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AURORAL IMAGES FROM SPACE: IMAGERY, SPECTROSCOPY, AND PHOTOMETRY

The Polar BEAR Mission required a multimodal instrument (comprising imagery, spectroscopy, and photometry) known as the Auroral Ionospheric Remote Sensor. The sensor produces auroral images in both dark and sunlit hemispheres and enables the remote sensing of ionospheric airglows to aid in the detection of ionospheric electron-density profiles and atmospheric background emissions.

INTRODUCTION

The correlation between auroral storm activity and magnetospheric events and their combined effects are significant in the investigation of radio scintillation phenomena and in the remote sensing of ionospheric airglows. Ionospheric data will be useful in developing better models of electron-density profiles and in establishing a background emissions measurement base. Whereas vacuum-ultraviolet (VUV) imagery permits both daytime and nighttime operation, visible/near-ultraviolet (UV) imagery is useful only during nighttime operation. The Auroral Ionospheric Remote Sensor (AIRS) is a very-low-level signal-photon detection instrument with a sensitivity of 30 R (1 rayleigh $= 10^6$ photons/ $(\text{cm}^2 \cdot \text{s})$) for VUV channels and approximately 1000 R for the near-UV/visible channels.

OPERATION

The AIRS instrument is a multimodal system with selected imaging, spectrometer, and photometer operations at four wavelengths with a limit of one image per orbit at each selected wavelength. AIRS is a second-generation instrument with much added sophistication over the single-channel Auroral Ionospheric Mapper system on the HILAT spacecraft.[1]

AIRS is a four-channel system that operates simultaneously in the VUV, near-UV, and visible spectral bands. Two channels are designed to operate in the VUV using an Ebert-Fastie spectrometer. The other two channels use a filter-selector system. All four are aligned to view the same auroral scene (i.e., the north polar cap) via appropriate optics and a scan-mirror system. In effect, a line-scan image of the auroral scene is created by the scan mirror operating in the orbit cross plane, with the orbit in-plane direction provided by the forward motion of the spacecraft. All four channels also can operate in the photometer mode by locking the scan mirror in the nadir-viewing position. The two VUV channels can operate in a spectrometer mode as well, with the scan mirror locked in the nadir-viewing position and the Ebert-Fastie spectrometer performing a spectral scan.

The Polar BEAR host spacecraft for the AIRS instrument provides a three-axis stabilized platform. The spacecraft altitude is approximately 1000 km, with a polar circular orbit at a 90° inclination. The orbital period is approximately 110 min, including a 27-min period of instrument on-time over the north polar cap. The operational lifetime of the AIRS instrument is at least 1 year, with a 3-year goal desirable.

The spacecraft has a forward orbital velocity of approximately 6.6 km/s at the satellite–ground subtrack point. With the AIRS instrument in a line-scan imaging mode of operation, the duration of the line scan and the equivalent forward motion of 1-pixel height must be compatible to provide a near-contiguous-image scan system. This, in conjunction with the desired number of image pixels per line scan, angular resolution, and spacecraft-attitude characteristics, gives an imaging line scan of $\pm 67.2°$ in 2.36 s with an 0.64-s retrace time for a total of a 3-s line-scan period. Because of telemetry constraints, image line-scan data are collected over only $\pm 65.2°$ for a total of 326 pixels per line. All four simultaneous channels are optically aligned to yield a coincident image-pixel structure. The angular line scan in the orbit cross plane has been selected to view horizon-to-horizon at an average altitude of 1000 km, with a 5° margin at each end to allow for roll perturbations in the spacecraft attitude. Figure 1 shows the system's basic scene geometry and the imaging scan-path detail. The image-pixel distortion increases with the off-nadir viewing angle. The distortion is corrected for image display by the ground-system image data processing computer.

The imaging mode of operation produces a single ground-level pictorial swath that is approximately 6709 km wide. This occurs once per spacecraft orbit for each of the four instrument channels. In the VUV spectrum, two images are formed at preselected 3-nm-increment spectral windows between 115 and 180 nm, with a 24-nm separation between the two channels. In the near-UV and visible channels, either the 630- and 391.4-nm channels or the 337.1- and 225-nm channels are activated simultaneously. The imagery viewed from a 1000-km altitude will yield a 6.5- × 26.7-km spatial resolution in the VUV with coincident pixel imaging of 26 × 39.26 km in the near-UV/visible spectrum. The photometer mode exhibits the same field of view (FOV) as the instantaneous field of view (IFOV) in the imaging mode; however,

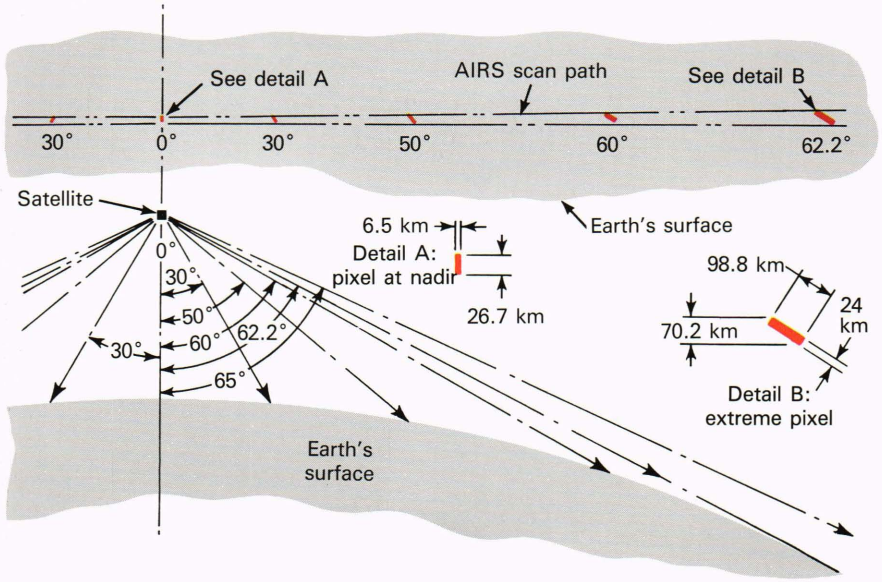

Figure 1 — AIRS pixel-footprint projection as a function of image scan-path angle.

