SCIENCE INSTRUMENTATION FOR THE STUDENT NITRIC OXIDE EXPLORER

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Abstract

The Student Nitric Oxide Explorer (SNOE) is a small satellite to be designed built and operated at the University of Colorado under the Student Explorer Demonstration Initiative (STEDI) from the Universities Space Research Association. The goal of the STEDI program is to demonstrate that low cost satellite missions can be done with large student involvement. The primary science goals of SNOE are to measure thermospheric nitric oxide (NO) and its variability over the lifetime of the mission. SNOE will also monitor the solar irradiance at soft X-ray wavelengths and the auroral energy deposition at high latitudes. Three science instruments are required to achieve the simultaneous measurements: an ultraviolet spectrometer for NO; a solar soft X-ray photometer; and a far ultraviolet photometer for studying the aurora. The instruments are designed to represent a minimum impact on the spacecraft, particularly in terms of data storage and interactions with the command and data handling system. The focus of this paper is the outline of the design of the science instruments. We discuss why these instruments are well suited for smaller, lower cost satellite missions.

Keywords: Ultraviolet Instrumentation, Remote Sensing, Aurora, Airglow, Solar Irradiance

1. Introduction

The Student Explorer Demonstration Initiative (STEDI) is a program funded by the Universities Space Research Association (USRA). The goal of STEDI is to demonstrate the feasibility of low cost satellite missions which incorporate large student involvement in the design, fabrication, and operational phases. Two missions have been funded: the Student Nitric Oxide Explorer (SNOE, "*snowy*") and the Tomographic Experiment using Radiative Recombinative Ionospheric EUV and Radio Sources (TERRIERS, Boston University, D. M. Cotton, PI). Each mission is funded at a level of 4.3 million dollars for two years of design and fabrication and one year of mission operations. The cost of the launch vehicle is not included in this amount.

SNOE is a small spinning spacecraft with a 550 km orbit and nominal lifetime of one year. The mission science goals include measuring thermospheric nitric oxide (NO) and its variability. SNOE also measures the solar irradiance at soft X-ray wavelengths and the auroral energy deposition at high latitudes. Solar soft X-rays and auroral energy are thought to produce the large variability in NO observed with previous experiments such as the Solar Mesosphere Explorer[1,2]. Three science instruments are required to achieve the simultaneous measurements of NO, solar soft x-rays, and auroral energy. These are an ultraviolet (UV) spectrometer for NO, a solar soft X-ray photometer, and a far ultraviolet photometer for studying the aurora.

In order to meet the financial constraints of the STEDI program while accomplishing the science goals, the instrumentation must be designed to have a minimum impact on the spacecraft. Data rates must be kept to a minimum so that lower cost communications systems may be utilized. On SNOE, data is only stored for the portion of the spin during which relevant measurements are made. The output of each of the channels is electronically the same, minimizing the complexity of the interactions with the spacecraft microprocessor. In order to meet design cost limitations, instruments with heritage from other satellite missions and sounding rocket experiments are used. In this paper, we discuss the science goals of SNOE and the instrumentation used to accomplish those goals.

2. Science Overview

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 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. Significant questions concerning the production and variability of NO remain unanswered.

Nitric oxide has a maximum density of about $3x10^7$ cm^{-3} near 110 km (see Figure 1). In the polar region the mean density is several times greater and highly variable sometimes being as much as 10 times larger (see Figure 2). 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. Nitric oxide radiates in the infrared while the major constituents of the atmosphere do not.

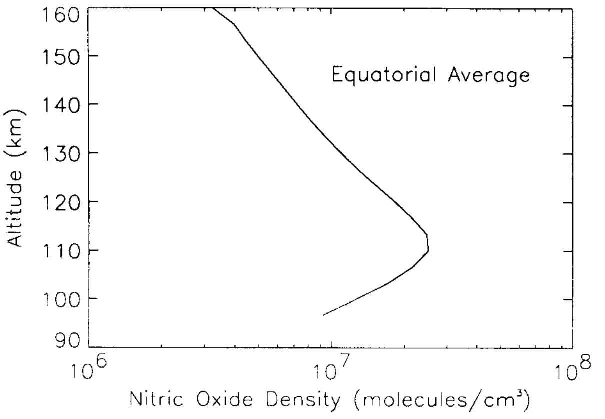


Figure 1. Nitric oxide density as a function of altitude. This profile is an average of SME observations in the equatorial region at times of low to moderate solar activity.

