No. 93 A PROGRAM OF ASTRONOMICAL INFRARED SPECTROSCOPY FROM AIRCRAFT

by G. P. KUIPER, F. F. FORBES, AND H. L. JOHNSON

June 30, 1967

ABSTRACT

A program of astronomical infrared spectroscopy from aircraft is developed based on the facilities offered by the NASA CV 990 Jet, with its 65° window ports and its gyrostatically controlled heliostats. A 12-in. horizontal telescope on shock mounts was added, equipped with standard astronomical attachments for spectral observation of the PbS region of the infrared. Table 1 summarizes the vertical distribution of water vapor in the atmosphere in the middle latitudes which determines the relative efficiency of flight operations from different heights. A description is given of the NASA-developed procedures for observation of planets and stars of different declinations. Table 4 summarizes the eight operational flights that took place in the spring of 1967. The efficiency of this approach was much increased when it was shown that a medium-resolution Block interferometer could be used in spite of aircraft vibrations or expected scintillation effects.

1. *Introduction*

Ground-based astronomical spectroscopy has well-known serious barriers. At jetcraft altitudes (10–20 km), the ozone absorptions still prohibit useful work at $\lambda < 3000$ Å; but the peculiar distribution of atmospheric water vapor (scale height in troposphere about 1.6 km versus 8.0 km for air generally) makes possible at these altitudes a very large reduction of the infrared telluric bands, most of which are due to H_2O. This is most important because the infrared spectrum contains the fundamental molecular vibrations and their lower overtones. Thus, at these altitudes basic information on the composition, temperature, and stratification of planetary atmospheres may be derived, as well as properties of the exposed planetary surface.

The development of large commercial jets cruising safely at altitudes of at least 40,000 ft (12 km) makes their ceiling altitude a convenient stepping stone. Large instruments can be carried to this altitude and operated under laboratory conditions; yet no special safety devices (pressure suits or oxygen helmets) are needed, as even sudden partial decompression of the cabin does not pose fatal risks. For operations above 45,000–50,000 ft (14–15 km), aircraft with limited space and much smaller payloads must be used and observers must operate in pressure suits. This limits these higher altitudes at present to special projects. Supersonic transports will in time provide larger capabilities above the present 40,000–45,000-ft level.

Some excellent work has been done at still higher altitudes, up to 120,000 ft (36 km), using unmanned balloons. The potentialities of this approach have recently been summarized in several articles in *Applied Optics* (see Supplementary References). The logistics of balloon operations are much more complex than those of aircraft, and special atmospheric conditions must be awaited for launch. Also, failure rates are not negligible, and telescope and accessories may be damaged or lost at launch or during landing. No such problems exist with aircraft, where two or three missions per week are feasible and the astronomical program can be planned beforehand to the minute. Of cardinal importance is the ability in aircraft to check out in flight the complex recording equipment and to make quick repairs or substitutions with backup units when called for. Also, one has complete certainty as to the circumstances under which the observations were made. The equipment and attachments, as well as the scientific and technical staff, can be readily adapted to the requirements of each flight. The relative merits of the unmanned-balloon approach versus the use of manned operations from aircraft therefore involve numerous factors, scientific and logistic, that must be carefully weighed.

2. *Atmospheric Conditions and Available Equipment at 40,000 ft (12 km)*

The average tropospheric scale height for water vapor ($\sim$1.6 km) indicates that in the middle latitudes (30°–50°), where the tropopause is about 11–12 km high, a reduction of some 2000 times in the ambient atmospheric water-vapor content will be attained over sea level and of some 600 times over a typical mountain observatory (2 km, 6600 ft). Above the tropopause, the water-vapor content is nearly constant up to an elevation of about 20 km. Above this level there is still some uncertainty. Earlier measures, made from balloons, showed a steady increase with a broad maximum indicated near 30 km. It was found, however, that balloons often exude considerable quantities of water vapor at high altitude. In a compilation of all available data up to 1962, Junge (1963) therefore included only such series in which measures made during the balloon ascent agreed with those made on the descent. In Table 1 we have used Junge's data up to 25 km, and in turn averaged these with the results of a very thorough study extended over a year made by Sissenwine, *et al.* (1966) over north-central California (lat. 40° N, long. 122° W) up to elevations of 32 km. These latter are of special interest here because our spectral observations are made from nearly the same geographic position. The averages so derived in Table 1 still indicate a water-vapor maximum in the middle stratosphere, but less pronounced than in Junge's (1963) compilation and now centered around 25 km. Table 1 gives, in addition, an alternative distribution for altitudes above 18 km based on the assumption of a constant mixing ratio as advocated by English observers and recently by Calfee and Gates (1966). These authors, reviewing much recent work, some from high-altitude aircraft, conclude, "the stratosphere is dry and the distribution, although slightly variable, is well fitted by a constant mixing ratio throughout the stratosphere" (2 or 3 parts per million).

On either model it is apparent from Table 1 that the 12–13-km level is very well suited for operations, not merely logistically because of available aircraft, but also scientifically. Full advantage is then taken of being above the relatively wet troposphere and just below the level (13 km) at which observers must wear safety devices in the aircraft. Only a further reduction of other atmospheric components (CO_2, N_2O, CH_4), as well as of the strongest water-vapor bands, will make supplementary observations at much higher altitudes necessary. Spectroscopic observation at the 12–14-km level cannot easily distinguish between the two models (Houghton 1963).

The intensity of the telluric water-vapor bands depends not merely on the integrated abundance along the atmospheric path but also on the pressure.

TABLE 1

AVERAGE VERTICAL DISTRIBUTION OF WATER VAPOR (MIDDLE LATITUDES)*

Altitude (KM)	Altitude (1000 FT)	log R		log ρ	log W		W (μ)	
0	0	−2.4:		−2.9	−0.3:		5000:	
2	6	−2.8		−3.0	−0.8		1600.	
4	13	−3.1		−3.1	−1.2		600.	
6	20	−3.5		−3.2	−1.7		200.	
8	26	−3.9		−3.3	−2.2		60.	
10	33	-4.4^{5}		−3.4	-2.8^{5}		14.	
12	39	−5.1		−3.5	−3.6		2.5	
14	46	−5.5		−3.6	−4.1		0.8	
16	52	−5.5		−3.8	−4.3		0.5	
18	59	−5.5	−5.6	−3.9	−4.4	−4.5	0.4	0.3
20	66	−5.3	−5.6	-4.0^{5}	-4.3^{5}	-4.6^{5}	0.5	0.2
25	82	−4.8	−5.6	−4.4	−4.2	−5.0	0.6	0.1
30	98	−4.8:	−5.6	−4.7	−4.5:	−5.3	0.3:	0.05

*R = average mixing ratio, H_2O/air, by weight; ρ atmospheric density; average W water vapor, weight in grams per 1 km path length in clear air; W (μ) same, in microns liquid equivalent.

Since for strong bands the product $\sqrt{NP}$ is relevant, the contribution to the stronger bands would decrease with altitude even for the left-hand column in Table 1.

In an important pioneering effort, a series of high-altitude solar spectra between 1.0–6.5 μ was obtained from a Canberra jet with an open port by Houghton, *et al.* (1957, 1961) at the Royal Aircraft Establishment, Farnborough, England. The altitudes ranged up to 48,000 ft (14.6 km), and the spectra show the need of reaching at least 40,000 ft (12 km) in astronomical IR spectroscopy. We have obtained a series of solar calibration spectra for 1.0–2.5 μ from altitudes of 1.5–12.5 km (5,000–41,000 ft), with the equipment used on the planets Venus and Mars. The resolution is 20 cm^{-1}, less than the 2 cm^{-1} (at 2.4 μ) to 11 cm^{-1} (at 1.1 μ) used by Houghton, *et al.* (1961), but with more accurately controlled levels of the continuum. These spectra are reproduced in *Comm. LPL* No. 94 and will in their range, 1.0–2.5 μ, serve as references in medium- to low-resolution astronomical spectroscopy.

The moisture distribution of Table 1 is representative of only the middle latitudes where the tropopause lies near the 11–12-km level instead of 7–8 km as in the polar areas, or 18 km as in the tropics. The boundary between the tropical and the middle-latitude circulation zones varies with the seasons, being around 30° in winter and 45° in summer. Near the boundary, the tropopause may be double, often accompanied by a jet stream. This region is likely to be turbulent and is best avoided in observing runs. Since the tropopause is normally well above the upper boundary of cloud formations (only thunderstorm cumuli may penetrate the lower stratosphere), the 12–14-km zone in the middle latitudes is seen to be remarkably suited to astronomical observations in the infrared.

