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A system overview of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)

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ABSTRACT

The AVIRIS instrument has been designed to do high spectral resolution remote sensing of the Earth. Utilizing both silicon and indium antimonide line array detectors, AVIRIS covers the spectral region from 0.41 μm to 2.45 μm in 10-nm bands. It was designed to fly aboard NASA's U2 and ER2 aircraft, where it will simulate the performance of future spacecraft instrumentation. Flying at an altitude of 20 km, it has an instantaneous field of view (IFOV) of 20 m and views a swath over 10 km wide. With an ability to record 40 minutes of data, it can, during a single flight, capture 500 km of flight line.

1.0 INTRODUCTION

The science of remote sensing has advanced especially rapidly over the last several years through observational research using increasingly capable sensor systems. As technology has advanced, making possible sensors of higher spatial, spectral, and radiometric performance, the ability to discriminate among features on the Earth's surface has also advanced. Just as the 7-band Thematic Mapper aboard Landsats 4 and 5 represented a significant step beyond the earlier 4-channel Multispectral Scanner, the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) technology described here, with its 224 contiguous spectral channels, will provide a quantum leap ahead of instruments now available and initiate a new, extremely powerful class of Earth remote sensing instruments.

Results from recent experiments with the high spectral resolution Airborne Imaging Spectrometer (AIS)[1] have shown the utility of using this class of instrument for Earth surface material discrimination and identification.[2] As a result of this research, AVIRIS has been designed to take advantage of the typically narrow diagnostic absorption features of these surface materials throughout the 0.4-μm to 2.45-μm region of the spectrum by providing 224 contiguous spectral bands 10 nm wide over this region.

The origins of imaging spectrometry at the Jet Propulsion Laboratory (JPL) lie in the design of the Near Infrared Mapping Spectrometer (NIMS) to be flown on the Galileo spacecraft in 1989.[3] NIMS will use cross-track scanning and platform motion to generate spatial information together with a linear array of discrete detectors to provide signals from spectral energy dispersed by a grating in the spectrometer. The AVIRIS concept grew from the NIMS experience, from development and use of the AIS, from development activity in indium antimonide line array detectors, and from work designing an instrument for the USDA Forest Service called FLAME, which used scanning infrared optics and which served as a starting point for the AVIRIS scanner design.

The second-generation instrument described here will image the entire spectral region from 0.4 μm to 2.45 μm over a swath 614 pixels wide, which, besides providing high spectral resolution spectra of each pixel, permits feature identification and location from the data. The data base acquired from the AVIRIS program should make possible the next major step in Earth remote sensing--an Earth-orbiting imaging spectrometer.

2.0 CONCEPT

The AVIRIS instrument is essentially a group of four spectrometers that view the ground through a scanner while being carried over the test site in an aircraft. At any one moment the spectrometers are viewing a spot on the ground 20 meters square. This pixel is viewed simultaneously in 224 spectral bands. A spatial image is built up through the scanner motion, which defines an image line 614 pixels wide perpendicular to the aircraft direction, and through the aircraft motion, which defines the length of the image frame (see Figure 1). The data are collected on a tape recorder for later analysis.

The recorded data set forms a data cube of which two axes represent spatial dimensions and the third represents a spectral dimension, as shown in Figures 1 and 2. The spectral data carry information corresponding to the composition of the ground being viewed and the intervening atmosphere. Computer processing of the data will produce an image of the test site in any of the 224 spectral bands, the spectrum corresponding to any of the pixels in the scene, or an image of the test site with those pixels corresponding to a perpendicular spectra marked off.

