

# FLIGHT TEST RESULTS FROM THE LOW POWER TRANSCEIVER COMMUNICATIONS AND NAVIGATION DEMONSTRATION ON SHUTTLE (CANDOS)

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## ABSTRACT

The Low Power Transceiver (LPT) is an advanced signal processing platform that offers a configurable and reprogrammable capability for supporting communications, navigation and sensor functions for mission applications ranging from spacecraft TT&C and autonomous orbit determination to sophisticated networks that use crosslinks to support communications and real-time relative navigation for formation flying. The LPT is the result of extensive collaborative research under NASA/GSFC's Advanced Technology Program and ITT Industries internal research and development efforts. Its modular, multi-channel design currently enables transmitting and receiving communication signals on L- or S-band frequencies and processing GPS L-band signals for precision navigation. The LPT flew as a part of the GSFC Hitchhiker payload named Fast Reaction Experiments Enabling Science Technology And Research (FREESTAR) on-board Space Shuttle Columbia's final mission. The experiment demonstrated functionality in GPS-based navigation and orbit determination, NASA STDN Ground Network communications, space relay communications via the NASA TDRSS, on-orbit reconfiguration of the software radio, the use of the Internet Protocol (IP) for TT&C, and communication concepts for space based range safety. All data from the experiment was recovered and, as a result, all primary and secondary objectives of the experiment were successful. This paper presents the results of the LPTs' maiden space flight as a part of STS-107.

## INTRODUCTION

The Low Power Transceiver (LPT) is a software programmable radio sponsored under various technology development initiatives by the National Aeronautics and Space Administration (NASA). Technological advancements in digital signal processing and RF components, together with an ever present need for smaller and lower powered spacecraft

subsystems, formed the basis for original LPT designs. The original LPT concept centered on a novel application of a digital matched filter to integrate the functions of spacecraft communications and navigation in a small, low power implementation. However, as the product evolved, additional spacecraft system infrastructure and more advanced signal processing was added. As a result, a new class of device has emerged that truly enables next generation space missions and operations concepts. This new device is a highly scalable and programmable platform suitable for mission-specific tailoring of communications, navigation or other signal processing needs, on-orbit reconfiguration, and autonomous operation.

The first demonstration of the LPT in an orbital environment occurred during the STS-107 mission of Space Shuttle Columbia, January 16 – February 1, 2003. Termed the "Communications and Navigation Demonstration on Shuttle" (CANDOS), the demonstration primarily proved the functionality and capability of the LPT while in orbit. It also proved the LPTs ability to qualify for and survive the launch and space flight environment of the Shuttle cargo bay. The demonstration consisted of the following six experiments:

### GPS-Based Navigation

GPS-based navigation and orbit determination were demonstrated during four independent experiment opportunities. The navigation software computed both a point solution and a Kalman filter solution. The Kalman solution was generated with the GPS Enhanced Orbit Determination Experiment (GEODE) software developed at the NASA Goddard Space Flight Center (GSFC), and was incorporated in the command and data handling computer integrated with the LPT for this mission.

For each experiment opportunity, the payload bay (and hence GPS antenna) was pointed toward zenith for at least two orbits in order to maximize GPS visibility.

While these GPS opportunities provided the primary analysis data, other periods where few, if any, GPS satellites were visible were also valuable for evaluating GEODE performance (a common shuttle attitude for STS-107 was payload bay pointed towards the Earth). GEODE's ability to propagate through these periods of low to no GPS visibility and its subsequent reconvergence when GPS satellites came into view again was evaluated. The shuttle's Postflight Attitude and Trajectory History (PATH) ephemeris and near real-time ground navigation vectors generated by Shuttle Mission Operations served as reference sources for GEODE's performance evaluation.

#### NASA Ground Network Communications

Ground Spaceflight Tracking and Data Network (GSTDN) compatibility was demonstrated during 37 separate contacts with NASA S-band tracking stations at Wallops Island and Merritt Island.

#### NASA TDRSS Communications

Tracking and Data Relay Satellite System (TDRSS) compatibility was demonstrated during more than 52 hours of contact with NASA's geostationary relay satellites. The events included both single access (SA) and multiple access (MA) services, and utilized both one-way and two-way links.

#### On-Orbit Reconfiguration

Demonstrated by uploading new digital signal processor firmware to the LPT in order to reprogram its flash memory. A slightly modified image of DSP firmware was uploaded to the LPT's alternate Flash RAM bank via TDRSS. When the upload was complete, a command was sent to switch the boot bank in the LPT and re-boot the experiment. This operation illustrated the capability to completely alter the signal processing capabilities of the device remotely, as future spacecraft might require in order to adapt to evolving mission objectives.

#### Space Based Range Safety

During the Space Based Range Safety demonstration, the LPT simultaneously communicated with both TDRSS and the Dryden Flight Research Center (DFRC) GSTDN station while maintaining strict link margin on both RF command links and while simultaneously producing position and velocity estimates derived from its GPS receiver. A sequence of commands was simulated on the forward links and verified through real-time acknowledgements on the return links. This experiment demonstrated for the first time on-orbit the capability of a single device to provide the functions of both position location and reliable commanding, both key concepts for a space-based range safety system. The use of a space-based

range is expected to aid in the reduction of launch costs and support launches from virtually any location on Earth without increasing the risk of public safety.

#### Mobile-IP

Mobile-IP-enabled Cisco network routers were utilized in each of the GSTDN and TDRSS ground stations, and the LPT used an off-the-shelf Mobile-IP protocol stack to transfer commands and telemetry between the payload operations control center and the experiment, demonstrating the protocols' viability for use in certain spacecraft systems.

