No. 126 A HIGH-RESOLUTION SOLAR SPECTROMETER FOR AIR-BORNE INFRARED OBSERVATIONS

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November 22, 1968

ABSTRACT

The construction and operation of a 4-meter Czerny-Turner scanning spectrometer in the NASA Convair 990 Jet aircraft are described. The design of the spectrometer and its mounting support permit high resolution in spite of aircraft vibrations. Maximum resolution achieved was about 60,000, close to the theoretical limit of the optics.

1. *Objectives*

This paper describes the construction and operation of a 4-meter Czerny-Turner spectrometer for observations of the solar spectrum in the region 0.8–5.0 μ from the NASA Convair 990 aircraft at altitudes of 39,000 to 42,000 ft (12–13 km).

Ground-based astronomical spectroscopy in the infrared is severely hampered by strong telluric absorptions, with H_2O the most prominent absorber. In a discussion of the importance of infrared studies at conventional aircraft altitudes, Kuiper, *et al* (1968) pointed out that the scale height of water vapor in the atmosphere is about 1.6 km while that of the remainder of the air is about 8.0 km. Thus, at altitude 12 km the water vapor concentration is reduced by a factor of about 10^3 while the ambient air pressure is reduced only by a factor of 5.

Because of the strength and complexity of the absorption bands between 0.8 and 5.0 μ, a drastic reduction of the H_2O concentration alone is insufficient for a survey of solar lines in these regions. Resolutions up to 0.1 cm^{-1} are desirable to reach the fainter solar lines, given the various broadening effects present and the need to resolve blends as much as possible.

2. *Instrumental Requirements*

The restrictions placed on airborne spectral observations are severe. Aircraft dimensions restrict the size and weight of the spectrometer. On a given flight the observing time is limited by fuel load and flight path, demanding rapid operations. A compromise in resolution and recording speed must be reached on the basis of feasible spectrometer dimensions.

Sunlight must be introduced into the spectrometer with a telescope limited in aperture by available windows and the strength of window materials. Effective infrared transmitters are generally thin crystaline substances obtainable with clear apertures of 6 inches or less. Because of limb darkening, the guiding accuracy of the aircraft-telescope combination must be sufficient to keep the sun's image nearly centered on the spectrometer entrance slit during the observing period.

Aircraft vibrations require the spectrometer components to be rigid. The amplitude and frequency of vibrations in the aircraft depend on spectrometer location and orientation, which must be considered in the spectrometer design. For example, vibrations of frequencies perceptible to the touch are often of 50 times greater amplitude in the aft sections of an airplane than those in forward positions.

Finally, the equipment and its mounting to the aircraft must be capable to withstand emergency landing conditions with accelerations up to 9 G. This requirement constrains the spectrometer design and the shock and vibration mountings permitted.

3. *The 4-Meter Spectrometer*

Scanning spectrometers of the Ebert and Czerny-Turner types have been used successfully at the Lunar and Planetary Laboratory for several years (see Kuiper, *et al,* 1964), both in the laboratory and at the telescope. Several medium-large high-quality diffraction gratings have been used interchangeably between spectrographs and spectrometers. These gratings are plane, 128 x 154 mm in size, and are readily adaptable to different instruments.

In experiments with the Laboratory's 0.9-m spectrometer ("B"), the maximum resolution $\lambda/\Delta\lambda$ achieved was 7000 at 2.1 μ (corresponding to 3 Å). In order to obtain resolutions better than 1 Å with existing gratings and detectors, an instrument of 4 meters focal length was designed, near the maximum length that could be carried through the doors of the NASA CV-990. With the maximum beam diameter of 5 inches, governed by the dimensions of the gratings, the optical system operates at F/31, sufficient for sun and laboratory sources at $\lambda < 10\ \mu$.