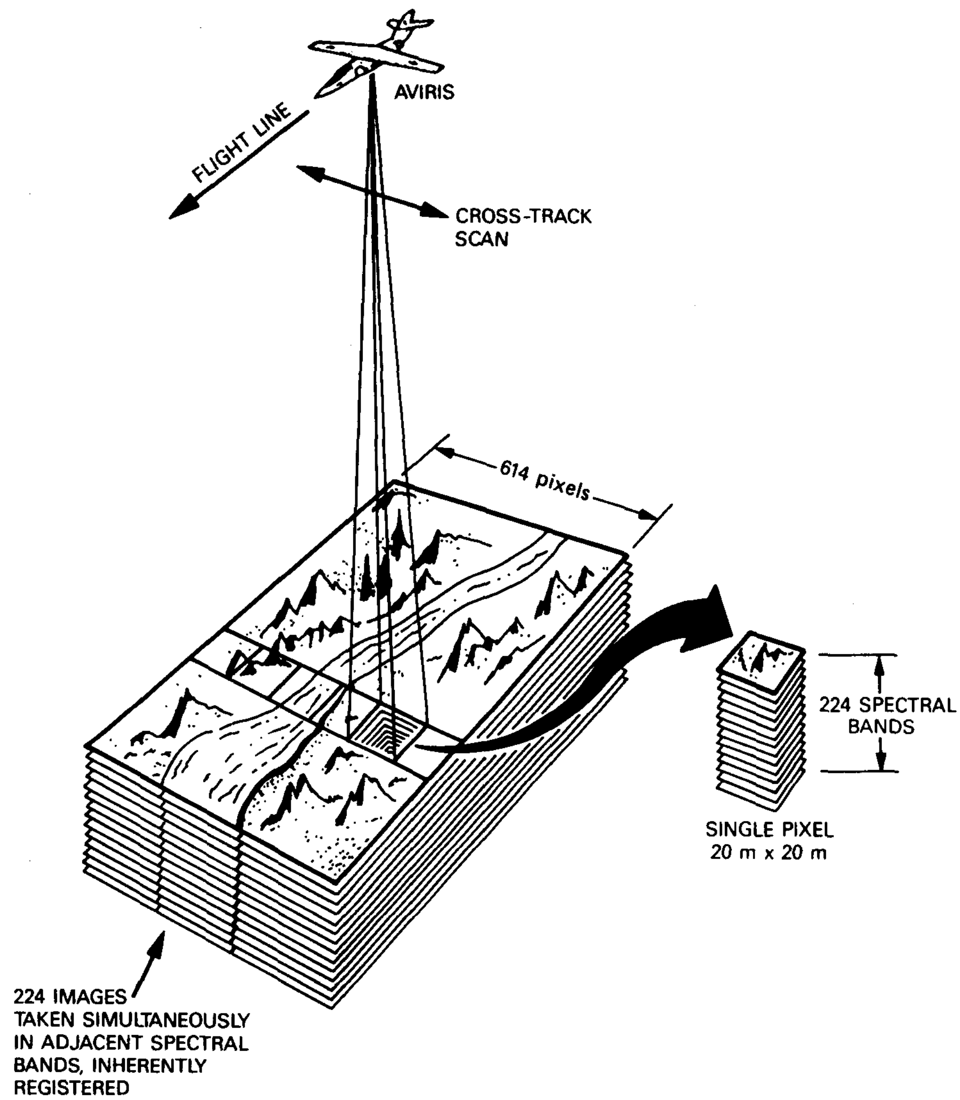

Figure 1. AVIRIS data collection.

3.0 DESIGN CRITERIA

The performance parameters for the AVIRIS instrument were determined, for the most part, from several key science requirements. Some compromise was necessary to accommodate the environmental constraints imposed by the U2 aircraft and to match the performance available from the chosen detectors.

The spectral sampling requirement for the AVIRIS instrument was determined by two key science requirements: The desire to detect shifts in the chlorophyll spectrum on the order of 10 to 40 nm at 0.7 μm, and the desire to resolve spectral features as narrow as the kaolinite doublet at 2.2 μm. Previous work with the AIS instrument had determined that the 10-nm sampling chosen for AVIRIS would be adequate. The instrument's longwave cutoff point of 2.45 μm was chosen to avoid viewing thermal emissions.

Signal-to-noise ratio (S/N) requirements were determined by analysis to be at least 100 to 1 at 0.7 μm for detection of the chlorophyll shift and 50 to 1 for detection of the kaolinite doublet. These requirements were for a surface albedo of 0.5 viewed through a standard LOWTRAN atmosphere with 23-km visibility.

