# The Student Nitric Oxide Explorer

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## ABSTRACT

The Student Nitric Oxide Explorer (SNOE) is a small scientific spacecraft designed to launch on a Pegasus™ XL vehicle for the Student Explorer Demonstration Initiative. Its scientific goals are to measure nitric oxide density in the lower thermosphere and to analyze the solar and magnetospheric influences that create it and cause its abundance to vary dramatically.

The SNOE (“*snowy*”) spacecraft and instrumentation is being designed and built at the University of Colorado Laboratory for Atmospheric and Space Physics (LASP) by a team of scientists, engineers, and students. The spacecraft is a compact hexagonal structure, 37" x 39", weighing approximately 280 lbs. It will be launched into a circular orbit, 550 km altitude, 97.5 degrees inclination for sun-synchronous precession at 10:30 AM ascending node. It is designed to spin 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.

The spacecraft structure is aluminum, with a center platform section for the instruments and subsystems. Static solar arrays are supported by a truss system. A spacecraft microprocessor handles all subsystem, instrument, and communications functions in an integrated fashion, including command decoding, attitude control, instrument commanding, data storage, and telemetry. The spacecraft is scheduled for launch in early 1997 and will be operated by students at LASP.

For more information on the SNOE project, please visit *http://lasp.colorado.edu/snoe/*.

*Keywords: Spacecraft, Remote Sensing, Nitric Oxide, Thermosphere, Ionosphere, Solar, Ultraviolet, Aurora, Airglow, Education*

## 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 scientific and/or technology 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 firm budget limit of $4.3M was applied to the spacecraft, instruments, and all operations exclusive of communications services and the launch vehicle. STEDI missions will fly on a Pegasus™ XL as one of two payloads, using approximately half of the launch capacity.

The Student Nitric Oxide Explorer (SNOE), scheduled for launch in 1997, will be the first of the STEDI missions, followed by TERRIERS (Boston University) and CATSAT (University of New Hampshire). Meeting the two-year development schedule is the key to cost control on the project. A small leadership team, streamlined management, and minimal interference from the sponsoring agency are critical to the project’s success. Collaboration with the Ball Aerospace Corporation and with the National Center for Atmospheric Research (NCAR) provides guidance to LASP engineering and management. An additional collaboration with JPL provides a small technology experiment—the microGPS receiver for orbit determination. Students are involved in all aspects of the project. Under the supervision of University and industry mentors, they are designing and building the spacecraft and instruments, writing the flight software, integrating the subsystems, and testing everything. Mission operations will also be performed by a mostly student team. The student training effort is coordinated through a course offered continuously in the CU Department of Aerospace Engineering Sciences by SNOE principal investigator Prof. Charles Barth.

## 2. SCIENTIFIC OBJECTIVES

Nitric oxide is an important minor constituent of the upper atmosphere that exhibits strong solar-terrestrial coupling. Nitric oxide directly affects the composition of the ionosphere, the thermal structure of the thermosphere, and may be transported downward into the mesosphere and stratosphere where it can react with ozone. However, significant unanswered questions about nitric oxide remain.

The scientific objectives of the Student Nitric Oxide Explorer are:

• to determine how variations in the solar soft X-radiation produce changes in the density of nitric oxide in the lower thermosphere, and

• to determine how auroral activity produces increased nitric oxide in the polar regions.

Nitric oxide (NO) has a maximum density of about $3x10^7$ $cm^{-3}$ near 110 km. In the polar region the mean density is several times greater and highly variable, sometimes as much as 10 times larger, as shown in Figure 1. The importance of nitric oxide in the upper atmosphere is the result of its chemical, electrical, and radiative properties. Nitric oxide is more easily dissociated and ionized than the principal molecular constituents, nitrogen and oxygen. It radiates in the infrared while the major constituents of the atmosphere do not. Thus, it plays an important role in ionospheric chemistry at all latitudes, and controls the thermal balance of the lower thermosphere.

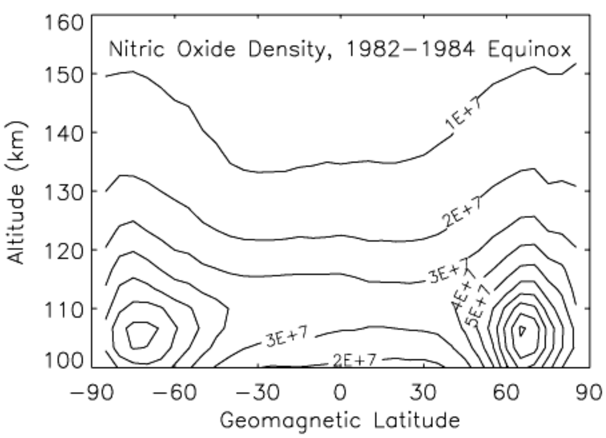


Figure 1. Latitudinal distribution of nitric oxide. Contour plot of the average nitric oxide density shows that the maximum density occurs in the auroral region.

