Miniature Analog GPS Translator for Trident Reentry Body Accuracy Analysis

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The Johns Hopkins University Applied Physics Laboratory (APL) conceptualized and developed the dual-frequency overlay, wideband analog Global Positioning System (GPS) translator in the early 1990s to independently evaluate the performance of Navy reentry body (RB) GPS receivers. Analog GPS translators provide the means to receive raw GPS data at a RB and frequency-translate that data for transmission to ground receiving stations for subsequent postflight analysis and trajectory reconstruction. The latest in APL-developed full-bandwidth, dual-frequency analog GPS translators is the Miniature Analog Translator (MAT), which incorporates state-of-the-art commercial-off-the-shelf and semi-custom technology to enable high performance in a miniature package while keeping cost at a minimum.

INTRODUCTION

Postflight processing of translated Global Positioning System (GPS) signals enables superior metrics resolution in determining the flight path and scoring accuracy of Trident reentry bodies (RBs). The first 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 in the early 1970s. The primary component of that evaluation system, known as SATRACK (for SATellite TRACKing), was developed to provide the missile guidance evaluation capability for Trident. The signal-processing aspects of SATRACK were based on a missile signal-relay concept called a translator that rebroadcast GPS satellite signals from the missile to the ground.[1, 2] Signals from GPS satellites are received at the missile and—after frequency conversion, filtering, addition of a pilot carrier tone (used as a postflight tracking aid), and amplification—are retransmitted to ground receiving stations where they are sampled and recorded for postflight analysis. Note that the translator itself does not perform any signal-tracking functions; it simply "frequency translates" the all-in-view GPS signals to S-band and downlinks them to ground receiving stations. This inherent simplicity of operation of an analog translator makes it a key and powerful component of weapon system testing and evaluation (T&E) instrumentation.

Translating the dual-frequency, full-bandwidth GPS L_1 C/A (coarse acquisition) and P/(Y) (encrypted precision) codes along with the L_2 P/(Y) code signals allows the end user to correct for the effects of the ionosphere (through the use of dual-frequency correction techniques) and to benefit from the ranging precision provided by the wideband P (precision) code. In addition, the recorded translated data can be reprocessed, allowing the maximum amount of information to be recovered from the data. The reprocessing of raw signal data is not possible when signal tracking is performed at the missile (i.e., using a receiver).[1]

After the flight, the sampled GPS translated data are archived and sent to APL, where they are processed using the postflight receiver (PFR). If inertial data are available from the missile, as typically is the case, they are used to create a reference trajectory that accurately represents the high-frequency components of the trajectory but has low-frequency errors (e.g., accelerometer and gyro bias and scale factors). The inertial trajectory is used to allow the PFR to track lower signal levels by reducing the tracking-loop bandwidths of the receiver and increasing the coherent integration times as compared to noninertially aided real-time receivers. In addition, the GPS satellite broadcast message bits also are provided to the PFR to allow greater than 20-ms coherent integration times and to increase the allowable unmodeled phase disturbances that can be tracked by the PFR. Using this information, the PFR performs the signal processing required to extract the pseudorange and phase measurements from the GPS signals for all satellites that are in view. The pseudorange and phase measurements are compensated for the following errors: satellite clock, ionospheric distortions, tropospheric delays, antenna to center-of-navigation lever arms, antenna phase, phase wind-up due to antenna rotations, S-band downlink effects, cycle slips, and relativity. In addition, estimates of the measurement noise on both the range and phase are computed.

The corrected pseudorange and phase measurements, along with their uncertainties, then are optimally combined in a large Kalman filter (several hundred states, in most cases) to estimate the fundamental errors, such as accelerometer biases and gyro scale factors, in the inertial system. These estimated errors then are used to allow refinement of the trajectory to create a high-fidelity best estimated trajectory (BET). For extremely high-dynamic regions of the flight, the inertial trajectory may be updated based on the initial GPS trajectory to provide a more refined reference trajectory that can be retracked to provide even more GPS measurement data. Although the analog translator concept originally was chosen because of its hardware simplicity and commensurate reliability, the myriad of benefits gained from postprocessing translator-derived data produce a superior navigation solution not possible via other means.