The ground instantaneous field of view (GIFOV) was chosen to be 20 m. A GIFOV of 10 m would have been preferred, but with the scan rate already set at 12 scans/sec by the aircraft flight parameters and the scanner dimensions set by a requirement to use an existing scanner, this would have required a shorter detector integration time than could

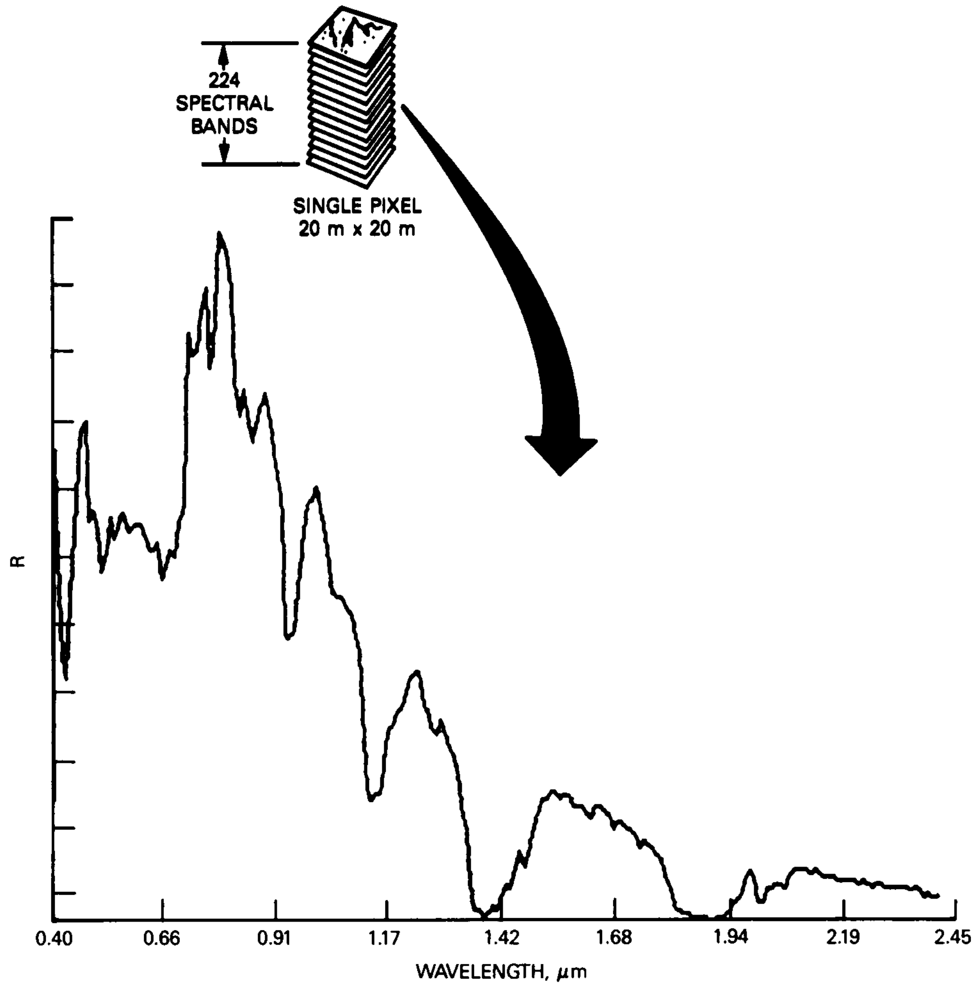

Figure 2. Spectrum from single pixel.

have been achieved. The field of view (FOV) was chosen to be 30 deg. This provides 614 spatial pixels in the scan direction and a swath width of over 10 km.

One remaining consideration that influenced the basic design of AVIRIS was the need to keep the instrument's operation as simple as possible. The pilot is confined in a high altitude suit which makes it awkward for him to operate the instrument. In addition, he has a full-time job simply flying the aircraft. For these reasons, AVIRIS has only two basic control functions--power and record.

4.0 INSTRUMENT DESCRIPTION

AVIRIS is modular in construction, consisting of six optical subsystems and five electrical subsystems. The optical subsystems (a scanner, four spectrometers, and a calibration source) are coupled together through optical fibers. The use of optical fibers to interconnect optics (thought to be unique in this application) was necessitated by the need to incorporate four separate spectrometers while keeping each spectral band less than one octave wide, to avoid spectral contamination from grating overlap. This concept provided additional benefits in that it greatly simplified the mechanical layout of the instrument and allowed the various subsystems to be aligned and tested independently of each other.

The electronics are packaged by major function, and include the signal chain, the digital control section, data buffers, the roll correction gyro, and the power supplies. This provides considerable isolation between the signal chains and other noisier circuitry. Full advantage was taken of the U2's and ER2's payload capacity to provide complete RFI shielding for each package.