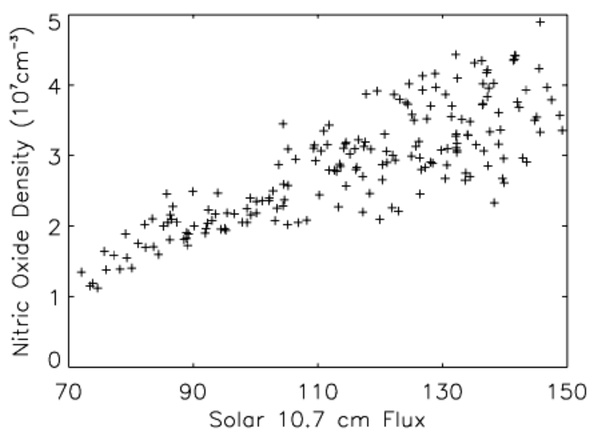


Figure 2. Variation of nitric oxide with solar activity. The nitric oxide density at 110 km is plotted as a function of the solar 10.7 cm flux which is an index of solar activity.

Nitric oxide chemically reacts with ozone to form nitrogen dioxide which in turn reacts with atomic oxygen to reform nitric oxide. This is a catalytic cycle which destroys ozone while leaving the odd-nitrogen intact. Any nitric oxide that is transported downward from the lower thermosphere into the mesosphere and stratosphere may participate in the catalytic destruction of ozone. This can occur during polar night when photodissociation of nitric oxide does not occur[1].

The principal source of nitric oxide in the lower thermosphere is the reaction of energetic nitrogen atoms with molecular oxygen. These nitrogen atoms need to have excess energy, either electronic or kinetic, in order for the reaction with molecular oxygen to proceed rapidly. Sources of the energetic nitrogen atoms are ionospheric reactions and energetic electron impact on molecular nitrogen. Energetic electrons created by photoionization (photoelectrons) and by auroral particle bombardment (auroral secondary electrons) create nitric oxide both by dissociating molecular nitrogen and by ionizing all neutral species, which drives ion-neutral and dissociative recombination reactions that create excited nitrogen atoms. While all of the solar extreme ultraviolet radiation (10.0–102.6 nm) and soft X-radiation (0.1–10 nm) ionizes the upper atmosphere, it is only the most energetic photons that are able to produce photoelectrons with sufficient energy to make energetic nitrogen atoms from the dissociation of molecular nitrogen.

The hypothesis has been proposed that the variation in the density of low latitude nitric oxide at 110 km is caused by the variation in the solar output of soft X-rays in the wavelength range 2–10 nm and that the solar soft X-rays vary with a greater amplitude than does the solar extreme ultraviolet radiation[2]. The evidence for this hypothesis comes from three years of observations of thermospheric nitric oxide from the Solar Mesosphere Explorer[3]. The SME observations show that the nitric oxide density at low latitudes varies with the 27-day solar rotation period and with the 11-year solar cycle. The variation of nitric oxide correlates with the solar 10.7 cm radio flux which is a solar index measured from the ground. The correlation is due to the partial ability of the 10.7 cm flux to track solar EUV and soft X-rays. However, Figure 2 shows that the solar 10.7 cm flux is an imperfect index of the solar radiation that is causing the changes in nitric oxide density.

The first objective of SNOE is to test this hypothesis by simultaneous measurement of the solar soft X-ray irradiance and extreme ultraviolet irradiance in the wavelength range 2–30 nm and nitric oxide density in the lower thermosphere. Comparison of the observations will show the functional relationship between nitric oxide density and solar variation, which will be used to test and revise photochemical models[2,4].

Global observations of nitric oxide from satellites have shown that the maximum amount of nitric oxide occurs in the polar regions centered at geomagnetic latitudes of 65°N and 65°S, and in the altitude region between 100 and 110 km (see Figure 1). A plausible explanation is that polar region nitric oxide is produced by the impact of auroral electrons, which also excite auroral emissions in the ultraviolet and visible portions of the spectrum. The intensity of these emissions may be used to determine the flux of auroral electrons[5]. SME observations of nitric oxide in the polar regions show that there are large variations in nitric oxide density and that these variations are related to auroral activity[6,7]. However, there is no satisfactory quantitative relationship between nitric oxide density and indices of auroral activity such as planetary amplitude (*Ap*).

The second objective of SNOE is to determine how auroral activity produces increased nitric oxide near the poles. This will be accomplished by measuring the intensity of the ultraviolet aurora in the 130–180 nm region, which includes atomic oxygen emission lines and the Lyman-Birge-Hopfield bands of $N_2$. The relationship between the auroral region nitric oxide density and the time history of auroral intensity will be used to determine if bombardment by auroral particles is the dominant process producing polar nitric oxide.

## 3. MISSION DESIGN

### 3.1 Investigation Concept

The scientific objectives require the simultaneous observation of nitric oxide in the lower thermosphere, the solar irradiance in the soft X-ray region of the spectrum, and ultraviolet emissions from the auroral zone. These observations require remote sensing instruments. Nitric oxide measurement requires a limb-scanning telescope and UV spectrometer, the solar instrument needs to point at the sun and have some wavelength discrimination, and the auroral emissions can be viewed in the nadir. These requirements lead to a spinning satellite in low Earth orbit. With the spin axis normal to the orbital plane, a UV spectrometer will scan through the limb of the earth in the orbital plane, an auroral photometer will scan through the nadir, and solar photometers will scan through the sun. Analysis of the nitric oxide photochemistry requires a sun-synchronous orbit (inclination 97.5°). A 10:30–22:30 local time is chosen as the best compromise between instrument safety (avoidance of the noon-midnight plane) and solar array illumination. A circular orbit with an altitude of 550±50 km is chosen to provide close viewing for limb scans and low enough atmospheric drag for a mission lifetime of at least one year.

