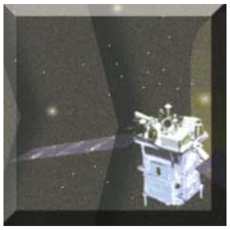

TIMED GPS Navigation System (GNS): Design, Implementation, and Performance Assessment

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The APL-developed GPS Navigation System (GNS) satisfies derived TIMED spacecraft requirements by providing position, velocity, time, Earth-to-Sun vector, and defined orbital event notifications to onboard instruments, spacecraft control computers, and the Mission Operations Center. The GNS data products enable the mission's event-based commanding concept of operations. The system generates tables of both position-based event predictions and orbital element sets for each predicted ground station contact for up to 60 h in advance. The GNS is a Standard Positioning Service receiver system with access to the GPS civilian ranging coarse/acquisition code. It was designed to be a state-of-the-art spaceborne system optimized for autonomous on-orbit operations. The GNS on-orbit test program encompassed the typical "launch + 30 days" checkout period as well as periodic in-flight test sequences where the two GNS processors aboard TIMED are operated and compared against ground-based tracking systems. To date, both are functioning flawlessly and navigation products have surpassed mission accuracy requirements.

INTRODUCTION

APL developed the TIMED (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics) mission to study an important region of the Earth's atmosphere called the MLTI (mesosphere, lower thermosphere, ionosphere). The MLTI includes the region from 60–180 km above the Earth's surface, and until recently was the least explored and understood region of our atmosphere. The principal objective of the TIMED program is to investigate and understand the energetics of the MLTI region including its pressure, temperature, density, and wind structure and the relative importance of various energy sources and sinks in the region. To best study the MLTI, the TIMED spacecraft, with its suite of four remote sensing instruments, was developed and placed into a 625-km circular orbit at a 74.1° inclination on 7 December 2001 and is expected to continue its investigation through 2006. The on-orbit instruments are augmented by an array of ground-based and airborne instruments which together will provide the basic measurements required by the science team. Details of the TIMED mission, including participants, status, science, etc., may be found at http://www.timed.jhuapl.edu/mission/ and in companion articles in this issue of the *Digest*.

A critical mission design decision made early in the TIMED program was to incorporate “event-based commanding” to reduce mission operations costs (see Kusnierkiewicz, “TIMED Mission System Engineering and System Architecture,” this issue). Event-based commanding is realized when an identifiable event, or set of events, is used to initiate an activity or sequence of activities on the spacecraft. This approach is in contrast to the more typical time-tagged commanding, which usually requires extensive ground controller interaction.

For TIMED’s implementation of event-based commanding, the majority of events are derived from spacecraft position data or relative positions of the spacecraft, the Earth, and the Sun. Through a systematic requirements definition and flow-down process, a derived requirement was established for the TIMED spacecraft to incorporate an onboard autonomous navigation system using DoD’s Global Positioning System (GPS), a constellation of orbiting spacecraft and associated ground-based control systems. Furthermore, it was determined that the navigation system would be implemented as part of the TIMED Integrated Electronics Module (IEM) (see the article by Marth, this issue). The TIMED GPS Navigation System (GNS) was developed by APL to satisfy these derived requirements.

The GNS is designed to autonomously provide real-time position, velocity, time, Earth-to-Sun vector, and defined orbital event notifications (e.g., terminator crossings, ground station contacts, encounters with the South Atlantic Anomaly region and polar regions). In addition, it generates tables of both position-based event predictions and tables of orbital element sets for each predicted ground station contact for up to 60 h in advance. The GNS data are also incorporated into the TIMED instrument data packets on the spacecraft. This provides geodetic references for the data and facilitates time and position correlation of the flight instrument data with data gathered by terrestrial instruments, thereby enabling the maximum science return from all data sources. This article describes the design, implementation, testing, and on-orbit performance assessment of the TIMED GNS.

BACKGROUND

Spacecraft tracking techniques have evolved since the first orbiting satellite, Sputnik, was launched in 1957. APL scientists measured the Doppler shift of Sputnik’s radio beacon and quickly deduced its orbital parameters. Soon thereafter, the Laboratory invented and developed the Navy Transit Satellite Navigation System,[1] the world’s first space-based navigation system that served the military and civilian community for over 35 years. The satellites in the Transit constellation were low-Earth-orbiting spacecraft, and the system was not often used for navigation of other spacecraft, although APL did operate several experimental systems. Rather, NASA and DoD developed ground-based orbit determination systems for spacecraft by using complex ground systems and coherent transponders that resided on the spacecraft. Variants of these early systems are still in use today. Another Doppler-based system, DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite), was developed by the French Space Agency and has been operational since the early 1990s. However, the high operational costs and data latency inherent in the above systems have spurred the development of other techniques to provide real-time high-accuracy positioning and timing data for spacecraft through the use of GPS.

Over the past 30 years, APL and other organizations have demonstrated the feasibility of using GPS for deriving the position of satellites and other high-dynamic platforms. The Laboratory and the Navy quickly capitalized on the availability of GPS to become the first committed users of the system. This resulted in the development of SATRACK,[2] an APL-invented system that utilizes GPS translators and ground-based signal processing systems for trajectory reconstruction and guidance system evaluation of Trident missiles[3] and reentry bodies.[4] The first use of GPS-based navigation was on Transat, an APL spacecraft launched in 1978 that operated for over 10 years.[5] Transat was a Transit navigation satellite with an onboard GPS translator and was used to validate the SATRACK system approach. APL then led the development of GPSPAC,[6] the first spaceborne GPS receiver for autonomous positioning that flew on LANDSAT 7 and several DoD payloads. In the 1990s, NASA used GPS receivers on the TOPEX/Poseidon spacecraft, and more recently other programs have adopted GPS-based navigation systems for spacecraft.[7] The TIMED GNS builds on all these innovations by providing the first fully autonomous, radiation-tolerant, built-for-space system designed with extensive capabilities that facilitate low-cost mission operations.

GNS OVERVIEW

The requirements development and flow-down process for the TIMED mission and spacecraft resulted in the top-level requirements and definition of the GNS. Subsequently, the GNS’s detailed performance, electrical, mechanical, and environmental requirements were derived. While designed specifically for TIMED, the GNS satisfies the functional requirements that would typically be placed on a spaceborne autonomous navigation system for a low- or medium-Earth-orbit host vehicle. Other value-added functional requirements intended to lower mission operations costs and improve operational flexibility are also satisfied. The top-level GNS design requirements derived for TIMED are summarized below:

- Estimate the position and velocity (state vectors) of the spacecraft
- Estimate UTC (Universal Time Coordinated) time and transfer it to the Command and Data Handling (C&DH) system
- Estimate the Earth-Sun vector (used by the TIMED Attitude Control System)
- Provide real-time and predicted position-based event notifications such as ground station contacts
- Operate in a non-GPS navigation mode (described later in this article)
- Support on-orbit software reprogramming
- Be in compliance with CCSDS (Consultative Committee for Space Data Systems) command/telemetry standards
- Reside in the IEM chassis

The GNS is a Standard Positioning Service receiver system with access to the GPS civilian ranging coarse/acquisition (C/A) code that modulates the GPS L1 (1575.42 MHz) signal. While the GNS design team drew on APL's 30-plus years of GPS systems development experience, the GNS was designed from the start as a state-of-the-art spaceborne system optimized for autonomous on-orbit operations. With this fresh-start approach, performance compromises that may have been required when adapting terrestrial receiver designs for space applications were avoided.