Our first concrete application of high-altitude aircraft to planetary astronomy was a program developed by Dr. Kuiper with Dr. P. St. Amand at the Naval Ordnance Test Station, China Lake, California, in April 1965. It used an A-3B Jet, having a ceiling of about 44,000 ft (13.4 km) which, without major modifications, could accommodate refracting telescopes up to 3- or 4-in. aperture, fastened in a window through a swivel vacuum junction. Mr. Carl Gillespie, our high-altitude observer, found that hand-guiding had sufficient precision (1–2 arc min) for certain integrated measures in the far infrared. The program was developed further by Dr. Frank Low and Mr. Carl Gillespie, and three groups of flights took place in 1966. The results relate mostly to the sun and the sky brightness at 1 mm and will be published elsewhere. The sky radiation attributable to water vapor dropped sharply to inappreciable amounts at an altitude somewhere between 37,000–44,000 ft (11.3–13.4 km) depending on conditions, confirming the general picture of Table 1. The observations were suspended early in 1967 through the tragic loss of the competent crew and the aircraft, on a flight not connected with the IR program.

Planetary and stellar spectroscopy in the near infrared in practice requires a telescope of at least 12-in. aperture on which observations can be made at least over an hour with a guiding precision of 1 arc min or better. Exploratory discussions with Dr. Michel Bader and Mr. Robert Cameron of the NASA-Ames Laboratories early in 1966 led to the formulation of such a program with the NASA Convair 990 Jet. In this aircraft a row of 12 × 14 in. clear-aperture windows was available at 65° above the horizon and also facilities for mounting a telescope with attachments and supporting electronics; further, a gyro-controlled heliostat, allowing continuous guiding with a precision of 10–20 arc sec for at least an hour; while the astronomical operations could be performed with the convenience of a physical laboratory, no pressure suit being required. Formal proposals for a flight program were made in December 1966, and through support by both NASA Hq., and NASA-Ames the authors were assigned time during April-June 1967 in a schedule that was already nearly filled. The aircraft is based at Moffett Field, California (30 mi SE of San Francisco). The relevant features are described below.

On the left side of the aircraft a series of extra window ports allow observation from 65° ± 10° elevation. The window port assigned to this program is located over the wing, for maximum stability and minimum vibration. Its position with respect to the various control points is shown in Figure 1. The dimensions and construction of the window port itself are shown in Figure 2. An outside metal shield, flush with the aircraft skin, protects the optical surface during takeoff and landing. When not in operation a pane of safety glass protects the optical window from the inside. The cross section of the fuselage is shown in Figure 3, which indicates also the position of the two seat rails to which the telescope is fastened. The incoming beam from the 65° window is intercepted by a gyrostatically controlled

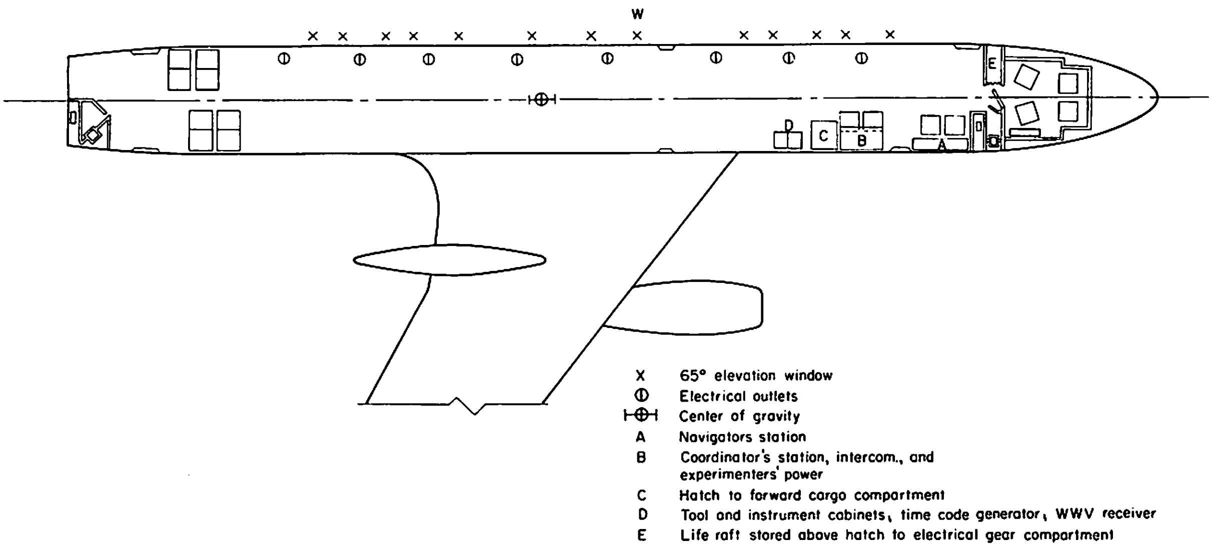


Fig. 1 Floor plan of control points in NASA 990 Jet. *W* gives position of window used in planetary observations.

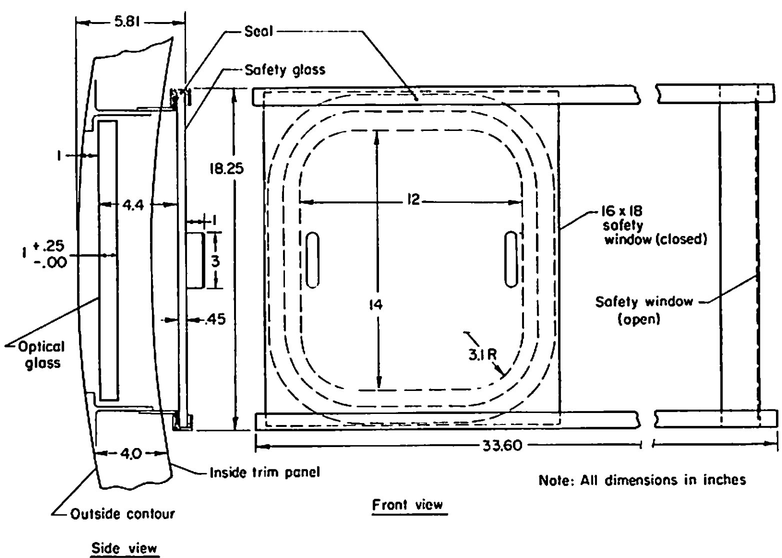


Fig. 2 Construction and dimensions of window port.

