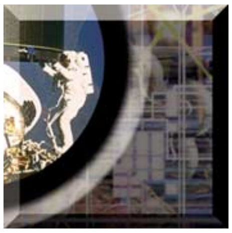

Autonomous Navigation and Crosslink Communication Systems for Space Applications

Albert A. Chacos, Patrick A. Stadter, and William S. Devereux

The need to reduce overall spacecraft program costs while meeting aggressive mission objectives gives significant impetus to the space industry to develop smaller, lighter, and more power-efficient spacecraft and spacecraft subsystems. APL can provide critical navigation and communications capabilities that meet the needs of the space industry. By leveraging GPS Navigation System (GNS) technology developed for the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics Program, as well as NASA Advanced Technology Development and grant programs, systems are under development that address the requirements of broad classes of space missions. The derived designs provide fundamental navigation and communications support for space systems in a small, low-mass, and reduced-power implementation that meets the stringent requirements of numerous mission classes.

INTRODUCTION

The business environment in the U.S. space program has changed substantially in recent years. It is anticipated that space systems and technology investments by private industry will soon surpass the space investments of NASA and the DoD. Furthermore, with the growing trend in both government and industry toward low-cost satellites and missions, lower-cost, highly integrated flight systems will be required. Modern navigation and communication systems can help space system developers and operators achieve lower total life-cycle costs while meeting aggressive operational and scientific objectives.

APL has been an innovator in the science and engineering of space-based navigation systems since the early days of the space program. These efforts included initial Doppler tracking and navigation solutions of Sputnik and the invention, design, development, deployment, and initial operation of Transit, the world's first space-based navigation system for the DoD. The DoD's Global Positioning System (GPS), a constellation of orbiting spacecraft and their attendant control system, ushered in a new era for both terrestrial and spaceborne navigation solutions. The Laboratory and the Navy quickly capitalized on the availability of GPS and became the first committed developers and users of the GPS-based system with SATRACK,[1] a system for the generation of "best estimated trajectories" of submarine-launched ballistic missiles under test and evaluation. APL then led the development of GPSPAC,[2] the first spaceborne GPS receiver.

More recently, as part of NASA's Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) Program,[3] the APL Space Department has developed the spaceborne GPS Navigation System (GNS). GNS technology has served as the baseline capability for several new systems that will have direct applicability to NASA, DoD, and commercial space programs. These systems, developed under NASA-funded Advanced Technology Development (ATD) programs and grants, include a smaller, lighter, lower-power GNS dubbed the GNS-II, and the Crosslink Transceiver (CLT), a complete spaceborne autonomous navigation system augmented with multispacecraft crosslink communication and ranging capability. The TIMED GNS, the evolution to the GNS-II, and the design, applications, and initial embodiment of the CLT are described in this article.

NASA, DoD, and commercial space programs are all striving for reduced life-cycle costs and higher returns on investments. This can be achieved by reducing costs associated with flight hardware, launch, and mission operations. Any system that contributes to reducing these costs brings value to space programs. As flight hardware becomes more highly integrated and as device technology improves, lower-power electronics provide more functionality and better performance relative to legacy systems. This typically lowers overall power requirements, permitting the spacecraft power system to be smaller, lighter, and lower in cost. Significant potential savings can thereby be realized through reduced launch costs if physically smaller subsystems facilitate the use of correspondingly smaller, cheaper launch vehicles. Furthermore, as flight systems become more autonomous, the use of ground-based tracking facilities can be reduced or eliminated, and staffing requirements for mission operations teams can be minimized. Low-cost, low-power, and highly capable spaceborne navigation and communication systems contribute to reduced life-cycle costs for space-based enterprises.

TIMED GNS

APL developed the GNS as a vital component of the TIMED spacecraft, which the Laboratory designed for the NASA Solar Terrestrial Probes Program. The GNS is TIMED's spaceborne navigation and timekeeping system. It is designed to autonomously provide position, velocity, time, Sun vector, and defined orbital event notifications (e.g., terminator crossings and encounters with the South Atlantic Anomaly [SAA] region) in real time. (The Sun vector is a GNS output data product providing a vector from the center of the Earth to the center of the Sun at the time of navigation fix. It is used by the attitude system in generating a spacecraft-to-Sun vector.) In addition, the GNS generates tables of position-based event predictions, up to 60 h in advance, and provides tables of orbital element sets for each predicted ground station contact, again for up to 60 h in advance, for use by the ground system in pointing the dish antenna toward the TIMED spacecraft.