All communications conducted between the operations control center and the LPT throughout the experiment used the Internet Protocol (IP). Both TCP/IP and UDP/IP varieties were used in order to demonstrate the feasibility of using the protocol to communicate with future spacecraft. All control and monitoring software embedded in the LPT experiment utilized the IP protocol, which was implemented using a commercial off-the-shelf (COTS) version of Linux running on a Pentium-class processor. This configuration allowed ground controllers to use standard internet tools to manage the experiment. In addition, a recent extension to the IP protocol stack known as Mobile IP was successfully demonstrated. Mobile IP autonomously addressed IP packets as required to route message traffic between the LPT and the control center, regardless of the ground station (TDRSS or GSTDN) it was communicating through. This is significant because the network topology changed as the Shuttle flew in and out of view of numerous ground stations. The ability of the protocol to make this transparent to the end user has demonstrated its viability for use in future missions.

In the following sections, a brief overview of the LPT electronics and signal processing will be presented, followed by a summary of the flight experiment hardware and software. Analysis of the data and experience gathered during the various experiments is then summarized. The paper concludes with an overview of future plans for the LPT.

## THE LOW POWER TRANSCEIVER

### Architecture

The LPT is a collection of interchangeable hardware modules that form a software programmable platform for a variety of general purpose or specialized communications, navigation and signal processing capabilities. The hardware modules are loosely based on the mechanical specifications found in the PC/104 Consortium's PC/104-Plus Specification<sup>1</sup>. Modules that comprise the basic transceiver include:

- I/O and Power Supply Modules
- Digital Signal Processing Modules
- RF Transmitter Module
- RF Receiver Module
- Power Amplifier Module

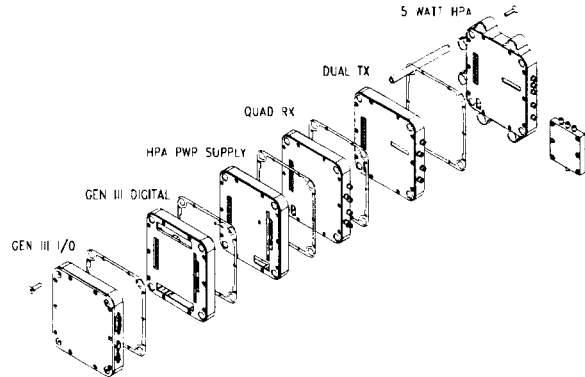


**Figure 1. The Low Power Transceiver**

These modules stack together in various combinations to form a complete LPT. Figure 1 shows the “core” LPT (approx. 5”W x 5”D x 3”H) module stack. Each module consists of one or more printed circuit boards (PCBs), a housing ring to which the PCBs mount, a heat plate and thermal pads, and EMI gaskets. Once assembled, the modules stack together and are rigidly fastened using four connecting rods, as illustrated in Figure 2. This technique allows additional modules to be added to expand the transceivers’ capabilities. Both PC/104 standard and non-standard stackable connectors provide for electrical connectivity between various modules. Additionally, two “chimneys” run vertically inside the housings and provide for additional module-to-module cabling. When assembled, the housings form a rigid structure suitable for use in the most rugged launch vehicles environments. Furthermore, the combination of heat plates, thermal pads and rigid structure provide a low resistance thermal path between hot components and a cold plate to which the LPT is mounted. Finally, the heat plates and EMI gaskets provide sufficient RF isolation between modules to simultaneously operate in both transmit and receive directions and to satisfy EMI/EMC requirements.

Each unique LPT implementation may contain up to four dual- or quad-band RF receivers and up to two

single- or dual-band RF transmitters. In typical implementations, the band assignments support one or more two-way communications systems (e.g. TDRSS, STDN, AFSCN, Crosslinks) and an L1/L2 GPS receiver, as illustrated in Figure 3.



**Figure 2. Expanded View of the “Core” LPT**

Receiver modules perform the functions of low-noise amplification (LNA), band limiting, frequency conversion, automatic gain control and digitization for the receivers. Each receiver path functions independently and simultaneously, and is designed generically such that it may be tailored to operate over a wide range of frequencies. In current implementations, the radio may be tuned to operate at any RF over the range from 500 MHz to 2500 MHz simply by populating the PCBs with appropriate discrete components (e.g. filters and VCOs). The hardware can support instantaneous bandwidths up to 50 MHz, limited by the 100 Msp/s, 8-bit A/D converters. The digitized samples from each receiver feed a time-multiplexed bus structure implemented over a stackable connector. The bus structure allows as many as four receiver modules to be stacked into a single LPT, where each module is addressed sequentially, and samples are processed by a digital module. This capability allows the LPT to process as many as 16 receive bands simultaneously, a configuration that is also suitable for implementing multi-element phased array antennas where each receiver path is assigned an individual element. In this case, the digital beamformer is integrated with the LPT receiver to form an optimal use of digital resource and further integrate the communications subsystem.

Transmitter modules perform the functions of D/A conversion, frequency conversion, band limiting, automatic level control and amplification up to 1 watt of RF power. Like the receiver modules, each transmitter is designed to be tuned over a range of frequencies between 1800 MHz and 2500 MHz by

