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TWO INSTRUMENTS FOR FAR-INFRARED ASTROPHYSICS

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(Ph.D. Thesis)

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ABSTRACT

We describe two instruments for far-infrared astrophysics. The first is a broad-band photometer used on White Mountain for astronomical observations from 10 to 30 cm^{-1} (300 GHz to 1 THz ; λ , 1 mm to $330\text{ }\mu$). The optical system of the telescope includes a light-weight, high-speed, chopping secondary. The L^4He -cooled photometer uses low-pass filters and a L^3He -cooled, composite bolometer. The system performance is evaluated, and the site is compared to other possible platforms.

The second project is a balloon-borne spectroradiometer to measure the cosmic background radiation from 3 to 10 cm^{-1} (100 GHz to 300 GHz ; λ , 3 mm to 1 mm). The apparatus has five band-pass filters with excellent rejection at higher frequencies, a low-noise chopper, and an internal calibrator. We describe the design and use of calibrators for such an experiment and develop a model of calibration procedures. The calibrations of several reported measurements are analyzed with this model, and flaws are found in one procedure. Finally, the system performance is used to estimate the accuracy this experiment can achieve.

I. INTRODUCTION

This thesis describes two separate projects in far-infrared astrophysics. Both were chosen to exploit new opportunities using our group's particular capabilities. Their common goal was to make important, previously unattainable observations, one extending the scope of submillimeter astronomy, the other probing the early universe.

The first project is a mountaintop photometer for submillimeter astronomy. It is described in Chapter II. The second, covered in Chapter III, is a balloon-borne spectroradiometer. This instrument is designed to measure the spectrum of the cosmic microwave background radiation.

The mountaintop experiment is described only here, so the discussion of it is intended to be comprehensive. However, this thesis only summarizes the present state of the balloon-borne experiment. That apparatus represents a continuing, group effort already totaling over twenty man-years. Earlier versions have produced spectral measurements and have been discussed elsewhere (Mather, 1974; Woody, 1975; Woody and Richards, 1981). Consequently, we do not describe these previous experiments here nor trace the entire evolution of the experimental design.

The particular opportunity that prompted our mountaintop experiment was a new, high-altitude observatory. In the discussion of that experiment, we explain why this seemed to be a good chance to exploit our detector, cryogenic, and optical experience. That discussion also examines why that experiment did not achieve its objective.

The balloon-borne project builds directly on our earlier spectral experiments. By incorporating a few changes into the existing equipment, an opportunity was created for a new measurement largely independent of our previous results. Particular attention was paid to the calibration procedure, producing a detailed model described here. This model, when applied to other experiments measuring the cosmic background radiation, illuminates specific flaws in one calibration procedure, that of Professor Gush (1981, 1982).

For our cosmic background radiation experiment to succeed, the apparatus must operate with precision and reliability. Tests of the assembled system revealed problems, *now being corrected*. The resulting experiment should produce a measurement of significance to cosmology.

II. THE WHITE MOUNTAIN SUBMILLIMETER PHOTOMETER PROJECT

A. INTRODUCTION

Astronomy has been much enlivened in the past few decades by a continual expansion of its observational scope. Until the 1960's, astronomers were essentially limited to two regions of the electromagnetic spectrum: the visible, with frequencies from $\sim 14,300 \text{ cm}^{-1}$ ($\lambda \sim 700 \text{ nm}$) to $\sim 25,000 \text{ cm}^{-1}$ ($\lambda \sim 400 \text{ nm}$), and the radio, at frequencies below $\sim 0.1 \text{ cm}^{-1}$ (3 GHz). Since then, new detectors and new platforms, some in space, have added and expanded spectral regions, producing an invigorating flood of unexpected discoveries (Avrett, 1976). One such region, not yet well explored, is the submillimeter range, here taken to be from $\sim 10 \text{ cm}^{-1}$ ($\lambda = 1 \text{ mm}$) to $\sim 40 \text{ cm}^{-1}$ ($\lambda = 250 \mu$).

This definition of "submillimeter" is motivated by the transmittance of the atmosphere. At frequencies below this region, at millimeter wavelengths, the atmosphere is transparent enough that astronomical observations can be made near sea level, while above the submillimeter, the atmosphere becomes so absorptive that observations must be made from airplanes, balloons, or satellites. The submillimeter range is a transition between these two limits. Figure 1 (Trob and Stier, 1975) shows the calculated atmospheric transmittance in the millimeter and submillimeter spectral regions for an altitude of 4200 meters and two column densities of precipitable water vapor, 1.2 mm and 0.6 mm. Two partially transmitting windows are apparent, around 22 cm^{-1} ($\lambda \sim 460 \mu$) and 28 cm^{-1} ($\lambda \sim 370 \mu$). Since common, sea level, column densities are measured in cm, groundbased observations

Fig. 1. Calculated Atmospheric Transmittance from Mountaintops.

in this region can only be done from high, dry peaks, such as Mauna Kea. Even there, the broad-band submillimeter emissivity of the atmosphere, which is more than 95%, limits system performance.

The objects studied at submillimeter frequencies were not discovered in the submillimeter. The lack of a sky survey in this frequency region has restricted broad-band photometric observations to continuum sources already known from observations in the adjacent spectral regions. Since the flux from non-thermal, continuum radio sources falls with increasing frequency, most of the objects studied in the submillimeter are thermal sources. The locations of these sources are suggested either by higher frequency infrared observations or by radio-line measurements which indicate nearby molecular clouds. Those thermal sources for which the submillimeter emission dominates the total continuum power are those whose Planck brightness functions, $B(\nu, T)$, peak in the submillimeter. Since the peak of $B(\nu, T)$ is at about $\nu = 2T$ for ν in cm^{-1} and T in K, these sources have temperatures ~ 10 to 20 K.

Some high resolution spectroscopy is also done in the submillimeter range (Phillips et al., 1980a, 1980b). Since this spectral range is rich in molecular lines, this technique should become an important probe of some molecular cloud conditions. In particular, it may well be important for regions very different from the cool clouds described above: for example, a shocked molecular cloud at ~ 2000 K (Watson, 1981). Again, however, the objects studied have been previously identified from other observations.

In 1976, our group was offered the half-time use of a telescope on the 3950 meter plateau south of White Mountain, a 4342 meter (14245 foot) peak in California, east of the Sierra Nevada. This site, in the rain shadow of the Sierras, has exceptionally dry winters with precipitable water vapor reaching lows under 2 mm.¹ As Figure 1 would indicate, submillimeter astronomy was possible here and, in fact, was already being done (Smith et al., 1979). Two scientific goals motivated us to accept the offer and to begin a submillimeter astronomy program.

First, an ongoing project within our group was a balloon-borne infrared telescope designed to survey the sky from 3 cm^{-1} to 1000 cm^{-1} in six frequency bands. It was anticipated that this survey would discover new sources, with a positional accuracy of about 10 arcminutes. A submillimeter instrument sensitive from 10 cm^{-1} to 32 cm^{-1} ($\lambda = 1\text{ mm}$ to $300\text{ }\mu$) on White Mountain could potentially both improve this positional accuracy for other observers and also provide detailed submillimeter maps of these new sources.

An additional incentive was the report of detector-noise limited seeing on the best nights from White Mountain (Werner, 1976). The detector then being used there was a pumped ^4He -temperature ($\sim 2\text{ K}$) bolometer. Our group had the experience and materials necessary to construct a ^3He -temperature ($\sim 0.3\text{ K}$) bolometer detector system. From

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¹Water vapor column densities were measured three times daily from Barcroft Laboratory on the plateau with a meter designed by J. Westphall of Caltech. This device measured the brightness of the sun in two frequency bands, one centered on a water vapor line and one just off the line. From the measured brightness ratio, the column density could be inferred.

our measurements, a 0.3 K bolometer should have an order of magnitude better noise equivalent power (NEP) than a 2 K bolometer with the same time constant (Richards and Greenberg, 1982). This greatly enhanced detection performance, if translated to increased sky sensitivity, would allow dimmer classes of sources to be examined than had previously been possible. Submillimeter astronomy from White Mountain thus seemed a fine use of both our technical capabilities and, potentially, our survey results.

B. TELESCOPE

The telescope on White Mountain was obtained in a collaboration with Caltech.. Originally, Professor R. Leighton had built it for the $2\ \mu$ sky survey (Neugebauer and Leighton, 1969). It was an equatorially mounted, light-weight, 1.6 m, f/1 paraboloid figured by spinning setting epoxy at a constant angular velocity. The epoxy was supported by a roughly machined aluminum dish mounted on a aluminum honey-comb structure. When hardened, the epoxy was aluminized to make it reflective. The resulting extreme lightness allowed the entire primary mirror to wobble in hour angle, chopping the beam on the sky by a few arcminutes. A simple, bottom-looking, Low-type, detector cryostat was mounted at the prime focus. For the $2\ \mu$ sky survey, the telescope was locked on the meridian and the rotation of the Earth moved sources through the beam.

During the testing of our photometer, we checked the reflectivity of the aluminized epoxy mirror in the submillimeter spectral region and found it to be essentially unity. For this test, a simple reflectometer was constructed using a Golay detector with a fluorogold

filter and a chopped LN_2 (77 K) source. The reflectometer was calibrated by measuring the known reflectances of metals and of absorbers. The mirror was at least 95% reflective.

We also checked the figure of this mirror using visible light and found it to have a blur circle of 3 arcminutes. This test was accomplished by measuring the size of the image of a bright star in the focal plane. When cracks appeared on the mirror after particularly severe weather, the optical quality of the image was rechecked by pointing at a bright star and looking at the mirror from the prime focus. The entire mirror was always simultaneously illuminated, except for narrow, ~ 1 cm, stripes along the cracks. As these stripes occupied only a small fraction of the total area, the performance of the main mirror was barely degraded.

C. OPTICAL SYSTEM

For our detector, we abandoned the prime focus optical system, both because of our group's familiarity with top-looking dewars and because of the limited range available in chopping frequency and amplitude. We instead utilized the Cassegrainian optical scheme then used for the balloon-borne survey. This configuration is shown in Figure 2. The converging $f/1$ beam from the primary is intercepted by the secondary mirror and converted to an $f/6.3$ beam focused inside of our photometer which is mounted in front of the primary. In our design, the beam was chopped on the sky by rocking the secondary mirror. With a high-speed chopper and fast detector, we hoped to reduce contributions to the sky noise due to fluctuations in the atmospheric emittance and transmittance.

Fig. 2. White Mountain Telescope.

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The optical design of the secondary mirror is remarkably simple. The primary, a paraboloid, produces a point-image of the center of its field at its geometric focus, the prime focus of Figure 2. If a hyperboloid is interposed in the converging beam with one of its geometric foci coincident with the parabolic focus and if the hyperboloid is of sufficient lateral extent to intercept the entire converging beam, then all the radiation is refocused to the other hyperbolic focus. In the design, we had a choice of hyperboloids which satisfied this criterion. Other constraints on the design included the physical size and construction of the existing telescope, the desired frequency of chopping which limited the maximum moment of inertia of the mirror, the allowable obscuration of the primary, and the level of off-axis aberrations. This last criterion proved unimportant, as the optics within our photometer collected radiation only in a relatively small area of the focal plane around the optical axis. Also, obscuration of the primary was not an issue as the center 20 cm was obstructed by our photometer in any event. The final choice of secondary mirror parameters, $a = 38.80$ cm and $b = 39.04$ cm with a diameter = 15.875 cm, were fixed by choosing a diameter which obscured only the chopper drive mechanism and a focal plane location that matched the optical system of the balloon-borne sky survey telescope.

The secondary mirror was made from 6061-T651 aluminum, roughly machined in the Physics Departmental shops, then over-aged at 260°C (440°F) for 12 hours. The final figuring to the precise hyperboloid was done at the diamond-machining shop of Lawrence Livermore Laboratory. There, this technique had been developed to machine aluminum

and copper surfaces smoothly enough for coherent reflections at 1000 cm^{-1} ($\lambda = 10\text{ }\mu$) in connection with high power CO_2 laser programs. The diamond-machining procedure maintains the microscopic structure of the bulk metal and thus provides surfaces of lower emissivity than are obtained by mechanical polishing. This can be an important consideration in both high power-density lasers (Tinkham, unpublished) and also the low-background survey project. For our application, the lowered emissivity was not important because of the high atmospheric emissivity. The technique was used only because of our familiarity with it and the desire to quickly produce a light-weight mirror.

The support and drive for the secondary mirror, as well as the drive electronics, were designed and built by the Berkeley Astronomy Department. The support featured two rotatable stages supported by Free-flex^{TM} pivots (Bendix), one carrying the secondary and the other, moving in opposition to reduce vibration, holding the driver transducers (Ling Altec Model 203). Additionally, the mount to the telescope allowed the entire assembly to be rotated about the optical axis by 90° while remaining on the telescope. Though chopping in hour angle was usual, to minimize the atmospheric signal, the possibility of chopping in declination if an object had east-west extension seemed potentially useful. The drive electronics for the chopper were copied from an existing Caltech design using feedback from velocity and position transducers (Schaevitz 125 VTA and 050 DC-B).

Unfortunately, this chopper system did not work. The mechanical design had a relatively massive aluminum mirror support whose moment

of inertia was much larger than that of the mirror. Additionally, the drive and feedback transducers were not physically connected to the mirror mount which led to erratic response. Finally, since the mechanical properties, such as moment of inertia and angular spring constant of the mirror and mount, were unavoidably different from those in Caltech's system, the feedback system was not stable.

