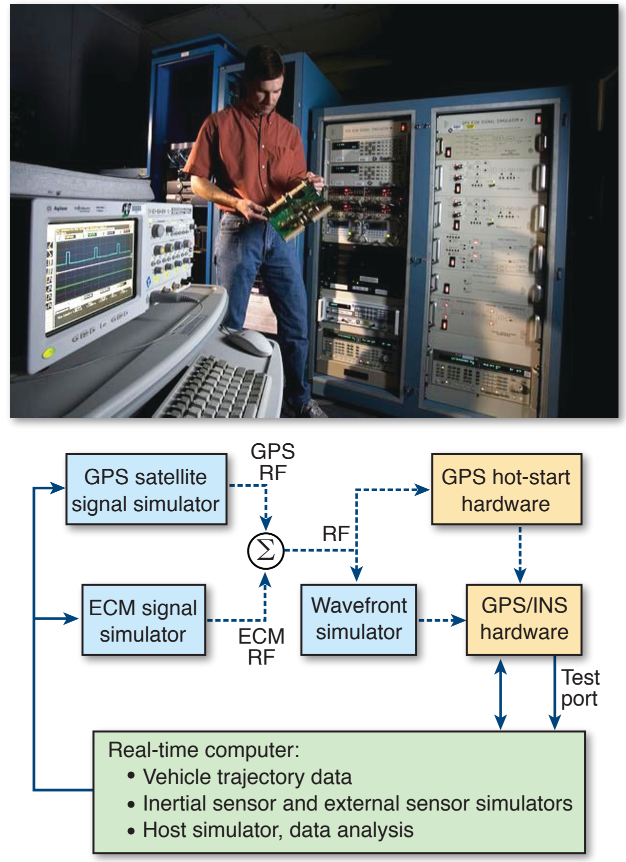

Figure 7. NAVSIL facility (upper) and sample configuration (lower). ECM, electronic countermeasures.

signal and jamming generators along with custom navset interfaces and real-time inertial sensor algorithms usually driven by truth motion data from an offline 6-degree-of-freedom (6DOF) simulation of a weapon's flight, although in some cases an online 6DOF simulation is used. As indicated in Fig. 7, this online simulation would then close the guidance and steering loops around a test article. However, NAVSIL usually feeds the navset with the same signals and inertial sensor inputs that it would see in flight, and thus achieves an evaluation of navset characteristics during flight and of the final navigation error distances achieved.

Of course, in a NAVSIL test exercise nothing actually moves, and it is necessary to make the system think it is flying. For the INS, the sensor inputs to inertial navigation, that is, the gyro and accelerometer measurements, are generated by highly refined models of the navset inertial measurement unit and fed to the inertial system processor. This procedure is standard and is replicated in many facilities. The special strength of NAVSIL is the level of refinement and fidelity applied to the other half of the problem, namely, to make the GPS set think it is flying. NAVSIL contains multiple state-of-the-art GPS signal simulators that combine to produce a raw

GPS RF signal that matches what would be seen by the weapon antenna along the simulated flight profile. To evaluate jamming impacts, NAVSIL provides the capability to mix this GPS RF signal with the RF signals from a multifunction jamming-signal-generation suite that can simulate a wide variety of waveforms (broadband or narrowband, continuous wave, frequency swept, etc.) from up to six stochastically independent sources.

In a typical test run, a jamming threat lay-down is defined in terms of the geographic positions of jammers together with their types and characteristics. The 6DOF simulation output of a weapon flight profile is used to drive both the GPS and electronic countermeasures simulators to produce the appropriate RF combined GPS/jamming signal, and the navset under test responds as it would on a real mission.