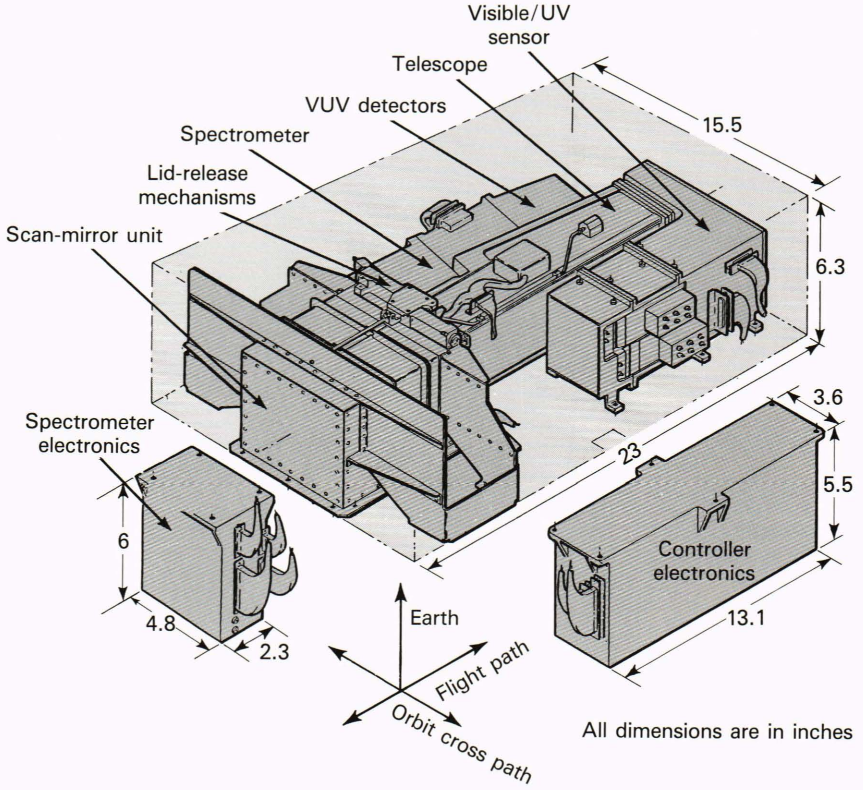

Figure 2 — Outline drawing of the AIRS instrument.

the instrument views only the nadir-image pixel at the preselected wavelengths for all four channels. The spectrometer mode also views only the nadir-image pixel, but only the VUV channels are being scanned in wavelength. The near-UV/visible channels continue to operate in the photometer mode.

The VUV channels give a line-scan image with a 25% overlap in the direction of the spacecraft orbit and with contiguous stepping in the orbit cross plane. The near-UV/visible channels have a 50% overlap in the direction of the orbit plane and a 75% overlap in the orbit cross plane. The system design is such that the spatial resolution of the near-UV/visible channels is approximately 25% that of the VUV channels in the orbit cross-plane direction. This arrangement is a trade-off between spatial resolution and sensitivity.

Figure 2, an outline drawing of the AIRS instrument, shows the two electronics packages fastened to the underside of the spacecraft's payload instrument deck. The electro-optics unit, which contains the telescope, spectrometer, sensor units, and scan-mirror unit, is attached to the earth-viewing surface of the spacecraft's instrument-mounting deck. The entire AIRS system (including interconnecting electrical harness) weighs 10.45 kg, consumes an average maximum power of 9.5 W, and has a total data rate of 3536 bits/s.

The scan-mirror unit is protected by a closed lid equipped with a pyrotechnic release mechanism that allows the two halves of the clamshell lid to open after reaching orbit. The lid release was actuated 8 h after launch by a common spacecraft command that also was used to release several antennas. All four sensor channels view the earth scene via the common scan mirror.

The number of commands available for the AIRS instrument from the spacecraft was limited to three. To accommodate the various AIRS operating modes and provide the required wavelength selections for both the VUV and near-UV/visible channels, it was necessary to develop a controller electronics package that would embody six command sequences and one index sequencer. This entailed the use of one command for an on/off function, with the remaining two commands for the command- and index-sequencer function selections.

Because of the spacecraft orbit and the 27-min AIRS operation time over the north polar region, some shielding was needed to avoid unwanted radiation from free electrons in the space environment. This was particularly important since the AIRS instrument is a photon-counting system operating with extremely low signal levels. Shielding with tantalum plates placed in strategic locations around the four sensor units allows discrimination against free electrons with energies up to 3 keV, which is adequate to handle the active orbital segment of AIRS operation. Orbital radiation levels dictated the use of radiation-hardened CMOS electronics. This will permit an accumulated radiation dosage of 10^5 rads, which is compatible with the 3-year operational lifetime goal for AIRS.

The AIRS instrument has been operating satisfactorily as described above since turn-on in November 1986. Figures 3a and 3b show some typical imagery that has been generated from the orbiting spacecraft.