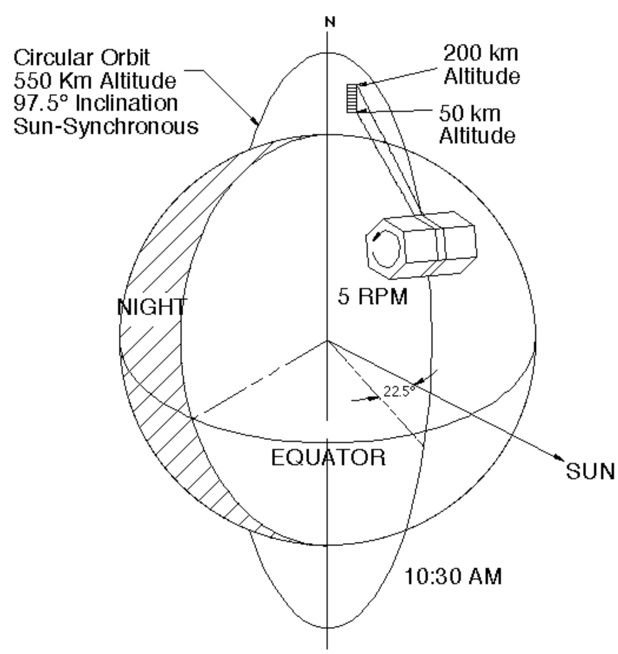


Figure 3. Mission scenario.

### 3.2 Experimental Method

The nitric oxide density will be determined by measuring gamma band fluorescent emissions with an ultraviolet spectrometer. The physical size and optical design of the instrument is similar to the SME ultraviolet spectrometer[8]. It will measure the (1,0) 215 nm and (0,1) 237 nm bands using the self-absorption technique demonstrated in a rocket experiment[9]. Limb measurements will be made from 50 to 200 km with altitude resolution of ~3.5 km by using the spinning motion of the satellite. Measurements below 70 km will be dominated by Rayleigh scattering from the neutral atmosphere, which will be used to calibrate the tangent ray height. The design of the auroral photometer is based on UV photometers that were developed for the Mariner 5 flight to Venus.[10] Photometers of this type[11] were also flown on OGO-5 and 6. Two photomultiplier tubes with cesium iodide photocathodes are used with calcium fluoride and barium fluoride filters to separate the atomic oxygen 130.4 nm line from the LBH bands and the atomic oxygen 135.6 nm line. The auroral photometer will detect auroral emissions over the polar regions during night; during daytime it will measure the far-ultraviolet dayglow. Solar soft X-rays will be measured using photometers that have been developed at LASP and NCAR for rocket experiments and for the Earth Observing System.[12] Thin metallic films directly deposited on silicon photodiodes are used to discriminate between wavelength bands in the 1–30 nm range.

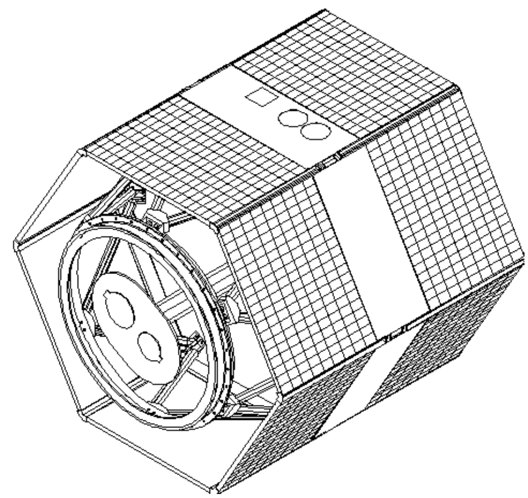

Figure 4. The SNOE spacecraft

### 3.3 Spacecraft Overview

The SNOE spacecraft (S/C) is a hexagonal aluminum structure, 37" high and 39" across at its widest point. Current estimated weight is 260 lbs; with contingency, the total weight is 280 lbs. It is spin-stabilized at 5 rpm about the x-axis, which is oriented normal to the orbital planeThe instruments and primary S/C components are mounted on a solid platform in the center section. The outer sections of the S/C are constructed of truss work to hold the twelve solar panels and launch vehicle attach fitting.