A special refinement in NAVSIL is its ability to support laboratory evaluation of modern anti-jam systems that incorporate a controlled reception pattern antenna. Such an antenna employs multiple elements and special processing that enable the system to place antenna gain nulls in the direction of detected jamming sources. To test these systems, NAVSIL developed and built a sophisticated device to provide a realistic simulation of the signals from such a multielement antenna. This device is called a wavefront simulator (WFS). A WFS outputs individual signals for each simulated antenna element. These signals have the gain and phase characteristics of each RF input signal arriving at that element. The relative combinations of gain and phase for each RF input signal across all of the WFS outputs model the apparent line-of-sight arrival angle. The resulting ensemble of output signals provides a simulation of the spatial orientations of the signal sources in the tested scenario. The current-generation NAVSIL WFS will support dynamic spatial motion signals (either GPS satellites or jammers) as received. This NAVSIL WFS was used extensively during the design, development, integration, and acceptance testing of the Tomahawk Block IV Advanced GPS receiver before its Navy Fleet release in 2009.

During two decades, the steadily evolving NAVSIL GPS/INS hardware system test capability has proven its value in supporting system designer choices, anomaly resolution, and system performance evaluation.[14] Weapon systems supported include the Tomahawk Block III upgrade in the mid-1990s, the current Tomahawk Block IV, Terrier Lightweight Exo-Atmospheric Projectile technology demonstrator, Standard Missile 3 and 4, JDAM, and others. As a general-purpose GPS testing facility, NAVSIL has even executed the independent verification and validation of the TIMED GPS Navigation System (GNS) (see *Timed GPS Navigation System*).

TIMED GPS Navigation System

The TIMED spacecraft, launched in December 2001, uses an APL-developed GNS to provide fully autonomous onboard orbit determination for the spacecraft.[15] The mission of this APL-built Earth-orbiting spacecraft involves upper atmospheric remote sensing. Measurement sequences, as well as many spacecraft command and control operations, can be initiated based on position alone. Thus, the capacity for autonomous orbit determination leaves the spacecraft able to accomplish much of its mission in a nearly fully autonomous mode, significantly easing the burden on and subsequent costs of mission operations. Figure 8 shows the architecture of this