APL conceptualized and developed the first dual-frequency (L_1, 1575.42-MHz and L_2, 1227.6-MHz) overlay, wideband (C/A and P code) analog translator, the Wideband Translator (WBT), in the early 1990s to independently evaluate the performance of Navy Trident RB GPS receivers. The Full Signal Translator (FST) followed, significantly reducing translator volume, weight, and power. The latest in APL-developed full-bandwidth, dual-frequency analog GPS translators is the Miniature Analog Translator (MAT). The field-programmable MAT uses a dual-heterodyne technique to simultaneously down-convert and overlay the full GPS L_1 and L_2 spectrums and then up-convert that composite signal to the programmed S-band downlink frequency. A frequency-selectable pilot carrier tone is coherently synthesized and summed with the overlaid GPS signals to aid GPS tracking. A high-efficiency solid state power amplifier (SSPA) amplifies the composite S-band signal to greater than 5 W for downlink transmission to telemetry sites. The MAT functional concept is depicted in Fig. 1.

The MAT also can be configured for GPS L_1 C/A and L_2 C (civil) code signal translation as well as L_1 and L_2 M (military) code simply by changing its bandwidth. Mechanically, the MAT design is compact and modular and can be mounted in the host vehicle as a monolithic unit or be volumetrically distributed by subsystem module to maximize the use of available vehicle space. The MAT is designed to operate in the dynamic environments, from launch to deployment to reentry, that are typical of RBs.

MINIATURE ANALOG TRANSLATOR

The advent of conventional prompt global strike (CPGS) applications has made compulsory the requirement for significant volume and power reductions for reentry vehicle T&E instrumentation because of additional volume requirements for navigation, guidance, and

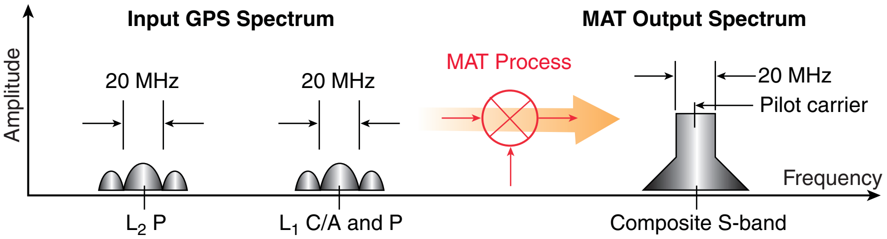

Figure 1. MAT signal-processing concept.

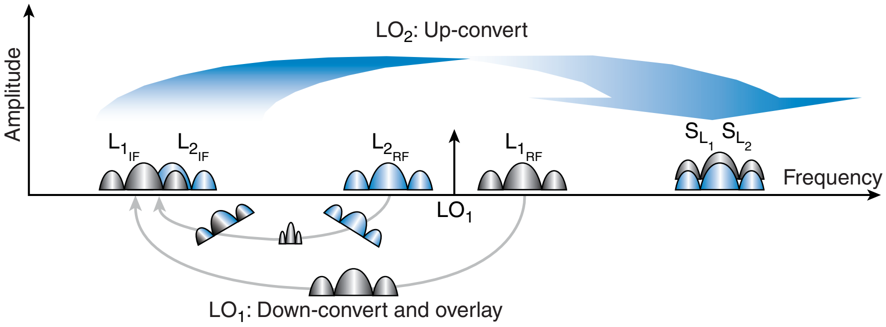

Figure 2. MAT overlay concept.