The TIMED GNS incorporates commercial-off-the-shelf and custom hardware and software components. It is space qualified, radiation tolerant, and optimized for low and medium Earth orbit applications. Drawing on APL's 28 years of GPS systems development expertise, the GNS provides a state-of-the-art space-based system featuring superior performance over terrestrial designs adapted for space applications.

The GNS accesses the GPS civilian ranging or coarse/acquisition (C/A) code which modulates the L1 (1575.42 MHz) signal. The system has extensive command and telemetry capability, providing access to raw and intermediate data products as well as on-orbit software reprogramming capabilities. It accommodates the large GPS signal dynamic range resulting from orbital velocities of approximately 7000 m/s and implements robust signal acquisition, navigation, and orbit determination algorithms. A more complete description of the system as developed for TIMED can be found in Ref. 4.

The GNS (Fig. 1) consists of a zenith-oriented antenna, a preamplifier, and radio-frequency (RF) downconverter; the APL-designed low-power, radiation-hardened, high-speed ASIC called the GPS Tracking ASIC (GTA); and a dual-processor–based computer system. Noteworthy is the GTA, which implements all the GPS-specific digital hardware functions, including 12 independent tracking channels, timing and control functions, and built-in test. The device accepts up to 4 downconverted inputs, each independently multiplexed to any of the 12 tracking channels. It was designed to permit multiple devices to be daisy-chained in a master/slave configuration to yield a receiver with up to 72 parallel tracking channels. The GTA was developed using VHDL (VHSIC Hardware Description Language), prototyped using field-programmable gate arrays and implemented in one pass using a Honeywell 2300 series CMOS gate array. It is radiation hardened to 1 Mrad (Si) and latch-up immune, has low single event upset rates, operates from –55° to +125°C, and dissipates only 150 mW of power.

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 selected 32-bit processor, the Mongoose-V (M-V), was available from the vendor. Therefore, two M-V radiation-hardened devices—the tracking processor (TP) and the navigation processor (NP)—were incorporated to reduce risk. Both operate at 12 MHz from 5-V supplies and communicate via a dual-port random-access memory. The major TP software tasks are as follows:

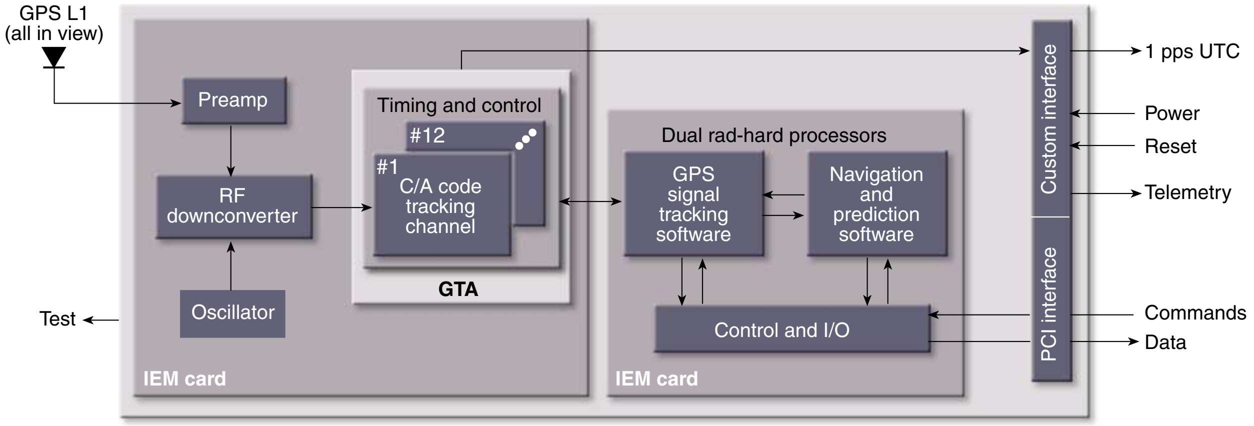

Figure 1. TIMED GNS simplified block diagram (IEM = integrated electronics module).