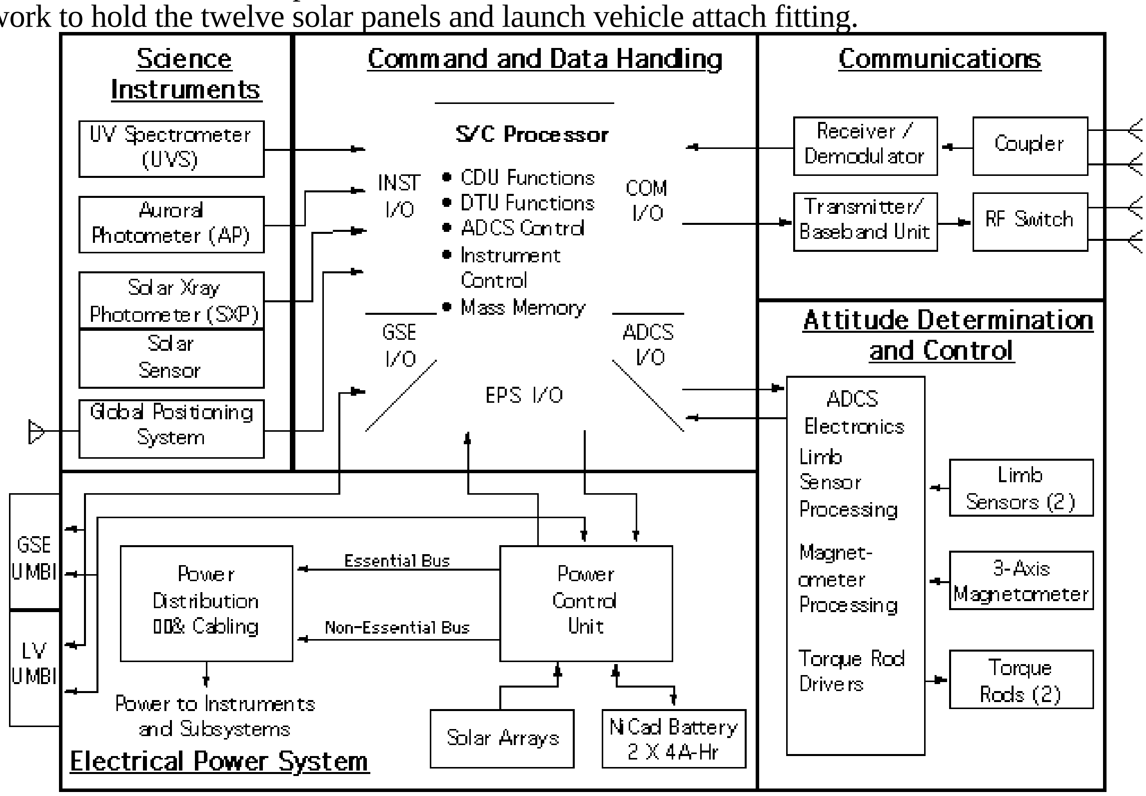


Figure 5. Spacecraft simplified block diagram

An integrated approach to all subsystems and instruments has been 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.

The power system is a direct energy transfer system using a combination of 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.

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 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.

## 4. SPACECRAFT STRUCTURE

The S/C structure consists of a central mounting plate, a launch adapter, 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. Attached in a band to the periphery of the central support plate, between the solar arrays, are six thermal radiator plates. The plates have apertures for the instruments. Multi-layer insulation (MLI) covers the open hexagonal ends of the S/C. Materials used in the assembly are principally aluminum. The assembled S/C fits within the dynamic envelope of a Pegasus™ XL launch vehicle with ample room for secondary payloads. The hexagonal structure is 39" maximum width and the overall S/C height is 37".

The first consideration in configuring the payload is to assure spin stability by designing the spin axis moment of inertia to be larger than the transverse axes moments of inertia. By careful distribution of components on the central plate and application of only 11 lbs of spin balance weights, the current configuration achieves a fully balanced S/C with a spin-to-transverse moment of inertia ratio of 1.2.

The S/C design involves four primary structural components: the central equipment and instrument mounting plate, two solar array assemblies and their support structures, the adapter structure that mates the S/C to the launch vehicle, including a separation assembly (Marmon clamp and actuator), and two antenna masts. In addition to these elements there is a thermal control system that is described below. A drawing of the S/C configuration is shown in Figure 6.

The central mounting plate provides support for the S/C electronics, instruments and cables. The launch adapter, solar panel structures, and antenna assemblies are mounted on it. It also provides a thermal path for heat generated in the interior of the S/C to reach the thermal radiators. The central mounting plate is fabricated from two weight-relieved aluminum plates in a “clamshell” arrangement, with 0.19" thick face sheets.

The launch vehicle adapter structure mates the S/C to the launch vehicle. The assembly consists of twelve struts (1" diameter and .083" wall thickness) which connect the central plate to a 23.25" diameter Marmon clamp on the launch vehicle end. The struts are attached to the Marmon clamp and central plate in pairs through connection blocks. During integration the adapter structure will be attached to the launch vehicle Marmon clamp using a clamp band.

The two hexagonal solar array assemblies consist of six 0.5" thick honeycomb panels that are approximately 18.75" wide by 13.5" tall. Solar cells are bonded to the surface of the honeycomb material using traditional mounting techniques. Two edges of each honeycomb panel attach to axial supports which serve as columns providing axial (spin axis) rigidity. Each set of six assembled solar panels is a monocoque, using the panels as shear ties. The assembled structure joins to the S/C by bolting the axial supports to thermal flexures which in turn are bolted to the central mounting plate. The thermal flexures consist of a thin (0.1") “blade” of titanium 1.0" in length. This approach allows the S/C equipment to be managed thermally without concern for the varying solar panel temperatures. The construction of the top and bottom solar array structures is essentially identical.

