Global Positioning System Translators for Precision Test and Evaluation

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The first Global Positioning System (GPS) signal translator was developed as part of the accuracy evaluation system conceived at APL in response to the Navy's Trident Improved Accuracy Program. One goal of that program was to identify the additional test and evaluation capabilities that would be required to ensure that the deployed Trident weapon system could meet a new high-accuracy system requirement. The primary component of that evaluation system, known as SATRACK, became operational in 1978 for the Trident I missile. It was subsequently upgraded to meet the requirements for the Trident II missile. SATRACK was developed to provide the missile guidance evaluation capability for Trident. The signal processing aspects of SATRACK are based on a missile signal relay concept using GPS satellite signals. We named the signal relay a "translator" to distinguish its unique function. In this article we discuss the origin and evolution of translators, highlight APL's contribution to this technology, identify the important issues regarding translator use, and consider the future applications of this technology. The article focuses on precision test and evaluation; however, it should be noted that APL also pioneered the use of GPS translators for range safety.

(Keywords: GPS translators, Missile system test and evaluation, Satellite positioning.)

INTRODUCTION

Early studies in support of the Trident Improved Accuracy Program led to several important conclusions:

1. Confident assessment of Trident accuracy, from a reasonably sized flight test program, required a measurement technique beyond the end-point scoring techniques used for earlier Fleet Ballistic Missile Polaris and Poseidon weapon systems.
2. Current or anticipated range radar systems were not able to provide the needed measurement precision.
3. A satellite-based system was required to provide adequate geometry and measurement precision.

These conclusions were reached in 1972, before the Global Positioning System (GPS) development program was begun. As a result of these conclusions and the need for an accuracy evaluation capability, the Navy began to develop a special satellite system. To minimize the cost of the satellite-based system, the satellites were to be simple range-code modulated radio beacons with no real-time positioning service capability and the constellation would have been restricted to six satellites. The missile hardware would have provided a simple radio relay of the signals broadcast by the satellites. Signal recording would have been provided as a simple extension of the normal telemetry support function required for all flight tests (i.e., the translator output signal would use the missile telemetry band). All positioning operations for the satellites and the test missile would have been accomplished at a postprocessing facility at APL. The satellite ephemeres would be determined only for a period surrounding each flight test, from the results of postflight processing of data that could easily be provided by the Navy Navigation Satellite System (Transit) ground stations. We named the missile radio relay a "translator" to emphasize that the missile hardware received the satellite signal, translated it to a missile telemetry frequency (S-band), and then rebroadcast the received signal (i.e., no signal processing or tracking functions were provided by the missile hardware). The translator name also indicated that this signal relay device was for missile tracking, not for communications. After the GPS development program was initiated, the Trident accuracy evaluation concept was modified to be compatible with that system, but the basic measurement ideas remained unchanged. The GPS user system developed by APL for this capability is known as SATRACK. In a companion article in this issue, T. Thompson, L. J. Levy, and E. E. Westerfield discuss the broader aspects of SATRACK development.

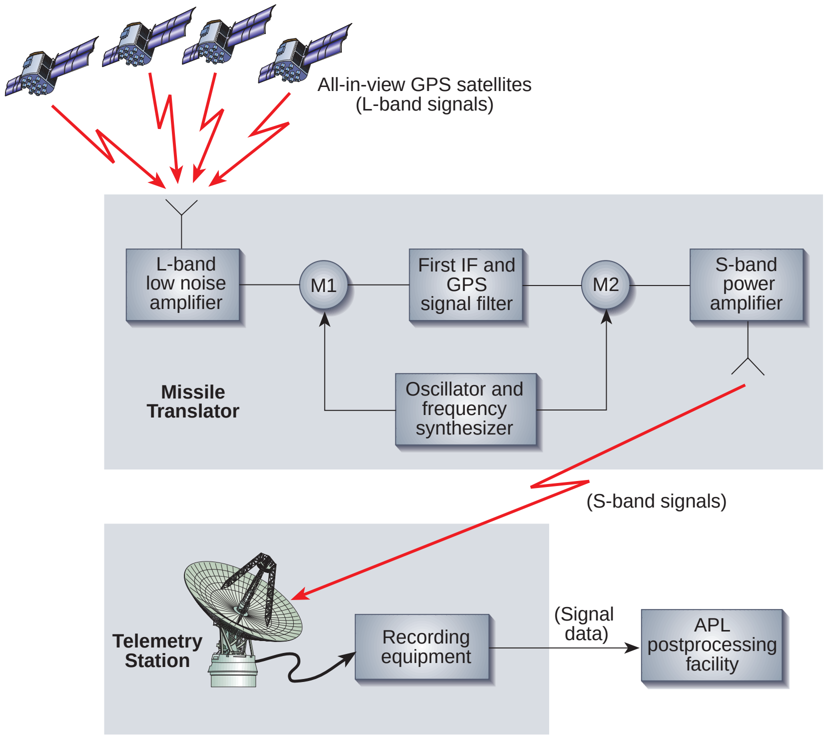


Figure 1. Translator concept. Global Positioning System (GPS) signals received by the missile's L-band antenna are amplified by a low-noise preamplifier, converted to an intermediate frequency (IF) by the first mixer (M1), filtered and further amplified at the IF, converted to S-band by another mixer (M2), and retransmitted to the telemetry station through the missile's S-band antenna. Signal data recorded at the telemetry station are sent to the APL postprocessing facility for signal tracking and missile system analysis.