control hardware and because of longer-duration battery usage associated with long-duration range-extension maneuvers. In response to that need, APL has developed the MAT, a very small (<8 in^3), lightweight (<1.0 lb), low-power (<20 W) GPS dual-frequency overlay analog translator. The MAT is APL's latest in advanced translator technology, incorporating all the capabilities of its predecessors (WBT and FST) while adding features like field-programmable pilot and downlink frequency control, closed-loop automatic gain control (AGC), and high-efficiency (>65% power-added efficiency) SSPA in a compact and mechanically versatile package. Advanced commercial-off-the-shelf (COTS) technology using quad flat no-lead (QFN) packaging was exploited to produce high-density, multilayer, double-sided printed circuit board (PCB) layouts that provide significant volumetric reduction and the ability to package subsystem modules together as a monolithic unit or distributed (by module), allowing installation even in noncontiguous volumes. The MAT design is robust and has been developed to meet or exceed the temperature, vibration, and shock environments typical of Trident RBs.

Overlay Concept

As previously mentioned, the MAT is a GPS dual-frequency (L_1 and L_2) overlay [down-converting local oscillator (LO) centered between L_1 and L_2] analog translator. GPS L_1 and L_2 signals are received from an external preamplifier at the input to the MAT where they are filtered and amplified before being heterodyned down to an intermediate frequency (IF). Placing the down-converting LO exactly between the two GPS frequencies allows a single hardware channel to be used to convert both the L_1 and L_2 signals to the same IF (equal to one half of the frequency difference between L_1 and L_2). Note that the first LO is actually offset slightly to avoid zero-Doppler overlap between L_1 and L_2. A consequence of this overlay technique is that the L_2 signal is spectrally inverted (because of high-side LO injection mixing); however, that inversion is easily removed via postprocessing of the recorded translator data. After IF filtering and addition of the pilot carrier at the IF, the composite L_1/L_2/pilot signal is heterodyned up to S-band for amplification by the SSPA and subsequent downlink. The MAT overlay conversion concept is depicted in Fig. 2.

Functional Operation

A block diagram of the MAT is shown in Fig. 3. GPS signals are input to the MAT via an external low-noise amplifier (LNA) that provides amplification and preconversion gain. The MAT overlays those GPS signals as described above, adds the pilot carrier signal at the IF, and then up-converts that composite signal to the user-selected S-band frequency. The SSPA amplifies the S-band signal to 5 W for downlink transmission to ground stations. A high-stability, low phase noise, temperature-compensated crystal oscillator (TCXO) serves as the frequency/phase reference for the three phase-locked loop (PLL) synthesizers that coherently generate the two LO frequency conversion and pilot carrier signals. The MAT operates on +28.0-V host vehicle power and consumes approximately 20 W. Output S-band and pilot carrier frequencies can be programmed independently through a serial interface accessible via the translator subsystem module.

Frequency Model

Mathematically, the MAT operates as a signal-minus-LO and LO-minus-signal differencer in the down-converting, overlay mixer stage and as a signal-plus-LO summer in the up-converting mixer stage. This operation is represented pictorially in Fig. 4.

In Eqs. 1–4, the MAT S-band output frequency was arbitrarily chosen to be 2363.91 MHz, and the pilot carrier S-band frequency was set to 2365.20 MHz. Referring to Fig. 4 and Eqs. 1–3, K_o represents the down-converting LO frequency multiplier and is equal to 140.14, K_u represents the up-converting LO frequency multiplier and is set to 219, and K_P represents the pilot carrier frequency multiplier and is set to 17.52.