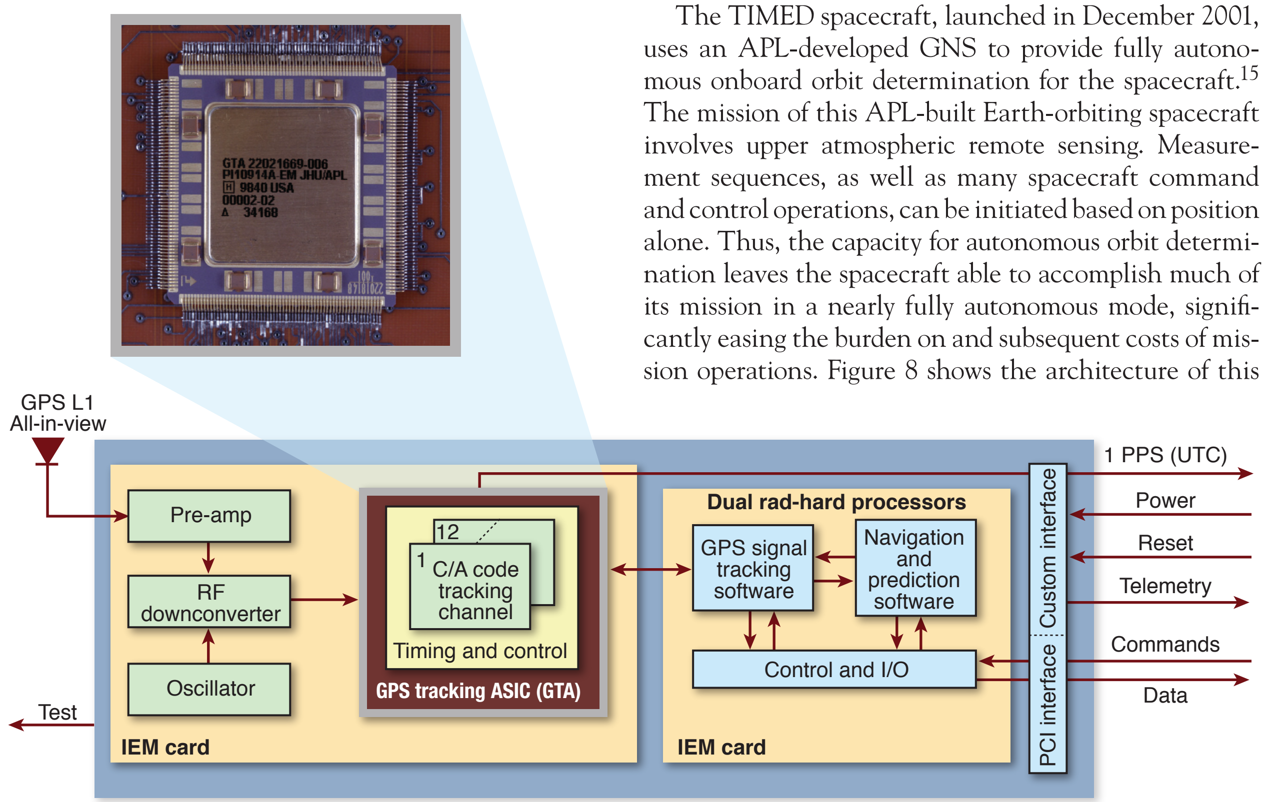

Figure 8. The TIMED GNS system and associated GPS tracking ASIC. (Upper) Twelve-channel GPS tracking ASIC. (Lower) GNS system architecture [on two cards in the spacecraft's Integrated Electronics Module (IEM)]. (Derived from Ref. 15.)

device. The GNS accesses the civilian C/A ranging code that modulates the GPS primary L1 signal. Although the development team drew on APL's decades-long GPS development experience, the GNS was designed from the start as a state-of-the-art spaceborne system optimized for autonomous on-orbit operations. With this fresh-start approach, performance compromises that may have been required when adapting terrestrial receiver designs for space applications were avoided. The GNS was designed specifically for the hostile space environment. The core electronics, the APL-developed low-power radiation-hardened application-specific integrated circuit (ASIC) called the GPS Tracking ASIC, or GTA, can sustain total dose radiation in excess of 1 Mrad (Si). With more than 220,000 gates, the GTA is the largest space-qualified ASIC ever developed at APL and implements all required GPS-specific digital hardware functions, including 12 independent tracking channels and timing and control functions.

With its robust tracking, orbit determination, and autonomous integrity-monitoring algorithms, rad-hard electronics, and dual-processor design, the GNS has been a critical enabler for TIMED's low-cost mission operations approach and the program's successful science campaign. TIMED has begun its 10th year of on-orbit operations.

Deep-Fade GPS

APL's efforts in weak signal GPS acquisition and tracking represent a case study in the ongoing interaction between civilian and national security space developments. As an outgrowth of weapon system anti-jam studies, APL developed and proposed to the space community a unique methodology for acquiring and tracking severely attenuated GPS signals. (Severe attenuation is, after all, sort of an inverse of the jamming problem.) The problem was how to accurately navigate a spacecraft in an elliptical orbit measuring about 300 km by 30 R_E (where R_E is the mean Earth radius).[16] Because the GPS "shell" sits at about 3.2 R_E, such spacecraft would spend most of a 4-day orbit outside this shell, where the signal strength would be greatly reduced owing to geometry (seeing principally backlobes of the GPS antennas) and the large distance. In time, numerous cross-departmental discussions within APL led to recognition that the same technique could have significant national security application in military situations of heavily attenuated signal, e.g., indoor operations. The approach taken actually has its roots in message bit aiding techniques that enable an extension of the coherent integration time, developed first for SATRACK. It was also an enabling technique for measurements of GPS signals reflected from the ocean surface for detection of sea and wind states.[17] The development of this approach for the original space application (the 300 km by 30 R_E orbit case) did not proceed beyond an analytical/theoretical level. National security applications, however, have resulted in construction and successful demonstration of prototype systems.