BASIC CONCEPT

The basic translator concept is shown in Fig. 1. GPS satellite navigation signals are provided at two L-band frequencies (designated L_1 and L_2) to allow for correction of signal refraction through the ionosphere. The primary frequency (L_1) is modulated with two different ranging codes: a narrowband C/A (clear/acquisition)-code and a wideband P (precision)-code. The secondary frequency (L_2) carries only the P-code modulation. Both frequencies also carry message modulation to provide satellite position and timing data users need for navigation. To restrict the precision of unauthorized users, the frequency source for all signals is programmed to drift in an apparently random fashion (referred to as selective availability) and the P-code signals are encrypted (referred to as anti-spoof). Authorized users are provided with the means to correct for both of these signal conditions. From the translator perspective, only signal frequency and bandwidth matter. Satellite signals received at the missile are simply amplified, shifted to an intermediate frequency, filtered to cover the satellite signal modulation bandwidth, shifted to the desired output frequency, and amplified for transmission to the ground station. The ground station simply receives the translated GPS signals, shifts the carrier frequency to near zero, and then coherently samples (signal amplitude and phase) and digitally records the full signal data.

All frequency conversions are based on the translator oscillator and synthesizer. The synthesizer also creates an S-band pilot carrier signal as a direct multiple of the translator oscillator that is used as a tracking aid. Tracking of this carrier frequency provides for correction of translator oscillator variations and also aids in the removal of signal dynamics in the missile-to-ground transmission. The recorded data are subsequently played back at a special facility at APL where the satellite signals are tracked using delay-locked loops for range code modulation tracking and phase-locked loops for carrier phase tracking. All necessary selective availability and anti-spoof corrections are easily applied in the postflight tracking environment. The recovered range and phase data are then used in a postflight processing system to evaluate the missile's accuracy.

The translator passes signals for all satellites in view of the missile antenna, and the postflight receiver obviously provides all-in-view satellite signal tracking (currently it is common for a Trident missile to see 15 to 18 satellites during a test flight). To simplify the concept description, a single-frequency translator is shown in Fig. 1. Single-frequency designs are typically based on translating only the L_1 C/A-code signal because its modulation bandwidth is only 2 MHz; full coverage for P-code modulation requires a 20-MHz bandwidth. Naturally, single-frequency translator systems do not have the capability to directly correct for signal refraction caused by the ionosphere. In the remainder of this article we will discuss most of the translator designs that have become available over the years, including the most recent wide-bandwidth dual-channel translator required for the most precise applications.

The translator concept was selected because of the simplicity of the missile hardware. Originally, this choice was largely motivated by the desire to minimize the size, weight, and costs of the missile flight-test hardware. However, it was quickly apparent that the benefits to postflight tracking of GPS signals go well beyond those motivations. Being able to replay signals many times allows a level of processing refinement and adaptations for the unexpected that are not possible when signal tracking is accomplished in the missile (i.e., using a GPS receiver approach). The hardware and operational simplicity of the translator approach is more reliable and robust than a missile receiver approach. These benefits are readily apparent from the Trident flight-test experience. Since the second translator flight test in 1978, the system has successfully provided accuracy data for more than 165 Trident flight tests. The first translator flight test was the 17th pad-launched test missile of the Trident I test program (i.e., the 17th developmental Trident I missile flight test). Although the translator on the first flight failed, it provided a short period of signal data that were successfully tracked in the postprocessing facility, an important milestone for the SATRACK development community. Since then, the two translator systems (Trident I and Trident II) have successfully provided accuracy evaluation data for all required test flights. They also have provided flawless range safety support since that first flight test in 1978. In all, translators have successfully provided accuracy and range safety support on all 254 Trident I and II missile flight tests since that first flight. A description of the Trident I translator system, its development, and early flight-test results was given at a Position and Navigation Symposium[1] and in an earlier *Technical Digest* article.[2]