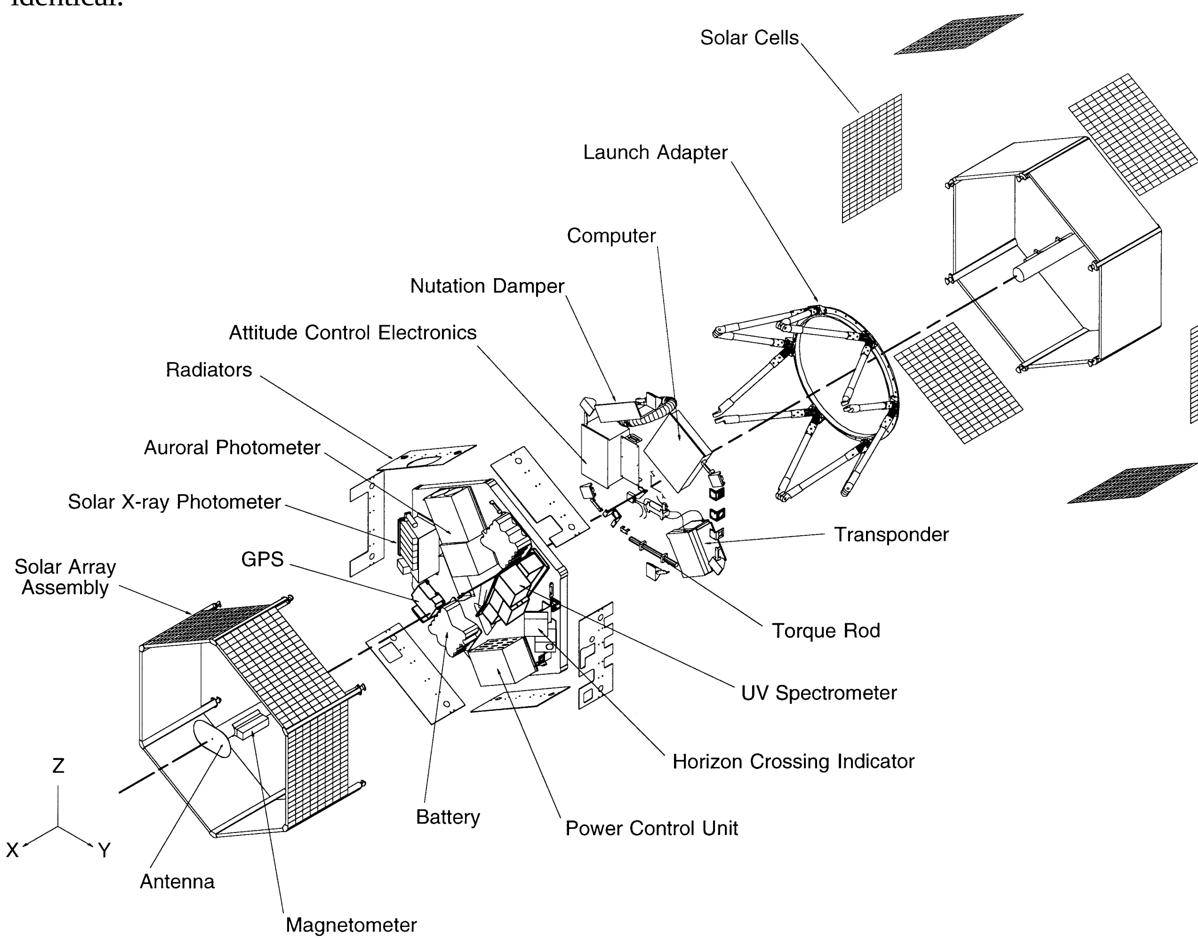


Figure 6. Spacecraft diagram

There are two patch antennas located on the spin axis at each end of the S/C. The antennas consist of a support tube and a thin plate. This assembly mounts to each side of the central mounting plate. The column provides structural support for the antenna, and precisely positions it so that the ground plane of the antenna sits above the solar arrays.

A finite element model of the S/C structure was constructed using Cosmos/M, consisting of 2278 elements and 1652 nodes. The structural model includes the adapter structure, the mounting plate and solar arrays. Masses representing S/C electrical and sensor components and scientific instruments were also included. Modal analysis of the first ten modes determined responses and displacements. The first mode frequency is 41 Hz, corresponding to a cantilever mode off the launch adapter Marmon clamp assembly.

## 5. SCIENTIFIC INSTRUMENTS

### 5.1 Ultraviolet Spectrometer

The ultraviolet spectrometer (UVS) measures the densities of nitric oxide between the altitudes of 50 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.

The spectrometer has a focal length of 125 mm and uses a 3600 l/mm mechanically ruled plane grating which produces a dispersion of 2.15 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 2.8 ms. To minimize requirements on the S/C, data will only be stored for the downward limb scan.

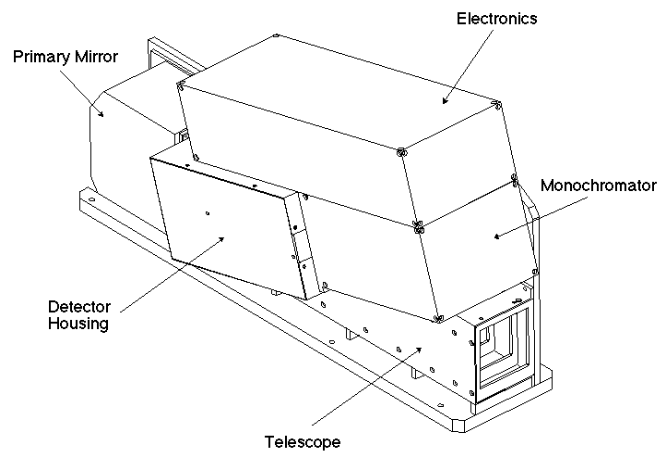

Figure 7. Ultraviolet spectrometer.