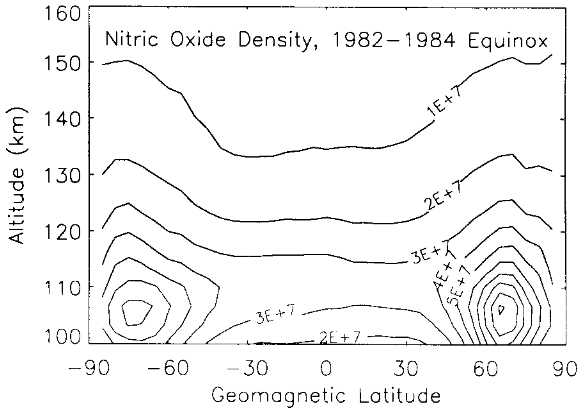


Figure 2. Latitudinal distribution of nitric oxide. Contour plots of the average nitric oxide density shows that the maximum density occurs in the auroral region.

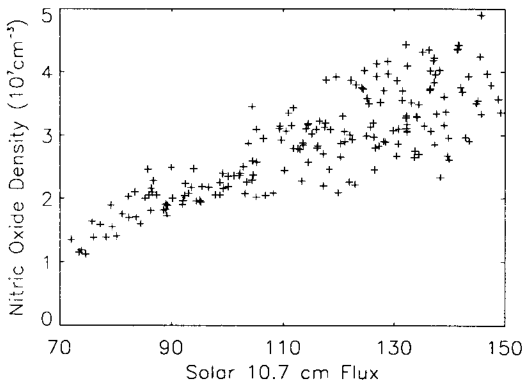
Nitric oxide plays an important role in ionospheric chemistry at all latitudes, because the energy necessary to ionize it is less than the energy needed to ionize the major constituents, molecular nitrogen and atomic and molecular oxygen. Nitric oxide is a source of ionization in the D-region, the lowest region of the ionosphere. In the E and F1 regions of the ionosphere, nitric oxide is an important participant in the ion-molecule and charge exchange reactions. Any change in the density of neutral nitric oxide produces changes in the composition and electron density of the ionosphere.

Nitric oxide plays an important role in the energy balance of the thermosphere. Since it is a heteronuclear molecule, it is able to radiate in the infrared portion of the spectrum, while molecular nitrogen and oxygen, being homonuclear molecules, are not. When nitric oxide density is high, its thermal emission at 5.3 μm makes a significant contribution to the cooling of the atmosphere.

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. An opportune time for downward transport to take place is during polar night when photodissociation of nitric oxide does not occur[3].

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. Nitrogen atoms at normal temperatures in the lower thermosphere produce only a small amount of nitric oxide. 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) thus 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 (30.0–102.6 nm) and soft X-radiation (0.1–30 nm) produces ionization in the upper atmosphere, it is only the most energetic photons that are able to produce photoelectrons with sufficient energy to produce energetic nitrogen atoms from the dissociation of molecular nitrogen. For example, in the ionization of molecular nitrogen, a solar photon of wavelength 30.4 nm (41 eV) produces a photoelectron with sufficient energy (25 eV) to dissociate molecular nitrogen and produce an energetic nitrogen atom in the ^{2}D state (2.4 eV).

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[2]. The reasoning behind this hypothesis is that the absorption coefficients of the atmospheric constituents are such that the solar soft X-rays are absorbed in the 100–120 km altitude region and that the ionization by the soft X-rays produces a copious source of photoelectrons. The hypothesis further states that the solar soft X-rays vary with a greater amplitude than does the solar extreme ultraviolet radiation. The evidence for this hypothesis comes from three years of observations of thermospheric nitric oxide from the Solar Mesosphere Explorer[1]. 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 two solar indices, the solar Lyman alpha irradiance which was measured from the SME spacecraft and the solar 10.7 cm radio flux which is a solar index that is measured from the ground (see Figure 3). Neither of these emissions plays an actual role in the production of nitric oxide in the thermosphere—the correlation is due to the partial ability of Lyman alpha and the 10.7 cm flux to track solar EUV and soft X-rays. An examination of Figure 3 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.