By machining away much of the mirror mount, we reduced the moment of inertia of the support to match that of the mirror. We also connected the various transducers to the mirror mount by installing brass bolts above each transducer and soldering either small lengths of piano wire or shim stock into both the bolt and a threaded rod connected to the transducer. This afforded a connection rigid in compression yet laterally flexible. Additionally, the feedback from the velocity and position transducers was removed and the system was run open-loop. The opposing motion of the drive transducers was also blocked.

These changes produced a chopping system which performed adequately. Chopping frequencies from a few hertz to 80 hertz with beam throw of at least 10 arcminutes were achieved. Surprisingly, little acoustic noise was transmitted to our detector when running the chopper open-loop. Only our flexible transducer couplings were troublesome. In use, these proved of poor reliability with one failure approximately every 20 hours of chopper running time. Since they were easy to replace with a hand-held soldering iron, no change was made.

D. PHOTOMETER

The optical design of our photometer is shown in Figure 3. In the instrument, the incoming radiation first passed through a 250 μ Mylar window which sealed the L⁴He-bath space. At the focal plane, there was an aperture stop wheel. Then the radiation entered a short length of 2.49 cm light pipe, followed by a Winston concentrator (Winston, 1970) which defined the angular extent of the beam. Another Winston concentrator recollimated the radiation to $\sim f/1.5$ for passage through any of several filters in a filter wheel. After next passing through a 50 μ Mylar window into the vacuum space around the bolometer, the radiation was finally collected by a truncated Winston concentrator onto a composite bolometer.

This photometer was contained in a super-insulated commercial dewar from SCT Corp., made to our specifications. The dewar was supported in front of the primary mirror by a tube passing through a central hole in the primary, as shown in Figure 2. This location, rather than the more usual location behind the primary, was forced on us by the space constraints of the existing telescope mount; it did, however, allow us to adapt the design of the survey telescope.

Since the focal plane was 28 cm below the top of the dewar, the aperture stop wheel remained cold (~ 77 K). There, three different circular apertures could be rotated into the beam, corresponding to 1, 3, and 10 arcminute diameter circles.² These apertures were cut in

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²The scale at the focal plane was 0.249 cm per arcminute.

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Fig. 3. White Mountain Photometer.

a 1/4 inch (0.64 cm) thick piece of Eccosorb MF-110 (Emerson and Cuming, Inc.; Canton, MA). While non-circular apertures could have been used in principle, we found no compelling arguments for their use in a general purpose instrument. The apertures were switchable by rotating a shaft at the top of the cryostat by hand.

The acceptance angle of the beam-defining Winston concentrator, 7.6° full angle, was chosen to underfill both the secondary and primary. At the secondary, the diameter accepted by the concentrator was 14.99 cm which corresponded to a 15.10 cm diameter on the secondary if it was tilted enough to shift the beam 1.5° on the sky. To insure that the beam did not spill over here, the secondary was 15.88 cm (6.250 inch) in diameter. Only 0.89 of the area of the main mirror was used, since the beam from the primary mirror was 15.91 cm in diameter at the secondary. We could accept no larger beam if we were to avoid spilling the 149.0 cm diameter geometric beam off the 158.0 cm diameter primary when chopping the beam 1.5° on the sky.

Only two of the filters we had available in the filter wheel were used frequently. Their passbands were $3 - 18 \text{ cm}^{-1}$ and $3 - 31 \text{ cm}^{-1}$. In both cases, the lower frequency limit was fixed by the cutoff from the small aperture of the Winston concentrator. Just as in a waveguide, this structure has a lowest-frequency, transmitted mode, below which all the radiation is reflected. Simple scaling of measurements by S. McBride on smaller Winston concentrators determined the frequency of this mode in our instrument. The upper frequency limit was set by the filters. Filter 1 consisted of fluorogold, black

polyethylene, and a low-pass capacitive mesh filter designed to have an edge at 18 cm^{-1} . This mesh filter had six layers, each made using standard photoresist techniques with images of square grids. The underlying metal was aluminum evaporated onto one side of thin (12.7μ) Mylar. Four of these meshes were 150 lines per inch (5.9 lines per millimeter), one was 100 lines per inch (3.9 lines per millimeter), and one, 125 lines per inch (4.9 lines per millimeter). These meshes were separated by metal washers to which they were epoxied, forming a multilayered Fabry-Perot filter. The properties of single capacitive grids are well-known (Ulrich, 1967) and their combination has been discussed by many authors (Sakai and Genzel, to be published, and references therein). Filter 2 simply consisted of fluorogold and black polyethylene. The transmittance of each filter component, including the low-pass mesh stack, was measured and then the transmittance of the filter was calculated. These filter transmittance curves are plotted in Figure 4. The effect of the low-frequency cutoff of the concentrator is not included.

The composite bolometer was identical to those described elsewhere (Nishioka, Richards, and Woody, 1974; Nishioka, 1976). At the time of its construction, supplies of germanium suitably doped for thermometry in this temperature range, $\sim 0.35 \text{ K}$, were scarce. A commercial germanium thermometer with its existing leads (Lake Shore 15247) was used in this bolometer. This bolometer had a dark electrical NEP of $5 \cdot 10^{-15} \text{ W/Hz}^{1/2}$ at its operating temperature of 0.35 K . Because of the undesirably high impedance of the thermometer, $20 \text{ M}\Omega$, the dominant contribution to the system noise was current noise in the J-FET preamplifier. This noise was a factor of six above the thermal

Fig. 4. Transmittance of Filters in Photome er.

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fluctuation noise limit, $(4kT^2G)^{1/2}$, set by the bolometer leads.

The measured time constant was 1 ± 0.5 ms, so that $\omega = 1$ at 160 Hz. Both the last Winston concentrator and the bolometer were in a vacuum can and cooled by a small $L^3\text{He}$ -bath, pumped internally by an adsorption pump.

The design of the ^3He refrigerator in the photometer is shown in Figure 5. When warm, the ^3He gas was contained in a tank outside of the photometer dewar. During operation, the boiling liquid ^3He was pumped internally by a molecular sieve (Linde Corp.) adsorption pump. The larger, external, $L^4\text{He}$ -bath was necessary to initially condense the ^3He , to cool the adsorption pump, and to reduce the heat flowing into the ^3He -cooled pot.

To operate the refrigerator, liquid ^4He was first transferred into the dewar bath space, adsorbing the gaseous ^3He on its pump. The external tank was valved off and the $L^4\text{He}$ -bath pumped to cool the refrigerator well below the triple point of ^3He at 3.32 K. By then heating the adsorption pump electrically within its vacuum space to ~ 40 K, the ^3He pressure could be raised sufficiently that it condensed on the stainless steel tubing immersed in the $L^4\text{He}$ -bath and dripped into the internal pot. When the pressure of the ^3He system reached the equilibrium ^3He pressure at the temperature of the pumped $L^4\text{He}$ -bath, the electrical heating of the pump was stopped. A ^4He exchange gas was then admitted into the vacuum space around the adsorption pump, cooling it to ~ 2 K and so pumping the $L^3\text{He}$ -bath to ~ 0.35 K.

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Fig. 5. Schematic Diagram of ^3He Refrigerator.

The optical alignment of the photometer-telescope combination was checked with a double-ended He-Ne laser placed between the secondary and the photometer. The collinearity of the laser with the optics in the photometer was maintained by centering one beam on both the center of the top window and the center of the aperture stop. The other laser beam was then centered on the secondary mirror by adjusting the dewar support tube. Since the secondary was centered on the telescope by its mount, the photometer was now positioned correctly. A DC electrical current applied to the secondary drive transducers allowed us to adjust the angle of the secondary so that the laser beam hitting the center of the secondary was reflected exactly back on itself. The remaining free adjustment, the position of the secondary mirror along the axis of the primary mirror, was optimized while observing a bright submillimeter celestial source. As the dewar support tube was left installed while the Caltech group used their prime focus instrument, this alignment proved durable. In practice, the photometer and secondary could easily be mounted, and the DC chopper bias and secondary position both simply optimized on the signal from a planet, to achieve satisfactory alignment without the use of the laser.

This photometer performed adequately on White Mountain, but had several weaknesses. To avoid noise from modulation in the background power when boiling liquid ^4He was in the field optics, the ^4He -bath was kept pumped below the λ -point. Over an observing session of several days, small leaks into the bath would then produce enough air ice in the dewar to jam the aperture stop wheel, which had a weak and convoluted drive shaft. Additionally, the cryogenic system required

recycling about once a day. This involved allowing the pumped $L^4\text{He}$ -bath to warm up to ~ 4.2 K and evacuating the vacuum space around the adsorption pump with a diffusion pump for one to two hours. Without this step, the adsorption pump remained well coupled to the bath and could not be heated to pressurize and recondense the ^3He . After refilling the $L^4\text{He}$ -bath, the rest of the cooling cycle took approximately another hour, so that the bath lifetime plus recycling time filled a day. Due to the mass and awkwardness of our dewar, we ran sufficient vacuum lines and pump lines that we could perform this recycling of our instrument while it remained on the telescope. Nonetheless, the procedure required two people, and the several hours it took was significantly longer than the 15 minutes a day needed to maintain a ^4He -cooled, Low-type dewar at the prime focus.

The idea behind this photometer development was that the increase in sensitivity would more than compensate for the increased complexity of operation. When the sensitivity of the photometer was actually tested, however, our sensitivity was worse than that of the Caltech ^4He -cooled photometer. The major limitations of our system sensitivity were the high amplifier-related noise, which resulted at least partially from the undesirably high impedance of the bolometer, and an unexpectedly low system optical efficiency of 0.5%. Both of these problems could have been improved with further development, but at the start of the observing season, further development was postponed. Our photometer-chopper combination did still have the capability of chopping at unusually high frequencies, up to four times the frequency used by the Caltech group.

E. ATMOSPHERIC OBSERVATIONS

This high-frequency capability could allow us to exploit any reduction in sky noise at these higher frequencies. We might then be able to observe in noisy, but still transmissive, conditions by chopping above any rolloff. In this, we were only partly successful. A high-frequency rolloff did exist at least much of the time, but the atmosphere rarely was dry enough for any submillimeter observations.

Observations of the frequency spectrum of sky noise were made under various sky conditions, ranging from overcast to clear.³ In all cases, the frequency being measured was set by a lock-in amplifier connected to the output of our detector. The output of this lock-in was instantaneously sampled many times, and the noise determined by calculating the standard deviation of the resulting distribution. At each frequency, the noise was measured in three modes: the photometer beam on the sky chopping with an amplitude of 10 arcminutes, the photometer beam on the sky with zero amplitude, and the beam blocked at the top window, but with full secondary motion.

Figure 6 shows typical noise measurements taken through filter 2, fluorogold and black polyethylene. The upper lines connect points taken in the first mode, that is, with chopping on the sky. The second and third modes were indistinguishable and produced the points around the lower line. A clear excess of sky noise above system noise is evident below ~ 70 Hz.

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³We never experienced a night with good submillimeter transmittance and very low levels of sky noise, though others reported such nights (Smith, 1978). Sky noise in such a situation may differ from our observations.

Atmospheric Noise Observations

Fig. 6

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By chopping at 80 Hz, we could avoid this noise. In contrast, the prime focus instrument was restricted to a 30 Hz maximum chopping frequency and was usually run at 20 Hz to reduce microphonics. This reduction in our sky noise allowed us to achieve signal-to-noise ratios on bright sources within a factor of two of those of the existing Caltech system despite our low optical efficiency. To gain this advance, we did have to sacrifice the large-amplitude capability of our secondary ($\sim 1^\circ$ at 10 Hz), as our maximum chopping amplitude at 80 Hz had fallen to 4 arcminutes. The loss of large-amplitude chopping was unimportant since an increase in sky noise with chopping amplitude precluded the use of large amplitudes in any case.

To evaluate the submillimeter atmospheric transmittance, the signal from a known bright source was measured through filters 1 and 2. The brightness temperatures and angular sizes of the sources used, the planets Mars, Jupiter, and Saturn, were well-characterized. The ratio of the signals from the two filters then yielded a measurement of the submillimeter atmospheric transmittance, since only filter 2 transmitted the flux present in the atmospheric windows at 22 cm^{-1} and 29 cm^{-1} . A crude box approximation to the atmospheric transmittance in Figure 1 was used in interpreting this ratio. This method worked well, with good planet to planet consistency when two were simultaneously observable. It also correlated well with the daytime water vapor measurements, and with nighttime observations of clouds or frost. The greatest submillimeter transmittance inferred by these measurements was 40%, achieved on two nights in our 13 weeks of observing. The

vast majority of the time, though, the measured submillimeter transmittance was less than 10%, and in fact, consistent with zero.

F. ASTRONOMICAL OBSERVATIONS

Submillimeter observations were already being made from White Mountain by Professor G. Neugebauer's group at Caltech. While their program involved only bright sources, we concentrated on fainter sources. This forced us to devise a new observing method; in particular, the pointing accuracy of the telescope needed improvement. Some progress was made, but the necessary accuracy was never achieved. Additionally, systematic dome-related signals became important at this lower signal level.