## 5.2 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.

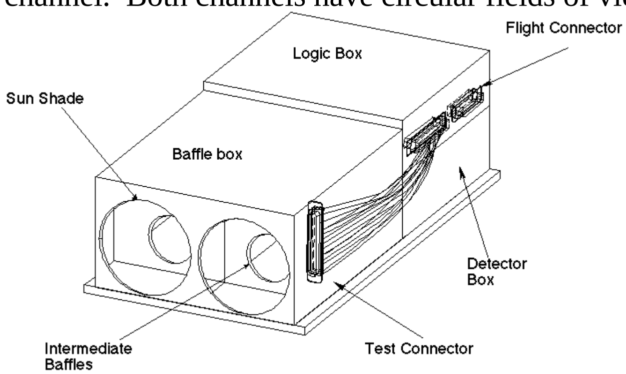

Figure 8. Auroral photometer

The detectors are identical phototubes with magnesium fluoride ($MgF_2$) windows and cesium iodide (CsI) photocathodes. Channel A has a calcium fluoride ($CaF_2$) filter placed in front of the detector and channel B 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 A, allowing a combined measurement of the LBH bands, the OI doublet at 135.6 nm, and the OI triplet at 130.4 nm. Channel B 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) will be stored.

## 5.3 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 bandpasses 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

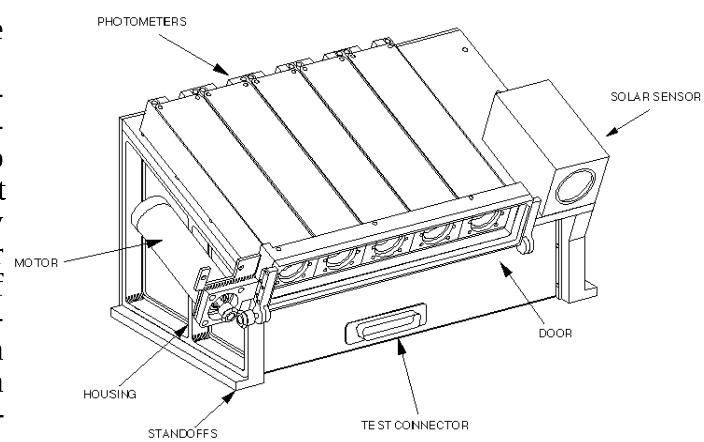

Figure 9. Solar X-ray photometer

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. Instruments of this design have flown on LASP and NCAR sounding rockets six times[12].

### 5.4 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. Estimated 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.

## 6. COMMAND AND DATA HANDLING

The command and data handling approach is to implement as many command and telemetry functions as possible in software, programming 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 a high rate 128 kbps playback channel. Realtime frames are also multiplexed into the high rate channel.

The main loop steps through 40 elements of a vector table, containing pointers to modules designed to execute in under 25 ms. Each step occurs at 25 ms intervals regardless of the length of the module execution, so the entire loop executes once per second. 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 modular approach leads to simplified flow-tracking and debugging of the flight software, and is an innovative but reliable method for S/C operation.

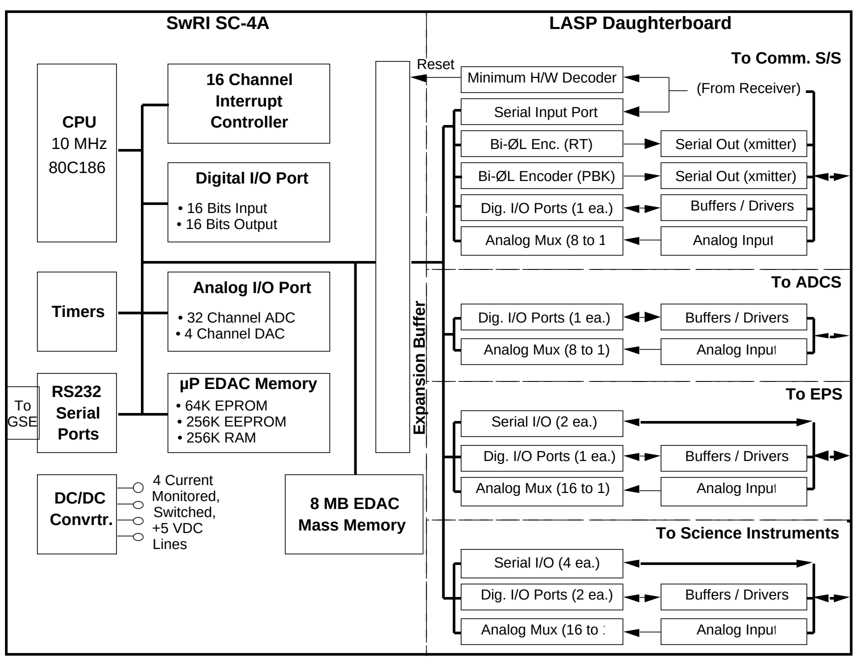


Figure 10. Spacecraft Processor block diagram

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, an expansion buffer for a daughter board, and four separate current monitored power lines in order to protect the unit from catastrophic damage due to latch-up. All memory includes single bit correction, and double bit error detection and correction (EDAC). Instead of an external mass memory unit, the 8 Mbyte internal mass memory of the SC-4A is employed for data storage. The custom LASP daughterboard provides the interface to all instruments and subsystems using field-programmable gate array (FPGA) chips, as illustrated in Figure 10.

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 small hardware 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.

## 7. ELECTRICAL POWER SYSTEM

The Electrical Power System (EPS) generates energy, stores it for use during peak demand cycles (e.g., transmitter operation) and during orbit eclipse, and controls the distribution of power to the required S/C and payload systems. Figure 11 is a simplified functional block diagram of the EPS. This figure shows the primary EPS functional elements as well as the monitoring and switching circuits used in the generation and control of S/C power.

