N88-14328

S3-74
116612
6 P.

AVIRIS foreoptics, fiber optics and on-board calibrator

M. P. Chrisp, T. Chrien and L. Steimle

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, California 91109

ABSTRACT

The foreoptics, fiber optic system and calibration source of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) are described. The foreoptics, based on a modified Kennedy scanner, is coupled by optical fibers to the four spectrometers. The optical fibers allow convenient positioning of the spectrometers in the limited space and enable simple compensation of the scanner's thermal defocus (at the -23°C operating temperature) by active control of the fiber focal plane position. A challenging requirement for the fiber optic system was the transmission of the spectral range 1.85 to 2.45 microns at .45 numerical aperture. This was solved with custom fluoride glass fibers from Verre Fluore. The on-board calibration source is also coupled to the spectrometers by the fibers and provides two radiometric levels and a reference spectrum to check the spectrometers' alignment. Results of the performance of the assembled subsystems are presented.

1. INTRODUCTION

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) was designed as a NASA facility instrument to fly on-board a U2 aircraft. The objective of the instrument is to provide high resolution spectral data for remote sensing. This spectral data is used to explore techniques for mineral identification, directly from exposed surface spectra and indirectly from the spectra of stressed vegetation. A complete review of the use of high resolution spectral data in remote sensing is given by G. Vane.[1,2] The instrument has been completed and numerous flights have taken place during this year (1987), the results of which are reported in this session.[3]

The instrument consists of a whiskbroom scanner connected by optical fibers to four spectrometers, shown schematically in Figure 1. As the triangular scan mirror rotates, a point on the ground is viewed in turn by each of the four spectrometers. In the spectrometers, the dispersed light is detected by cooled indium antimonide or silicon linear arrays. The calibration source is also connected by optical fibers to the spectrometers and provides information on their spectral alignment and radiometry.

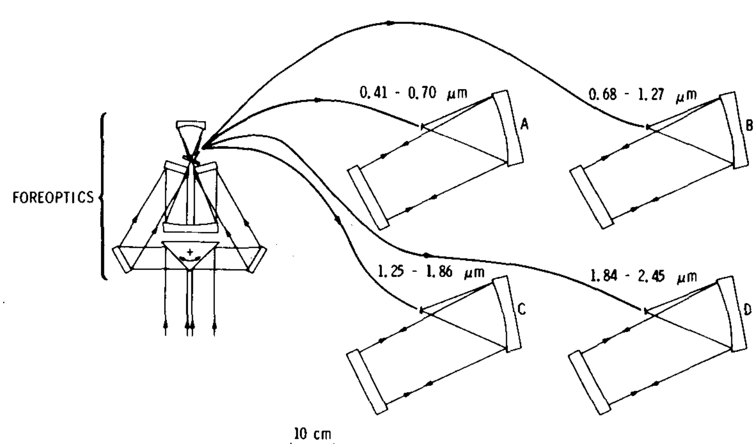

Figure 1. Optical schematic for airborne visible/infrared imaging spectrometer (AVIRIS)

This paper deals with part of the optical system, the foreoptics (scanner), fiber optics and on-board calibration source. The design, implementation, technical challenges and performance of these systems are described. The off-axis Schmidt spectrometers are described in a separate paper by Macenka and Chrisp.[4]

2. DESIGN DESCRIPTION

The main challenge in the design of the optical system was fitting the system into the limited volume available in the U2 bay, which constrained the foreoptics' and spectrometers' configuration. The initial proposed approach to do this (before the optical fibers were introduced) is shown in Figure 2. In this approach the light from the foreoptics is directed by dichroic beamsplitters into the three spectrometers. Note that the spectrometers have to be on the same optical bench structure as the foreoptics, which defines their entrance slit. Any movement between the foreoptics and the spectrometers will cause a spectral shift. This large optical bench structure is a great disadvantage because of the scanner vibration and the temperature excursion of the bay to -23°C at the operating altitude. The introduction of the optical fiber system greatly simplified the design by enabling the spectrometers to have separate optical bench structures which could be positioned independently with respect to the scanner.