The Caltech group was primarily interested in star formation. Their observational program thus centered on molecular cloud-dust complexes associated with evidence of recent star formation: compact HII regions, bright near-infrared sources invisible in the optical, and OH or H₂O masers. Maps of the brightest of these sources were already nearing completion.

The observations of the Caltech group were limited to these bright sources by the pointing ability of the telescope. Since the existing declination and hour angle sensors were not adequate to point within their 3 arcminute beam, they built up their maps by offsetting a small amount from a bright source that could be easily detected in a few seconds of integration. This required a submillimeter flux of at least $\sim 5 \cdot 10^3$ Jy. Because of errors in the tracking system of the telescope, it was necessary to check back on the bright source every

10 to 15 minutes. These limitations prevented observations of dim sources except in the immediate neighborhood of a bright source.

Our primary scientific aim at White Mountain was to explore new, as yet unobserved, submillimeter sources. Our balloon-borne survey had not flown, so we had no new, bright sources to center a map around. Also, an early suggestion to measure large-scale diffuse emission by exploiting the 1.5° beam throw of our chopper at low frequencies had to be abandoned. Not only did an increase in sky noise with chopping amplitude make this unattractive, but the presence of significant structure on the scale of our maximum beamsizes (Rouan *et al.*, 1977) would have required detailed mapping of many square degrees to extract any diffuse component. As a consequence of these limitations, we were left with an observing program based on small, faint objects taken from known lists.

A variety of these objects existed. Some were point-like sources: the outer planets, Uranus and Neptune; several extragalactic objects; and a selection of Miras in Leo. Others should have been resolvable in our 3 arcminute beam: the Crab Nebula and a subset of the darkest of Lynds's clouds (Lynds, 1962). All had maximum estimated fluxes less than 100 Jy and were well away from known, bright, millimeter or submillimeter sources. Since our photometer had not achieved a great improvement in sensitivity, we would need long integration times, of order an hour, to detect such objects even on a good night. And that required a telescope which could be pointed accurately.

The pointing ability of the telescope was improved by two changes. First, the declination axis was more carefully aligned with the Earth's axis. This was accomplished by photographing the pole star with a camera attached to the telescope frame. A half hour exposure with the telescope fixed produced an arc determining the celestial pole. Continuing the exposure while slewing the telescope in hour angle made another arc that showed the orientation of the declination axis. Successive corrections made by adjusting the support of the telescope reduced the misalignment of the axes from several degrees to less than 15 arcminutes.

The second change for the telescope was the installation of better sensors on the declination and hour angle axes. Commercial angular position sensors (Inductosyn) were obtained in the fall of 1978, calibrated, and installed. The pointing error was then measured by tabulating the difference between the predicted reading, assuming no error, and the actual reading required to point the telescope at a celestial object. A selection of objects, spanning the declination range of interest, were followed in hour angle to produce these tabulations. In this way, we attempted to produce pointing correction functions for both declination and hour angle which we could use to accurately point the telescope using only these sensors.

We wished to use submillimeter sources for defining these functions, but poor weather, the shortage of such sources off the galactic plane, and our desire for covering a large range in declination forced a compromise. The optical finder telescope attached to the main telescope was used, and correction functions based on the visible position

were collected. Consequently, any motion of the submillimeter beam relative to the telescope support, due perhaps to the elastic support of the primary mirror or flexure in the photometer support tube, would not be included in these functions; they would only measure errors originating in the telescope support.

Typical results, obtained for α Leo (Regulus), are plotted in Figures 7a and 7b. In the plots, the error in the predicted position is plotted versus hour angle. Figure 7a is the right ascension correction; Figure 7b, the declination correction. While most nightly tracks stay within a beam width (3 arcminutes) of some average line, occasional larger shifts in the declination error are evident. These jumps continued to occur sporadically on both axes. We did not isolate their cause or eliminate them, and as a result, we could never reliably point as we wished.

Nevertheless, the best estimates derived from these pointing measurements were used, once. On the excellent night in the winter 1978-79 season (10-11 March), attempts were made to observe M82 and Uranus. All failed to detect celestial flux, but they did succeed in revealing another phenomenon. The signal recorded while nominally observing Uranus is plotted versus time in Figure 8. The telescope was moved between each pair of points in an attempt to shift Uranus from one chopped beam to the other. The dashed lines indicate a repositioning of the dome sheltering the telescope.

Some interaction of our photometer with this dome is apparent. In retrospect, this was not unreasonable; the 1.6 m telescope beam passed through a 1.8 m slot which was repositioned by the observer.

Right Ascension Correction for α Leo

Fig. 7a

XBL 8211-6886

Declination Correction for α Leo

Fig. 7b

XBL 8211-6887

Fig. 8. Dome-Signal Interaction.

No sensors were installed on the dome. Consequently, the repositionings of the dome relied on only visual estimates.

To eliminate these errors, a simple resistive potentiometer was coupled to the dome. Then, a straightforward calculator program computed the azimuth of a celestial source as a function of time. Together, these should have allowed us to regularize our dome repositionings.

The end of that observing season stopped both our attempts to point accurately and our efforts to eliminate the interference from the dome. A reevaluation of our photometer project was made that summer and is summarized in the next section.

G. CONCLUSION

When we began our White Mountain project, we intended to use our detector technology to create new observing possibilities. Our first goal, to simply improve on the sensitivity of existing systems with a quieter detector, was thwarted by our poor optical efficiency, but could doubtless have been obtained with further instrumental developments. We could still exploit another aspect of our detector technology, the fast time constant of a ^3He -cooled bolometer, by using the high-frequency chopping secondary. However, the resulting reduction in sky fluctuations only improved the sensitivity of our system to a level comparable to that of the existing system.

The last advantage we tried to exploit was simple integration time; we had many weeks available at the telescope. This advantage was nullified by an inability to accurately point the telescope.

Without accurate pointing, we could not actually integrate on a single spot, and our weeks of time could not be combined into tens of hours of integration time.

All of the above difficulties could be overcome by sufficient effort. However, a more serious problem arose during the observing season. The weather on White Mountain was surprisingly bad compared with previous years. Only one or two usable nights were obtained in a year of observation. Examination of the weather data which were used in the decision to site the telescope at White Mountain shows that they were collected over an unusually dry period. With the resumption of more normal rainfall, the prospects for submillimeter observations from White Mountain began to look very poor.

To examine the feasibility of further observations, we compared several methods of broad-band submillimeter astronomy. An explicit assumption of optimal system performance was made, corresponding to the background fluctuation limit in detector NEP from each platform. The justification for this assumption was not that this had been achieved, but rather that we wished to know from where it would be most profitable to reach this limit, given that all platforms should be equally affected by problems such as low system transmittance. That is, are mountaintops an intrinsically advantageous place from which to do submillimeter photometry?

Table I lists both the parameters of the various platforms and derived figures of merit, F and G . The four platforms considered were an idealized White Mountain, a pointed, balloon-borne telescope modeled after the existing NASA-Goddard instrument, our group's survey

Table I.

Platform	A [cm ²]	θ [Arc-] minute	A Ω [cm ² -sr]	S	ϵ	t	NEP [W/Hz ^{1/2}]	$\frac{F}{F_{WM}}$	$\frac{G}{G_{WM}}$
White Mountain (1 year)	1.77 10 ⁴	5	0.0294	0.04	0.1	10 hr	1.75 10 ⁻¹⁴	1	1
Pointed Telescope on Balloon (1 flight)	1.17 10 ⁴	5	0.0194	0.9	0.1	1 hr	7.5 10 ⁻¹⁵	11	11
Survey Telescope on Balloon (1 flight)	0.78 10 ⁴	16	0.1336	0.95	0.05	0.05 s	1.35 10 ⁻¹⁴	0.016	0.16
KAO (1 flight)	0.78 10 ⁴	2	0.0021	0.9	1	1 hr	2.5 10 ⁻¹⁵	22	3.5

telescope, and the Kuiper Airborne Observatory (KAO). The first three parameters, the collecting area, A , a possible beam size, θ , and the throughput, $A\Omega$, were simple properties of the telescopes. The next parameter, S , was a convolution of the atmospheric transmittance of each platform with the emission from a 25 K blackbody, normalized to the balloon-borne survey value. While somewhat extending the definition of submillimeter, this blackbody was chosen as representative of objects actually observed. Inclusion of a frequency-dependent source emissivity, $\sim \nu^{1-2}$, would shift the results still more in favor of the higher altitude platforms. In all cases, the system transmittance, τ , was taken as unity. The other parameters included were a broad-band average emissivity of the atmosphere-telescope combination, ϵ , and an estimate of an achievable integration time, t . For each platform the background fluctuation limit for the noise equivalent power was calculated using Equation (1)

$$\begin{aligned}
 (\text{NEP}_{\text{BFL}})^2 &= 2 \int_0^{\nu_{\text{max}}} \frac{A h^2 \nu^4 \epsilon \Omega \tau}{c^2} \\
 &\times \left\{ \frac{1}{e^{h\nu/kT} - 1} + \frac{\epsilon}{(e^{h\nu/kT} - 1)^2} \right\} d\nu
 \end{aligned} \tag{1}$$

where the integral was taken up to a ν_{max} fixed by the high frequency limit of atmospheric transmittance for White Mountain, or over the peak of the blackbody to 60 cm^{-1} for the other systems. The inclusion of the true variable atmospheric emissivity, $\epsilon(\nu)$, rather than an average ϵ , would have little effect on our result.

Two figures of merit were then calculated: for point sources

$$F = \frac{A S \sqrt{t}}{NEP_{BFL}} \quad (2)$$

and for extended objects filling all listed beams

$$G = \frac{A \Omega S \sqrt{t}}{NEP_{BFL}} \quad . \quad (3)$$

These are proportional to the signal-to-noise ratios achievable on these hypothetical sources from each platform. The figures in these last two columns are those figures of merit, normalized to the values from White Mountain.

Some conclusions were drawn from Table I. First, a pointed telescope carried on a balloon or airplane had an enormous advantage in sensitivity over White Mountain. Therefore, any observations of fainter sources from known lists should be undertaken from these higher platforms. Second, a survey instrument flown with a balloon could be used to scan a large fraction of the sky in a single flight while reaching flux limits comparable to those from White Mountain. Using Table I and Equation (3), we see that when looking for extended sources, as when mapping the galactic plane, White Mountain would survey only forty beamsized patches in a year to a given sensitivity, covering a total solid angle of less than one square degree, while a survey from a balloon would search of order ten thousand square degrees to the same sensitivity on a single flight. From this, we concluded that using the White Mountain system in a survey mode, blindly searching for new sources, was inefficient. Over all,

mountaintops, such as White Mountain, seemed poor platforms for broad-band submillimeter astronomy.

A suggestion was then made to attempt broad-band millimeter astronomy with the existing system, since atmospheric transmittance in the millimeter was less critically dependent on the weather. Unfortunately, an analysis similar to that in Table I indicated we would again be at a competitive disadvantage.

Table II compares a White Mountain-based millimeter system with a similar one on the 5 meter telescope on Mount Palomar, which was then being used for millimeter observations, and with a 10 meter, millimeter telescope near sea level, as was then being built. The same parameters were used as in Table I, except that S was replaced by an averaged atmospheric transmittance, η . No source spectrum needed to be assumed, as both platforms transmitted nearly the same spectral bandpass. Only the normalized point source figure of merit, F/F_{WM} , was evaluated, as most suggested objects were extragalactic. White Mountain again was at a significant disadvantage when compared to the larger telescopes. While the 10 meter telescopes did not yet have operating bolometric systems, such systems were already planned. The large efforts necessary to improve the pointing of the White Mountain telescope and to increase the transmittance of our photometer thus could not be justified by the possibilities of millimeter astronomy there.

Table II.

Platform	A [cm ²]	θ [Arc- second]	A Ω [cm ² -sr]	η	ϵ	t [hr]	NEP [W/Hz ^{1/2}]	F F _{WM}
White Mountain	1.77 10 ⁴	165	0.0089	0.8	0.2	10	5.86 10 ⁻¹⁶	1
Mount Palomar	1.96 10 ⁵	50	0.0089	0.5	0.5	10	1.37 10 ⁻¹⁵	3
Sea Level 10 Meter	7.85 10 ⁵	25	0.0089	0.5	0.5	10	1.37 10 ⁻¹⁵	12

In the late spring of 1979, the White Mountain photometer project was terminated. It had become clear that this was not an experiment in which our group's expertise could be exploited to advantage. Rather than working against the intrinsic advantage of other platforms, we turned to the cosmic background experiment in which our expertise could be better utilized.

III. THE COSMIC BACKGROUND RADIATION SPECTRORADIOMETER PROJECT

A. INTRODUCTION

The creation of the universe is generally accepted to have occurred about 20 billion years ago, with an expansion from an initial hot, dense phase in a "big bang". Few relics of that expansion can be observed today. Some information has been gleaned from the visible matter; its density, clumping in galaxies and clusters of galaxies, general recession in the Hubble flow, and elemental and isotopic composition all yield clues (Peebles, 1971). Some other relics presumed to be present are not yet directly observable: a neutrino background, whether of massive or massless neutrinos, and a gravity-wave background. The discovery of the cosmic microwave background radiation and its immediate interpretation as the blackbody relic of such a hot "big bang" (Penzias and Wilson, 1965; Dicke, et al., 1965) increased the acceptance of this theory enormously and led it to preeminence.