How does it work? The most powerful means of detecting a strongly attenuated signal is to increase the coherent integration time in the receiver (see Box 2). The postprocessed (i.e., postcorrelation) signal to noise ratio grows linearly with the coherent integration time, other things being equal and stable. Normal GPS uses integration times of order 1–20 ms. Ordinarily integration times cannot be usefully extended beyond 20 ms, because the GPS signal is overlaid with a 50-Hz message bit sequence that causes the summed signal inputs potentially to reverse sign every 20 ms at the message bit transitions. APL has shown that integration can be successfully extended significantly beyond this limit, by carefully timing the integration segments to exploit a portion of the GPS message whose bit stream can be predicted *a priori*. APL has conducted studies and fielded real-time hardware that achieves integration times of 600 ms, yielding 15- to 20-dB increases in the level of attenuation that can be accommodated.

GPS at the Moon

Looking perhaps to the ultimate space application for GPS beyond the constellation, APL has done an analysis that suggests that GPS could even be used to navigate assets at the Moon, at a distance of some 60 R_E. The signals involved are attenuated by an additional 6 dB relative to the originally studied 30-R_E case. More importantly, and in contrast to the Earth-orbit situation described in *Deep-Fade GPS*, the spacecraft spends no time below the GPS constellation. The situation is further complicated by the relatively poor geometry for "triangulating" the spacecraft position from measured GPS ranges, as the entire GPS constellation, when viewed from the Moon, subtends an angle of just under 8°.

Nevertheless, an APL analysis shows that quite accurate GPS-based orbit determination is possible for a spacecraft orbiting the Moon.[18] For the analyzed case, much of the difficulty is overcome with a high-gain antenna; indeed, a 30-dB antenna, which at the GPS L-band requires about 1 m aperture, has a main lobe that about matches the angle subtended by the GPS shell as viewed from the Moon. Under such gain conditions, often there will be a few GPS satellites whose main beam or sidelobe signals can be tracked without resort to weak signal techniques. Most of the time, though, not enough satellites can be tracked to provide a point solution (which takes four satellites), and even when a point solution can be achieved its accuracy is severely degraded by the weak geometry. The second key feature is then the compilation of the resulting measurements over long orbit arcs, even over whole orbits.

The dynamics of orbiting spacecraft in the combined lunar and Earth gravitational fields are well known and enable a well modeled Kalman filter to compile even single-satellite measurements over multiple orbits, overcoming the limitations and achieving accuracies on the order of tens of meters.

Although at this point this work represents only an analytical prediction, the results are under review for possible application to future lunar navigation and communication systems.

GOING FARTHER AFIELD

Moving farther afield, APL is making significant contributions to the advancement of navigation techniques for missions into deep space. In this arena we are dealing with current spacecraft in orbit about the Sun, on their way to Mercury, Pluto, and beyond. In the future we will be dealing with spacecraft targeting precision landings on the Moon and possibly soft (very soft) Touch and Go (TAG) operations for missions to collect and return to Earth samples from comet or asteroid targets. As in the navigation areas described so far, the fundamental measurements are again Doppler, time, and range.

Deep Space

The basic navigation questions that can be asked from Earth for a spacecraft on a deep space mission are, "How far away is the spacecraft?" and "How fast is it moving?" [Technically, one could add one more: a measurement of angles to the spacecraft (right ascension and declination) achieved by Delta differential ranging. This type is not addressed here, although it is fundamentally an extension of the range measurement capability.] The rest is accomplished by compiling these measurements with dynamic models into a trajectory that fits all the data. "How far?" is answered by measuring the roundtrip travel time of signals that move from Earth to the spacecraft and back. The solution to the question "How fast?" is essentially a Doppler measurement. APL has contributed in both areas.

Noncoherent Doppler

The Doppler measurement in a standard radar system deals with a reflected signal: the radar transmits, the object reflects, and the reflected signal is received and analyzed. For deep space missions, the process has to be more complicated: any reflected signal is attenuated by $1/R^4$, where R is the distance of the spacecraft from the Earth station, and the distances involved are simply too large. Instead, the space version operates in a coherent transponder mode: A signal is transmitted from Earth to the spacecraft, and the carrier phase of that signal is tracked on board. A new signal is then constructed that is coherent in phase with the received carrier, but much more powerful, and is retransmitted to Earth (usually at a different frequency). This technique has been standard since the earliest deep space missions.