- Accept and apply acquisition aids (PRN code, Doppler search range)
- Execute sky-search algorithm in absence of aids
- Control GTA hardware functions
- Acquire and track up to 12 GPS space vehicles simultaneously
- Generate validated GPS message subframes
- Determine space vehicle transmit time for latched data
- Provide tracking and command capability

The TP provides GPS signal acquisition, tracking, and data processing functions and outputs code transmit time, carrier phase, and message data for each satellite tracked. (Code transmit time is processed into pseudorange by the NP.) An optimized "lost in space" or "sky search" signal acquisition algorithm was designed and implemented to minimize the cold-start time-to-first-fix and on-orbit signal acquisition problems.

The major NP software tasks are as follows:

- Provide subsystem command and telemetry capability
- Complete pseudorange calculations using transmit times provided by the TP
- Build and periodically update the GPS message and almanac tables
- Execute a Kalman filter crank to provide a TIMED state vector every 30 s
- Generate acquisition aids every 180 s (with Doppler rate information for interpolation by the TP)
- Generate control for steering the 1 pps signal to align with UTC epochs
- Generate and output short- and long-term propagation data products

These NP tasks include command, control, and telemetry processing and the execution of navigation and orbit determination algorithms, including an extended Kalman filter (EKF) and two types of orbit propagators. The NP autonomously generates highly accurate estimates of the spacecraft's position, velocity, and time, which will allow TIMED's event-based commanding mission operations to support reduced program life-cycle costs by minimizing ground personnel required to plan and execute the mission. In addition, position-based events will be detected in real time (for instrument use) and predicted for days in advance (for mission operations team use).

The core of the NP software is the Kalman filter task, which consists of two main parts: the EKF and the short-term propagation (STP) task. The Kalman filter updates the state vector and covariance on 30-s intervals; the STP generates all of the data products, which are output at 1-s intervals. The STP data products are

- Inertial position and velocity
- Earth-centered, Earth-fixed position (lat./long./height) and velocity (east/north/up)
- Time
- Earth-to-Sun vector
- Day/night (terminator crossing) event notification flag
- SAA region event notification flag
- Polar region event notification flag
- Ground station (primary and backup) event notification flags
- Data validity flags

Approximately every 12 h, a long-term propagator (LTP) task is executed so as to predict the primary and backup ground station contacts and the SAA 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 at solar max. 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

Center use the LTP data products on the ground (LTP data products are not used onboard).

Figure 2 shows the TIMED spacecraft optical bench with its two GPS antennas. The antennas are mounted on the bench to accommodate a planned (two-dimensional) attitude determination experiment. With the antennas on the bench, structural deflections are minimized, thereby providing optimal correlation between the star tracker–derived attitude reference and the GPS-derived data.

The testing of spaceborne GNSs is clearly important, but complex to implement. APL has a GPS simulation laboratory to perform this crucial job. The laboratory is equipped for extensive testing using GPS constellation simulators and an engineering-model GNS. The TIMED GNS was subjected to numerous extended tests during 1999 and 2000 at the subsystem and spacecraft levels. Multiple 8-day-long tests were performed on the TIMED GNS software builds to verify proper operation of the system.

ONGOING EVOLUTION OF GNS-BASED SYSTEMS

The GNS was designed to be part of the integrated electronics module (IEM; see the article by Lew et al., this issue) for the TIMED spacecraft (Fig. 3) 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 embarked on a modified configuration of its avionics suite that relies on a 4 × 4 in. form factor with a more versatile board interconnect approach. Leveraging the department's NASA-funded ATD 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, most importantly, to be augmented to satisfy other mission requirements.

