The SNOE Spacecraft: Integration, Test, Launch, Operation, and On-orbit Performance

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Abstract. The Student Nitric Oxide Explorer (SNOE) was launched on 26 February 1998. Its objectives are to measure nitric oxide density in the lower thermosphere, to analyze the solar and auroral fluxes that create it and cause its variation, and to demonstrate the feasibility of low-cost, University-based missions that include a high degree of student participation.

The SNOE spacecraft and instruments were designed and built at the University of Colorado Laboratory for Atmospheric and Space Physics (CU/LASP). It travels in a 580 × 550 km, sun-synchronous orbit with a 10:30 AM ascending node. It spins at 5 rpm with the spin axis normal to the orbit plane. It carries three instruments: An ultraviolet spectrometer to measure nitric oxide altitude profiles on the limb, a two-channel ultraviolet photometer to measure auroral emissions in the nadir, and a five-channel solar soft X-ray photometer. An experimental GPS receiver is also included for orbit determination.

This paper describes completion of the SNOE project through integration and test, launch site operations at Vandenberg AFB, the early-orbit campaign, and routine mission and science operations. The on-orbit performance of the spacecraft subsystems is assessed, including the passive thermal regulation system as well as the electrical and computer systems. SNOE is in good health and appears to be headed for a long and successful mission.

1. Introduction

The Student Explorer Demonstration Initiative (STEDI) is a program administrated by the Universities Space Research Association (USRA) and funded by NASA. Its goal is to demonstrate that significant experiments can be accomplished with small satellites and constrained budgets. The original design parameters for low-earth-orbit experiments were "300 pounds to 300 nautical miles" for one year in polar or near-polar orbit. A budget limit of $4.3M was applied to the spacecraft, instruments, and all operations exclusive of communications services and the launch vehicle.

The Student Nitric Oxide Explorer (SNOE), was the first of the STEDI missions to launch. It will be followed by TERRIERS (Boston University) and CATSAT (University of New Hampshire). Collaboration with the Ball Aerospace Corporation and with the National Center for Atmospheric Research (NCAR) provided guidance to LASP engineering and management. An additional collaboration with JPL provided a small technology experiment—the microGPS receiver for orbit determination. Students were involved in all aspects of the project. Under the supervision of University and industry mentors, they designed and built the spacecraft and instruments, wrote the flight software, integrated the subsystems, and conducted the test program. Mission operations are now being performed by a mostly student team at the LASP Space Technology Research building on the University of Colorado at Boulder east campus.

2. Scientific Objectives

The SNOE scientific objectives are to understand how solar soft X-rays and auroral energetic particles and heating cause drastic changes in the amount of nitric oxide (NO) in the upper atmosphere.[1] Nitric oxide is an important minor constituent of the lower thermosphere-ionosphere region that directly affects the thermal structure of the thermosphere, the composition of the ionosphere, and may be transported downward into the mesosphere and stratosphere where it can react with ozone.[2] It is known to vary with solar and geomagnetic activity, but significant unanswered questions about nitric oxide concerning the magnitude of that variation and the interplay between its causes remain.

The scientific objectives require the simultaneous measurement of nitric oxide in the lower thermosphere, the solar irradiance in the soft X-ray region of the spectrum, and a measurement of auroral activity. Three instruments were therefore designed: a limb-scanning ultraviolet spectrometer, a solar X-ray photometer, and an auroral photometer. Nitric oxide density is determined by measuring gamma band fluorescent emissions with an ultraviolet spectrometer that measures the (1,0) 215 nm and (0,1) 237 nm bands. Limb measurements are made from 50 to 200 km with altitude resolution of ~3.5 km by using the spinning motion of the satellite. Solar soft X-rays are measured using photometers that have been developed at CU/LASP for rocket experiments and for the Earth Observing System.[3] Thin metallic films directly deposited on silicon photodiodes are used to discriminate between wavelength bands in the 1–30 nm range. The auroral photometer is based on UV photometers that were developed for the Mariner 5 flight to Venus.[4] Two photomultiplier tubes filters detect auroral emissions over the polar regions during night, from which energetic particle fluxes may be inferred.

3. The SNOE Spacecraft

3.1 Mission Design

Analysis of nitric oxide photochemistry requires a sun-synchronous orbit (inclination 97.75°). A 10:30–22:30 local time was chosen as the best compromise between instrument safety (avoidance of the noon-midnight plane) and solar array illumination. These requirements lead to a spinning satellite in low Earth orbit. With the spin axis normal to the orbital plane, the UV spectrometer scans through the limb of the earth in the orbital plane, the auroral photometer scans through the nadir, and the solar photometers scans through the sun. A circular orbit with an altitude of 550 km was chosen (later revised to 580 km; the actual orbit attained was 580 × 550 km) to provide close viewing for limb scans and low enough atmospheric drag for a mission lifetime of at least one year.

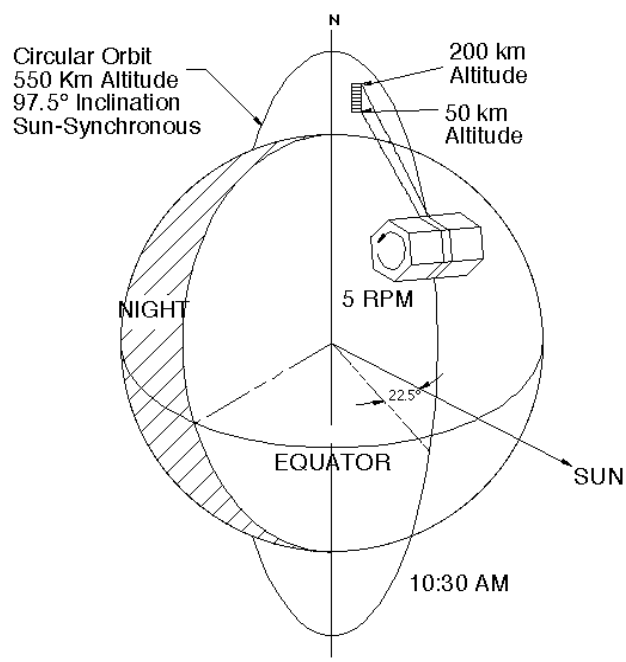

Figure 1. Mission Scenario.

3.2 Spacecraft Overview

The SNOE spacecraft[5] is a hexagonal aluminum structure, 37" high and 39" across at its widest point. Weight is 254 lbs. It is spin-stabilized at 5 rpm about the x-axis, which is oriented normal to the orbital plane.

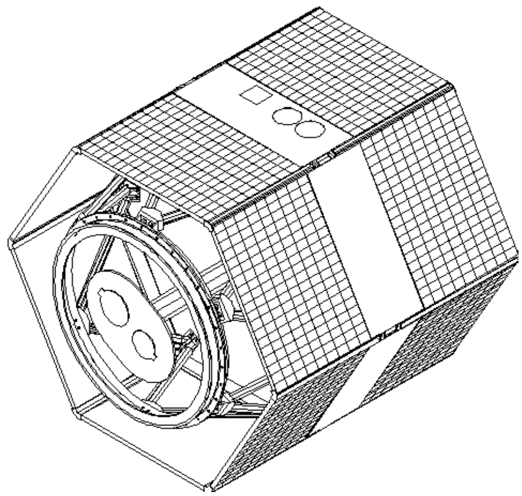

Figure 2. Spacecraft Structural Drawing

The S/C structure consists of a central mounting plate, a launch adapter for the marmon clamp attach fitting, two hexagonal solar arrays, and two antenna masts. The mounting plate supports the scientific instruments, S/C electronics, and equipment. These components attach to both sides of the mounting plate. Two patch antennas protrude slightly above the ends of each solar array. Materials used in the assembly are principally aluminum, with aluminum honeycomb used in the solar panels.

Attached in a band to the periphery of the central support plate, between the solar arrays, are six thermal radiator plates. The radiators have apertures for the instruments. The solar arrays are thermally isolated from the central plate by titanium flexures, so that they may fluctuate in temperature without affecting components mounted on the plate. Multi-layer insulation (MLI) covers both sides of the central plate and the open hexagonal ends of the S/C.