Figure 3 shows the AVIRIS instrument and the placement of its major subsystems, including the scanner and foreoptics; the spectrometers and dewars; the electronic pack-

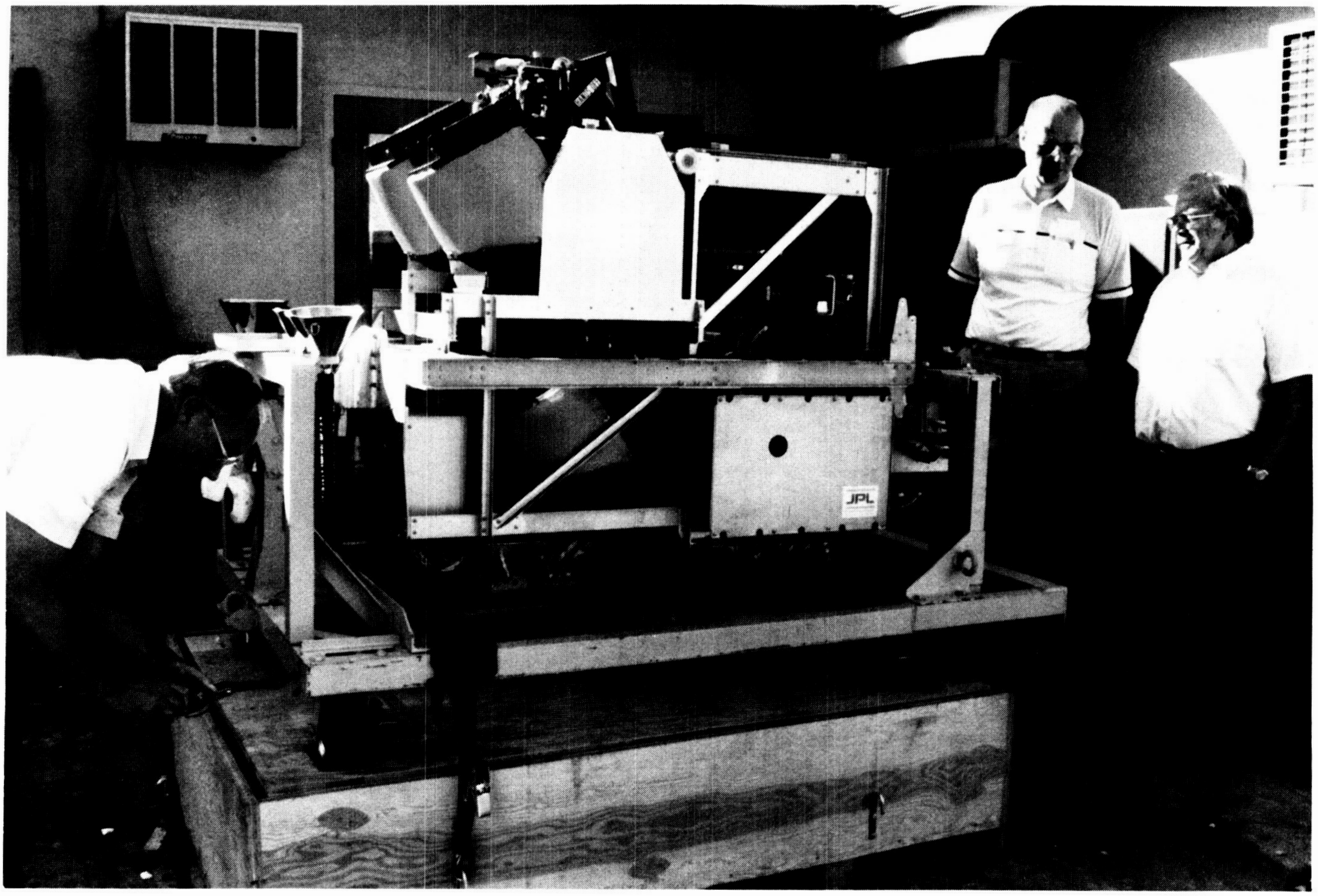

Figure 3. AVIRIS.

ages; and the tape recorder. The weight of the instrument is 720 lbs, and the instrument fits in an envelope 33 in. wide by 63 in. long by 46 in. high.