TRANSLATORS

Trident I Translator

APL did some early breadboard testing of the original Navy-unique accuracy system translator, but apart from that brief experience all translator development has been based on GPS signals. (Actually, consideration of GPS signal translation started before the custom satellite constellation approach was abandoned. The final custom satellite proposal included GPS-like signals to allow better coverage for early missile flight tests and to provide a straightforward transition to GPS as its constellation evolved.) The expected signal levels from the GPS satellites coupled with the anticipated performance of the missile GPS antenna indicated that there would be very little signal tracking margin. GPS provides three different positioning signals: two as modulations on the primary frequency (L_1 = 1575.42 MHz) and the third on a second frequency (L_2 = 1227.6 MHz). A narrowband (2-MHz bandwidth) modulation on L_1 provides the strongest signal power, a wideband (20-MHz bandwidth) modulated signal on L_1 is at half that level, and a similar wideband modulation on L_2 is at one-fourth that level. It is difficult to realize now how much uncertainty there was regarding our ability to reliably track GPS signals postflight with the Trident I design conditions. It was believed that it would be very difficult to track the narrowband signal and virtually impossible to track either of the other signals. In addition, the signal-recording capabilities available during the Trident I system design would not support the data rates needed for recovery of the wideband signals.

Two GPS frequencies are provided to correct for signal refraction in the ionosphere along each satellite signal path. Since we could not count on recovering two GPS signal frequencies with the Trident I translator system, we incorporated a dual-frequency ground transmitter that would provide a measurement of the electron density profile as the missile transited the ionosphere. The profile data were used to condition a model of the ionosphere. Then the model was used to estimate refraction errors along each of the GPS satellite-to-missile L_1 signal paths. The second ground station transmit frequency was set at one-fourth the

L_1 frequency (i.e., 393.855 MHz). Subsequently, this second frequency was used with a set of $L_1/4$ ground transmitters as the primary range safety tracking system for the Trident I missile, replacing the radar beacon capability. Later still, during the transition to the Trident II configuration, the $L_1/4$ capability was replaced by a GPS-translated L_1 narrowband range safety tracking system. Although these ionospheric correction techniques were acceptable for the Trident I test objectives, the Trident II requirements could not be met without direct measurements of refraction along each of the satellite signal paths (i.e., Trident II required a dual-frequency GPS translator).

The Trident I translator provides signal translation for the narrowband L_1 signal transmission from all-in-view GPS satellites. Within the bandwidth of the translated signals, the GPS signal power received is very much smaller than the thermal noise power generated by the translator preamplifier. The translated GPS signal output, in S-band, appears to be band-limited thermal noise. With regard to GPS signals, it is impossible to saturate the translator with any practical number of GPS satellites. Digital data from the ground recording equipment sample the full GPS translated signal bandwidth, including all-in-view satellite signals, and the postflight tracking system recovers the range and carrier phase data along each satellite signal path. The second channel of this translator was required to operate with a positive input signal-to-noise ratio to meet range safety requirements. This requirement was accommodated by time multiplexing the second frequency transmission. In addition to the two translated signal channels, the translator includes a signal tone (pilot carrier) that is used to aid the postflight tracking operation. As noted, the pilot carrier is a direct multiple of the translator oscillator used to form the frequencies that produce the translated signal outputs. A track of the pilot carrier provides a measure of the S-band signal dynamics and the translator oscillator that can be removed from the GPS signal tracking function.

The Trident I GPS antenna was restricted to four separate patches on the outer surface of the missile. If the four patches were simply summed, the antenna pattern would have had a large number of interferometer nulls in the missile roll plane. Since antenna phase variations add directly to signal dynamics, the postprocessing function was designed to remove those variations using a model of the antenna. Because we expected that it would be very difficult to adequately model the four-element interferometer, the antenna system included a time multiplex capability that switched between two dual interferometer patterns formed by opposite pairs of the four antenna patches. The multiplex switch clock frequency was set high enough to be outside the bandwidth of the posttracking phase-locked loops (i.e., 434 Hz). This multiplex technique allowed continuous phase tracking of signals from both antenna pairs in those regions where both had adequate signal levels. The signal overlap made it possible to restrict the data processing to signals that more easily matched the antenna models (i.e., in most instances, when one pair was in the interference region, the other was not). The posttracking function requires knowledge of the position of the antenna multiplex switch, and this was provided as amplitude modulation on the pilot carrier signal. The translator S-band output signal included signal translation for GPS L_1 narrowband ranging signals, signal translation for the time multiplexed $L_1/4$ ionosphere and range safety signal, and an amplitude-modulated pilot carrier. Pictures of the APL prototype translator and an RCA production translator for the Trident I missile are shown in Fig. 2. Both were designed to the same specifications and are representative of the GPS technology of the mid-1970s.