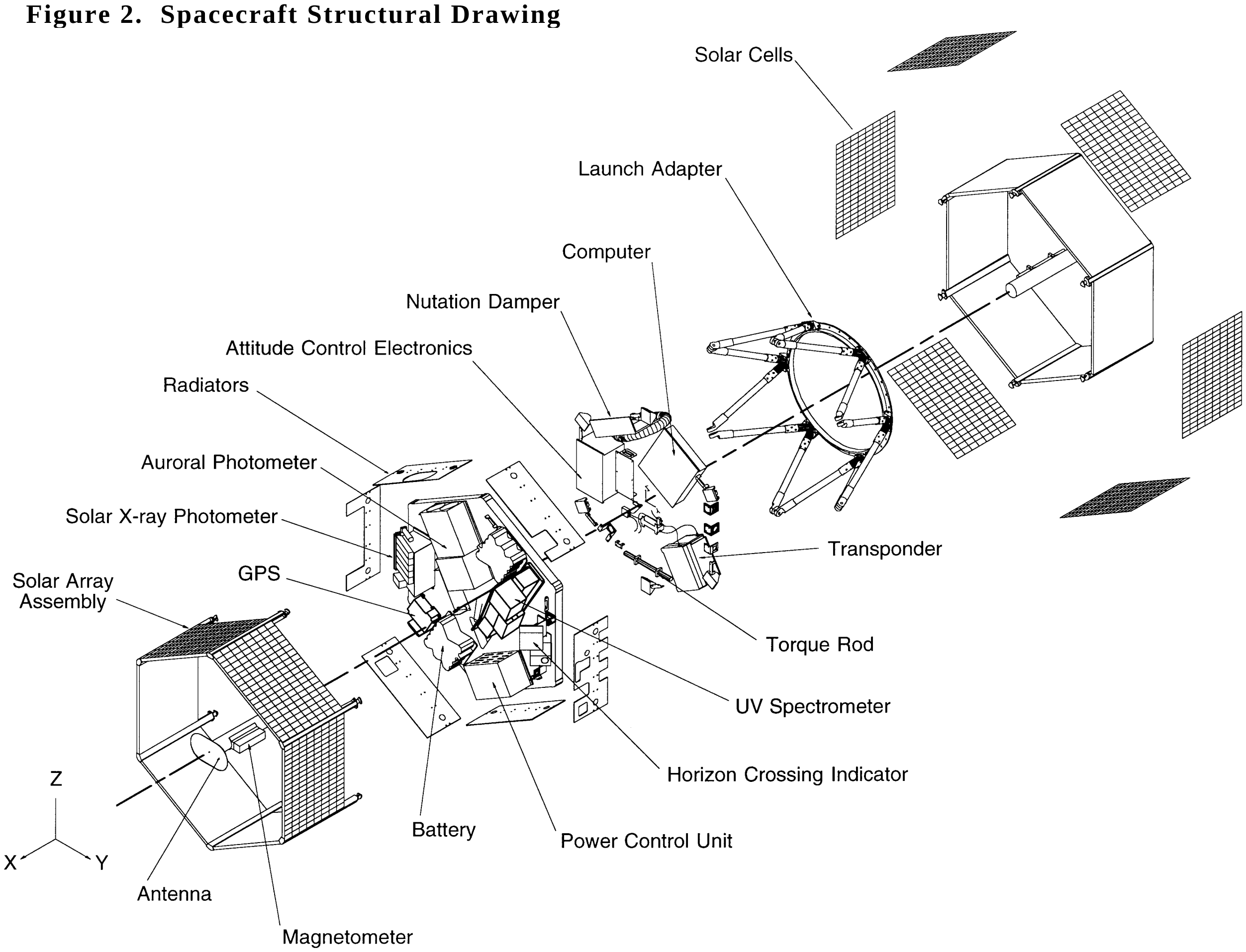

Figure 3. Spacecraft Expanded Diagram

An integrated approach to all subsystems and instruments was adopted—the spacecraft is conceptually similar to a single instrument with multiple sensors. Most functions traditionally accomplished using special-purpose hardware are instead implemented in software.

The Command and Data Handling system receives, decodes and distributes commands, formats digital and analog data, stores commands for later execution and stores data in a mass memory for downlink transmission. The flight computer is a SwRI SC-4A, which is based on an Intel 80C186 processor using standard PC architecture. A LASP daughterboard provides the interface to all instruments and subsystems, and the 8 Mbyte mass memory holds >24 hours of data, which is downlinked once per day. Flight software is described in a companion paper.[6]

The power system is a direct energy transfer system using switched arrays and a partial shunt to provide unregulated D.C. power at 24 to 32 volts. The solar arrays consist of 24 strings of 76 cells each. Two batteries with 21 4-ampere-hour NiCd cells each are used to store energy. Battery charge is maintained by a voltage/temperature controlled shunt regulator and array switching. Orbit-averaged S/C power consumption is 35 W.

An open-loop Attitude Determination and Control System (ADCS) is used to keep the spin axis normal to the orbit plane, maintain the spin rate, and generate a limb reference pulse for the instruments. A magnetometer and two horizon crossing indicators are used for attitude determination. After determining the attitude and spin rate errors on the ground, stored commands are sent to the S/C, which are then issued when the magnetic field is at the proper angle to control the attitude and spin rate using precession and spin torque rods.

The communications system uses a NASA compatible S-band receiver/demodulator for the uplink and a transmitter/baseband unit for the downlink. Coupled microstrip patch antennas are used for the uplink and switched microstrip patch antennas are used for the downlink. The realtime data rate is 512 bps and the playback rate is 128 Kbps. Commands are uplinked at 2 Kbps. Data and commands are packetized using CCSDS standards.

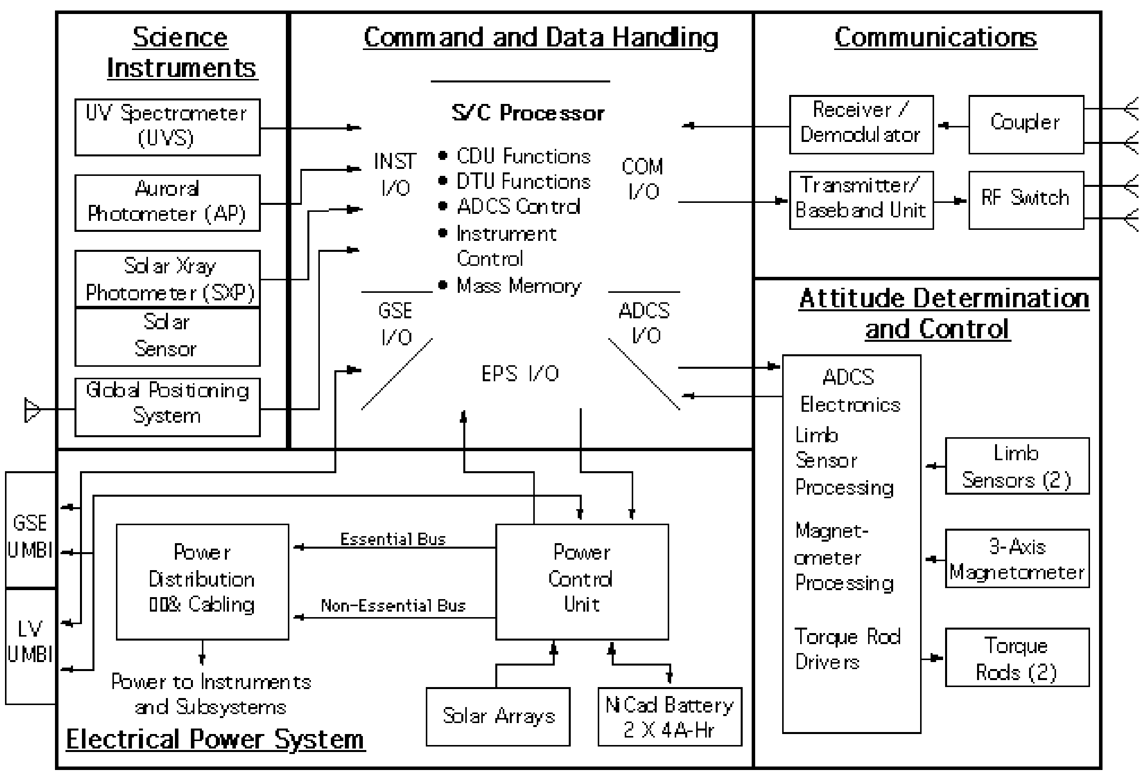

Figure 4. Spacecraft Simplified Block Diagram

4. Scientific Instruments

4.1 Ultraviolet Spectrometer

The ultraviolet spectrometer (UVS) measures the densities of nitric oxide between the altitudes of 100 and 200 km in the terrestrial upper atmosphere by observing the (1,0) and (0,1) gamma bands. The UVS design consists of an Ebert-Fastie spectrometer, an off-axis telescope, and two phototube detectors.