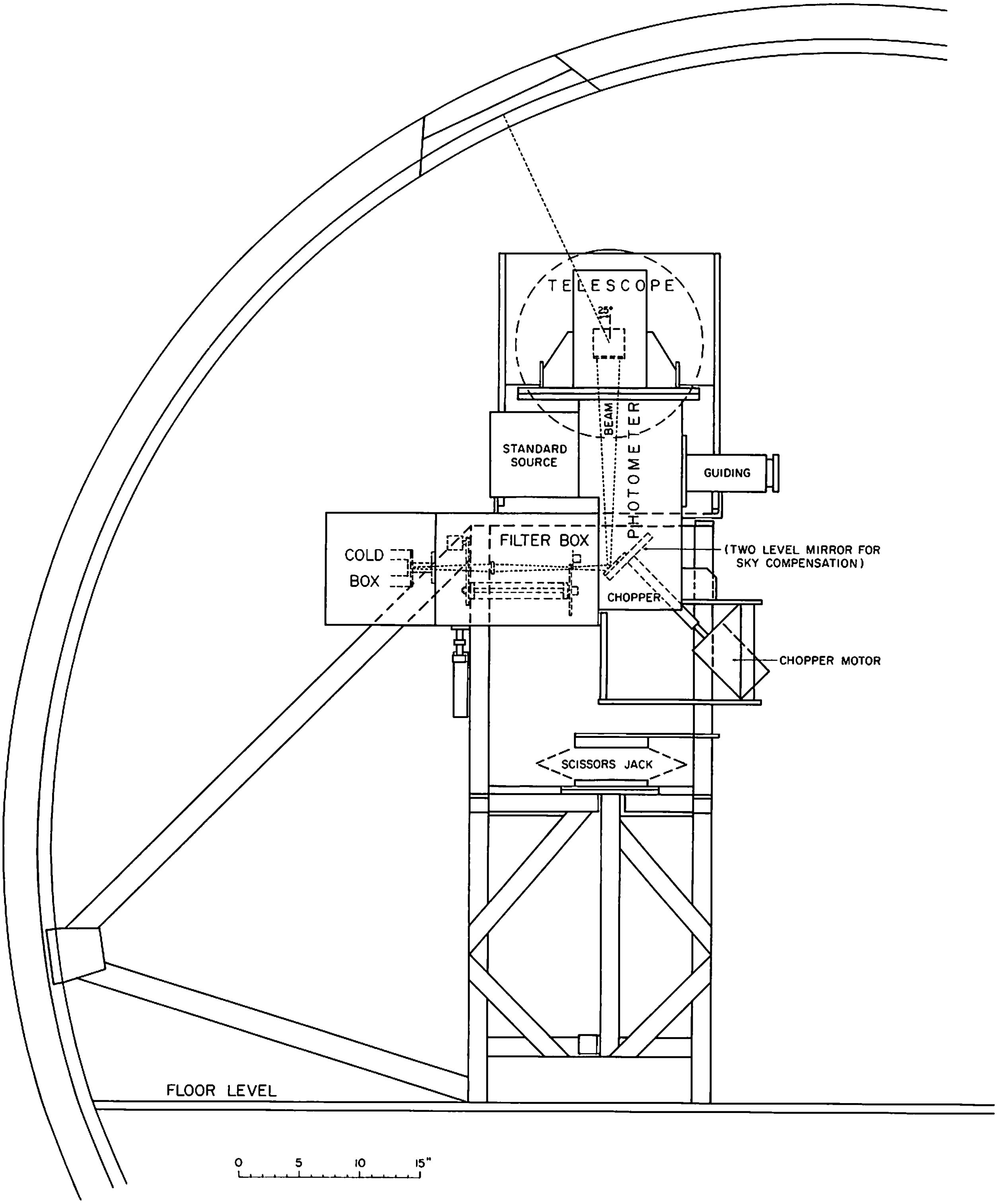


Fig. 3 Cross section of telescope, support, and window normal to aircraft axis. Cf. Fig. 4.

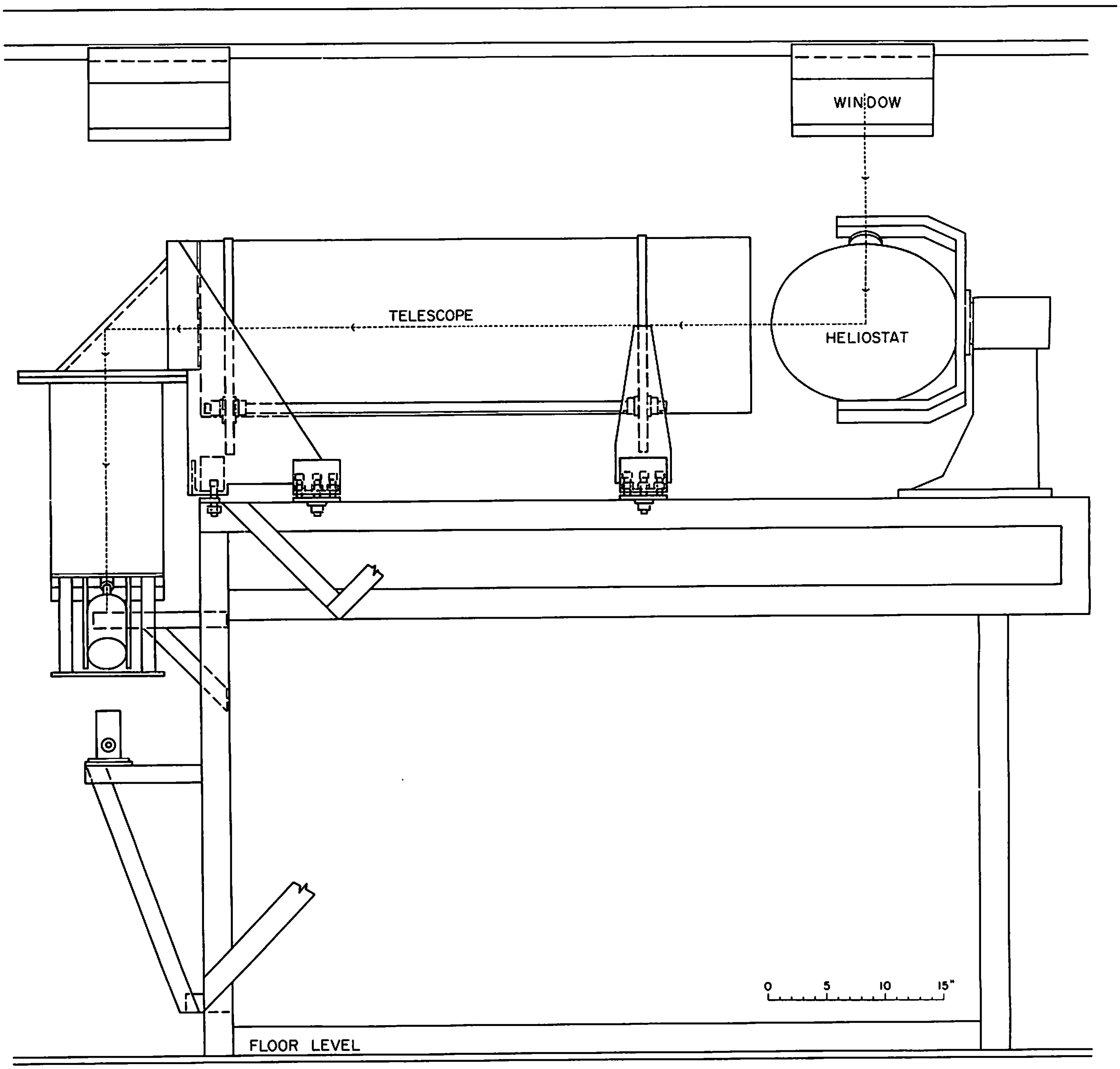


Fig. 4 Longitudinal projection of telescope and accessories.

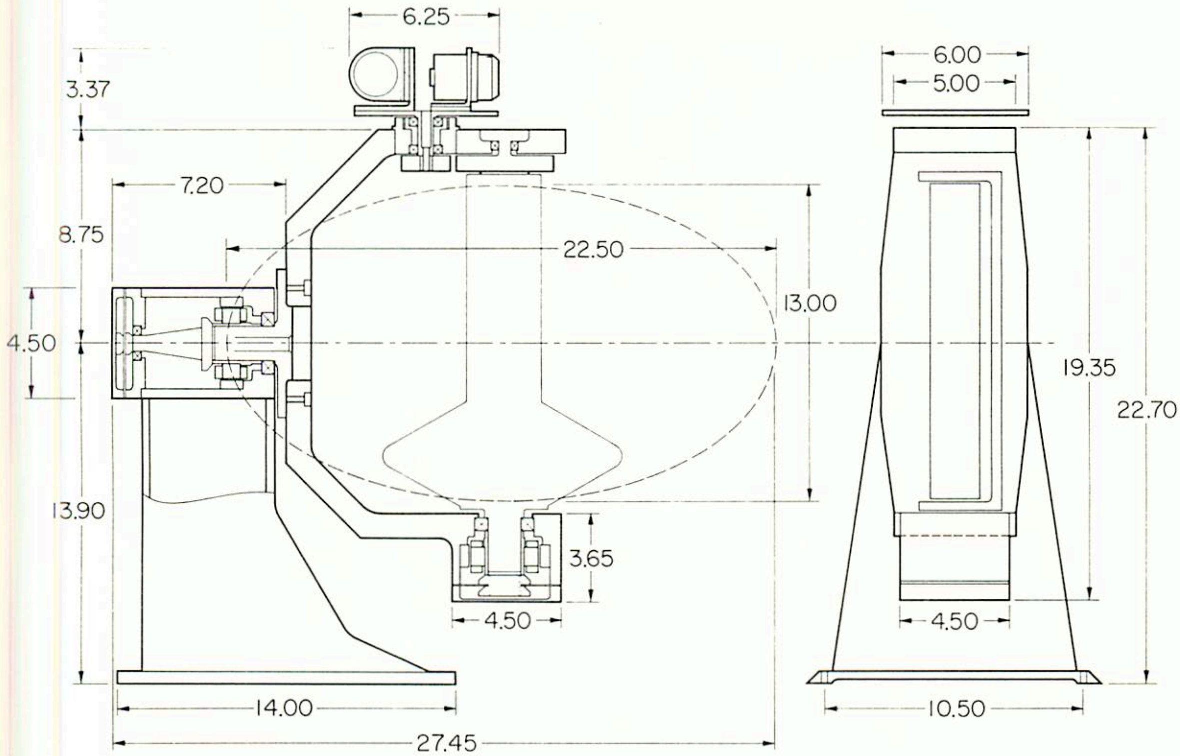


Fig. 5 Dimensions and controls of heliostat mirror. Cf. Fig. 4.

