The SATRACK System: Development and Applications

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SATRACK has been a significant contributor to the development and operational success of the Trident Weapon System, and it continues to provide a unique monitoring function that is critical to the maintenance of the U.S. sea-based strategic deterrent. This article reviews the background and evolution of this unique Global Positioning System user application (the first committed user) and discusses its support of other systems of national importance. Its connection to APL's pioneering contributions to the development of the technology and methodology supporting successful deployment of the sea-based strategic deterrent is reviewed. Basic concepts and implementation specifics of the evolving system design are described, and its extended use and performance improvements over the past 25 years are presented.
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INTRODUCTION

SATRACK was developed to validate and monitor the Trident missile guidance error model in the System Flight Test Program. It is the primary instrumentation and processing system responsible for accuracy evaluation of the Navy's Strategic Weapon System. Instrumentation and processing systems available when the Trident Development Program began could not meet this need. APL conceived and led the development of the SATRACK system to fulfill this requirement. Prototype instrumentation required for the missile and ground station data collection functions were developed at APL to validate the concept, and we generated specifications controlling the development of the operating missile and ground station hardware. We also developed and operate the SATRACK processing facility, which includes a unique preprocessing hardware and software configuration and an extensive postprocessing analysis capability. Additionally, the APL satellite tracking facility has operated as a backup SATRACK recording site for all East Coast test flights since 1978.

SATRACK fully met all its guidance subsystem evaluation requirements and also provided weapon system error model insights that would not have been possible without its unique ability to detect and allocate small error contributors to miss distances observed in the flight test program. SATRACK not only validated the Trident system accuracy, but the test-derived and -validated system error models have allowed the command authority to confidently assign and allocate targets to sea-based strategic resources.

The next section will discuss the background leading to SATRACK's development as a natural extension from APL's role in the development of the Fleet

Ballistic Missile Evaluation System and the Navy Navigation Satellite System (Transit). Then, following a discussion of the basic concepts, this article will trace the system's evolution:

- SATRACK I—A technology project to develop and demonstrate the instrumentation and processing system using the Trident I missile (1973–1983)
- SATRACK II—The operational system designed to meet system requirements for the Trident II missile (1983–present)
- Other applications—Uses of SATRACK for Army and Air Force missile test applications (1983–present)
- SATRACK III—Current system upgrade and future applications

BACKGROUND

From 1967 through early 1971, APL conducted a series of studies to support concept development of the Defense Navigation Satellite System (DNSS). These studies addressed a variety of configurations capable of meeting DNSS requirements and eventually led to a concept proposal called Two-In-View (TIV) Transit. The name was chosen to indicate that DNSS requirements could be met with only two visible satellites (in contrast to the alternate concepts that required four visible satellites) and that it could evolve naturally from the already operational Transit system. We chose this concept because it was the lowest-cost approach to meeting DNSS requirements.

The ability to provide three-dimensional positioning with the required accuracy using two satellites is possible only because their motion relative to a user is significant. The alternate concepts were based on simultaneous range measurements to four satellites. Since these concepts were not benefited by high relative motion, they incorporated satellite constellations at higher altitude. The higher-altitude constellations were selected because they achieved the required global coverage with a smaller number of satellites. This choice was partly motivated by the incorrect assessment that system costs increased as the required number of satellites increased. However, fewer satellites were possible because the area that each served expanded in direct relation to the reduction in the number of satellites, and costs for signal services tend to have a direct relationship to service area, not to the number of satellites. To a first-order approximation, positioning satellite system costs are independent of constellation altitude. Further discussion of these topics and the prevalent views of the time is available from Refs. 1–3.

The last performance study of the TIV Transit system addressed its ability to provide trajectory measurements of SLBM test flights. The study showed that SLBM measurement objectives could be met, and an interim report published in late 1971 formulated the tracking concepts and missile and ground station capabilities needed to support TIV Transit measurements of SLBM flight tests. However, by mid-1972 it was clear that none of the then-proposed DNSS concepts would be developed, and the missile tracking concept was temporarily forgotten.

In a parallel chain of events, the Navy's Strategic Systems Programs organization was asked to address the suitability of the Trident Weapon System for more accurate targeting requirements. Several studies were initiated to consider this question. The primary issues concerned possible system improvements to achieve the desired accuracy. An important secondary concern regarded the method by which the accuracy of the new system would be validated.

It was soon evident that the impact scoring techniques used for Polaris and Poseidon evaluations would not be adequate. A new methodology that provided insights into major error contributors within the flight test environment would be needed so that accuracy projections could be based on a high-confidence understanding of the underlying system models. The technique of comparing observed test impact statistics with results computed from models used for development (i.e., "shoot and score" approach) was unacceptable. Assessing performance models in the flight test environment requires guidance-independent measurements with sufficient precision to separate out the important contributors to system inaccuracy. The existing range instrumentation (missile tracking and trajectory estimation) was largely provided by radar systems, and it was not clear that they could provide the needed measurement accuracy or coverage in the broad ocean test areas.

In early 1973, we initiated a study to compare current range radar with TIV Transit measurement capabilities in relation to needed SLBM accuracy evaluation objectives. The study results showed that only a satellite-based measurement system could meet future requirements. APL presented the SATRACK concept to the Navy's Strategic Systems Programs staff in May 1973. The proposed system was based on a custom satellite design patterned after TIV Transit satellites, but simplified by the removal of any requirement for real-time positioning service. A six-satellite constellation would support two flight test windows per day. These concepts were proposed to minimize costs. Missile hardware and ground support capabilities were unchanged from the concepts defined in 1971.