The GPS L_1 signal is heterodyned down to the IF via low-side injection and then summed up to the selected S-band output frequency by the following relationship:

$$\begin{aligned} S_{L_1} &= L_1 - K_o(f_o) + K_u(f_o) \\ &= 1575.42 - (140.14*10) + (219*10) \\ &= 2364.02 \text{ MHz} . \end{aligned} \tag{1}$$

The GPS L_2 frequency is heterodyned down to the IF via high-side injection and then summed up to the selected S-band frequency. Mathematically,

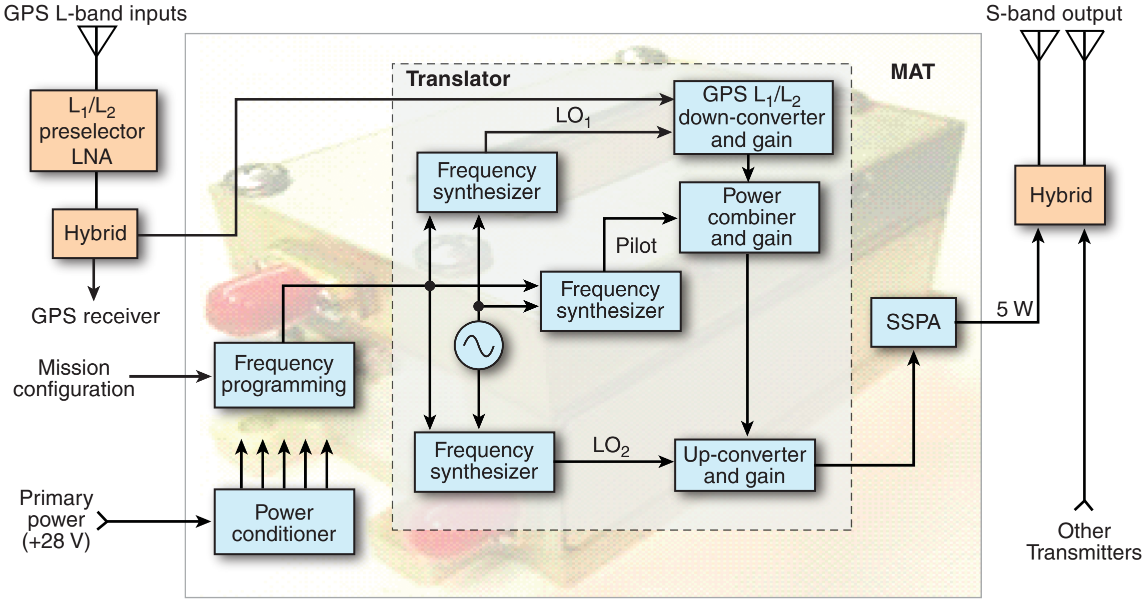

Figure 3. MAT functional block diagram.

$$
\begin{aligned}
S_{L_2} &= K_o(f_o) - L_2 + K_u(f_o) \\
&= (140.14 * 10) - 1227.6 + (219 * 10) \qquad (2)\\
&= 2363.80 \text{ MHz}.
\end{aligned}
$$

The pilot carrier frequency is synthesized at the IF and then summed up to the selected S-band frequency by

$$
\begin{aligned}
S_P &= K_P(f_o) + K_u(f_o) \\
&= (17.52 * 10) + (219 * 10) \qquad (3)\\
&= 2365.20 \text{ MHz}.
\end{aligned}
$$

The MAT composite S-band output is then the sum of all three signals:

$$S_{MAT} = (S_{L_1} + S_{L_2} + S_P)\,. \qquad (4)$$

Notice in the S_{L1}, S_{L2} frequency relationship, there is a 2364.02 MHz – 2363.80 MHz = 220 kHz offset; this is the aforementioned zero-Doppler offset, designed to prevent frequency overlap of the L_1 and L_2 signals.

LNA and Overlay RF

Because the received GPS signal levels at the missile are extremely low (–158.5 dBW for L_1 C/A code)[3] and the bandwidth necessary for reception of the full *P* code signals is at least 20 MHz, if an LNA with a noise figure of 2.0 dB is implemented, the thermal noise level at that LNA input (ignoring antenna and antenna-to-LNA contributions)—where *k* is Boltzmann's constant, *T* is the temperature (290 K), *B* is the bandwidth (in Hz), and *NF* is the noise figure (in dB)—will be

$$
\begin{aligned}
&10\log(kTB) + NF \\
&\quad = 10\log(1.3807 \times 10^{-23} * 290 * 20 \times 10^{-6}) + 2 \qquad (5)\\
&\quad = -129 \text{ dBW}.
\end{aligned}
$$