A functional block diagram of AVIRIS that indicates the relationship between the major subsystems is shown in Figure 4. The instrument is operated under the control of the

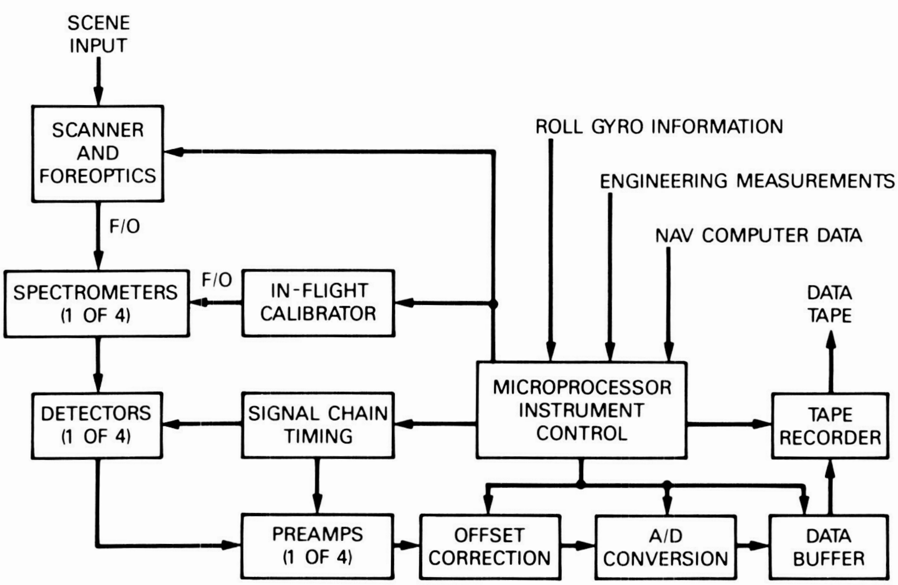

Figure 4. AVIRIS functional block diagram.

digital control subsystem (the heart of which is an Intel 8085A-2 microprocessor) in response to inputs from the power switch and the record switch. When the instrument is powered up, it goes through an initialization sequence, which includes synchronization of the shutters in the foreoptics and onboard calibrator, homing of the calibrator's filter wheel, and a self-check of the instrument's status. Included in the initialization sequence is the focusing of the foreoptics to accommodate changes due to temperature.

When the record switch is actuated by the pilot, the control section conditions the instrument by doing an offset correction for each of the 224 detector elements and resetting the roll correction gyro. The control section then puts the instrument through a calibration sequence measuring dark current and the calibrator output through each of its filter positions prior to the start of data recording. A similar calibration sequence is performed at the end of the data run. The calibration data are recorded on the high-density tape (HDT) on which the science data are recorded.

The control subsystem also interfaces with the plane's navigation computer to receive flight parameter data, which are recorded along with the science and calibration data. Data pertaining to the operation of the instrument are also recorded.

Viewing of the scene is done with the scanner operating at a rate of 12 scans/sec. The scanner operates in a scan-flyback mode with an efficiency of 70% and is momentum-compensated. During the flyback time, the dark-current performance of the detectors is measured and recorded. To avoid recording blank spots on the tape, the data taken during the active portion of each scan are rate-buffered and sent to the tape recorder during both the scan and flyback period. With a data rate of 17 Mbits/sec, the recorder can record 40 minutes of data on a flight. Four data channels, representing each of the four spectrometers, are read simultaneously from the scanner, requiring further buffering to get the output of each of the 224 spectrometer detector elements in the proper order on the HDT.

The scanner operates continuously, with its drive phase locked to the data system's master clock. An encoder signals the start of each scan. Aircraft roll compensation is accomplished by matching this start signal to the output of the roll gyro and delaying the start of data collection on the scan line enough to put the center pixel in the nadir position.

A foreoptics assembly mounted on top of the scanner collects the light from the pixel being viewed and sends it to the four spectrometers via four optical fibers. The four optical fibers, each 200 µm, or one pixel, in diameter, lie in a row looking at adjacent pixels on the ground. Buffers in the digital section recombine their output in the proper sequence before the data are sent to the tape recorder. The fibers carrying the visible and near-infrared part of the spectrum to their respective spectrometers are made of silica glass. The other two fibers, which carry the shortwave infrared to their respective spectrometers, are made of fluoride glass.

It is necessary to compensate for thermal focus shifts in the scanner and foreoptics by adjusting the focus position of the fiber bundle. This is done under microprocessor control by moving the end of the fiber bundle in and out with a stepper motor. The microprocessor measures the temperature of the optical assembly and adjusts the focus accordingly, using a stored table of position values. Focus is maintained over a temperature range of -30 deg to +30 deg C.

