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A BALLOON-BORNE MICHELSON INTERFEROMETER FOR SOLAR SPECTROSCOPY IN THE 10-100 MICRON REGION

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Abstract. — A Fourier spectrometer of the Michelson interferometer variety has been constructed for the study of the far infrared solar spectrum through the stratosphere at resolutions down to 0.5 cm\(^{-1}\).

Details of the design, construction and performance of this balloon-borne system, both optical and electronic, are given.

The instrument was first flown during August 1965. Despite some difficulties, the interferometer system performed as expected and some useful data was obtained. The system will be flown again as soon as possible.

Résumé. — Un spectromètre de Fourier, du type Michelson a été construit pour l'étude du spectre solaire dans l'infrarouge lointain à travers la stratosphère, avec des résolutions allant jusqu'à 0.5 cm\(^{-1}\). Nous donnons des détails sur le principe, la construction et les performances de ce système au point de vue optique et électronique.

Le premier vol a eu lieu en août 1965. Malgré quelques difficultés l'interféromètre a fonctionné suivant les prévisions et quelques résultats utiles ont été obtenus. Un nouveau vol aura lieu dès que possible.

Introduction. — The infrared region beyond about 13 microns is unavailable for ground-based astronomical observations because of the low transparency of the atmosphere. Even a source as strong as the Sun is invisible between 40 and 300 microns [1]. The major cause of the absorption is atmospheric water vapour, which is, however, largely confined to the troposphere. Near infrared spectrometers lifted into the stratosphere (that is, above about 20 kilometers) by means of balloons have shown that the resultant atmospheric transparency is considerably enhanced [2, 3]. One therefore has grounds for hope that a similar improvement would be observed in the far infrared. If this were found to be true, then the significant payload capacity of modern balloons could be exploited for astronomical purposes.

However, before one can embark on an ambitious program of astronomical observations in the far infrared, the stratospheric transmission and the manner in which it varies must be fully explored. Such an exploration was the purpose of this experiment.

The standard approach to such a measurement (which was followed in this case) is to employ the Sun as an extra-atmospheric light source and to determine how the received spectrum varies as a function of the air-mass. Where the absorption is weak, the spectra may be extrapolated to zero atmosphere and hence one may determine not only the atmospheric transmission as a function of zenith distance but also the solar spectrum itself. However, this can only be done satisfactorily if the signal/noise is good and if the spectral resolution is small enough to minimize line blending.

Instrumental approach. — To make such a measurement of the stratospheric transmission from solar spectroscopy in the far infrared we have constructed a Fourier spectrometer of the classical Michelson interferometer type. The instrumental aperture is 50 mm, the spectral range roughly 50-1 000 cm\(^{-1}\) (10-200 microns) and the planned resolution a little better than 1 cm\(^{-1}\).

i) Interferometer Optical System. — The mechanical and optical design of the instrument was controlled by the fact that the instrument is required to operate in a remote environment whilst being both reasonably light and sufficiently rugged to withstand
the shocks of launch and landing. Figure 1 shows a top view of the main interferometer body.

Collimated radiation enters from the right (as seen in the photograph) and strikes an uncoated, 6 micron thick, Mylar beamsplitter which reflects some of the energy to the reference condenser and detector (top right). The remainder of the energy passes through to another, identical, beamsplitter in the interferometer proper. The moving plane mirror is seen immediately to its left, whilst the fixed mirror is below. At center top is the signal condenser and detector.

The detectors are diamond-windowed thermocouples covered by 150 micron thick black polyethylene low-pass filters. The beamsplitters are made by stretching 6 micron thick Mylar in lapped rings having an interlocking ridge-and-groove to increase the tension. Films flat to 5 visible fringes over the entire 75 mm aperture are easily made. As a consequence, visible alignment is not difficult provided that airborne vibrations (such as speech) are eliminated. This vibration has never been observed to affect the performance at 10 microns. All the mirrors in the system are made from fused silica. The moving plane mirror is spring-loaded to a simple kinematic slide based on an optically worked fused silica block and is driven by a precision screw and a hysteresis synchronous motor (center left in figure 1). The total travel is 25 mm and the maximum deviation of the mirror from true parallelism is $\pm 2$ arc seconds. Position reference is provided by a moiré fringe generator (seen just below the mirror carriage) giving a fringe every 4 microns of movement. Direct calibration of the moiré fringes against the mercury green line indicates that the fringe spacing is 4.000 $\pm$ 0.001 microns.