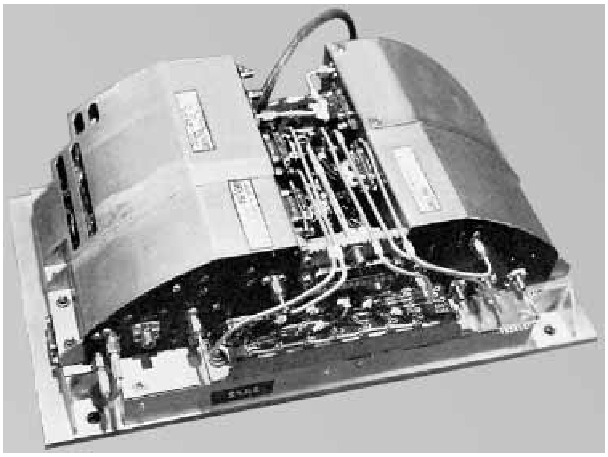
As the lead design agent for the SATRACK system, APL developed signal simulation capabilities that provided dynamic translated signals from simulated Trident I flight profiles that were recorded on prototype telemetry station recording equipment. This equipment included dynamic signal simulation from five GPS satellites and a functional replica of the missile translator hardware, including simulation of the missile GPS and telemetry antenna characteristics and the missile-to-ground S-band signal dynamics. The recorded data were played back to test the postflight tracking system being developed for the APL postflight processing facility. This simulation and prototype activity provided initial validation for the signal recovery and tracking concepts of the system.

A second development activity at APL produced two prototype Trident I missile translators (Fig. 2) that were flown on a satellite. This satellite, known as Transat, was launched in 1977. It was developed by APL to provide Trident I–type test opportunities with *real* translated GPS signals on a regular basis during SATRACK development. This second activity provided direct validation of the trajectory measurement capabilities of the system.

The third development activity at APL supported generation of formal specifications for the telemetry station equipment, subsequently developed by Interstate Electronics Corporation (IEC), and for the missile translator, subsequently developed for Lockheed Missiles & Space Company (LMSC) by Cubic and RCA. In addition to these three activities, APL had full responsibility for development of the postflight processing subsystem and provided the technical interface with the GPS Joint Program Office.

Transat was an important element of the original SATRACK development program. It was produced by

(a)



(b)

Figure 2. Trident I (C4) translators: The two translators shown were designed to the same specifications. The base dimensions are approximately 6.5 × 12.3 in. (a) The prototype designed at APL was subsequently used in a satellite for system demonstration and checkout activities. (b) One of the production units designed by RCA has supported C4 test flights since 1978.

adding components to a spare operational Transit satellite. The Transit satellite used was one of the original satellites built at APL. Two translators of the type shown in Fig. 2 and deployable boom antennas were part of a penthouse structure mounted on the top surface of the original satellite. The Transit gravity gradient boom assembly was moved to the top of the new penthouse structure. The antenna booms were used to provide an antenna array with the same diameter as the Trident I missile. Transat's translator antenna configuration was designed to replicate as exactly as possible the phase conditions that would be experienced with missile test flights, including the antenna multiplex arrangement. Transat maintained its full Transit navigation signal capabilities so that it could also be used as an operational satellite. Furthermore, the navigational signal capabilities provided an independent Transat trajectory measurement capability that could be directly compared to the GPS translator measured trajectory. Transat not only provided support for the Trident I system but also was used to support range safety ground equipment tests for Trident II and for several other programs into the late 1980s.

Trident II Translator

Meeting the Trident II accuracy evaluation requirements called for a dual-frequency GPS translator design. The L_2 frequency on GPS satellites could be modulated with either the narrowband or the wideband ranging signal. Normal GPS use, however, required the wideband signal on the second frequency. Navy and Air Force representatives met at the beginning of the Trident II translator development project to consider various GPS signal options to meet the Trident II requirements. Eventually, it was decided that the Trident II test program should be supported by a third frequency available on the GPS satellites (L_3 = 1381.05 MHz). This third frequency was not intended for positioning service. However, it did have the same stability as the other frequencies, its normal use was intermittent, it could be modulated with the narrowband ranging signal, and, most importantly, its use would not affect other users of the L_2 signal. A memorandum of agreement was established to set the conditions for L_3 support. Basically, the agreement was that L_3 transmissions with the narrowband ranging modulation would be made available for a period covering each Trident II test flight. Therefore, the Trident II translator was designed to relay the GPS L_1 and L_3 frequencies, each modulated by the narrowband (2-MHz) ranging signal. It is important to understand that the reduced-bandwidth ranging modulation is of little significance to the accuracy evaluation mission. The important measurements are the signal carrier phase tracking results, which provide range change measurements with millimeter precision. The ionospheric correction for the accuracy evaluation objectives is primarily related to the phase tracking precision achieved at each frequency and to the frequency separation between the two signals. The increase in ranging noise associated with the narrower-band ranging codes is easily overcome by the smoothing provided by the phase measurements.