The proposal was accepted and preliminary development was initiated. However, 1973 was also the year that the Global Positioning System (GPS) development began. With the emergence of GPS, we were asked to consider its use in place of the specialized satellite constellation. Our studies indicated that the

GPS could be applied to the SLBM accuracy evaluation system with some changes to the missile and ground station designs. There was a technical concern regarding the available signal power and ionospheric correction capabilities as well as a programmatic concern regarding the number of satellites that would be available for early Trident test flights, but otherwise, the GPS capabilities were expected to be adequate. In July 1974, the Improved Accuracy Program was initiated to consider the implications of modifying Trident to support an improved accuracy requirement. SATRACK development was initiated to support the program, and in September 1974, DoD Research and Engineering directed the Navy to use GPS for SATRACK, making it the first committed GPS user system.

BASIC CONCEPTS

The SATRACK concept is shown in Fig. 1. Signals from GPS satellites are relayed by the test missile to receiving equipment at a launch-area support ship (LASS) and a downrange support site (DRSS). At the beginning of the Trident Flight Test Program a ship was used for downrange support; now that support is provided by a land station. The missile hardware was called a translator to emphasize that no signal tracking functions are accomplished in the missile (i.e., the signals are simply "translated" to S-band and retransmitted). The evolution of translator systems is discussed in a companion article by Thompson and Westerfield elsewhere in this issue. The receiving equipment at the LASS and DRSS also does not provide a SATRACK signal tracking function (although the DRSS does provide a lower-accuracy real-time tracking capability to support range safety). The translated signals received at both sites are sampled at a high enough rate to capture the desired signal spectrum. Precision tracking of the GPS signals is actually accomplished at the APL postflight tracking facility through playback of the recorded translator signals.

After the signal tracking data are recovered and several systematic corrections are applied, the derived satellite-to-missile (link) range and integrated Doppler data are used in a large Kalman filter that provides estimates of trajectory-observable model parameters (this terminology is used because not all model parameters produce observable signatures in any specific trajectory geometry). The processing methodology developed at APL properly combines *a priori* model data and trajectory-observable model data for each flight test.

Significantly, the critical measurements are provided by carrier phase tracking of the GPS-to-missile signals. The GPS signal phase measurements (i.e., integrated Doppler) sense range changes along each signal line of sight to a small fraction of a wavelength (i.e., a few millimeters). These measurements, which are compared with their values computed from guidance sensor data and satellite position and velocity estimates, provide most of the information. Range measurement noise in the recovered GPS range-code signals is of secondary importance. In essence, the inertial sensors provide high-frequency motion information better than the signal processes, the Doppler information senses the systematic errors associated with the inertial sensors, and the range data provide an initial

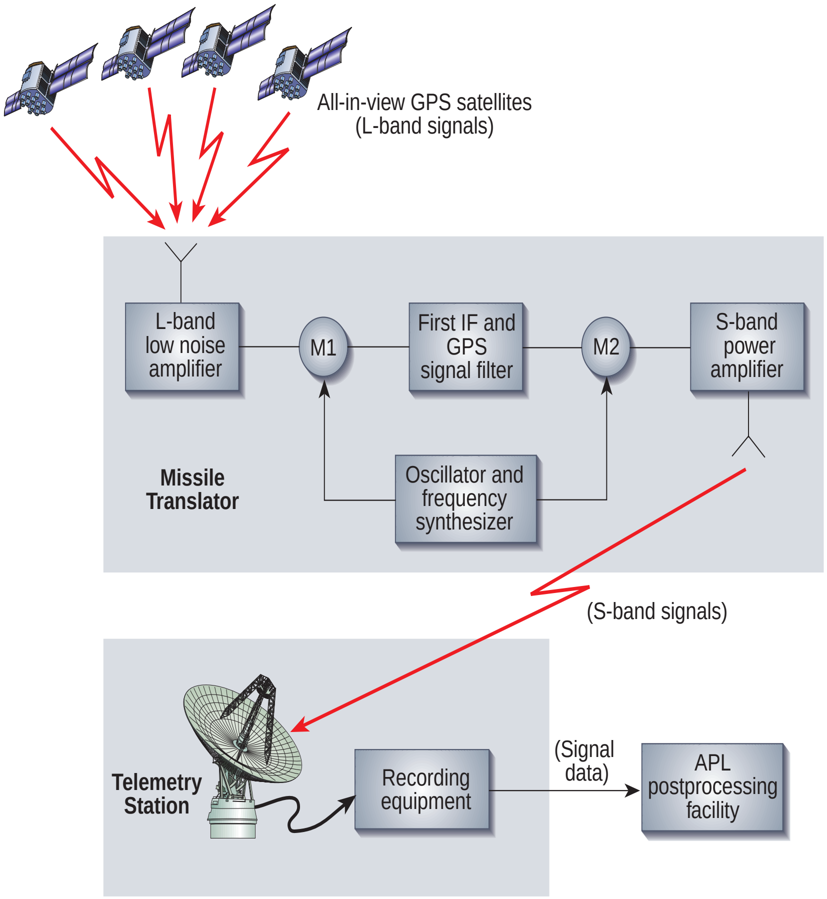

Figure 1. SATRACK measurement concept. Signals transmitted from the Global Positioning System satellites are received at the missile, translated to another frequency, and relayed to the telemetry station, where they are recorded for later playback and postprocessing at APL.

condition for all the dynamic measurements. Therefore, range noise (i.e., noise in the range tracking loops) can be smoothed over the full flight interval. The range noise remaining after this process is smaller than other bias-like uncertainties that set the limit on absolute position accuracy (e.g., satellite position).