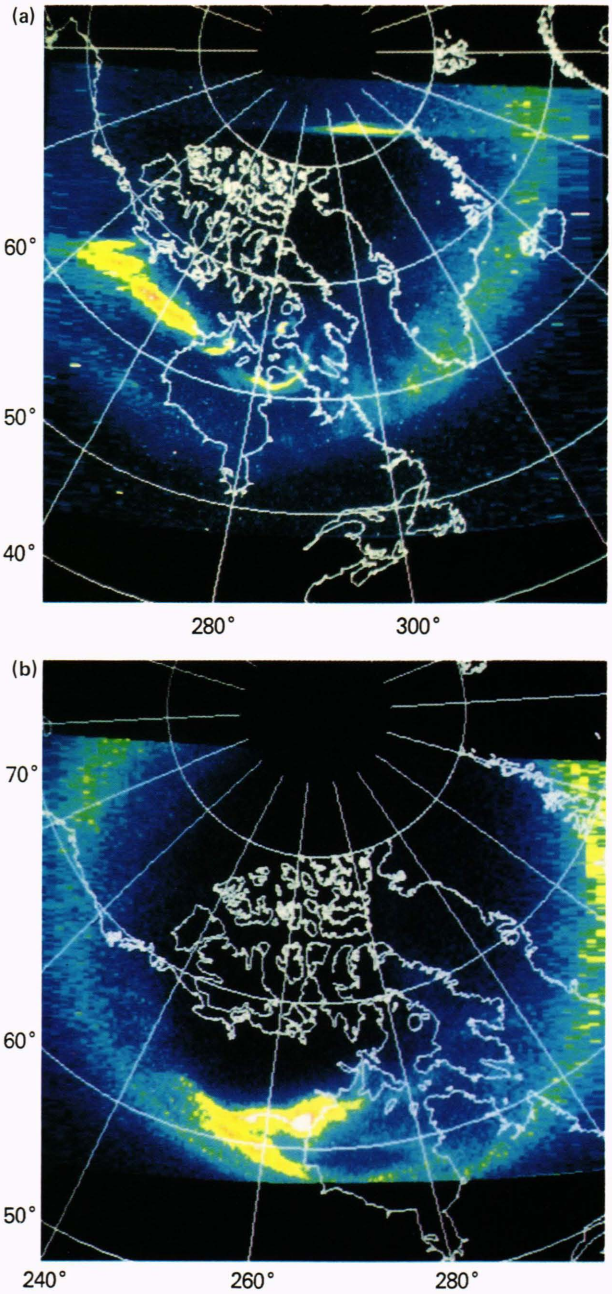

Figure 3 — (a) VUV spectrometer imagery, 391.4 nm, January 3, 1987 (Day 3), 0538:47–0550:18, at Sondre Stromfjord; (b) near-UV (fixed λ channel) imagery, 130.4 nm, January 15, 1987 (Day 15), 0624:58–0633:33, at Sondre Stromfjord.

DESIGN

The AIRS instrument is divided into several basic blocks. Figure 4, which shows the actual flight hardware, can be compared to the outline drawing of Fig. 2. The scan-mirror unit provides a common input path for all of the sensor subsystems.

The scan mirror feeds the optical signal to the off-axis parabolic telescope mirror that has a 1-cm aperture at its center. Most of the optical signal is reflected to a spectrometer operating in the VUV wavelengths. The portion of the optical signal passing through the 1-cm aperture in the telescope mirror is viewed by a visible and near-UV sensor system.

The portion of the optical signal passing to the spectrometer is focused onto the spectrometer's entrance slit by the telescope mirror. The spectrometer spreads the VUV (11.5- to 180-nm) input-signal spectrum image over an output area equipped with a dual-slit plate. The two slits are separated to yield a 24-nm differential between the two emergent optical outputs. Each output is collected on the photocathode of two separate photomultiplier-tube-sensor packages where photon counting is performed.

The portion of the optical signal passing through the 1-cm aperture in the telescope mirror is viewed by a refractive/objective lens that in turn feeds a complex of mirrors, beamsplitters, and a filter selector that produces two emergent beams. Each beam is in a different spectral

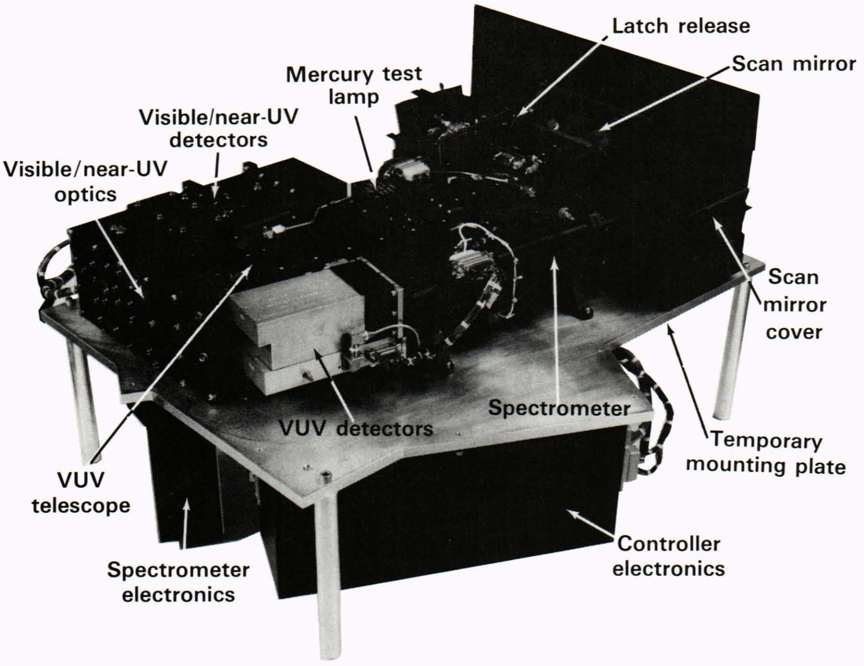

Figure 4 — AIRS flight hardware.

band and each is collected on the photocathode of a separate photomultiplier-tube sensor for photon counting.

The common input scan mirror for the four simultaneous, optically coaligned channels (each in a different spectral band) is driven by a stepper motor at 0.4° per step in the imaging mode. An alternative is to lock the stepper motor so that the scan mirror views only the nadir position, thus automatically turning the four imaging channels into photometer-type operation. It is also possible to select a spectrometer mode of operation for the VUV system while in the nadir-view lock position, which permits an end-to-end VUV spectral scan for each of the two VUV channels.