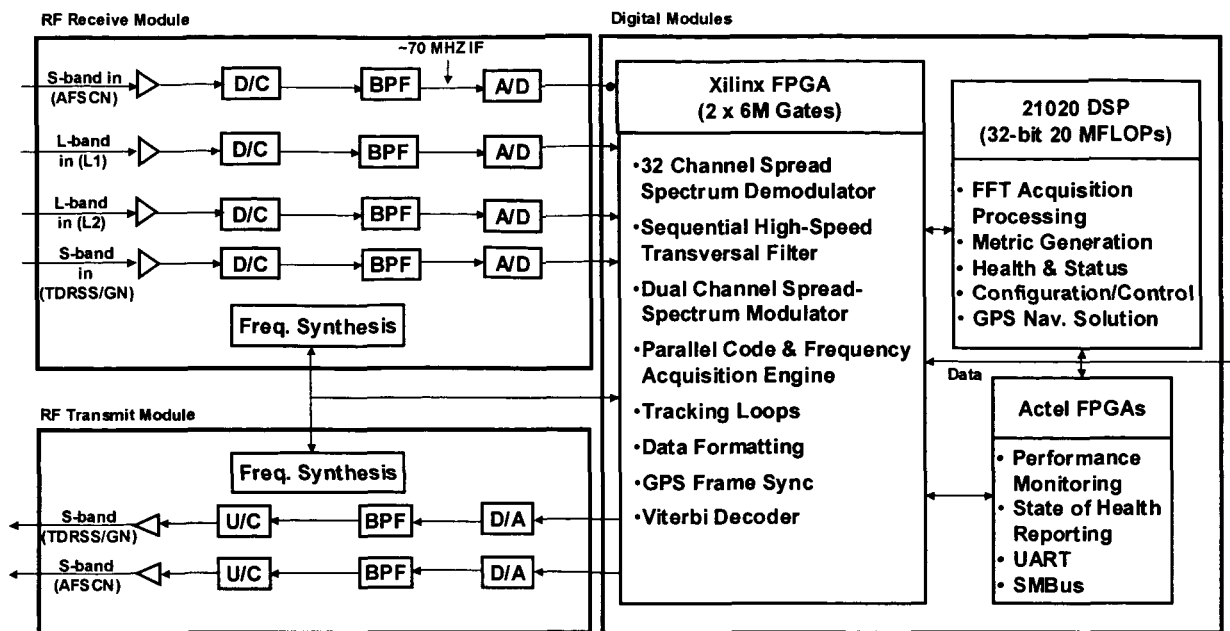


Figure 3. Block Diagram of the LPT

populating the PCBs with the appropriate discrete components. The tuning range is limited only by the power amplifier used on the board – the remaining circuitry is suitable for use down to 500 MHz. The transmitter modules support instantaneous bandwidths up to 70 MHz, using a 70 MHz IF and a 14-bit, 160 Msp/s D/A converter.

The digital modules form the foundation of the software radio, and perform all modulation, demodulation and other signal processing functions in the LPT as well as some data post processing functions. Each LPT contains one or more Xilinx Virtex-II series FPGAs, a number of Actel SX FPGAs, a digital signal processor (DSP), and non-volatile, reprogrammable memory for application storage. In general, the FPGAs contain the high-speed signal processing logic while the DSP is responsible for low-rate signal processing, metric generation, post processing and overall control, health and status of the LPT. Sufficient Flash memory is included to store two complete images of both the FPGA and DSP firmware. This feature enables the LPT to be remotely reprogrammed in its entirety and provides fault tolerance during reprogramming. Selection of the “boot bank” is controlled external to the LPT.

#### Software Programmable Signal Processing

The single largest “enabler” technology for the LPT is its heavy reliance on FPGAs and DSP. Due to its flexible, programmable nature, the LPT is suitable to host virtually any form of signal processing. In existing

implementations, the LPT firmware is designed to process up to 32 independent data channels from any combination of RF bands. In a typical configuration, 28 of these data channels are dedicated to processing GPS L1 and L2 signals (fourteen each), leaving four channels for data communications. Each of these channels is physically identical, operates independently, and may be connected to any RF receiver band.

In addition to the generic communications receiver, specific signal processing is incorporated in the LPT to process GPS navigation signals using the civilian C/A codes. The most notable LPT GPS capability is its “time to first fix.” On average, when provided with no a priori information regarding the GPS constellation relative to LPT time or position, and whether on the Earth’s surface or in orbit, the LPT is able to search for all spacecraft, over the entire Doppler uncertainty region, and over all PN code offsets, in order to produce an estimate of position in approximately two and a half minutes.

#### Mitigating Radiation Effects

In order to meet the cost requirements of a wide range of applications, the LPT is designed to accept components with varying degrees of radiation tolerance and reliability grade. Commercial or industrial grade components offer full functionality and good thermal performance for relatively low cost. Components with known radiation tolerance and tested for reliability are often required for space applications.

The "space" grade LPT uses only components characterized for radiation tolerance. In nearly all cases, component level latch-up immunity is guaranteed to be  $> 100 \text{ MeV-cm}^2/\text{mg}$  and total ionizing dose (TID) is at least 40 kRad. Additionally, the LPT housing provides approximately 200 mils of aluminum shielding to increase the box-level TID tolerance even further. However, a small number of components (specifically the low-power A/D and D/A converters) have a lower degree of tolerance to radiation. For these devices, the latch-up threshold is approximately  $10 \text{ MeV-cm}^2/\text{mg}$  and TID is estimated in the 5-10 kRad range (before accounting for housing shielding). Fortunately, these devices have a very small physical cross section, so the probability of latch-up is still quite small and oftentimes tolerable. These devices are monitored for latch-up and are reset as required at the device level without impacting box-level functionality. On-going development will identify alternative components for these devices in order to improve the overall radiation tolerance of the LPT design.

The only device susceptible to single-event-effects (SEEs) in the LPT is the Xilinx Virtex-II FPGA. This susceptibility stems from the sensitive memory cells contained in each device. To mitigate the system-level impact of these SEEs, deliberate design techniques are employed. These techniques include partial reconfiguration of the device (i.e., scrubbing) and the use of triple module redundancy (TMR) in the design of the FPGA logic, and effectively reduce the single event upset (SEU) rate of the programmable logic to zero.

These techniques do not protect the non-programmable logic portions of the device, which remain susceptible to SEUs and potentially lead to single event functional interrupts (SEFIs) of the device. Each of these SEFIs has its own signature, and upon detection the FPGA is reset and reprogrammed. Fortunately, the cross section of these portions of the FPGA is extremely small, so the probability of any SEFIs occurring is not significant for the LPT.

### CANDOS PAYLOAD

For the CANDOS experiment, the LPT and its suite of antennas made up one of six experiments that formed an integrated Hitchhiker (HH) cross-bay payload deemed Fast Reaction Experiments Enabling Science, Technology, Applications and Research (FREESTAR). LPT experiment components included one LPT electronics stack, three S-band antennas and one L-band antenna, all mounted to the top of the HH Multi-Purpose Equipment Support Structure (MPES) via two HH Single Bay Pallets (SBPs). The LPT electronics box and its antennas are shown mounted to the FREESTAR payload in Figure 4.