The spectrometer installation in the CV-990 has been illustrated in *LPL Comm.* No. 123, Figs. 1a and 1b, which includes the 12-inch feeder telescope and heliostat, units that were available from the planetary IR program (smaller units would of course have sufficed for the sun). The grating is supported on a table provided with a six-speed motor drive. At the focus of the 6-inch camera (shown with the collimator in Fig. 1; focal length 392 cm), the detector serves as the analyzing slit. Lead-sulfide and lead-selenide detectors are available in a variety of dimensions. The focal plane end of the spectrometer (mounted in the laboratory) is shown in Figs. 2 and 3. Highest spectral resolution is obtained with detectors of 0.10 or 0.05 mm width and 1.5 and 2.0 mm length, acquired from Eastman Kodak (PbS Ektron) and Santa Barbara Research Corp. (PbS and PbSe). They are factory-mounted in small bakelite Amphenol plugs to which Microdot low-noise coaxial cables are soldered. The detectors are operated in dry-ice temperature ($-78°$C). The preamplifier and amplifier are external to the spectrometer.

The amplifier and preamplifier were designed by Dr. H. L. Johnson and constructed under his supervision. The design is similar to that published by Kuiper, *et al* (1962), except that the new preamplifier uses solid-state components. A Sanborn recorder (Hewlet-Packard Model 7700) with response time of 10^{-2} sec. is used for rapid data acquisition.

Because of the great cost of aircraft operations, high reliability of the spectrometer was essential. For this reason, a *modular design* was adopted. The least reliable elements in the system are the chopper motor and the grating drive motor. A slit-chopper module was constructed in duplicate, each unit having alignment screws permitting optical adjustment before flight. A 900 rpm Gaylord-Rives (No. B-3274) synchronous motor and a four-blade chopper give a chopping frequency of 60 Hz. The assembly permits synchronization of lamp and photocell to the amplifier system at other chopping frequencies, but normally they were used at the 60 Hz line-frequency available in the aircraft, which is suitable to a cooled detector.

The grating drive module is seen in Figs. 3 and 4. An Insco multi-speed motor drives a single thread worm and a 360-tooth gear upon which the grating rests. Adjustment screws are provided for the optical alignment of the module. A double conical bearing carries the rotation axis of the worm gear and grating, and it was found that this is the component most susceptible to vibration in flight. The optical lever from grating to camera mirror to detector being 8 meters, small rotations of the grating surface cause considerable displacements at the detector. This module could probably be improved for flight operations by the use of *two* well-separated bearings. The grating drive will need some improvement for future laboratory use. As noted in *LPL Comm.* 124, a periodic error in the dispersion, while not seriously interfering with operations, required more detailed wavelength calibration subsequently than would have