There are no optical adjustments in the usual sense. All adjustment is performed using shim-stock and oversized holes, and is suprisingly simple. The entire instrument can be stripped, re-assembled and realigned within 3-4 hours and, once aligned, shows no tendency to drift. With only minor precautions being taken, the instrument has been transported many thousands of km and required no readjustment for over a year. The instrument is light (10 kg) and will operate in any orientation except inverted.

**ii) ELECTRONIC SYSTEM.** One of the more serious problems in Fourier spectroscopy is that of insufficient dynamic range in the electronic system. In far infrared solar spectroscopy, this difficulty is further aggravated by the large increase expected in the solar continuum intensity as we go from long to short wavelengths. In practice, this effect is considerably reduced by the slow rise of the low-pass optical filtering employed. Even so, it was felt necessary to design for a dynamic range of $5 \times 10^5$. Furthermore, there was the possibility that the stability of the
The electronic system might be affected by the expected 5% drop in the voltage of the mercury cells used as power supplies, during the course of a balloon flight (about 5 hours). These difficulties were successfully overcome by careful attention to current drains and by the rather unusual design of the amplifier system.

Although it is possible to design a linear amplifier with a dynamic range of $5 \times 10^5$, neither the on-board magnetic tape recorder nor the telemetry have a dynamic range much in excess of 100. We therefore used a cascaded amplifier system, depicted schematically in figure 2.

The signal and reference detectors operate in opposition, one being loaded with a large capacitor to match the differing time constants. The difference signal is fed, via a matching transformer, to a Nuvistor preamplifier. Following the preamplifier is a 6-pole active bandpass filter whose primary function is to ensure the adequacy of the optical filtering. That is, all electronic frequencies corresponding to wavelengths shorter than 10 microns are heavily attenuated. The price paid for this filtering is a phase dispersion of $4 \pi$ across the passband ($6.4$ cps centered at $13.05$ cps).

However, a continuously scanning interferometer of this type has little chance of producing symmetrical interferograms, in any case, so that it had been decided at the outset to use a power transform reduction. In practice, in fact, the asymmetry is not marked (see Fig. 7).

Following the active filter is the synchronous demodulator (a Synchroverter). The ripple filter employed is a passive LC network, rather than the conventional RC integrator, because such a network has a squarer passband and better rejection than an RC circuit. It was felt to be necessary, in view of the closeness of the intelligence frequencies (0-3 cps) to the chopping frequency ($13.33$ cps). At this point, an output is taken, via a buffer amplifier, to Channel 1 of the recorder/telemetry system.

A cascaded amplifier system could result in disaster if differential phase-shifts occur between outputs. The final amplifier stages were therefore chosen to be 2 wide-band, chopper-stabilized, D.C. amplifiers (Philbrick SP 656) with outputs after each (Channels 2 & 3). Hence 3 identical interferograms are produced with a factor of 100 gain between each one. Near zero path difference, Channel 3, and sometimes Channel 2, saturates, but Channel 1 never does. On the other hand, at large path difference, Channel 3 clearly shows the noise of the system, whilst Channel 1 shows nothing. The three interferograms are combined into one on the computer.

The reference waveform for the synchronous demodulator is generated at the chopper in a conventional manner. To guard against possible thermal drifts, the reference waveform is also passed through a 6-pole active filter identical to that in the signal side.

The reference waveform is also passed through a 6-pole active filter identical to that in the signal side.

![Fig. 2. — Schematic of the electronic system.](image)

![Fig. 3. — Schematic of the complete optical train.](image)
Channel 4 of the output system records the moiré fringes whilst Channel 5 records temperatures and the relative azimuth of the biaxial Sun-seeker (described below) and instrument package. Channel 6 is grounded, for reference purposes. A seventh channel is currently spare.