The process just described relies on coherence at the spacecraft between the received and constructed signals. In the late 1990s at APL, it became desirable to drop this coherence requirement, and APL engineers devised a method by which the phase difference between received signal and the spacecraft local reference is measured at uplink reception, and this difference is then incorporated into a message on a separately developed downlink signal. The message relates to the Doppler shift of the uplink signal as observed at the spacecraft. When this signal is received at the ground, further Doppler-shifted on return, a bit of algebra yields a result identical to what would have been achieved had a fully coherent Doppler turnaround been employed.[19] This system architecture allows separate developments of the uplink and downlink slices of the spacecraft electronics module. This system was flown and checked out on the Comet Nucleus Tour (CONTOUR) spacecraft and is now flying on the New Horizons spacecraft en route to an encounter with Pluto.

Regenerative Ranging

APL was the first to implement a regenerative ranging technique, originally proposed in 1999 by a team at the Jet Propulsion Laboratory,[20] on an operational spacecraft. The New Horizons spacecraft, en route to Pluto and currently traveling between the orbits of Saturn and Uranus, faces eventual operational distances of 30 astronomical units or more at which mission-critical navigation must be performed. (One astronomical unit equals the mean radius of the Earth's orbit about the Sun, or about 150 million kilometers.)

In the standard ranging technique for deep space, a set of ranging tones is transmitted to the spacecraft. When these tones are turned around in coherent onboard processing, the result at Earth reception is a sequence of delayed tones whose timing can be compared with the transmitted tones to derive a sequence of ambiguous roundtrip "light times." A software algorithm is then used to solve for the corresponding unambiguous two-way range between the tracking station and the spacecraft. In the regenerative technique this set of ranging tones is replaced by a pseudorandom code generated from a set of six binary codes (lengths relatively prime), which are combined in AND and OR operations and phase modulated onto the uplink carrier. At the spacecraft, the codes are separately tracked by a set of parallel correlators. Then comes the "regenerative" part: A clean copy of each code, in phase lock with the received version, is locally generated and modulated back onto the downlink signal. When the resulting signal is received at the ground, processing unravels the phase history of each code, and the combination provides two-way unambiguous range measurements to the spacecraft with precision equal to or better than the precision provided by the standard ranging technique.

Where is the advantage? In the standard process with ranging tones, the receiver bandwidth on the spacecraft must accommodate the modulating tone (the standard figure is 1.5 MHz for a set of tones whose highest frequency is 1 MHz). In the regenerative process, although the input bandwidth must be wide enough to accommodate the chipping rate of the codes (~2 MHz), the eventual tracking loop that maintains lock on the code can operate at loop bandwidths of order 1 Hz or even less, giving a reduction of some 6 orders of magnitude in the noise power passed by the system. The result is a substantial reduction in the impact of system noise on the range measurement, a critical factor for spacecraft moving to distances of many astronomical units. For the New Horizons mission, the benefit has a direct physical realization: the system accuracy goals are achieved by using the medium-gain antenna on the spacecraft, whereas the high-gain antenna must be used at Pluto distances when standard turnaround ranging is used.

Deep Space Timekeeping

A third key activity involving spacecraft navigation is maintenance of accurate timekeeping on board the spacecraft, even as the spacecraft may be light-hours from Earth. For instance, an important mission requirement can be accurate alignment of scientific measurement data with our Earth-based knowledge of the spacecraft trajectory. Spacecraft instrument data are tagged with time as known on board, while the navigation solution, generated on Earth, provides a trajectory as a function of an Earth-based time reference.

How accurately must this alignment be known? The answer depends on the mission. For some missions, e.g., NASA's Solar Terrestrial Relations Observatory (STEREO) mission (built by APL), the mapping from spacecraft to Earth time needs to be accurate to ~1 s. In the case of NASA's Mercury Surface Space Environment Geochemistry and Ranging (MESSENGER) mission (again built by APL), a science desire for precise measurements of the Mercury surface demands a mapping that is accurate to within ~1 ms.

