Collecting Reentry Body GPS Translator Data Near Impact Using the Over-the-Horizon Buoy

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*D*uring Trident missile tests, range-safety requirements can mandate that the ship instrumented with the Navy Mobile Instrumentation System (NMIS) be located at a distance from the reentry body impact location that places it over the horizon. Currently, without line of sight, the NMIS cannot collect reentry body telemetry and GPS translator data to impact. The over-the-horizon (OTH) buoy is being developed as a new NMIS subsystem that provides the capability to record reentry body to impact while the ship is located over the horizon. A prototype OTH buoy was designed and tested during two Trident missile tests. The engineering tests successfully demonstrated the OTH buoy's ability to record reentry body telemetry and GPS translator data to impact. This article presents the translated-GPS recording system used on the prototype OTH buoy and the corresponding results of the two engineering tests.

INTRODUCTION

Traditionally, reentry body (RB) telemetry and GPS translator[1] data during the terminal phase of flight are collected by instrumentation aboard the Navy Mobile Instrumentation System (NMIS) that is installed on the T-AGS 60 Pathfinder class of naval ships. The NMIS instrumentation subsystems allow the collection of radar, optical, acoustic, meteorological, telemetry, and GPS translator data in the broad ocean area. Currently, line of sight between the NMIS and RB is required for the NMIS subsystems to record RB telemetry and GPS translator data to impact. During Trident missile tests, range-safety requirements mandate up to a 25-mile standoff for the ship instrumented with the NMIS. This places the ship over the horizon from the RB impact location. As shown in Fig. 1, when the RB falls below the ship's line of sight, the NMIS is not able to record RB telemetry and GPS translator data continuously to impact.
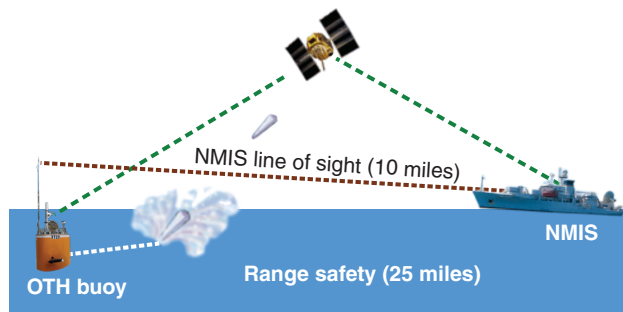
Figure 1. RB signal visibility near impact. The OTH buoy is positioned to recover signals from the RB when it drops below the signal horizon of the NMIS ship.

In support of the Navy's Strategic Systems Program (SSP), the over-the-horizon (OTH) buoy is being developed as a cost-effective and sustainable subsystem for the NMIS that allows RB telemetry and GPS translator data to impact to be collected when the ship is located over the horizon. A prototype OTH buoy was developed by Gryphon Technologies, LLC, in collaboration with APL to support testing during Follow-On Commander Evaluation Test 36 (FCET-36) and Demonstration and Shakedown Operation 19 (DASO-19). The combination of these tests demonstrated the OTH buoy's ability to record RB telemetry and GPS translator data to impact.

OTH BUOY OVERVIEW

The OTH buoys will be used during future Trident missile tests in which the NMIS is required to be over the horizon from the projected RB impact location. The NMIS will deploy three OTH buoys near their predetermined locations. (Using three spatially separated buoys significantly reduces the likelihood of the system being in a degraded portion of the RB transmit antenna pattern and provides redundancy in case of a buoy failure.) Once deployed, the OTH buoys will use an onboard GPS receiver to control travel to and stationkeeping at their preassigned positions, and the NMIS will travel to a location that meets range-safety requirements. Using satellite communications, the buoys will provide the NMIS operators with real-time operational status and buoy health. During the test, the NMIS operators will receive a projected RB

impact time from the test director. Using satellite communications, the NMIS operator will program the OTH buoys with recording start and stop times for up to three sequential RBs. (Note that the RB spacing must be at least 12 s in time, allowing for 10 s of data recording and 2 s to reconfigure the settings for the next RB.) During each recording the OTH buoy will record the RBs' two telemetry and one GPS translator signals. When the test is complete, the OTH buoys will be recovered, and the recorded telemetry and GPS translator data will be extracted and delivered to the appropriate organizations for analysis. The OTH buoy's battery life is conserved by only applying power to the telemetry and translated-GPS recording subsystems approximately 30 min before the first planned RB impact, which allows the OTH buoy to support an 8-h launch window and maintain communications with the NMIS for up to 48 h after it is deployed.