The SATRACK system configuration is shown in Fig. 2. Signals transmitted by GPS satellites are tracked by the GPS tracking network for several days surrounding the missile test flight. The tracking data from this operation are processed to derive satellite ephemerides and clock estimates that have the highest possible accuracy during the missile flight interval. The ephemerides and clock estimates are used by the postflight receiver and missile processor to provide the SATRACK data products for each flight.

During the missile flight, all in-view GPS satellite signals are received at the missile, translated to S-band, and retransmitted to the surface station. The translated GPS signals are recovered with the same station tracking antenna used for all the missile telemetry signals. The translated GPS signal data are separated into range safety and accuracy operations. The range safety function processes the lower-accuracy GPS signals to provide a real-time tracking solution for the range command. The real-time accuracy function is provided by simply sampling and recording the GPS signals (i.e., by sampling the signals at a rate that captures the full bandwidth of the selected range-code modulation).

The telemetry data are also recorded for postflight analysis. These data, along with GPS ephemeris and clock data, are used to provide tracking aids for the postflight receiver and measurement estimates for the missile processor. Raw tracking data from the postflight receiver are corrected for known systematic errors (e.g., antenna lever arm) before being passed to the missile processor. The missile processor is a large Kalman filter that operates on the raw guidance sensor measurement data supplied by missile telemetry. With these data and satellite ephemeris and clock estimates, the processor computes the expected satellite measurement data. These expected data are compared to the actual satellite measurements, and the observed differences are used to drive the filter model to a best estimate of the underlying guidance model errors.

Assuming that the data processing has not identified a system fault (i.e., an error component well outside its expected performance), the processed data from each flight test are used to provide estimates of major contributors to impact miss. Figure 3 shows a hypothetical diagram used to allocate contributions to impact miss. The method is based on projecting each error contributor and its uncertainty into the impact domain. The first-level allocation is at the subsystem level (initial conditions, guidance, and deployment and reentry); a

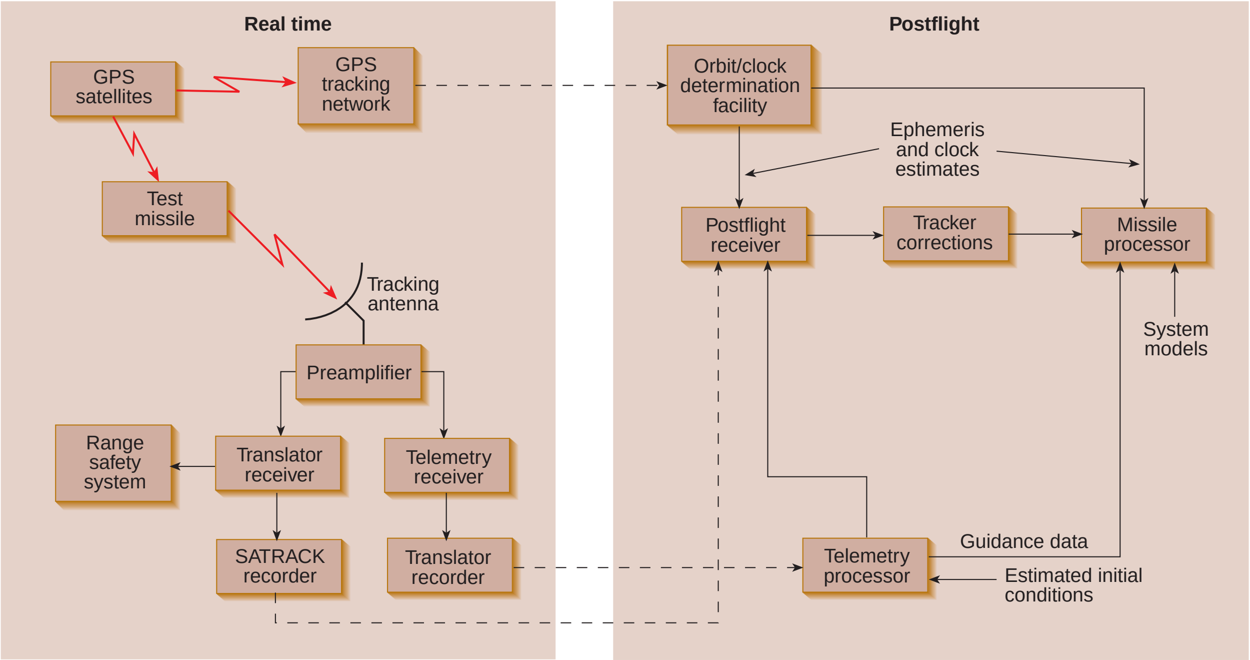

Figure 2. Basic SATRACK configuration. For a number of days surrounding the missile flight, GPS signals are received, tracked, and recorded at the GPS tracking sites. During the missile flight, GPS signals are received by the missile, translated in frequency, and transmitted to the surface station(s). A tracking antenna at the station receives the missile signals, separates the various components, and records the data. The postflight process uses the recorded data to give satellite ephemerides and clock estimates, tracked signal data from the postflight receiver, and missile guidance sensor data. After the signal tracking data are corrected, all the data elements and the system models are used by the missile processor to produce the flight test data products.