The GNS was designed for the hostile radiation environment of space. It is latch-up immune, has a very low single-event-upset (SEU) rate and, except for the computer memory, is hardened to >300 krad (Si). The core electronics can sustain total dose radiation in excess of 1 Mrad (Si). The system has extensive command and telemetry (C&T) capability and provides access to raw and intermediate data products. It accommodates the large GPS signal dynamic range resulting from orbital velocities of approximately 7 km/s and implements robust signal acquisition, navigation, orbit determination, and autonomous integrity monitoring algorithms.

TIMED's spacecraft-level fault protection scheme relies on two independent IEM systems that provide complete redundancy, and therefore two complete and independent GNS processors are implemented on the TIMED spacecraft. At any one time, either GNS 1 or GNS 2, or both, can be operated. The detailed functional description of a single GNS is provided below.

GNS FUNCTIONAL DESCRIPTION

Figure 1 is a simplified block diagram of the GNS. The receive antenna is located on the spacecraft's optical bench on the zenith-pointing surface. (TIMED is three-axis stabilized with nadir- and zenith-pointing surfaces when nominally oriented.) The pre-amplifier, consisting of pre-select filters and a low noise amplifier, is located just underneath the optical bench and generates the dominant component of the system thermal noise power. The remainder of the system, composed of an RF downconverter, a baseband signal processing subsystem, and a dual microprocessor, is located on two Stretch-SEM-E circuit boards and housed in the TIMED IEM.

L-band signals transmitted by GPS's constellation of orbiting spacecraft are received by the GNS's antenna and pre-amplifier. The RF downconverter, using a low-noise temperature-compensated crystal oscillator (TCXO) as a frequency reference, downconverts a 2-MHz component of the L-band spectrum to baseband and converts it to a 2-bit, 3-level digital signal. GPS signal acquisition and processing are performed in software in concert with the APL-developed low-power radiation-hardened application specific integrated circuit (ASIC) called the GPS Tracking ASIC, or GTA. The GTA, at 220,000 gates, is the largest space-qualified ASIC ever developed at APL and implements all required GPS-specific digital hardware functions, including 12 independent tracking channels and timing and control functions.

The two GNS processors work in tandem with the hardware to satisfy all functional requirements and

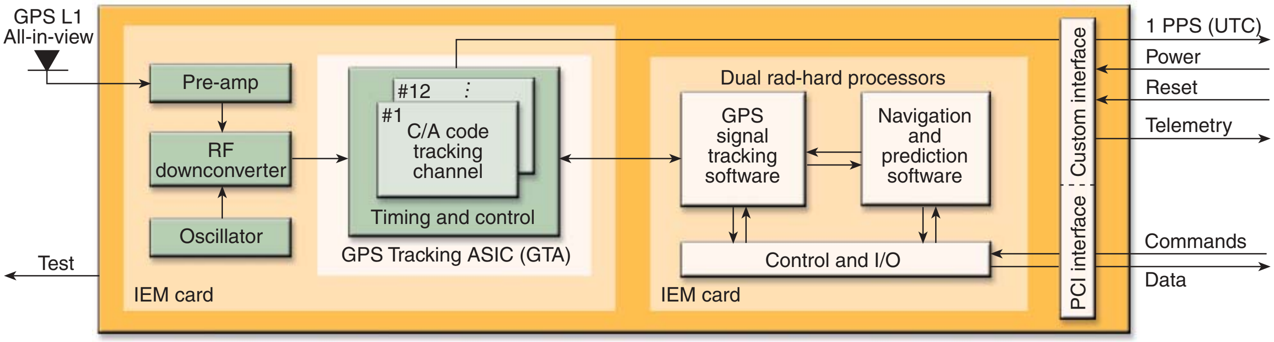

Figure 1. Simplified GNS block diagram.

generate all required data products. One processor implements GPS signal tracking and control algorithms while the other implements navigation algorithms, controls system mode or state transitions, and controls the C&T interface to the spacecraft's C&DH system. The software operates fully autonomously and requires no commands, even at start-up or reset; however, extensive commanding capability is provided as a contingency.

A typical start-up sequence involves the acquisition and phase tracking of GPS ranging signals and the recovery of broadcast message data. When at least four different GPS space vehicles (SVs) are in track, navigation (the generation of position, velocity, and time data) then follows. SV signal acquisition can occur either as (1) an aided acquisition mode, which exploits prior knowledge of a GPS almanac and TIMED spacecraft state vector (stored in nonvolatile memory or received via command), or (2) the default "sky-search" mode, which does not require any *a priori* knowledge. Time to first fix (TTFF) after power-up or full reset for the sky-search mode is on the order of 13 min; use of aided acquisition reduces the TTFF to about 2 min. For the TIMED orbit, 8 to 10 GPS SVs are typically in view of the GNS antenna at any given time, and each is tracked for about 20 min. The software manages the command and control of the tracking channels so that as each SV sets over the local horizon, one or more rising SVs are replaced in the active SV list and are subsequently acquired and tracked. Once a first position fix has been accomplished, the GNS subsystem continuously updates the navigation data. These data are transferred to the C&DH subsystem where they are broadcast to onboard subsystems and instruments and eventually to the ground stations.

GNS DETAILED DESIGN

The GNS has five major elements: (1) GNS antenna, (2) RF subsystem, (3) baseband electronics subsystem, (4) dual-processor subsystem, and (5) system software. A functional description of each element is summarized below.

GNS Antenna

The GNS antenna is a single-element microstrip patch bonded to a truncated, cone-shaped ground plane. The antenna is painted with Aeroglaze A-276 thermal control paint and coated with 1200 Å of SiO_2 to protect the paint from atomic oxygen erosion on orbit. The element is tuned, after compensation for the effects of the paint, to receive right-hand circular polarized signals at the GPS L1 frequency of 1575.42 MHz with a nominal bandwidth of 5 MHz. APL procured the antennas from Ball Aerospace and Technology Corp. as a modification to an existing space-qualified design. The shaped ground plane provides for excellent gain (nominally –2.5 dBiC) at 10° elevations. Antenna gain on the order of 5 dBiC is achieved at zenith. The antenna is mounted atop a graphite epoxy pedestal, which in turn is mounted on the zenith optical bench, providing a full hemisphere of unobstructed coverage. Detailed gain and phase measurements have been made, including some on an RF mock-up of the spacecraft, to characterize the antenna performance and to permit phase corrections to be made during ongoing attitude determination experiments.