heliostat, the overall dimensions and construction of which are seen in Figures 4 and 5. During operations, the heliostat mirror is not kept parallel to itself as the plane rolls or pitches; instead it is corrected by *half* the angular amounts, which causes the reflected beam of a stationary object to remain parallel to the plane's fuselage. As a result, the image of a planet would be stationary in a telescope attached to the aircraft structure if its azimuth and elevation were stationary. Normally, the observations are made when the planet is in transit, and the plane flies west. Since the heliostat has drives with adjustable rates in both coordinates, the altazimuth drifts can be compensated for. In addition, there are manual overrides for small erratic motions resulting from uncompensated motions of the aircraft. The assemblage of telescope, heliostat, and window port is seen in Figures 4 and 6.

The telescope used in this program is a cassegrain of 12-in. aperture, F/4 primary and F/13 secondary, provided by this Laboratory. The F-ratio was so chosen that the photometers and other attachments in use at the Catalina Observatory could be used without change.

Two attachments have been used so far: (1) a Block interferometer with resolution of 20 cm^{-1}, using uncooled PbS cells, kindly lent to us by Mr. Lawrence Mertz pending the receipt of a Block interferometer on order; and (2) a Johnson photometer equipped with rotating interference wedge filters covering the region of 1.2–4.2 microns. The photometer has a lead-sulfide cell, ¼ × ¼ mm, liquid-nitrogen cooled (NEP $= 1.5 \times 10^{-11}$ W).

The output of either instrument is recorded on magnetic tape and displayed in parallel on an oscilloscope. The wedge spectra are also recorded on the high-speed (0.01 sec response time) recorder. These extra attachments are used for monitoring purposes. Figures 3, 4, and 7 show the telescope with the photometer and filter-wedge device attached. The electronics equipment is mostly kept in the frame that supports the telescope; cf. Figures 4, 6, and 7.

The telescope is attached to the aircraft by shock mounts so that vibration during takeoff and landing, and in flight, are damped. Except for one flight at ceiling altitude, when the outside temperature had dropped to −60° C and parts of the wing flow approached the velocity of sound, causing a special

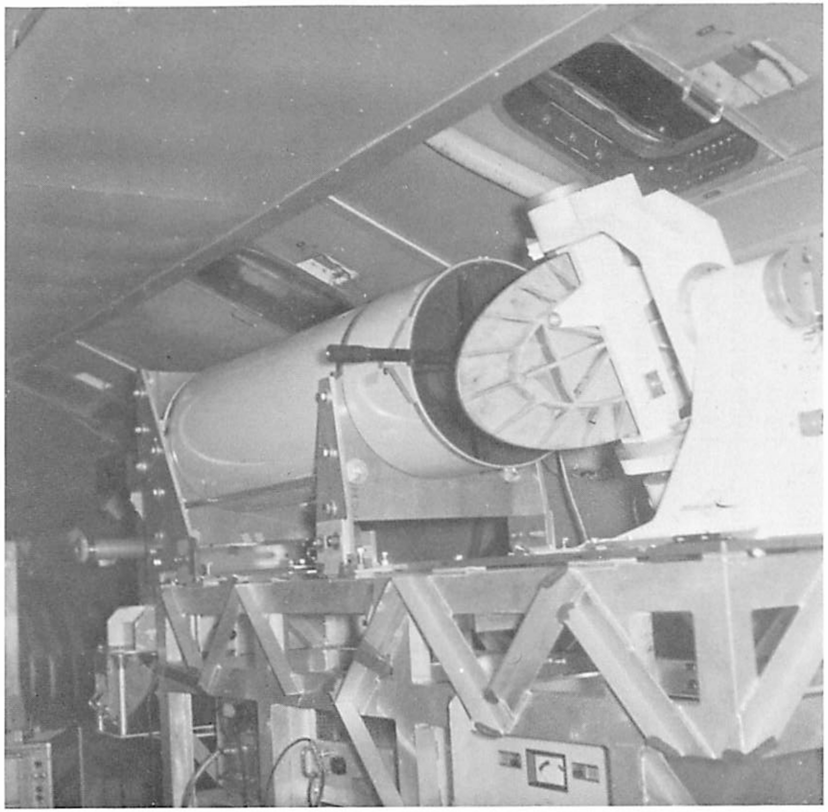


Fig. 6 Photograph of telescope mount and accessories. Cf. Figs. 3–5.

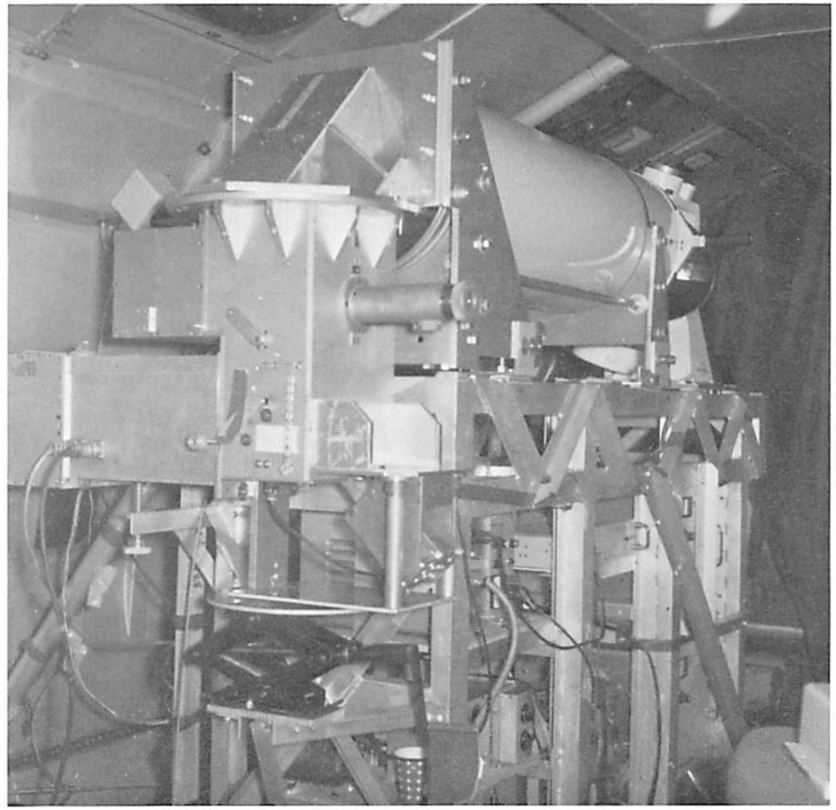


Fig. 7 Photograph of telescope and filter-wedge attachment to photometer. Cf. Fig. 6.

vibration that was transmitted to heliostat and telescope, the vibration damping, though not complete, was quite effective as judged at the guiding eyepiece. Also, the gyroscopes, when started in their proper orientations, performed nearly within their specifications (about 10 arc sec) even during periods of mild turbulence. The IR devices were attached to the telescope in flight and, during the takeoff and landing, were stowed in padded boxes securely anchored to the floor. The interferometer was attached to the telescope through special separators that further reduced vibrations; this proved essential.

As already indicated, the operational procedure developed by NASA-Ames consisted of observing a planet near meridian passage by flying the aircraft at the appropriate time on an east-west course whose latitude made the planet's altitude above the southern horizon 65° ± 5° or at most ±10°. Thus, for Mars (decl. −7°) the geographic latitude at observation was approximately 23° N, for Venus (decl. +26° to +21°), 46° to 41° N. In order to allow observations to continue for an hour or more, the east-west track was slightly curved, based on a schedule computed in advance at NASA-Ames. For example, parts of the Venus flight schedule of May 14 are reproduced in Table 2. The corresponding schedule for the moon, observed immediately afterwards for calibration, is shown in Table 3.