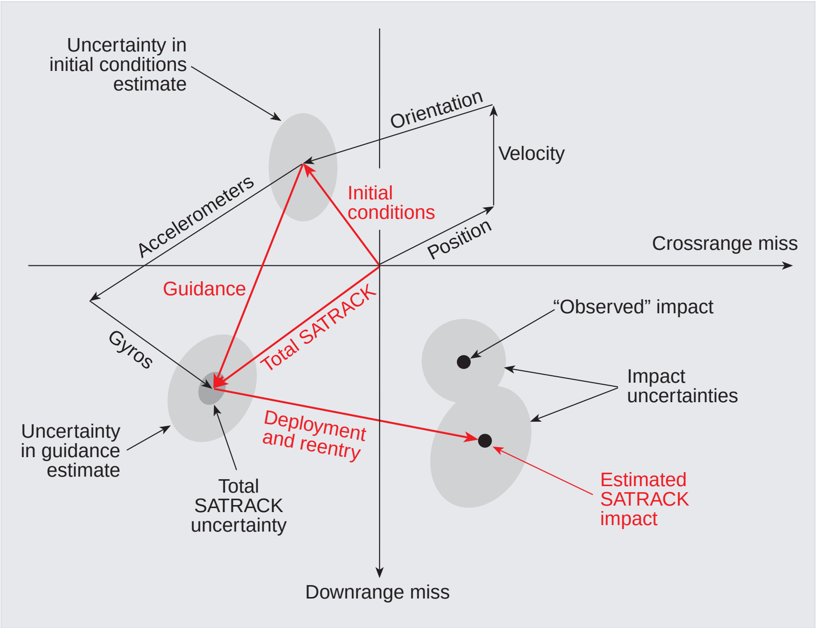

Figure 3. Hypothetical example of SATRACK impact evaluation. Each error estimate provided by the SATRACK process is projected into the impact domain, showing its downrange and crossrange contribution to impact miss (the center of the coordinate system is the aim point). Uncertainties for each estimate are also projected. The estimated errors and their uncertainties are tested for statistical consistency with system models and other independently measured results (e.g., the initial conditions derived from launch area instrumentation).

second level provides data for major error groups within each subsystem (e.g., accelerometers). A third level, not shown in the figure, produces estimates of fundamental error terms of the guidance model (e.g., an accelerometer scale factor error). In addition, SATRACK provides a point estimate of the initial conditions and a pre-deployment estimate; however, its principal purpose is to evaluate guidance subsystem error. The results from each flight are checked for statistical consistency with independent measures of impact, initial conditions, and several other factors.

As noted previously, limitations of test geometry will prohibit observations of all errors in any single flight test. However, since each flight provides observations of the underlying missile guidance error models, the data from many flight tests can be combined. The final cumulative analysis of flight test data produces a guidance error model for the Trident Weapon System. It combines observations from each flight to derive a tactically representative missile guidance model based completely on flight test data. This model is used with other similarly derived subsystem models to develop planning factors used to assign weapon system targets.

SATRACK has evolved over a quarter century. The original development for the Trident I missile (C4) began in earnest in 1974.[4] The C4 version (SATRACK I) was a technology development program aimed at (1) gaining insight into what was needed for improved accuracy and (2) developing an adequate accuracy evaluation system. SATRACK, as it evolved, is the fulfillment of the second major objective. SATRACK I proved that it could provide adequate estimates of guidance subsystem errors for individual flights. It was a pioneering effort in that both the tracking methods and the large Kalman filter processing techniques were pushing the state-of-the-art.

The second phase (SATRACK II) was a major upgrade in response to the stringent measurement requirements set by the Accuracy Evaluation System study.[5] The study established the total weapon system instrumentation requirements for the Trident II (D5) missile in accordance with specified accuracy evaluation objectives, including SATRACK as well as other prelaunch, in-flight, and reentry area instrumentation. SATRACK II has been operational since 1987.

A general upgrade has been initiated to replace aging components of the D5 test system. The new SATRACK ground recording equipment is currently in the final stages of checkout, upgrading at the post-flight facility is well along, and preliminary design of replacement missile test components is beginning. Furthermore, efforts have been focused for the last several years on a new GPS translator system to support Trident reentry body testing. The upgraded system will not only modernize the facility hardware and software functions, it will also substantially extend SATRACK performance capabilities.

SATRACK EVOLUTION

SATRACK I

The C4 missile design was well under way before it was decided to implement the SATRACK system. The proposed design approach did minimize the required additional missile electronics and it did take advantage of the existing S-band antenna; however, a new GPS antenna had to be added. The C4 design constraints held the GPS antenna configuration to four elements spaced uniformly around the missile circumference.

With the wide spacing between antenna elements, signal sums would cause strong interferometer null patterns. To minimize the problems associated with removing antenna phase effects in the postprocessor, opposite pairs of antennas were summed to form two-element interferometers oriented 90° from each other. The translator input was time multiplexed between the two interferometers. The time multiplex rate was set high enough to be outside the bandwidth of the signal tracking loops so that both inputs could be tracked simultaneously when the signals were strong enough. However, the tracking data used by the system's Kalman filter were selected to include only tracking data from the regions of each antenna where the phase effects were well understood (i.e., away from the null regions). Although this was a reasonable compromise within the set constraints, it led to an antenna design with a very poor gain over a large region (i.e., the specified gain was more than 14 dB below an ideal isotropic antenna, 0 dBi, over 15% of the coverage region). This poor gain, coupled with the levels of GPS satellite signals, represented a challenging condition for signal tracking.

Signal refraction through the ionosphere at the GPS prime frequency (L_1 = 1575.42 MHz) is significant, and it must be corrected for precision positioning applications. GPS provides a second frequency signal (L_2 = 1227.60 MHz) that is used with the prime frequency to compute the needed correction for signal refraction. Modulations applied to each frequency provide the basis for epoch measurements used to determine the distance to each satellite (range measurements). Two range-code modulations are applied to the L_1 frequency, one having a 2-MHz bandwidth and a second having a 20-MHz bandwidth. The L_2 frequency, however, is modulated only with the 20-MHz bandwidth ranging code.