The prototype OTH buoy is a modified portable impact location system (PILS-2) buoy (shown in Fig. 2). PILS-2 is an existing NMIS subsystem consisting of a constellation of 9–12 buoys that are used to determine the impact location by measuring the difference in arrival times of the sound generated by the RB's impact in the ocean. A block diagram of the PILS-2 buoy and the modifications made to support the telemetry and GPS translator recordings are shown in Fig. 3.

Both telemetry and GPS translator signals are located within the same S-band frequency region (2200–2400 MHz). The common frequency range allows the telemetry and translated-GPS recording systems to share the equipment that receives, filters, and amplifies the S-band signals as shown in Fig. 3. The omnidirectional S-band antenna is right-hand circularly polarized (RHCP) and has a maximum gain of 3 dB. The low-
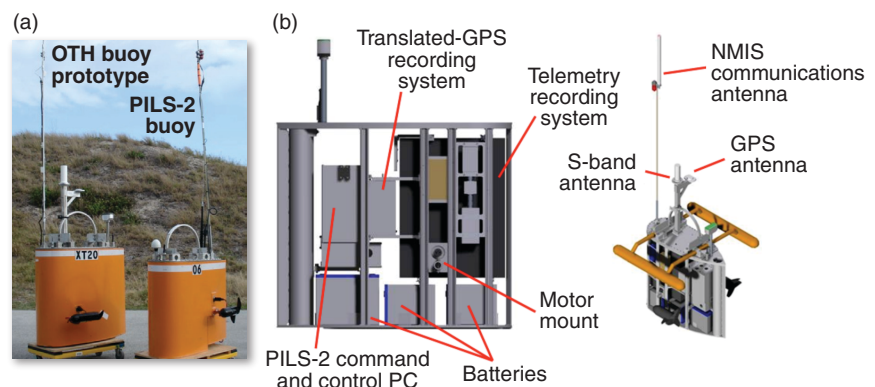

Figure 2. Prototype OTH buoy layout. (a) The hull for the prototype OTH buoy was enlarged to incorporate the addition of the telemetry and translated-GPS recording systems. (b) The telemetry recording system is a 19-in. rack-mount recorder that is mounted vertically in the prototype OTH buoy. The translated-GPS recording system is a five-slot VME chassis mounted vertically in the prototype OTH buoy. (Reprinted with permission from Ref. 2.)
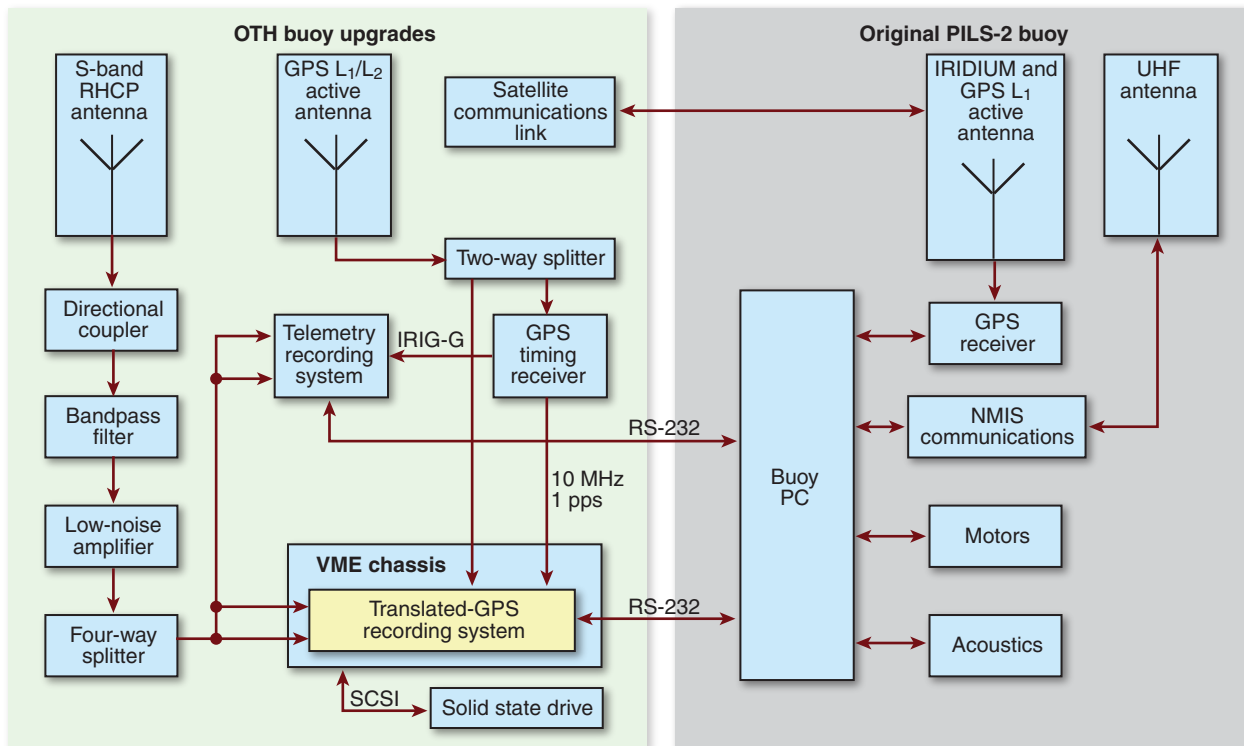
Figure 3. Prototype OTH buoy block diagram. The OTH buoy is an upgrade to the existing PILS-2 buoy that adds the capability for satellite communications with the NMIS and recording of RB telemetry and GPS translator data. The gray background indicates components of the original PILS-2 buoy. The green background indicates components that are specific to the OTH buoy. Components shown in blue are COTS, and components shown in yellow are custom-designed by APL.