The antennas on the Trident II missile were greatly improved. Both the GPS dual-frequency antenna and the S-band telemetry antenna are wraparound arrays that minimize phase variations in the missile roll plane. There is no need for antenna multiplex switching with this design; therefore, the pilot carrier is not modulated. The range safety system was now based on real-time tracking of the GPS narrowband L_1 signal at the telemetry sites. The Trident II translator then included signal translation for L_1 and L_3 narrowband GPS ranging signals and a pilot carrier tone. The changes made to improve accuracy evaluation capabilities also simplified translator design and postflight tracking operations.

The new translator, shown in Fig. 3, was developed for LMSC by RCA, and the modified ground equipment was developed by IEC. APL again provided technical oversight for these activities and developed the corresponding changes required for the APL postflight processing facility. Viewing the Trident II instrumentation development from the translator perspective fails to capture the full significance of the changes to the accuracy evaluation system. The goal of the Trident II accuracy evaluation system design was to establish a full range of test instrumentation and analysis methodologies that could meet an established set of technical objectives and guidelines for the Trident II system accuracy. The APL program that established all instrumentation requirements (not only the translator) for Trident II evaluation was called ACES (ACcuracy Evaluation System),[3] which is discussed in a companion article in this issue on weapon system test and evaluation by Coleman and Simkins.

Ballistic Missile Translator

The Range Applications Joint Program Office (RAJPO) initiated a program, in the mid-1980s, to develop a translator system for general test missile applications. The concepts were based on the Trident experience. The translator produced by this program provided only narrowband L_1 signal translation and a pilot carrier. It was designed to provide the same range safety capability (i.e., real-time computation of missile position at the ground station using translated GPS signals) used by Trident, and the ground system included a signal-recording capability that was compatible with the APL postflight tracking facility. The pilot carrier and L_1 relative frequency relationships are identical to those used for the Trident II translator. APL supported RAJPO throughout a competitive procurement process for development of the ballistic missile translator (BMT). We supported development of the request for proposal and evaluation of the proposals. Since this program was initiated, we have continued to provide technical support to RAJPO for GPS translator systems. Most recently, that support has been for the Translated GPS Range System (TGRS) development program. The BMT development contract was awarded to IEC, and a modest number of BMTs were produced under that contract. The current TGRS development contract was also awarded to IEC.

Figure 3. Trident II (D5) translator. This is an RCA production D5 translator on a test fixture. This model translator has flown in all D5 test missiles. The base dimensions are approximately 7.0 × 9.6 in.

One of the primary users of BMTs has been the National Missile Defense Program. An early interceptor flight test for that program included BMTs in both the target and interceptor. The translators and associated real-time ground-based positioning hardware and software were used to substitute for the ground-based radar system that was still under development and not scheduled to be available. The real-time positions for each body, computed in the ground equipment from translated signals, were used to produce steering commands in a way similar to what would have been provided by the ground-based radar. The steering is required only to get the target into the field of view of the interceptor's infrared seeker. The seeker output then drives the interceptor control function into intercept. The interceptor, known as the Exoatmospheric Reentry Intercept Subsystem (ERIS), was flight tested in January 1991 and March 1992.

APL provided the postflight processing of the two ERIS interceptor tests. Since the refraction errors caused by the ionosphere could not be removed from the data, the absolute trajectory measurements for either body were not as accurate as those routinely provided for Trident. However, a differential measurement between the two bodies (i.e., determination of the relative position vector as seen in body-to-body link difference measurements) is not limited by refraction differences. Refraction errors are highly correlated when the bodies are close to each other (i.e., near intercept). The uncertainties achieved in determining relative position were approximately 60 cm. The relative position measurement provided by the GPS solution was consistent with the direct intercept result in the first ERIS test. The measures of uncertainty were identical for the two intercept tests. APL continues to support the National Missile Defense Program with postflight tracking and analysis of their current flight tests.

Several BMTs were modified to include an L_2 translator signal channel. This translator, known as a dual-band translator (DBT), was designed to support early

U.S. Air Force Peacekeeper missile flight tests. APL participated in developing the flight test instrumentation and processing plans, supported IEC's testing of the DBT, and postflight processed two Peacekeeper flight tests. A unique aspect of the DBT signal processing was that the L_2 wideband signal was restricted to the same 2-MHz translator bandwidth as the narrowband GPS signal. The DBT output is similar to that of the Trident II translator with the restricted bandwidth L_2 signal in place of the Trident L_3 signal. Restricting the bandwidth of the ranging modulation causes two things to happen: first, the restriction limits the total signal power available for tracking and, second, it reduces the ranging precision by an additional factor that is related to the apparent bandwidth of the limited signal. As noted, the limitation to ranging precision was of secondary concern for the Peacekeeper application; the more serious limitation was the total reduction of signal power. Fortunately, the Peacekeeper GPS antenna design provided some mitigation for the reduced signal power. The antenna was good enough to maintain nearly constant tracking of signal phase in a small-bandwidth, phase-locked tracking loop based on signal aiding from the primary signal track at L_1. The processing results for the Peacekeeper tests were very good, possibly the best ever achieved outside the Trident experience. However, the limited-power second frequency did reduce the responsiveness of the refraction corrections to the dynamics of the limited tracking bandwidth of the second frequency. This reduced responsiveness can limit dynamic observations as the missile passes through the peak electron density region of the ionosphere. The apparent refraction rates can be quite large in these regions.