As one of the few observable relics of this creation, many experiments on the spectrum, polarization, and anisotropy of this radiation were undertaken (Weiss, 1980). The spectral experiments are of particular interest here. The earliest measurements were made with ground-based, single-mode, microwave radiometers at low frequencies, less than 3 cm^{-1} (90 GHz). Those measurements showed a Rayleigh-Jeans spectrum, with an antenna temperature of $\sim 2.8 \text{ K}$. If the radiation was indeed from a 2.8 K blackbody, it must follow a true Planck spectrum and peak at $\sim 6 \text{ cm}^{-1}$ (180 GHz). Measurements in this region were needed to confirm its thermal origin.

These measurements are not possible from a ground-based instrument, since the atmospheric opacity is too large. Platforms above much of the atmosphere are necessary. An additional complication is the necessity of using cold instruments, less than 4 K, to avoid an overwhelming emission from the spectrometer. The first actual measurements in this spectral region were thus indirect; near-UV absorption lines in the interstellar medium were used to infer rotational temperatures there (Thaddeus, 1972). These measurements clearly fell below an extrapolated Rayleigh-Jeans curve, but were too imprecise to show an actual decrease in flux. Later, direct measurements from rockets and balloons confirmed this non-Rayleigh-Jeans behavior.

A selection of the measurements available now is plotted in Figure 9. The justification for this selection has been discussed elsewhere (Richards, 1980, 1982). The most striking feature of these data are their close agreement to a $\sim 2.7 - 3.0$ K Planck spectrum from 0.01 cm^{-1} (408 MHz), deep in the Rayleigh-Jeans limit, to 12 cm^{-1} (360 GHz) in the Wien region. At a finer level, an unexpected, large scatter is apparent at the highest frequencies. Formally, the data are inconsistent with a Planck curve (Woody and Richards, 1979, 1981). It is hard to judge the validity of such statistical tests on these data, since the errors are predominately systematic and estimated subjectively, and so not obviously random. Still, when the data of Woody and Richards are analyzed alone, presumably easing the interpretation of the test, there is still a deviation. This deviation is in the form of an excess near the peak, but a deficit at higher frequencies.

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Fig. 9. Cosmic Background Measurements.

This deviation can be seen better in Figure 10, which is a plot of flux versus frequency. While the deviation from a Planck spectrum, the solid line in Figure 10, is apparent, it seems small, only $\sim 10\%$. Since this radiation fills the universe, though, the energy represented by this spectral perturbation is huge. If viewed as an excess on a 2.8 K blackbody, it requires an energy input of the order of that which would have been released if all the hydrogen in the universe had been burned to helium. Clearly, if this deviation is real, something dramatic has happened since the formation of this radiation.

The original predictions of a blackbody remnant were based on simple, homogeneous models for the universe. These models do not reproduce the observed clumping of the matter into galaxies. Deviations from a Planck curve were thus expected at some level (Sunyaev and Zel'dovich, 1980). Most proposed refinements would re-ionize some matter, dumping energy into the background radiation after its formation. The energy can come from any number of sources; turbulence, matter-anti-matter annihilation, and the decay of heavy, exotic particles are some examples. The net result of these processes is to scatter low-energy photons to higher energy, since the re-ionized matter would be hotter than the radiation field. That is not the form of the observed deviation, so these models do not fit the data as well as a Planck curve (Woody and Richards, 1981).

Models of this deviation which utilize frequency-dependent emission processes are relatively unconstrained and can be made to fit the observations. Rowan-Robinson, Negroponte, and Silk (1979) have

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Fig. 10. Woo y and Richards's Spectral Measurement.

carried out calculations using the red-shifted dust features from a pre-galactic generation of stars to increase the flux in the frequency range from 3 to 8 cm^{-1} . They obtained a satisfactory fit to at least one plausible, weighted average of the observations by this theory.

As has been pointed out by the original experimenters and others, this spectral deviation could be due to some unexpected instrumental effect and so not be cosmological (Weiss, 1980). This suspicion arose because the result of Woody and Richards is well-fit by a 2.7 K black-body with an unphysical emissivity of ~ 1.27 , which is shown as a dashed line in Figure 10. This could have come either from an error in calibration or from an undetected change in instrumental response during observation. This possibility continues to cloud the interpretation of these results.

B. EXPERIMENTAL DESIGN

The importance of the spectrum of the cosmic microwave background in determining the history of the early universe motivated us to check Woody and Richards's result. To be useful, a check would have to both be accurate, fixing the flux to a few percent, and also be as independent of the previous experiment as possible.

To meet these goals, we have designed a new apparatus to measure this spectrum from 3 to 10 cm^{-1} . The new experiment is based on the balloon gondola of Woody and Richards. Partial independence has been achieved by changing the experiment in many important respects. This helps avoid the possibility of repeating any undetected systematic errors.

The primary change has been in the method of spectroscopy; the Martin-Pupplett interferometer has been replaced by five band-pass, Fabry-Perot filters, used in first order. This change both allows an in-flight warm calibration and also forces a new method of atmospheric subtraction. Additionally, we have enlarged the earthshine shield, installed a low-temperature, internal calibrator, and improved the design of all the calibrators.

Several important features remain unchanged from the previous experiment. The composite bolometer has not been modified, and the basic antenna design has been retained. Also, the internal cryogenic systems, both for ^4He and ^3He , have been kept.

The design of this experiment has been critically shaped by previous experiments. Earlier balloon-borne filter spectroscopy of the cosmic background radiation by Muehlner and Weiss (1970, 1973a, 1973b) contributed many improvements in technique, ranging from antenna design to window removal. They also showed, however, the necessity of either a high-resolution measurement fit to a detailed atmospheric model, or narrow filters with little atmospheric contamination. Additionally, their measurements indicated the need for better detectors at these low flux levels.

Our group's earlier experiments used better detectors, first ^4He -cooled, then ^3He -cooled, composite bolometers. They also chose the first alternative for atmospheric subtraction, a high-resolution spectrum and a detailed atmospheric model (Woody and Richards, 1981).

This also allowed a search for line-like features in the background radiation, which were still considered a possibility when that experiment was designed.

Our present experiment has been designed for the latter alternative. Its five narrow filters have been located in atmospheric windows and have been made with good out-of-band rejection. The $\sim 1 \text{ cm}^{-1}$ width of these filters is not narrow enough to obviate some assumption concerning the spectrum of the sky. Fortunately, our group's earlier experiment has found only a smooth continuum with no strong lines. Given this shape, each resulting measurement could then be interpreted as the brightness [$\text{watt}/(\text{cm}^2 \text{sr cm}^{-1})$] of this continuum near a band center. Alternatively, a blackbody could be assumed, and the measurements interpreted as temperatures near the band centers. We will adopt the former choice here, although both interpretations will eventually be of interest.

The good fit of the atmospheric model in our previous experiment allows an estimate of the atmospheric contribution in each band. As explained in Section E, this contribution should be small and vary as the secant of the zenith angle. The detector performance achieved in our previous experiments should allow a good determination of this fit.

The problems associated with this filter spectroscopy stem from these same features, low resolution and the need for scans in zenith angle. The use of discrete filters raises the possibility of unexpected high-frequency leakage, in our case, from higher-order filter

transmittance peaks. Also, stray radiation from hot sources within the apparatus is somewhat more likely to be chopped in a filter-spectrometer than to be interference-modulated in a Fourier spectrometer. Great care has been exercised in the design of the new experiment to avoid these difficulties. The ways in which out-of-band radiation can prejudice the calibration of the experiment, and measurements which can be made to detect its presence, are discussed in Section D.

Scans in zenith angle require an antenna with sufficient side lobe rejection to eliminate radiation ("earthshine") from the hot, 300 K, Earth. The excellent antenna of our previous experiment has been retained, and a more extensive earthshine shield designed. In addition, these measurements require that the apparatus with its baths of liquid cryogen be tipped. The possibility exists of angle-dependent changes in the instrumental response. This effect must be checked with great care.

The remaining changes in the instrument all involve the calibration and were motivated by the questions concerning the measurement of Woody and Richards. A calibration is only valid for a measurement if either all the relevant conditions are identical for both the calibration and measurement or any differences are correctly accounted for. Clearly, it is best to calibrate during the flight with as little reliance on laboratory measurements as possible.

The ideal location for any calibrator is outside of the apparatus and filling the entire beam. Although a low-temperature calibrator in this location is possible on rocket or satellite experiments, it is

very difficult to provide in the balloon environment. Radiation from warm objects must be prevented from reflecting or scattering from the surface of the calibrator and entering the accepted throughput of the radiometer. The ambient air must be prevented from freezing on the cold surface of the calibrator. If a window is used for this purpose, then both emission and reflection from it cause additional problems.

In practice, all successful experiments to date have been calibrated by inserting a low-temperature absorber into a cold region of the cryostat in the laboratory before and/or after the measurement. Ideally, this absorber should be black. Also, the ratio of the throughputs from the sky and from the calibrator should in principle be unity, or at least accurately known at all important frequencies. At least two calibrator temperatures are required. To minimize reliance on system linearity, the calibrator temperatures should not be too different from the sky temperature.

In our new experiment, we include a variable-temperature, cold, in-flight calibrator inside of our cryostat. This calibrator lessens our dependence on laboratory calibrations. We have also provided an external, ambient temperature (~ 250 K) calibrator to fill the input beam of the radiometer. Although some saturation in detector output is expected with an ambient temperature calibrator, the effect of this saturation can be measured before the flight. This nonlinearity is considerably less for our narrow-band filter experiment than for the broad-band experiment of Woody and Richards.

Flight measurements of this warm external calibrator can also be used to test for changes in transmittance due to frost in the upper portion of the optical system. It additionally provides a flight test for filter degradation which can cause leakage of high-frequency radiation. The detailed description of the use of these calibrators is also contained in Section D.

With these changes in technique and in calibration, this measurement has a different sensitivity to many possible systematic errors that are hard to rule out in the previous experiment. Any jump in overall system response, such as that suggested to explain the data of Woody and Richards, would have no effect on our measurement because of our in-flight calibrators. Any unexpected atmospheric emission would largely be removed by our zenith angle scans. Finally, any questioning of calibrator blackness should be resolved by comparisons of our laboratory calibrators to obviously black, large calibrators above the optics. A detailed estimate of our probable errors must wait until Section F, after our description of instrument and calibration.

C. APPARATUS

1. SPECTORADIOMETER

This instrument shares many features with the earlier balloon-borne instrument of Mather, Woody, and Richards (Mather, 1974; Woody, 1975; Woody and Richards, 1981). This section first describes all its essential features, but then only discusses in depth those new to this experiment. Descriptions of features previously used are provided in the above references.

Our spectroradiometer is a cryogenic instrument, cooled by liquid ⁴He to reduce instrumental emission. It is contained in the same super-insulated, commercial dewar previously used. That dewar is mounted in an aluminum-frame gondola, which also contains batteries and telemetry electronics. The mount of the dewar is pivoted and controlled by a screw drive to allow a variation in zenith angle. The mount has been modified since the previous experiments to increase the maximum allowable zenith angle to 60°. The gondola also serves as a base to support the expanded earthshine shield.

The gondola again hangs on a long, ~ 500 meter, line below the balloon supporting it, so as to move the beam of the antenna well away from the balloon. The gondola is driven to rotate at about two revolutions per minute rather than rotating freely as previously. This allows us to detect any azimuthal variation in the atmospheric signal.

The spectroradiometer itself also retains many features of the previous instruments, but with some detailed changes and a few major ones. A diagram, Figure 11, illustrates the functional parts of our instrument. The hatched area is the optical beam. Starting at the top of the instrument, it first passes a new earthshine collar, A, above the optics. Below the mouth of the antenna it enters a horn, B. This horn was used previously. While out of the geometric beam, it fills much of the singly-diffracted antenna side lobes with a reflection of the sky. As in previous experiments, the Mylar window present above the horn during the ascent is removed during observations.

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Fig. 11. Cosmic Background Spectroradiometer.

The geometric beam is defined by the antenna structure below the horn. The large, copper, Winston concentrator, C, (Winston, 1970) is again used, although lower in the optics. The beam is recollimated below the large concentrator by a new, short concentrator-and-lens combination, D (Keene et al., 1978).

A beam-switch, E, allows this new instrument to view either the sky, with the beam we have been following, or a duplicate short concentrator, F, and internal calibrator, G. The selected beam propagates through an oversize light pipe to a flat mirror and is reflected down through our low-pass filter, H, chopper, I, and filter wheel, J. The beam terminates on the composite bolometer, K, previously used.

The internal $L^3\text{He}$ -bath, L, which cools the bolometer remains unchanged. Its design is similar to that of the White Mountain instrument previously described, except that here the ^3He is condensed by pumping only a small, internal $L^4\text{He}$ -bath to avoid pumping on the main bath before launch. Also unchanged is the large $L^4\text{He}$ -bath, with its separate internal can surrounding the lower optics and superfluid pumps to fill this can and cool the optics.

Figure 12 is a diagram of the instrument in flight configuration. Only a portion of the planned earthshine shield is shown. This shield, and the collar mentioned earlier, fill much of the double-diffracted side lobes of the beam with the sky. These side lobes correspond to those rays, coming in at large angles to the optical axis, which fill part of the beam by first diffracting at the top of the horn and then

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Fig. 12. Spectroradiometer in Flight Configuration.

diffracting again at the bottom of the horn. Similar shields have been used on our previous instruments.