RF Subsystem

The RF subsystem is composed of a pre-amplifier and an L-band downconverter. The pre-amp is a space-qualified COTS device with a pre-select L1 filter and a low-noise amplifier. The filter has a 3-dB bandwidth of 30 MHz and a 90-dB bandwidth of 250 MHz. The downconverter is based on a COTS triple-superheterodyne downconverting integrated circuit, the Plessey GP2010, adapted for the GNS design. The GP2010 is a commercial-grade plastic-encapsulated microcircuit (PEM).

Because of the evolving and ever-growing need to fly commercial devices while maintaining acceptable parts reliability, APL has developed, independent of TIMED, a flight qualification process for PEMs. As required by that process, a large number of GP2010s were purchased from the same manufacturing lot so that lot qualification could be performed. The qualification process began with standard inspections and electrical testing. Samples were then randomly drawn to form three groups. Each group was then subjected to a series of strenuous electrical and environmental tests, including 1000-h high-temperature tests, thermal cycling, and 85°C/85% humidity life tests. A post-test random sample of parts was then subjected to destructive parts analysis. Actual flight parts received a stabilization bake and final visual inspection. In addition, special handling procedures defined by APL for PEM devices were followed throughout the purchase, assembly, and system testing phases.

A high-stability, low-noise TCXO provides the fundamental local oscillator for the system. The oscillator's phase noise is less than –65 dBc at a 1-Hz offset from the carrier and –95 dBc at 10 Hz, with a frequency error of less than ±1 part per million over all operating temperatures. A surface acoustic wave filter in the second intermediate frequency provides filtering of out-of-band signals and noise and establishes the system bandwidth. The downconverter also generates the system clock for the GTA and outputs a sampled 2-bit, 3-level signal for digital processing.

Baseband Electronics Subsystem

The baseband electronics subsystem interfaces to the downconverter and primarily consists of the

APL-developed GTA (Fig. 2).[8] The GTA implements 12 independent digital circuits for acquiring and tracking the downconverted GPS signals; a data router for routing up to four different downconverted inputs to any of the 12 tracking channels; a time base, clock, and interrupt generator; and a 16-bit microprocessor memory-mapped interface. (Multiple GTA devices can be daisy-chained in a master/slave configuration to support up to 72 channels.) Each of the 12 tracking channels incorporates full in-phase and quadrature tracking loops that correlate local replicas of the GPS pseudorandom noise (PRN) codes with the received signals. When acquiring and tracking GPS signals, numerically controlled oscillators (NCOs) are steered by the control loop filters of the tracking processor (TP) to force alignment of the receive PRN codes and the locally generated replicas that are clocked by the NCOs. Similarly, the reconstructed transmitted carrier signal is tracked by a carrier tracking loop. Each of the 12 channels also serves as a signal search engine when new GPS satellites come into view of the GNS antenna.

Another major function performed by the GTA is that of generating a 1-pulse-per-second (1 PPS) clock to control the spacecraft's timing system. Under control of a tracking loop in the Kalman filter (KF) of the navigation processor (NP), an NCO is continually controlled such that it outputs a 1-PPS signal that is steered to be aligned with GPS 1-s epochs. GPS epochs are related to UTC epochs by a known offset which is provided in the GNS output telemetry data.

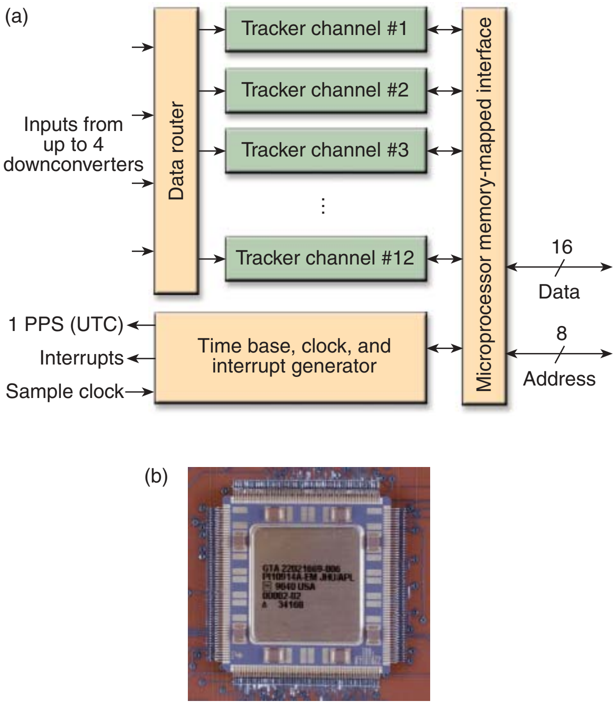

Figure 2. GTA (GPS Tracking application specific integrated circuit [ASIC]): (a) functional block diagram, and (b) flight-qualified GTA device (overall size = 1.45 × 1.45 in.).

The GTA was designed using a Synopsys VHDL design environment and synthesized using Synopsys Design Compiler and Test Compiler tools. The design was verified with VHDL test benches using the Synopsys VSS simulator and by prototyping the design with field-programmable gate arrays (FPGAs). The test benches were used extensively to correct the functional faults in the design, and then the FPGA prototypes were used to help debug performance-related problems. Once performance faults were discovered, they were verified using a test bench to minimize the number of hardware iterations required. Once the debug/testing process was completed, the design was submitted to Honeywell for fabrication, packaging, and flight qualification.

Despite its high level of complexity, the inherent difficulty in testing the millions of possible logic states, and the large number of gates, the GTA was successfully realized in a single foundry pass on an HR2300 series CMOS gate array from the Honeywell Solid State Electronics Center. The device is radiation hardened to >1 Mrad (Si), is latch-up immune, has very low SEU rates, and operates from –55° to +125°C. The GTA operates on 5 V for input and output signal drivers and on 3.3 V for internal circuits, and dissipates only 150 mW.

Dual-Processor Subsystem

In what is seemingly becoming a typical "just-in-time" design scenario, the GNS's computer system was designed before the full capabilities of the Mongoose-V (M-V) were available from the vendor. Therefore, two M-V radiation-hardened devices—the TP and the NP—were incorporated to reduce risk. The dual-processor system was implemented on a single Stretch-SEM-E card (Fig. 3), one side per processor. The designs were derived from that of the IEM C&DH processor (see the article by Marth, this issue).

Both GNS processors operate at 12 MHz from 5-V supplies and communicate via a dual-port random-access memory (DPRAM). The M-V is a Synova, Inc. adaptation of the MIPS R3000 processor architecture. Like the GTA, the M-V is implemented on a rad-hard HR2300 series gate array from Honeywell. The hardware configurations of the two processors are nearly identical except that only the NP has a C&T interface with the spacecraft, and only the TP has a C&DH interface with the GTA. The NP communicates with the spacecraft via an arbitrated 8-KB DPRAM that is connected to PCI (peripheral component interconnect) hardware on the spacecraft side. Communication between the NP and the (subordinate) TP is achieved using another arbitrated 8-KB DPRAM, half of which is also used as boot memory for the TP. The TP interfaces with the GTA via a custom address and data bus used for sending control and configuration information and receiving data and status.