The CANDOS flight hardware demonstrated its ability to survive the launch and open space environment for 16 days, thereby accomplishing a significant secondary objective of surviving the launch and space environments. During its time on orbit, no significant LPT hardware or software anomalies were observed.

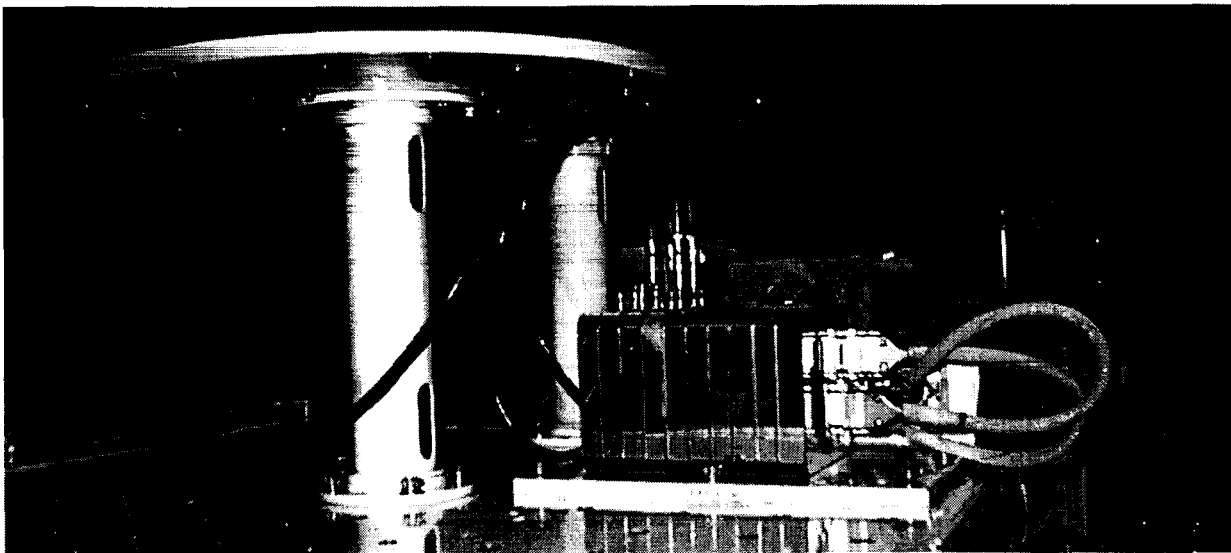


Figure 4. STS-107 Hitchhiker Cross-Bay Bridge with LPT and Other Experiments

### COMMUNICATIONS

### TDRSS Communications and Mobile-IP

The mission timeline provided 97 communications opportunities, 52 using the TDRSS S-Band Single Access (SSA) service and 45 using the S-Band Multiple Access (MA) service. The purpose of this objective was to verify that the LPT is capable of closing a two-way link with the TDRSS while in orbit. Of the 52 SSA events, 47 were considered 100% successful and resulted in two-way communications flow. Of the 45 MA events, four were unsupported as a result of Shuttle attitude at the time of the event and limitations in the experiment field of view. Of the 41 MA events that were supportable, 39 were considered 100% successful and resulted in two-way (35 forward and return link) or one-way (4 return link only) communications flow as intended. All of the one-way services were scheduled as return-only services (no forward link scheduled). Of the seven remaining events (5 SSA and 2 MA), four were considered partially successful in that at least one of the forward or return links operated without anomaly. Only one of these partially successful events was caused by an anomaly within the LPT. The three unsuccessful events were not supported by the experiment as a result of the need to cycle experiment power for unrelated reasons.

Event Type	Number of Supportable Opportunities	% LPT Success
SSA	52	96%
MA	41	95%

During all of these events, the standard off-the-shelf Mobile-IP stack that was built into the on-board Linux operating system supported all data communications. Standard HDLC packet framing was used on all links. On the ground, packet routing was established automatically and securely using the standard Mobile IP protocol that comes with Cisco routers. The protocol automatically set-up IP routing tunnels between the control center and the experiment as the Shuttle came

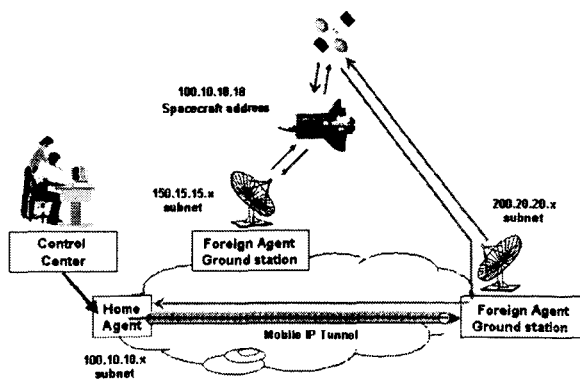


Figure 5. Mobile-IP Network

into view. **Error! Reference source not found.** illustrates the complete Mobile-IP network used during the mission.

The following functions were demonstrated using this framework:

- Blind commanding using a UDP/IP command uplink to turn the transmitters on over a static IP tunnel
- Real time telemetry using UDP/IP
- Reliable file delivery from the CANDOS payload to the control center (e.g. navigation system logs, comm system logs) and from the control center to the CANDOS payload (stored commands, data files, software updates) using both TCP/IP based 2-way file transfer protocols (Secure Copy Protocol (SCP)) and one and 2-way UDP-based Multicast Dissemination Protocol (MDP)
- On-board clock synchronization to ground standard time using Network Time Protocol (NTP)
- Autonomous on-board message data routing
- Secure LPT commanding from, and reliable file delivery to, a remote site (NASA/MSFC)
- Multiple simultaneous secure sessions between the control center and the spacecraft conducting commanding and reliable file transfers
- Multi-station reliable file transfers (automatic resumption after handover)
- File delivery across one-way links with application-level Reed Solomon coding

In total, more than 52 hours of TDRSS communications were accomplished, and all primary and secondary objectives were accomplished. Both the SSA and MA services were used successfully, using both high and low gain antennas and both transmitters in the LPT (one at a time). Of the problems observed, three of seven were caused by experiment misconfigurations. Only one of the anomalies was attributed to the LPT firmware, and it did not significantly impact the verification of the objective. All operations were conducted according to the GSFC IT Security Branch approved CANDOS security plan.