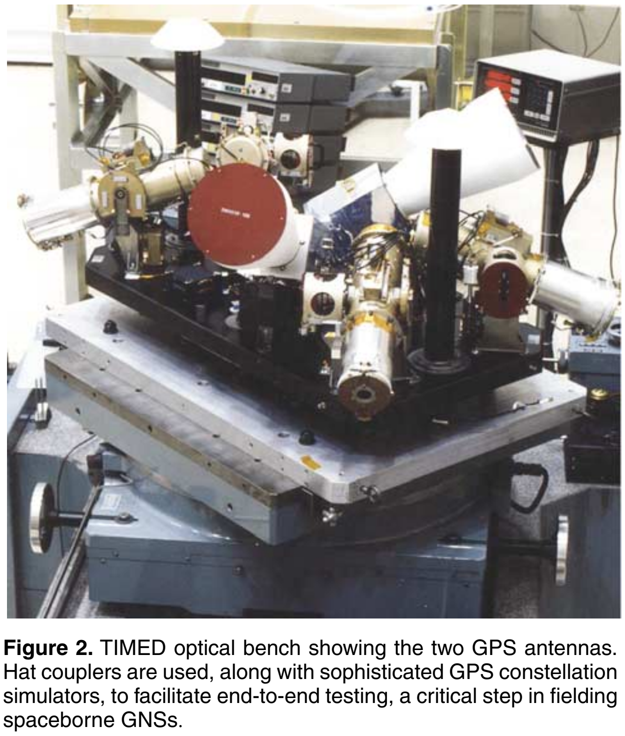

Figure 2. TIMED optical bench showing the two GPS antennas. Hat couplers are used, along with sophisticated GPS constellation simulators, to facilitate end-to-end testing, a critical step in fielding spaceborne GNSs.

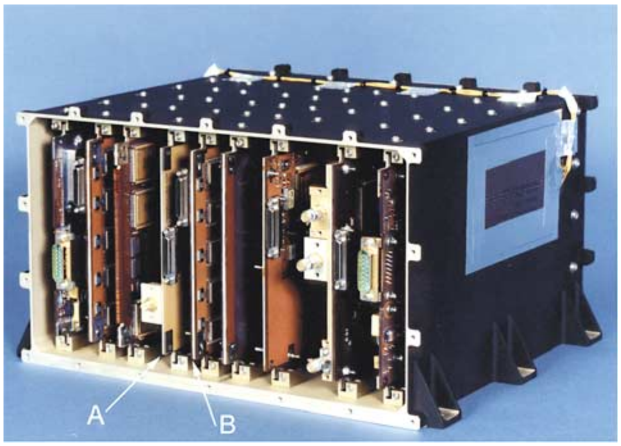

Figure 3. TIMED IEM showing the GNS receiver card (A) and processor card (B).

GPS Navigation System-II

In its simplest form, the GNS-II consists of two 4 × 4 in. stacking cards. One of the key steps in reducing mass, size, power, and cost was to transition from the dual-processor design of the TIMED GNS (Fig. 1) to a single-processor design. The TIMED GNS used a dual-processor system largely as a risk mitigation approach, since hardware and software development was under way for more than a year prior to the availability of the processor, and there was significant uncertainty about expected performance. In the GNS-II, 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 krads (Si). A third board is needed if supplied power is an unregulated 28 V. The processor memory and the DC/DC converter would possibly set radiation limits below 300 krads (Si), depending on mission and cost requirements.

The GNS-II architecture is a configurable system that can be implemented to satisfy many different mission requirements. Comparisons to the TIMED GNS quantify the improvements in mass, volume, power, features, and expandability. Particular features include a standard asynchronous serial interface and software control over processor clock frequency for power reduction. The GNS-II architecture will support 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.

Crosslink Transceiver

The CLT takes the simplified GNS-II architecture and augments it with a crosslink communication and ranging module. This integrated navigation and communication system is suitable for multiple distributed formation flying spacecraft. The navigation performance characteristics of the CLT are the same as those of the GNS, yet the volume, mass, and power requirements have been substantially reduced while considerable functionality has been added.

As such, the CLT is a technology that directly supports the integrated development and implementation of 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 such as uplink/downlink capability and bistatic remote sensing using reflected GPS processing for sea-state assessment and other applications.

The CLT is focused primarily on the distribution of information for command and control of multiple assets engaged in coordinated operations.[5] Thus, the CLT supports multiple communications architectures and is designed to provide dynamically adaptive communications connectivity. Specifically, using a hybrid frequency division multiple access/code division multiple access (FDMA/CDMA) approach, the deployment of CLT subsystems in multiple assets can support connectivity and ranging among spacecraft clusters in a scalable manner.[6]

To enable information exchange and asset control, the CLT disseminates directives for vehicle coordination and provides ancillary data exchange needed to support intelligent control strategies. The nature of the crosslink data is not limited to high-level control directives; indeed, lower-level control approaches (e.g., decentralized control methodologies that rely on state vector sharing) are also supported.