Brilliant Pebbles

APL developed the intercept instrumentation system for the Strategic Defense Initiative's Brilliant Pebbles (BP) vehicle in the late 1980s. The GPS tracking capabilities of this design were also based on the Trident experience, but unlike the previous system designs, BP required that the translated signal be encrypted, which required a digital translator. The second challenge was in meeting previously unattainable size and weight requirements imposed by the BP vehicle. APL had previously developed a prototype digital translator for a sonar buoy positioning application.[4] The BP translator design extended those concepts and introduced a novel composite design approach that met the difficult BP requirements. The design approach combined translator and telemetry transmission capabilities into a single unit referred to as the GPS/telemetry transmitter (GTT).[5] Since the translator, telemetry, and encryption capability were combined into a single design, the GTT was smaller and lighter than the telemetry transmitter and encryption devices it replaced, as illustrated in Fig. 4. Although the BP program was canceled before it achieved flight test status, the GTT was fully developed and flight qualified. The new translator design for the TGRS program is similar in many respects to the GTT. It is a digital unit with combined translator and telemetry transmitter capability. However, the TGRS translator design has been extended to include dual-frequency GPS signal translation, and it has considerable flexibility with regard to selecting how much of the output digital capacity is assigned to each function.

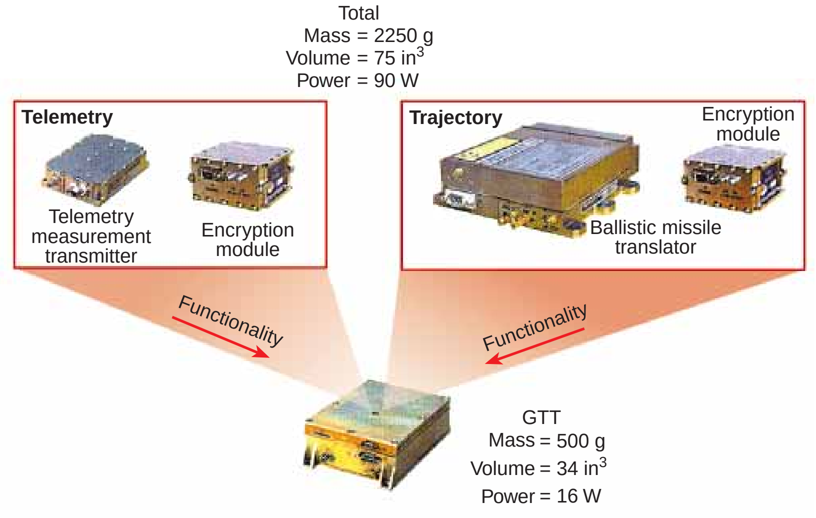


Figure 4. The Brilliant Pebbles GPS/translator transmitter (GTT) designed at APL and a representation of the vehicle hardware it replaced. The trajectory measurement equipment replaced is notional; the encryption module cannot actually be used with the analog ballistic missile translator. However, the functions of translator and telemetry data encryption and transmission were both accomplished by the GTT, and the sizes and weights of the replaced hardware are representative of the hardware then available.

Extended Navy Test Bed Translator

In 1994, APL initiated development of a special translator for use in a special Trident test reentry body. The reentry body, known as the Extended Navy Test Bed (ENTB), was being developed for special test purposes. Evaluations of the ENTB configuration required a new GPS translator with full-bandwidth dual-frequency capability. The first flight test was scheduled for December 1995. To meet this schedule, APL had to deliver the new translator in less than 1 year from the start of development. Fortunately, we were midway through an Independent Research and Development (IR&D) Program to demonstrate a low-cost translator technique that could use the complete GPS positioning signals at the start of the ENTB translator development. (This was pure serendipity; the IR&D program was motivated by our interest in evaluating precision missile intercept systems.) Using the IR&D concepts as a starting point, we designed a wideband translator (WBT) that could translate the wideband modulations from both GPS positioning frequencies.

