THE SSTI LEWIS BETTER, FASTER, AND CHEAPER
GUIDANCE, NAVIGATION, AND CONTROL SUBSYSTEM

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Abstract

The NASA Small Spacecraft Technology Initiative was among the first of the high performance, low cost spacecraft programs. It was NASA's postulate that by leveraging U.S. technology investments and minimizing customer management oversight, significant reductions in cost and schedule could be realized, while advancing the state of the art in spacecraft performance. Use of the latest in sensor, processor, and structures technology enabled the SSTI Lewis Guidance, Navigation and Control Subsystem to significantly improve its pointing capabilities over most lightsat programs. The combination of vastly reduced customer oversight, extensive subsystem heritage from previous programs, and the flexibility to use in-house, high reliability design and testing practices allowed the subsystem to complete under the original budget, and in less than two years. Compared with other high quality lightsats, the SSTI Lewis GNCS has superior performance, was completed in less time, cost less to produce, and is of equal or higher quality.

SSTI Lewis Overview

The NASA Small Spacecraft Technology Initiative is intended to demonstrate new techniques that will speed the development and trim the costs of next-generation spacecraft. The 2-year, low cost endeavor challenges not only the technical but also the schedule and financial aspects of the program.

The TRW-built "Lewis" SSTI lightsat (Figure 1) offers advanced capabilities and will furnish data to a wide range of users. More than 25 new technologies and state-of-the-art components will demonstrate the expanded capabilities needed for planned future missions.

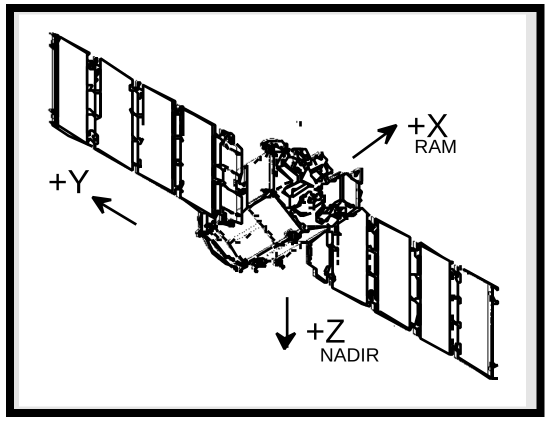

Figure 1. SSTI Lewis Spacecraft

The Lewis spacecraft consists of three main modules: the payload module, housing technology demonstrations, payload sensor electronics and its 4 Gbit mass memory unit (with up to 12 Gbit capacity); the avionics module, containing the core bus components; and the battery and propulsion module, which houses the nickel hydrogen battery and the hydrazine propulsion subsystem. The lightweight, all-composite structure is extremely strong and is highly resistant to thermally-induced deformations.

Lewis will orbit the earth in a 517 km circular, sun-synchronous orbit. Its mission life requirement is one year, with a five year goal. The spacecraft is currently in storage, awaiting a late 1996 launch date, on a Lockheed Martin LMLV-1 booster. Low cost ground operations will be performed by TRW at its Chantilly, Virginia site, with NASA help from an additional ground station in Poker Flat, Alaska, post-processing operations at Stennis Space Center, and Deep Space Network coverage during early orbit operations and in the event of an emergency.

A centerpiece payload sensor is the TRW-built Hyper Spectral Imager, which will view the earth in 384 hyper spectral bands (existing on-orbit capability is 7 bands). This instrument's requirements for fine position and attitude knowledge, attitude stability and jitter drive the need for the high-performance Guidance, Navigation and Control Subsystem (GNCS). NASA's need for lower cost and quicker turnaround drove the GNCS's budget and schedule.

Better GNCS

The Lewis GNCS is comprised of a baseline subsystem, which can meet all main payload objectives, plus technology demonstrations that will gain flight heritage for even more advanced GNCS capabilities on future spacecraft. The GNCS has precise pointing capabilities and full redundancy that make it a superior subsystem to those of other lightsats.

Baseline GNCS

The Lewis baseline GNCS draws from the heritage of the TOMS-EP, STEP, and NEAR spacecraft, and is augmented with the latest processor, navigation, propulsion, and attitude determination technologies to produce a highly capable, state of the art, low cost subsystem.

Figure 2 shows a block diagram of the Lewis baseline GNCS hardware. The TRW standard Coarse Sun Sensor Assemblies (CSSAs), used on TOMS-EP and many other programs, provide 4π steradian view to locate the sun from any attitude. These sensors are mounted on the outboard corners of the solar arrays, and are used for initial sun acquisition and for the sun-pointing Safe Haven mode.