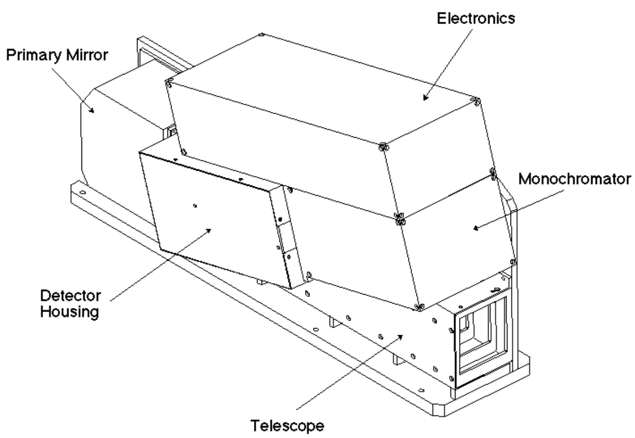

Figure 5. Ultraviolet Spectrometer.

The spectrometer has a focal length of 125 mm and uses a 3600 l/mm mechanically ruled plane grating which produces a dispersion of 1.8 nm/mm at the detectors. The phototubes each have fused silica windows and a cesium telluride photocathode. The telescope is an off-axis parabola with a 250 mm focal length. The UVS is mounted with its optical axis perpendicular to the spin axis of the S/C. Its telescope images the entrance slit of the spectrometer on the limb with the long axis of the slit parallel to the horizon. The image of the slit on the limb is 3.5 km high, which determines the fundamental altitude resolution of the instrument. The integration time is 2.4 ms. To minimize requirements on the S/C, data is only stored for the downward limb scan.

4.2 Solar X-Ray Photometer

The solar X-ray photometer (SXP) measures the solar irradiance at wavelengths from 2 to 31 nm. Each of the five photometer channels contains a silicon photodiode; wavelength selection is accomplished by thin metallic films deposited directly onto the diode surface. Coatings are selected so that overlapping band-passes can be used to isolate key parts of the solar soft X-ray and hard EUV (or "XUV") spectrum at low resolution. The fields of view are ~70° full-cone to obtain a solar measurement once per spin during the day. The integration time is 62.5 ms. Each photodiode is followed by a current amplifier and a voltage-to-frequency converter, resulting in a sequence of pulses with a frequency proportional to the diode current. Part of the measured current is due to visible-wavelength radiation entering through microscopic flaws in the coating. To measure these background currents a door mechanism fitted with a fused silica window is included. When the door is closed the signal is completely due to background visible light. The door is opened and closed periodically, and the X-ray signal obtained by subtracting data taken with the window closed from data taken with the window open. A small two-axis sun sensor is co-aligned with the SXP to measure the solar incidence angle for the instrument, since the measured signal will vary as the cosine of this angle.

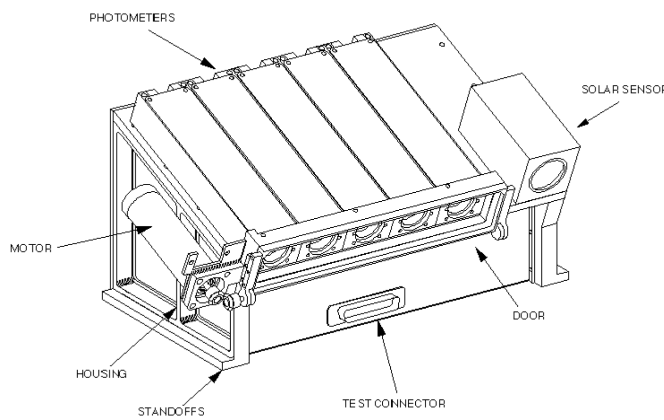

Figure 6. Solar X-ray Photometer

4.3 Auroral Photometer

The auroral photometer (AP) is a two-channel broad-band instrument that will be used to determine the energy deposited in the upper atmosphere by energetic auroral electrons. The channels consist of two Hamamatsu phototube detectors, a UV window/filter for each channel, and a field of view limiter for each channel. Both channels have circular fields of view, 11˚ full-cone. The detectors are identical phototubes with magnesium fluoride (MgF_2) windows and cesium iodide (CsI) photocathodes. Channel 1 has a calcium fluoride (CaF_2) filter placed in front of the detector and channel 2 has a barium fluoride (BaF_2) filter. The combination of the CsI photocathode and the CaF_2 filter produces a bandpass from 125 to 180 nm for channel 1, allowing a combined measurement of the LBH bands, the OI doublet at 135.6 nm, and the OI triplet at 130.4 nm. Channel 2 has a 135 to 180 nm bandpass, providing a measurement of the LBH bands and the OI doublet at 135.6 nm with the exclusion of the OI triplet at 130.4 nm. The AP and UVS photomultiplier electronics are identical, resulting in significant economies in fabrication and operation. As with the UVS, the AP is mounted with its optical axis perpendicular to the S/C spin axis. The AP produces continuous data with an integration time of 183 ms, but only the downward-looking 180° of each spin (limb-to-limb nadir scan) is stored.

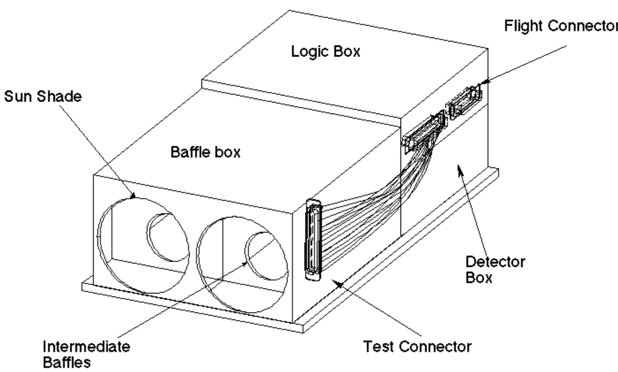

Figure 7. Auroral photometer

4.4 GPS Receiver

A small GPS receiver for orbit determination is included on SNOE as a technology experiment. This instrument, the JPL microGPS "bit-grabber", is the result of a collaboration between JPL, NASA Code O, the CU Aerospace Sciences Engineering department, and LASP. The microGPS electronics box is approximately 2.5" × 4.5" × 2.0" and a small integral antenna views through a radiator aperture as do the other instruments. Mass is 1.5 lbs. Power consumption is 2.1 W while operating, but orbit average power is reduced to about 0.02 W by extreme duty-cycling. This is the essence of the microGPS approach—the receiver turns on for a few seconds, samples available signal from the GPS constellation, and then goes back into "sleep" mode. It does this three times per orbit, which is the minimum number necessary to fully specify the orbit. The signal is not processed on board but is stored in S/C memory until the next downlink. Data processing and orbital determination is then done after-the-fact on the ground.