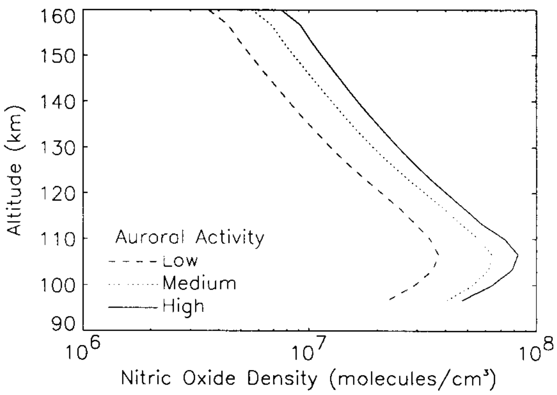


Figure 3. Variation of nitric oxide with solar activity. The nitric oxide density at 110 km is plotted as a function of the solar 10.7 cm flux which is an index of solar activity.

Figure 4. Nitric oxide density in the auroral region. SME observations show that nitric oxide density varies with auroral activity.

The first objective of SNOE is to test this hypothesis. The solar soft X-ray irradiance in the wavelength range 2–31 nm will be measured with a solar X-ray photometer. The nitric oxide density in the lower thermosphere will be measured with an ultraviolet spectrometer (215–237 nm) that observes the fluorescence of nitric oxide in the gamma bands. The comparison of the measured nitric oxide at low latitudes (25°S–25°N) between 100 and 120 km with the solar soft X-rays will show whether or not this hypothesis is correct. Further, the comparison of the observations will show the functional relationship between the magnitude of the nitric oxide density and the soft X-ray irradiance.

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 2). The most plausible explanation is that the polar region nitric oxide is produced by the impact of auroral electrons. When auroral primary electrons (energies 1–10 keV) bombard the atmosphere, they produce large numbers of secondary electrons. Those secondary electrons with energies greater than 13.3 eV are able to dissociate molecular nitrogen and produce energetic nitrogen atoms which in turn produce nitric oxide. Secondary electrons with energy greater than 15.5 eV ionize molecular nitrogen leading to the production of energetic nitrogen atoms. Photochemical theory indicates that any nitric oxide produced in the auroral zone will have a lifetime of greater than a day; thus, it is the auroral activity of the previous day or longer that should determine the amount of nitric oxide present. During the auroral bombardment process, the secondary electrons also excite molecular nitrogen and atomic oxygen to produce auroral emissions in the ultraviolet and visible portions of the spectrum. The intensity of these auroral emissions may be used to determine the flux of the auroral electrons. The theory of auroral excitation is well-developed[4]. 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[5,6]. Figure 4 shows average nitric oxide density profiles for conditions of low, medium, and high auroral activity. The geomagnetic index Ap was used to sort the observations into low, medium, and high activity; however, there is not a satisfactory quantitative relationship between nitric oxide density and the Ap index.

The second objective of SNOE is to determine how auroral activity produces increased nitric oxide in the auroral regions. This will be accomplished by measuring the nitric oxide density with the ultraviolet spectrometer and by measuring the intensity of the ultraviolet aurora with the auroral photometer. The auroral photometer will determine the intensity of the Lyman-Birge-Hopfield (LBH) bands of molecular nitrogen and the atomic oxygen resonance (130.4 nm) and forbidden (135.6 nm) lines, which are excited by auroral electron impact. Since the ultraviolet aurora will be measured on the nightside every orbit (96 min.) in both the north and south hemispheres, a global time history of auroral activity will be determined. The intensity of the auroral flux will be determined from the intensity of the LBH bands. The intensity of the atomic oxygen 130.4 nm line will be related to the auroral intensity through a radiative transfer calculation. The relationship between the auroral region nitric oxide density and the time history of auroral intensity will be used to determine if in fact electron bombardment by auroral particles is the dominant process in producing polar nitric oxide.