insertion-loss bandpass filter is installed to eliminate any interfering RF signals outside the 2200-MHz to 2400-MHz frequency range. The low-noise amplifier provides approximately 26 dB of gain, which is sufficient to ensure that the system's noise figure is essentially set by the low-noise amplifier's low-noise figure. This low-noise figure, in turn, helps to maximize the receivers' sensitivity to weak signals. A four-way power splitter is used to provide two S-band data signals to the telemetry recording system and two S-band data signals to the translated-GPS recording system.

The GPS timing receiver provides the buoy with a highly accurate reference time and frequency. It receives its GPS signal from the active L_1/L_2 GPS antenna. The timing receiver also provides an Inter-Range Instrumentation Group (IRIG-G) timing code; a GPS-disciplined, high-stability, low-phase-noise 10-MHz reference with a 1-s Allan variance of 1×10^{-11}; and a 1-pulse-per-second (pps) signal that is synchronous to the 10-MHz reference and accurate to within 100 ns of Universal Coordinated Time. The telemetry recording system collects the IRIG-G timing code. (It is extracted with the recorded telemetry data to provide an absolute time reference.) The translated-GPS recording system uses the 10-MHz and 1-pps signals from the GPS timing receiver

as the basis for its local oscillators (LOs) and internal timekeeping. The translated-GPS recording system also shares the active GPS L_1/L_2 antenna with the GPS timing receiver.

The telemetry recording system is composed of two commercial off-the-shelf (COTS) telemetry receivers and a COTS solid-state telemetry recorder. The OTH buoy records two pulse-code-modulated/frequency-modulated telemetry data channels sampled at 5 megasamples per second (MSps), one IRIG-G timing channel sampled at 1 MSps, and the automatic gain-control voltage of one receiver sampled at 1 MSps. The telemetry recording system records the telemetry data in a strategic treaty-compliant format; the GPS translator data are not subject to the treaty requirements.

TRANSLATED-GPS RECORDING SYSTEM OVERVIEW

With a history of designing and building systems that generate, record, and analyze translated-GPS data as old as GPS itself, APL was tasked with finding a solution to the OTH buoy translated-GPS recording requirement. When no COTS solution was found, APL leveraged similar work being done to update an exist-

ing translated-GPS recording system (for another SSP application) that would also meet the requirements of the OTH buoy. By accelerating its development schedule to meet the FCET-36 engineering test, APL was able to develop a translated-GPS recording system that met both sponsor needs. A brief introduction to translated-GPS is presented in Box 1, and the specifications for the translated-GPS recording system are shown in Fig. 4 and Table 1.