5. Integration and Test

During the build-up and testing of each instrument and subsystem, personal computers were used for acquiring data, controlling equipment, and displaying and analyzing test data. During integration and system testing a Unix workstation was used to monitor and control the S/C and to manage and analyze test data. Additional workstations residing in the Project Operations Control Center (POCC) were used to remotely conduct and monitor S/C tests. The test system had the ability to communicate with the spacecraft either through a test connection or through the communications system. A power control console and commercial RF equipment completed the ground support electronics. The S/C, its mechanical and electrical ground support equipment, and the computer that controlled it resided in a class-100,000 clean room at LASP, with a downflow clean tent protecting the spacecraft itself.

Software used in ground testing was either commercial software or software that LASP has developed and used on previous projects. This includes the LASP Operations and Science Information Support (OASIS) software for monitoring and controlling the S/C and scientific instruments, which is currently used on the Earth Observing System and other NASA projects. A virtue of OASIS for spacecraft development and operations is that the same software is used for integration and test as is used for flight operations. This also provides flight controllers with training by monitoring and controlling the S/C during ground test.

Integration commenced with an extended component shake-out phase as problems were discovered with individual subsystems and their interaction with the flight computer and daughterboards. Since most of the subsystems and instruments were designed and fabricated at CU/LASP, the centralized nature of the project facilitated rapid identification and repair of anomalies. A computerized anomaly reporting and tracking system was used to keep management informed as the system was debugged. The spacecraft was disassembled and re-assembled several times during integration for subsystem changes and final instrument calibrations. Final revisions of the flight software were also made during this phase of the project.

End-to-end testing was the hallmark of the SNOE project. Functional testing was conducted using an OASIS program that rigorously tested all subsystems and interactions and recorded all data for evaluation and archiving. A short-form functional that took about an hour to conduct, and a long-form functional that could take more than a day, were included. The short form was useful for a quick check on S/C health while the long-form was used for definitive evaluation.

After successful completion of a long-form functional test, the final assembly of thermal blankets and radiators was done, and the environmental test program started. These tests were done at the facilities of the Ball Aerospace Corporation in Boulder Colorado. The order of tests was determined mostly by facility availability. A 7-day thermal vacuum and thermal balance test were performed first. Long-form functional tests were run at each of five hot and cold dwells. This was followed by a separation shock test and spin balance. Launch vehicle electrical interface testing was done in conjunction with the separation shock test, since engineers from the launch vehicle team had to be present to fire the pyroelectric marmon clamp release. Anomalies identified in the launch vehicle interface having to do with the S/C turn-on circuitry were discovered, which were remedied by changes to the power control unit. This was done at LASP while waiting for the vibration table to become available. The S/C was then subjected to sine burst (10 g) and random (6 g) vibration tests. Long-form functionals were performed at LASP before and after the vibration tests, and the launch vehicle interface was re-tested to verify the changes made. Full mission simulations of 2 days and 5 days were then run, with flight controllers operating the spacecraft around the clock from the LASP POCC while an engineer observed the S/C as it resided in its clean room. Plugs-out tests and a final long-form functional were performed prior to shipment by rental truck to Vandenberg AFB.

6. Launch Operations

The SNOE spacecraft arrived at Vandenberg on 15 December, 1997, and was unpacked at the NASA building 836 facility. Launch site operations were deliberately kept simple, with no installations or modifications planned in the field. The core launch site team on the S/C side consisted of just three people. Battery charging, short-form and long-form functional tests, RF tests, and a plugs-out test were completed in two days. The S/C was then repacked, and moved to the Orbital facility at building 1555 on 20 December.

SNOE launch under the NASA Ultralight Expendable Launch Vehicle (UELV) program was designated as the primary payload of a dual launch on a Pegasus XL vehicle supplied by Orbital. The secondary payload was the BATSAT communications satellite built by Orbital. Launch site electrical and mechanical interface tests between SNOE, the BATSAT adapter cone, and the Pegasus XL, revealed only two small problems: two pins for the RF inhibit had to be switched in a harness connector, and the addition of a SNOE turn-on command to the Launch Panel Operator software was needed for test, since the S/C could not be activated by its GSE once mated to the launch vehicle, without running a full flight simulation or pulling the backup activation breakwire.

SNOE was returned to its shipping container for storage and the SNOE and Orbital launch site teams adjourned for the holidays on 23 December 1997 to 4 January 1998. After return to the field, the adapter cone harness and test software modifications were performed, electrical interface testing was completed, and the spacecraft mated to the marmon clamp / adapter cone assembly.

Flight simulation 3 on Pegasus-BATSAT-SNOE was performed by Orbital using an extended test harness prior to mechanical mate on 14 January. Mission launch was then delayed by a series of problems on the launch vehicle side, including questionable pyro driver units and a vehicle telemetry anomaly. These were repaired, and flight simulation 4 was performed on 22 January, and final closeouts and fairing installation were performed on 28–29 January. The 20th Pegasus mission was transported to the hotpad on 31 January and mated to the L1011 carrier aircraft.

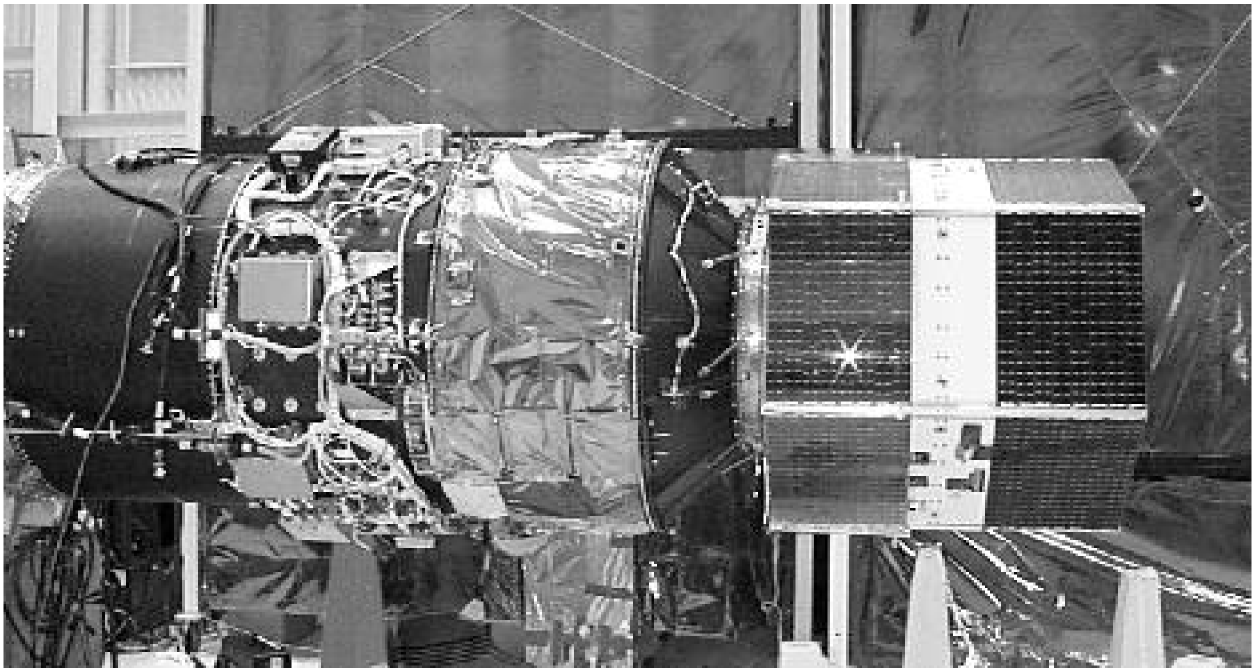

Figure 8. Pegasus Third Stage, BATSAT, Adapter Cone, and SNOE

Following the L1011/Pegasus combined systems test and NASA launch readiness review, a period of terrible weather ensued, which, together with competition from other range activities, postponed launch several times. The Pegasus was de-mated on 6 February and returned to building 1555, and, after a change of flight termination system receivers, returned to the hotpad on 21 February. Following L1011 mate and combined systems test, a break in the weather was identified for the night of 25-26 February.