A critical aspect of the CLT communications approach is that it is explicitly designed to support formation flying missions, which require capabilities such as dynamic adaptivity, scalability, and robustness. As such, the CLT is designed to simultaneously receive data from multiple spacecraft, and the signal structure is such that it will support a variety of logical command and control architectures (e.g., centralized, hierarchical, fully distributed) by providing a flexible communications infrastructure.

The CLT provides both an absolute and relative navigation solution (position and velocity), precision time recovery, and a steered 1 pps output. Orbit determination is provided by reception of GPS signals and processing by an EKF. In addition, crosslink signals support relative navigation, with the potential for both direct solutions as well as relative GPS solutions that rely on the computation of double differences of GPS data in a pair-wise manner among spacecraft.

Ranging, using crosslink pseudorandom noise codes, can supplement the GPS measurements in the relative navigation solution to enable more rapid convergence of the solution for low Earth orbit missions. Crosslink ranging data can entirely replace GPS measurements for highly elliptical or deep space missions. In this case, the relative clock error and range can be solved on a per-link basis. The range estimates and information dissemination establish the relative geometry of the constellation, subject to an indeterminate rigid-body rotation.[7] Although the determination of attitude information is not currently a primary focus of CLT development, the baseline design concept supports the incorporation of multiple antennas and the processing software needed for the solution of the attitude problem.

A near-term low-power version of the CLT, the NanoSat CLT (NCLT),[8] is under development (see the boxed insert for capabilities). The NCLT will provide an integrated navigation and crosslink communication system for physically limited spacecraft such as those being developed for several near-term technology demonstration missions. These missions include the DoD/NASA University Nanasatellite Program, NASA Space Technology-5 (ST-5), and AFRL TechSat-21 Program. The NCLT is a multicard, stand-alone system that is built on the nominally 4 × 4 in. form factor with a low-power implementation focus designed to meet mission requirements. The system implements three fundamental functions (onboard processing, GPS receiver, and crosslink communications). It, like the CLT and GNS-II, uses expensive flight-qualified processors; therefore, significant cost and power savings are achieved by implementing the full functionality of the GNS on a single processor. This approach is particularly attractive to commercial users and manufacturers owing to the corresponding reduction in parts count and the potential for further cost reductions through production streamlining.

The NCLT GPS receiver card is shown in Fig. 4. Operationally, this system will provide crosslink communication and absolute and relative navigation capabilities to the spacecraft at 1–4 W average power. The NCLT 4 × 4 in. form factor has proven to be very practical to develop (given the funding available) and,

THE NANOSAT CLT

Features

- Fully spacecraft flight-qualified
- APL-designed GTA
  - 4 selectable inputs and 12 tracking channels
  - VHDL-based design
  - >200,000 gates
  - 1 Mrad (Si)
  - Design permits cascading up to 6 GTAs
- Fully autonomous operation from cold start
- Navigation software uses an extended Kalman filter
  - 9 dynamic states
  - Up to 36 satellite states (3 per satellite)
  - Force model uses Jacchia high-altitude density table and EGM96 15 × 15 gravity table
- Steered 1 pps output aligned with UTC 1-s epochs
- Real-time products output once per second
  - Position (CIS in x, y, z)
  - Position (CTS in latitude, longitude, and height)
  - Velocity (CIS in x, y, z)
  - Velocity (CTS in east, north, and up)
  - Time (CCSDS CUC with 0 h, 6 Jan 1980 starting epoch)
  - Earth-to-Sun unit vector (CIS in x, y, z)
- Real-time event notifications output once per second
  - In/out of primary ground station contact region
  - In/out of backup ground station contact region
  - In/out of defined SSA region
  - In/out of defined polar region
  - Day/night at subsatellite point for terminator crossing notification
- Acquisition aids generated once every 180 s
- Extensive command and telemetry capabilities
- Supports on-orbit reprogramming of application software
- Supports commanded uploading of parameter tables
  - Solar flux and mean solar flux
  - Geomagnetic index
  - Polar wander, x and y
  - UT1-GPS
  - GPS almanac
  - Ground station, SAA, and polar region coordinates
  - Acquisition aids table
  - Default sky-search space vehicle list
  - Gravity, drag, and Earth nutation tables
  - State vector (for non-GPS navigation)
  - Numerous configuration parameters