Table 4 lists the flights made during April–June 1967. The April 21–23 flights were out of Moffett Field, over the eastern Pacific off the coast of Mexico, with the actual trajectories shown in Figure 8. (The flight trajectories differ somewhat from those computed because the latter are derived on the assumption of no wind or some average value. At the 40,000-ft level, wind velocities often exceed 100 knots.) The May 14 Venus flight took place over southern Canada, as illustrated in Figure 9.

The April flights were mostly experimental and showed some instrumental weaknesses that were corrected for the May and June flights. Among these were improved telescope focusing, an arrangement that allowed continuous guiding on the Johnson photometer, and improved mounting of the interferometer to reduce vibrations. The choice of the optical window was also reconsidered. Three windows (each about 1 in. thick) were available, composed of soda-lime, borosilicate crown, and fused quartz, respectively. It was initially assumed that *fused quartz* would be the most suitable, and it was used in the April flights. It was found, however, that the partial transmission of fused quartz from 3.0–3.6 microns was no compensation for the disadvantages resulting from absorptions at 1.4 and 2.2 microns. For this reason, the *borosilicate crown* window was used in the May and June flights. The transmission curves of the three windows, measured with the Perkin-Elmer spectrometer at NASA-Ames, are shown in Figure 10. Windows transparent for the region beyond 2.5 microns are urgently needed for future infrared spectroscopy. Possibilities under consideration include the use of Infrasil ($\lambda < 4\ \mu$), an Irtran 5 mosaic ($\lambda < 9\ \mu$), a polycrystalline silicon mosaic ($1.1 < \lambda < 1000\ \mu$), and an open window port connected with a vacuum-proof telescope.

A description of the Block *interferometer* has been published by its inventor, Lawrence Mertz (1965*a*, *b*), who graciously permitted the authors to use his personal instrument on the NASA 990 flights. A traveling mirror causes an interferogram with resolution of 20 cm^{-1} to be made every 0.8 sec. During 30 min. some 2000 interferograms are therefore produced. They are recorded on an Ampex Model 860 magnetic tape recorder. The reductions consist of, first, co-adding these records in one or two (or any other small number) of master interferograms; whereupon each of these is reduced to a spectrum by an IBM 1131 computer program cited by Mertz (1966). The very rapid scan of the interferometer appears to avoid the troubles that have in the past beset some of the slower interferometers.[1]

The present Mertz interferometer uses two standard uncooled PbS cells because of their rapid frequency response (>1000 cps). In the new Block interferometer now under construction (having 10 cm^{-1} resolution), cooled InAs detectors will be used instead, with a roughly 20-fold gain in sensitivity.

The *filter wedge* characteristics are shown in Figures 11–13. Figure 11 shows a combination of two semicircular filters cemented together into a single filter wheel about 10-cm diameter. One half transmits the region 1.3–2.5 μ, as indicated in Figure 11*a;* the other half from 2.1–4.2 μ. The bandwidths of the transmission peaks are listed in Table 5 and are seen to be close to 1 percent throughout the region covered. Figure 11*b* shows the peak transmission as a function of wavelength. It is noted that each filter

[1] Mertz (1965*a*) correctly stresses that the published critiques of earlier unsuccessful interferometers did not deal with unavoidable basic difficulties; and that, for instance, his technique of very rapid scans suffices to overcome disturbing scintillation effects (even without ratio recording). A similar comment was published by G. P. Kuiper in *Comm. LPL*, 1, 180, Jan. 1963.

TABLE 2

COMPUTATIONS OF VENUS FLIGHT TRAJECTORY, MAY 14, 1967

UT	LAT.	LONG.	OBJECT ELEVATION	OBJECT AZIMUTH	AIRCRAFT HEADING	AIRCRAFT BANK ANG.	OBJECT BEARING TO FLIGHT PATH
19^h 16^m 60^{s}0	46° 5.6	69° 55.9	69° 22.0	168° 19.5	263° 4.5	0° 2.0	265° 15.0
19 21 60.0	46 1.6	70 51.8	69 28.5	169 5.5	263 50.5	0 2.1	265 15.0
19 26 60.0	45 58.2	71 47.8	69 34.3	169 52.1	264 37.1	0 2.2	265 15.0
19 31 60.0	45 55.3	72 43.8	69 39.4	170 39.3	265 24.3	0 2.3	265 15.0
19 36 60.0	45 52.9	73 39.8	69 43.7	171 27.1	266 12.1	0 2.3	265 15.0
19 41 60.0	45 51.1	74 35.9	69 47.4	172 15.4	267 0.4	0 2.4	265 15.0
19 46 60.0	45 49.8	75 31.9	69 50.3	173 4.1	267 49.1	0 2.4	265 15.0
19 51 60.0	45 49.1	76 27.9	69 52.5	173 53.1	268 38.1	0 2.5	265 15.0
19 56 60.0	45 49.0	77 23.9	69 54.0	174 42.5	269 27.5	0 2.5	265 15.0
20 1 60.0	45 49.4	78 20.0	69 54.6	175 32.1	270 17.1	0 2.5	265 15.0
20 6 60.0	45 50.4	79 16.0	69 54.6	176 21.8	271 6.8	0 2.5	265 15.0
20 11 60.0	45 52.0	80 12.0	69 53.8	177 11.6	271 56.6	0 2.5	265 15.0
20 16 60.0	45 54.1	81 8.0	69 52.2	178 1.4	272 46.4	0 2.5	265 15.0
20 21 60.0	45 56.8	82 4.0	69 49.9	178 51.0	273 36.0	0 2.5	265 15.0
20 26 60.0	45 60.0	82 60.0	69 46.8	179 40.5	274 25.5	0 2.5	265 15.0
20 31 60.0	46 2.8	83 56.1	69 44.0	180 29.8	275 14.8	0 2.4	265 15 0
20 36 60.0	46 6.1	84 52.2	69 40.4	181 18.6	276 3.6	0 2.4	265 15.0
20 41 60.0	46 10.0	85 48.2	69 36.2	182 7.1	276 52.1	0 2.3	265 15.0
20 46 60.0	46 14.5	86 44.3	69 31.1	182 55.3	277 40.3	0 2.3	265 15.0
20 51 60.0	46 19.4	87 40.3	69 25.4	183 43.0	278 28.0	0 2.2	265 15.0
20 56 60.0	46 25.0	88 36.4	69 19.0	184 30.2	279 15.2	0 2.1	265 15.0

TABLE 3

COMPUTATIONS OF MOON FLIGHT TRAJECTORY, MAY 14, 1967

UT	LAT.	LONG.	OBJECT ELEVATION	OBJECT AZIMUTH	AIRCRAFT HEADING	AIRCRAFT BANK ANG.	OBJECT BEARING TO FLIGHT PATH
20^h 16^m 60^{s}0	46° 52.8	81° 36.5	63° 6.2	132° 9.5	226° 54.5	0° 0.	265° 15.0
20 21 60.0	46 26.4	82 18.4	63 39.2	132 20.9	227 5.9	0 0.	265 15.0
20 26 60.0	45 60.0	82 60.0	64 12.3	132 32.8	227 17.8	0 0.	265 15.0
20 31 60.0	45 33.4	83 41.0	64 46.1	132 45.5	227 30.5	0 0.	265 15.0
20 36 60.0	45 6.9	84 21.8	65 20.0	132 58.7	227 43.7	0 0.	265 15.0
20 41 60.0	44 40.5	85 2.4	65 54.1	133 12.7	227 57.7	0 0.	265 15.0
20 46 60.0	44 14.2	85 42.9	66 28.3	133 27.3	228 12.3	0 0.	265 15.0
20 51 60.0	43 48.1	86 23.2	67 2.7	133 42.5	228 27.5	0 0.	265 15.0
20 56 60.0	43 22.1	87 3.4	67 37.2	133 58.6	228 43.6	0 0.	265 15.0
21 1 60.0	42 56.2	87 43.5	68 11.7	134 15.5	229 0.5	0 0.	265 15.0
21 6 60.0	42 30.5	88 23.5	68 46.4	134 33.2	229 18.2	0 0.	265 15.0
21 11 60.0	42 4.9	89 3.4	69 21.1	134 51.9	229 36.9	0 0.	265 15.0
21 16 60.0	41 39.5	89 43.2	69 55.8	135 11.6	229 56.6	0 0.	265 15.0
21 21 60.0	41 14.2	90 22.9	70 30.6	135 32.5	230 17.5	0 0.	265 15.0
21 26 60.0	40 49.2	91 2.6	71 5.4	135 54.6	230 39.6	0 0.	265 15.0