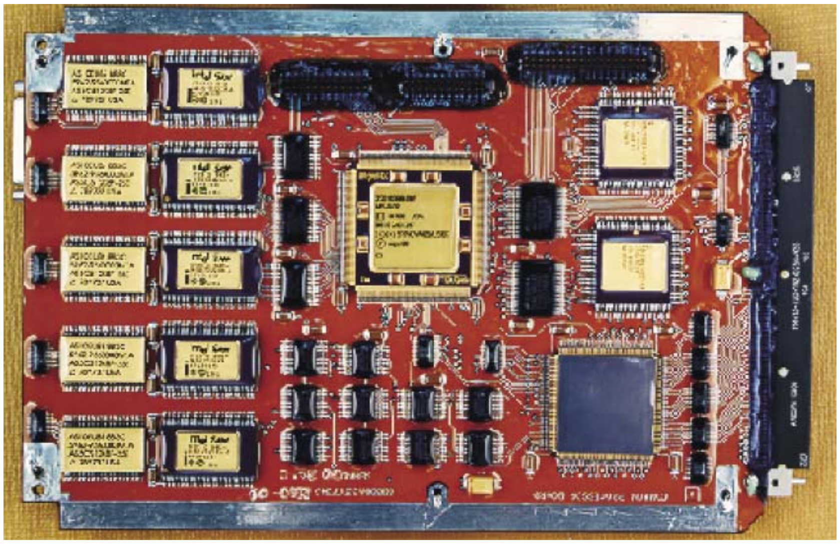

Figure 3. The GNS dual-processor card (one side; overall size = 5.96 × 9.00 in.).

System Software

The GNS software is partitioned between the TP and NP based on functional requirements, system topology, and required and available processor throughput (Fig. 4). The TP performs all high-rate interrupt-driven software control of the GTA, while the NP performs low-rate non-interrupted navigation calculations and interacts with the external world (Table 1). All NT and TP software is written in ANSI C, except for a minimal amount of assembly code for initialization.

The TP does not use an operating system (OS) because of unacceptable interrupt latencies on its high-rate interrupt (≈667 μs). For each signal acquired, the TP software uses a third-order phase-locked loop to track the carrier and an aided first-order, delay-locked loop to track the C/A code. A signal monitor is used to determine when a channel drops lock, in which case the processor autonomously tries to reacquire the satellite with a short search. If this fails, the channel switches to the sky-search acquisition mode, or if aided by the NP, to the aided acquisition mode. The software makes carrier phase and pseudo-range measurements every second for each satellite in track and outputs these data to the NP.

The NP makes limited use of an embedded OS (Nucleus Plus by Accelerated Technologies) for task switching, interrupt handling, and events and semaphores. The goal was to minimize the cost of porting the software to another processor that might not be supported by this OS, or to an alternate OS. The core of the NP software is the KF task. The KF is essentially a data-corrected simulation that provides the current best estimate of the position and velocity of the TIMED satellite's center of mass. Measurement updates normally occur every 30 s and process GPS range and phase measurements for up to 12 satellites in track. The state propagation in the KF contains a Jacchia upper atmospheric density model and a gravity model using degree and order 15 spherical harmonics from the EGM96 database. The prediction capability of the KF is primarily limited by atmospheric density fluctuations in reaction to solar activity, which were near maximum during the early stages of the TIMED mission. In addition to the spacecraft position and velocity, the KF uses GPS time transfer to drive the GTA's measurement clock and 1-PPS output to be coincident with GPS time 1-s epochs.

The KF contains a short-term propagator (STP) for generating real-time GNS output data products for the spacecraft (position, velocity, time, Sun vector, event notification flags, and data validity flags). The STP uses a 5th-degree polynomial to fit the Cartesian components of position at three orbit propagator epochs. The coefficients are selected so that the interpolating polynomial matches position and velocity at the boundary points. The polynomial is used to interpolate position and velocity to 1-s intervals. These 1-s state vectors are distributed with an associated time-of-validity to the spacecraft.

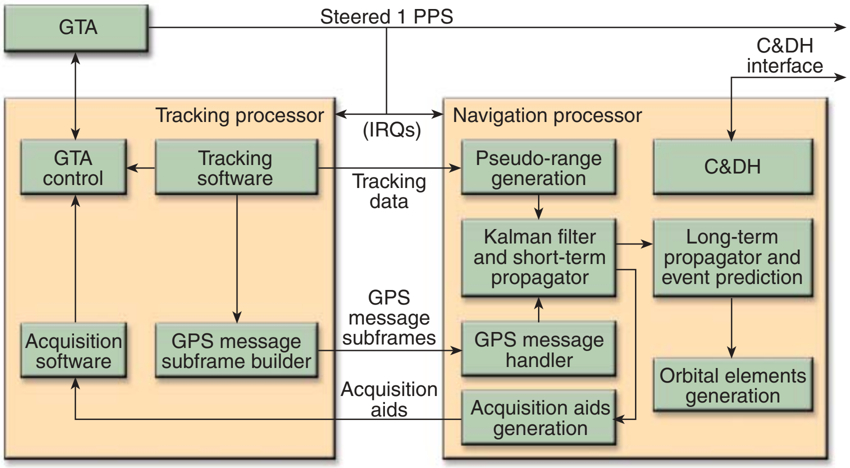

Figure 4. Block diagram showing GNS software partitions between the tracking processor and navigation processor (IRQs = interrupt requests).

Table 1. Tasks performed by the tracking and navigation processors.

TP tasks	NP tasks
Accept and apply acquisition aids (PRN code, Doppler search range)	Provide C&T capability
Execute sky-search algorithm in the absence of aids	Complete pseudo-range calculations
Control GTA hardware functions	Build and periodically update GPS message and almanac tables
Acquire and track up to 12 GPS space vehicles simultaneously	Execute a Kalman filter crank to provide a TIMED state vector every 30 s
Determine space vehicle transmit time for latched data	Generate acquisition aids every 180 s (with Doppler rate information for interpolation by the TP)
Provide tracking and command capability	Generate control for steering the 1-PPS signal to align with GPS (UTC) time 1-s epochs
Provide tracking data to the NP	Generate and output short- and long-term propagation data products
Build GPS message subframes	Incorporate RAIM (receiver autonomous integrity monitoring)

Every 12 h, a long-term propagator (LTP) task is executed to predict the primary and backup ground station contacts and the South Atlantic Anomaly and polar region encounters for the next 60 h. The duration of the propagation is limited by the required accuracy of the data, which is largely dependent on the uncertainty of the atmospheric density. During LTP execution, a state vector corresponding to each predicted ground station contact is saved and used to generate an orbital element set for the respective contact. The Mission Operations Center and the instrument Payload Operations Centers use the LTP data products on the ground (LTP data products are not used onboard). (See the article by Rodberg et al. for a description of the Mission Operations Center and Payload Operations Center.)