SNOE final arming was completed on schedule at 03:00 UTC on 26 February 1998. The launch checklist proceeded with no significant anomalies. L1011 engines were started at 05:30 and wheels up was at 06:10. Pegasus drop occurred at 07:05 and SNOE was turned on at 07:14. Separation was at 07:15. SNOE was launched into a 580 km x 550 km orbit at 97.75 degrees inclination. Inclination and apogee were exactly as targeted, while perigee was 30 km low but well within the targeted range.

7. The Early Orbit Campaign

First contact at Poker Flat, Alaska was successful. Voltages and currents were nominal. The non-essential bus was turned on and a communications sequence uploaded. Second contact with the DSN station at Madrid, Spain, was also successful. The attitude determination control system was turned on and tested. The power profile was excellent. Communication links exceeded expectations. The command and data handling system functioned properly. Temperatures were within nominal ranges. The computer was successfully restarted from EEPROM on the fifth pass. During the next two days, the SXP was turned on, the first attitude control sequence executed by stored command, and the 1.2 day watchdog reset timer tested.

The only anomalies to occur during the first three days on orbit were two spurious hardware command accepts, once turning off the non-essential bus, and once resetting the spacecraft computer. The only other surprise was that the solar arrays generated more power than expected, so one of the four array-string switching circuits was turned off.

Operations during the first two weeks on-orbit continued to go well. The electrical power system was kept at 75% capacity, with one switching circuit turned off. Spacecraft temperatures settled down in this power mode, with central plate, instruments, and subsystems in the 15–20 °C range, about 5 °C higher than designed but well within the normal range, and solar panels fluctuating from -20 to 20 °C. There were no apparent problems with the structure.

Attitude data from the first set of maneuvers were analyzed, and the spacecraft responded properly to attitude control commands. The spin axis was nearly aligned with orbit normal. Its motion during the course of an orbit described two circles about the orbit normal vector varying from 0.4° to 1.0° in radius. Spin-up maneuvers were successful, and the spin rate was held to 5.0±0.1 rpm with a daily spin-up. The spin axis precession rate in right ascension was within ~0.1°/day of the orbit normal precession rate, with the axial torque rod residual magnetism in the “minus” state, so daily axial adjustments were small.

The command and data handling system functioned well with the exception of a few spurious hardware command accepts. An additional command accept occurred on 9 March, resetting the spacecraft computer. The operational strategy instituted to avoid this anomaly was to request the ground stations to delay bringing up the transmitter carrier until well after acquisition of signal from the spacecraft, so as to avoid transmitting noisy data to the spacecraft. Other than this workaround and a few problems working out procedures with the ground stations, communications were nominal.

The SXP door was operated on 1 March, and a solar X-ray measurement obtained. The door was operated once per day through the remainder of the early orbit campaign. Solar X-ray data with the door open and closed were compared, and good X-ray signals were obtained in all channels. The UVS was activated on 3 March and engineering and scientific data verified in a low-resolution mode. On-board spin correction of the horizon crossing delay was activated on 6 March, and on-board roll-correction initiated on 10 March. These were found to be working properly and the UVS was put into its nominal high-resolution mode, also on 10 March. The AP was activated on 5 March and performed nominally. Full-spin and half-spin data were taken to verify solar rejection, after which it was placed in its nominal mode.

8. Mission Operations

8.1 Tracking and Communications

SNOE ground communications are handled by the NASA Autonomous Ground Services (AGS). This program has the goal of reducing mission costs through use of small, automated ground stations. The prototype AGS station will be located at Poker Flat, Alaska, and will be backed up by the existing 8-meter Transportable Orbit Tracking Station (TOTS) at that location. Until the first AGS stations come on-line, the TOTS systems at Poker Flat and Wallops Island are used for SNOE communications. DSN facilities were used during the early orbit campaign to provide additional coverage and backup.

S/C communications use standard NASA S-band protocol. Ranging is not provided since SNOE has a transceiver rather than a transponder, and so tracking past the early orbit campaign is done using NORAD orbit elements and daily predicts.

Command and data relay is over T1 lines to Goddard Space Flight Center and then to the SNOE POCC at LASP using ISDN service. TCP/IP is used throughout. This provides the operations team with real-time access to the S/C during passes and rapid acquisition of playback data.

8.2 Mission Operations

S/C and instrument health and safety are monitored at the POCC located in the LASP Space Technology Research building using OASIS Command and Control (OASIS-CC) software. Flight controllers also use this software to prepare and transmit commands to the S/C during a pass. Most of the activities during a pass are coordinated using procedures written in the Colorado Systems Test and Operations Language (CSTOL) that is part of OASIS-CC.

After a pass, all of the data from the S/C are processed and made available to the flight engineers, who monitor the long-term health of the satellite and its instruments. Orbit and attitude determination is performed by specialists on the flight engineering team, and stored commands for the next day’s orbital maneuvers prepared for upload. During routine operations two contacts per day are used, typically one in the morning and one in the afternoon.

8.3 Data Processing and Analysis

After each contact with the S/C, real-time and playback data recorded during the contact are processed. Updated ephemeris of satellite position are computed and combined with processed attitude data. The resultant orbit-attitude data—S/C position, velocity and spin vectors, spin reference angle and spin rate—are stored on five-minute centers. Engineering data are converted to standard units and stored at the sampled rate (generally equal to the 12 s spin period). Level-1 science data processing is performed, combining instrument count rates and time-tags with ancillary engineering data. All science, engineering, and orbit/attitude data are stored in a commercial relational database purchased from the SyBase corporation.

The science team analyzes the Level-1 data and applies calibrations and inversions to create Level-2 (geophysical unit) and Level-3 (daily abstract) data products. Higher level data products will be provided to collaborating scientists using netCDF format files, and abstract data will also be made available through an HTML interface.

9. On-Orbit Performance

9.1 Command and Data Handling

The command and data handling approach implements most command and telemetry functions in software[6], implemented on a standard-architecture flight computer using a commercial C++ compiler. The software design employs a "main loop" that repeats indefinitely, calling individual modules that handle specific tasks such as processing commands, storing science and engineering data, and managing telemetry. Telemetry design is based on a CCSDS-compliant packetized system, and has a 512 bps "realtime" capability for contingency operations in addition to the nominal high rate 128 kbps channel. Realtime frames are also multiplexed into the high rate channel. Stored commands are queued in a command buffer for execution at the appropriate time. Instrument data is handled asynchronously by generation of a data-ready interrupt, which is noted by the processor but not processed until the software is ready to empty the instrument data buffer.

The Southwest Research Institute (SwRI) SC4A flight computer includes a 10 MHz Intel 80C186 CPU, watchdog timer and other programmable timers, interrupt controller, serial ports, 8 MByte of mass memory, 64 Kbyte of EPROM, 256 Kbytes of EEPROM, 256 Kbytes of RAM, 32 channel analog-to-digital converter, 8 channel digital-to-analog conversion, multiple digital I/O ports, and an expansion buffer for daughter boards. All memory includes single bit correction, and double bit error detection and correction (EDAC). The 8 Mbyte internal mass memory of the SC-4A is employed for data storage. The custom LASP daughterboards provide an interface to all instruments and subsystems using field-programmable gate array (FPGA) circuits.

CDU functions are implemented through a combination of hardware and software. Command verification, checking, and decoding occurs in software, and simple hardware output ports and appropriate driver circuitry are used to issue serial digital and discrete commands (both low and high level) to the remainder of the S/C. Bi-$Ø_L$ encoding is also done in hardware. A limited hardware command decoder is also provided that can reset the SC-4A by ground instruction. This is included to give command access in case the SC-4A ever fails to automatically reset.

Two of the three principal concerns prior to SNOE launch pertained to the C&DH system. The first is the known susceptibility of the limited hardware command decoder to misinterpreting a noisy signal as an emergency hardware command. A bug in the FPGA logic made it possible for any bit sequence beginning with the CCSDS 2-byte identifier header and containing a valid hardware command word at the correct distance would be interpreted as a hardware command, even if the CCSDS header did not begin a valid packet. Thus, during noisy acquisition or loss of signal, or in any other situation leading to a random sequence of received bits, it is possible for a hardware command to inadvertently execute. This has happened 2–3 times per month on-orbit so far. The effect is not catastrophic, as the only possible hardware commands are to reboot the computer or to turn off the non-essential bus. It is an annoying feature of the S/C, however, and results in occasional loss of about half a day of science data.