As Fig. 5 illustrates, the translated-GPS recording system is composed of an S-band downconverter (SBDC), a baseband converter and recorder (BCR), and a mezzanine card used to connect the SBDC and BCR when installed in a COTS Versa Module Eurocard (VME)-64X backplane (a minimum of three VME slots are required). The mezzanine card provides an interface to the time and frequency reference signals. The translated-GPS recording system provides a SCSI-2 (small computer system interface) for recording data. For the
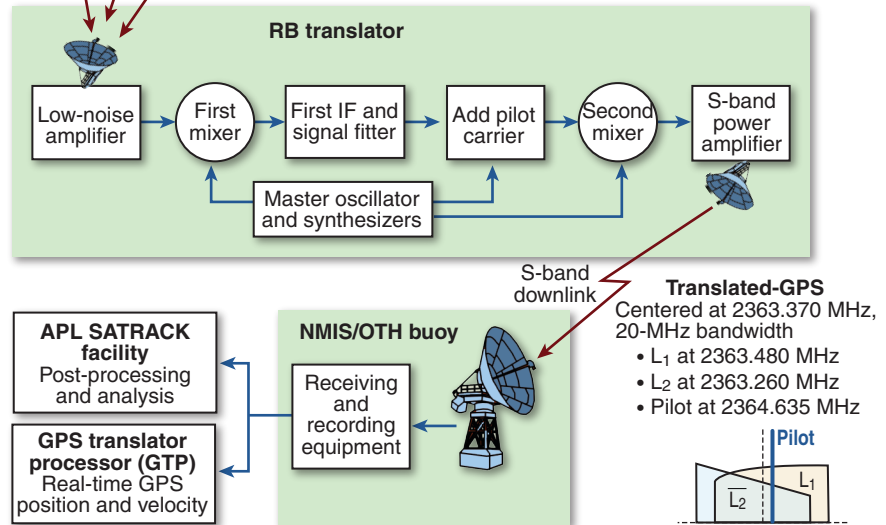

Figure 4. GPS translator system block diagram. GPS signals received at the RB L-band antenna are amplified and heterodyned to overlay the L_1 and L_2 signals in a common 20-MHz signal channel. After a pilot carrier tone is added, the composite signal is heterodyned to S-band, amplified, and transmitted using the RB S-band antenna. The NMIS ship (and buoy) S-band antennas receive the translated signals. The NMIS both records the signal data for subsequent processing at APL and produces a real-time trajectory. The buoy only records translator data for post-processing. Similar translated-GPS systems are used on Minuteman III and several Missile Defense Agency missile systems. (Adapted with permission from Ref. 2.)

prototype OTH buoy, the translated-GPS recording system was installed in the prototype OTH buoy's five-slot VME-64X chassis. (The additional space was used to house the GPS timing receiver, power supply, and L-band power splitter.) A 2-GB SCSI solid-state drive (SSD) was used to record the translated-GPS data.

BOX 1. INTRODUCTION TO TRANSLATED-GPS

Analog GPS translators provide an independent data source to assess the performance of weapon system components for flight accuracy evaluation. GPS L_1 and L_2 signals are relayed to ground-receive assets via an analog translator onboard the RB. Translators have several advantages relative to a real-time GPS receiver:

- Analog translators have simpler hardware designs than GPS receivers, making them more reliable.

- Analog translators have no processing logic, ensuring that they behave exactly the same way every time they are used, as compared with GPS receivers, which can behave sporadically or unexpectedly.

- All-in-view wideband GPS raw signals are recorded for post-flight processing. There is no in-flight tracking of GPS signals, so no data "drop-outs" occur such as those that can occur with GPS receivers.

- Under normal flight conditions, post-flight tracking enables improved tracking performance.

- In an abnormal flight condition, post-flight tracking provides information to support evaluation of the abnormality and often allows tracking that could not be provided by an onboard receiver.

- Because there is no onboard data processing of translator signals, strategic treaty telemetry requirements do not apply to translator data.

- Post-flight trajectory analysis using integrated inertial measurement units and post-plasma translated-GPS data typically provides 50% uncertainty (circular error probability) on the order of 1 to 2 m.[5]

Table 1. Translated-GPS recording system specifications for OTH buoy.