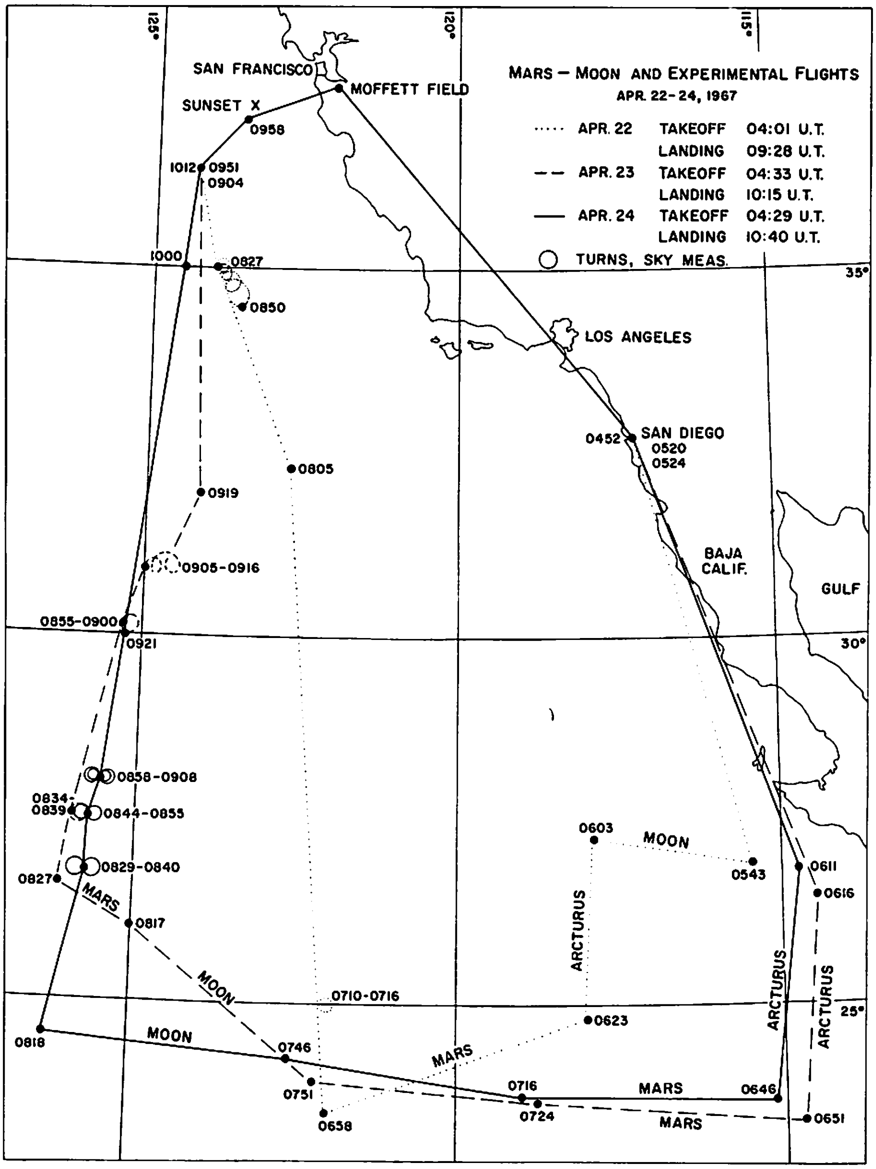


Fig. 8 Trajectories for three experimental flights, April 1967. The turns indicated were made for Dr. Low's IR program.

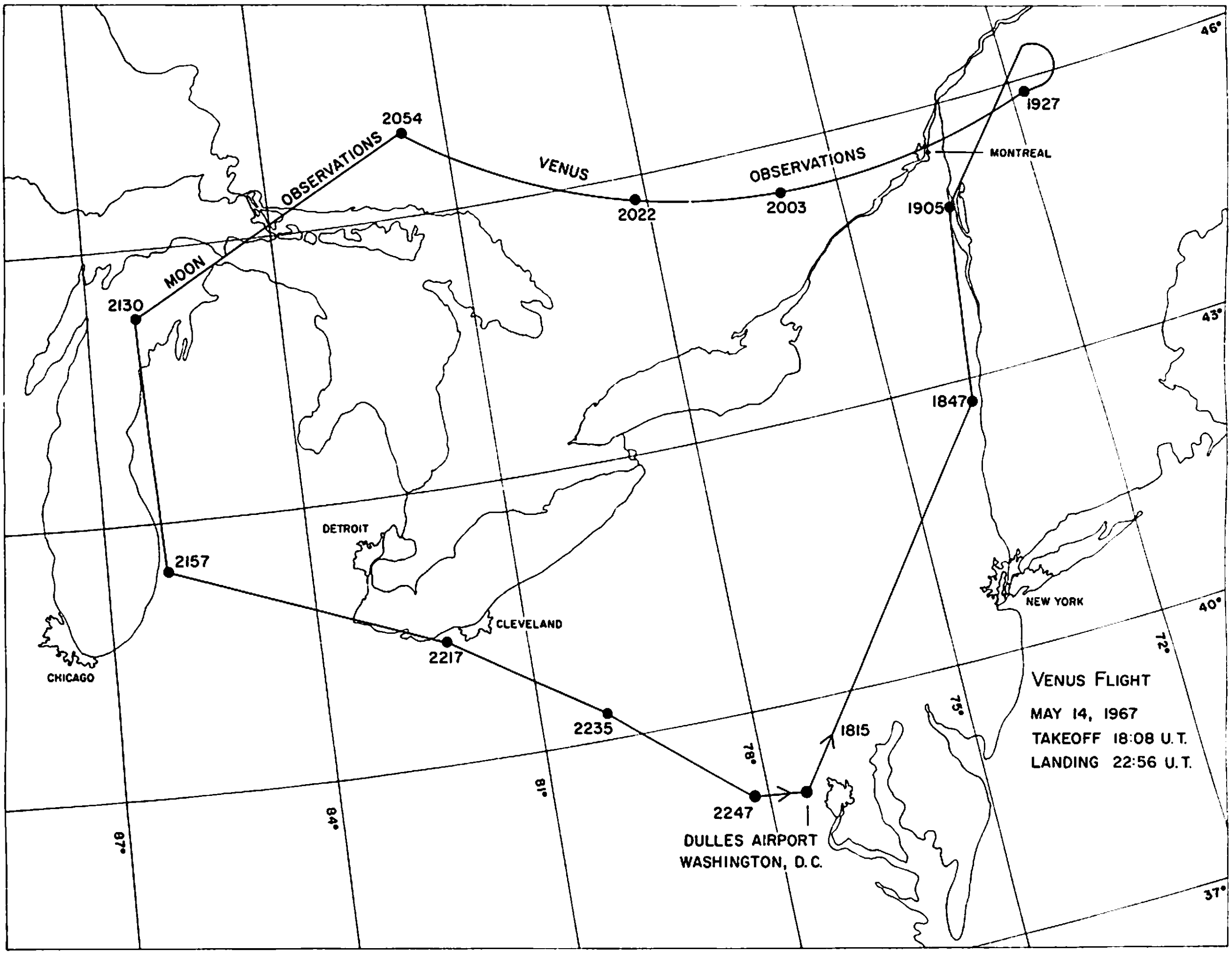
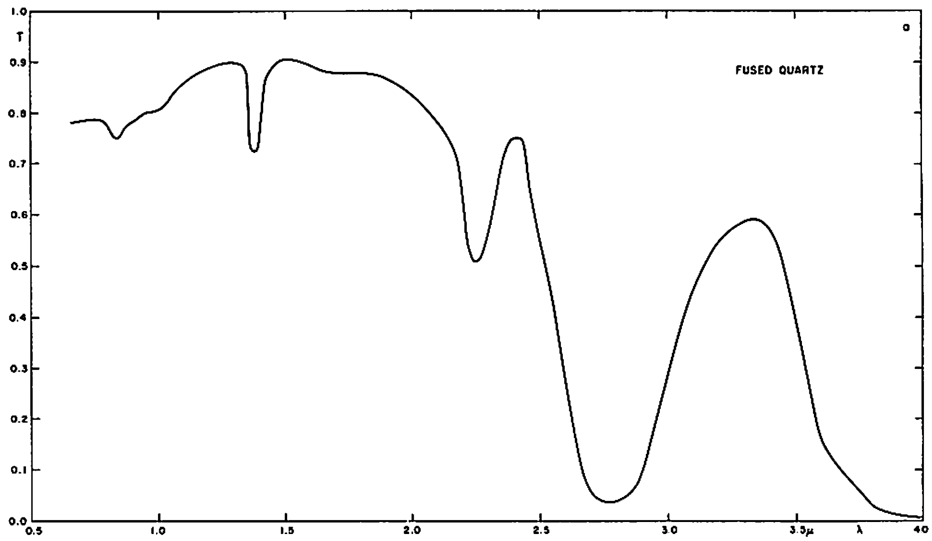