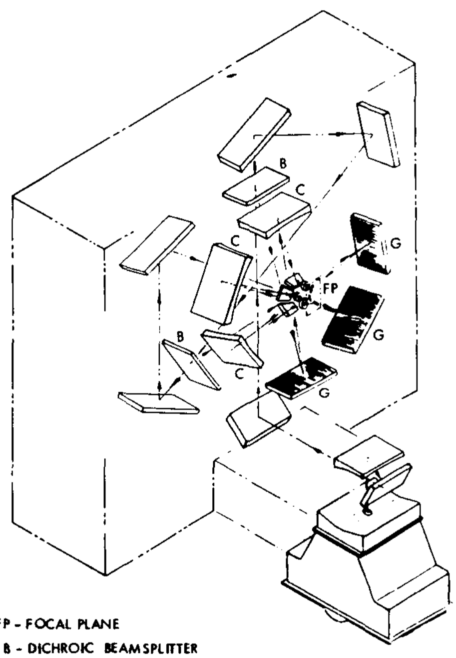

Figure 2. Initial design approach

Table 1. Optical system parameters

AΩ PRODUCE	1.3×10^{-4} cm^2 sr
EFFECTIVE PUPIL DIAMETER	14.5 cm
INSTANTANEOUS FIELD OF VIEW (IFOV)	1 mrad
FIELD OF VIEW (FOV)	30^0
GROUND RESOLUTION ELEMENT	20 m
SPECTRAL SAMPLES PER GROUND RESOLUTION ELEMENT	220
SCAN RATE	12 scans/sec
SCAN EFFICIENCY	70%
EFFECTIVE FOCAL LENGTH OF FOREOPTICS	20 cm

2.1 Foreoptics

The optical parameters of the foreoptics are given in Table 1. The foreoptics completely determines the spatial performance of the optical system. The foreoptics system is based on a modified Kennedy scanner, which was converted to provide the correct IFOV and to make efficient use of the limited field of view required. The scanner was initially designed with a four sided rotating mirror to scan an FOV of approximately 160°. To efficiently use the required 30° FOV, the rotating mirror was replaced by an oscillating two sided triangular mirror, giving a scan efficiency of 70%. Scans are taken in only one direction and the flyback speed is approximately twice as great as the scan speed. The large facets on the two sided mirror also removed the vignetting in the system, resulting in an aperture increase by a factor of ~1.3.

In the initial system the detectors had originally been placed at the focus of the paraboloid mirror. To provide the correct IFOV of 1 mrad this image is magnified 1.3 times by an ellipsoidal mirror, which relays the image to the fiber optics focal plane via a fold flat with a hole in it. The fibers are placed very close together so the total image field angle required from the foreoptics is only 5 mrad. (The ellipsoid actually increases the usable image field slightly by compensating for the coma from the paraboloid.)

The reduced field of view (30°) for the system enabled the baffling of the original design to be improved. The foreoptics looks out of the aircraft through a window of fused silica, which improves the thermal environment for the instrument. The fused silica is water free, to avoid the absorption bands present in the infrared region.

2.2 Fiber optics

The use of fiber optics provides a number of advantages: The spectrometers can be positioned independently from the foreoptics, allowing efficient use of the available aircraft volume. The spectrometers are isolated from the vibration inherently present in the scan drive. The spectrometers are also thermally isolated from the foreoptics and are in temperature controlled enclosures, greatly simplifying their design. Using the fibers to split the light into the spectrometers at a field plane avoids the use of a series of dichroic beamsplitters, which would decrease the transmittance.

The fiber optics are required to transport the light efficiently from the foreoptics to the spectrometers. A single fiber is used for each spectrometer, and the core size (200-micron diameter) forms the field stop in the foreoptics and the entrance slit for the spectrometer. The .45 numerical aperture (N.A.) of the foreoptics determines the fiber N.A. requirement, and the wavelength range for each spectrometer is given in Figure 1. The fibers had to be thinly clad (clad diameter <250 microns), so that they could be packed closely together in the foreoptics focal plane to coincide with the usable image field.