With this input thermal noise level, the GPS signals will be ~30 dB below that noise at the input of the LNA; therefore, the translator output is simply amplified, filtered, frequency-converted thermal noise with the GPS signals buried 30 dB below that noise.

$$-158.5 \text{ dBW} - (-129 \text{ dBW}) = -29.5 \text{ dB}\,. \qquad (6)$$

When processing spread spectrum signals such as GPS, it is convenient to measure signal strength in terms of the ratio of GPS signal power to noise density (C/N_o) because ultimate GPS tracking bandwidths are on the order of a few hertz. It is important to note that, although noise dominates the translator output and

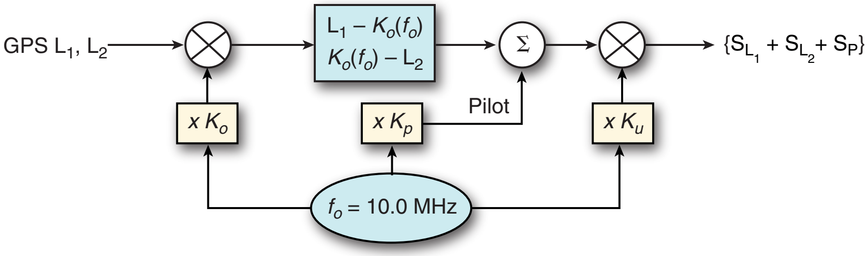

Figure 4. MAT frequency model.

it may seem that the LNA noise figure is not of great consequence (just more noise?), careful consideration indeed must be given to that parameter and its effect on GPS signal-to-noise (C/N_o) level. As an example, the received GPS C/N_o (again ignoring antenna and antenna-to-LNA effects) using the above GPS L_1 C/A signal level and LNA noise figure would be

$$\begin{aligned} &L_{1\,(\mathrm{CA})} - 10\log(kT) - NF \\ &\quad = -158.5 - (-204) - 2 \\ &\quad = 43.5\ \mathrm{dB{\cdot}Hz}\,. \end{aligned} \tag{7}$$

If, however, a LNA with a noise figure of 5 dB were used, the received GPS signal level would degrade an additional 3 dB to 40.5 dB·Hz. Recall also that a consequence of overlay operation in translators is an additional degradation in GPS C/N_o on each signal (L_1 C/A, L_1 P, and L_2 P). This loss results from the fact that when the L_1 and L_2 signals (i.e., noise powers) are overlaid, each signal is contaminated by the other's noise. If we assume equal noise powers for each channel, then the total $L_1 + L_2$ noise power will be doubled and the C/N_o loss incurred will be 3 dB in each signal. Note that if the L_1 and L_2 noise powers are *not* equal (e.g., LNA gains and/or bandwidths are different), the C/N_o degradation one signal causes the other to incur will not be equal either. For example, if the L_2 noise power was reduced by 3 dB in relation to the L_1 power, the C/N_o degradation to L_1 would only be 1.8 dB, whereas the L_2 signal C/N_o degradation would be 4.8 dB. Calculation of these values is given in the *Appendix*.

Once the GPS L_1 and L_2 signals have been overlaid, they remain that way until separated on the ground by receiving and/or recording equipment. Overlay operation yields two important advantages: (*i*) since the GPS signals flow through the translator cascade as one composite signal, all electrical delay effects are common mode, thus equal in each signal and (*ii*) the downlink bandwidth required to transmit all the GPS signals is only 20 MHz (whereas 40 MHz would be required for adjacent wideband transmission).