The four spectrometers are heated to maintain proper focus in the aircraft environment. Each spectrometer takes the signal received from the foreoptics and focuses a portion of its spectral content on a line array detector mounted in a dewar. The visible portion of the spectrum is monitored by a 32-element line array silicon detector. The short-wavelength infrared is monitored in the other three spectrometers by three 64-element line array indium antimonide detectors.

The aircraft flight parameters and the spatial imaging requirements define the detector integration time to be 87 µsec. This has presented some challenges in the instrument's design. The readout rate of the detectors is being pushed to near its limit, requiring special attention to be paid to the timing stability of the detector drive waveforms as well as to transients in the detector output waveforms.

The short integration time produces a small output signal on the order of only a few percent of what the detectors are capable of. Because of this, element-to-element variations in the detector outputs are a significant fraction of the full-scale signal. To keep the signal chain from saturating on these extraneous signals, the onboard microprocessor measures the dark current offset of each detector element just prior to a data run and applies these offsets as a correction to the data as they are being collected. An additional concern is created by the fact that changes in the integrated dark current corresponding to a temperature change of just a few degrees centigrade will also drive the signal chain into saturation. To prevent this, the dewars, which operate at liquid nitrogen temperatures, are fitted with constant pressure relief valves. Even though the ambient pressure changes during a flight from 14.7 psi on the ground to 4.5 psi at altitude, the pressure inside the dewars varies no more than a few tenths of a psi so that the detector temperatures are stable within one degree centigrade.

A detailed listing of the AVIRIS instrument parameters appears in the appendix.

5.0 CURRENT INSTRUMENT PERFORMANCE

The AVIRIS instrument is currently in the field for its first flight season. The calibration data taken prior to releasing it for flight and the flight data taken this season show the instrument to be working within all of its design requirements except for its signal-to-noise (S/N) performance. This S/N performance is summarized in Table 1. The requirement at 0.7 µm has been met. While the requirement at 2.2 µm has yet to be met, this performance has been adequate to allow the detection of the kaolinite doublet in the data taken to date. A comparison of the measured to predicted S/N indicates that additional performance can be achieved. The shortfall in S/N is due to excess noise and not a deficit of signal. Several noise mechanisms have been identified and are scheduled to be addressed this fall during an upgrade of the instrument.

Table 1. Signal-to-Noise Performance

Band	Wavelength (µm)	Required S/N	Measured S/N[a]
A	0.7	100:1	150:1
B	1.0	None	140:1
C	1.6	None	70:1
D	2.2	50:1	30:1

[a] The measured performance is for integrating sphere data corrected for viewing a scene with 50% albedo through a standard mid-latitude, midsummer atmosphere with 23-km visibility.

The geometric performance of AVIRIS meets all of the design requirements; an example of its high quality can be seen in the image shown in Figure 5. This photograph, which represents one of 224 spectral bands, was processed by only a simple stretch. The picture is a view of a portion of San Francisco in the 1.026-µm spectral band. The Golden Gate Bridge, which is about one AVIRIS pixel wide, shows clearly, as do the two support towers. Note the lack of geometrical distortion and the uniform shading across the width of the picture. Geometric performance as measured during calibration is presented in Table 2.

The spectral performance of AVIRIS also meets its design requirements and is presented in Table 3.

An additional difficulty has been encountered with the AVIRIS instrument this first flight season; this difficulty has to do with the stability of the spectrometers' signal output. The temperature control currently being used does not maintain the spectrometers completely in focus. Additionally, the method used to mount the spectrometers to the instrument frame distorts their geometry and lowers their performance. These problems will be corrected during the instrument upgrade activity this fall.

6.0 CONCLUSION

The successful design and implementation of the Airborne Visible/Infrared Imaging Spectrometer places the remote sensing science community on the threshold of a new era. In spite of the limitations noted in instrument performance during the initial operating season, early data returns indicate great utility to the science community. After completion of the NASA-sponsored performance evaluation period in 1987, upgrades will be performed to the instrument which will bring it to a fully operational state. AVIRIS is expected to be the major source of high spectral resolution imagery until the High-