SYSTEM FAULT PROTECTION

As noted previously, the TIMED GNS was designed for completely autonomous operation, including the self-detection of anomalous conditions caused by internal (hardware or software) faults, unexpected or out-of-spec GPS signal conditions, or anomalous TIMED spacecraft conditions or orientations. Receiver autonomous integrity monitoring (RAIM) is one facet of the GNS's fault protection scheme. The GNS implements a RAIM technique called "fault detection and exclusion." The software excludes any measurements from use in the KF whose residuals exceed a defined threshold. These residuals are the difference between the measured pseudo-range and the predicted pseudo-range based on the state estimate propagated from the last KF update. An out-of-range residual is defined as one that deviates from the prediction by 20 times the residual standard deviation computed by the KF covariance analysis. If some, but not all, residuals at a single epoch are out of range, they are not used. If all the residuals at a single epoch are out of range, the KF is re-initialized. Whenever a large residual event occurs, a message is output in the telemetry data.

Since launch, the RAIM element of the GNS fault protection system has been autonomously implemented on several occasions. Upon investigation, it was determined that these events resulted from one of two causes:

1. *Use of a GPS ephemeris bracketing a scheduled outage of a GPS satellite*. Each GPS SV continually broadcasts ephemeris information that a receiver uses to compute its location. This ephemeris represents a short-duration fit to the GPS SV orbit that is accurate for a few hours and is normally updated by the SV every 2 h. An interruption in the ephemeris updating occurs when a GPS satellite is taken offline, which happens, for example, when it is repositioned. These outages can last for many hours. On several occasions, when the SV was returned to service, the old ephemeris (still in the GNS's data store) was incorrectly reused. When the old ephemeris is used on a spacecraft that has been restationed, the predicted residual is understandably large. In these several instances, the RAIM algorithm properly detected this condition and simply disregarded the range data from the SV in question. The relevant SV remained out of all subsequent KF solutions until a new ephemeris was broadcast and recovered by the tracking software.

2. *False PRN code lock.* Each broadcast GPS signal is modulated with a PRN code that, by design, correlates poorly with the codes used on the other SVs. Despite this favorable cross-correlation property, cross-lock can occur in some rare cases. When it does, the system "thinks" it is tracking one signal from a particular GPS SV when in fact it is tracking another, resulting in a very large residual. Again, the RAIM system autonomously detected this situation several times and removed the pseudo-range data from consideration by the KF.

Another fault protection scheme described below is built into the GNS's dual-processor subsystem. Computer memories in the space environment are susceptible to SEUs, with some (more costly) parts having better SEU rates than others for a given energetic particle environment. A cost-performance trade was conducted for the TIMED mission and it was decided that, given the TIMED orbit and the expected exposure, relatively low-cost RAMs with modest SEU performance characteristics would be employed. To combat the expected SEUs, the GNS processors were designed with error detection and correction circuits to autonomously detect and correct single-bit errors (double-bit errors can only be detected; the system is reset in that event). To date, the GNS has detected four double-bit errors, consistent with pre-launch predicted SEU rates. In each case the system autonomously reset and restarted itself into the aided acquisition mode and was fully operational in a matter of minutes without the assistance or intervention of ground controllers.

There are conceivable GNS subsystem failures (antenna damage or performance degradation, oscillator or RF system problems, etc.) or spacecraft conditions (loss of attitude control, excessive electromagnetic interference, etc.) that could cause a disruption in the ability of the GNS to track some or all of the available GPS signals. If conditions were to continue to exist such that no GPS spacecraft are being tracked (for whatever reason) when measurement data are required for processing by the KF, the system has a fault protection scheme where it will "flywheel." In that event, the KF is designed to accurately propagate the orbit and continue to generate the standard output data products. The flywheel operation continues until measurement data are available. If no data are available, the accuracy of the data products degrades because of uncertainties in the force models; in that case, new state vectors computed by the ground system that are based on Doppler measurements and/or NORAD tracking can be periodically uplinked by ground controllers and used to seed the propagator. This would be a high-cost endeavor, but the program's overall data management scheme would be preserved.

In over 16 months of on-orbit operation, including over 300,000 GPS SV tracking sequences encountered to date, these autonomous system fault protection rules have operated flawlessly, detecting and properly reacting to a handful of anomalous conditions, resulting in an on-orbit system availability of 99.98%.

GNS QUALIFICATION TEST PROGRAM

"Test as you fly; fly as you test" has been a sound practice in the APL Space Department for decades; however, developing a comprehensive test campaign and providing a realistic test environment for the GNS was a significant challenge. A GNS test plan was formulated to define the framework and specifics of the test program, and a sophisticated test suite and ground support equipment (GSE) were developed to implement it. The test program encompassed testing for each hardware and software module, the integrated GNS, the integrated GNS/IEM, and the full IEM with the spacecraft. Early on-orbit verification and periodic on-orbit testing were also conducted and have included comparisons against radar and TDRSS (Tracking and Data Relay Satellite System) tracking data. In addition, the software was evaluated by way of stand-alone independent verification and validation activities.

A critical function of the GSE is to generate realistic RF signals for the system to receive and process during testing. The signal characteristics must take into account the location and precise relative motions of the simulated TIMED spacecraft and all the spacecraft in the GPS constellation, effects owing to the transmit and receive antennas, and atmospheric propagation effects for each GPS-to-GNS link. The GSE also provides a realistic simulation of all spacecraft electrical interfaces.

A significant component of the GNS test suite is the commercially available Nortel STR 2700 GPS constellation simulator. The system provides an accurate simulation of the GPS signals that are expected on orbit. Ten GPS signals of varying amplitude and frequency/phase are simultaneously generated. The signal characteristics are calculated each 0.1 s as a function of simulated spacecraft attitude, GPS satellite transmit antenna pattern, GNS receive antenna pattern, and relative positions of the GPS constellation and the simulated TIMED spacecraft. The particular TIMED orbit that the test director wants to "fly" is defined off-line by a user motion file generated with BG-14 propagation software seeded by the requisite TIMED state vector. These tests verified the basic operation of the timing circuits, tracking channel hardware, 1-PPS generator, TP software, and the vast majority of the NP software.

After subsystem testing, GNS system-level performance was thoroughly tested, evaluated, and characterized (Fig. 5). The accuracy of GNS real-time navigation data products, including position, velocity, and time, was measured and checked for compliance with system

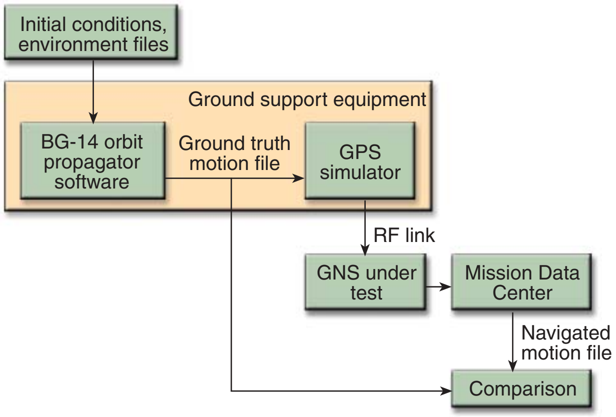

Figure 5. GNS end-to-end test system block diagram.

requirements. Autonomy requirements, including GPS SV signal acquisition without prior knowledge of position or time (the aforementioned "sky-search" mode), were fully verified. Many tracking threshold and tracking quality tests were performed, and susceptibility to both in-band and out-of-band continuous wave interference tones and broadband jamming signals was assessed. System fault protection and anomaly tests were also conducted to characterize GNS response to GPS satellite outages, random or systematic errors in the broadcast GPS navigation message, and GPS signal attenuation of various levels.