Achieving such accuracies requires precision oscillators on the spacecraft, thorough calibration of any delays in the time-tagging process and in the generation of spacecraft telemetry, and accounting for the one-way light time (and associated uncertainties) as evaluated by the navigation function. The assessment must also make a careful and precise accounting for relativistic effects (Shapiro delay, frequency reference shifts due to spacecraft velocity and depth in the Sun's gravitational well) (personal communication, S. B. Cooper, APL, 2009). All testing to date shows that APL's MESSENGER complete timekeeping system is functioning as predicted and that the required accuracies are being achieved.[21]

NEW MISSION AREAS

Innovation in space navigation continues at APL, both in important future mission categories and in advanced-concepts navigation well outside the standard Doppler, range, and time measurements described in this article.

Precision Landing Technology

A highly challenging area for upcoming space science missions involves precision landing on small nonterrestrial bodies. APL did the first such landing when the Near Earth Asteroid Rendezvous (NEAR) spacecraft touched down on the asteroid 433 Eros in February 2001.[22] The NEAR landing on Eros represented a new first for the U.S. space community—indeed, the first landings on the Moon, Venus, and Mars were achieved by the space agency of the former Soviet Union. More recently, APL has been heavily involved in preliminary design and performance testing of a candidate system for autonomous precision navigation to landing sites on the Moon, as might be required, for example, to support resupply missions to a previously established lunar base. APL also has been studying the landing of missions on much smaller bodies with very little local gravity, e.g., asteroid landing missions or, in a recent proposal, a landing on the Mars moon Deimos, for which the local gravity is less than that of Earth by a factor of approximately 2500. For such a touchdown in essentially zero gravity and, in the case of an asteroid or comet, on a body of unknown ability to sustain any reaction force, system knowledge of position and velocity relative to the object surface needs to be extremely precise and in real time.

As one of several efforts in these areas, APL is adapting precision navigation techniques developed and thoroughly evaluated at APL for low-flying precision weapon delivery, particularly the Digital Scene Matching Area Correlation (DSMAC) technology developed for the Tomahawk cruise missile program (see, for example, Ref. 23). As applied to lunar landings, under NASA's Autonomous Landing and Hazard Avoidance Technology (ALHAT) program, the approach involves two passive optical cameras, pointed in roughly orthogonal directions, that take images of the local terrain and compare them to prestored maps to generate position estimates.[24] The system has already undergone flight testing using both helicopter and airplane platforms in a lunar-like region of the southwest desert and is into a second design cycle. As applied to the precise control requirements of either a lunar or asteroid touchdown, the approach may be augmented with comparison of a sequence of frames to estimate descent rate and surface relative horizontal velocity.

XNAV Program

One of the more exotic navigation approaches under investigation at APL is to measure, using an X-ray telescope on board a spacecraft, the arrival times of individual photons from known X-ray pulsars.[25] APL has developed algorithms that recover timing and Doppler data that in turn permit navigation of spacecraft. Pulsars are naturally occurring sources suitable for navigation throughout our solar system and beyond. Figure 9 shows the basic timing data obtained by processing X-ray photon time-of-arrival data from the pulsar in the Crab Nebula. The horizontal axis is simply the phase relative to the cycle time of the pulsar, ~33.1 ms. The data were obtained from the universal stellar aspect camera on the Naval Research Laboratory's Argos satellite, and the result shown in Fig. 9 is one of many results of the Defense Advanced Research Projects Agency-funded Autonomous X-ray Pulsar-Based Spacecraft Navigation (XNAV) program, a joint effort of APL, Ball Aerospace, Los Alamos National Laboratory, and the National Institute of Standards and Technology. By binning the received X-ray photons in time, and searching for the strongest signal, the local phase of the pulsar signal and even Doppler relative to the pulsar period can be determined and provided as inputs to the navigation solution. A derivative of XNAV, which uses X-ray photons from a time-modulated X-ray source for purposes of communication, was developed at NASA's Goddard Space Flight Center (GSFC). The earliest results of this X-ray communication, or Xcom, were demonstrated by frequency modulating the GSFC-designed X-ray source by using recorded music, and subsequently demodulating the detected X-ray signal by using an APL-designed phase-locked loop circuit.