Description	Value
Maximum power	1.5 A at 12 V 1.75 A at 5 V total power <40 W 3.25 A at 3.3 V
RF frequency range	2200 to 2400 MHz
RF input power range	−70 to 0 dBm
RF bandwidth	20 MHz
Receiver channels	2 (S-band) 1 (L-band)
Data storage	2-GB SSD
Data rate	15 MB/s (three channels at 5 MB/s)
Storage capacity	Approximately 130 s of data (2-GB drive at 15 MB/s)
Stored data format	Sampled digital (20-MHz raw spectrum, not processed GPS)
Stored data timing	Integrated with data
System reconfiguration time	Less than 2 s
System control	RS-232
Data offload	Ethernet (not implemented for prototype OTH buoy)

The SBDC consists of three 20-MHz instantaneous bandwidth receiver channels. One channel receives GPS signals, and two channels receive translated-GPS signals. The local GPS channel receives both the L_1 (20-MHz bandwidth at 1575 MHz) and L_2 (20-MHz bandwidth at 1227.6 MHz) signals that are down-converted to near baseband and overlaid as shown in Fig. 6 before being digitally sampled and transmitted to the BCR. The local GPS data provide a true GPS time reference and also are used to measure the ionospheric-induced delay on the GPS signals. The two translated-GPS channels receive the 20-MHz bandwidth GPS translator data (consisting of 20-MHz bandwidth overlaid L_1 and L_2 GPS signals and the pilot carrier as shown in Fig. 6) that are down-converted to near baseband before being digitally sampled and transmitted to the BCR.

The BCR receives the three channels of 20-MHz bandwidth data from the SBDC and generates the in-phase and quadrature signals for each channel. The in-phase and quadrature data are
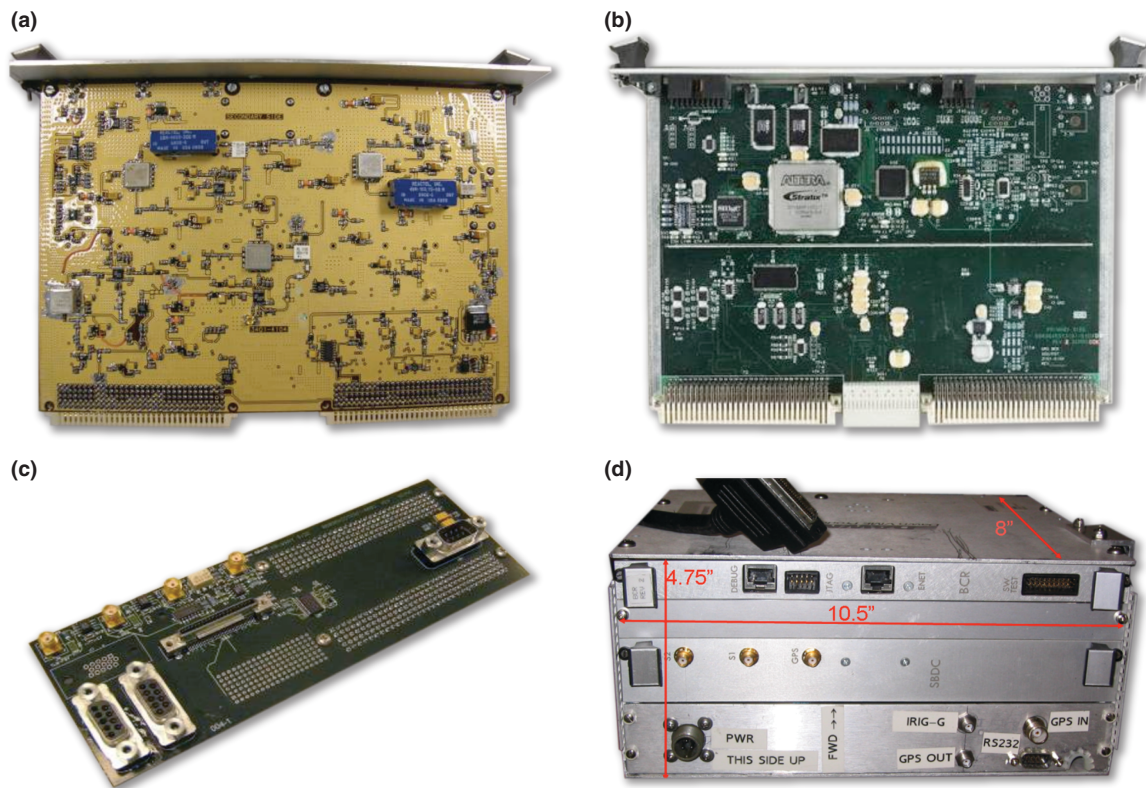