All modes of instrument operation are determined by ground command, which controls the position selection of the command and index sequencers in the electronics controller unit. Table 1 lists the various operational, backup, and test modes that may be selected.

The VUV spectrometer operates with a separate electronics package that also is controlled by the electronics controller unit. The spectrometer grating is rotated by a stepper motor with a 0.3-nm resolution. An optical readout device determines the position of the low end of the wavelength range, from which a reference counter is indexed to yield the exact grating wavelength position.

The operation of the AIRS instrument can be inhibited partially or totally by two independent illumination sensors, both of which view the same object scene via the input scan mirror. One sensor controls only the inhibit function for the VUV channels and is triggered by high-level inputs (e.g., direct solar radiation). The sensor will not inhibit on inputs such as earth albedo. The other illumination sensor controls only the inhibit function of the visible and near-UV channels. This unit will trigger on-earth albedo input levels. Both illumination sensors operate automatically but can be overridden manually. Tables 2 and 3 give specific design characteristics for the VUV and visible/near-UV channels, respectively.

Electro-Optics

A generalized optical schematic without the scan mirror is shown in Fig. 5. The optical paths for the VUV-spectrometer-wavelength-selector dual-channel system are apparent. The Ebert-Fastie spectrometer uses a split refocusing mirror. The second half of the mirror, receiving the spectra from the grating, has a longer focal length than the first half, which inputs the optical rays into the grating. The technique allows an adequate physical separation of the two spectrometer exit slits and thereby facilitates the use of two independent photomultiplier-tube sensors, thus creating two independent VUV channels. The spectrometer input is equipped with a dark shutter to allow periodic checks of the residual dark counts originating from the photomultiplier sensor photocathodes. Additionally, a mercury test lamp is available for in-flight checks of the spectrometer's wavelength calibration. The lamp is not intended for signal sensitivity calibration other than on a relative basis. The nitrogen purge fittings, which are for ground-based prelaunch storage and operation, give adequate protection for the optical surfaces against high humidity or other contamination. The VUV spectrometer was provided by Research Support Instruments, Inc., of Cockeysville, Md.

The centrally located aperture of the telescope mirror provides the gateway and field stop for the visible/near-UV subsystem. A detailed illustration of the total optical train is shown in Fig. 6. Here, one may observe the dark shutter directly behind the aperture, which operates sequentially with the dark shutter in the VUV subsystem. The VUV dark shutter closes for 1 or 5 min, followed

Table 1—AIRS command sequencers.

Sequencer A0	*VUV wavelength position pairs (detector 1: detector 2 (nm))*
1	121.6:97.6
2	130.4:106.4
3	135.6:111.6
4	141.0:117.0
5	145.6:121.6
6	149.3:125.3
7	154.4:130.4
8	159.6:135.6
9	162.5:138.5
10	165.4:141.4
11	167.0:143.0
12	173.3:149.3
13	175.0:151.0
14	183.3:159.3
15	191.0:167.0
16	199.0:175.0
Sequencer A1	*Scan mode*
1	Imaging
2	Spectrometer
3	Photometer
4	Imaging with alternate VUV wavelength
Sequencer A2	*Supplemental functions (any combination of)*
1	Scan-motor secondary drive
2	Spectrometer motor 3 times power drive
3	VUV sun-sensor override
4	Detector 3 sun-sensor override
Sequencer A3	*Test mode*
1	No test mode
2	Dark shutter test
3	Optical test
4	Extended dark shutter test
Sequencer A4	*Detector power control (any combination of)*
1	Detector 1, power off
2	Detector 2, power off
3	Detector 3, power off
4	Detector 4, power off
Sequencer A5	*Supplemental functions (any combination of)*
1	Spectrometer-motor secondary drive
2	Cover switch override
3	Detector 4 sun-sensor override
4	Visible/UV-filter position

Table 2—VUV trimode design characteristics.

Pixel size:
6.5-km (0.373°) orbit-plane direction
26.7-km (1.53°) cross-plane direction
Line-scan FOV: 130.4°
Telescope mirror size:
4.8 × 6.2 cm (off-axis parabola)
Telescope focal length: 22.95 cm
Telescope *f*-stop (effective): *f*/3.8
Pixel dwell time: (7.03) 10^{-3} s
Pixel accumulation time (6.83) 10^{-3} s
Scan cycle time: 3 s
Image scan time: 2.36 s
Flyback time: 0.64 s
Wavelength scan time: 2.36 s (115 to 180 nm)
Wavelength scan step: 0.3 nm
Nadir-pixel sample interval (photometer mode):
326 samples for a total of 2.29 s
Spectral resolution (spectrometer mode):
3-nm increments between 115 and 180 nm
Wavelength selection: 115 to 180 nm (0.3 nm/step)
VUV channel separation: 24 nm
Data pixels per scan: 326 (8 bits each)
Sensitivity: 30 R/count at 130 nm
Dynamic range: 25 to 2 × 10^5 R (imaging mode)

Table 3 — Visible/near-UV bimode design characteristics.

Pixel size:
26.00-km (1.49°) cross-plane direction
39.26-km (2.25°) orbit-plane direction
Line-scan FOV: 130.4°
Telescope (refractor) size: 1 cm
Telescope (refractor) focal length: 10 cm
Telescope *f*-stop (effective): *f*/4.3
Pixel dwell time: (7.03) 10^{-3} s
Pixel accumulation time: (6.83) 10^{-3} s
Scan cycle time: 3 s
Image scan time: 2.36 s
Flyback time: 0.64 s
Spectral resolution: 1.0 nm (630, 391.4, 337.1 nm)
17.5 nm (225 nm)
Data pixels per scan: 326 (8 bits each)
Sensitivity (kR/count) measured at
630.0 nm: 3.5
391.4 nm: 0.317
337.1 nm: 0.481
225.0 nm: 1.6
Dynamic range (imaging mode) at
630.0 nm: 3.50 to 2,630 kR
391.4 nm: 0.31 to 1,120 kR
337.1 nm: 0.48 to 774 kR
225.0 nm: 1.60 to 1,202 kR

immediately by a like closing period for the visible/near-UV dark shutter. The optical train uses a common objective lens for later beam separation by way of spectrally tuned beamsplitters. Each of the two beams passes through a filter selector where two combinations of spectral bandpasses may be obtained. Selection "A" yields 630 and 391.4 nm and selection "B" yields 337.1 and 225 nm. All filters have a 1-nm bandpass, except for the