The second concern with the C&DH system is that the latch-up resistance of the SC-4A and daughterboard are not well known. A great deal of effort prior to launch at LASP and

SwRI went into design of appropriate power circuitry to prevent a bad radiation hit from causing high current draw to the computer through semiconductor latch-up. However, it was not possible to test the computer in a radiation chamber. Soft latch-up, which could paralyze the computer logic without causing high current draw is also a concern. A related problem is that the computer power circuit is not designed to recover from a loss and subsequent slow restoration of power. Therefore, the ultimate fallback of the C&DH design is a late addition—a long-term watchdog timer that cycles the computer power if no command is received in 1.2 days, to clear any such event. The watchdog was tested during the early orbit campaign and performed properly, but has not yet proven necessary. No latch-up events have occurred to date.

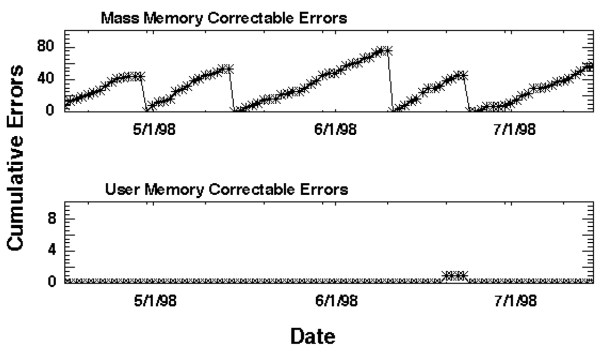

Figure 9. Flight Computer Correctable Errors

Software has performed flawlessly and no software-related resets have yet occurred. Two minor module patches have been made on-orbit. Error correction of single-event upsets has also performed well. About three mass memory errors per day are corrected on average; there has been no apparent correlation with magnetic disturbances or known energetic particle events. Cumulative mass memory and user memory correctable errors are plotted in Figure 9 for the period 15 April to 15 July 1998. The counter restarts at zero at each computer reset, of which there were four in the time indicated. User memory errors have been very rare. There have been no uncorrectable (double-event) errors as far as we can tell.

9.2 Electrical Power System

The Electrical Power System (EPS) consists of 12 body mounted solar arrays, two batteries, and a power control unit. Each solar panel contains two strings for a total of 24. The strings consist of seventy-six 2.3 cm × 4.1 cm silicon photovoltaic cells. The 24 strings are organized into four switching circuits of six strings each, with the six strings distributed one to each S/C face to prevent current fluctuation when one or more circuits are switched off.

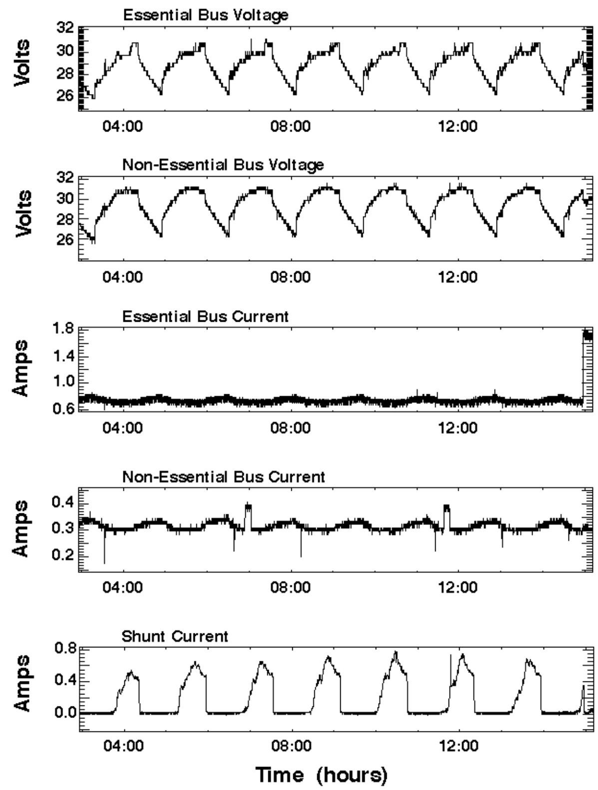

Figure 10. EPS Voltages and Currents

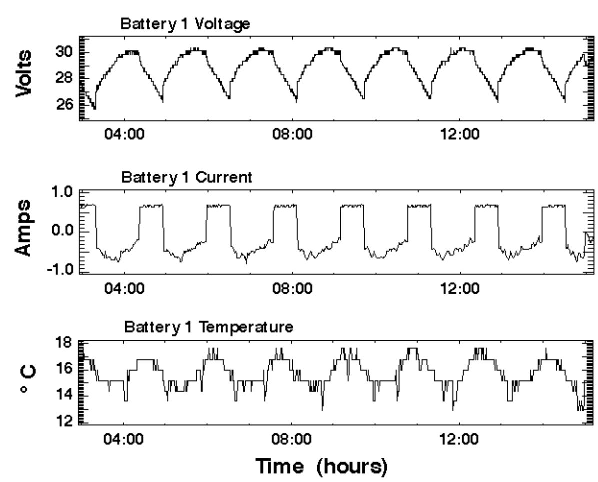

Figure 11. Battery 1 Parameters

Energy is stored in two 21-cell 4-Amp-hour NiCd battery packs. Only one battery is necessary for operation but two are provided for redundancy; a one-time relay can be used to remove one battery from operation if it fails. A shunt regulator is used to prevent overcharging of the batteries by clamping the bus voltage to a level set by selectable voltage/temperature curves. Power distribution includes an essential bus and a non-essential bus. Circuits on the essential bus are the EPS itself, the receiver, and the flight computer. The non-essential bus is switched off automatically in the event of an undervoltage, and can also be switched off by command. The solar panels, batteries, and power control unit were all designed and fabricated at LASP.

The EPS has overperformed since launch, with total orbit-average power generation capability of ~60 W. Since the S/C only requires ~35 W orbit-average, one of the four switching circuits was turned off shortly after launch, as described in Section 7, to prevent overheating of the S/C since the shunts can only handle about 15 W. Since this adjustment, EPS performance has been nominal. Key voltages and currents from 16 July 1998 are plotted in Figure 10 to give an indication of the orbital cycle of the EPS as it enters and leaves eclipse.

The batteries appear to be in excellent health. Battery 1 voltage, current, and temperature for the same interval as shown in Figure 10 is plotted in Figure 11, and a three month trend plot for the period 15 April to 15 July 1998 is shown in Figure 12, with the daily high, low, and average values plotted.

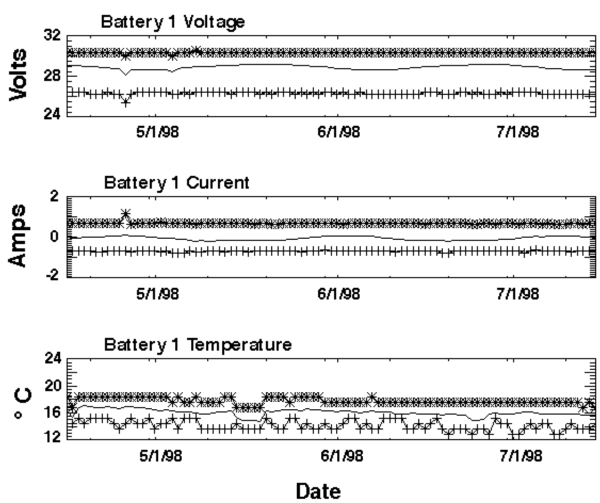

Figure 12. Battery 1 Trends

9.3 Communications system

The S-band communications system consists of a transmitter, receiver/demodulator, hemispherical antennas, coupler, RF switch, and filter. The equipment was purchased from Cincinnati Electronics, with the exception of the antennas which were designed and built by LASP. The 2 Kbps NRZ-M command data are received using NASA compatible PCM/PSK/PM modulation. Realtime telemetry modulation is PCM/PSK/PM, and the playback is PCM/PM.