### GSTDN Communications and Mobile-IP

The mission timeline provided 37 communications opportunities, utilizing either the Wallops Flight Facility or the Merritt Island (MILA) ground stations. The purpose of this objective was to verify that the LPT is capable of closing a two-way link with a GSTDN station while in orbit. Of the 37 events, one was unsupported as a result of Shuttle attitude at the time of the event and limitations in the experiment field of view. Of the 36 events that were supportable, 27 were

considered 100% successful and resulted in two-way (26 forward and return link) or one-way (1 forward link only) communications flow as intended. Of the nine remaining events, eight were considered partially successful in that at least one of the forward or return links operated without anomaly.

Event Type	Number of Supportable Opportunities	% LPT Successful
Wallops	21	90%
MILA	15	93%

Mobile-IP was also used during all of these events, in identical fashion to that described for the Space Network and despite the relatively low 2 kbps standard GSTDN forward link data rate.

In total, more than 6 hours of GN communications were accomplished. Both Wallops and MILA ground stations were used successfully. Of the anomalies observed, six of nine were caused by experiment misconfigurations or inconsistencies between the operations concept and the way the experiment was configured. All three remaining anomalies affected the LPT's ability to acquire the forward link subcarrier. The cause of this anomaly was never identified, and it has been unreproducible in ground testing using spare flight hardware.

#### Range Safety

The mission timeline provided 13 communications opportunities utilizing the Dryden Flight Research Center (DFRC) ground station and/or the TDRSS. The purpose of this objective was to verify that the LPT is capable of closing a two-way link, with greater than 9 dB of link margin, simultaneously with both a ground-based and space-based relay. Due to Shuttle attitude and antenna field of view limitations, only five of the 13 events actually included both DFRC and a TDRS. The remaining eight included only a single TDRS (1 event) or only DFRC (7 events). The first 12 events were successful in accomplishing error-free, two-way communications. Both links during the final event appear to have suffered from an interfering signal, as telemetry indicates intermittent communications, with periods of very high signal strength as well as intermittent drop-outs and periods of relatively low signal strength. Numerous Doppler profiles are also evident, suggesting more than two signals were in view. In general, for events where both a TDRS and DFRC were available, link margins significantly exceeded 9 dB, except at event boundaries when antenna gain resulted in substantial pointing loss to one target or the other. Table 1 summarizes Eb/No and link margin estimates based on the LPT's coherent AGC for the 13

range safety events. Note that for events where only a TDRS or DRFC were in view, the LPT receiver channel configured for the target not in view false locked to the signal from the target that was in view. The Eb/No difference observed in these cases (typically ~23 dB) closely approximates the cross-correlation protection provided by the 1023-chip TDRSS PN spreading codes used in this demonstration.

**Table 1: Range Safety Link Summary**

Event Type	Estimated TDRS Eb/No	Estimated DFRC Eb/No	Achieved Link Margin
DFRC	9-10 (false lock)	34-36	>24 dB
DFRC	9-12 (false lock)	32-36	>22 dB
DFRC	10-13 (false lock)	32-36	>22 dB
DFRC	7-12 (false lock)	30-36	>20 dB
WSGT	30-32	6-9 (false lock)	>20 dB
DFRC	9-12 (false lock)	31-34	>21 dB
DFRC/STGT	21-32	30-35	>11 dB
DFRC/STGT	24-25	34-35	>14 dB
DFRC	No Lock	21-35	>11 dB
DFRC	No Lock	26-32	>16 dB
DFRC/STGT	25-31	34-36	>15 dB
DFRC/STGT	20-32	28-36	>10 dB
DFRC/WSGT	13-30	22-29	>12 dB*

In total, more than 6 hours of Range Safety communications were accomplished. The Dryden ground station was used successfully. Other than the interference\* observed during the last event, no anomalies were observed during any of the events, resulting in 100% success of this objective.

## NAVIGATION

### Navigation Software Overview

The LPT navigation software is comprised of 4 main functions: 1) point solution, 2) GEODE orbit determination, 3) channel assignment, and 4) data logging. The point solution function is a standard weighted least squares algorithm for computing position and clock bias when at least 4 GPS satellites are tracked. Velocity and clock drift are computed from a polynomial fit to 3 successive position/bias solutions.

GEODE provides a 9-element Kalman filter that solves for position, velocity, drag coefficient, clock bias, and clock drift. It also includes high-fidelity force models

for the geopotential, atmospheric drag, and sun/moon gravitational perturbations. The expected GEODE position accuracy is 20 m one-sigma.

The channel assignment function determines which satellites are to be tracked. When less than 4 satellites are tracked and a position is unavailable, the function will perform an open-sky search until at least 4 satellites are tracked. Once at least 4 satellites are tracked and a position solution is available, the channel assignment function will use the current position, GPS almanac, and current orbiter attitude to determine which satellites are in view and then command the LPT to track them. An initial GPS almanac file is available onboard the LPT, and is updated as new data is received from the GPS constellation. An uplinked attitude timeline file provides the orbiter's attitude based on the mission timeline for determining the direction the GPS antenna is pointing with respect to the GPS constellation.

The data logging function logs selected database messages for post-flight analysis. The message types and logging frequency are determined by a configuration file that can be uplinked to the LPT as needed. Over 150M of navigation telemetry was collected during the mission.

#### GPS Experiment Overview

The CANDOS objectives during the GPS experiments were to:

- Maintain track of at least 4 satellites.
- Achieve GEODE convergence.
- Demonstrate using an uplinked attitude timeline to select which satellites to track.
- Demonstrate GEODE propagation during GPS outages and subsequent reconvergence.