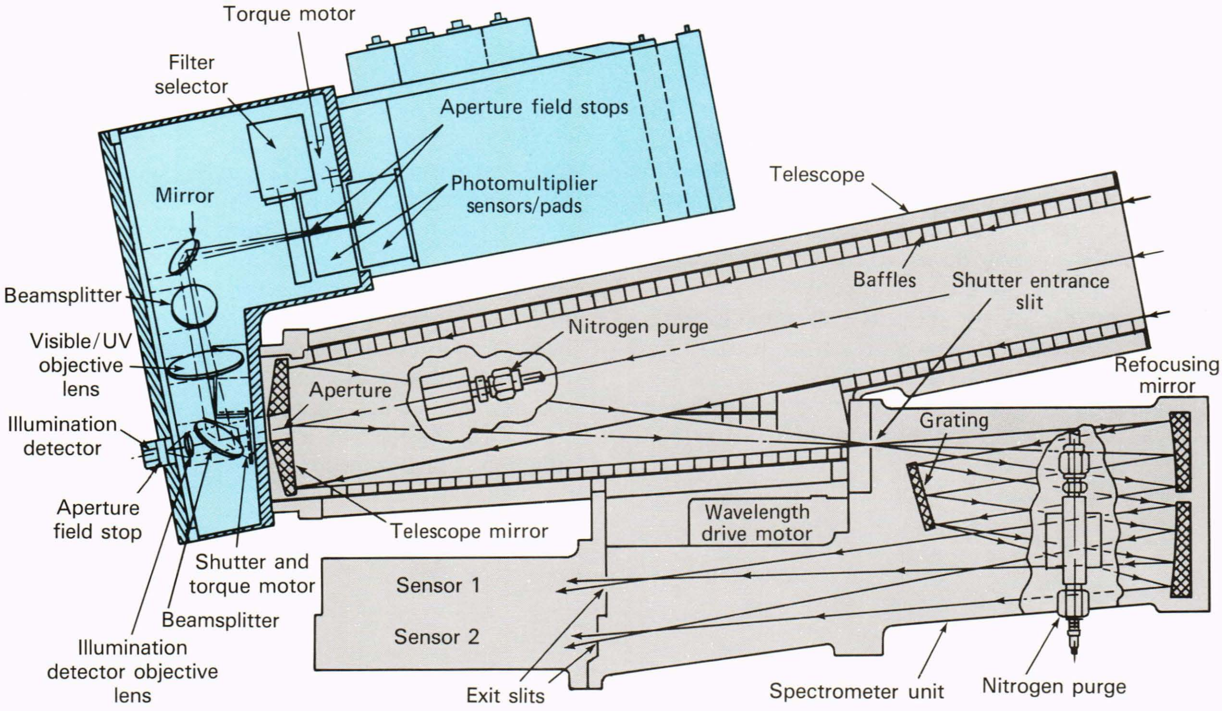

Figure 5 — AIRS optical schematic.

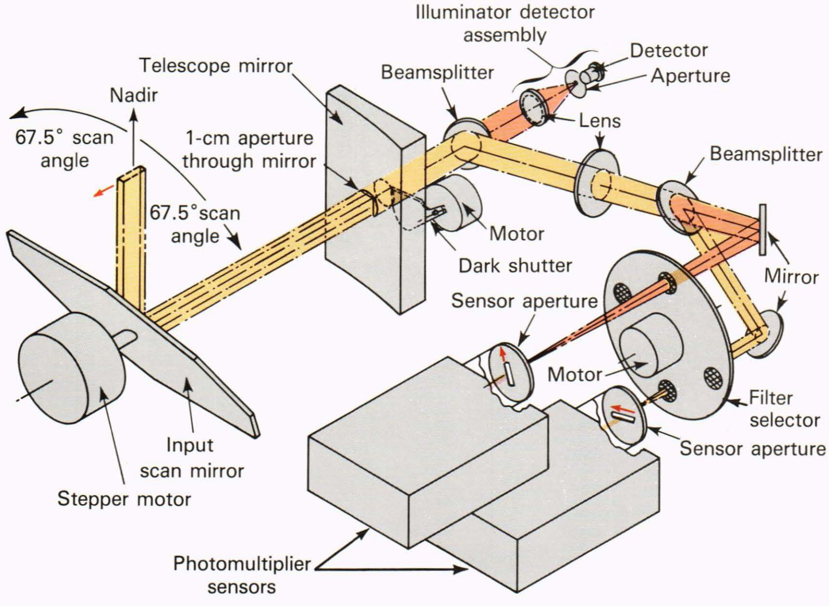

Figure 6 — Fixed λ optical train.

225-nm filter, which has a 17.5-nm bandpass. The images produced by the objective lens come into focus at an aperture plate for each of the two photomultiplier-tube sensors. The orientation of the slit apertures results in a coincident erect pixel as viewed through the input scan mirror.

The photomultiplier-sensor units all contain EMR photomultiplier tubes. The two tubes used in the VUV channels are EMR-510G-09 types with a magnesium fluoride window and a cesium iodide photocathode. The tube used in one of the near-UV channels is an EMR- 741N-09 with a magnesium fluoride window and a bi-alkali photocathode. The other tube for the visible/near-UV channel is an EMR-541N-01 with a glass window and a bi-alkali photocathode. Each channel has its own high-voltage power supply and pulse amplifier discriminator. The visible/near-UV sensor units are equipped with a special gating provision to enable operation inhibit of the photomultiplier tube during a portion of each image line-scan interval when viewing a scene that includes the day–night terminator.