After the GNS was fully integrated with the IEM, a subset of tracking and navigation performance tests was repeated to verify compatibility with the IEM environment, including measuring the GNS's susceptibility to the S-band transmitter located several cards away in the IEM. Thermal-vacuum and vibration testing rounded out the integrated test operations before final installation of the IEM on the spacecraft. After installation, a series of GNS command, tracking, and navigation tests was repeated to verify compatibility with the spacecraft environment. This included a free radiation test in which the S-band telemetry transmitter and all spacecraft science instruments were turned on. Mission operation tests were also conducted, demonstrating proper GNS operation in the context of planned ground operation procedures.

An important sequence in the test program concerned validation of the proof-of-development (POD) GTA devices. The PODs were a first set of packaged parts from Honeywell; if these tested successfully, die from the same foundry run would be packaged as flight parts. Because the tracking software and special test software were developed in parallel with the GTA, the tools were in place to thoroughly evaluate the POD GTAs upon their delivery. Detailed testing of all the GTA processor interfaces and the internal command and data registers was performed. Acquisition, drop lock, and signal tracking tests were also done using the GPS simulator. Stationary, low-dynamic, and high-dynamic (i.e., orbital) motion scenarios were exercised. Tracking and verification tests were repeated over temperature. With all GTA operational modes fully evaluated, it was concluded that the first-pass foundry run was successful, and Honeywell was given the go-ahead to package and flight-qualify the flight devices using the remaining die.

To verify long-term, autonomous operation of the GNS, the system was subjected to numerous extended pre-launch tests during 1999 and 2000 at the subsystem and spacecraft levels. A number of 8-day user motion files were generated. This permitted the GNS to fly the various scenarios, unattended, for periods often lasting the full 8 days. In this way, the system was fully exercised with well over 4000 sets of signal acquisition, tracking, and signal loss (due to setting satellites) sequences during continuous navigation and event detection/prediction operations. These extended tests were performed on the final software build to verify proper operation of the system.

GNS ON-ORBIT PERFORMANCE ASSESSMENT

The GNS on-orbit test program encompassed both the typical "launch + 30 days" checkout period in December 2001 and periodic (and ongoing) in-flight test sequences where both GNS 1 and GNS 2 were operated. The initial evaluations included assessments of all GNS data products, e.g., reasonableness checks, self-consistency checks within each GNS, and comparison checks between GNS 1 and GNS 2. After basic operation was verified, detailed performance assessments were carried out. The accuracy of GNS position and velocity was evaluated by comparison with orbit trajectories derived from C-band radar skin tracking and Doppler measurements using TDRSS assets. All tests to date indicate that both GNS systems have functioned flawlessly and all navigation products surpass mission accuracy requirements. A description of these performance assessment activities and summaries of navigation performance follow.

Initial Post-Launch Assessment

Although it was desirable to attempt GPS acquisition and navigation immediately after the fairing was jettisoned ($\approx t$ = 4 min, 41 s), this was not possible owing to the configuration of the two spacecraft (TIMED and Jason), the dual payload attachment fitting (DPAF), and the second-stage rocket. Until Jason spacecraft separation ($\approx t$ = 55 min, 20 s) and DPAF separation ($\approx t$ = 59 min, 40 s), both of which occurred at an altitude of 1300 km, the GNS antennas were enclosed and not able to receive broadcast GPS signals. Soon after DPAF separation (when GNS operations became possible), the second-stage rocket motor maneuvered to enter the final TIMED circular orbit of 625 km. Final separation from the second stage was achieved at t = 125 min, 0 s.

GNS operations and our initial performance assessment during this critical period are described below.

To enable the onboard utilization of GNS data products as soon as possible while allowing a careful assessment of performance, the two GNS systems were placed in different modes before launch: GNS 1 in a separation sequence mode, and GNS 2 in a normal GPS navigation mode. The state diagram illustrating the modes and transitions is shown in Fig. 6.

By design, the separation sequence mode also enabled GPS-aided acquisition capabilities and consequently all of the GNS 1 tracking channels quickly locked onto the available signals within seconds after the DPAF was ejected at 1300 km. The system stayed in the separation sequence mode during orbit re-phasing until notification by the C&DH of TIMED separation from the second stage at an altitude of 625 km. It then transitioned to the non-GPS navigation mode, started propagating a separation state vector (stored prior to launch), and began the output of all standard GNS navigation products—without making use of GPS measurement data. This approach provided the spacecraft with valid, but relatively inaccurate, navigation products as soon as possible and prior to verification that successful on-orbit GPS tracking and GPS-based navigation had occurred.

In contrast, GNS 2 was placed in a GPS navigation mode and constrained to use the sky-search GPS acquisition algorithms to enable on-orbit testing of a GNS in an autonomous configuration from a quasi–cold-start condition. (While the system was powered before launch, no *a priori* knowledge of the GPS almanac, the TIMED state vector, or time was allowed to be exploited.) When DPAF separation occurred, and despite attitude maneuvering that often pointed the GNS antennas away from the GPS constellation, the tracking channels quickly began locking on to GPS signals, and precision time set occurred within 8 min. The measured TTFF was less than 12 min, fully consistent with analytical predictions and measurements made before launch using the GPS simulator.

After careful analysis of telemetry data by the GNS team, a command to place the GNS 1 into GPS navigation mode was sent roughly 7 h after launch. Precision time set occurred almost immediately, since GPS satellite signals were already in track prior to the transition to GPS navigation mode. Within 6 min, the time validity flag transitioned to the time VALID state. The position and velocity validity flags transitioned to the VALID states within 25 and 54 min, respectively. These flags, generated by the KF, indicate that the position and velocity parameters meet their respective accuracy requirements. (The KF-estimated velocity certainly met requirements prior to 54 min, but the covariance simulation in the KF assumed that selective availability was still on, and was therefore quite conservative.) Comparisons were then made between GNS 1 and GNS 2 tracking, navigation, and housekeeping data products, all with favorable results. It was determined that throughout this critical initial post-launch period, both GNS systems were operating flawlessly.