The vertical distribution of nitric oxide in the thermosphere has been measured many times from sounding rockets. A recent rocket experiment has demonstrated a technique that is relatively insensitive to calibration errors[7]. Since this technique uses the simultaneous measurement of a partially self-absorbed and an optically-thin emission band to determine the nitric oxide density, the result is primarily dependent upon the absorption oscillator strength of the nitric oxide gamma band which is determined from a laboratory measurement. This experiment was flown in June, 1994 and June, 1995. The simultaneous two-band measurement is the technique proposed for this satellite experiment.

Solar soft X-rays in the wavelength region 4.4–6.0 nm were measured in a series of satellite experiments by the Naval Research Laboratory during the 1960's and in the late 1970's. These Solar Radiation Satellites (SOLRAD) are no longer operational, but there are current data analysis activities. During the SME nitric oxide observations, there were no satellite measurements of solar soft X-rays. Solar X-rays in the 0.1–0.8 nm wavelength region are currently being measured by the GOES series of satellites and quick-look data is readily available. However, these X-rays do not significantly affect the density of nitric oxide in the lower thermosphere.

The ultraviolet aurora has been extensively imaged from the Dynamics Explorer satellite[8]. The brightest images are those of the atomic oxygen 130.4 nm line which is an optically-thick emission. There is also an extensive set of images of the wavelength band which includes the optically-thin atomic oxygen 135.6 nm line and a series of LBH bands. The POLAR satellite launched in 1996 includes an instrument that will image the ultraviolet aurora in the LBH bands. Recent rocket experiments made simultaneous measurements of the dayglow LBH bands and the solar extreme ultraviolet and soft X-radiation[9,10]. A model has been developed to relate the intensity of the LBH bands and the 135.6 nm line to the flux of photoelectrons[10].

3. Mission Overview

SNOE will be launched on a PEGASUS XL in May 1997. The SNOE spacecraft is spin stabilized with the spin axis normal to the orbital plane. The sun-synchronous orbit is circular at 550±50 km altitude with 97.5° inclination. A 10:30–22:30 orbit is selected to meet the science and design requirements. The design requirements are that the solar panels receive sufficient illumination, but that the orbit is sufficiently far from the noon-midnight plane that it will not precess into it during the mission lifetime. Precession can occur due to launch vehicle injection errors. An orbit in the noon-midnight plane is undesirable as it places the sun into the fields of view of the two airglow instruments for part of each spin. The sun is much brighter than the airglow and would saturate the detectors. A program lifetime in orbit of one year is anticipated. For the target altitude range, actual satellite lifetime should be longer, which provides extra launch margin. Requirements for comprehensive mission success are measurements for a period of 81 days (three solar rotations) of nitric oxide altitude profiles, auroral energy flux along the satellite orbit, and solar X-ray emissions. A detailed description of the mission is provided by Solomon *et al.* (11). Figure 5 shows a schematic of SNOE in orbit.

4. Instrument Descriptions

The science instrumentation for the SNOE mission consists of: (1) an ultraviolet spectrometer to measure nitric oxide density, (2) an auroral photometer to measure the flux of energetic electrons entering the Earth’s atmosphere at high latitude, and (3) a solar soft X-ray photometer to measure the solar irradiance at wavelengths from 2 to 28 nm. The specifications of the individual instruments are now given.

4.1 Ultraviolet Spectrometer

The primary function of the ultraviolet spectrometer (UVS) is to measure the densities of nitric oxide between the altitudes of 50 and 200 km in the terrestrial upper atmosphere by observing the NO (1,0) and (0,1) gamma bands. The UVS design was developed under the SME program and was successfully flown on SME. Figure 6 shows an optical layout and perspective drawing of the UVS. It consists of an Ebert-Fastie spectrometer, an off-axis telescope, and two Hamamatsu 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 1.86 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 and is used to image the spectrometer slit on the Earth’s limb. The combination of the spectrometer and the detectors produces a spacing of 22 nm between the two channels and the exit slits will be sized to give each detector a 3.6 nm bandpass. The grating in the spectrometer will be set to place the (1,0) gamma band (215 nm) on one detector and the (0,1) gamma band (237 nm) on the other detector. Both channels have a sensitivity of ~18 counts/second per Rayleigh/Angstrom.