Table 2 summarizes the four GPS experiment periods, along with two unscheduled GPS tracking opportunities (orbits 64 and 156). As shown, the orbiter provided a stable attitude for tracking the GPS constellation during each of the 4 experiments. The attitude column shows which orbiter body axis is in the direction of the local vertical (LV; points toward the Earth) and which is in the direction of the velocity vector (VV). The orbiter body coordinates convention is +X axis out the nose, +Y axis out the right wing, and +Z completing the right-hand rule (out the belly). The GPS antenna boresight is along the orbiter's -Z body axis (outward from the payload bay).

**Table 2: GPS Experiment Timeline**

Exp. No.	Orbit No.	Shuttle Attitude	Planned Duration (H:MM)
1	55	+ZLV -YVV	3:07
2	101	+ZLV +YVV	4:10
3	116	+ZLV +YVV	3:10
4	132	+ZLV +YVV	3:51
-	64	-Z Solar Inertial	-
-	156	-XLV +YVV	-

Prior to each GPS experiment period, any necessary files were uplinked (e.g., updates to the navigation configuration, attitude timeline, or logging configuration). At the beginning of each GPS experiment period, the navigation software was initialized from a cold-start. Once the open-sky search algorithm acquired at least 4 GPS satellites, a point solution was computed and used to initialize GEODE.

#### Ground Navigation Vector Comparisons

JSC provided the current ground navigation batch solution vector once per orbit for comparison with the GEODE estimate. Table 4 shows the vector comparisons for each of the experiments. The one-sigma JSC vector accuracies are approximately 360 m in position and 0.314 m/s in velocity (for 2 hours following an attitude maneuver). The GEODE solution was not corrected for the distance between the GPS antenna and the orbiter's center of mass for these comparisons. All but one of the GEODE vectors were within the 1-sigma uncertainty of the JSC vectors, with the first comparison of the fourth experiment being less than 2-sigma.

#### BET Comparisons

The GEODE state vectors were compared to the Postflight Attitude and Trajectory History (PATH), also known as a Best Estimate of Trajectory (BET), generated by the NASA Johnson Space Center (JSC). [2] The estimated accuracy of the BET's position and velocity in radial, in-track, and cross-track components is shown in Table 3. [3] Because of the large uncertainties in the BET relative to predicted GEODE accuracies, no corrections for antenna location or shuttle attitude were made to the GEODE states.



**Table 4: JSC Vector Comparisons**

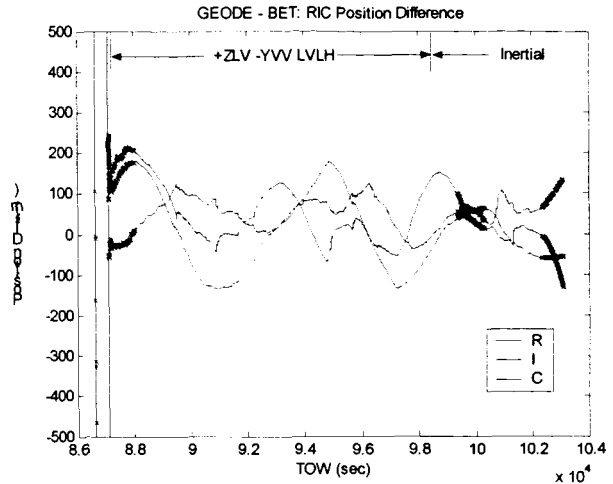
Orbit	GPS Exp.	GPS TOW (sec)	Position Difference (m)	Velocity Difference (m/s)
55	1	88,813	179.0	0.170
56	1	94,633	149.6	0.186
57	1	100,453	248.0	0.270
64	-	137,714	47.1	0.063
101	2	341,594	25.1	0.078
102	2	347,893	97.8	0.122
116	3	423,271	132.4	0.141
117	3	429,126	225.2	0.283
132	4	509,701	439.8	0.520
133	4	515,532	243.2	0.212
156	-	636,373	80.2	0.154
157	-	642,193	110.6	0.071

**Table 3 : Predicted BET 3 $\sigma$  Accuracies**

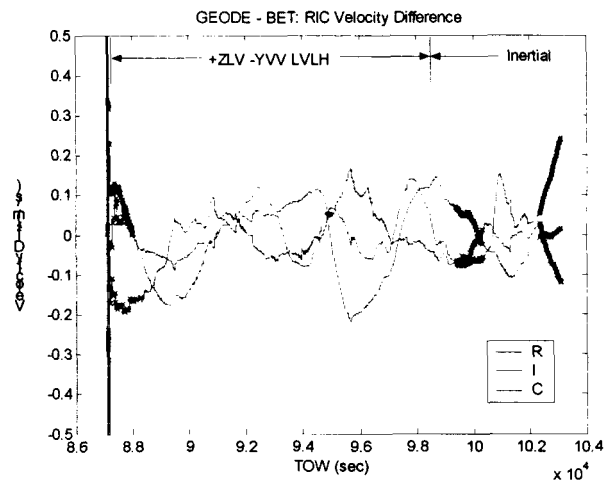
Component	Position (m)	Velocity (m/s)
Radial	200	0.45
Intrack	450	0.20
Crosstrack	200	0.25

Experiment 1

Figure 6 and Figure 7 show the radial, intrack, and crosstrack position and velocity differences for the first GPS experiment. The shuttle attitude is indicated along the top of the figure, and the “x” symbols on each curve indicate where GEODE was not converged. As shown, GEODE converged within 25 minutes of being initialized. At the end of the experiment, approximately 98,500 seconds GPS time of week (TOW), the shuttle transitioned to an inertial attitude hold and GEODE became unconverged as the LPT dropped satellites due to poor visibility. However, as the shuttle’s attitude improved for tracking GPS satellites, GEODE reconverged for approximately 30 minutes before the attitude caused the LPT to lose track of GPS again.