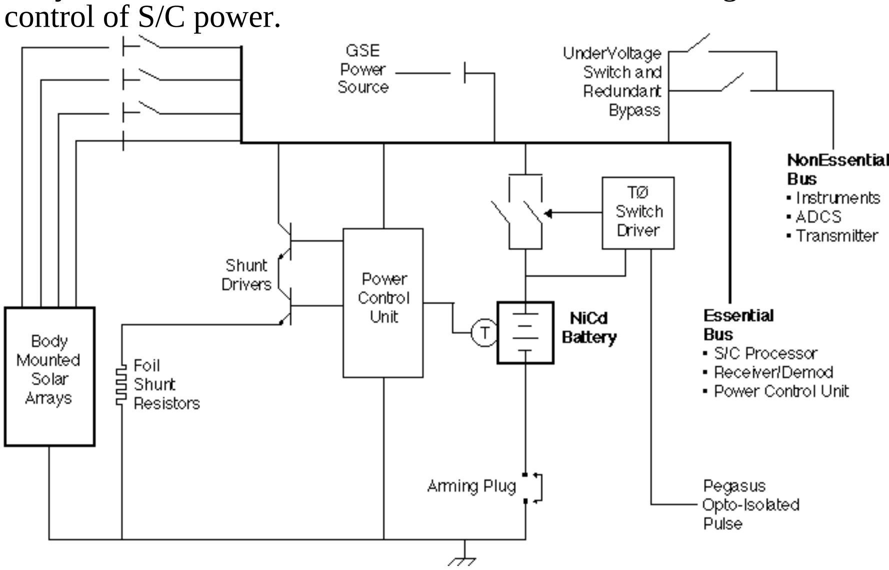


Figure 11. Electrical power system block diagram

Power is generated by body mounted solar arrays. There are twelve rectangular panels, each containing 2 array circuits (strings) for a total of 24 strings generating 24–32 volts. The strings consist of seventy-six 2.3 cm × 4.1 cm silicon photovoltaic cells. Diode isolation of the individual array circuits from the bus is used to prevent a failure in an array string from causing a failure of the entire power generation system. Assuming one-year degradation of 20% and a 30° solar angle of incidence, the solar arrays will generate >44 watt orbit average power at EOL, providing a >25% margin.

The solar cells are purchased from Heliokinetics. The 10 Ω -cm, 8 mil thick cells are AR coated and delivered with pre-installed cover glass and interconnection butterfly fittings. Criteria and procedures for selection of the individual flight solar cells include testing for cell open circuit voltage and short circuit current. Assembly of the arrays is performed by students at LASP.

Energy required for peak loads and during the eclipse portion of the orbit is stored in two 21-cell 4-Amp-hour Nickel Cadmium (NiCd) battery packs. The batteries use Sanyo N cells, tested, integrated and qualified at LASP using a flight proven Ball Aerospace process. The power usage profile produces an average battery depth of discharge of <10%. 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 battery and the associated generation of excess heat. Shunt regulation is performed by clamping the bus voltage to a level set by predetermined voltage and temperature curves (V-T control). Bus clamping action (regulation) is implemented by a two mode shunt controller which uses a combination of conventional linear shunt regulation (fine control mode) along with solar array string switching (coarse control mode).

The coarse control is achieved using switched array strings controlled by the V-T controller in a closed loop fashion. There are 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. Fine control is performed by a linear regulator that shunts excess power into resistors mounted on the inside of the solar panels. The V-T controller uses 4 voltage-temperature curves selected by uplink command. Power distribution includes two primary power busses; the essential bus and the non-essential bus. Circuits on the essential bus are the EPS itself, the command receiver/demodulator, and the S/C processor. All other loads are considered non-essential and are therefore disconnected when the bus voltage monitor detects a low voltage condition.

## 8. COMMUNICATIONS SYSTEM

The NASA compatible communications system, consisting of a receiver/demodulator, transmitter/baseband unit, hemispherical antennas, coupler, RF switch, and filter, provides a traditional yet low-cost approach. The transmitter and receiver are purchased from Cincinnati Electronics. The 2 Kbps NRZ-M command data is transmitted using NASA compatible PCM/PSK/PM modulation. Realtime telemetry modulation is PCM/PSK/PM, and the playback is PCM/PM.

The receiver features a double conversion technique that eliminates EMI generating multiplier circuitry and uses a single local oscillator to reduce costs, power consumption and parts count. The receiver acquisition threshold is -124 dbm and the command sensitivity is -115 dbm at a BER of $10^{-6}$. Demodulation is performed directly at the 16 KHz subcarrier through implementation of a modified Costas loop.

The transmitter/baseband unit provides 5 watts of output RF power. The unit accepts 512 bps Bi-$Ø_L$ realtime data and PSK modulates a 1.024 MHz subcarrier. The baseband unit phase modulates the transmitter with either the subcarrier or with the 128 Kbps Bi-$Ø_L$ playback data. The power amplifier uses GaAs FET power devices operating as a class AB amplifier to reduce generation of spurious signals.