The strongest GPS signal is the narrow-bandwidth L_1 signal; the L_2 signal is at one-fourth the power level of the L_1 signal. The wide bandwidth and lower power characteristics of the L_2 signal, combined with the antenna constraints for C4, precluded its use in the SATRACK I system. Therfore, the C4 translator was designed to use only the narrow-bandwidth GPS signal. The narrow bandwidth code signal is referred to as the clear/acquisition (C/A) code, and the wide-bandwidth code is normally referred to as the protected or precision (P) code. Sometimes the P code is called the P/Y code to indicate that the P code is encrypted.

Since the C4 translator would be using only the GPS L_1 C/A signal, another means was needed to correct for ionospheric refraction. Because of our development of and operational experience with Transit, we had an extensive background in ionospheric science. We had developed and evaluated models of the ionosphere, and we understood their limitations. We therefore decided to provide a ground-based satellite-like transmitter (i.e., a pseudosatellite) with two frequencies. Measurements of these two signals yielded a measure of refraction along the signal path between the missile and the pseudosatellite. These data gave an estimate of the electron density profile in the region of the missile flight path. The profile was then used to adjust our best available ionosphere model, which was then applied to estimate the refraction correction for each GPS satellite-to-missile L_1 signal path. The primary pseudosatellite signal is similar to the GPS L_1 signal. The second pseudosatellite signal was set at one-fourth the L_1 signal frequency (the $L_1/4$ signal), and it was modulated with a 200-KHz bandwidth ranging code. Another natural use of the $L_1/4$ signal was for SLBM range safety. By adding extra $L_1/4$ pseudosatellites at selected range sites, the required (lower-accuracy) real-time trajectory measurement is determined in relation to the three or more pseudosatellite locations. This range safety system was qualified during early C4 flights, which were equipped with both translators and C-band radar transponders. (Although the range safety system shares components with SATRACK, it is normally treated as a separate system and we will not discuss it further.)

The Laboratory provided overall technical direction for the SATRACK system and developed and continues to operate the unique postflight processing subsystem. Missile hardware development was part of the Navy's missile development contract with Lockheed Missiles and Space Company, and the ground recording and range safety equipment development was added to the Navy's contract with Interstate Electronics Corporation.

Another major challenge in SATRACK development was implementation of the large Kalman filter processing technique. To get a head start on developing the required C4 postflight processing software, the proposed methodology was applied to radar data collected for Poseidon (C3) missile flight tests. We recognized from the outset that the radar data would be inadequate because of shortfalls in system geometry and velocity measurement accuracy; however, valuable analysis insights and practical experience would be gained in the process. The C3 processing would be applied to data available from selected earlier Demonstration and Shakedown Operation (DASO) flight tests and all subsequent C3 DASOs (after March 1975) until the beginning of the C4 Missile Flight Test Program. DASOs were selected because the radar geometry was very weak in the operational test area.

An improved tracking capability was subsequently added to collect Doppler data from missile telemetry signals to supplement the radar data. This capability, called the Telemetry Doppler Metric Measurement System (TDMMS), was based on the use of telemetry signal Doppler differences as observed at multiple receiving sites. The hardware to record these data for postflight processing was in place to support two C3 DASO tests and C4 tests beginning with C4X-13. (The "X" flight designation applies to developmental flight tests conducted from a launch pad.) In all, six C3 radar, two C3 radar/TDMMS, two C4X radar, six C4X radar/TDMMS, six C4-PEM (Production Evaluation Missile) radar/TDMMS, and three C4-DASO radar/TDMMS flight tests were processed with the modified SATRACK postflight processing software. The last three C4X flights and all the C4-PEM/DASO flights processed with the radar/TDMMS system were also processed with the GPS/SATRACK system. TDMMS processing was improved on C4 flights beyond C4X-19 by using a translator signal, known as the pilot carrier, for the Doppler measurement rather than the telemetry signal.

The overlap of radar/TDMMS and GPS measurements was extended to overcome the limited number of GPS satellites available through the early C4 tests; it also provided an opportunity to compare the GPS processing results with radar and radar/TDMMS results. In these early C4 tests, the final best estimates of missile system performance were derived from a process that combined the data from all available methods. However, once the satellite support reached the expected levels, its accuracy was sufficiently superior to the radar/TDMMS that there was no longer any benefit from the combining process. Radar/TDMMS processing yielded only a part of the total validation activity associated with SATRACK development.

It is easy now to forget how much of this technology was yet to be proven when SATRACK development started. GPS was in a concept demonstration phase, the missile translator and digital postflight tracking capabilities were untested, and the Kalman filter processing techniques were being extended significantly beyond the existing state-of-the-art. The SATRACK Development Program included a substantial effort to validate all aspects of its accuracy (i.e., we had to validate the validation system).[6] In addition to the radar/TDMMS work, SATRACK accuracy was validated with a comprehensive simulation system and the use of a unique SATRACK test satellite.

A hardware-in-the-loop simulation facility was developed that produced simulated data inputs for all the major processing elements of the system from software simulations of GPS satellite motions and a test missile flight trajectory. The software simulation produced GPS satellite tracking data files, including simulated errors, as if they were provided by the GPS tracking facilities. These simulated data were sent to the Naval Surface Warfare Center (NSWC) for processing (using prototype software being developed for SATRACK operation). NSWC then produced satellite position and velocity estimates (i.e., ephemerides) and clock files that were returned to the APL postprocessing facility. The missile flight simulation produced simulated telemetry guidance data, including errors, and these were also forwarded to the postprocessing facility.