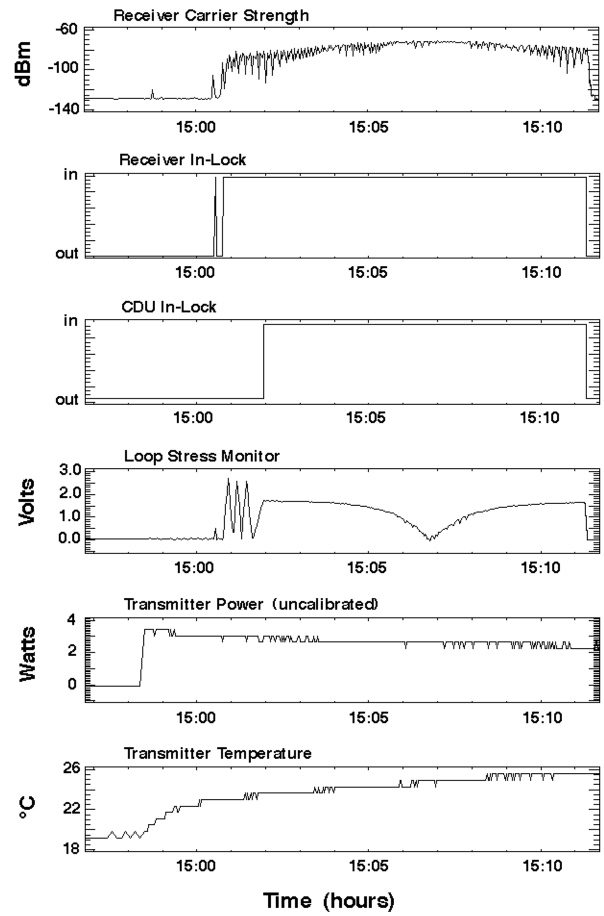

Figure 13. Communications System Parameters During a Typical Ground Contact

The transmitter/baseband unit provides 5 watts of output RF power. The unit phase modulates the transmitter with 128 Kbps Bi-$Ø_L$ data. The power amplifier uses GaAs FET power devices operating as a class AB amplifier to reduce generation of spurious signals. There are two receive and two transmit patch antennas, one of each type on the ground plane mounted on an antenna mast on each end of the S/C. The command antennas are coupled to provide omnidirectional coverage; the telemetry antennas are selected through the RF switch.

Performance of the communications system has been excellent. Parameters from a typical pass, this one also on 16 July 1998, are shown in Figure 13.

The third of the principal concerns prior to SNOE launch was a possible anomaly in the receiver system. Approximately one time out of 100 turn-ons, the receiver would power up in a spurious mode of the subcarrier oscillator crystal, effectively shifting the uplink data rate from 2 Kbps to 2.2 Kbps. This "command lock-out" condition caused a great deal of concern in the last days before SNOE shipment. When it was finally diagnosed, Cincinnati immediately identified the necessary change, but the SNOE team decided not to implement it because of the short time until launch. Instead, the spacecraft would launch with the known anomaly, and, in the unlikely even that it occurred on-orbit, simply shift the ground station uplink data rate accordingly. The spurious subcarrier frequency did not occur on initial turn-on, and has not occurred since.

9.4 Attitude Determination & Control

SNOE is a passive spin-stabilized spacecraft that uses an open-loop attitude determination and control system (ADCS) to keep the spin axis normal to the orbit plane, limit nutation, maintain a stable spin period, and generate payload timing signals. Attitude determination is accomplished using two horizon crossing indicators (HCI) in a V-pair configuration. Two electromagnets (torque rods), one aligned with the spin axis (x-axis) and a second normal to the spin axis are used to correct S/C alignment and spin rate. Torquing is performed open-loop using stored command sequences which are uplinked from the control center. Spin rate is also adjusted by stored command. A spin magnetometer measures magnetic field orientation relative to the z-axis so that the z-axis torque rod can be modulated to alter spin rate. Nutation is controlled by a fluid-filled ring damper. The favorable spin/transverse moment of inertia ratio of ~1.2 gives the S/C intrinsic spin stability; once the S/C y-axis is aligned with the orbit normal, only occasional adjustment of the spin rate and ~1 °/day spin axis torquing to adjust for orbital precession is required.

Initial attitude injection of the spacecraft by the Pegasus XL was nearly perfect, with the spin axis aligned within a degree of orbit normal, and the spin rate with 5% of the targeted 5.0 rpm. Tip-off rates were moderate but are not exactly known; an indication is given by the difference between HCI disk times as shown in Figure 14. Nutation of the spin axis appears as the modulation envelope of the half-orbit roll-yaw cycle, here starting three hours after launch (when the ADCS was activated) on 26 February 1998. The nutation damper effectively removed the nutation within two more hours, and by eight hours after launch it was entirely gone.

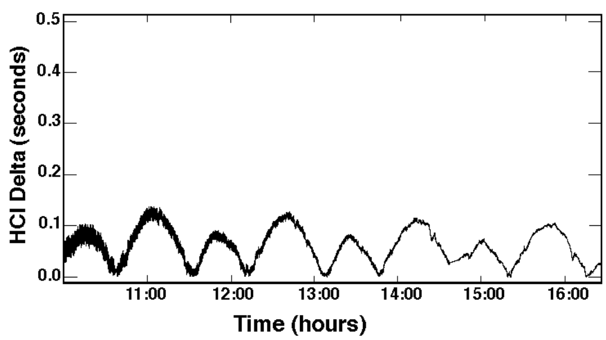

Figure 14. Nutation Damping after Launch

The spin rate of the S/C shows a slight diurnal cycle as the solar arrays heat and cool, superimposed on a slow decay, as seen in data from the second day of the mission shown in Figure 15. Since then, the spin rate has been held to 5.0±0.1 rpm by daily spin-up maneuvers.

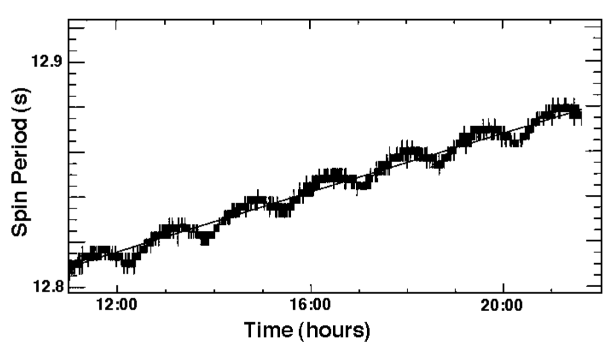

Figure 15. Spin Rate Oscillation and Decay

Other than periodic spin-ups, the main task of the ADCS analyst is to keep the spin axis aligned with orbit normal. This involves precessing the spin axis ~1°/day to keep up with the sun-synchronous motion of the orbit plane, and reducing any oscillation of the spin axis about its average direction. By performing axial torque rod maneuvers at appropriate magnetic field orientations (generally near the magnetic equator, at low declination angle) this oscillation has been reduced to one circle per orbit of about 0.6° in radius in right ascension/declination space. This motion is shown for 16 July 1998 in Figure 16, where the left circle shows the spin axis direction before the daily maneuver, and the right circle its direction after the maneuver is performed. The straight line represents the location of orbit normal as it increases in right ascension during the course of the day. The dark crosses show the locations of polar crossings. With the axial torque rod residual magnetism in the "minus" state, the spin axis tends to increase in right ascension, so daily axial adjustments have continued to be of moderate duration. This secular precession rate and the circling about orbit normal are probably both attributable to the residual magnetism of the spacecraft. The SNOE science requirement for pointing control is only 5°, so the <1° deviation is acceptable.