Figure 5. Translated-GPS recording system components. (a) SBDC. (b) BCR. (c) Mezzanine card. (d) Translated-GPS recording system installed in the chassis used for the prototype OTH buoy. From top to bottom in the chassis: BCR, reserved/empty slot, SBDC, and two lower slots containing the power supply and GPS timing receiver. The mezzanine card is installed on the back side of the VME chassis.
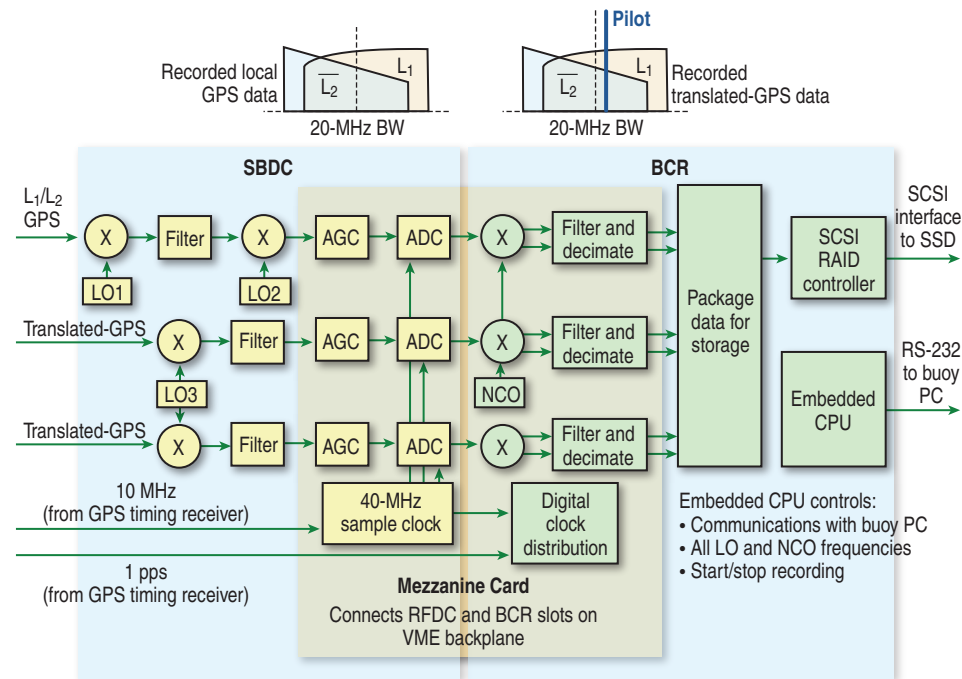
Figure 6. Translated-GPS recording system block diagram. The translated-GPS recording system records a single local L_1/L_2 GPS and two translated-GPS signals. The signal is down-converted and digitized on the SBDC, then sent to the BCR via the mezzanine card. The BCR centers the data at baseband, then filters and formats it for storage on a SSD. ADC, analog-to-digital converter; AGC, automatic gain control; NCO, numerically controlled oscillator; BW, bandwidth.

centered at baseband, filtered, time-stamped, formatted, and stored on the SSD. The BCR also contains an embedded processor that receives commands via an RS-232 serial interface. The command interface allows the OTH buoy's command and control computer to tell the translated-GPS recording system what GPS translator frequency to record s well as the associated start and stop times.

ENGINEERING TESTS RESULTS

Engineering tests for the prototype OTH buoy were performed during FCET-36 (November 2006) and DASO-19 (November 2007). Both FCET-36 and DASO-19 provided opportunities to record RB telemetry and local GPS data. FCET-36 also included a RB instrumented with a full signal translator,[1] providing an opportunity to record GPS translator data. For both engineering tests, the prototype OTH buoy was located approximately 500 yards downrange and 500 yards crossrange from the planned RB impact point, and the NMIS was not located over the horizon. Therefore, the NMIS also was able to record RB telemetry and GPS translator signals to impact (when available) by using the onboard S-band telemetry array and mast-mounted splash antennas. The NMIS-recorded telemetry and GPS translator

data were used as a basis for comparison when the quality of the data recorded by the prototype OTH buoy was evaluated.