IF and Pilot

Down-conversion of the GPS L_1 and L_2 signals results in a nominal "center-of-the-noise" MAT IF of 173.91 MHz [mathematically, $(L_1 - L_2)/2$]. A surface acoustic wave (SAW) bandpass filter establishes the MAT fundamental bandwidth of ~20 MHz at that IF frequency, providing full recovery of all GPS L_1 and L_2 signals. Note that the "noise pedestal" output spectrum typical of analog translators is shaped by this SAW filter. The amplitude-adjustable [i.e., signal-to-noise ratio (SNR)] pilot carrier tone is summed with the overlaid GPS signals in the IF after the SAW filter so that it can be placed not only within the 20-MHz signal bandwidth but also outside that bandwidth (further increasing its SNR) if desired. The pilot carrier power is nominally set to be 10 dB below the 5-W total MAT S-band output power, yielding a pilot SNR of 33 dB in a 1-kHz bandwidth.

$$\begin{aligned} &PilotSNR \\ &= Pilot\ Power - (TotalPower - (10\log(20\times10^6/1\times10^3))) \\ &= 33\ \mathrm{dB}\,. \end{aligned} \tag{8}$$

Frequency Synthesizers

The MAT LO frequency conversion and pilot carrier signals are coherently generated from the master oscillator via serial load PLL frequency synthesizers that are programmed from an EEPROM (electrically erasable programmable read-only memory)/flash-based microcontroller. The synthesizers are programmed via a serial interface accessed from the translator subsystem module. The LO signals drive active mixer stages to accomplish the frequency up- and down-conversions. A TCXO oscillator running at 10.0 MHz supplies the master reference frequency to each synthesizer. The oscillator has an overall frequency stability of ±0.5 ppm and an acceleration sensitivity of $\Gamma \leq 1 \times 10^{-9}$ Hz/g in each axis. Low single-sideband (SSB) phase noise on the master oscillator results in an output pilot carrier 0.1-s Allan variance of $<2.0 \times 10^{-10}$.

Up-Conversion and SSPA

The composite L_1/L_2/pilot signal is heterodyned up to a user-selected output frequency by summation in the up-conversion active mixer with the up-conversion LO. Frequency control of this LO, hence the MAT S-band output frequency, is accomplished via the serial PLL programming mentioned earlier. The up-converted S-band signal is filtered with a ceramic-based bandpass filter before being sent to the SSPA. A driver amplifier increases the composite signal amplitude to the required level for the final power-amplification stage input. The high-efficiency SSPA operates slightly in compression (1.0 to 1.5 dB) to produce the required output of greater than 5 W (+37.0 dBm).

MAT MECHANICAL DESIGN

Mechanically, the MAT design is modular and consists of two main subsystems: translator and power amplifier/power conditioner. Housings are made of machined 6061-T651 aluminum finished with an iridite chemical conversion coating. Printed circuit wiring boards are mounted on bosses within the housings, and there is a lid on or between each housing which has a "lip" machined into it, mirroring its housing counterpart and providing a degree of electromagnetic interference (EMI) suppression. Figure 5 shows the subsystems, circuit boards, and their associated lids that comprise the MAT. Blind-mate connectors provide the RF and DC interconnections between subsystems.