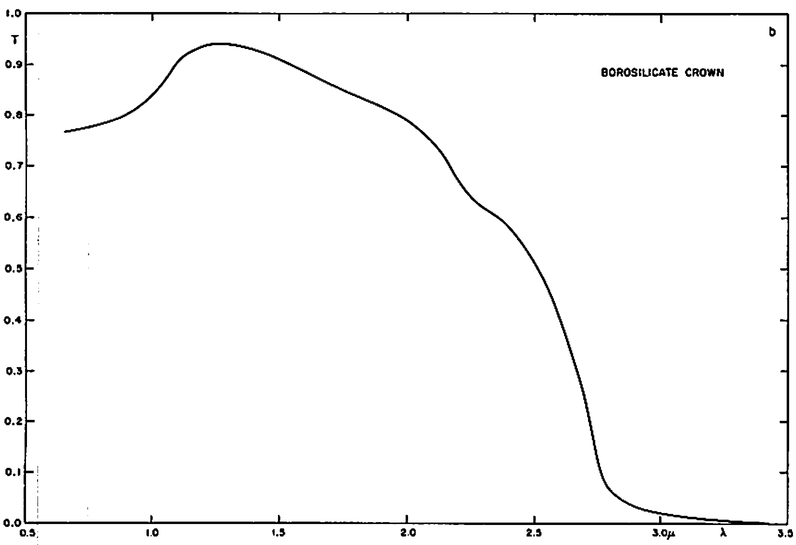
Fig. 9 Trajectory of Venus flight, May 14, 1967.

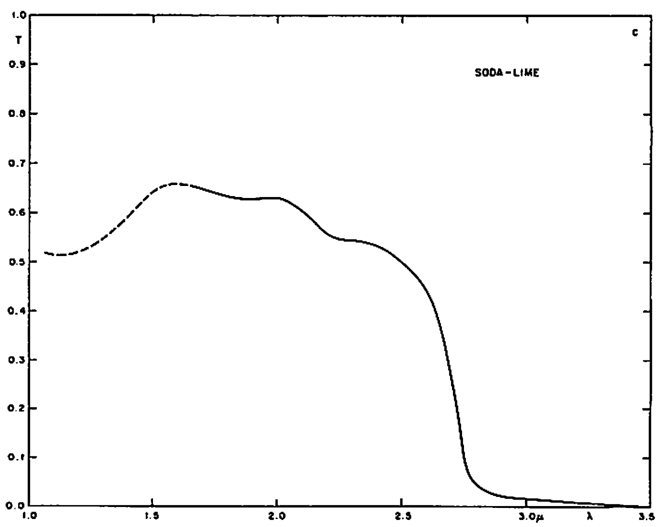
TABLE 4

NASA, AMES 990 JET, IR SPECTROSCOPY FLIGHTS APRIL-JUNE 1967

1967 Date	Time	Object	R.A.	Dec.	Local Transit Time
Fri, April 21	8 PM	Moon	11:59	+ 3:42	21:57
	9 PM	Mars	13:25	− 6:55	23:23
Sat, April 22	9 PM	Moon	12:53	− 3:20	22:46
	10-12 PM	Mars	13:24	− 6:56	23:17
Sun, April 23	9 PM	Moon	13:47	−10:14	23:37
	10-12 PM	Mars	13:22	− 6:50	23:12
Sun, May 14	2-3 PM	Venus	6:24	+25:47	14:56
	4 PM	Moon	7:53	+26:11	16:25
Sun, June 11	2 PM	Moon	8:34	+24:03	15:15
	3-4 PM	Venus	8:34	+21:06	15:15
Mon, June 12	6 PM	Moon	9:39	+19:20	16:14
	7-9 PM	Mars	13:02	− 6:52	19:37
Tue, June 13	6 PM	Moon	10:32	+14:07	17:03
	7-9 PM	Mars	13:03	− 7:00	19:34
Fri, June 23	11-2 PM	Sun	6:07	+23:26	12:02







Figs. 10a, b, and c Transmission curves of three available optical windows.

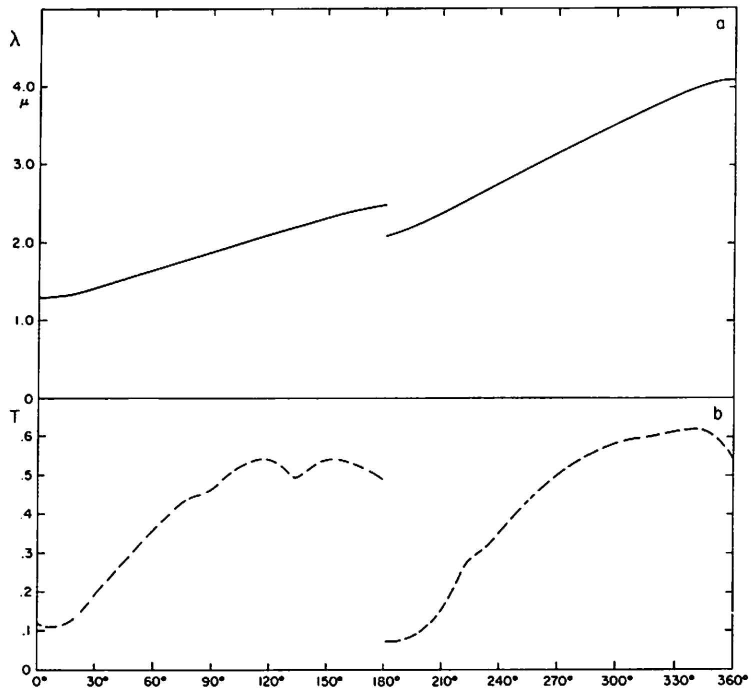


Fig. 11 Wavelength (*a*) and peak transmission (*b*) versus orientation of filter wheel having 1 percent bandwidth (Table 5).

is efficient only for approximately two thirds of its octave. Figure 12*a* shows similarly a complete interference wedge (two symmetrical halves) for the region 1.85–3.65 μ. Its peak transmission is very good, as is seen from Figure 12*b*. Figure 13 reproduces the shapes of the transmission peaks of the second filter. Its bandwidths in terms of filter position and wavelength are shown in Table 6. The filter wheels in the photometer turn at the rate of once per 10 sec.

Application of both the Mertz interferometer and the 1–4 μ filter wheel are presented in the following *Communications*.

A third attachment to be used in the program is a *grating spectrograph* with a short-focus camera, giving 40 Å/mm in the photographic infrared. The grating has 600 lines/mm, is blazed for 1.6 μ first order or 8000 Å second order. The collimator focal length is 37.5 in. = 95 cm; the camera focal length, 8 in. (20 cm).