During FCET-36, the instrumented Enhanced Navy Test Bed RB included two telemetry links (launch and reentry). The OTH buoy successfully recorded telemetry, local GPS, and translated-GPS data. However, corrosion damage was evident on SBDC when the OTH buoy was disassembled. The corrosion ultimately was attributed to a lack of conformal coating on the translated-GPS recording system circuit boards (not performed because of the aggressive schedule objectives) and exposure to the salty air in the Cape Canaveral area. The corrosion that formed on the SBDC caused sporadic loss of the LOs' phase-lock but did not inhibit the translated-GPS recording system from successfully recording 1 min of GPS translator data as planned.

During DASO-19, the prototype OTH buoy was damaged in transit to the RB reentry area, resulting in seawater entering the interior of the buoy. As a result of the water damage, only local GPS data were recorded (no telemetry data were recorded).

Analysis of the RB telemetry data recorded during FCET-36 showed that the post-plasma RB telemetry data recorded by the prototype OTH buoy were of sufficient quality for use during flight-test analysis.[2] The prototype OTH buoy recorded telemetry data were of similar quality to the data recorded with the NMIS antennas and are usable for approximately the last 2 s of RB flight (post-plasma).

Local GPS Post-Processing Analysis

The local L-band GPS data recorded during both FCET-36 and DASO-19 engineering tests were extracted from the prototype OTH buoy and analyzed in the APL SATRACK (SAtellite TRACKing)[3] facility. Because the L-band data results from the two engineering tests were similar, only the results for DASO-19 are presented here. Pseudorandom noise (PRN) code numbers are used to differentiate the various GPS satellites. Of the 10 vis-
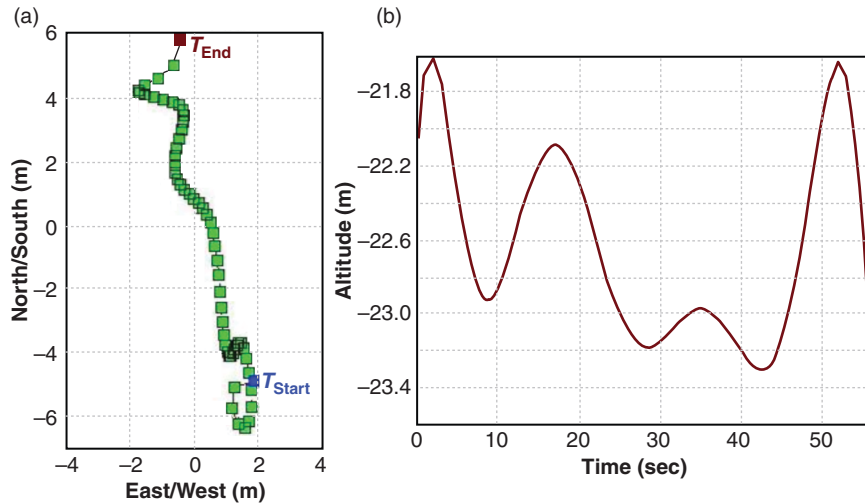
Figure 7. Computed prototype OTH buoy relative position during DASO-19. (a) TStart indicates the position at the beginning of the recording period, and TEnd indicates the position at the end of the 1-min recording. The green squares indicate the buoy's position at 1-s intervals. (b) Buoy's altitude relative to the WGS-84 ellipsoid. (Reprinted with permission from Ref. 2.)

ible GPS satellites, three (GPS PRNs 4, 8, and 11) were not used in the navigation solution because of either poor signal quality or unacceptable tropospheric uncertainties. The L_1 and L_2 measurements from GPS PRNs 2, 13, 16, 20, 23, 25, and 27 were used to create ionospherically corrected pseudorange and carrier-phase measurements. The measurements were corrected for tropospheric effects by using locally measured meteorological data. These measurements then were used to compute the carrier-smoothed buoy position over the approximately 60 s of data.