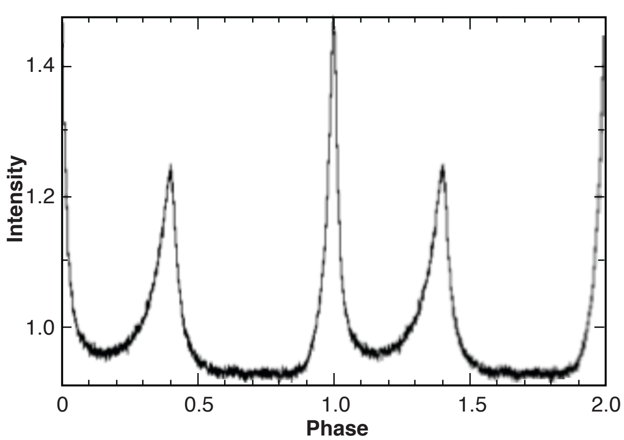

Figure 9. X-ray pulsar timing provides a natural-source basis for space navigation. Shown is the result of the process of binning individual photon arrival times over many pulsar cycles according to the observed cycle time of the pulsar.

THE FUTURE

For decades since its inception, and continuing today, APL has been a prized national resource for navigational innovation, and for the detailed and painstaking work required to turn an innovative idea into highly precise techniques and whole systems that meet critical national needs. Where might such work lead in the future? Following are a few key areas.

Protecting Our Space Assets

With all the excitement that has accompanied the 53 years of the space age up to today, an important consequence is that we as a nation, and the world as a whole, have become critically dependent on our space assets. They help navigate our airplanes and ships, provide data for weather forecasting (think hurricanes) that could only be dreamed of before the 1960s, and support our communications. In the area of national defense, spacecraft systems provide all these functions as well as a whole suite of reconnaissance, surveillance, and intelligence-gathering capabilities on which we depend. On 11 January 2007 the Chinese used a ground-based missile to destroy one of their own aging satellites, in a "test" that alerted the world to the potential vulnerability of some of these assets (for a timely report, see, for example, Ref. 26). The areas of both defensive and offensive counterspace are receiving increasing attention by our nation's security forces.

GPS User Studies

GPS Development Support

The GPS system, especially as it supports military operations, is under constant evaluation for upgrade, and significant upgrade programs, e.g., GPS III, are underway. APL has been funded by the Air Force GPS Directorate (Space and Missile Systems Center) to carry out multiple study and evaluation efforts to define the direction of critical upgrades, both to the GPS ground system and to user equipment for ground and airborne forces. Given the Laboratory's level of interaction with all forces, and with its deep knowledge of navigation, GPS operation, navigation security, and user needs, APL is a strong potential resource for the GPS Directorate to improve the security of the GPS for our warfighters.

GPS Exploitation

Two emerging areas of exploitation are under study at APL. In one, a Distress Alert Satellite System that has been under development at NASA's GSFC uses repeaters on board the GPS spacecraft to capture and retransmit to ground stations distress beacon signals generated by users. Because of the coverage structure of the GPS constellation, these signals can be picked up virtually instantaneously by multiple satellites and can be analyzed on retransmission to the ground to provide a position solution for the transmitting beacon. APL is currently assessing the applicability of this technology to other uses.