All translators are essentially made up of amplifiers, heterodyning circuits (i.e., mixers), filters, a central oscillator, and frequency synthesis to produce the local oscillator signals for each mixer. In the WBT design, the first local oscillator is set between the two GPS frequencies. Therefore, the first mixer output overlays the two GPS signals, and the first intermediate frequency is equal to half the difference between the two frequencies (actually a small offset is included to avoid Doppler crossover). This technique minimizes cost by providing dual-channel capability in a single-channel design. It also has the advantage of halving the translator output bandwidth needed for full signal recovery, and it ensures equal signal delay effects in both channels. It has the disadvantage of combining the preamplifier noise from both signals into the tracking function. The reduced performance resulting from the noise overlay is not sufficient to offset the other benefits of this design approach. A single surface acoustic wave filter at the first intermediate frequency sets the channel bandwidth. In the WBT, the channel filter bandwidth is 20 MHz to provide full recovery of all GPS positioning signal components. A second mixer is used to produce the output S-band signal of the translator. It would be difficult to configure a simpler translator.

This was the first full-bandwidth GPS translator, but no range equipment was available to record the translated signals. As noted earlier, the recording technology available when the original Trident translators were designed could not provide the data rates needed for wideband GPS signal recording. Fortunately, this is an area in which there has been phenomenal growth in technology. Taking advantage of current technology, APL was able to develop the required recording equipment and to fit it into a briefcase-sized instrumentation case, as shown in Fig. 5. Designated simply as portable ground equipment (PGE), a single unit accepts S-band signals from both right- and left-hand circularly polarized antenna outputs and records all the data required for postflight tracking. The PGE recording rate is greater than 12 MB/s, and it can record at that rate for more than 1000 s. A single PGE weighs 42 lb (19 kg). APL also developed a new postflight tracking configuration to support the WBT.

Two WBTs were flown on a Trident test flight in December 1995. One was on the first ENTB flight and the second was in support of a reentry plasma experiment. Both tests were successful, and the WBTs, PGEs, and postflight tracking subsystems met all their performance objectives.[6,7] Two more WBTs successfully supported a Trident test flight in December 1997. Another important test based on this translator capability was conducted as a follow-on IR&D project. That project, related to our interest in precision missile intercept testing, demonstrated 2-cm relative positioning in a high-dynamic rocket sled test at Holloman Air Force Base. (It is discussed in a companion article in this issue by T. Thompson.)

Figure 5. Extended Navy Test Bed receiver/recording equipment. The suitcase shown here with the laptop control computer includes all the hardware needed to record duplicate (for right- and left-hand circularly polarized downlink signals) full-bandwidth, dual-frequency GPS signals for more than 1000 s. The suitcase is designed to connect to the telemetry station multiplexer that distributes S-band telemetry signals to all telemetry receivers.

Summary

Table 1 summarizes the general characteristics of the missile GPS translators discussed and two more currently in development. The DGT (digital GPS translator) is the product of the previously mentioned TGRS program. The FST (full-signal translator) is functionally equivalent to the WBT. As noted earlier, the WBT was developed quickly and there was not sufficient time to take advantage of the latest technology. FST development is a planned follow-on to the WBT development program. The Transat translators were C4 (Trident I missile) prototypes, and the two units were flown to provide redundancy for this critical element of the SATRACK development program. The C4 and D5 (Trident II missile) translators combined have flown on 254 missile flight tests.

Table 1. Translator evolution (as of 1 April 1998).

Translator	Developer	Sponsor	Frequency	Channel bandwidth (MHz)	Output power (W)	DC power (W)	Size (in.)	Weight (lb)	No. flown
Transat	APL (1977)	Navy	L_1 & $L_1/4$	2 & 0.2	5	<135	12.3 × 6.5 × 3.9[a]	13	2
Trident I	RCA (1978)	Navy	L_1 & $L_1/4$	2 & 0.2	5	162	12.3 × 6.5 × 3.9[a]	16	[b]
Trident I	Cubic (1978)	Navy	L_1 & $L_1/4$	2 & 0.2	5	162	12.3 × 6.5 × 3.9[a]	13	[b]
Trident II	RCA (1985)	Navy	L_1 & L_3	2 & 2	5	147	7.0 × 8.7 × 4.4[c]	20	100
GTT[d]	APL (1989)	SDIO	L_1	2	1	16	4.0 × 5.4 × 1.6	2	None
BMT	IEC (1985)	RAJPO	L_1	2	3	56	5.8 × 6.2 × 1.6	3	>30
DBT	IEC (1989)	USAF	L_1 & L_2	2 & 2	5	70	5.8 × 6.2 × 3.0	4	2
WBT	APL (1994)	Navy	L_1 & L_2	20 & 20[e]	5	45	6.2 × 4.0 × 1.6	2	4
DGT[d]	IEC	RAJPO	L_1 & L_2	Various[f]	5	50	3.6 × 2.1 × 1.3	1	[g]
FST	APL	Navy	L_1 & L_2	20 & 20[e]	5	25	4.4 × 4.2 × 1.3	1	[g]

BMT, ballistic missile translator; DBT, dual-band translator; DGT, digital GPS translator; FST, full-signal translator; GTT, GPS translator/transmitter; SDIO, Strategic Defense Initiative Organization; USAF, U.S. Air Force; WBT, wideband translator.