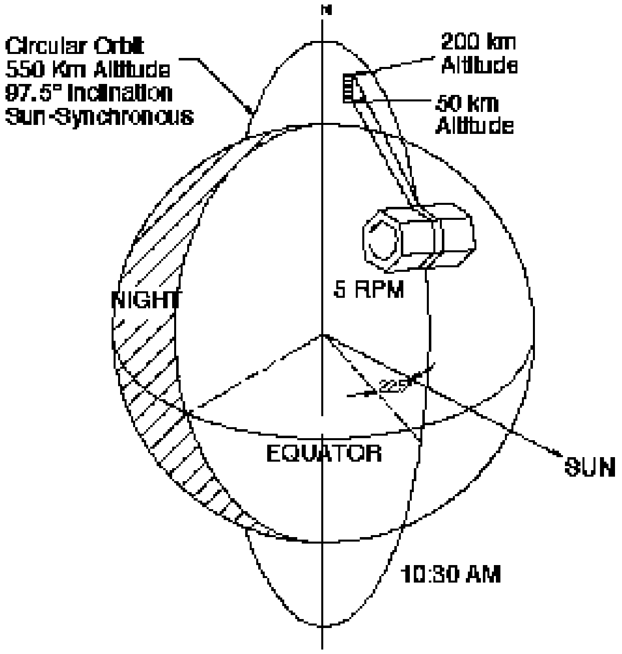


Figure 5. Schematic view of SNOE in orbit.

The UVS is mounted with its optical axis perpendicular to the spin axis of the spacecraft. Its telescope images the entrance slit of the spectrometer on the Earth’s 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. Figure 6 shows the pointing of the UVS in orbit. The integration time of the UVS is set to 2.8 milliseconds. Once the spacecraft has achieved orbit, the UVS high voltage will be turned on and each channel will produce a continuous stream of data. To minimize requirements on the spacecraft, data will only be stored for the downward limb scan. Allowing for some overscan, this produces 64 samples per spin from each channel. The storage operation will be initiated by a signal derived from a horizon crossing indicator in the Attitude Determination and Control System (ADCS). The data are stored in a buffer which will be periodically emptied, time-tagged, and stored by the spacecraft microprocessor. The UVS electronics are identical to the auroral photometer electronics; a functional block diagram appropriate to both of these instruments is shown in Figure 7.

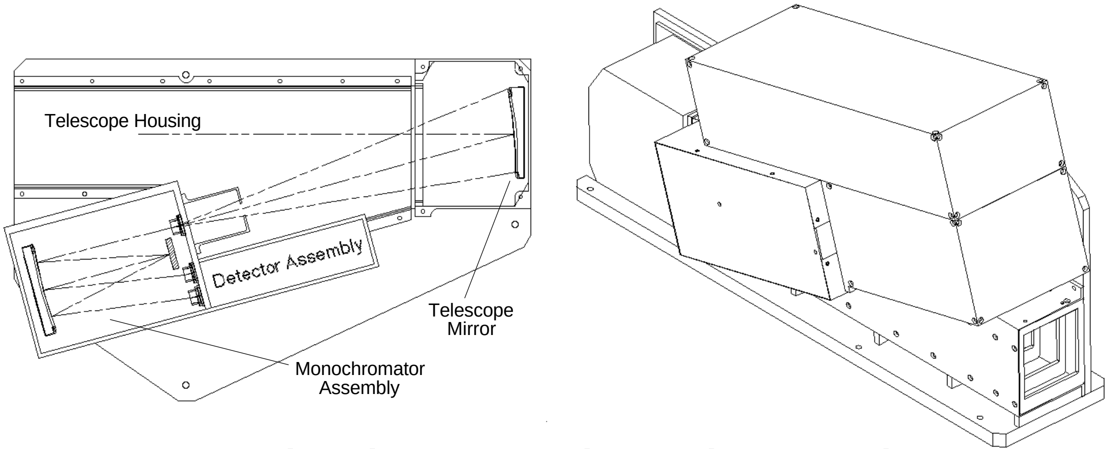


Figure 6. Ultraviolet Spectrometer layout and perspective drawing.