In another area, APL has been working closely with NASA's Langley Research Center to evaluate system and science requirements for a future climate-related mission exploiting GPS radio occultation. In such a mission, a low-Earth-orbiting spacecraft observes GPS satellites "rising" and "setting" relative to the limb of Earth. The difference between the measured phase of the received signal and the phase expected from geometry alone provides a measure of the refractive effects of the atmosphere through which the signal has passed. Although work in this area has been ongoing at other centers during the past decade, the NASA Langley Research Center mission will be greatly enhanced by greater sensitivities and a more refined compensation for ionosphere effects than the earlier systems required. APL is working to define the system needs relative to the mission climate science requirements and to identify the principal methodologies, both in terms of hardware and data analysis, that need to be employed.

SUMMARY

This article reviews a sampling of APL accomplishments and efforts in navigation technology and applications. Although by no means comprehensive, the list of activities reported in this article gives some indication of the extent and importance of these efforts. They range throughout the history of APL from the 1940s to today, under and across the sea, in the air, on land, and in space. The efforts include space navigation from near-Earth orbit to the Moon and into deep space and military and civilian activities, from experimental studies in weak-signal GPS to full-system implementations, and cover the range of techniques from measurements of Doppler, time, and range to image-based precision landing and exotic measurements on X-ray pulsars. With such a history and such a breadth of experience and ongoing activities, APL can expect to remain in the forefront of this area, providing navigation solutions to critical problems in the years to come.

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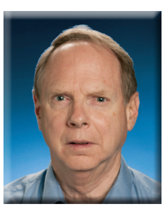
The Authors

Robert L. Henderson is a member of APL's Principal Professional Staff and an analyst in the Mission Design, Guidance and Control Group. He holds a B.A. in physics from Carleton College and M.S. and Ph.D. degrees in physics from Cornell University. Dr. Henderson joined APL in the Space Department in 1999 after an extensive career with General Dynamics and Texas Instruments, where he worked on precision guidance for air-breathing missiles. In the Space Department, he has supported advanced system concept studies for spacecraft and high-altitude balloon systems and led the early development of advanced weak-signal GPS techniques. He has served as Section Supervisor and Group Supervisor in the Space Systems Applications Group and in various staff assignments investigating lunar landing technologies and spacecraft autonomy issues. His current interests include development of an APL-centered space navigation capability. **William S. Devereux** is a member of APL's Principal Professional Staff and is Supervisor of the Engineering and Technology Branch in the Space Department. He holds a B.S. in electrical engineering from the University of Maryland and an M.S. in electrical engineering from The Johns Hopkins University. Mr. Devereux joined the Space Department in 1980. He has led the development of a number of GPS-based aircraft, missile, and spaceborne tracking and navigation systems. He also led the development of a space-qualified multifunction GPS transdigitizer/telemetry transmitter system for the Strategic Defense Initiative's Brilliant Pebbles Program, the first full-signal dual-frequency GPS translator system for the Navy that culminated in four highly successful flights on Trident reentry bodies, and the autonomous spaceborne GNS for NASA's TIMED mission. **Thomas Thompson** received a B.S.E.E. from Lafayette College in 1960 and an M.S.E.E. from The Johns Hopkins University in 1968. He is a member of APL's Principal Professional Staff in the Global Engagement Department. He joined APL's Space Department in 1960 and served as a group supervisor, a branch supervisor, and the chief engineer. Mr. Thompson was first assigned to RF hardware design for the Transit development program. In the mid-1960s and early 1970s he was a prime contributor to studies supporting concepts for a future satellite navigation system and the "Two in View" Transit proposal. In 1971 he contributed to the original SATRACK proposal and subsequently assumed technical leadership of its development. In 1983, he joined System Planning Corporation, where he led development of specialized radar instrumentation. He returned to APL in 1992 and led development of an important upgrade to the SATRACK system for Trident reentry body flight test evaluations as well as independent research and development activities focused on GPS missile intercept instrumentation. He also led the SATRACK support work for the Air Force Minuteman and Army THAAD activities and contributed to several Missile Defense Agency target instrumentation development programs. He continues to support missile test instrumentation development and participates in flight test analysis for Trident, GMD, and THAAD projects. For further information on the work reported here, contact Robert Henderson. His e-mail address is bob.henderson@jhuapl.edu.



Robert L. Henderson

William S. Devereux

Thomas Thompson

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