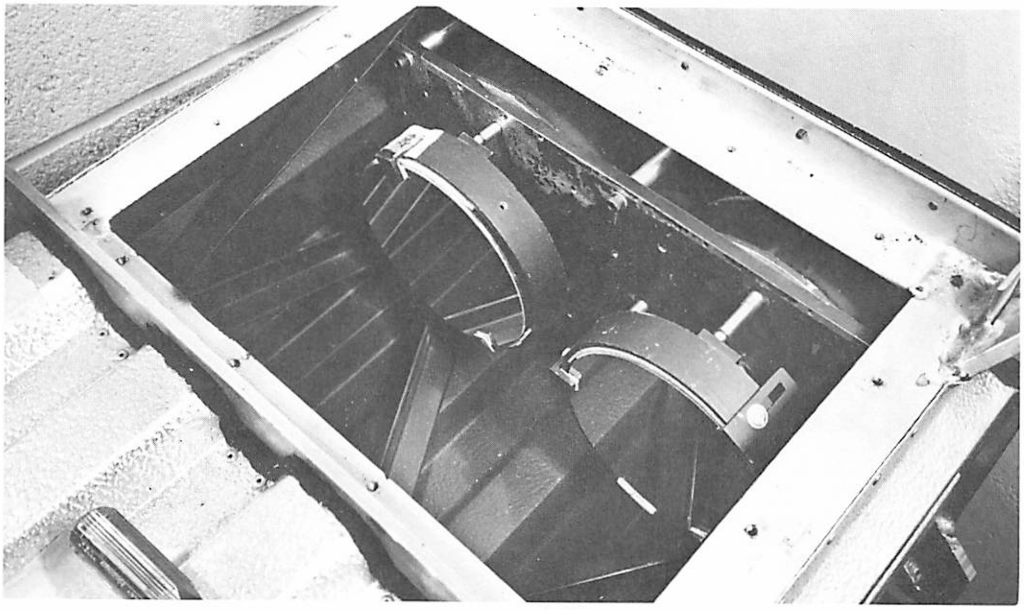

Fig. 1 Top view of camera and collimator mirrors, with cover plate removed. Note mounting of mirror cells, controlled by adjustment screws shown in *LPL Comm.* 123, Fig. 1a.

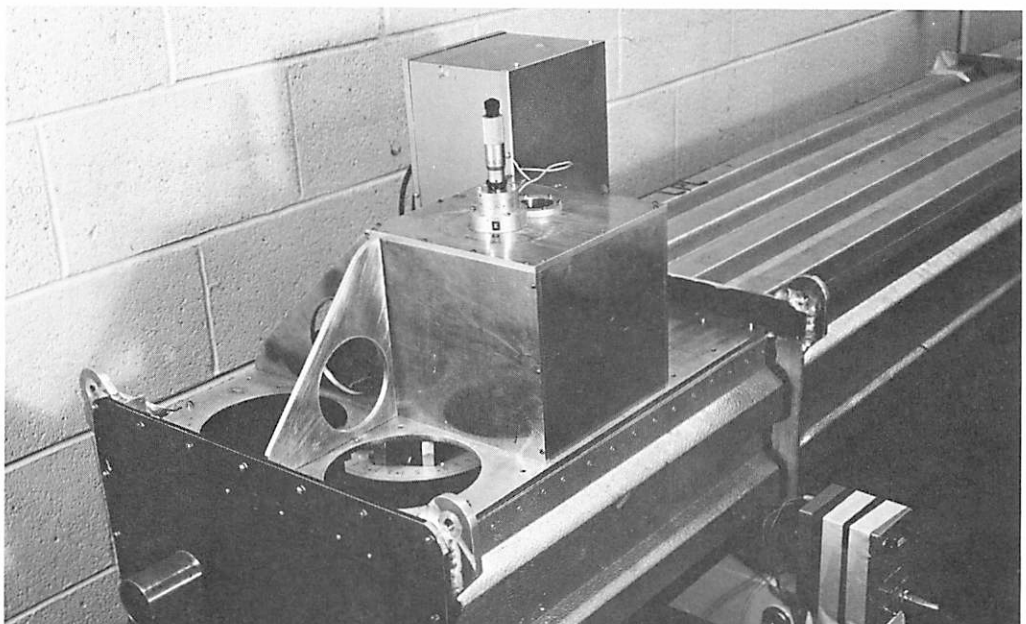

Fig. 2 Focal plane end of 4-meter spectrometer containing entrance slit (with chopper in front), grating and drive, and detector mounted in cold box. Micrometer screw seen on top for focusing detector; small crank at bottom, for hand setting of grating position.