Expected performance

- Position uncertainty less than 20 m (rms)
- Velocity uncertainty less than 2 cm/s (rms)
- Time uncertainty less than 200 ns (rms)
- Mean time to first fix less than 14 min
  (Uncertainties are based on system testing with a Nortel STR2760 GPS simulator and independent verification and validation testing with an IEC Model 2400 GPS simulator)

Note: CCSDS = Consultative Committee for Space Data Standards, CIS = Conventional Inertial System, CTS = Conventional Terrestrial System, CUC = CCSDS Unsegmented Time Code, GTA = GPS tracking ASIC, pps = pulse per second, SAA = South Atlantic Anomaly, VHDL = VHSIC Hardware Description Language.

as a near-term implementation of the CLT design, it takes advantage of a reduction in the TIMED 5 × 8 in. GNS boards (visible in Fig. 3).

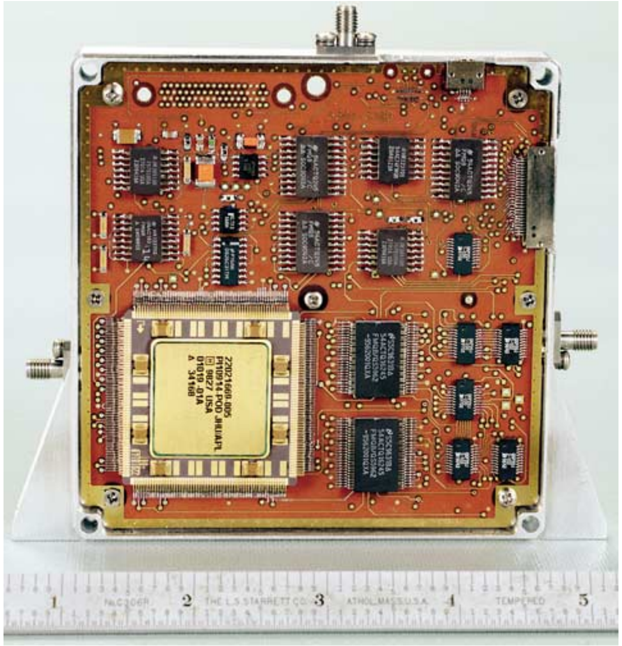

Figure 4. NanoSat CLT miniaturized GPS receiver card.

The NCLT boards are stacked via a backplane connector within a shell, resulting in mass, volume, and power reduction. The NCLT leverages current development at the Laboratory on the CONTOUR and MESSENGER programs. In addition, the miniaturized GPS receiver card used in the NCLT, CLT, and GNS-II systems was developed by leveraging NASA ATD funds before the specific need arose with the DoD/NASA University Nanosatellite Program.

Through the development of this compact design, the generic architecture that encompasses the GNS-II, CLT, and NCLT implementations is a practical example of technology reuse and operational flexibility. For example, by augmenting the GNS-II architecture with the NCLT crosslink capabilities through the addition of the crosslink communications cards, the GNS becomes capable of relative navigation and crosslink communication in addition to absolute GPS-based navigation and orbit determination.

The NCLT can use a single-frequency crosslink, time-division multiplexed technique consisting of consecutive transmissions by each satellite in the constellation. The nominal design, however, uses the FDMA/CDMA concept of the CLT with three frequency channels. Given the short length of the NanoSat Program, there was insufficient time to obtain three frequency assignments for the crosslinks. The flexibility of the NCLT design overcame the frequency allocation process impediments, and the single-frequency time division multiple access (TDMA) design has allowed the development effort to continue. Because of the need to support the TDMA approach for the NCLT, timing and control issues must be addressed by system software.

FORMATION FLYING

The success of many future NASA and DoD operations will require distributed space systems coordinated to act as unified, semi-autonomous systems. This concept, termed *formation flying*, facilitates improved capability and robustness by distributing functionality among multiple space-based platforms. Distributed spacecraft systems have been conceived to enable complex sensing tasks, e.g., coherent distributed aperture processing, co-observation, multipoint observation, and distributed interferometry, that may be beyond the abilities of single spacecraft systems.

Formation flying systems differ from traditional satellite constellations since the fundamental concept involves treating the formation as a coordinated whole, working to achieve common objectives rather than controlling each spacecraft in the constellation individually. Operationally, such systems are in their infancy and many near-term missions are focused on the demonstration of foundational technology. Navigation solutions, both absolute and relative, provide the knowledge for distributed spacecraft systems to correlate and align sensor observations, determine control actions, and support tasking of sensors during system operations. It is the knowledge of spacecraft state that provides the means to process gathered data and to control system operations.