2.3 On-board calibrator

The purpose of the on-board calibrator is to check the spectral and radiometric alignment of the spectrometers during the operation of the instrument to ensure the accuracy of the spectral data. To do this the calibrator's output must be invariant over the small temperature excursions around the operating temperature (-23°C) and stable during the time period of the instrument operation.

The arrangement of the on-board calibrator is shown schematically in Figure 3. Light from a filament lamp is imaged by a concave metal mirror through a filter wheel onto the fiber optics leading to the spectrometers. The fibers are at the meridional focus so the astigmatism of the mirror blurs the filament image, reducing the sensitivity of the system to movement. The mirror and structure are monometallic so thermal effects are minimized. The rotating shutter in the foreoptics enables the light from the foreoptics to be shut off during calibration. The filter wheel in the calibrator has four positions, one of which cuts the light off. Two of the positions are used for neutral density filters to provide two radiometric levels, and the other position is used for a didymium rare earth filter to provide a reference spectrum, shown in Figure 4. This spectrum is relatively independent of the operating temperature, unlike a dichroic.

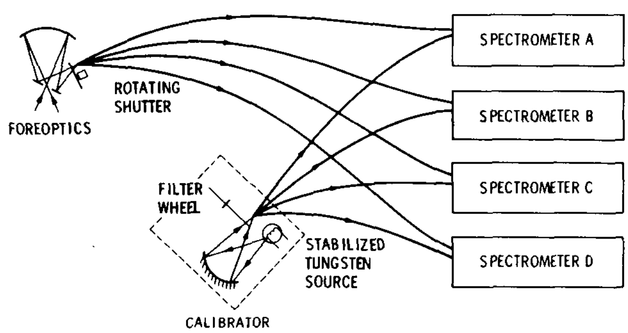

Figure 3. On-board calibrator

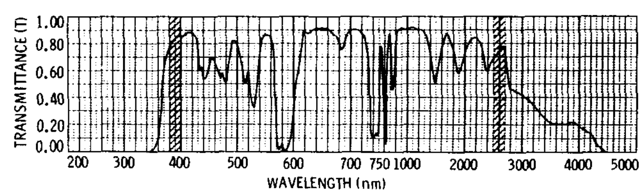

Figure 4. Didymium rare earth filter transmittance

3. DESIGN IMPLEMENTATION

3.1 Foreoptics

The basic modifications to the Kennedy scanner consisted of replacing the rotating mirror with a two sided oscillating mirror and magnifying the image by an additional ellipsoid. The two sided triangular mirror was diamond turned and hardmounted at three points to a new shaft design. Interferograms taken of the assembly show that it is repeatable within the surface flatness tolerance of 1.5 waves (~600 nm) over the 7.5 inch length. The ellipsoid mirror is aluminum and was polished by conventional metal mirror techniques. The mirrors in the foreoptics (except for the ellipsoid mirror) were coated with protected silver to avoid the aluminum absorption dip at 0.8 microns.

The depth of focus of the foreoptics is ±0.04 mm (for a 5% drop in the modulation transfer function (MTF) in the track direction at 3.15 cycles/millimeter [c/mm]). Since the focus changes by .58 mm in going from room temperature to the -23°C operating temperature, active focus control is necessary. This was implemented by moving the fiber optics focal plane (Figure 5) by a stepper motor according to a temperature sensor in the foreoptics. The best focus positions were found experimentally by placing the foreoptics in a temperature controlled chamber. These were then used to generate a look-up table for the stepper motor position with temperature. The system works successfully and no problems have been encountered.