The figure also illustrates the use of our ambient temperature calibrator. The beam to the sky can be reflected by an oversized, aluminum mirror into the oversized, ambient calibrator. This reflection avoids cooling the calibrator in the outrushing, helium gas (Meuhlner and Weiss, 1973a; Woody and Richards, 1981). The calibrator itself is a long, hollow, 15" wedge of 1/2 inch plywood, covered with aluminum sheet metal to eliminate all transmittance. If specular reflection dominates, the calibrator would have an emissivity greater than 0.9999. Any small, diffuse reflectivity will limit the emissivity first, but we cannot measure emissivity to such accuracy. For our purposes, it will suffice to show the calibrator has an emissivity greater than 0.99 by comparing it in the laboratory with other, even larger boxes above the optics.

By careful arrangement, the mirror can be stowed inside the mouth of the calibrator. An aluminum sheet covers the stowed mirror and calibrator, so that the earthshine shield is continuous.

Figure 12 also demonstrates that the liquid helium filling our lower optics tilts with zenith angle. While an obvious effect, this change may affect the optical performance of our instrument. Consequently, the instrumental calibration must be checked over the range of zenith angles used.

The major changes we have made are in the spectroradiometer. They can be grouped into two sets. One set improves our calibration procedure by installing the internal calibrator and beam-switch, and the related lowering of the beam-defining concentrator. The other set changes the method of spectroscopy and so involves the installation of the filter spectrometer and new chopper.

Both sets of changes are included in Figure 13, which is a cross-section through the lower optics. In the previous instruments, a mirror at the position of our beam switch mirror, E, directed the radiation into one port of a Martin-Puplett interferometer (Martin and Puplett, 1969). The radiation exited from the other port to the bolometer through a polarizing chopper near the chopper shown, P. In this earlier instrument, the radiation passing the aperture, B, was recollimated by another, long, Winston concentrator.

The set of calibration changes gained two advantages by replacing that concentrator with the short concentrator-and-lens combination, parts C and D in Figure 13. First, the sky-viewing aperture, B, was lowered 30 cm, into the can filled with liquid helium. An uncertainty in the earlier experiment was thus removed; it is now certain that the sky-viewing aperture is filled with liquid helium. Because of its finite index of refraction, the presence or absence of liquid helium in this aperture would vary the throughput reaching the sky, and so the signal, by 5% (Woody and Richards, 1981).

Fig. 13. Cross Section Through Lower Optics of Spectroradiometer.

Second, there was room to duplicate this shorter combination below the switch and so to install the beam-switch, E, and the internal calibrator, L. The beam-switch changes beams by rotating a portion of the apparatus 180° about the axis, F.

Care has been taken to maintain the symmetry of these paths. The shorter, copper concentrators, C and G, are identical to within machining tolerances. The beam-defining concentrator, A, has had a short portion, I, duplicated for the lower path. Only one lens, D, is used, which rotates with the beam switch. The symmetry is broken by the second mirror, M, however, so we cannot rely on only this internal calibrator. Rather, the asymmetry must be characterized by comparing the signals from the internal calibrator with those from various laboratory calibrators. That process is described in Section D. The construction of the calibrators is discussed in this section, part 2.

This set of calibration changes produces one additional modification. A 30 cm long, 6 cm diameter, copper, light pipe now is soldered to the top of the large, Winston concentrator and extends to the bottom of the horn. The thermometers and a heater on these optics, used for testing antenna emission, have all been moved up accordingly.

The effect of this extension on the side lobe response of our antenna should be negligible. A simple argument supports this conclusion. The Winston concentrator accepts radiation only within an angular range $\sim f/8$ and preferentially from the center of its top aperture. The light pipe extension is stubby enough, at $f/8$, that most accepted

rays will reflect only once. This spreads the spatial pattern of accepted rays out, taking more from near the edge of the light pipe at the bottom of the apodizing horn. Since the strength of the side lobe response is approximately proportional to the fraction of accepted rays from within a wavelength of this edge, this does increase our side lobe response. An analysis of a uniform acceptance across this aperture has shown even that extreme case to have a small enough side lobe response, with an earthshine shield, to permit our measurement (Woody, 1975). As the effect of the light pipe extension is only to slightly degrade the centrally-concentrated Winston pattern toward the uniform case, we are confident no significant side lobe response is produced.

The second set of modifications changes the method of spectrometry. The drive shaft previously powering the moving interferometer mirror now drives a spur gear to advance the filter wheel, Q in Figure 13. The polarizing chopper is replaced with a 125 μ Mylar chopper wheel, with alternate clear and aluminized sections, P.

The filters themselves have three parts. The fixed glass element, O, is common to all bands and cuts off radiation above 20 cm^{-1} . Each of the five, band-pass filters in the filter wheel then includes the other two parts: a stack of Fabry-Perot filters made by evaporating a capacitive, aluminum grid on Mylar sheets, and a high-pass, grill filter soldered into the filter wheel. The theory and construction of these filters have been described elsewhere (Timusk and Richards, 1981).

The measured system response is shown in Figure 14 for each filter. More detail is visible in the logarithmic response plots in Figures 15 to 19.

These spectral responses were measured by filling the geometric beam of our instrument with the beam from our large, laboratory, Michelson interferometer (Joyce, 1970). The beam was expanded from its standard $f/1.5$, in a 1.1 cm light pipe, by a long, hollow, metal cone. The beam entered the instrument at the top of the horn through a 50 μ Mylar window. No correction was made for this thin window, nor for the unfilled side lobes of the antenna.

The interferometer was scanned in path length, and the signal from our bolometer recorded. For these measurements, the chopper in Figures 9 and 11 was fixed on a clear section, and the chopper in the Michelson interferometer used. Additional, high-frequency information was obtained by fixing the Michelson interferometer at zero-path-difference and inserting previously characterized, high-pass, grill filters into the beam just below the interferometer. A selection of these, with low-frequency limits from 6 cm^{-1} to 18 cm^{-1} , was available.

To interpret the resulting signals, the Michelson interferometer must be characterized as a light source. In a separate experiment, the output of the Michelson interferometer at zero-path-difference was fed to our laboratory, Martin-Puplett interferometer, and the signal measured as the Martin-Puplett interferometer scanned. Then, a blackbody in an oven replaced the Michelson interferometer, and its signal was also recorded. These measurements suffice to characterize

Fig. 14. System Responsivities - Linear Plots.

XBL 828-6417

Fig. 15. System Responsivity with 3 cm^{-1} Filter - Log Plot.

Fig. 16. System Responsivity with 5 cm^{-1} Filter - Log Plot.

XBL 834-5526

Fig. 17. System Responsivity with 7 cm^{-1} Filter - Log Plot.

XEL 854-5525

Fig. 18. System Responsivity with 9 cm⁻¹ Filter - Log Plot.

XBL 834-5524

Fig. 19. System Responsivity with 10 cm^{-1} Filter - Log Plot.

the Michelson interferometer as a light source, if it is an ideal Fourier transform device. This appears to be true below 50 cm^{-1} (Mather, 1974).

The properties of the Michelson interferometer as a light source so derived agree with simple estimates. Its output spectrum at zero-path-difference, with our 125μ Mylar beamsplitter, is that of a $\sim 900 \text{ K}$ blackbody multiplied by a theoretical beamsplitter profile. Superimposed on this are oscillations similar to those observed by Dr. John Mather (1974) and attributed by him to interference in the transparent envelope of the arc lamp.

The measured spectral signal for each filter was then divided by the brightness spectrum of the Michelson interferometer to yield the five spectral response curves in Figure 14. A spurious signal at twice the frequency of the peak transmittance has been removed. This feature is a by-product of our computer phase-correction routine. The actual signal level here was checked in the process of measuring the general, high-frequency response with the grill filters, described below. Additionally, the transmittance at low frequencies, below the cut-on of the grill filter in the filter wheel, is set at zero. This is in agreement with all our measured transmittance spectra of other grills.

To reach the low transmittance at high frequencies shown in the logarithmic plots, the signals with the external, grill filters in the beam were used. First the known, transmittance spectrum of a grill filter is multiplied by the Michelson interferometer brightness spectrum. Then, the signal measured with that grill filter in the beam and the interferometer at zero-path-difference is used to set a value

for a filter transmittance near the grill edge. By repeating this with a sequence of grill filters with increasing frequencies, this continuum hypothesis has been shown to be internally consistent. At the highest frequencies shown, $\sim 25 \text{ cm}^{-1}$, our signal-to-noise deteriorates because of the falling output power of the interferometer. We rely then on the well-known properties of glass to guarantee low transmittance above 25 cm^{-1} . For the atmospheric calculations summarized below in Section E, we assumed no less than a constant transmittance equal to one third of the noise limit in Figures 15 to 19.

Finally, the overall scale in the figures has been adjusted. The scale for each filter is chosen so that the predicted signal through it from an 11.0 K blackbody equals the measured signal with the laboratory calibrator at that temperature.

A new chopper is the other major modification needed to change the method of spectroscopy. Unlike the previous instrument, our spectroradiometer is sensitive to a signal offset. No later, Fourier transform exists to eliminate its effect. Acoustic signals from the chopper had to be reduced; this required many changes. The aluminized Mylar design was chosen to minimize stirring of the liquid helium. Also, the previous, stainless steel, tubular, chopper drive shaft has been replaced by a thinner, solid, carefully straightened, stainless steel shaft. A point-contact, Teflon bearing has been installed at the lower end of the shaft. Along the shaft, the Teflon, sling bearings have been replaced with Teflon, edge-contact bearings, and additional such bearings installed to constrain the shaft. At the top, a keyed,

Delrin, sliding joint accommodates differential thermal contraction. Finally, a *direct-drive motor* has replaced the *motor-and-gear* arrangement previously used.

With these modifications, no signal offset attributable to the chopper is apparent. Nonetheless, chopper-related noise still increases our noise level relative to the chopper-off level.

This chopper and the filter wheel are contained in machined brass enclosures. The space around the chopper has inserts of black, absorbing foam to lower its internal reflectivity. The filter wheel container has rings of Eccosorb installed around both the beam entrance and exit to reduce leakage around the filter wheel.

All joints in this structure have been sealed with aluminum tape. Additionally, the chopper shaft has extensive, interlaced, Eccosorb baffling above its entrance hole. Similar baffling blocks the entrance of each shaft into the liquid-helium-filled can. All tubes leading into it are also blocked with Eccosorb. The joint at the top of the can is sealed with aluminum tape.

With these precautions, no evidence of a signal from leakage radiation is found for any of the five filter bands. Without the precautions, signals were present in all filter bands when the instrument and all calibrators were ~ 1.7 K. At such a low temperature, no detectable signal should have been present in our 5, 7, 9, and 10 cm^{-1} filter bands. The presence of clear signals indicated leakage before these modifications.

2. CALIBRATORS

These two sets of modifications produced our new spectroradiometer. With the other changes in the gondola and earthshine shield, Section F shows that we can measure the spectrum of the cosmic background radiation to a precision of a few percent. To insure sufficient accuracy requires a dependable calibration. In particular, low-temperature, black absorbers that can be inserted into the antenna are needed.

Three such calibrators have been constructed. All use Eccosorb CF-110 or MF-110 (Emerson and Cuming, Inc.; Canton, MA) as the absorber, and encase the absorber in a vacuum can for thermal isolation. All have thin, Mylar windows to pass radiation. After a brief description of each calibrator, their optical properties are estimated.

One calibrator was built by Dr. David Woody for the previous experiment. A cross section view of it in the antenna is drawn in Figure 20. In this calibrator, the absorber, A, is a grooved sheet of Eccosorb MF-110 attached to a copper heat sink. Thermometers, T, and a heater, H, are also mounted to the heat sink.

The second calibrator is drawn in Figure 21. This calibrator has the same outside diameter, so as to fit into the antenna at the same level as the previous calibrator. Its absorber is a 0.378 cm thick, 30°, hollow cone of Eccosorb CF-110, cast into a 0.005 cm thick, copper-foil cone. The copper foil is then soldered to a hollow, copper, conical heat sink. Again, a heater and thermometer are mounted on this heat sink. In this case, a means of lowering temperature is available. An internal pot can be filled with liquid helium and

XB 304-4947

Fig. 20. Grooved Laboratory Calibrator and Its Match to Antenna.

XBL 83I-5053

Fig. 21. Conical Laboratory Calibrator.

pumped on to lower the temperature of the absorber below that of its surroundings.

The final calibrator is the internal one viewed with the beam-switch and shown in Figure 11. Because only a truncated, antenna concentrator could fit in the available space, a smaller window, of 13 μ Mylar, was used. A larger mass of Eccosorb CF-110 could be used, since measurements of the thermal conductivity of Eccosorb were available (Halpern, 1982). These showed a thermal conductivity $\sim 0.8 \frac{\text{mW}}{\text{cm-K}}$ and a boundary conductance of at least $1.0 \frac{\text{mW}}{\text{cm}^2\text{-K}}$. The boundary conductance is then comparable to the bulk conductance for a thickness of 0.8 cm. If our heat flow is set by radiation, then in the extreme case of a 20 K calibrator radiating to 0.0 K with its entire throughput, a thickness of 2 cm would produce a ΔT of only 10^{-2} K. This error, $\Delta T/T = 5 \cdot 10^{-4}$, is completely acceptable.