NO concentrations can be determined through inversion of the altitude profiles of the observed NO airglow features. Of the two features observed, only the (1,0) band is attenuated as it travels through the atmosphere. The attenuation is due to self absorption by NO molecules along the path. The ratio of the brightnesses of the attenuated and unattenuated emission is dependent upon the abundance of NO. The relationship between this ratio and the column density of NO has been determined and can therefore be used in remote sensing of NO[7]. This technique will be employed by SNOE. The use of emission ratios rather than absolute brightnesses provides improved accuracy because ratios do not depend on the absolute calibration of the instrument. The need for only two emissions allows the use of simple detectors rather than the more expensive and intricate imaging detectors frequently used.

4.2 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. It is a copy of airglow photometers developed by LASP and flown on OGO-5 and -6 in the late 1960's. A perspective drawing of the AP is shown in Figure 7. The channels (A and B) 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 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 sensitivity of channel A at 130.4 nm is ~3.5 counts/second/Rayleigh and the sensitivity of channel B at 135.6 nm is ~14 counts/second/Rayleigh. 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 spacecraft spin axis. The AP produces continuous data but at a much lower rate than the UVS. Only the downward-looking 180° of each spin (limb-to-limb nadir scan) will be stored. The integration time for each channel is set to 183 milliseconds which provides 32 samples per channel per spin. Data from the AP is stored in its buffer, which is periodically emptied by the spacecraft microprocessor. A block diagram of the logic electronics is shown in Figure 7.

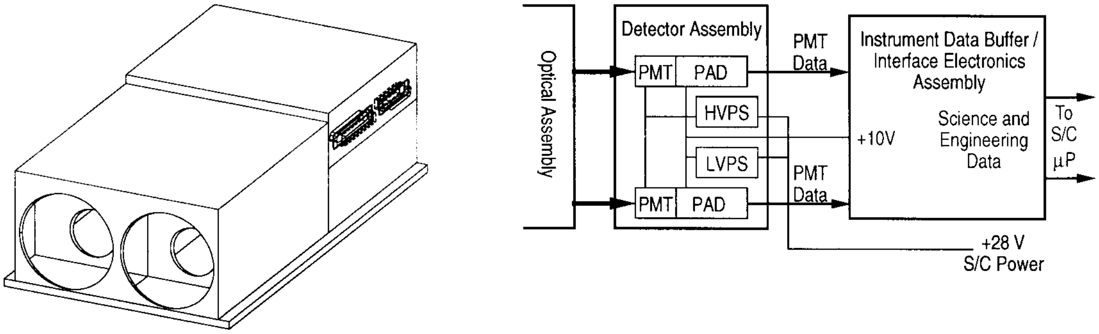


Figure 7. Auroral photometer prospective drawing and functional block diagram.

The pass band of channel B is dominated by the N_2 LBH bands, the brightness of these airglow features is directly proportional to the energy deposited into the atmosphere[10]. Channel A is dominated by the OI feature at 130.4 nm. The ratio of OI and N_2 emissions is a function of the characteristic energy of the impinging auroral electrons[12]. Thus, the simple 2 channel photometer system is capable of describing the energy input to the atmosphere.

4.3 Solar X-Ray Photometer

The solar X-ray photometer (SXP) measures the solar irradiance at wavelengths from 2 to 31 nm. Each photometer channel contains a silicon photodiode; wavelength selection is accomplished by thin metallic films deposited directly onto the diode surface. Five photodiodes are flown, Table 1 lists the different coatings and their thicknesses. 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, including the 2–10 nm irradiance.

The fields of view are ~70° full-cone to obtain a solar measurement once per spin during the day. The SXP is mounted to point 22.5° from the spacecraft spin axis. This geometry places the sun at the center of the field of view once during each dayside spin for a 10:30 orbit.

Table 1. Solar X-ray photometer channels

Channel	Metallic Coating	Thickness (nm)	Passband (nm)	Active Area (cm^2)
1	Ti	250	2–5	0.1
2	Sn	600	2–10	0.1
3	Zr/Ti/C	200/5/50	10–17	0.1
4	Al/C/Sc	200/50/50	17–31	0.1
5	none	–	UV-Visible	.0001

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. These pulses are counted over 62.5 millisecond integration periods by the instrument electronics and stored in a data buffer that is periodically emptied by the spacecraft microprocessor. The use of the voltage-to-frequency converter has the advantages of allowing a larger dynamic range in the measurements and providing an output equivalent to that of the phototubes in the other instruments. Instruments of this design have flown on LASP and HAO sounding rockets six times[9,13]. A perspective drawing and functional block diagram of the instrument electronics are shown in Figure 8.