The input scan mirror is rotated by a stepper motor that is operated by the controller electronics. Each step is 0.4° with a holding period equal to the scene pixel integration and readout time. The synchronism between the readout-pixel-processing electronics and the stepping of the scan mirror, which is 10.2 × 13.3 cm, is maintained by an optical readout device attached to the scan mirror. Figure 7 shows the nature of the design.

The parameters of the reflective telescope include a 4.8- × 6.2-cm off-axis parabolic mirror with a focal length of 22.95 cm and an effective speed of *f*/3.8. This, in conjunction with the VUV-spectrometer entrance slit of 1.5-mm width × 6.16-mm length, results in an IFOV of 0.373 × 1.53°.

The visible/near-UV refractive/objective lens is a Suprasil I type with a focal length of 100 mm operating at *f*/4.3. The scene is focused on the 2.6- × 3.92-mm aperture slits just preceding the photomultiplier sensors. This combination results in an IFOV of 1.49 × 2.25°.

The illumination-sensor optics for the VUV system takes the form of an emersion optic type of silicon phototransistor detector with a simple FOV-limiting baffle system. The illumination sensor for the visible/near-UV is somewhat more sophisticated, with a separate objective lens and field-stop aperture as shown in Fig. 8. The FOV for the VUV illumination sensor is ±10° at 0.1 of maximum response, and the FOV for the visible/near-UV illumination sensor is ±5.5° at 0.1 of maximum response. It is unlikely that the VUV illumination sensor would trip the VUV AIRS photomultiplier tube inhibit function, which is set for solar-type inputs. Its function

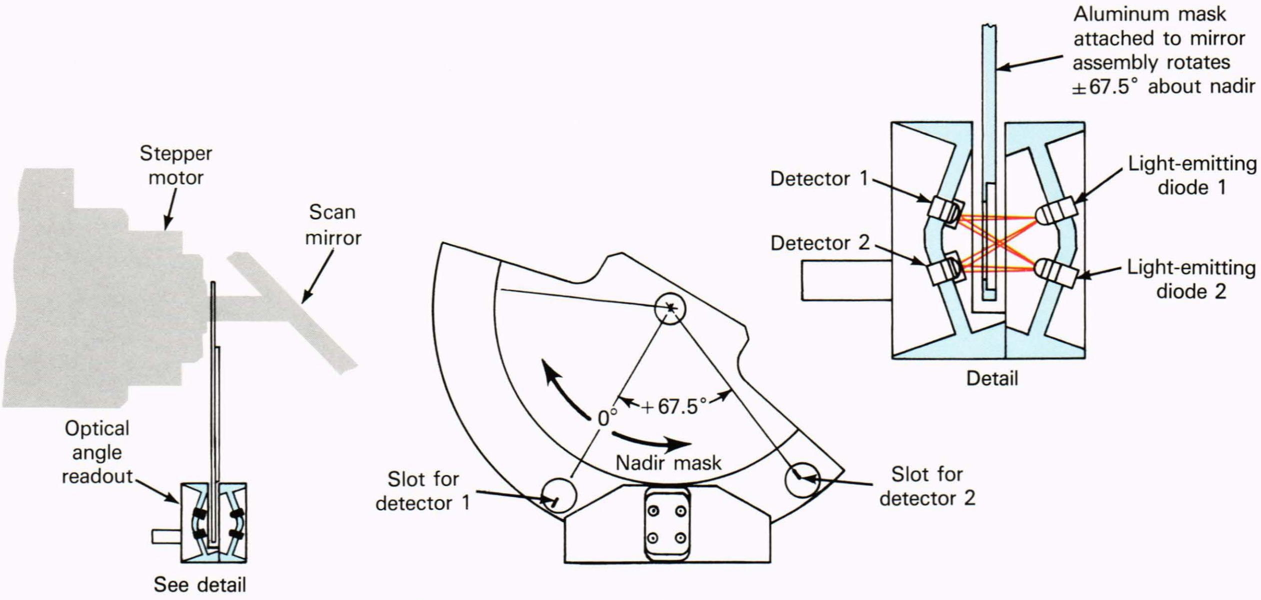

Figure 7 — AIRS scan-mirror optical readout.

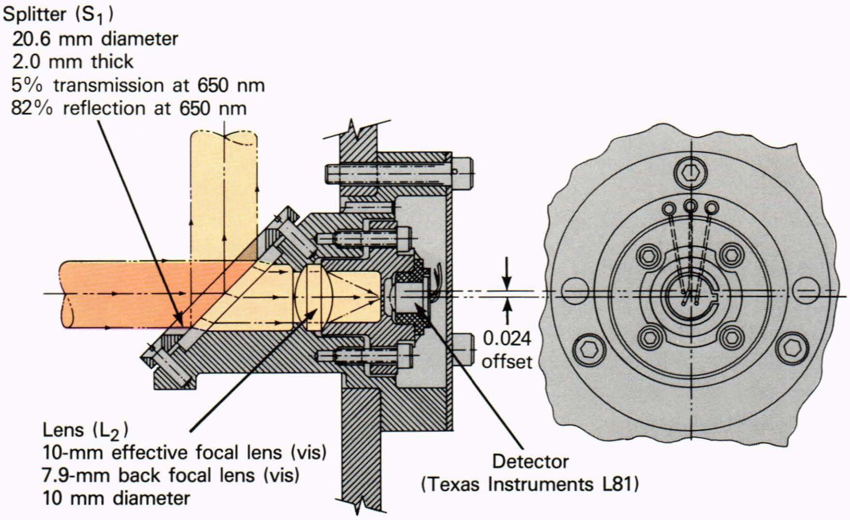

Figure 8 — Visible/near-UV illumination sensor optics.

is to handle any possible unscheduled events. The visible/near-UV illumination sensor is designed to inhibit photomultiplier operation on each line scan or albedo sighting.