[a] Rectangular envelope; actual unit has shaped top surface to match pod contour; also requires separately mounted switch unit.

[b] Together these two units have flown on 154 flight tests.

[c] Also requires a separate 7.5 × 4.5 × 2.0 in. preamplifier unit: weight = 5 lb, power = 8 W.

[d] Digital unit with encryption capability for translated signal and telemetry data channel (to 10 Mb/s).

[e] Two signals are overlaid in a common 20-MHz downlink bandwidth.

[f] Use of L_2 signal optional; when used, it overlies L_1. Three translator bandwidth choices with telemetry data channel; fourth choice is a 16-MHz translated signal only; encryption is optional for all choices.

[g] Still in development.

FUTURE SYSTEMS

Unlike GPS receivers, there is no high-volume nonmilitary market for GPS translators. Therefore, even though translators are much simpler than receivers, there are many GPS receivers available at lower cost. The available low-cost receivers are not really adequate for precision high-dynamic measurement support, but moderately priced receivers are being designed for missile guidance applications, and these may be adequate for some test and evaluation applications. Certainly, any of these receivers have more than the required precision needed to meet range safety requirements. Their suitability for range safety use will depend more on reliability characteristics. The issue with regard to accuracy evaluation of high-value weapon systems is related to the level of GPS-to-missile signal measurement accuracy required and the acceptable level of risk. No receiver can provide more precise measurements than a properly configured translator system, but the receivers may be adequate for some applications. The risk factors for a receiver configuration are higher for three reasons:

1. Receivers have more complex hardware.
2. Receivers need preflight initialization.
3. Translator postflight tracking can adapt to unexpected test conditions.

A receiver configuration may be designed to overcome the first two factors, but such a receiver is likely to cost considerably more than the equivalent translator and it will likely be larger and heavier. Only the translator configuration has the ability to reexamine the receiver input signals in the postflight environment and thereby adjust for the unexpected. The translator's tracking precision benefit is also achieved through its postflight tracking capability. It is always possible to optimally adapt the postflight tracking bandwidths to the actual flight conditions, simply because the input signals can be replayed as often as needed.

The only known benefit for a receiver configuration is associated with the output bandwidth requirement. A full GPS signal translator requires a 20-MHz bandwidth, whereas a receiver can output tracking loop data (range and phase) with a data rate of a few kilobytes per second, which is easily accommodated by standard missile telemetry. This is an important issue only if the translator output is within the standard missile telemetry band and if the band is fully occupied. In that circumstance, the only way to use a translator is by shifting its output signal to a different band. A different translator output frequency can be supported with no change in output power using the same ground station antenna aperture. That is, by simply adding a feed and preamplifier to the normal telemetry tracking antenna, the translator system continues to gain most of the infrastructure benefit achieved by setting the translator output frequency in the telemetry band. Naturally, this choice will also affect the antenna configuration on the test missile, but there are often simple ways to meet this requirement. It is not truly valid to think of translated GPS signals as telemetry data; they are, after all, tracking signals. It is more reasonable to think about the translator output bandwidth in relationship to alternative tracking systems (e.g., radar). In any such comparison, the translator can be shown to be very efficient. In those applications where the evaluation system capability is dominated by phase tracking performance (e.g., Trident or Peacekeeper), translator output bandwidth can be reduced to about 10 MHz with very little overall degradation. This bandwidth is only required to capture sufficient signal energy from the wideband L_2 signal. In those cases where the ionospheric refraction rates are low, the bandwidth can be further reduced. The bandwidth requirement for this type of application is not driven by the need to support lower ranging uncertainty in the range tracking loops. If a lower-bandwidth, second-frequency signal were available with sufficient frequency separation, the translator bandwidth requirement could be reduced accordingly. Only those evaluation systems that require high-precision ranging (e.g., precision interceptors) need to retain the full translator bandwidth.

The overall benefits of GPS translator systems will continue to make them the instrument of choice for high-value precision weapon system evaluations. The better instrumentation configuration will normally provide quantifiable confident performance assessments with fewer tests. Furthermore, since the national test ranges are currently making a significant investment in TGRS, there will be program cost benefits associated with using that system. Finally, with regard to precision interceptor testing, there is virtually no other instrumentation candidate that is anywhere close to meeting flight-test evaluation objectives. Our views on the requirements for high-precision interceptor testing and the need for GPS translator instrumentation for interceptor test programs are discussed in a companion article in this issue by T. Thompson.

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