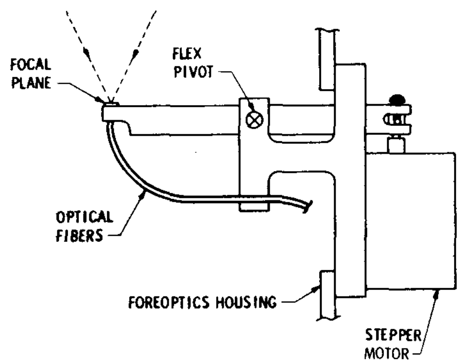

Figure 5. Active focus mechanism in foreoptics

3.2 Fiber optics

Spectrometers A and B are joined to the foreoptics by 1.9 m lengths of fiber, and C and D by 1.2 m lengths. For spectrometers A and B (0.41 to 1.27 microns) Nippon Sheet Glass (NSG) fiber SI 200H was used. This is a doped glass fiber, and measurements of its transmittance at an N.A. of .45 are shown in Figure 6.

For spectrometers C and D (1.25 to 2.45 microns), finding a suitable fiber with a transmittance/meter >0.9 (attenuation < 458 dB/km) at an N.A. of 0.45 proved to be quite challenging. The problems with silica fibers in this region are the strong absorption bands around 2.2 microns. Even low water content fibers proved to have too strong absorption bands.

The first solution proposed was to use a teflon coated fluoride glass fiber. Initial transmittance measurements of this at an N.A. of .17 showed that it had sufficient transmittance, but when these measurements were repeated at a .45 N.A., the transmittance was too low. This was identified as probably being due to scattering at the rough interface between the teflon and the glass. A different approach was therefore needed.

Most of the work on fibers in the near I.R. region has concentrated on communications problems, so the fibers developed typically have an N.A. of 0.17. Since the fiber throughput goes as the square of the N.A., much of the light would have been lost if one of these fibers had been used. The problem was discussed with the following major establishments concerned with I.R. fiber development:

Bell Labs	Naval Research Laboratory
Hughes	British Telecom
Spectran	Furakawa (Japan)
Verre Fluore	General Dynamics

Only Verre Fluore (France) thought that it would be possible to meet our requirements of N.A. and transmittance by the development of a special fluoride glass fiber, consisting of a core glass of zirconium fluoride and a cladding glass of beryllium fluoride. A contract was placed with the company, and a fiber which met our requirements was successfully developed on schedule. Its transmittance is given in Figure 6.

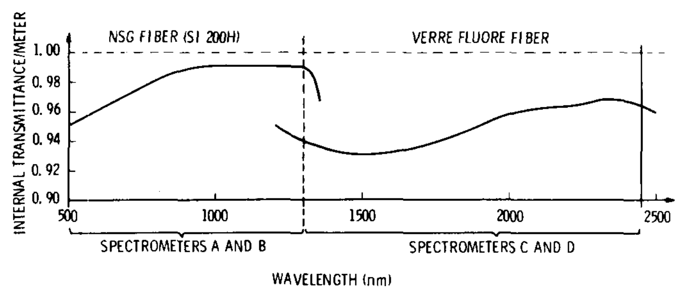

Figure 6. Fiber transmittance (measured at 0.45 N. A.)

The development of the fiber cable harness proved to be a process of iteration. The main problem was that in order to place the fibers close together in the foreoptics focal plane, their protective polymer claddings had to be stripped off. This considerably weakened the fiber and careful stress relief was necessary in going from the rigid mounting block to the flexible tubes. For the spectrometer the tight bend radius (~2 inches) and minimal space also created difficulties. No joins were allowed in the cable because of the associated transmittance losses. After a few iterations a successful cable harness was developed, with the fibers set in an epoxy block in the foreoptics and then connected by thermoplastic tubing to capillary metal tubing which feeds them into the spectrometers. This harness is removable, facilitating changing of the fibers if one should break.

3.3 Calibration source

Measurements of the calibration source show a 0.5% change in the light output per 10°C. Tests of the instrument show that there is a 2.2% variation of the light output over a period of 30 minutes due to fluctuations in the power supply. This will be improved by the installation of a stabilized power supply, which was proposed in the initial stages but later removed because of weight constraints which have since been relaxed.