The missile and satellite trajectories, including simulated errors for satellite positions and clocks, were also used to drive satellite signal generators to produce simulated GPS signals. These, in turn, were passed through digitally controlled phase shifters and a time multiplexing switch to emulate the missile GPS antenna network. This antenna network simulator was connected to a missile translator hardware simulator that produced the translated GPS signals at S-band. An S-band antenna hardware simulator produced the outputs, which were recorded by prototype telemetry station receiver and recording equipment. The hardware simulator drivers were conditioned to encompass all anticipated effects, including signal propagation through the ionosphere and troposphere. The recorded data produced by this simulation capability were equivalent to the data that would be received from a telemetry site. These data, too, were sent to the postprocessing facility.

The postprocessing facility now had all the inputs expected for an actual flight test: GPS ephemerides and clock files from NSWC, telemetry data, and the translated signal data tape. The facility then processed these data as if they had come from an actual flight test and produced an estimate of the underlying model errors that could be compared to the model errors used to produce the simulated data. The process provided a complete test of the processing system to the extent that the simulations were valid representations of the real world. Segments of the simulation capability were used in many test support activities associated with developing the processing hardware and software at the postprocessing facility. Two complete formal runs of the simulator were used to conclude this element of the SATRACK system validation.

A second very important test and validation element, conceived by the APL SATRACK design team, was based on tracking a satellite configured to act like a C4 missile in its coast phase. Transat was produced by modifying a Transit satellite that was in standby storage at APL. The modifications included the addition of a structural extension that comprised a C4 translator prototype (actually two for redundancy) and an antenna array that matched the performance characteristics of the C4 configuration. Once in orbit, Transat provided regularly available missile-like test opportunities for SATRACK system and hardware validation tests. Transit navigation system capabilities were maintained in Transat so that it could serve as an additional operational navigation satellite when it was not being used for SATRACK test purposes. The Transit capabilities were also the basis for independent satellite trajectory measurements that could be compared with translator-derived trajectory measurements for validation purposes.

Transat was launched in October 1977 before any GPS satellites were available. In early November, the satellite was checked out in the Transit mode to verify that it was ready to support operational navigation users. It was then switched to the Transat mode, and initial tests were conducted with the APL pseudosatellite. Through May 1978, Transat was primarily used to test equipment at the eastern and western test ranges. These tests provided the capability to check real system data interfaces using pseudosatellite signals with an emphasis on range safety system testing. Transat also proved to be an effective tool for checkout of the TDMMS. However, validation of GPS tracking concepts would have to wait until at least two satellites were available.

In June 1978, the first missile translator flight test, C4X-17, occurred. Only one GPS satellite was available for this test, and the translator failed after a short period of operation. However, the test was significant to the SATRACK developers because it was the first time that we were able to demonstrate that actual translated GPS signals could be successfully tracked at the APL postflight tracking facility using data recorded by one of the range telemetry sites. The C4X-18 flight test in August 1978 was supported by two GPS satellites, and the missile translator worked perfectly throughout the flight. Since then, translators have performed successfully on all flight tests. This test provided the first opportunity to complete a full missile evaluation with SATRACK and initiated the first opportunities for Transat evaluations of the GPS capabilities.

The SATRACK processing facility was now operating at an intense level. Transat validation activities were just getting started, radar/TDMMS C4 processing was continuing, normal SATRACK C4 processing was beginning, system validation runs were concluding, and we were first beginning to evaluate the actual ephemeris accuracy for GPS satellites. The original estimates for these errors reflected into range and range rate uncertainties for each satellite line of sight were 12 ft and 0.005 ft/s, respectively.

To directly assess the value of these errors during each Transat or missile flight test period, data were collected at an accurately surveyed location. We referred to this data collecting as "static missile tests." These tests provided a direct observation of the link range and range rate errors relative to those computed from the satellite ephemeris. The formal simulation validation runs were completed in January 1979, and a four-satellite Transat validation test was conducted in March 1979. That Transat test and the static missile results indicated that the GPS ephemeris was not providing the expected accuracy. In the early days, we cross-checked ephemeris data from NSWC with data from the GPS Master Control Station (the official system source) and with data provided by Aerospace Corporation. A careful analysis of all the available data indicated that the GPS ephemeris errors were about 3 times larger than expected for the period covering C4X-18 (two GPS satellites), C4X-19 (three GPS satellites), and C4X-21 (four GPS satellites) flight tests.[7] The limited number of satellites and the larger-than-expected ephemeris errors were the major difficulties; all other aspects of the system performed as expected.

The process of evaluating sources of ephemeris errors continued through the end of 1981; 8 to 10 different software configurations were evaluated. While this evaluation was being conducted, the initial baseline ephemeris generation software was being maintained through all flight tests to that time. However, in January 1982, a new baseline was selected that produced an improvement of about a factor of 2. To maintain consistent processing results, all previously processed C4 DASO and operational test flights (about 20) were reprocessed with the new baseline ephemeris generation software. On the basis of the limitations of the early C4X flight tests, SATRACK processing results were compared to radar/TDMMS results into the early operational tests.[8] After the baseline was adjusted, C4 trajectory accuracy achieved with the SATRACK I system, based on the first 31 DASO and operational flight tests, had a position uncertainty of 35 ft and a velocity uncertainty of 0.09 ft/s at body deployment.[9]

Some finer-grain improvements in ephemeris were subsequently achieved by adding an additional GPS data collection site at APL, and Transat supported range safety testing as late as May 1982. For the most part, the SATRACK I project was complete, although translators continue to support all C4 flight tests. In all, translators have successfully supported range safety and accuracy processing requirements for 154 C4 flight tests through the end of 1997.