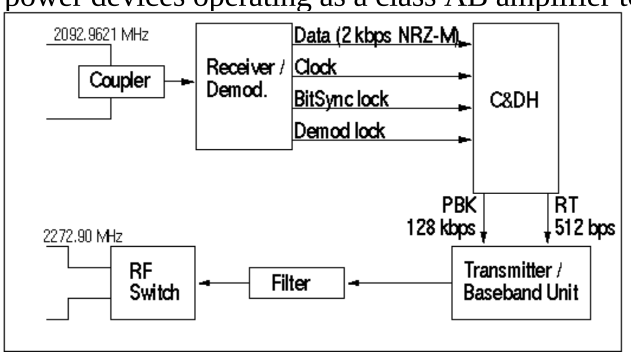


Figure 12. Communication system simplified block diagram

Each antenna assembly consists of wide-beam command and wide-beam telemetry radiating elements mounted on a common ground plane. The radiating element is a 1/2 wavelength disc etched by chemically removing copper cladding from a Teflon-impregnated fiberglass substrate. Right-hand circular polarization is achieved by positioning the feed point on the radiating element. The command antennas are coupled to provide omnidirectional coverage; the telemetry antennas are selected through the RF switch to improve the link margin while reducing interference

Command uplink and telemetry downlink margins are large: 8 db for command uplink, 15 db for realtime telemetry downlink, and 7 db for playback telemetry downlink, assuming use of a 4 meter AGS antenna. Margins are much larger if the 11 meter antenna at Wallops Island is used in a contingency situation.

## 9. ATTITUDE DETERMINATION AND 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 will be required.

In addition to providing attitude information, the attitude sensors also generate timing signals for use by the science payload. The HCI limb pulses initialize timer circuits that enable data taking during the appropriate portion of the S/C spin period. The limb crossing measurement obtained from the HCI will be better than

1° precision, but that is not sufficient for accurate analysis of the nitric oxide density profiles. Therefore, Rayleigh scattered sunlight from the atmosphere measured on the limb by the UVS will be used to calibrate after-the-fact limb timing knowledge; this technique was used effectively on SME.

## 10. 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 for each battery and at selected baseplate locations are included for contingency operation in case part of the S/C runs too cold. The solar panels are kept thermally isolated from the central plate by titanium flexures as described above in section 4 so that they may fluctuate in temperature while the subsystems and instruments remain fairly stable. This design has been analyzed using the SINDA-85 and TRASYS mathematical models, showing that the batteries and instruments should operate in the range 0–10 °C.

## 11. GROUND SUPPORT SYSTEM

The SNOE Ground Support System (GSS) provides the hardware and software needed for instrument and subsystem development, integration, test and pre-launch support. During the build-up and testing of each instrument and subsystem, personal computers are used for acquiring data, controlling equipment, and displaying and analyzing test data. During integration, system testing and pre-launch, two Unix workstations are used to monitor and control the S/C and to manage and analyze test data. Additional personal computers are used for flight software development. One of the Unix workstations resides in the Project Operations Control Center (POCC) and is used to conduct and monitor S/C tests. The other Unix workstation is co-located with the S/C at all times and connects to the S/C through a test connection or through the communications system to provide test engineers with the information and control that they require.

Almost all of the software used in ground testing is either commercial off-the-shelf (COTS) software or software that LASP has already 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. The hardware, software and procedures used for ground testing will be re-used during on-orbit operations. This reduces system development cost and makes it much easier to move from the test environment to on-orbit operations. It also permits us to provide student S/C controllers with extensive training by monitoring and controlling the S/C during ground test.

## 12. MISSION OPERATIONS

### 12.1 Tracking and Communications

SNOE ground communications will be handled by a new NASA initiative, the 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. AGS antenna sizes will be in the 3–5 meter range; it is anticipated the Poker Flat station will have a 5 meter antenna. S/C communications will use standard NASA S-band protocol. Active tracking and ranging is not provided in the baseline configuration, and so all tracking will be done using NORAD orbit elements and daily predicts. During the orbit injection and acquisition phase, NASA will provide full standard services based out of Wallops Island, which can also be used as a backup in case of problems at Poker Flat.

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

### 12.2 Mission Operations

S/C and instrument health and safety will be monitored at the POCC located in the LASP Space Technology Research building using the OASIS Command and Control (OASIS-CC) software package. Flight controllers will also use this software to prepare and transmit commands to the S/C during a pass. Most of the activities during a pass will be coordinated using procedures written in the Colorado Systems Test and Operations Language (CSTOL) that is part of OASIS-CC. Using canned procedures greatly reduces the work-load on the controllers. Prior to launch, the student flight controllers and flight engineers will develop and test the CSTOL procedures for both normal and contingency operations of the S/C.

After a pass, all of the data from the S/C will be processed and made available to the flight engineers, who will monitor the long-term health of the satellite and its instruments. Any commands needed to update S/C operations will be prepared by the flight engineers. Because SNOE is a relatively simple spacecraft, no special planning and scheduling system is required. Instead, commands will be encoded into CSTOL procedures and transferred to the flight controllers, who will run the procedures to send the commands during a pass. Orbit and attitude determination will be performed by specialists on the flight engineering team.

### 12.3 Data Processing and Analysis

After each contact with the S/C, real-time and playback data recorded during the contact will be processed. Level 0 processing will be performed to produce the best possible set of packets. Then engineering data will be extracted and checked employing the same OASIS-CC software used to assess S/C health during real-time contacts. An updated ephemeris of satellite position will be 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—will be stored into the database on one-minute centers.

After the necessary engineering and orbit-attitude have been computed, Level 1 science data processing will be performed. The science team will then analyze the data into higher level data products. All science, engineering and ancillary data products will be stored in a common database. A catalog will be provided so that scientists and engineers can quickly determine which data are available and the quality of the available data. We will provide software for extracting data from the database, interpolating orbit-attitude parameters, and deriving common orbit-attitude parameters needed in science analysis. We will use platform-independent data formats such as HDF or CDF to transfer data to the science team. All data will also be made available over Internet to other investigators.

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