This internal calibrator is epoxied with Stycast 2850 FT (Emerson and Cuming, Inc.; Canton, MA) into a thin, copper-foil can. The thermometer is mounted on this can. If the heater were also mounted on the copper foil, temperature gradients would exist in the foil when the calibrator was heated. Instead, the heater is installed part way along the single thermal link to the bath, insuring no large heat flow in the calibrator.

The copper backing plays two roles in these calibrators. First, its conductivity is sufficient to deliver the radiative heat flow for temperatures up to 20 K with little temperature gradient (less than 1 mK). Second, it reflects the radiation, transmitted through the absorber once, back into the absorber. Thin, weak foils are used in the

conical calibrators to allow the copper to deform, so that differential thermal contraction will not break the foil-Eccosorb bond.

Several separate effects must be evaluated to estimate the optical properties of these calibrators. The match of each calibrator to the antenna must be considered, as the calibrator is not far away, but in the antenna itself. The emissivity of the Eccosorb structure must be estimated, and finally, the effect of the calibrator window must be calculated.

The Mylar window both absorbs and reflects. The absorptivity of our Mylar was measured at the Max Planck Institute, Stuttgart, and it was shown to be less than 1 neper/cm in our frequency range, 3 to 10 cm^{-1} . This produces negligible absorption in our calibrator windows.

The reflectivity of our 50 μ Mylar was also measured there and had a maximum value of 0.2, at 10 cm^{-1} . This is in agreement with its known index of refraction, 1.76. The effect of this reflection depends on the calibrator geometry.

The first two calibrators described are located 25 cm above the small aperture, in the antenna concentrator. Their vacuum windows are bowed inward in a spherical curve of approximately 6.2 cm diameter. Any reflection from the windows would be redirected downward, but predominantly at angles rejected by the concentrator. This radiation would become randomized within the cavity formed by the antenna and calibrator. The calibrator is lossy while the antenna is shiny and its aperture small; most radiation paths must then originate from the calibrator. Equivalently, the small aperture cannot "see itself" in reflection over most of its throughput.

A calculation of this effect in the case of a true Winston concentrator and spherical mirror requires numerical raytracing. An estimate can be obtained by approximating the concentrator as a straight cone and using the image ball formalism (Mather, 1974). The curved, reflective Mylar can be included as a converging lens between two cones, one real, one a reflected image. The estimate of the throughput that can "see itself" requires a calculation of the solid angle subtended by the image ball of the reflected cone at the image ball of the real cone. Because of the convergence of the curved mirror, this estimate yields only ~ 0.03 of the reflected rays returning to the aperture. With the Mylar reflectivity of 0.2, more than 0.99 of the radiation passing downward through the aperture of the antenna must come from the calibrator.

Our internal calibrator is closer to the aperture, and its window is smaller. If its radius of curvature were about 3 cm, the estimate above shows all reflected rays returning to the aperture. Here, the lens representing the curved Mylar focuses one image ball upon the other. In this case, only 0.8 of the radiation passing the aperture toward the detector would come from the calibrator. To avoid this, the 50 μ window was replaced by a 12 μ Mylar window. This change reduces the maximum reflectivity of the window to ~ 0.01 . As will be argued in Section D, this is sufficient for our internal calibrator.

An adequate calibrator would still require an intrinsically black absorbing structure behind these windows. The first calibrator described was not conical, but had a grooved surface. Its emissivity was estimated earlier (Woody and Richards, 1981), and found to be

greater than 0.98. We will check this estimate by comparing it to our conical, laboratory calibrator as well as to large, ambient calibrators.

An estimate of the emissivity of the Eccosorb structure of our conical, laboratory calibrator can also be made. The properties of Eccosorb MF-110 have been measured at low temperature by J. Peterson who found $n = 1.93 + 0.073i$. The conical, laboratory calibrator, shown in Figure 21 and discussed above, requires six specular reflections before an entering ray path can exit the Eccosorb structure. Assuming no diffuse reflection yields an emissivity greater than 0.995, except at our lowest frequencies, $\sim 3 \text{ cm}^{-1}$. There, the 0.3 cm thickness, designed around earlier, less accurate Eccosorb measurements, is not sufficient, and a reflectivity ~ 0.01 is estimated. If the reflected radiation were randomized as we estimate the window reflection to be, it would be unimportant, but we cannot assume this.

In the case of both the laboratory calibrators, comparisons with large, black, ambient calibrators will be available. If the laboratory calibrators prove inadequate, designs such as the internal calibrator will be used. Its large thickness of Eccosorb allows an emissivity greater than 0.995 even at 3 cm^{-1} . This thickness is enhanced by encasing its cone in a cylinder. In this geometry, rays once refracted in are trapped by total internal reflection for many passes through the Eccosorb. This calibrator will be described in Peterson and Richards (in preparation).

An estimate of the match between the antenna and each calibrator is needed to completely determine the optical properties of that calibrator. For the first, grooved calibrator, this quantity was measured. The curves in Figure 20 are the instrumental response for that calibrator and for a large, well-matched blackbody. These were measured with the Martin-Pupplett interferometer previously used (Woody and Richards, 1981). Their detailed similarity is strong evidence that the same modes are filled by both the sky and that calibrator. Consequently, no correction is required.

For our conical, laboratory calibrator, no direct measurement is available. It was designed, however, with an entrance structure identical to that of the grooved calibrator. Only the Eccosorb structure behind differs. It should then also have the same match to the antenna as the grooved calibrator and so also require no correction.

In the case of our internal calibrator, no such argument can be made. While it is separated from the aperture of the antenna, this separation is only about 6λ at 3 cm^{-1} . Consequently, a match identical to that of the sky cannot be simply assumed. We show in Section D that an identical match here is not critical. Essentially, this is because our use of the internal calibrator is as a transfer standard, with our fundamental standard the well-matched laboratory calibrators.

D. CALIBRATION PROCEDURE

1. MODEL

Calibration of instruments designed to measure the spectrum of the cosmic background radiation has presented difficulties in the past (Weiss, 1980; Woody, 1975). In order to analyze our calibration

procedure, we developed an algebraic model of our signal. This model is first described in detail, then applied to several experiments designed to measure the spectrum of the cosmic background radiation. The essential idea in this model is to account for the radiation filling the entire throughput of the detector in all instrumental configurations.

To introduce our model, we consider first a simplified system at the single temperature T_0 . It consists of an antenna limiting the throughput from the sky, a chopper, a frequency-selective element such as a band-pass filter, and a detector with total throughput $4\pi A(\nu)$. We let $\tau(\nu)$ be the frequency-dependent transmittance of this system when its antenna is filled with radiation from a distant source with brightness $F^{\text{sky}}(\nu)$, such as the room or the sky. This function, $\tau(\nu)$, is equivalently defined as the fraction of $4\pi A(\nu)$ actually from the sky. The power reaching the detector from the sky is then $4\pi A\tau F^{\text{sky}}$, where the frequency dependences have been suppressed for simplicity. We will continue to suppress frequency dependences, in the text and on the right hand side of all equations, except when first introducing a function.

If only a fraction, τ , of the throughput comes from the sky, then the fraction $1-\tau$ must come from inside the apparatus. In this idealized system, the radiation from the apparatus has a Planck spectrum with brightness $B(\nu, T_0)$. When viewing the sky with the chopper

on, we must then receive a total power

$$P^{\text{sky}}(\nu) = 4\pi A[\tau F^{\text{sky}} + (1-\tau) B(T_0)]. \quad (1)$$

If there is no leakage past the chopper when it's closed, then

$$P^{Cl}(\nu) = 4\pi AB(T_0). \quad (2)$$

The quantity detected is the difference, $P^{sky} - P^{Cl}$. Since the temperature of the bolometer changes insignificantly with incident power, that is, as the chopper turns, the power radiated by the bolometer itself cancels in the above power difference and has not been explicitly included.

In order to calibrate this system, we place a nearly black absorbing surface with temperature T_{cal} inside the antenna. The effective emissivity, $\epsilon(\nu)$, of this calibrator can be larger than the emissivity of the absorber because of multiple reflections in the multimode cavity which is formed by the absorbing surface and the antenna. The radiation entering the photometer from this calibrator will have brightness $\epsilon(\nu) B(\nu, T_{cal})$.

It cannot be assumed that the antenna matches the apparatus identically both to the calibrator and to the sky. A free space wave will be partly reflected by the impedance discontinuity at the entrance to the antenna. With a calibrator inserted into the near-field, this reflection can be changed. Consequently, the transmittance of the system when viewing the calibrator must be written $\tau(\nu) + \Delta\tau(\nu)$. The power reaching the detector from the calibrator is then

$$P(\nu) = 4\pi A\epsilon(\tau + \Delta\tau)B(T_{cal}). \quad (3)$$

The total power in the throughput $4\pi A$ which reaches the detector when the chopper is open is

$$P^{cal}(\nu) = 4\pi A\epsilon(\tau + \Delta\tau)B(T_{cal}) \\ + 4\pi A[1 - \epsilon(\tau + \Delta\tau)] B(T_0)$$

We now define $R(v)$ as the voltage responsivity of the detector including the effects of synchronous demodulation. The voltage measured when viewing the sky is then

$$S^{\text{sky}}(v) = R(p^{\text{sky}} - p^{\text{cl}}) = 4\pi AR\tau [F^{\text{sky}} - B(T_0)]. \quad (5)$$

The voltage measured when viewing the calibrator is

$$S^{\text{cal}}(v) = R(p^{\text{cal}} - p^{\text{cl}}) = 4\pi AR\epsilon(\tau + \Delta\tau) [B(T_{\text{cal}}) - B(T_0)]. \quad (6)$$

The object of the experiment is to obtain F^{sky} from a measurement of S^{sky} and one or more measurements of S^{cal} . This cannot be done unless ϵ and $\Delta\tau$ are known from independent measurements or calculations. If we can assume $\epsilon[\tau + \Delta\tau] = \tau$, then

$$F^{\text{sky}}(v) = \frac{S^{\text{sky}}}{S^{\text{cal}}} [B(T_{\text{cal}}) - B(T_0)] + B(T_0). \quad (7)$$

If T_{cal} is adjusted so that $S^{\text{sky}} = S^{\text{cal}}$, then $F^{\text{sky}} = B(T_{\text{cal}})$.

For an equivalent analysis which will be useful later, Equation (5) can be rewritten in terms of a normalized system transmission, t , and signal offset, Z .

$$S^{\text{sky}}(v) = t^{\text{sky}} F^{\text{sky}} + Z^{\text{sky}} \quad (8)$$

where $t^{\text{sky}}(v) = 4\pi AR\tau$

and $Z^{\text{sky}}(v) = -t^{\text{sky}} B(T_0)$.

Similarly, Equation (6) becomes

$$S^{\text{cal}}(v) = t^{\text{cal}} B(T_{\text{cal}}) + Z^{\text{cal}} \quad (9)$$

where $t^{\text{cal}}(v) = 4\pi AR\epsilon(\tau + \Delta\tau)$

and $Z^{\text{cal}}(v) = -t^{\text{cal}} B(T_0)$.

A plot of S^{cal} versus $B(T_{\text{cal}})$ yields a straight line parameterized by T_{cal} and with slope t^{cal} and intercept Z^{cal} . If, as before,

we assume $\epsilon(\tau + \Delta\tau) = \tau$, then $z^{\text{cal}} = z^{\text{sky}}$ and $t^{\text{cal}} = t^{\text{sky}}$. A possible calibration procedure would be to measure S^{cal} for a variety of values of T_{cal} , so obtaining z^{sky} and t^{sky} from the best-fit straight line. These could then be used to convert S^{sky} to F^{sky} . Any systematic deviation from a straight line would indicate a failure of the model.

Our analysis of real systems will use t and z parameters analogous to the ones defined for Equation (9). The advantage of this approach is that these functions can be directly measured. The equations analogous to Equations (1), (2), and (4) will necessarily contain new terms difficult to measure. These new terms are required to illustrate the relationships among the parameters and to show when these relationships fail.

Few actual instruments designed to measure the cosmic background radiation are well modeled by the simplified system above. Temperatures other than T_0 are usually present, and the fluxes from them must also be considered. In our apparatus for example, the detector operates at $T_d = 0.3$ K, which is significantly less than T_0 , ~ 1.7 K. The detector could see itself in reflection within the throughput $4\pi A$ both when the chopper is open and when it is closed. Also, because parts of the apparatus are warm, ~ 250 K, stray high-temperature radiation may leak to the detector. Such leakage can occur around drive shafts for the chopper, filter wheels, or mirror rotators. This stray radiation does not come from any one temperature, but rather from a superposition of all temperatures from T_0 to the highest temperature of the apparatus, T_1 . The brightness of this radiation then is

$$I(\nu, T_1) = \int_{T_0}^{T_1} a(T) B(\nu, T) dT \quad (10)$$

where $a(T)$ is the absorption at each temperature and must satisfy the constraint, $\int_{T_0}^{T_1} a(T) dT = 1$. The function, $a(T)$ is hard to predict or measure. For our model below, we will only use $I(\nu, T_1)$ and only need the observation that it depends on a $T_1 \gg T_0$. A more general model must allow fluxes such as these to appear in the fractions of $4\pi A$ not originating in the sky or calibrator.