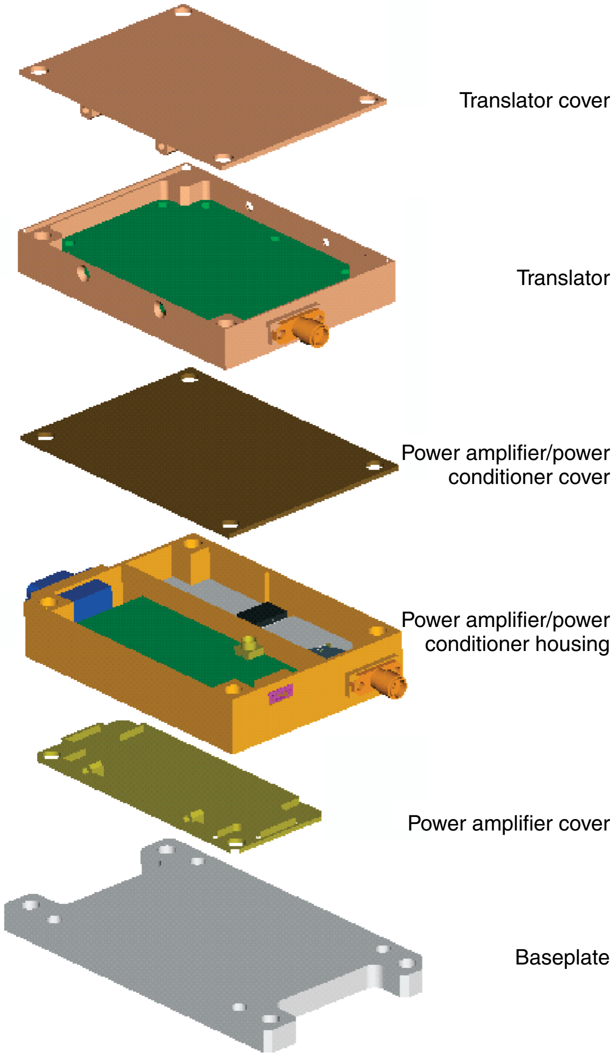

Figure 5. MAT exploded view.

This modular mechanical configuration allows the MAT to be assembled and mounted as one monolithic unit or be configured by individual subsystem and mounted in a volumetrically distributed manner. The MAT is conductively cooled (it does not rely on any convection) through its housings and baseplate. Electrical grounding to the host vehicle is accomplished via the MAT package itself. The MAT center of gravity is located within ±20% of the volumetric center of the package. The total weight is less than 1.0 lb.

FUTURE ENHANCEMENTS

As frequency allocations become more difficult to obtain, and with the advent of the GPS L_2 C code, the possibility of a MAT that relays the L_1 C/A and L_2 C codes in a reduced 2-MHz downlink bandwidth is not only intriguing but also easily accomplished via an IF filter change. Reducing the MAT downlink bandwidth by a factor of 10 to 2 MHz would facilitate frequency allocation and simplify mission-frequency planning (if multiple MATs were needed on concurrent flights), whereas ionospheric refraction corrections would still be possible because dual-frequency methodology would be retained. A vehicle prime power savings could also be realized because the downlink RF power requirement would likely reduce with a commensurate reduction in required MAT DC power and volume. Solution accuracies would be somewhat less precise than those using wideband (*P* code) data but, for many applications, would not only be suitable but also adequate. Future relaying of the L_1 and L_2 M codes also is possible with the MAT via bandwidth adjustment. With its modular design, the MAT could also be modified to translate the future safety of life L_5 frequency (1176.45 MHz) and its wideband C code when it comes online via the GPS Block IIF satellites.

In addition, long-range, long-duration missions, such as those proposed using hypersonic vehicles, require not only miniature but also power-efficient instrumentation, making the MAT a prime choice for this type of vehicle.

CONCLUSIONS

Translators continue to be an essential component of weapon system T&E. They provide the data for postflight accuracy analysis that allows independent verification of weapon system guidance components. They provide the data for real-time range-safety tracking that determines vehicle present position and instantaneous impact point. Perhaps even more important, they provide the means to understanding weapon system model issues, propagation phenomena, and hardware problems and failures. When compared to GPS receivers, translators have simpler hardware, do not require preflight initialization, and can adapt to unexpected test conditions through the use of postflight tracking.[1] The use of translators on future missions will continue to provide the Navy with precise, independent assessment of high-value weapon system performance under all conditions, predictable and unpredictable.