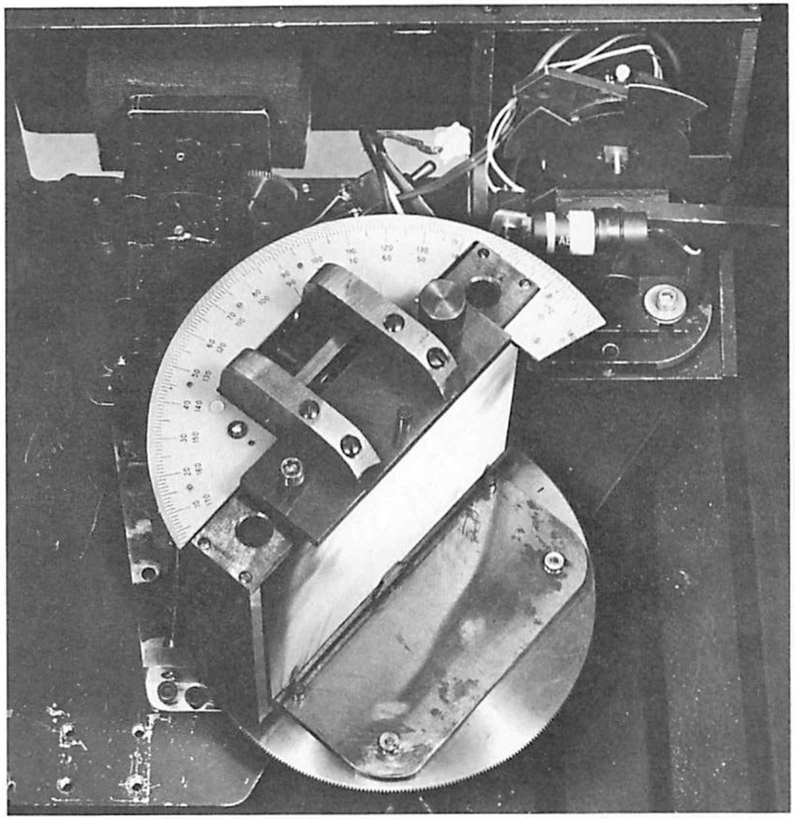

Fig. 3 Top view of grating drive assembly in spectrometer, with cover removed. Grating angles read to 0°.1 (for setting purpose) from large protractor shown (index mounted on top cover, removed). Grating surface is light-colored rectangle below center; worm gear engaged to worm, at left, driven by motor assembly seen at upper left (6 speeds). Chopper at upper right, with bar beyond used for phasing, and slit assembly just below it; channel to right contains micrometer screw for setting slit width.

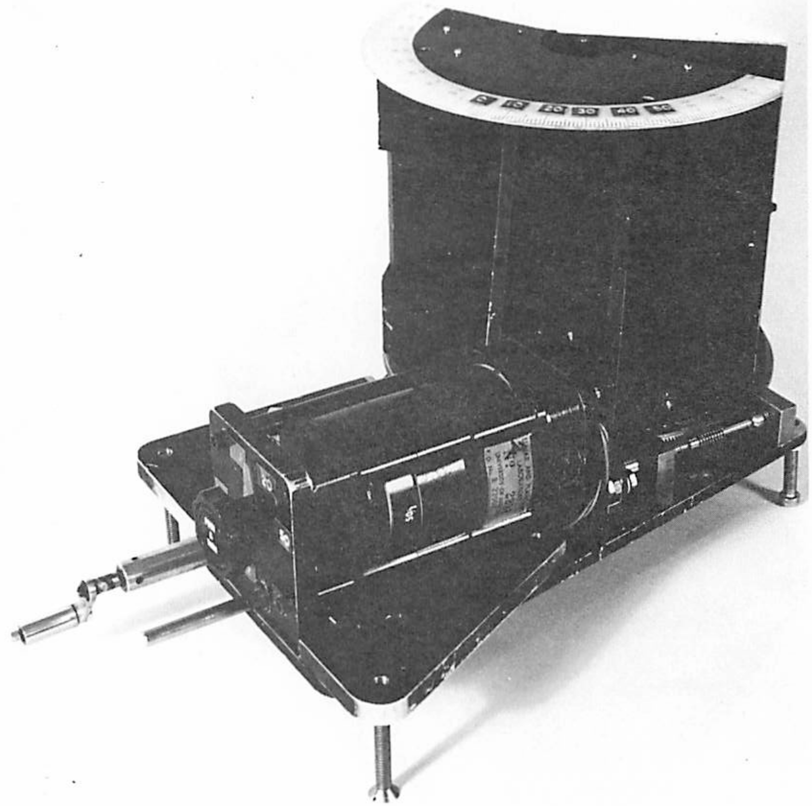

Fig. 4 Separate view of second grating-drive module, blackened (details differ from first unit, shown in Fig. 3).