Navigational Accuracy Assessment

The GNS navigation accuracy requirement is 300 m (3 sigma) for position and 25 cm/s (3 sigma) for velocity. Pre-launch covariance simulations indicated that the actual GNS performance would be substantially better than required. This has been borne out by post-launch analysis. These analyses have included an evaluation of telemetered self-consistency checks, comparisons with radar skin tracking data, and comparisons with traditional ground-based orbit determination solutions derived from tracking the TIMED RF signals via NASA's TDRSS assets. To detect any degradation of performance over time, the GNS evaluations have been spread over the life of the mission as shown in Fig. 7.

The quality of GNS navigation results was first verified from telemetered GNS KF data alone. These include figures of merit (FOMs) for position, velocity, and time and range residuals. The values are captured at 3-min intervals and are used to examine the internal consistency of the GNS solution. The FOMs logarithmically encode the standard deviation of the

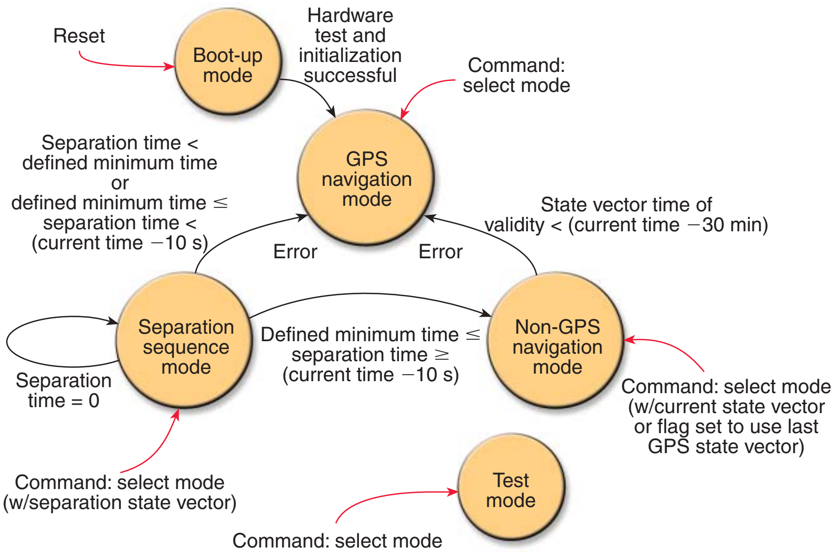

Figure 6. GNS mode state transitions. Black and red arrows denote algorithm-based and command-based transitions, respectively.

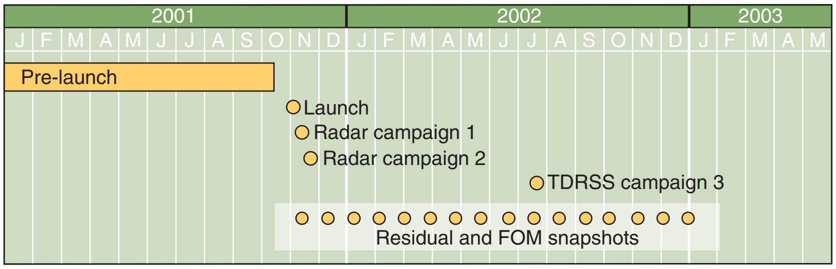

Figure 7. Timeline of GNS performance assessment activities (FOM = figure of merit, TDRSS = Tracking and Data Relay Satellite System).

navigation errors predicted by the KF covariance simulation. They thus represent the KF estimate of navigation accuracy, but do not directly depend on the GNS tracking data. They are primarily a function of the number of GPS satellites in track and their line-of-sight geometry, and the time since initialization (or re-initialization) of the KF. The position FOM is generally less than 20 m and the velocity FOM is less than 2 cm/s.

Another self-checking method is to evaluate range residuals, which are the difference between KF-generated range predictions and actual range measurements. The long-term behavior of the KF residuals is continually monitored. As can be seen in Fig. 8, the residuals are small relative to the position error requirement, and there have been minor fluctuations in the root-mean-square (RMS) KF residuals since launch that seem to have a periodic behavior. An effort to correlate these minor fluctuations to other known factors (e.g., solar activity, polar wander, spacecraft attitude maneuvers, etc.) is ongoing.

Radar Skin Track and TDRSS Comparison Analysis

The performance of the TIMED GNS receiver was also verified by comparison with trajectories generated by the Goddard Space Flight Center's Flight Dynamics Facility (FDF) based on radar skin track and TDRSS data. In both tests, external tracking systems tracked the TIMED spacecraft for 48 h and the resultant data were used to compute an orbit. The track data used in the radar skin track tests were from the network of NASA C-band tracking radars. The TDRSS trajectories are generally more accurate than the radar skin track trajectories owing to the more complete coverage of the space-based TDRSS system. A summary of the results of these comparisons, which took place in three campaigns, is shown in Table 2. In addition to the position and velocity comparison, the telemetered GNS-generated event flags were compared with event flags generated from the interpolated FDF trajectory and were found to be completely nominal.

The GNS acquired rapidly after launch and has been operating without interruption since the full GPS constellation was in view after attitude stabilization. The internal and external consistency analyses all indicate that the GNS is performing far better than required. In addition, there appears to be no degradation in the performance of the TIMED GNS over time.

ONGOING EVOLUTION OF GNS-BASED SYSTEMS

As noted earlier, the GNS was designed to be part of the IEM and to conform to the IEM's PCI interface protocols as well as the Stretch-SEM-E board form factor. Recently, the Space Department has updated the design of its scientific instruments' control electronics to rely on a 4 × 4 in. form factor with a more versatile board interconnect approach. Leveraging the department's NASA-funded Advanced Technology Development Program and a single M-V processor board developed for the CONTOUR and MESSENGER programs, the GNS has been transformed into a lighter, smaller, lower-power, single-processor navigation system called the GNS-II. This configuration allows the GNS-II to be used as a stand-alone system on a host of space platforms and, more importantly, to be augmented to satisfy other mission requirements. An example of this type of augmentation is the cross-link transceiver (CLT). Furthermore, versions of the GNS-II and CLT are in preliminary development that would rely on weak-signal tracking techniques and support the navigation of spacecraft in highly elliptical orbits that venture far outside the GPS constellation. The GNS-II and the CLT are briefly described below.

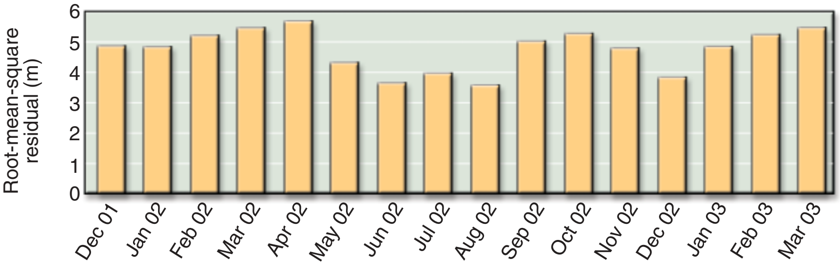

Figure 8. Once-per-month snapshot of Kalman filter range residuals showing that the residuals are periodic over time and are small relative to position error requirements of 20 m.