An analog, rather than a digital, recording technique is employed for reasons of simplicity. An on-board data automation system would increase the complexity of the system markedly. As it is, we may process the recovered analog tapes at leisure, using existing ground support facilities.

iii) FLIGHT SYSTEM. — The interferometer, its associated electronics and the foreoptics are enclosed in a single, insulating, package. Figure 3 shows a schematic of the entire optical train. The instrument package itself is shown in figure 4, in a test-stand.

The primary solar image is formed by the University of Denver biaxial Sun-seeker, which has been fully described elsewhere [4]. Suffice it to say that the entire system is contained in a tower about 2 metres tall, rotation of the tower providing the azimuth axis and rotation of a flat, the elevation axis. The 2-mirror system is in a Pfund arrangement, the telescope mirror being about 30 cm aperture with a focal length of some 150 cm.

At the solar image is a $45^\circ$ reflecting chopper, alternating the outgoing beam between Sun and sky. The beam then passes to a collimating mirror which has its surface roughened to scatter wavelengths shorter than about 5 microns [5]. Thereafter, the radiation is sent into the interferometer as described above.

The instrument enclosure is isolated both electrically and thermally from the environment, but in order to prevent the internal temperature from falling below $17^\circ$C, thermostated heaters, dissipating some 100 watts, are attached to the interior walls. The enclosure is suspended in the main gondola frame by an arrangement of chains and springs. During flight, the springs are tied down tightly with string. On impact, the strings break, dissipating some of the kinetic energy of the drop. Further crash protection...
is provided by a collapsible cardboard pad held beneath the entire system.

Figure 5 shows the system ready for flight. At the top is the tower of the Sun-seeker, in the center is the main gondola containing the instrument package and at the bottom is a lower gondola holding the recorder, telemetry and main power supplies, etc. In figure 6, the system is shown suspended from the launch vehicle shortly before lift-off. The lower crash-pad and telemetry antenna are clearly visible.

**System test.**—The most meaningful test that can be made of a Fourier spectrometer is to take the spectrum of a single emission line. Unfortunately, we have no line sources available to us in the region beyond 10 microns and the instrument is deliberately designed to be totally insensitive to shorter wavelengths. The only alternative we have, then, is to examine a known, continuous, spectrum and to compare the result to published data, taking due account of the instrumental transmission function. We therefore used the instrument, in its flight configuration, to take several spectra of the Sun from ground level. A typical interferogram resulting is shown in figure 7.

The reduction of this data is currently in hand.

**Flight operations.**—The system was flown for the first time on August 10, 1965 from Holloman AFB, New Mexico. The flight lasted some 4.5 hours and an altitude of 31 km was attained. The interferometer itself functioned well and was recovered with only minor damage.

However, it became apparent, shortly after launch, that there was serious image motion on the detectors. Consequently, the highest gain output (Channel 3) was saturated for almost the entire flight and even Channel 2 was subject to such violent variations in mean output as to make the data virtually useless. Nevertheless, some useful data was returned and one, low resolution, spectrum obtained when the system stabilized for about 1 minute at float. This spectrum, without further reduction, is shown in figure 8. A portion of the same spectrum, with the instrumental transmission function removed is shown in figure 9 together with a representation Rayleigh-Jeans law curve for comparison purposes. From this data it has been possible to deduce an approximate power law for the decrement of the solar continuum in the far infrared [6].
from this first flight to demonstrate that the technique is feasible and to show what modifications are required to make future flights more successful. However, there is abundant evidence that the interferometer itself needs no modification and we are hopeful that at the next attempt we shall come closer to the design resolution of $1 \text{ cm}^{-1}$ with much better signal/noise.

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Conclusion. — Enough useful data was obtained
Balloon R & D Test Branch, Holloman AFB, for the excellence and efficiency of the balloon flight operations.

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Bibliographie

[4] Goddard (A.), Juza (M.), Maher (T.) and Speck (F.), Rev. Sci. Inst., 1956, 27, 381. (The system flown was an improved version manufactured by the Hi-Altitude Instrument Co., Denver, Colorado.)