The all-new Narrow Field of View Star Tracker Assembly (NSTA) weighs less than eight pounds with lightshade, tracks up to six stars, and consumes just over six watts. The NSTA can track a magnitude 6.0 star at 0.3 deg/sec with an RMS accuracy of better than eight arc-seconds. Although it is lighter and more accurate than previous trackers, the NSTA contains extensive embedded software and state-of-the-art microelectronics, allowing for fewer parts and a lower unit cost than the older models.

The Three Axis Magnetometer (TAM), flown many times previously, provides information on the earth's magnetic field to calculate magnetic torquer momentum dumping commands.

The Gyro Reference Assemblies (GRAs), which have flown on the TOMS-EP and MSTI spacecraft, are tuned-rotor low-cost two-axis units. Three of the space qualified units are used for full redundancy.

The new Earth Sensor Assemblies (ESAs) are miniature static single axis sensors, employing thermopile detectors. Similar units have flown before, but these units are of higher quality, and will soon be used on at least two of the upcoming lightsat communication constellations. Although only two sensors are needed for a roll/pitch determination, the three single axis sensors provide redundancy and uninterrupted coverage during sun or moon interferences. The entire unit weighs only about two pounds.

The newly developed Tensorä GPS receivers are low cost, space flight qualified versions of the commercial TANS Vector receiver. Among the many improvements, the Tensor is more radiation tolerant than its predecessor[1]. Without additional filtering, these units will produce positional accuracy of better than 150 meters, allowing the HSI sensor to accurately pushbroom through a specific target on the ground. Time updates are also provided every second, accurate to less than one millisecond.

The reaction wheels and magnetic torquers provide the momentum control and dumping for the mission, and are based on the NEAR, TOMS-EP, and STEP programs. The fourth wheel is an on-orbit spare, and the magnetic torquers and magnetometers can be replaced by thrusters for momentum dumping in the event of a failure. Unlike earlier units, these wheels contain a grease/oil lubricant that results in even longer life.

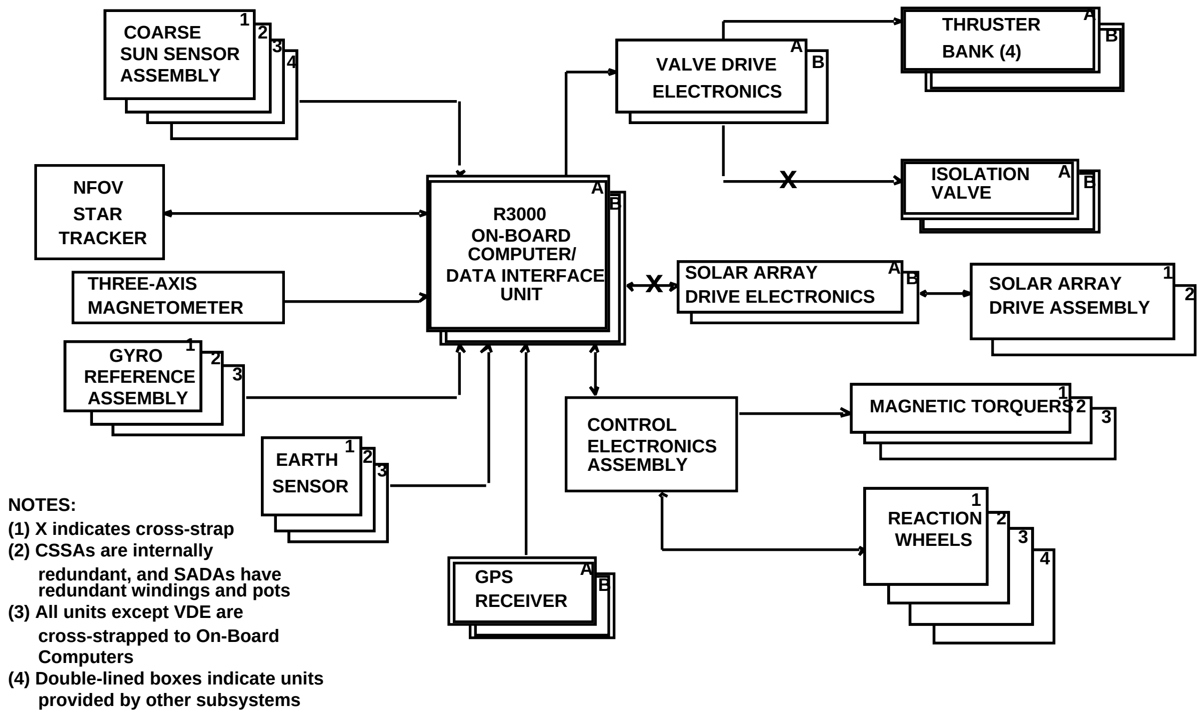

Figure 2. Lewis GNCS Block Diagram

The single axis Solar Array Drive Assemblies (SADAs) include slip rings to transfer power and signals to the vehicle, and redundant windings and potentiometers. The SADAs are driven by new, smaller, hybridized versions of their standard Solar Array Drive Electronics (SADE). The SADAs are used to continuously point the solar arrays at the sun, insuring adequate power with the rest of the vehicle nadir pointed.