GPS Navigation System-II (GNS-II)

As described earlier, the GNS employs a dual-processor system largely as a risk mitigation approach, since hardware and software development

Table 2. RMS trajectory differences.

Campaign (date)	Primary FDF[a] data	GNS side	Position difference (m) RMS/max.	Velocity difference (cm/s) RMS/max.
1 (13–14 Dec 2001)	Radar skin track	1	52/105	5.5/11.2
		2	52/104	5.5/11.1
2 (26–27 Dec 2001)	Radar skin track	1	25/46	2.5/4.2
		2	26/45	2.6/4.1
3 (26–28 Sep 2002)	TDRSS	1	20/51	2.0/5.0
		2	20/50	2.0/4.8

[a]FDF = Flight Dynamics Facility, Goddard Space Flight Center.

was under way for more than a year prior to the availability of the processor and there was significant uncertainty about expected performance. One of the key steps in reducing mass, size, power, and cost of the GNS-II was to transition from the dual-processor design of the TIMED GNS to a single-processor design. In its simplest form, the GNS-II consists of two 4 × 4 in. stacking cards as shown in Fig. 9; one card houses a single M-V processor subsystem, and the other houses the GPS receiver and tracking circuitry, including the RF and digital components described previously. If a host spacecraft supplies regulated DC power, this small two-board set implements the functionality of a full spaceborne GPS receiver which is radiation hardened up to 300 krad (Si). A third board, a DC/DC converter, is needed if supplied power is an unregulated bus voltage. The processor memory and the converter might set radiation limits below 300 krad (Si), depending on mission and cost requirements.

Comparisons of the GNS and GNS-II (Table 3) quantify the improvements in mass, volume, power, and interfaces for the GNS-II. Important features include a standard asynchronous serial interface for stand-alone operation (i.e., without an IEM) and software control over processor clock frequency for power reduction. The flexibility inherent in the GNS-II architecture will permit the support of future signal structures anticipated as part of the GPS modernization program, including C/A code on L2 (1227.6 MHz), the L5 (1176.45 MHz) civilian signal, and precise P(Y)-code and M-code tracking on both L1 and L2 signals.

Cross-Link Transceiver (CLT)

The CLT takes the GNS-II architecture and augments it with cross-link communication and ranging modules, resulting in an integrated navigation and communication system that is suitable for multiple formation-flying spacecraft.

The CLT implements the fundamental functions required to enable distributed spacecraft systems, including absolute and relative navigation, interspacecraft communications, and autonomous event detection for distributed command and control. The CLT is a scalable concept that can be augmented to provide integrated support of additional functionality (e.g., uplink/downlink capability, bistatic remote sensing using reflected GPS processing for sea-state assessment, etc.). The CLT is focused primarily on the distribution of information for command and control of multiple assets engaged in coordinated operations.[9,10] Thus, the CLT supports multiple communications architectures including TDMA (time

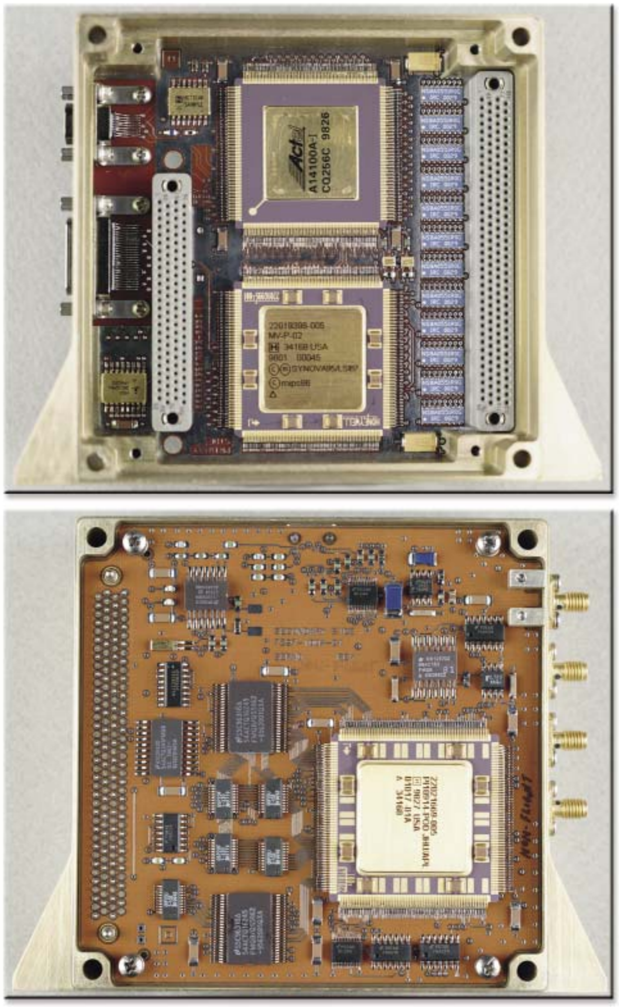

Figure 9. One form of the next-generation GNS (GNS-II) consisting of two 4 × 4 in. stacking cards.

Table 3. TIMED GNS and GNS-II comparison showing improvements realized.

	TIMED GNS	Evolved GNS-II
Form factor	2-card set, 6 × 9 in.	2-card set, 4 × 4 in.
Processor(s)	2 Mongoose-Vs	1 Mongoose-V
Weight	1.10 kg	0.45 kg
Power	7 W	5 W
Interface	PCI I/O	Serial I/O

division multiple access) and FDMA/CDMA (hybrid frequency division multiple access/code division multiple access) and is designed to provide dynamically adaptive communications connectivity.

A version of the CLT called the NanoSat Crosslink Transceiver (NCLT) was recently developed for NASA for the University NanoSatellite Program (Fig. 10). APL fabricated, tested, and delivered to the Goddard Space Flight Center three CLT flight units that will provide integrated GPS navigation and cross-link communication among microsatellites in a NASA/DoD formation-flying technology demonstration mission. The CLT units provide the core functionality of the GNS in a modular, miniaturized format that is augmented for integrated communication and relative navigation. The laboratory testing of the CLT units prior to delivery demonstrated a ranging precision of better than 1 m.

SUMMARY

With event-based commanding—made possible by the APL-developed GNS—TIMED has successfully demonstrated a new way of operating future scientific and commercial spacecraft. The GNS is a proven navigation solution for low- and medium-Earth-orbiting missions. The Laboratory is continuing to evolve space-based GPS navigation by further miniaturization and lower power consumption, and by incorporation of additional features such as interspacecraft ranging and communications.

Figure 10. Three NanoSat Cross-Link Transceiver (NCLT) systems as delivered to Goddard Space Flight Center in 2003 that will provide modular, integrated GPS navigation and cross-link communication among a formation of satellites.

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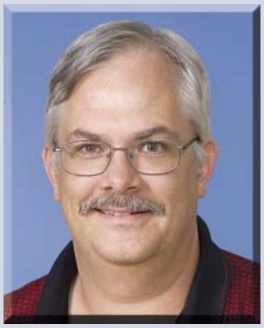

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