TABLE 1

RUNNING TIME (SECONDS/100 Å) AND DISPERSION (CM/100Å) FOR AVAILABLE MOTOR AND CHART SPEEDS AND 1200 LINES/MM GRATING AT λ 1.2 μ

PAPER SPEED (MM/SEC)		0.5	2.5	10.	50.
REDUCTION OF MOTOR SPEED	TIME NEEDED FOR 100 Å INTERVAL (SEC)	DISPERSION (LENGTH 100 Å INTERVAL IN CM)			
1	30	1.5	7.5	30	150
2	60	3.0	15.0	60	300
5	150	7.5	37.5	150	750
10	300	15.	75.	300	1500
20	600	30.	150.	600	3000
50	1500	75.	375.	1500	7500

Multiply all Table entries by 0.86 for 1200 l/mm grating at λ 1.0 μ; by 0.43 for 600 l/mm grating at $\lambda = 2.0\ \mu$; and by 0.215 for 300 l/mm grating at $\lambda = 4.0\ \mu$. (These cases refer to grating angles at 37°; for other angles α, multiply with the further factor sec α/sec 37° or cos 37°/cos α.

been necessary otherwise. However, the versatility of the drive motor, with its six gear shifts, was an asset in a program where observing time was at a premium. Table 1, prepared by Mr. L. A. Bijl, lists the available options of motor and chart speeds for a particular grating and grating angle. As indicated in the footnote of Table 1, the numbers are readily converted to other wavelength settings with the same grating or other gratings.

The cold box is shown in Fig. 2. The detector in its Bakelite mount is held in a brass cylinder that for focusing can be moved axially against a spring, using a metric micrometer screw with 1.5 cm travel. Focusing is accomplished in two stages: (a) the spectrum of an emission line source (fluorescent lamp) is formed on a translucent screen in a dummy detector assembly. Visual inspection gives the approximate focus; (b) repeated scans with various micrometer screw settings through the spectrum of a nearby H_2O vapor band refine the focus. The adjustment appears fairly insensitive to changes of $\pm$ 1 mm around the optimum focus, as expected at F/30. Usually step (a) is adequate.

The capacity of the cold box is 2 liters, sufficient to keep the detector cold for 8 hours. Thermal insulation is provided by a mantle of finely divided silica (Santocell.) A small electrically-heated sapphire window prevents condensation of water on the detector surface.

During the CV-990 flights the plane's interior is flushed with heated, compressed outside air. The moisture content of the cabin atmosphere is thus potentially quite low. However, the total water vapor introduced by the 20–25 scientists and other personnel aboard into the 16-m spectrometer path was found to be far greater than in the entire atmospheric column from aircraft to sun. A simple solution was achieved at no cost by continuously flushing the spectrometer interior with fresh air taken from the plane's airconditioning system. We confirmed on several occasions that this continuous flushing was essential to keep the instrumental H_2O vapor concentration within tolerable limits. For example, when an incandescent source was used for calibration in flight, the lines in the H_2O band at 1.13 μ were invisible when the spectrometer was flushed, but quite strong when the ambient cabin air was admitted. During the solar observations, the entire heliostat and telescope area were enclosed with plastic sheets and also flushed with outside air. The total optical path inside the aircraft is about 22 meters, of which less than one meter is through the ambient cabin air.

4. *Vibration Problems*

The total length of the instrumentation, consisting of heliostat, telescope, and spectrometer, is 6.3 meters. Over this distance flight-induced vibratory deformations of the fuselage vary in amplitude by values far greater than the relative displacements permissible for the optical components of the system. An analysis indicated that the weight of a *single* structure, to be suspended floating in the fuselage and of sufficient vibratory rigidity, would be a multiple of the flyable value for the airplane.