**Figure 6: Experiment 1 Position Difference**



**Figure 7: Experiment 1 Velocity Difference**

Experiment 2

Figure 8 and Figure 9 show the radial, intrack, and crosstrack position and velocity differences for the second GPS experiment. Even though the experiment was only for the duration of the +ZLV +YVV attitude hold, the subsequent -XLV -YVV attitude hold allowed the LPT to track enough satellites to maintain GEODE convergence for an additional 2.5 hours.

Following these two attitude holds, the navigation software continued to run for an additional 9 hours. Figure 10 shows the resulting position differences with the BET. The shuttle attitude was not favorable to tracking at least 4 GPS satellites after the -XLV -YVV attitude hold, and the GEODE position error increased as a result of unmodeled translational forces from multiple attitude maneuvers during this timeframe. The

intrack

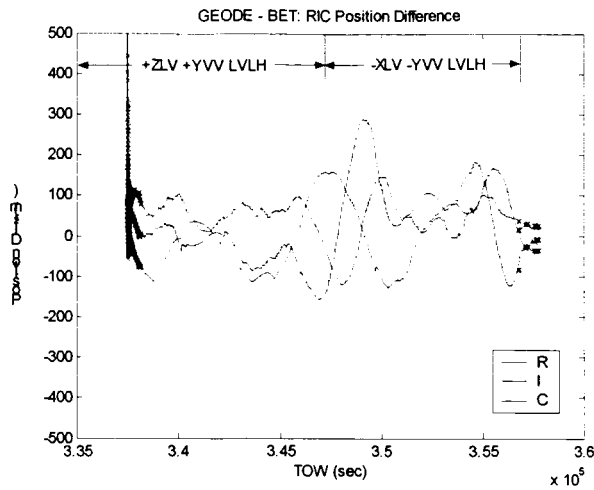


Figure 8: Experiment 2 Position Difference

position error relative to the BET grew to 9 km before the LPT again tracked 4 or more GPS satellites (approximately 382,000 seconds TOW), and within 13 minutes, GEODE had reconverged. This demonstrated the ability of GEODE to propagate through extended outages and reconverge when new measurements are available.

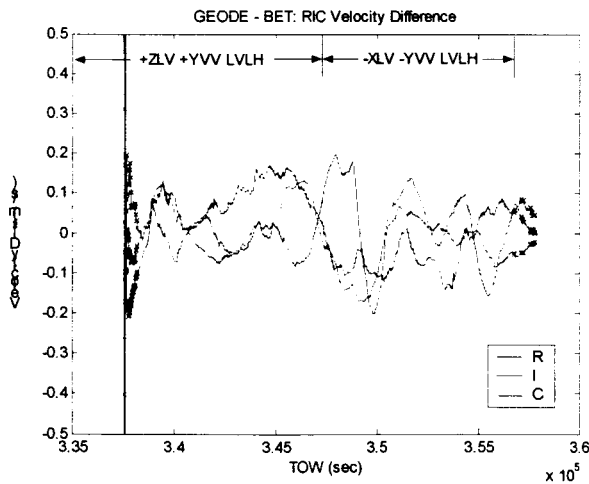


Figure 9: Experiment 2 Velocity Difference

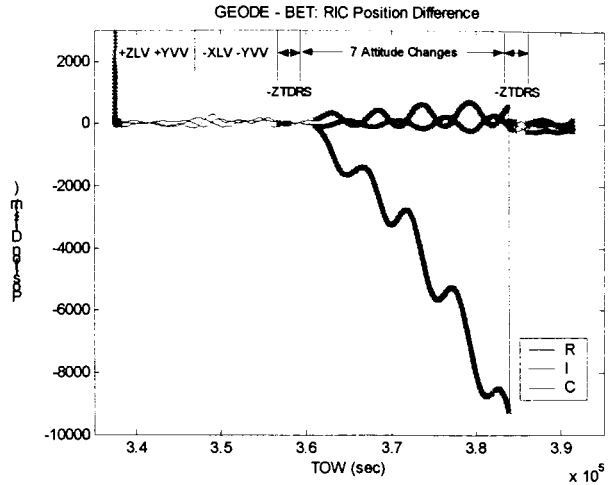


Figure 10: Extended Experiment 2 Position Difference

Orbit 156

Orbit 156 provided an unique opportunity to evaluate GEODE's performance under sporadic tracking conditions. Figure 11 shows the radial, intrack, and crosstrack position and velocity differences for the data collected starting at GEODE was initialized during the -ZLV +YVV attitude hold with the point solution, subsequently converged, and processed data for just under 1 hour before the LPT lost track of the GPS constellation at 27,100 seconds TOW due to an attitude transition. For the next 3 hours, GPS tracking was sparse and GEODE processed measurements when they were available. At approximately 41,000 seconds TOW, the shuttle maneuvered to a more favorable -XLV +YVV attitude, and GEODE reconverged as more GPS satellites were tracked.

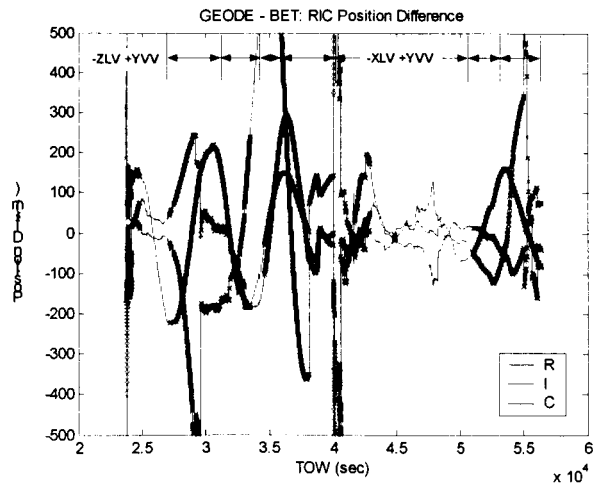
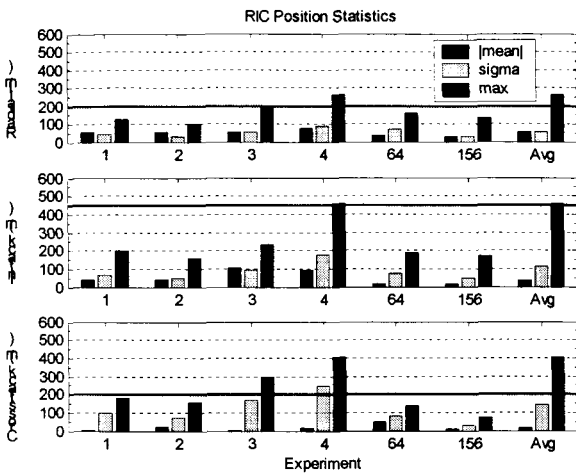