The GPS-derived trajectory for the prototype OTH buoy is shown in Fig. 7. T_{Start} indicates the position at the beginning of the recording period, and T_{End} indicates the position at the end of the 1-min recording. The green squares indicate the buoy's position at 1-s intervals. Figure 7 also shows the measured
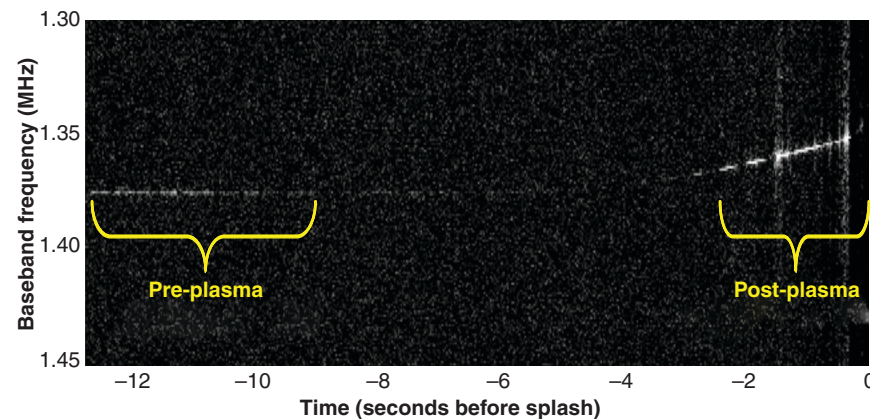

Figure 8. Spectrogram showing the translated-GPS pilot carrier's frequency versus time. The white line in the plot is the pilot carrier. The x axis represents the seconds prior to impact, and the y axis is the measured frequency. Notice that the pilot carrier is detectable 15 s before impact (pre-plasma) and also approximately 2 s before impact (post-plasma). (Reprinted with permission from Ref. 2.)

altitude of the buoy relative to the current World Geodetic System (WGS-84) ellipsoid. Based on the uncertainties in the tropospheric corrections, ionospheric corrections, satellite orbit errors, multipath-induced errors, ionospherically corrected range, and ionospherically corrected carrier-phase noise, the uncertainty in the local-level horizontal plane is approximately 0.5 m (root mean square); the uncertainty in the vertical dimension is approximately 0.6 m (1-σ).

Translated-GPS Post-Processing Analysis

The 1-min recording of translated-GPS data was extracted from the OTH buoy and analyzed at the APL SATRACK facility. The GPS translator output spectrum consists of two components, the 20-MHz bandwidth GPS signal and a pilot carrier. The pilot carrier is a tone overlaid with the GPS signal that nominally has a 30-dB signal-to-noise ratio in a 1-kHz bandwidth. Unlike the spread-spectrum GPS signal, the pilot carrier is easily detected and tracked. The combination of higher received signal power and higher frequency reduces the effects of the plasma on the S-band signal, as compared to the lower-power, lower-frequency GPS signals (for a detailed explanation of RB plasma effects, see Ref. 4). For these reasons, it is possible to receive and track the pilot carrier even when the GPS signal is not detectable.

Figure 8 shows a spectrogram of the pilot carrier's frequency versus time. The white line in the plot is the pilot carrier. The x axis represents the seconds prior to impact, and the y axis is the measured frequency. Notice that the pilot carrier is detectable 15 s before impact (pre-plasma) and also approximately 2 s before impact (post-plasma). Whereas

some of the discontinuities and loss of pilot signal in Fig. 8 were caused by plasma, others were a result of the previously mentioned sporadic loss of LO phase-lock. Regardless, the results indicate that the OTH buoy is a viable means to record the RB GPS translator data to impact.

The RB trajectory for FCET-36 resulted in the plasma-induced loss of GPS signals to extend to impact. As a result, post-plasma GPS data were not detectable in the GPS translator data (this also was true for the NMIS-recorded GPS translator data). Had post-plasma GPS data been available, it would have been integrated with inertial measurement unit data and analyzed in a manner similar to the processes described in Ref. 5. Based on this process, RB trajectory reconstructions have been demonstrated that have impact uncertainties of 1.2–3 m (50% circular error probability).

CONCLUSION

The OTH buoy is being developed as a new NMIS subsystem and consists of a PILS-2 buoy modified to include telemetry and translated-GPS recording systems. A prototype OTH buoy was built and tested during FCET-36 and DASO-19. The combination of these engineering tests demonstrated the OTH buoy's ability to record RB telemetry and GPS translator data to impact. The quality of the telemetry and GPS translator data recorded by the prototype OTH buoy has been determined to be sufficient for use in flight analysis. The effort to transition from the prototype OTH buoy to the deployable OTH buoy system is under way, providing the capability to record RB telemetry and GPS translator data to impact while the NMIS is located over the horizon.

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