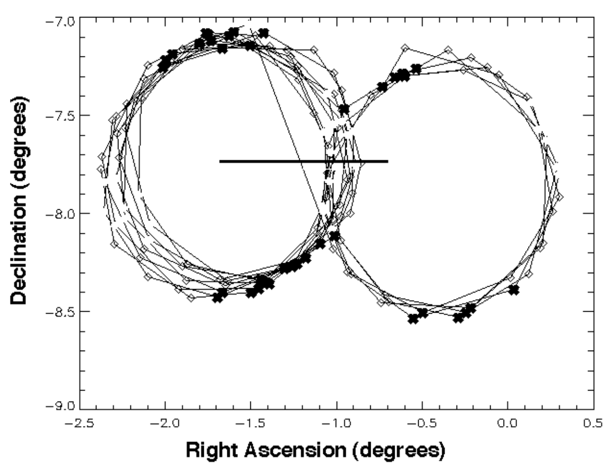

Figure 16. RA/Dec Plot for 16 June 1998

9.5 Thermal Control

The SNOE thermal control system is a mostly passive design employing radiators around the edge of the central plate, conductive isolation of the solar panels, and MLI blankets. Electrical heaters at selected baseplate locations are included for contingency. The solar panels are kept thermally isolated from the central plate by titanium flexures as described in Section 3.2 so that they may fluctuate in temperature while the subsystems and instruments remain fairly stable. This design was analyzed using the SINDA-85 and TRASYS mathematical models, yielding the prediction that the batteries and instruments should operate near ~10 °C.

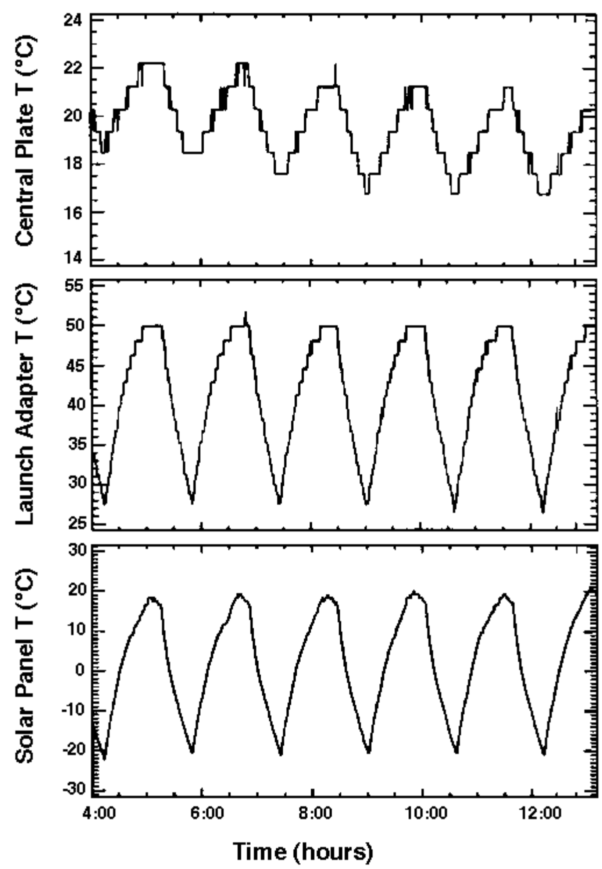

Figure 17. Selected Component Temperatures After Launch on 26 February 1998

Shortly after launch, it was realized that the S/C was running slightly hot. This was attributed to the high power levels generated by the solar arrays, as described in Sections 7 and 9.2. After switching off one of the four array switching circuits, central plate temperatures started to reduce, as shown in Figure 17. This figure also demonstrates the small diurnal changes in temperature of the central plate in comparison to the launch adapter and solar panels.

The spacecraft subsequently settled down with batteries and instruments averaging near ~15°. This is about 5° higher than expected but still very acceptable. Most of the difference is attributable to the excess power generated, even with the solar arrays at only 75% of capacity.

3-month trends for various component temperatures are shown in Figure 18, with daily high, average, and low values plotted.

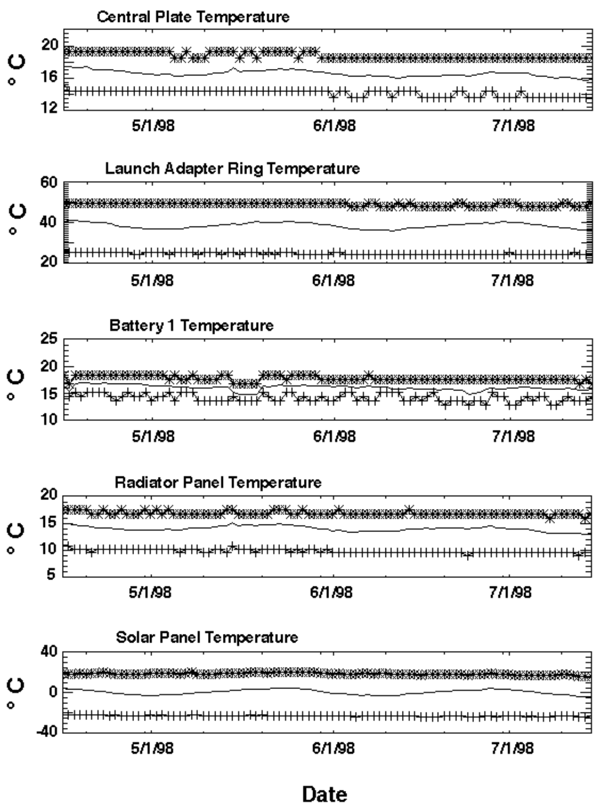

Figure 18. Three-Month Temperature Trends

10. Conclusion

As of July 1998, the SNOE spacecraft is in excellent health and appears to be headed for a long and scientifically productive mission. Scientific instruments are functioning well, and returning nearly continuous data. Power margins are very high and there have been no signs of solar array or battery degradation. The orbit is sufficiently high that re-entry should not occur for over a decade, and attitude is stable and controllable. As long as the flight computer continues to function without catastrophic latch-up, there are no known threats to the mission. Operations have been mostly uneventful, and the S/C is very robust, owing to its spin-stabilized design and multiple fallbacks in response to command or power anomalies. The S/C design lifetime was effectively two years, but at this time a three- or four-year mission seems possible.

The original goals of the STEDI program were to conduct significant space science experimentation, to demonstrate the feasibility of low-cost, university-based missions, and to do so with significant student involvement. SNOE has succeeded in all three, which has encouraged NASA to pursue the new University Explorer (UNEX) program. Meanwhile, the TERRIERS mission is complete and awaits its turn in the Pegasus launch queue, currently scheduled for December 1998. CATSAT is in fabrication, but its launch date is uncertain while NASA identifies its launch vehicle. After that, the STEDI program is complete, as NASA has decided to continue this type of activity under the auspices of UNEX. As a Demonstration Initiative, it must presumptively be judged a success.

The SNOE mission was designed, built, and operated by a combined team of professional engineers, scientists, and student research assistants. It was neither a standard NASA mission with student help, nor was it a college class project. It was an integrated effort. That, in fact, is where the principal educational value to the students was derived. By working as salaried employees in a professional, real-world aerospace engineering environment, the actual problems of design, fabrication and test are addressed in a way that best equips young engineers for their careers. The need to hire and train so many students for a project such as this places a constraint on the rapidity with which such missions can be built, despite the oft-cited observation that faster is cheaper. We paid our students at the top rates allowed by the University of Colorado. Most of them were employed half time during the academic year and full time during the summer, but often put in many more hours than required, as did the professional staff.

The SNOE project was an extraordinary challenge for the entire team, and would not have succeeded without enormous commitment to its goals. The mission employed a blend of modern approaches and known technologies, a combination of professional engineers with students, a mixture of higher-risk items with standard space flight procedures. There was no alchemy in the method, only the dedication of the people who applied it.

11. Acknowledgments

This paper represents the work of the entire SNOE team, including the LASP engineering and scientific staff, graduate and undergraduate students, USRA, NASA Orbital Launch Services and Autonomous Ground Services, Ball Aerospace, JPL, NCAR, the CU Aerospace Engineering department, and Arapahoe High School. Support for this project is provided by NASA/USRA cooperative agreement NCCW-0048 and USRA/CU cooperative agreement 1500-01.

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