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APPENDIX

The degradation in GPS C/N_o that occurs due to overlaying the L_1 and L_2 signals can be determined from the LNA channel noise power levels and their corresponding overlay power ratio. Defining A_{GPS} as the power level of the GPS signal of interest (in dBW), $S(f)_{LNA}$ as the noise power spectral density (PSD) at the LNA input (in dBW/Hz), and φ as one-half the noise power ratio (because the power difference will be distributed proportionally between the two channels) between L_1 and L_2 (in dB), we can calculate the C/N_o loss (in dB) due to the overlay of the L_1 to L_2 noise powers to be

$$\Delta_{C/N_0}(\varphi) = (C/N_0)_{GPS} - \left[(A_{GPS} \pm \varphi) - 10\log\left(10^{\left(\frac{S(f)_{LNA} + \varphi}{10}\right)} + 10^{\left(\frac{S(f)_{LNA} - \varphi}{10}\right)}\right)\right] \text{dB}\,. \tag{9}$$

The sign of φ in the quantity $(A_{GPS} \pm \varphi)$ is chosen positive for L_1 and negative for L_2 calculations. From our earlier example, using –158.5 dBW as the L_1 C/A power and 2.0 dB as the LNA noise figure yielded 43.5 dB·Hz as the GPS $L_{1(C/A)}$ C/N_o. If we take the L_1 channel noise power to be 3 dB above L_2, then $\varphi = 3/2 = 1.5$, and we have

$$\Delta_{C/N_0}(1.5)L_{1(C/A)} = 43.5 - \left[(-158.5 + 1.5) - 10\log\left(10^{\left(\frac{-202 + 1.5}{10}\right)} + 10^{\left(\frac{-202 - 1.5}{10}\right)}\right)\right] 1.76 \text{ dB}\,. \tag{10}$$

Assuming the L_2 P signal is 6 dB below L_1 C/A power (and noting that the sign of φ is now negative for L_2) results in 4.76 dB of degradation to the L_2 P C/N_o.

$$\Delta_{C/N_0}(-1.5)L_{2(P)} = 37.5 - \left[(-164.5 - 1.5) - 10\log\left(10^{\left(\frac{-202 + 1.5}{10}\right)} + 10^{\left(\frac{-202 - 1.5}{10}\right)}\right)\right] 4.76 \text{ dB}\,. \tag{11}$$

Plotting Eq. 9 as φ is swept from +6 dB to –6 dB results in Fig. 6. The C/N_o losses are reciprocal; as the L_1 noise power is increased (i.e., φ is positive), its C/N_o degradation is decreased while the L_2 C/N_o degradation increases and vice versa. The results for L_1 and L_2 from our example at L_1/L_2 = +3.0 dB are circled in Fig. 6.

Note that there is further degradation to the received C/N_o attributable to the S-band downlink received SNR of the form

$$\Delta_{C/N_o}(SNR_{DL}) = \frac{-1}{1 + \left(\frac{1}{SNR_{DL}}\right)}, \tag{12}$$

where SNR_{DL} is the received downlink SNR and $\Delta_{C/N_o}(SNR_{DL})$ is the GPS C/N_o degradation due to that received downlink SNR. This effect is a function of the entire downlink [antennas, dispersive loss, ground station antenna gain/system noise temperature (G/T), etc.] and not just translator output and is not discussed further here. As a reference, if SNR_{DL} is greater than 6 dB, the GPS C/N_o degradation is less than 1.0 dB.

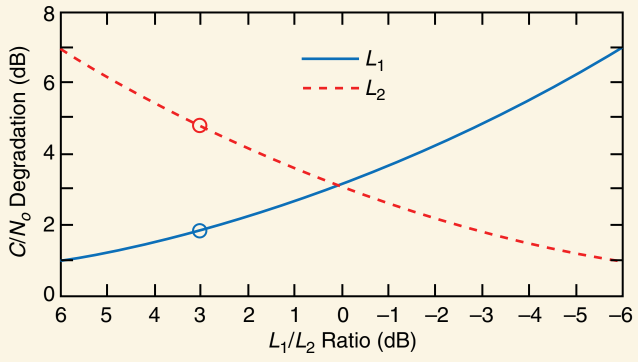

Figure 6. L_1 vs. L_2 C/N_o overlay loss.

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