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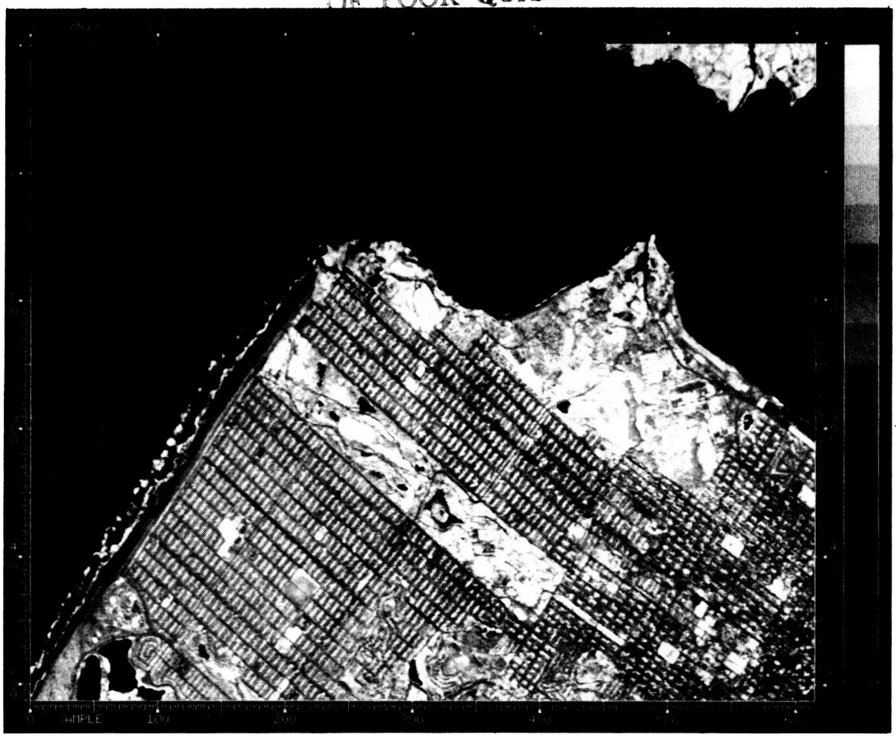

Figure 5. AVIRIS data product view of San Francisco in the 1.026-μm spectral band.

Table 2. Geometric Performance

Parameter	Required Performance	Measured Performance
Swath width (from U2)	$\geq$ 10 km	10.5 km
IFOV	$\leq$ 1 mrad	0.95 mrad
Spatial oversample	$\geq$ 15%	17%
Scan dynamics		
Scan rate	12 scans/sec	12 scans/sec
Cumulative pixel position error over scan (pixel size = 1.0 mrad)	0.5 mrad	0.26 mrad
Maximum pixel-to-pixel position error	0.1 mrad	0.06 mrad
Angular motion of scan drive housing due to vibration	0.1 mrad	0.01 mrad

Table 3. Spectral Performance

Parameter	Required Performance	Measured Performance
Spectral coverage	0.4 to 2.4 μm	0.41 to 2.45 μm
Spectral sampling interval	$\leq$ 10 nm	9.6 to 9.9 nm

Resolution Imaging Spectrometer (HIRIS) is launched on the NASA Earth Observing System (Eos) in the mid-1990s.

7.0 REFERENCES

1. G. Vane, A. F. H. Goetz, and J. B. Wellman, 1983, Airborne Imaging Spectrometer: A New Tool for Remote Sensing, Proceedings of the 1983 International Geoscience and Remote Sensing Symposium, IEEE Catalog No. 83CH1837-4.

2. G. Vane, 1985, High Spectral Resolution Remote Sensing of the Earth, Sensors V.2, No. 12, pp. 11-20.

3. I. Aptaker, in press, Near-Infrared Mapping Spectrometer for Investigation of Jupiter and its Satellites (SPIE Paper 834-24), proceedings of the SPIE conference held on August 17-21, 1987, in San Diego, California.

8.0 ACKNOWLEDGMENT

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9.0 APPENDIX: AVIRIS INSTRUMENT PARAMETERS

MISSION PARAMETERS
- Flight altitude - 20 km
- Ground-track velocity - 740 km/hr
- Velocity/height - 20 knots/km

PHYSICAL CHARACTERISTICS
- Weight - 720 lbs
- Width - 33 in.
- Length - 63 in.
- Height - 46 in.
- Window - 16.8 in. in diameter
  2.75 in. below scanner
- Power requirements - 28 VDC, 41 amps
  115 VAC, 400 Hz, 1 phase, 0.5 KVA
- Thermal operating environment - 0 to 30 deg C