Part of the measured current is due to visible-wavelength radiation entering through microscopic flaws in the photodiode coating. To measure these background currents a door mechanism fitted with a fused silica window is included. The fused silica allows all visible light to reach the photodiode but rejects light below 160 nm, thus when the door is closed the signal is completely due to background visible light. The window is opened and closed once in an orbit and the process is repeated every other orbit. The X-ray signal is obtained by subtracting data taken with the window closed from data taken with the window open. Transmission of the window is measured using the channel 5 photodiode which has no coating. The stable visible sunlight will be used to detect any window degradation. Dark currents will be measured by looking at the dark sky.

A small two-axis sun sensor is co-aligned with the SXP to measure the solar incidence angle for the instrument. This measurement is useful because the measured signal will vary as the cosine of this angle. This sensor was developed at LASP for the rocket program and was flight tested in on two sounding rockets; a copy will be fabricated for SNOE.

This instrument is well suited for use on small satellites. The simple output of a photodiode allows for low data rates and simplified control circuitry. The combined use of several photodiodes provides adequate spectral resolution while allowing a lower data rate than a readout detector in a grating spectrograph. The ability to directly deposit the thin film to the surface of the photodiodes is a significant simplification over the use of foil filters which are difficult to handle and tend to develop pinholes after time.

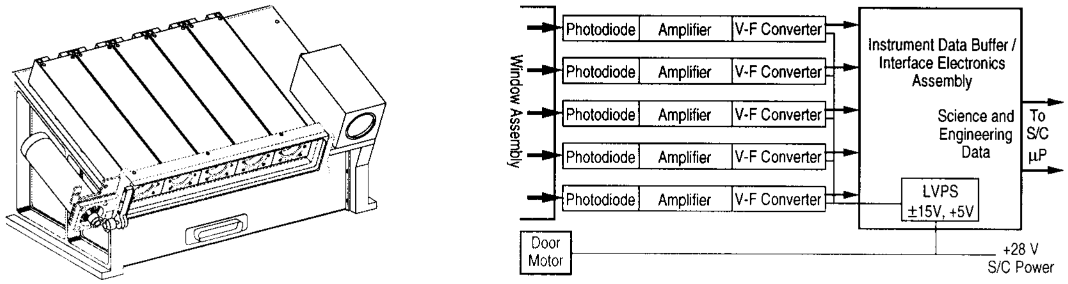


Figure 8. Solar X-ray photometer perspective drawing and functional block diagram.

5. Instrument Logic

The electrical interfaces to the spacecraft are identical for each instrument. This is possible because the UVS and AP have identical detector systems and because the output of an SXP channel is electrically identical to a PMT. Equivalent circuitry has the advantages of reducing both design and test time and therefore overall cost. Every spin, data storage for each instrument is initiated by a signal from a pair of Horizon Crossing Indicators (HCI).

The instrument logic performs the following functions: interprets command words from the spacecraft microprocessor, initiates data storage based upon signal from HCI, and informs the spacecraft microprocessor that the data buffer is ready to be read. The command word provides the logic interface with integration time, delay time between integration periods, and delay time between HCI pulse and data storage initiation. For the UVS and AP the delay time between integration periods is typically zero.

The electrical design for the logic interface is based upon Field Programmable Gate Arrays (FPGA). A single FPGA can be used to perform many logic functions and therefore dramatically reduces the number of integrated circuits required. The result is a streamlined design with reduced packaging and lower power requirements.

6. Summary

The science instruments for the SNOE mission have been described. SNOE is a low cost satellite mission utilizing large student involvement in all phases of the project. In order to accomplish the science goals while meeting the constraints of the STEDI program, relatively simple science instruments with high flight heritage are used. A design which minimizes the impact of the instruments on the spacecraft is crucial. Such a design is achieved on SNOE by using instruments which have identical electrical interfaces. Data rates are kept to a minimum by storing data only during those portions of the spin where useful measurements are made. SNOE will be launched in May of 1977 and will be operated in orbit for one year.

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