SATRACK II

The development of the Trident II (D5) missile began in 1981. To support this development, APL conducted the Accuracy Evaluation System study. That study supported development of the technical objectives and guidelines document that defined the accuracy evaluation requirements for the D5 Missile Flight Test Program. The SATRACK II requirements, defined by the Accuracy Evaluation System study, included significant performance enhancements.

It was clear that the D5 requirements could not be met without a dual-frequency GPS signal tracking capability to permit ionospheric corrections. The GPS signal structures were reviewed in a series of meetings with the GPS joint program staff. Unlike the L_1 signal, the L_2 signal could only be modulated by either the narrowband C/A code or the wideband P code. The possibility of temporarily switching to the C/A code modulation on L_2 to support Trident tests was considered impractical because of the effect on other users. Future satellites might have been modified to include the dual-code capability on both frequencies. However, the joint program staff suggested an alternative that would use a third GPS frequency (L_3). This transmission served a nonpositioning purpose. It was used only intermittently, it was derived from the same frequency source as the positioning signals, and it could have the C/A code modulation applied when needed for Trident test support. This approach was agreed to, and it became the baseline GPS signal concept for SATRACK II.

The implementation of a dual-frequency GPS capability naturally affected all other aspects of the system hardware configuration. The addition of another signal channel to the missile translator could increase the output bandwidth requirement and affect the telemetry station recording requirement. However, we recognized that the two GPS signals could be overlaid in a common translator channel. The signals could be separated during the signal tracking operation by virtue of the differences in their code structures, but at the expense of increased noise in each signal. Another benefit of the overlay was that the SATRACK I recorder would not need modification. We also realized that the range safety tracking capability could be based on the translated GPS signals, that is, this choice would eliminate the need for the $L_1/4$ translated signal channel. The initial system design was based on the common channel GPS approach, which we tested at APL. However, at the completion of the preliminary design phase, the SATRACK II baseline was established with a separate channel L_1/L_3 configuration, and the range safety system was based on the GPS L_1 C/A signal alone.

Another major effort in establishing the SATRACK II baseline concerned the missile antenna configuration. A careful study of the phase noise characteristics of several candidate configurations eventually led to the choice of a wraparound antenna array. This design was selected because it minimized phase variations in the missile roll plane, apart from small angular regions in the nose and tail directions. This choice was also important to the range safety configuration, not because of accuracy considerations but because it allowed for smoother, more continuous performance of the real-time signal tracking loops.

These were important but relatively straightforward upgrades to the SATRACK I system. All the missile and telemetry station hardware requirements were updated to include the modifications, and the APL simulation facility was updated to support development of the postprocessing facilities. The development of the upgraded postprocessing facility was then begun. The new missile hardware test equipment configuration was again provided within the Lockheed Missiles and Space Company development contract, and the telemetry station upgrades were provided within the Interstate Electronics Corporation contract.

The major hardware development effort at APL focused on a redesigned SATRACK postflight tracking configuration to enhance accuracy and throughput. The tracking system was upgraded to track 12 dual-frequency links from right- and left-hand circularly polarized translated signals (i.e., 48 range-code and carrier tracking loops). Similarly, the tracked data correction and editing software was enhanced to include automatic editing and analyst-interactive capabilities. The postflight tracking software was substantially improved using a modular architecture and better modeling techniques. However, the most significant development activity of SATRACK II was the implementation of the cumulative flight test accuracy evaluation capability. Although conceptualized during SATRACK I development, a formal theoretical basis for its design and its subsequent implementation were completed as part of the SATRACK II development program.

The pad-launched developmental D5 flight tests began in January 1987 (D5X-1) and ended in January 1989 (D5X-20). During that time, GPS satellite support was not yet continuous and not all tests could be conducted within the time period providing maximum satellite coverage. Furthermore, only the Block II satellites had the dual-frequency signal capability. These limitations were mitigated by new dual-frequency pseudosatellites, but they, too, were being introduced on the range during the D5X test series. Despite the coverage limitations, missile trajectory uncertainties at body deployment for the first five tests were from 13 to 20 ft in position and 0.03 to 0.12 ft/s in velocity. However, from the seventh test on, the uncertainties improved to 4 to 11 ft in position and 0.006 to 0.014 ft/s in velocity.[10] The position and velocity requirements set for the SATRACK II system were 20 ft and 0.01 ft/s, respectively. Whereas these requirements were met at deployment, they were being exceeded in the boost regions. Currently, the system is providing velocity accuracy below 0.01 ft/s in all flight regions; the position accuracy is now less than 3 ft. This performance gain was primarily due to GPS improvements (more satellites and more accurate ephemerides).

The first cumulative evaluation of the D5 Missile Flight Test Program was based on 19 tests that had used representative production guidance systems. This set included 4 of the described D5X flights and 15 later PEM, DASO, and Commander-in-Chief Evaluation Test flights.[11] Excellent results were obtained with this very early test sample, and subsequent evaluations have contributed significantly to improvements in the underlying weapon system error models. A companion article (Coleman and Simkins, this issue) describes the significant contributions achieved by the cumulative processing methodology.

Other Applications

At about the same time as SATRACK II development was beginning, the Range Applications Joint Program Office (RAJPO) initiated development of a translator for general missile test applications. APL provided technical support to RAJPO, and they eventually initiated a contract with Interstate Electronics Corporation to produce a ballistic missile translator (BMT) system for general-purpose range applications. The BMT provided an important test capability for numerous National Missile Defense (NMD) test flights that we have been supporting since the early 1990s. A special adaptation of the BMT was also used for two Air Force Peacekeeper ICBM flight tests that the Laboratory supported.