OPTICS
- Foreoptics
  - FOV - 33 deg
  - Active FOV - 30 deg
  - IFOV - 1 mrad
  - Effective focal length - 19.76 cm
  - Effective pupil diameter - 14.5 cm
  - Performance - Point source at infinity, 90% energy in 50 μm
  - A-Omega Product - 1.297×10^{-4} $cm^2 srad$
- Fiberoptics
  - Material - Silica (spectrometers A and B)
    Fluoride glass (spectrometers C and D)
  - Diameter - 200 μm
  - Numerical aperture - 0.45
- Spectrometers
  - Spectrometer A
    - Design - Double-pass Schmitt
    - Wavelength range - 0.41 to 0.70 μm
    - Sampling interval - 9.7 nm
    - Number of channels - 31
    - Grating - 117.65 l/mm
  - Spectrometer B
    - Design - Double-pass Schmitt
    - Wavelength range - 0.68 to 1.27 μm
    - Sampling interval - 9.5 nm
    - Number of channels - 63
    - Grating - 128.205 l/mm

Spectrometer C
- Design - Double-pass Schmitt
- Wavelength range - 1.25 to 1.86 μm
- Sampling interval - 9.8 nm
- Number of channels - 63
- Grating - 124.2236 l/mm

Spectrometer D
- Design - Double-pass Schmitt
- Wavelength range - 1.84 to 2.45 μm
- Sampling interval - 9.8 nm
- Number of channels - 63
- Grating - 128.6 l/mm

<u>Calibrator</u>
- Light source - Halogen lamp
- Filters - Blank
  - Wide-band low level
  - Wide-band high level
  - Holmium oxide

<u>DETECTORS</u>

<u>Spectrometer A</u>
- Type - Line array
- Number of elements - 32
- Material - Silicon
- Integration time - 87 μsec
- Detector active area - 200 x 200 μm
- Dead space between elements - 30 μm

<u>Spectrometer B</u>
- Type - Line array
- Number of elements - 64
- Material - Indium antimonide
- Integration time - 87 μsec
- Detector active area - 200 x 200 μm
- Dead space between elements - 30 μm

<u>Spectrometer C</u>
- Type - Line array
- Number of elements - 64
- Material - Indium antimonide
- Integration time - 87 μsec
- Detector active area - 200 x 200 μm
- Dead space between elements - 30 μm

<u>Spectrometer D</u>
- Type - Line array
- Number of elements - 64
- Material - Indium antimonide
- Integration time - 87 μsec
- Detector active area - 200 x 200 μm
- Dead space between elements - 30 μm

<u>DEWARS</u>
- Cryogen - LN_2
- Detector positional stability - 500 μin., all axes
- Hold time - 4 hr
- Operating position - No spillage for 60-deg tilt
- Operating pressure - 15.7 psia

<u>SIGNAL PROCESSING/DATA HANDLING</u>

<u>Signal Chains</u>
- Number - 4
- Gain - Spectrometer A: $A_V = 235$
  - Spectrometer B: $A_V = 375$
  - Spectrometer C: $A_V = 385$
  - Spectrometer D: $A_V = 750$
- Noise - 17-μV rms over 625-kHz equivalent noise bandwidth
- Offset - 20% of full scale
- Offset stability - Short-term (15-min) offset drift and nonuniformity is compensated to within 20% of full-scale signal
- A/D converter - 10 bits

<u>Data Formatting</u>
- Science data buffer size - 192 kbits
- Detector read rate - 1.37 μsec/spectral element

Spectral elements/pixel - 224
Pixels/scan - 614

Tape Recorder

Make - Ampex AHBR1700i high-bit-rate airborne recording system
Write rate - 17 Mbits/sec
Record time/flight - 40 min

MECHANISMS

Scanner

Scan rate - 12 scans/sec
Scan efficiency - 70%
Cumulative pixel position error - 0.26 GIFOV over scan (pixel size = 1.0 mrad)
Nonrepetitive misalignment - 0.4 GIFOV accumulative between corresponding GIFOVs over line in adjacent scan lines
Nonrepetitive center to center - 0.06 GIFOV variations in sample spacing
Actuator - 3-phase induction motor
Controlling parameter - Master clock
Drive - Cam and follower with momentum compensation

Focus

Temperature range - +30 to -30 deg C
Accuracy - 20 μm
Resolution - 2 μm
Actuator - Stepper motor
Controlling parameter - Foreoptics temperature

Shutter

Shutter rate - 12 Hz
Duty cycle - 70% open
Actuator - Stepper motor

Filter wheel

Number of positions - 4
Actuator - Stepper motor