The sensitivity of the VUV, UV, and visible channels may be expressed by the equation below, which defines the scene in terms of rayleighs required to result in a single count being detected.

$$R = \frac{16 r^2 N_s}{10^6 \, A D_o^2 \, \tau \, \beta \, \rho \, \gamma} ,$$

where r is spacecraft altitude (km), N_s is the number of signal photoelectrons, A is the projected pixel scene area viewed (km^2), D_o is the diameter of the optic collecting aperture (cm), τ is dwell time (s), β is optical efficiency, ρ is sensor quantum efficiency, and γ is the system spectral transmission. The system dark-counts-per-signal accumulation dwell time, τ, is less than 1.0 for all channels and is especially low for the VUV channels.

Tables 2 and 3 list individually measured spectral channel sensitivities for the appropriate values used with the above parameters for each channel. Variances between calculated and measured/calibrated sensitivities were minor and attributable to manufacturing variabilities in component characteristics.

Mechanics

An important feature of the AIRS is the redundant pyrotechnic cover-opening release mechanism shown in Fig. 9. Activation of either or both of the pyrotechnic squibs will result in the release of the scan-mirror cover.

The filter-selector mechanism for the visible/near-UV channels is driven by a small, Aeroflex, brushless DC torque motor that also is used to actuate the instrument dark shutters. The filter selector is a two-position device with fixed end stops and a dual-position holding spring. The dark shutter, the filter selector, and the intervening optical train are shown in Fig. 10.

The AIRS instrument was constructed mainly with magnesium alloy to reduce weight wherever practical. The structural design met with the Scout launch vehicle requirements. The thermal operating range of AIRS is from −10 to +30°C, with a survival range of −28 to +50°C.

Electronics

The AIRS electrical system is shown in Fig. 11. It consists of two electronics packages and the detectors, motors, and other electrical components on the electro-optics section.

The controller-electronics package is the main control unit for the AIRS instrument. It generates all timing signals used in the instrument, drives the mirror-scan motor, controls the operation of the visible/UV sensor and VUV spectrometer system (VUVSS), and provides the data, command, and power interface with the spacecraft. The controller package is a microprocessor-based unit and contains radiation-hardened CMOS logic devices to minimize power consumption and to provide a 3-year operational life.

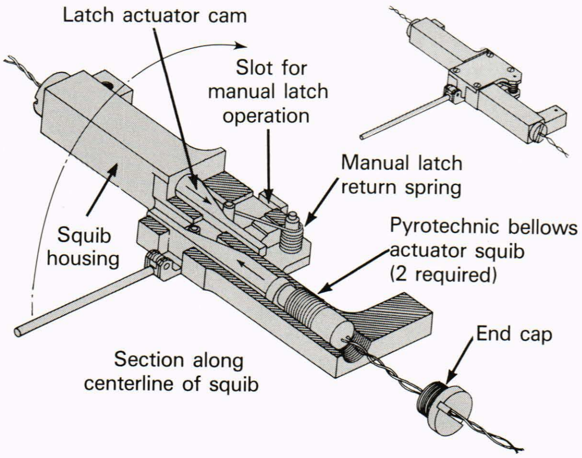

Figure 9 — AIRS scan-unit cover release mechanism.

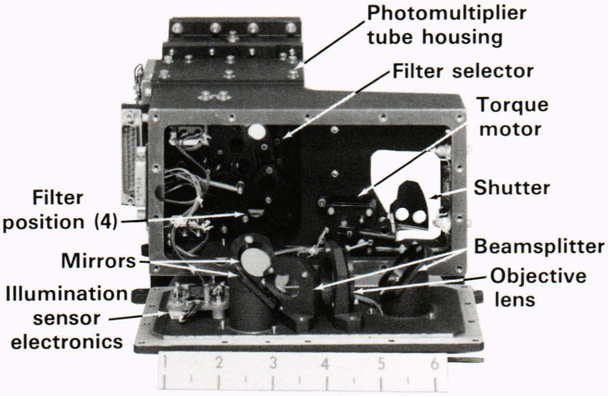

Figure 10 — AIRS visible/near-UV optical package.

The VUVSS electronics package contains the power-drive circuitry needed to interface the digital command signals from the AIRS controller to the various motors and sensors in the VUV spectrometer system. Redundant drive components are used where possible.

The AIRS command circuitry contains six command sequencers (labeled A0 through A5) and one index sequencer (six states). Two spacecraft pulse commands (A and B) are used to increment the command and index sequencers: the B command increments the index sequencer while the A command increments only one command sequencer at a time. The state of the index sequencer (0 through 5) determines which command sequencer (A0 through A5) will be incremented by the A command. The command circuitry is powered continuously so that commands can be received and sequencer values retained when AIRS is powered off.

The states of the six command sequencers determine the operating mode of AIRS. Each command sequencer contains 16 states and selects a different operating function (e.g., scan mode, wavelength position, test mode, and supplemental functions). Table 1 lists the command sequencer functions.

AIRS pixel data are obtained by photon-pulse counting. The integrated detector-output pulses are accumulated in 13-bit binary counters. The VUVSS electronics package contains two accumulators for the VUV detectors, and the AIRS controller contains two other accumulators for the visible/UV detectors. Before transmission to the ground, the 13-bit count is compressed to an 8-bit value, of which the most significant 3 bits represent an exponent and the least significant 5 bits represent a mantissa. The compressed value will cover a range of up to 8032 counts and is expressed by

$$\text{Net count} = 2^{\text{exp}} \times (\text{mantissa} + 32) - 32.$$

The AIRS operation consists of a repeating line-scan cycle of 3 s. The data collection portion of the line-scan cycle is divided into 326-step periods at 7.03 ms per step. During each step, the scan mirror is stepped from horizon to horizon (imaging mode), the spectrometer grating is stepped through its wavelength range (spectrometer mode), or the scan mirror and the grating are both held at fixed positions (photometer mode).