The first NMD test support we provided was for two exo-atmospheric reentry intercept subsystem (ERIS) test flights in January 1991 and March 1992. These tests demonstrated that differential GPS measurements between an interceptor and target, each equipped with a translator, could resolve the intercept vector geometry with submeter accuracy. The direct follow-on project of postflight tracking and analysis support to NMD is continuing, with the most recent intercept test series planned into 1999. The ERIS tests acted as a springboard to a series of independent research and development (IR&D) activities directed at achieving intercept vector geometry accuracy of less than 2 cm. The ability to achieve that level of accuracy was demonstrated with an IR&D project based on the use of a recently developed SATRACK instrumentation.

The U.S. Air Force Peacekeeper test support was a direct spin-off of the Navy Trident work. The postflight tracking and analysis work had the same general evaluation objectives for individual tests. However, with only two Peacekeeper flights evaluated using SATRACK, no basis for cumulative analysis existed. APL and the Charles Stark Draper Laboratory supported Peacekeeper contractors (TRW and Rockwell International) in a successful technology transfer of the Navy guidance evaluation capabilities.[12,13]

All objectives of the program were met. Of particular importance, the two tests showed that the GPS estimation uncertainties were better than the best available radar-based evaluation approach. Specifically, this test experience demonstrated the superiority of GPS over radar for evaluating inertial measurement unit hardware errors. In addition, it was concluded that GPS would provide highly accurate instantaneous impact point data for range safety.[12,13] Although success was achieved with the SATRACK approach, the Peacekeeper program was meeting its objectives with the available radar instrumentation. Therefore, the Air Force had no motivation to change its evaluation approach. However, Air Force reports recognized that the SATRACK methodology uncovered a previously undetected initial condition error. This finding led to a reassessment of the gravity model in the launch area and its influence on the Peacekeeper guidance model.

SATRACK III

The Navy will continue to test and evaluate the Trident Weapon System with the primary goals of detecting changes to system performance caused by aging components and assessing system modifications needed to extend its lifetime. In this regard, we recognize that SATRACK evaluation is only one part of system accuracy assessment, and accuracy assessment is only a part of the total weapon system evaluation. Equal diligence is needed in all aspects of monitoring and maintaining the Trident system.

Continued D5 accuracy evaluation support will remain the primary objective for SATRACK. However, in parallel with this activity, we have identified a natural extension of SATRACK capabilities that can support precision intercept evaluations for national and theater ballistic missile defense flight tests. This realization grew out of our ERIS flight test experience and our support to the Strategic Defense Initiative Organization for the development of a precision intercept test capability for the Brilliant Pebbles Program. Both of these projects and the continued support of NMD test objectives have, with Navy concurrence, taken advantage of the unique APL facilities developed for Trident. As noted in a companion article (Thompson, this issue) on a high-precision sled test, we successfully completed an IR&D project devoted to demonstrating the measurement capability needed for precision intercept test evaluations. An earlier IR&D project developed a translator design for this purpose that was the basis for a new Trident translator system used for supporting special reentry body tests.

The upgraded SATRACK postflight tracking facility will support existing C4 and D5 translators and reentry body translators as well as the replacement translator to be selected for the new D5 test missile kit. When completed, we will refer to this configuration as SATRACK III, which will take full advantage of technology growth in processing hardware and software to produce a workstation-based facility that is easily reconfigured to support a wide range of tests. The capabilities of the new configuration and the expected reduced test tempo of Trident flight tests naturally produce a processing capacity that can be extended to support critical ballistic intercept testing of other high-priority defense programs. Our studies indicate that this capability is required to adequately support model validation of precision missile intercept systems, and we have configured the postflight tracking subsystem architecture to be easily expanded to eventually support such tests.

The office responsible for general range applications, RAJPO, is developing a translator-based GPS range system (TGRS) that includes a capability for intercept support missions. This system is intended to serve both range safety and postflight evaluation objectives for a variety of range users. Many new applications are expected to use TGRS digital translators and their ground station recording equipment. A new upgrade to the APL postflight tracking facility will provide an interface for TGRS data processing in the near future.

SUMMARY

SATRACK has been a significant contributor to the successful development and operational success of the Trident system. It continues to provide a unique monitoring function that is critical to the maintenance of the Navy's strategic weapon system. As our nation moves toward a higher reliance on missile defense, the need to establish equivalent levels of assurance in those capabilities will require similar skills and facilities. Although Trident test and evaluation is our primary focus in the evolution of the SATRACK system, we are attempting to accommodate emerging requirements associated with missile defense system test and evaluation, as appropriate. SATRACK will continue to support the Navy's strategic weapon system operations and evolution for the foreseeable future. The Laboratory looks forward to continued support of the NMD program, and we hope to extend the use of this technology to a wider range of weapon system evaluations.

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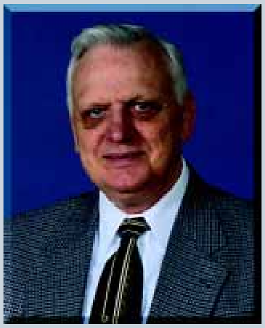

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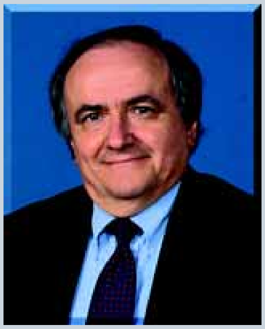

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