The thruster Valve Drive Electronics (VDE), one lbf hydrazine thrusters and latching isovalves are nearly identical to those employed on TOMS-EP and STEP. The propulsion design features the above flight proven, redundant components and an innovative, new technology composite overwrapped (GFRP) tank, which can hold up to 232 pounds of hydrazine. The propulsion subsystem is required to raise the spacecraft from its insertion altitude of 300 km to its final value of 517 km. Additional maneuvers are also required to maintain its operational orbit over the mission life.

The GNCS flight software algorithms and database reside in the TRW On Board Computer, which features an R3000 CPU. The OBC was developed under the Brilliant Pebbles program, with the first flight units built for Lewis. The OBC can operate at speeds of 25 MHz with a throughput of 18 VAX MIPS. It weighs less than 7 pounds and consumes 18 watts at the Lewis speed of 16.4 MHz. Two OBCs are on board for redundancy.

The fully redundant GNCS is operated at zero momentum bias, in a sun-synchronous orbit. The vehicle will operate primarily nadir pointed, but must also orient inertially for HSI sensor calibration, and to point the UCB (Ultraviolet Cosmic Background spectrometer) payload anti-sun during eclipse periods. Solar arrays are articulated in the pitch axis only; the orbit characteristics guarantee that the yaw axis is always maintained to less than 20 degrees from the sun line.

Flight software is coded in two languages, utilizing already developed Ada code from the Brilliant Pebbles and TRW Advanced Bus programs, and existing TOMS-EP C flight code. This method minimized the amount of new code required.

The GNCS flight code consists of 26 major subfunctions, including a six-state Kalman filter for stellar attitude updates and gyro bias estimates, a GPS-based spacecraft and sun ephemeris propagator with HSI payload real-time target update capability, and a full star catalog of well over two thousand stars.

The baseline GNCS's capabilities have been verified through test, analysis and simulation activities. The performance characteristics are listed in Table 1.

Table 1. Lewis GNCS Requirements Vs. Capabilities

Description	Requirement (3σ)	Capability
S/C Position Knowledge	150 meters	138 meters
Attitude Knowledge	10 arc-sec roll 30 arc-sec pitch 50 arc-sec yaw	6 arc-sec roll 23 arc-sec pitch 23 arc-sec yaw
Attitude Control	0.04 deg roll, pitch 0.5 deg yaw	0.02 deg roll, pitch 0.03 deg yaw
Drift Rate Stability	10 arc-sec in one second	4 arc-sec in one second
Off-Point in Roll Axis	22 degrees in either direction	25 degrees in either direction
Point Solar Arrays at Sun	5 degrees in pitch	4 degrees in pitch

The position knowledge is driven primarily by the GPS Selective Availability (SA) degradation, although filtering in the GPS receiver will reduce the error substantially[1].

Attitude knowledge is affected mainly by the star tracker's capability, especially the accuracy about its boresight. Since the spacecraft roll axis was determined to be the most sensitive axis, the star tracker boresight was located such that boresight errors present themselves in pitch and yaw only. Gyro drift and noise errors are of lesser importance, since Kalman filter attitude updates are performed every sixteen seconds. This relatively rapid update rate is possible because of the high-speed R3000 on-board computer.

Attitude control and drift rate stability error sources include reaction wheel quantization (approx. one RPM) and aerodynamic and magnetic disturbance torques. Some of the payloads and bus equipment contain permanent magnets, and therefore interact with the earth's field, especially over the poles. The inherent stiffness and low thermal expansion properties of the composite spacecraft structure also help minimize attitude determination and control errors.

Solar array pointing errors are primarily due to SADA potentiometer errors. More precise pointing of the arrays is possible using more elaborate filtering of the potentiometer data, but for cost purposes, the added flight software code was deemed not necessary.

Minimizing spacecraft jitter was also of primary importance, and a full dynamics analysis was completed to verify performance in the presence of reaction wheel, gyro, and miniature pulse tube cryocooler disturbances. Constrained layer damping tiles were attached to the composite structure at the mounting interface to the HSI payload, to minimize disturbances above 50 Hz, while not degrading the structure's static strength or stiffness[2].