Figure 11: Orbit 156 Position Difference

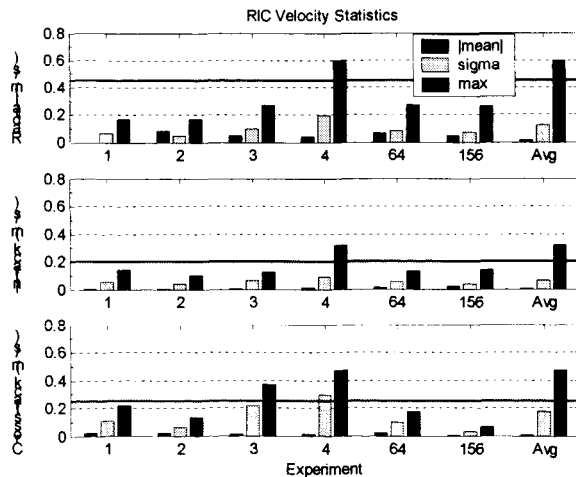
**BET Comparison Summary**

Figure 12 and Figure 13 show statistics for the radial, in-track, and cross-track components of the position and velocity differences between the BET and GEODE for the four GPS experiments and the data collected at orbits 64 and 156. Also shown are the average statistic values over all of the data, along with the predicted BET  $3\sigma$  uncertainties listed in Table 2 (red horizontal solid line).

Experiment 4 produced the largest differences with the BET, with the maximum value for all three components of position and velocity exceeding the predicted BET uncertainty thresholds. The cross-track position and velocity differences also exceeded the expected BET uncertainties in Experiment 3. All other periods were well bounded by the BET uncertainty thresholds.



**Figure 12: GEODE-BET Position Difference Statistics**



**Figure 13: GEODE-BET Velocity Difference Statistics**

**GEODE Pseudorange Residuals**

Aside from external references for comparison, another indication of GEODE's performance are the pseudorange residual statistics, which are shown in Table 5 for each GPS experiment. The 95% value was computed as the 95% point of the absolute residuals when ranked in ascending order. The first measurement at each processing epoch included significant errors from the LPT clock (up to 600 m) and was excluded from the statistics. The near-zero mean and approximately 13 m standard deviation are consistent with the expected 20 m one-sigma positioning performance for GEODE.

**Table 5: Measurement Residual Statistics**

GPS Experiment	Mean (m)	Sigma (m)	95% (m)
1	-0.4	12.6	25.3
2	0.2	12.2	24.5
3	-0.9	12.7	25.4
4	1.2	11.4	22.7

**THE FUTURE**

The LPT will provide primary TDRSS and AFSCN communications for the upcoming Air Force Research Laboratories' XSS-11 mission. It will also provide a GPS autonomous orbit capability similar to the one described in this paper but based on a "lite" version of GEODE. Late in the XSS-11 mission, the LPT firmware will be upgraded in order to demonstrate for the first time in orbit use of the new civil signal that will be available on the GPS L2 carrier when the Block IIR spacecraft are launched. In addition to XSS-11, the LPT will provide all primary communications and navigation for the formation flying TechSat-21 mission. In this application, the LPT provides space-to-ground communications through the AFSCN as well as inter-spacecraft communications and ranging via a crosslink. Navigation functions will include GPS-based absolute and relative (via differential GPS) autonomous orbit determination.

The evolution of LPT is far from over. On-going research and development activity will be adding considerably to the frequency range and agility of the LPT, to include operation as high as Ka-Band and the ability to tune over multiple RF bands on-the-fly. In addition, the LPT packaging system is evolving in an effort to preserve or improve upon the core LPT capabilities in only 8 cubic inches of volume – a cube measuring approximately two inches on a side. This new, light-weight form factor will help revolutionize spacecraft design by allowing the transceiver to be

placed near or inside antenna structures, virtually eliminating cable losses that plague existing spacecraft and limit the bandwidth available for science data. Additionally, it will act as an enabler for a new generation of nano-satellites whose entire mass is less than a conventional transceiver/transponder.

## **CONCLUSION**

The Low Power Transceiver is a flexible, software programmable radio that is revolutionizing the state-of-the-art in spacecraft TT&C and navigation technology. The foundation of the concept has been thoroughly developed and has now been demonstrated in an orbital setting.

As a result of the expert skill of the STS-107 mission planners, and due to the dedication and sacrifice of the crew of Columbia, the quantity and quality of data collected in all experiment areas far exceeded pre-flight mission expectations. All primary and secondary CANDOS mission objectives were successfully accomplished. Through the use of the communications links being demonstrated by the LPT, 100% of the performance data gathered by the experiment and required to validate mission objectives was transferred to the ground. The CANDOS experiment was a resounding success, accomplishing every primary and secondary objective established prior to the mission, as well as some extras thrown in during the mission itself. In the words of our NASA program manager, "the experiment was a great success." CANDOS has paved the way for future missions that will rely on the use of multi-mode communications, autonomous spacecraft navigation, IP in space, and space-based range safety. As it continues to evolve, the LPT will continue to enable newer, smaller, lighter, and more complex spacecraft.

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