4. SPATIAL PERFORMANCE

The MTF of the foreoptics is determined by the aberrations, image smear (due to aircraft motion and scan motion) and the fiber size. The system MTF is given by

$$MTF_{system} = MTF_{aberrations} \times MTF_{detector} \times MTF_{smear}$$

The system MTF in the scan and track directions is shown in Figure 7. The MTF is lower in the scan direction due to the image smear resulting from the integration time. In the track direction there is negligible image smear due to the aircraft motion. (The details of this type of calculation are given in Appendix 1 of Ref. 5.)

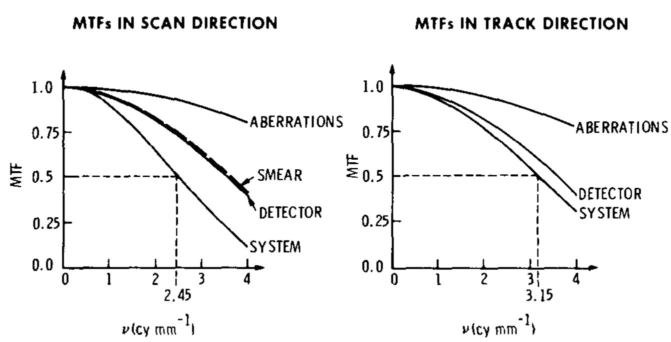

Figure 7. MTFs of AVIRIS system

The effective instantaneous field of view (EIFOV) is the spatial half wavelength for which the MTF is one half. From the graphs it can be seen that this results in:

EIFOV in scan direction = 20.5 m
EIFOV in track direction = 15.9 m

Measurements of the aberrations of the assembled foreoptics show that the spot sizes are in agreement with the aberration values used for the MTF curves.

5. STRAY LIGHT AND POLARIZATION

The stray light of the foreoptics was measured by mounting the system on a rotary table in front of a highly collimated source (1 mrad divergence). Measurements were taken as the table was rotated, giving the intensity of light in the image plane with angle. The primary aim of the stray light measurements was to check for unidentified stray reflections. The results showed that the stray light intensity within 0.1 degrees of the image is from 0.3% to 2%, and beyond 2 degrees from the image is less than 0.1%. The major portion of the stray light originates with the diamond-turned scan mirror, which was not post-polished. This diamond fly-cut mirror has been shown by measurements to have a much greater surface roughness than the grating blanks in the instrument, which were diamond-turned.

The polarization was measured in the visible by rotating a linear polarizer in front of the foreoptics. This gave a variation in transmittance of the system for the linear polarization of 5.5%. One of the useful features of the fiber optics is that they scramble the polarization, so the diffraction grating polarization efficiencies do not affect the system sensitivity to polarization.

6. CONCLUSION

The foreoptics provides the required spatial resolution and the thermal focus compensation adjustment works successfully within the required tolerance.

The fiber optics system has the required transmittance and optical throughput, and a practical cable harness has been developed. The fiber optics system has greatly simplified the instrument design and has been very successful. The on-board calibrator has sufficient temperature stability and will meet the long term stability requirements with an improved power supply.

The AVIRIS instrument has been flying since the beginning of 1987 and the spatial resolution of the operating instrument has been verified in a number of flights over test sites. This data is presented in one of the accompanying papers in this session.[3]

7. ACKNOWLEDGEMENTS

Thanks are due to Eric Fuller for his excellent work on the optomechanical assembly and Roscoe Donnel for his help with the fiber transmittance measurements.

The writing and publication of this paper were supported at the Jet Propulsion Laboratory, California Institute of Technology, by the National Aeronautics and Space Administration.

8. REFERENCES

1. Vane, G., "High Spectral Resolution Remote Sensing of the Earth," Sensors 2, 11 (1985)
2. Vane, G., and Goetz, A.F.H., "Terrestrial Imaging Spectroscopy," Remote Sensing of the Environment (in press) 24 (1988)
3. Vane, G., "First Results from AVIRIS," Int. Soc. Opt. Eng. 834 (1987)
4. Macenka, S.A., and Chrisp, M.P., "AVIRIS Spectrometer Design and Performance," Int. Soc. Opt. Eng. 834 (1987)
5. Slater, P.N., "Remote Sensing," Addison-Wesley (1980)