<u>Technology Demonstrations</u>:

In addition to the baseline GNCS, there are a number of GNCS-related technology demonstrations that are also flying on Lewis. These demonstrations hope to prove that even more advanced, low cost missions will be possible in the near future.

<u>Wide Field of View Star Tracker Assembly</u>. The WSTA, a modified NSTA with a 20x20 degree field of view, will be able to track up to six stars simultaneously at instrument magnitudes down to 4.5. This sensor has no external light shade, and will be able to provide nearly continuous three axis attitude updates at rates as high as five Hz. Among the goals of

this experiment are to demonstrate gyroless attitude determination.

Enhanced Attitude Control System Experiment*. The enhanced attitude control system (ACS) experiment is a technology demonstration experiment developed at the NASA Langley Research Center to evaluate advanced attitude control strategies. The purpose of the enhanced ACS experiment is to evaluate the feasibility of designing and implementing robust multi-input/multi-output (MIMO) attitude control strategies for enhanced pointing performance of spacecraft to improve the quality of the measurements of the science instruments. The objectives of the experiment are as follows:

1-To develop a MIMO ACS algorithm and flight software, and implement within the SSTI Lewis flight on-board computer software

2-To develop MIMO attitude control designs, based on robust and modern control theory

3-To conduct attitude control experiments by implementing the MIMO control designs (instead of the baseline normal mode controller) in the normal pointing mode

4-To evaluate the performance of MIMO attitude control designs by analyzing the telemetry data

An efficient algorithm, both in time and memory requirements, for the implementation of MIMO controllers has been developed. Two software implementations of the algorithm, in FORTRAN and C, have been developed and incorporated within the flight on-board computer software. The enhanced attitude control system is implemented as an independent module within the ACS software. MIMO attitude control designs for improved pointing performance have been developed for the SSTI Lewis spacecraft. The typical MIMO controller was an H-2/H-infinity controller designed for fine attitude pointing. Simulations by LaRC and TRW have validated the MIMO algorithm, and demonstrate that the MIMO controllers can improve the pointing performance of the spacecraft. It should be noted that the various MIMO control designs are implemented by simply uploading the controller data sets into the MIMO routine, which also indicates the ease of modifying the controller with MIMO control.

The design of MIMO controllers will continue through the first year of Lewis on-orbit operations, at which time the on-orbit enhanced ACS experiments will commence.

GPS-Based Attitude Determination. The GPS Attitude Determination Flyer (GADFLY) experiment will attempt to completely verify for the first time the accuracy of GPS-based spacecraft attitude determination. Similar experiments have flown previously, but those missions did not feature much more accurate means of determining the spacecraft's attitude. With the Lewis stellar-based attitude determination, a direct measurement of the GPS-based determination will be possible. GADFLY also features more advanced processing and filtering of the GPS data, a more robust receiver that is less susceptible to radiation effects, and precisely mounted antennas to achieve even greater accuracy than before.

Autonomous Orbit Maintenance System (AOMS)**. The Autonomous Orbit Maintenance System (AOMS) software contains two major components: the Kalman Filter (KF) software and the Orbit Control (OC) software. The KF software is re-used from the Microcosm Autonomous Navigation System (MANS) software developed under contract to the United States Air Force for the TAOS (STEP Mission 0) Program. This software has been minimally modified to meet the interface requirements of the SSTI program. The OC software has been developed specifically for the SSTI Lewis program. It is based on algorithms and concepts which have been patented by Microcosm. The software was developed in Ada for operation on the RH3000 processor.

The primary mission of the AOMS software is to provide on-board, autonomous orbit maintenance. For the Lewis program, the AOMS software will provide recommended orbit maintenance maneuvers as part of the down-linked telemetry stream. AOMS will calculate the required Δv needed to establish and/or

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maintain the proper orbit phase, at or near to the ascending node crossings.

AOMS is designed to function by making small, frequent orbit maintenance maneuvers, using short burns of low output thrusters. AOMS will recommend that orbit maintenance maneuvers be performed as often as once per orbit, if required. Over the lifetime of a satellite the total thruster action required to maintain an orbit should be the same regardless of whether the AOMS "many short burns" are used are if the traditional, infrequent but larger burn approach is used. In general, the advantages of the AOMS approach are:

1) Reducing cost by reducing the requirements for ground operations support

2) Allowing the use of smaller, lighter weight, low impulse thrusters, thereby reducing the total mass of the spacecraft.

3) Reducing the risk of operational errors since an error in a small magnitude burn is easier to recover from than a larger duration burn.