To construct this more general model, it is again convenient to divide the throughput when looking at a distant source into two fractions, τ coming from that distant source, such as the sky, and $1 - \tau$ arising from inside the instrument. This latter fraction must be further subdivided into three parts: the first, $f_0(\nu)$, from parts of the apparatus at T_0 , the second, $f_d(\nu)$, from the detector at T_d , and the third, $f_1(\nu)$, from the leakage, with brightness $I(\nu, T_1)$. These distribution functions, the f 's, must satisfy $f_0(\nu) + f_d(\nu) + f_1(\nu) = 1$. The power reaching the detector when viewing the sky with the chopper open is thus

$$P^{\text{sky}}(\nu) = 4\pi A \tau F^{\text{sky}} + 4\pi A (1 - \tau) [f_0 B(T_0) + f_d B(T_d) + f_1 I(T_1)]. \quad (11)$$

With the chopper closed, we have

$$P^{\text{cl}}(\nu) = 4\pi A [g_0 B(T_0) + g_d B(T_d) + g_1 I(T_1)], \quad (12)$$

where the g 's are defined similarly and $g_0(\nu) + g_d(\nu) + g_1(\nu) = 1$. If we now assume not just that $\epsilon(\tau + \Delta\tau) = \tau$, but that the calibrator is actually ideal, so that $\epsilon = 1$ and $\Delta\tau = 0$, then the power observed when

viewing this ideal calibrator is

$$p^{\text{cal}}(\nu) = 4\pi A \{ \tau B(T_{\text{cal}}) + (1-\tau) [f_0 B(T_0) + f_d B(T_d) + f_1 I(T_1)] \}. \quad (13)$$

The voltage measured when viewing the sky is now

$$S^{\text{sky}}(\nu) = 4\pi AR \{ \tau F^{\text{sky}} + [(1-\tau) f_0 - g_0] B(T_0) + [(1-\tau) f_d - g_d] B(T_d) + [(1-\tau) f_1 - g_1] I(T_1) \}, \quad (14)$$

and when viewing the calibrator is

$$S^{\text{cal}}(\nu) = 4\pi AR \{ \tau B(T_{\text{cal}}) + [(1-\tau) f_0 - g_0] B(T_0) + [(1-\tau) f_d - g_d] B(T_d) + [(1-\tau) f_1 - g_1] I(T_1) \}. \quad (15)$$

Our first, single-temperature model is recovered when $f_0 = g_0 = 1$.

Since τ does not factor out in Equations (14) and (15), an equation analogous to (7) would require two different calibrator temperatures to solve for F^{sky} . The alternative development of Equations (8) and (9) in terms of an offset Z and a slope t is still valid. In this case

$$t^{\text{sky}}(\nu) = 4\pi AR \tau \quad (16)$$

as before, but

$$Z^{\text{sky}}(\nu) = 4\pi AR \{ [(1-\tau)f_0 - g_0] B(T_0) + [(1-\tau)f_d - g_d] B(T_d) + [(1-\tau)f_1 - g_1] I(T_1) \}. \quad (17)$$

Since we still assume $\epsilon = 1$ and $\Delta\tau = 0$, we still have $t^{\text{cal}} = t^{\text{sky}}$ and $Z^{\text{cal}} = Z^{\text{sky}}$. Again the straight line obtained in a plot of S^{cal} versus $B(T_{\text{cal}})$ can be used to convert S^{sky} to F^{sky} .

Relaxing the calibrator assumptions leads to serious difficulties. If $\Delta\tau \neq 0$ and $\epsilon < 1$, Equation (13) must be rewritten

$$\begin{aligned}
p_{cal}(v) = & 4\pi A \epsilon (\tau + \Delta\tau) B(T_{cal}) \\
& + 4\pi A (1 - \tau) [f_0 B(T_0) + f_d B(T_d) + f_1 I(T_1)] \\
& - 4\pi A \Delta\tau [m_0 B(T_0) + m_d B(T_d) + m_1 I(T_1)] \\
& + 4\pi A (\tau + \Delta\tau) (1 - \epsilon) [n_0 B(T_0) + n_d B(T_d) \\
& \quad n_1 I(T_1)]. \tag{18}
\end{aligned}$$

The f 's are the same functions as in Equation (13), but the m 's and n 's are new distribution functions, again satisfying constraints

$$m_0(v) + m_d(v) + m_1(v) = n_0(v) + n_d(v) + n_1(v) = 1. \tag{19}$$

To help explain this profusion of functions, Figure 22 schematically shows their origins. Each large circle in the figure represents the entire throughput, $4\pi A$. Figure 22a corresponds to Equation (11), with the chopper open and the instrument looking at the sky. Here the throughput is broken into two fractions by the smaller, solid, circular line, τ , from the sky, and $1 - \tau$. The outer fraction of $4\pi A$ is subdivided into the fractions f_0 , f_d , and f_1 by the dashed lines. These represent the three sources of radiation possible: $B(T_0)$, $B(T_d)$, and $I(T_1)$. Figure 22b corresponds to Equation (12), with the chopper closed and no leakage. The dashed lines here divide $4\pi A$ into the three fractions: g_0 , g_d , and g_1 . This division has no relation to that of Figure 22a.

The case of the non-ideal calibrator is shown in Figure 22c. Again, the throughput is divided into two parts by a solid line, a fraction $\epsilon(\tau + \Delta\tau)$ from the calibrator, and the fraction $1 - \epsilon(\tau + \Delta\tau)$. Again, the outer fraction is subdivided by dashed lines into three regions. Since $1 - \epsilon(\tau + \Delta\tau)$ is not in general equal to $1 - \tau$, the f 's

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Fig. 22

cannot be used here. Defining new fractions, such as h_0 , h_d , and h_1 , however, obscures the $\Delta\tau = 0$, $\epsilon = 1$ limit. Our solution was to subdivide the $1 - \epsilon(\tau + \Delta\tau)$ fraction yet again, as in Figure 22d. There, the additional solid circles provide throughputs $4\pi A(1 - \tau)$, $-4\pi A\Delta\tau$, and $4\pi A(1 - \epsilon)(\tau + \Delta\tau)$.⁴ Since the $4\pi A(1 - \tau)$ is the same physical throughput as in Figure 22a, the same functions f_0 , f_d , and f_1 must apply to it. The other, new regions of throughput do not occur in Figure 22a and so cannot be assumed to have the same distribution functions. New functions, the n 's and m 's, have to be assigned. Since these distribution functions are for an entire fraction of $4\pi A$, for example the n 's for $4\pi A(1 - \epsilon)(\tau + \Delta\tau)$, they must implicitly depend on that fraction; that is, the n 's depend on ϵ and $\Delta\tau$, the m 's, on $\Delta\tau$ alone.

Using Equation (18), we can now write the signal measured with this non-ideal calibrator as

$$\begin{aligned}
 S^{\text{cal}}(\nu) = & 4\pi A \epsilon(\tau + \Delta\tau) B(T_{\text{cal}}) \\
 & + 4\pi A R \{ [(1 - \tau)f_0 - g_0] B(T_0) + [(1 - \tau)f_d - g_d] B(T_d) \\
 & \quad + [(1 - \tau)f_1 - g_1] I(T_1) \} \\
 & - 4\pi A R \Delta\tau [m_0 B(T_0) + m_d B(T_d) + m_1 I(T_1)] \\
 & + 4\pi A R (1 - \epsilon)(\tau + \Delta\tau) [n_0 B(T_0) + n_d B(T_d) + n_1 I(T_1)]
 \end{aligned}$$

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⁴Figure 22d is drawn with $\Delta\tau < 0$, for ease of presentation. If $4\pi A\Delta\tau > 0$, the $-4\pi A\Delta\tau$ throughput folds back on top of the $4\pi A(1 - \tau)$ part, and is subtracted from it. Additionally, the $(1 - \epsilon)(\tau + \Delta\tau)$ and $\epsilon(\tau + \Delta\tau)$ circles could grow out and eventually overlap the $1 - \tau$ circle if $\Delta\tau$ becomes large enough. In fact, $\epsilon(\tau + \Delta\tau)$ can itself be greater than τ . Our formalism still applies in these cases.

or rearranging

$$\begin{aligned}
 S^{\text{cal}}(\nu) = & 4\pi A \epsilon(\tau + \Delta\tau) B(T_{\text{cal}}) \\
 & + 4\pi A R[(1 - \tau)f_0 - g_0 - \Delta\tau m_0 + (1 - \epsilon)(\tau + \Delta\tau)n_0] B(T_0) \\
 & + 4\pi A R[(1 - \tau)f_d - g_d - \Delta\tau m_d + (1 - \epsilon)(\tau + \Delta\tau)n_d] B(T_d) \\
 & + 4\pi A R[(1 - \tau)f_1 - g_1 - \Delta\tau m_1 + (1 - \epsilon)(\tau + \Delta\tau)n_1] I(T_1). \quad (20)
 \end{aligned}$$

Equation (20) reduces to Equation (15), the ideal calibrator equation, in two limits: the first, as expected, when $\epsilon = 1$ and $\Delta\tau = 0$; the second, when $\epsilon(\tau + \Delta\tau) = \tau$, but also requiring $f_0 = m_0 = n_0$, $f_d = m_d = n_d$, and $f_1 = m_1 = n_1$. While this second possibility easily checks algebraically, its physical content may be obscure. Its first requirement, that $\epsilon(\tau + \Delta\tau) = \tau$, is obviously required if the calibrator is to mimic the sky; that is, if t^{cal} is to equal t^{sky} . The constraints on the distribution functions guarantee that the signal intercepts, Z , are also the same. Physically, this is a requirement that the regions of $4\pi A[1 - \epsilon(\tau + \Delta\tau)]$ separated by solid lines in Figure 22d be identically subdivided among the sources of internal radiation. These, though, are inherently distinct throughputs. For example, the $1 - \tau$ fraction of $4\pi A$ includes modes never passing through the antenna, while the $(1 - \epsilon)(\tau + \Delta\tau)$ fraction contains modes always coming down the antenna, but now partially filled by reflection from the calibrator.⁵ If the optical paths between the calibrator and detector are not highly lossy,

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⁵Figures 22c and 22d are deceptive in this regard. The fraction, $(1 - \epsilon)(\tau + \Delta\tau)$ is not a particular set of modes entirely reflected by the calibrator, but approximately a portion $1 - \epsilon$ of each mode in $4\pi A(\tau + \Delta\tau)$.

this latter, reflected fraction should be more likely to originate at the detector than the $1 - \tau$ fraction. The possibility that these fractions all have identical distribution functions can not be assumed.

The most important consequence of Equation (20) is that a development parallel to that in Equations (8) and (9) [or (16) and (17)] no longer suffices to solve for $F^{\text{sky}}(\nu)$. One can construct a similar linear plot of S^{cal} versus $B(T_{\text{cal}})$; that is, Equation (10) holds, but with

$$t^{\text{cal}}(\nu) = 4\pi R \epsilon (\tau + \Delta\tau) \quad (21)$$

and

$$\begin{aligned} Z^{\text{cal}}(\nu) = & 4\pi R [(1 - \tau)f_0 - g_0 - \Delta\tau m_0 + (1 - \epsilon)(\tau + \Delta\tau)n_0] B(T_0) \\ & + 4\pi R [(1 - \tau)f_d - g_d - \Delta\tau m_d + (1 - \epsilon)(\tau + \Delta\tau)n_d] B(T_d) \\ & + 4\pi R [(1 - \tau)f_l - g_l - \Delta\tau m_l + (1 - \epsilon)(\tau + \Delta\tau)n_l] I(T_l). \end{aligned} \quad (22)$$

It is not enough to have $t^{\text{cal}} = t^{\text{sky}}$, that is, have $\epsilon(\tau + \Delta\tau) = \tau$. As we have just seen, we need more information to relate Z^{cal} and Z^{sky} ; we need to know about the distribution functions and about $I(\nu, T_l)$. These problems with a non-ideal calibrator will be discussed in more detail below.

2. APPLICATION TO OUR EXPERIMENT

The general model developed above can now be applied to individual experiments. For each specific experiment, the equations above must be integrated over the particular frequency response of the instrument. Additionally, the equations must often be reapplied for several different calibrators, each with different parameters.

The first specific experiment we discuss is our own, described in Section C. In our calibration, we use three calibrators. Two of these, our laboratory calibrator and our ambient calibrator, are ideal. For these, Equations (14) and (15) apply directly. The third, our internal calibrator, may also be ideal, but we will not require it to be so. While we will also retain $I(T_1)$ in our equation for generality, we eventually conclude that the role it plays in our experiment is insignificant.