It was therefore decided (a) to divide the system into *two* units, one heliostat plus telescope, the other the spectrometer; (b) to provide each unit with rigidity sufficient to maintain alignment of its optical components under maximum amplitude of their harmonic response to fuselage vibrations; and (c) to control this response by suspending each unit separately by vibration absorbers.

The penalty for decoupling the two units comprising the optical path, namely, a displacement of the ray bundle at the interface under different oscillatory reactions of the two units, was made acceptable by locating the plane of separation close to the slit of the spectrometer, where the light bundle is narrowest, and because of the fact that the solar image at this point is 50 times wider than the effective slit length (100 mm vs. 2 mm).

The first unit containing heliostat, telescope and some of the electronic equipment and consisting of a boxframe of crossbraced aluminum angles, was attached to several points of the fuselage by vibration absorbers. To provide this unit with the required rigidity posed no serious problem as its length-to-diameter is low (1.85) and the masses of its components could be distributed quite evenly in its volume.

More of a problem was posed by the spectrometer unit, as its length-to-diameter ratio is high (9.5) and its main masses — the optical components — are located at its extreme ends. These components and, therefore, the end faces of the unit, have to remain parallel within 1.3 seconds arc; or, stated differently, the unit has to be of sufficient rigidity to prevent it from responding to flight-induced vibration with transversal vibrations with amplitudes of more than .05 mm at distances from the node up to 2 m.

The design developed to meet these constraints provides a rectangular tube fabricated of aluminum angles, crossbraced and covered with corrugated aluminum sheeting. Both ends are formed into boxes of aluminum plate, attached to bulkheads, providing the supports for the respective optical components. Eight tensioned steel cables attached to both ends of the tube and tilted 10° away from the tube axis toward the center, where they are supported by an external frame, serve to load the tube in compression. A total cable tension of 2455 lb (1120 kg) was chosen for a calculated safe column strength of the spectrometer tube of 3890 lbs (1770 kg). The weight of the complete assembly came to 189.3 lb (86 kg), and its length to 13 ft 6½ in. (4.13 meters), not counting the projecting screws and small entrance tube.

The unit was supported with vibration absorbers in two transversal planes, each located at the respective center of gravity of the instrument end boxes. Two three-dimensional trusses providing these suspension points were in turn attached with vibration mounts to the fuselage in such manners that their main axis of absorption is at right angles to those of the mounts supporting the instrument tube.

A stress analysis of the whole system indicated a safety factor of 4.9 for its weakest structural member under crash loading of 9g as specified by flight-safety regulations.

5. *Operation of the Spectrometer*

The 4-meter spectrometer was used on the CV-990 for a series of solar observations from July 2 to August 12, 1968, as described in *LPL Comm.* 123. In flight, the highest resolution obtained with a 1200 line/mm grating blazed for 1.0 μ, and a detector 0.10 mm wide, was about 0.2 Å. Reference is made to three preceding *Communications,* especially No. 124, for sample reproductions of solar spectra.

Acknowledgments. The construction and testing of the airborne solar spectrometer was sponsored by NASA through Grant NsG 161-61 and the University of Arizona Institutional Grant NGR-03-002-091.

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TABLE OF CONTENTS

No. 123 Arizona-NASA Atlas of Infrared Solar Spectrum — A Preliminary Report.......... 179
by G. P. Kuiper and D. P. Cruikshank

No. 124 Arizona-NASA Atlas of Infrared Solar Spectrum — Report II.............................. 197
by G. P. Kuiper, D. P. Cruikshank and L. A. Bijl

Addendum: Spectrum of the 1.13 μ H_2O Band.. 217
by Uwe Fink, L. A. Bijl, and A. B. Thomson

No. 125 Arizona-NASA Atlas of Infrared Solar Spectrum — Report III............................ 221
by Gerard P. Kuiper

Addendum: Laboratory Spectra of the ν_3 Band of CH_4.. 226
by Laurens A. Bijl

No. 126 A High-Resolution Solar Spectrometer for Air-borne Infrared Observations........ 233
by D. P. Cruikshank, F. A. de Wiess, and G. P. Kuiper