TABLE 5

Transmission Properties of Filter Wheel No. 1

Angle	λ(μ)	Bandwidth %	Half Brightness (μ)	
0°	1.2707	0.822	1.2655	1.2759
30	1.4279	0.995	1.4208	1.4350
60	1.6406	0.945	1.6329	1.6484
90	1.8637	0.918	1.8552	1.8723
120	2.0869	0.995	2.0765	2.0973
150	2.3012	0.955	2.2903	2.3122
180	2.4777	0.891	2.4667	2.4887
180	2.09	0.91	2.0811	2.1001
210	2.33	1.15	2.3482	2.3213
240	2.69	1.01	2.6747	2.7018
270	3.07	0.984	3.0544	3.0854
300	3.34	0.994	3.4352	3.4707
330	3.82	0.97	3.7995	3.8352
360	4.10	1.01	4.0943	4.1353

TABLE 6

Transmission Properties of Filter Wheel No. 2

Angle	λ(μ)	Bandwidth %	Half Brightness (μ)	
0°	1.855	2.70	1.83	1.88
15	1.990	2.52	1.96	2.01
30	2.14	2.34	2.11	2.16
45	2.31	2.60	2.28	2.34
60	2.45	2.86	2.41	2.48
75	2.60	2.69	2.56	2.63
90	2.72	2.58	2.68	2.75
105	2.95	3.05	2.90	2.99
120	3.11	2.90	3.06	3.15
135	3.26	2.76	3.21	3.30
150	3.41	2.94	3.36	3.46
165	3.55	2.70	3.49	3.60
180	3.64	2.75	3.59	3.69

3. Future Developments

While for many years the potential of aircraft carrying IR recording equipment above the terrestrial water vapor had been recognized, the technical problems and the sensitivity limitations of the detectors are only now being overcome. Of particular importance is the development by Mertz of an IR spectral interferometer using rapid scans. Even so, much additional development is needed to make a program possible for an adequate number of important objects. Extension must be made in several directions: (1) greatly increased detector sensitivity in the 1–3 μ region (as indicated in Section 2), which would allow extension of the program to much fainter objects; (2) the development of a window port transmitting up to at least 8 microns and, ultimately, an open port with a heated heliostat and a vacuum-proof telescope; (3) increased spectral resolution for the brighter objects; (4) for calibration purposes (wavelength standards) in planetary and stellar IR spectroscopy, solar spectroscopy with higher resolution; (5) the development of a much larger telescope with an open window port. All these extensions are possible and together they will open up a new branch of astronomy.

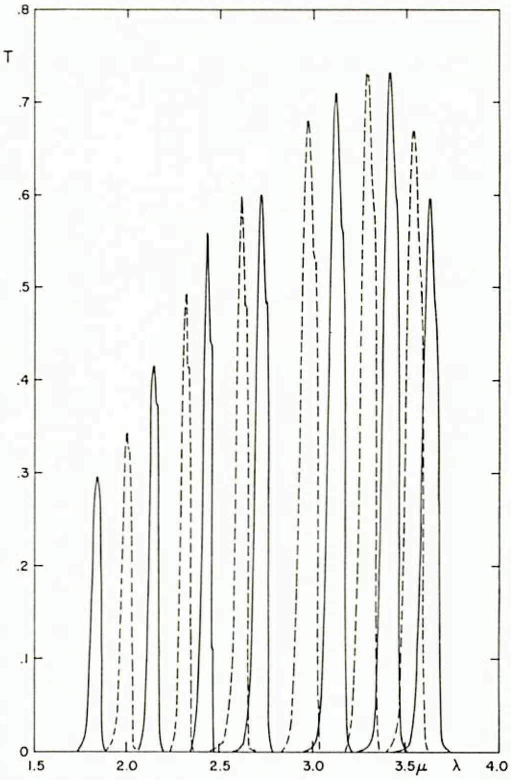


Fig. 13 Transmission peaks of filter wheel No. 2 for selected wavelengths.

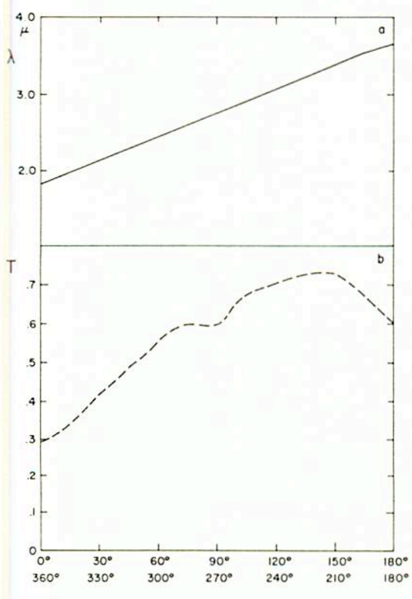


Fig. 12 Wavelength (*a*) and peak transmission (*b*) versus orientation of filter wheel having 3 percent bandwidth (Table 6).

Acknowledgments. The program here outlined, as explained in the text, was a sequel of our joint program with the Naval Ordnance Test Station. We are much indebted to Dr. P. St. Amand and the Commandant and staff of NOTS for their interest and generous assistance. The preliminary results published in these *Communications* were obtained with the NASA 990 Jet, made possible through mission-support by NASA Hq., and the facilities offered by the Airborne Sciences Group of the NASA-Ames Laboratories, headed by Dr. Michel Bader. Sincere thanks are due to Mr. R. Cameron and Mr. E. Peterson for assistance before and during the flights, and especially to the navigator, Mr. J. W. Kroupa, for translating our program wishes to acceptable flight schedules. The University Space Sciences Committee awarded the authors substantial grants that allowed us to get this program underway. Appreciation is expressed to Mr. Ferdinand de Wiess who designed and supervised the construction of the telescope support system and other components. We are much indebted to Mr. L. Mertz, Vice President of Block Associates, Cambridge, Massachusetts, for his interest in our program and for loaning us his interferometer. This instrument has proved a marvel

of simplicity and reliability under unusual field conditions and has so far been our principal spectral analyzer on the flights.

REFERENCES

Calfee, R. F., and Gates, D. M. 1966, "Calculated Slant-Path Absorption Distribution of Atmospheric Water Vapor," *Appl. Opt.*, **5** (2), 287–292.

Houghton, J. T. 1963, "Absorption in the Stratosphere by Some Water-Vapour Lines in the ν_2 Band," *Quart. J. Roy. Meteorol. Soc.*, **89**, 332–338.

Houghton, J. T., Hughes, N. D. P., Moss, T. S., and Seeley, J. S. 1961, "An Atlas of the Infra-Red Solar Spectrum from 1 to 6.5 μ Observed from a High-Altitude Aircraft," *Phil. Trans. Roy. Soc. London,* **254** (1037), 47–123.

Houghton, J. T., Moss, T. S., Seeley, J. S., and Hawkins, T. D. F. 1957, "Some Observations of the Infrared Solar Spectrum from a High-Flying Aircraft," *Nature,* **180** (4596), 1187–1188.

Junge, C. E. 1963, *Air Chemistry and Radioactivity* (New York: Academic Press), p. 6.

Mertz, L. 1965*a*, "Astronomical Infrared Spectrometer," *A. J.*, **70**, 548–551.

————. 1965*b*, *Transformations in Optics* (New York: John Wiley & Sons).

————. 1966, "Infrared Spectrum of Saturn's Ring,"*A. J.*, **66**, 747.

Sissenwine, N., Grantham, D. D., and Salmela, H. A. 1966, "Mid-Latitude Stratospheric Humidity Regime to 30 Km," *Interim Notes on Atmospheric Properties No. 73* (Presented at AFCRL Scientific Balloon Symposium, Portsmouth, N. H., Sept. 14, 1966).

SUPPLEMENTARY REFERENCES

Beer, R. 1967, "Fourier Spectrometry from Balloons," *Appl. Opt.*, **6** (2), 209–212.

Bottema, M. 1967, "Guiding of Balloon-Borne Telescopes by Off-Set Sun-Tracking," *Appl. Opt.*, **6** (2), 213–219.

Gassmann, G. J., and Pittenger, E. W. 1966, "Upper Atmospheric Research Using Aircraft," *Special Reports, No. 44,* Air Force Cambridge Research Laboratories, AFCRL-66–292, April 1966.

Gehrels, T. 1967, "Ultraviolet Polarimetry Using High-Altitude Balloons," *Appl. Opt.*, **6** (2), 231–233.

Kondratiev, K. Y., Nicolsky, G. A., Bandinov, I. Y., and Andreev, S. D. 1967, "Direct Solar Radiation up to 30 Km and Stratification of Attenuation Components in the Stratosphere," *Appl. Opt.*, **6** (2), 197–207.

Murcray, D. G., Murcray, F. H., and Williams, W. J. 1967, "A Balloon-Borne Grating Spectrometer," *Appl. Opt.*, **6** (2), 191–196.

Strong, J. 1967, "Balloon Telescope Optics," *Appl. Opt.*, **6** (2), 179–189.