These technology demonstration missions include ST-5, the NASA Nanosatellite Constellation Trailblazer mission. ST-5 is the fourth deep space mission in NASA's New Millennium Program. ST-5 will fly several advanced technologies for power systems, small satellites, and formation flying on three mini spacecraft of approximately 17 in. across × 8 in. high, and weighing about 47 lb. The ST-5 mission is a precursor to missions such as the Magnetospheric Constellation within NASA's Sun–Earth Connection Program.

The specific advantages generally attributed to the use of distributed spacecraft systems for complex sensing operations include increased capability, gradual performance degradation, improved system robustness, and cost-efficiency. Relative to single spacecraft systems, formation flying systems provide improved capability by facilitating the spatial disbursement of sensors, thereby supporting extended and adaptive baselines for distributed sensing tasks. This systematic approach also supports temporal sampling at variable resolutions.

Because capability is distributed among multiple assets, redeploying functioning assets can mitigate failures that impact individual spacecraft. Thus while performance in terms of resolution or coverage of a target area may be reduced owing to diminished assets, basic functionality is retained. Compensating for failures in this manner allows distributed spacecraft systems to realize an improved level of robustness beyond that of a single spacecraft approach. Finally, the goal of cost-efficiency inherent in the concept of formation flying systems is embodied in the fact that such systems rely on the collective faculties of multiple, individually limited assets. This often necessitates the use of small, economical spacecraft that can be deployed in clusters to reduce launch costs.

Realizing the advantages of distributed spacecraft systems requires system operations, coordination, and science that use the capabilities of individual assets collectively. This necessitates functionality in navigation, communications, and control to both enable and leverage complex interactions among spacecraft and between spacecraft and the environment. Addressing these functions in an integrated, unified manner provides a structured approach to distributed spacecraft system design and implementation. In addition, the complexity of distributed space systems requires the ability to effectively model and simulate the interactions among deployed assets in a realistic manner. This capability is embodied in the APL Distributed Spacecraft Modeling and Simulation Testbed that was developed to model formation flying systems as a means to assess and refine developed navigation and communication technologies.[9]

FUTURE PLANS

APL's GNS-based systems use state-of-the-art designs and processes and build on over 25 years of GPS technology development experience, including the TIMED Program's GNS, the APL-patented GPS-Linked Transponder (GLT),[10] and GPS translator and transdigitizer technology developed for DoD missile applications. The CLT will develop the key sensor and telecommunications technologies needed to enable absolute and relative navigation and network communications among formation flying spacecraft. In addition, the Laboratory's development efforts support the technology needed to conduct other spacecraft applications such as autonomous navigation (see the article by Guo, this issue) and attitude determination. Development of technologies that enable distributed spacecraft systems will help realize uncompromising science and technology goals beyond the capabilities of conventional space systems.

CONCLUSION

The use of spaceborne autonomous GPS navigation systems will lower mission and operations costs by greatly increasing the level of spacecraft autonomy. The use of spaceborne GPS systems will increase the scientific return of earth science missions by providing on-orbit real-time and ground-based orbit determination. Designs have been developed at APL for integrated GPS positioning, crosslink communications ranging, and relative navigation systems. With the TIMED mission design, GPS systems have been shown to be critical for event-based commanding mission operations. With the decision by the GPS Joint Program Office to embark on a GPS modernization program that will provide two additional civilian frequencies, the importance of spaceborne GPS applications, particularly for the commercial space industry, will continue to grow.

REFERENCES

[1] Duven, D. J., "Performance Experience of and Design Goals for the Satrack I and II Missile Tracking Systems," in *Proc. 1st Int. Symp. on Positioning with GPS* (Apr 1985).

[2] Hoffman, E. J., and Birmingham, W. R., "GPSPAC: A Spaceborne GPS Navigation Set," in *Proc. IEEE Position Location and Navigation Symp*. (1978).

[3] APL TIMED Web site, available at http://www.timed.jhuapl.edu/home.htm (accessed 1 Mar 2001).

[4] Devereux, W. S., Heins, R. J., Chacos, A. A., Linstrom, L. A., Asher, M. S., et al., "The TIMED GPS Navigation System (GNS)," in *Proc. 49th Int. Astronautical Congress*, IAF-98-U.5.02 (1998).