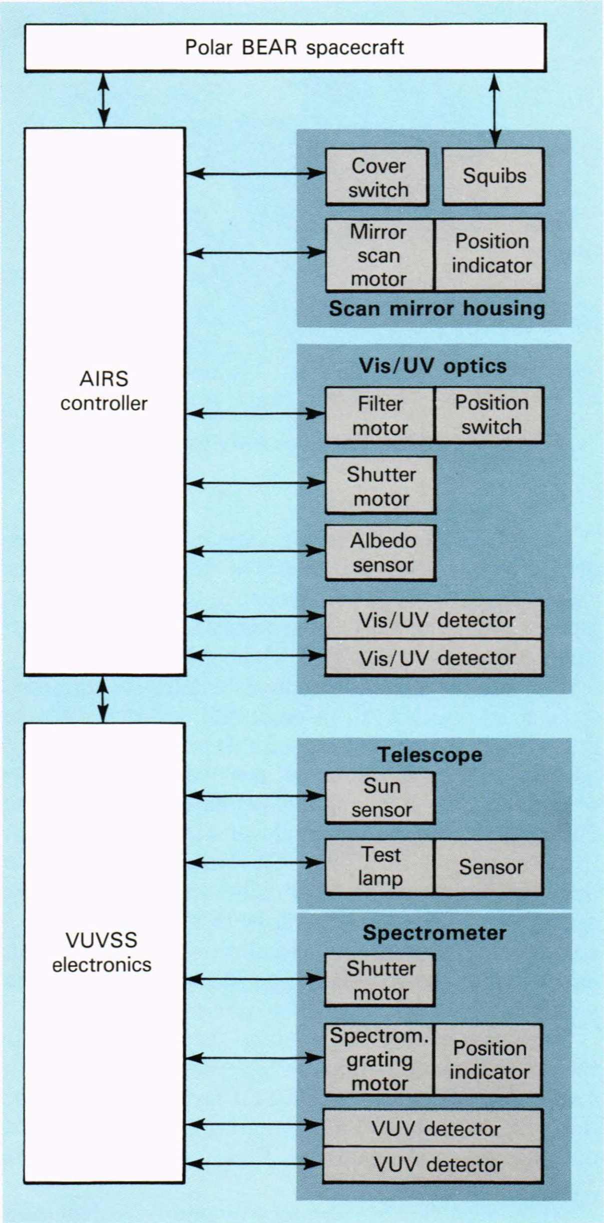

Figure 11 — AIRS electrical system.

During the data collection portion, 326 pixels are collected from each of the four detectors at 1 pixel per detector per step. The pixel accumulation period is 6.83 ms. Each pixel value is a compressed 8-bit count.

Each line scan also contains 16 bytes of status and housekeeping data. The status information includes a line-scan counter; the position of the spectrometer grating, filter wheel, and scan mirror; the command sequencer values; and the on/off status of test and backup functions. There are 16 analog housekeeping parameters (e.g., power bus voltage and current, motor currents, package temperatures, and integrated detector high-voltage monitors). Each housekeeping parameter is sampled every 12 s, and four parameters are included in each line scan.

One complete line scan of data (1326 bytes) is buffered in the AIRS controller before being output to the spacecraft telemetry system. The spacecraft contains no recording device, so telemetry data are transmitted to ground stations in real time. The AIRS communicates with the Polar BEAR science data formatter over a synchronous, serial data bus, sending a block of 221 bytes every 0.5 s.

Following the data collection cycle, a flyback cycle takes place, in which the scan mirror or grating is stepped back to its start position. Then the next line-scan cycle begins and is repeated until a timer in the spacecraft turns off power to all polar instruments. The polar instruments are powered for 27 min per orbit.

Calibration

The AIRS instrument was calibrated in two stages at the Air Force Geophysics Laboratory, Hanscom AFB, Mass. There was a preliminary calibration prior to environmental testing and a final calibration at the conclusion of all systems tests. Each calibration is a system end-to-end check. The VUV portion of AIRS was calibrated in a vacuum chamber. During calibration, instrument sensitivity versus wavelength, grating-step position versus wavelength, FOV, spectral bandwidth, and dynamic range were measured. Figure 12 shows the sensitivity versus wavelength calibration for each VUV channel. The

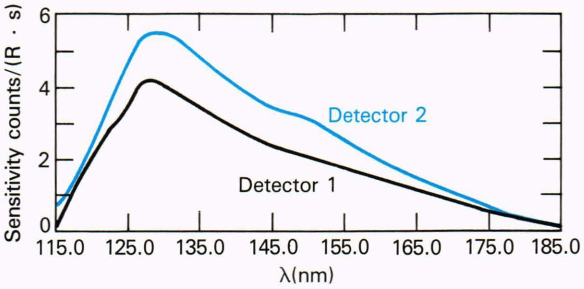

Figure 12 — AIRS VUV spectrometer sensitivity.

calibration of the visible/near-UV channels was performed in air.[2] Sensitivity calibrations for the different wavelength filter positions are given in Table 3.

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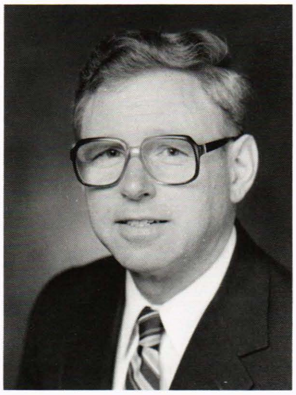
THE AUTHORS



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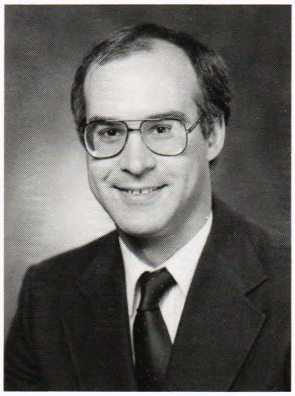

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