4) Provide predictable orbit phasing.

During the contracted operational life of the SSTI spacecraft, AOMS will not actually provide orbit maintenance or command for any control interfaces. However, after the completion of the other SSTI contractual obligations, it may be possible to create a software upload which allows AOMS to actually control the spacecraft.

Faster GNCS

The Lewis baseline GNCS was completed in just under 20 months for a number of reasons. First and foremost, the use of existing designs wherever possible allowed for rapid hardware procurement and software requirements definition. Incorporating a commercial-off-the-shelf philosophy, the subsystem was designed around existing flight hardware and software modules, while adding new technologies to improve its performance. For example, the attitude determination design used existing TOMS-EP gyros and flight software, but also employed the latest star tracker hardware and TRW Advanced Bus software to improve the attitude knowledge by more than a factor of ten.

TRW's stringent, in-house product assurance requirements were levied on the program, in lieu of government standards. This then eliminated the need for costly and time consuming translation analyses to verify performance against the government standards. TRW chose to use Class B parts with no additional screening for the Lewis program, leading to lower cost and faster parts procurements.

The subsystem schedule was further accelerated by reducing oversight without sacrificing quality. Relatively informal internal peer reviews by the Integrated Product Development Team were the heart of the quality assurance process. Visible NASA GNCS oversight was present only at the formal reviews. Deliverable documentation was limited to briefing presentation packages. Five major reviews were held to provide the customer sufficient insight that TRW's internal processes insured a quality, high performance product in a minimum schedule environment.

The subsystem design also contributed to the speed with which it was completed. Even with all of its capabilities, the GNCS only has three major modes, and a total of eight submodes. The advanced architecture and components allowed the GNCS to have these few modes, while still enabling a robust subsystem. This simpler design also meant that fewer modes needed to be tested, so the integration and test process was simplified and the schedule was further reduced.

Testing of the subsystem was streamlined compared with other programs. Although open-loop tests of all modes were performed on the spacecraft, the wheel-based normal pointing mode was not tested closed-loop with hardware because it is a lower risk mode. The normal pointing mode will only be employed once Lewis achieves its final orbital altitude of 517 km, when aerodynamic drag effects will be greatly reduced from those at the 300 km insertion altitude. Any problems encountered at that higher altitude will not require rapid solutions, so ground operators will have ample time to fix unforseen normal pointing mode problems.

Cheaper GNCS

The Lewis GNCS was less expensive than similar lightsat subsystems for many of the reasons listed in the previous section: extensive reuse of existing hardware and software designs, in-house product assurance requirements and few long-lead parts and parts screening requirements, minimal customer management oversight, a relatively simple design, and prudent testing. Shorter schedules generally result in lower costs.

In addition, the very small, dedicated staff of engineers working on Lewis kept the subsystem costs low. While all of the GNCS engineers were not colocated, effective use of telephones, facsimile machines, and electronic mail allowed the subsystem to be designed and tested with few face-to-face meetings. Since this was only a 20 month effort, it was possible for most of the staff to remain with the program from initial design through final testing, allowing the workers to operate at the peak of the "learning curve" with maximum efficiency.

For all the tasks involved in designing and testing this subsystem (hardware acquisition, linear analysis, simulation development, software requirements development, budgets, subsystem engineering, and subsystem integration and test), there were far fewer people directly involved compared with other programs. Nevertheless, all of these tasks were completed in less than 20 months, and the high quality subsystem was delivered for less than the original budgeted value.

Conclusions

Use of advanced sensor, processor, and structural technologies has increased the performance of the Lewis GNCS over most existing lightsats. Reuse of existing designs, minimal customer oversight, and prudent testing has reduced the time required to produce the subsystem. The use of a small, dedicated staff has allowed the Lewis GNCS to become an efficient and highly capable subsystem. The SSTI Lewis Guidance, Navigation and Control Subsystem has met all the desires of a better, faster, and cheaper lightsat program.

Acknowledgements

The author would like to thank Maribeth Roesler and Harry Schmeichel of TRW, and all of the other people who contributed to the success of the Lewis GNCS.

References

1. Fuller, R.A., B. Kemper, and J. J. Rodden, "Spacecraft Guidance and Control with GPS Tensorä ," 19th Annual AAS Guidance, Navigation, and Control Conference, AAS 96-075, February, 1996.

2. Nye, T. W., A. J. Bronowicki, R. A. Manning, S. S. Simonian, "Applications of Robust Damping Treatments to Advanced Spacecraft Structures," 19th Annual AAS Guidance, Navigation, and Control Conference, AAS 96-066, February, 1996.