[5] Stadter, P. A., "Discrete Event Command and Control for Formation Flying of Distributed Small Spacecraft Systems," in *Proc. 13th Annual AIAA/USU Conf. on Small Satellites*, SSC99-VI-4 (1999).

[6] Stadter, P. A., Devereux, W. S., Denissen, R. A., Duven, D. J., Asher, M. S., et al., "Interspacraft Communications Architectures for Formation Flying," in *Proc. AIAA Space Technology Conf. and Expo*, AIAA-99-4490 (1999).

[7] Olsen, E. A., Stadter, P. A., and Asher, M. S., "Long-baseline Differential GPS-based Relative Navigation for Spacecraft with Crosslink Ranging Measurements," in *Proc. Inst. of Naviation GPS Meeting 2000* (Sep 2000).

[8] Stadter, P. A., Chacos, A. A., Heins, R. J., Moore, G. T., Olsen, E. A., et al., "Confluence of Navigation, Communications, and Control in Distributed Spacecraft Systems," in *Proc. 2001 IEEE Aerospace Conf.*, Big Sky, MT (Mar 2001).

[9] Stadter, P. A., Kusterer, T. L., DeBolt, R. J., Clark, P. J., Chacos, A. A., et al., "Navigation Validation Using the Distributed Spacecraft Modeling and Simulation Testbed," in *Proc. 2001 IEEE Aerospace Conf.*, Big Sky, MT (Mar 2001).

[10] Devereux, W. S. et al., Patent #5,594,454 (14 Jan 1997).

ACKNOWLEDGMENTS: The CLT is supported by the NASA Technology Development Explorer Missions Program under grant NAG5-8665. The NanoSat CLT is supported by NASA SOMO grants NAG5-8655 and NAG5-9872. The authors acknowledge the generous support of the NASA TIMED Program for its backing of the NCLT development effort.

THE AUTHORS

ALBERT A. CHACOS is a member of APL's Principal Professional Staff and Supervisor of the Navigation Systems and Technologies Section of the Space Department's Space Systems Applications Group. He received a B.S. in aeronautical science from Embry-Riddle Aeronautical University (1974), a B.S.E.E. from the University of Maryland (1981), and an M.S.C.S. from JHU (1994). Since joining the Space Department in 1982, he has led hardware and software development efforts involving ground systems on a variety of programs such as SDIO's Delta 181, BMDO's MSX, and NASA's NEAR mission. He led the software development of the GNS for NASA's TIMED spacecraft and is currently working on a NASA grant to evolve and augment this technology. His e-mail address is al.chacos@jhuapl.edu.

PATRICK A. STADTER is a Senior Professional Staff engineer and Supervisor of the Distributed Spacecraft Systems and Technologies Section in the Space Systems Applications Group. He earned a B.S.E.E from the University of Notre Dame (1991), an M.S.E.E. from JHU (1993), and a Ph.D. from The Pennsylvania State University (1997). Dr. Stadter is the Principal Investigator of the NASA Explorer Missions Program to develop the Crosslink Transceiver for interspacecraft communications and navigation among multiple spacecraft, and the NASA-funded Distributed Spacecraft Modeling and Simulation Testbed. His research includes distributed command and control methods for autonomous underwater vehicles and combat dynamics, space-based target discrimination and identity fusion algorithms, and neuro-fuzzy techniques in pattern recognition. His e-mail address is patrick.stadter@jhuapl.edu.

WILLIAM S. DEVEREUX is a member of APL's Principal Professional Staff and Supervisor of the Space Systems Applications Group in the Space Department. He holds a B.S. in electrical engineering from the University of Maryland and an M.S. in electrical engineering from The Johns Hopkins University. Mr. Devereux joined the Space Department in 1980. He has led the development of a number of GPS-based aircraft, missile, and spaceborne tracking and navigation systems. He also led the development of a space-qualified multifunction GPS transdigitizer/telemetry transmitter system for SDI's Brilliant Pebbles Program, the first full-signal dual-frequency GPS translator system for the Navy that culminated in four highly successful flights on Trident reentry bodies, and the autonomous spaceborne GNS for NASA's TIMED mission. His e-mail address is will.devereux@jhuapl.edu.