The addition of our internal calibrator is easily incorporated into this model. When the beam switch in our instrument is facing the internal calibrator, we consider it as a second radiometer, one which can never view a far-distant object, but only its calibrator. Since the chopper and detector remain unchanged, the g 's, $R(\nu)$, and $A(\nu)$ do not change. Also, T_1, T_0 , and T_d are unchanged. Finally, the original $\tau(\nu)$ can be maintained by redefining a new correction, $\Delta\tau'(\nu)$. The other terms all may change from the values looking up at the sky, and so are primed below. The signal from the internal calibrator may then be written

$$\begin{aligned} S^{icall}(\nu) = & 4\pi AR\epsilon'(\tau + \Delta\tau')B(T_{ical}) \\ & + 4\pi AR[(1 - \tau)f_0' - g_0 - \Delta\tau'm_0' + (1 - \epsilon')(\tau + \Delta\tau')n_0'] B(T_0) \\ & + 4\pi AR[(1 - \tau)f_d' - g_d - \Delta\tau'm_d' + (1 - \epsilon')(\tau + \Delta\tau')n_d'] B(T_d) \\ & + 4\pi AR[(1 - \tau)f_1' - g_1 - \Delta\tau'm_1' + (1 - \epsilon')(\tau + \Delta\tau')n_1'] I'(T_1). \end{aligned} \quad (23)$$

Again, this can be rewritten

$$S^{icall}(\nu) = t^{icall}B(T_{ical}) + z^{icall} \quad (24)$$

where

$$t^{cal}(\nu) = 4\pi AR \epsilon'(\tau + \Delta\tau') \quad (25)$$

and

$$\begin{aligned} Z^{cal}(\nu) = & 4\pi AR[(1 - \tau)f_0' - g_0 - \Delta\tau'm_0' + (1 - \epsilon')(\tau + \Delta\tau')n_0'] B(T_0) \\ & + 4\pi AR[(1 - \tau)f_d' - g_d - \Delta\tau'm_d' + (1 - \epsilon')(\tau + \Delta\tau')n_d'] B(T_d) \\ & + 4\pi AR[(1 - \tau)f_1' - g_1 - \Delta\tau'm_1' + (1 - \epsilon')(\tau + \Delta\tau')n_1'] I'(T_1). \end{aligned} \quad (26)$$

Since this internal calibrator will only be used below as a transfer standard, this result will prove adequate.

Until now, this section has considered flux at a single frequency. With any spectrometer, these signals must be integrated over the instrumental resolution; in our case, over our filter bands. Fortunately, this integration can be accomplished with little change in the form of these equations. Integrating Equation (8) for a single filter yields

$$\begin{aligned} \langle S^{sky} \rangle &= \int_0^\infty S^{sky}(\nu) d\nu = \int_0^\infty t^{sky}(\nu) F^{sky}(\nu) d\nu + \int_0^\infty Z^{sky}(\nu) d\nu \\ &= \langle t^{sky} \rangle F^{sky}(\bar{\nu}) + \langle Z^{sky} \rangle. \end{aligned} \quad (27)$$

No frequency dependences have been suppressed. Rather, the shape of $t^{sky}(\nu)$ and $F^{sky}(\nu)$ has been used in the first term to define $\bar{\nu}$, and a single number $\langle t^{sky} \rangle$. The second term has simply been integrated to produce the number, $\langle Z^{sky} \rangle$. Similarly, Equation (9) produces

$$\langle S^{cal} \rangle = \langle t^{cal} \rangle B(\bar{\nu}, T_{cal}) + \langle Z^{cal} \rangle. \quad (28)$$

The $\bar{\nu}$ in Equation (28) is the same $\bar{\nu}$ as in Equation (27), if $F^{\text{sky}}(\nu) \approx B(\nu, T_{\text{cal}})$ and if $\epsilon(\nu)$ and $\Delta\tau(\nu)$ are not rapidly changing. If $\epsilon(\nu) \approx 1$ and $\Delta\tau(\nu) \approx 0$, we must also have $\langle t^{\text{cal}} \rangle = \langle t^{\text{sky}} \rangle$ and $\langle Z^{\text{cal}} \rangle = \langle Z^{\text{sky}} \rangle$ [see Equations (16) and (17) and the discussion following].

In our experiment, $\bar{\nu}$ can be calculated given $t^{\text{sky}}(\nu)$, the measured system spectral response for each filter, described previously, and an approximate shape for $F^{\text{sky}}(\nu)$ and $B(\nu, T_{\text{cal}})$ in the filter pass-band. These approximate shapes can both be taken as Planck functions, for any calibrator with $\epsilon(\nu) \approx 1$ and $\Delta\tau(\nu) \approx 0$, and also for $F^{\text{sky}}(\nu)$, given the result of Woody and Richards (1981).

Two points must be emphasized in interpreting Equations (27) and (28). First, $\bar{\nu}$ is a slowly varying function of T_{cal} . The value of $\bar{\nu}$, for a given filter, will be independent of T_{cal} as long as the peak of $B(\nu, T_{\text{cal}})$ is well above the pass-band. As the temperature falls, the peak will move to frequencies below the pass-band, and $\bar{\nu}$ will also fall. This effect is calculable and is included in the analysis below. The second point is that $\langle Z^{\text{sky}} \rangle$, $\langle Z^{\text{cal}} \rangle$, and $\langle Z^{\text{ical}} \rangle$ all clearly depend on T_0 , T_d , and T_1 , and should be determined as functions of these temperatures.

Our calibration procedure can now be described fully. Three calibrators are used: the laboratory calibrator, ambient calibrator, and internal calibrator. For each filter, the laboratory calibrator is used before a balloon flight to relate the internal calibrator parameters, $\langle t^{\text{ical}} \rangle$ and $\langle Z^{\text{ical}} \rangle$, to $\langle t^{\text{sky}} \rangle$ and $\langle Z^{\text{sky}} \rangle$. During the flight, these relationships, with observations of the internal and ambient calibrators, allow us to find $F^{\text{sky}}(\bar{\nu})$ for each filter.

The equations for the sky signal and these three calibrator signals are

$$\langle S^{\text{sky}} \rangle = \langle t^{\text{sky}} \rangle F^{\text{sky}}(\bar{\nu}) + \langle Z^{\text{sky}} \rangle \quad (27)$$

$$\langle S^{\text{cal}} \rangle = \langle t^{\text{cal}} \rangle B(\bar{\nu}, T_{\text{cal}}) + \langle Z^{\text{cal}} \rangle \quad (28)$$

$$\langle S^{\text{amb}} \rangle = \langle t^{\text{amb}} \rangle B(\bar{\nu}, T_{\text{amb}}) + \langle Z^{\text{amb}} \rangle \quad (29)$$

$$\langle S^{\text{ical}} \rangle = \langle t^{\text{ical}} \rangle B(\bar{\nu}, T_{\text{ical}}) + \langle Z^{\text{ical}} \rangle. \quad (30)$$

Since our ambient and laboratory calibrators are ideal, we know

$$\langle t^{\text{amb}} \rangle = \langle t^{\text{lab}} \rangle = \langle t^{\text{sky}} \rangle \text{ and } \langle Z^{\text{amb}} \rangle = \langle Z^{\text{lab}} \rangle = \langle Z^{\text{sky}} \rangle.$$

The importance of the laboratory calibrator will be in its ability to reach low T_{cal} , so as to accurately determine $\langle Z^{\text{cal}} \rangle (= \langle Z^{\text{sky}} \rangle)$.

Its measurements will fix two parameters,

$$u = \frac{\langle t^{\text{cal}} \rangle}{\langle t^{\text{ical}} \rangle} = \frac{\langle t^{\text{sky}} \rangle}{\langle t^{\text{ical}} \rangle} \quad (31)$$

$$w = \frac{\langle Z^{\text{cal}} \rangle}{\langle Z^{\text{ical}} \rangle} = \frac{\langle Z^{\text{sky}} \rangle}{\langle Z^{\text{ical}} \rangle}. \quad (32)$$

These parameters, with $\langle S^{\text{sky}} \rangle$, $\langle S^{\text{amb}} \rangle$, $\langle S^{\text{ical}} \rangle$, T_{amb} , and T_{ical} , all measured in-flight, allow several solutions for $F^{\text{sky}}(\bar{\nu})$.

In essence, our calibration procedure overdetermines this model.

Equations (27) through (30) are a system of four equations with now only one unknown, $F^{\text{sky}}(\bar{\nu})$. We will use one solution here

$$F^{\text{sky}}(\bar{\nu}) = \frac{B(\bar{\nu}, T_{\text{amb}}) - \frac{w}{u} B(\bar{\nu}, T_{\text{ical}})}{\langle S^{\text{amb}} \rangle - w \langle S^{\text{ical}} \rangle} [\langle S^{\text{sky}} \rangle - w \langle S^{\text{ical}} \rangle] + \frac{w}{u} B(\bar{\nu}, T_{\text{ical}}). \quad (33)$$

This equation has two simple limits. First, if $w = u = 1$ and $\langle S^{\text{sky}} \rangle = \langle S^{\text{ical}} \rangle$, then $F^{\text{sky}}(\bar{\nu}) = B(\bar{\nu}, T_{\text{ical}})$, as expected. Second, if T_{ical} goes to zero, taking $B(\bar{\nu}, T_{\text{ical}})$ to zero, then $\langle S^{\text{ical}} \rangle = \langle Z^{\text{ical}} \rangle$. In this case, the two $w \langle S^{\text{ical}} \rangle$ terms only subtract the signal intercepts, $\langle Z^{\text{sky}} \rangle$, from the signals, $\langle S^{\text{sky}} \rangle$ and $\langle S^{\text{amb}} \rangle$. The ratio of $\langle S^{\text{amb}} \rangle - w \langle S^{\text{ical}} \rangle$ to $B(\bar{\nu}, T_{\text{amb}})$ is now the system responsivity, which, when divided into $\langle S^{\text{sky}} \rangle - w \langle S^{\text{ical}} \rangle$, yields the sky flux.

Since actual laboratory values for $\langle t^{\text{sky}} \rangle$ and $\langle Z^{\text{sky}} \rangle$ will be available, a solution could also be written

$$F^{\text{sky}}(\bar{\nu}) = \frac{\langle S^{\text{sky}} \rangle - \langle Z^{\text{sky}} \rangle}{\langle t^{\text{sky}} \rangle}. \quad (34)$$

The virtue of Equation (33) lies in its partial independence of $R(\nu)$. Any multiplicative change in $R(\nu)$ constant within a filter pass-band, taking $R(\nu)$ to $\alpha R(\nu)$, has the same effect on $\langle t^{\text{sky}} \rangle$ and $\langle t^{\text{ical}} \rangle$, $\langle Z^{\text{sky}} \rangle$ and $\langle Z^{\text{ical}} \rangle$. The ratios u and w remain unchanged. Still, Equation (34) and the analogous measured fluxes,

$$F^{\text{ical}}(\bar{\nu}) = \frac{\langle S^{\text{ical}} \rangle - \langle Z^{\text{ical}} \rangle}{\langle t^{\text{ical}} \rangle} \quad (35)$$

and

$$F^{\text{amb}}(\bar{\nu}) = \frac{\langle S^{\text{amb}} \rangle - \langle Z^{\text{sky}} \rangle}{\langle t^{\text{sky}} \rangle}, \quad (36)$$

are of use to us.

Relationships, such as those in Equations (35) and (36), use the overdetermination produced by our calibration procedure to test our model. Internal consistency obviously would increase confidence in the final results, but inconsistencies can allow us to diagnose how the model has failed. Most easily imagined failure modes have clear signatures.

One such example would be some cold beam obstruction during flight. This failure mode includes ice or other objects in our antenna. The primary effect on the model would be a decrease in u , the ratio of the $\langle t \rangle$'s. Such a change would force

$$\frac{F^{amb}(\bar{v})}{F^{ical}(\bar{v})} < \frac{B(\bar{v}, T_{amb})}{B(\bar{v}, T_{ical})}$$

for all filters. Unless the effect of such failure on u could be accurately modeled, reliable values for $F^{sky}(\bar{v})$ could not be obtained.

Another failure mode of our model would be a filter failure. The experiment is particularly sensitive to increased high frequency leakage. This would change $t^{sky}(\bar{v})$, and so $\langle t^{sky} \rangle$ and $\bar{v}$. The most vulnerable components of our filters are the multilayer, evaporated, metal meshes. A failure there would be restricted to one filter band. Any increase in transmittance at high frequencies would increase $F^{amb}(\bar{v})$ much more than $F^{ical}(\bar{v})$ since $T_{ical} \ll T_{amb}$. Here then, we would see

$$\frac{F_{\text{amb}}(\bar{\nu})}{F_{\text{cal}}(\bar{\nu})} > \frac{B(\bar{\nu}, T_{\text{amb}})}{B(\bar{\nu}, T_{\text{cal}})}.$$

Since this failure would be restricted to the one, failed band, we could identify the failure mode and disregard that band.

Another failure mode is a change during flight in the signal intercept flux. This could be produced by changes during flight in τ , $\Delta\tau'$, ϵ' , or the distribution functions, f_i , g_i , f'_i , m'_i , or n'_i . These, however, would involve changes in the internal geometry or composition of the apparatus, which are likely to be observed directly before flight. We do not expect these changes during flight.

The signal intercepts are also functions of T_0 , T_d , and T_1 . These temperatures will change during the flight as functions of time and perhaps even zenith angle. The temperatures T_0 and T_d are well-defined, and the dependence of the signal intercepts, $\langle Z^{\text{sky}} \rangle$ and $\langle Z^{\text{cal}} \rangle$, on T_0 and T_d can be measured in the laboratory. Both temperatures will be recorded during flight. Changes in T_1 , and so in $I(\nu, T_1)$, are also certain in flight and are hard to simulate in the laboratory. As discussed, all evidence of $I(\nu, T_1)$ has been eliminated by extensive, cold, $\sim T_0$, baffling around all connections and shafts from warm parts of the cryostat.

The presence of a large leakage term can be detected in the signal offset, $\langle Z \rangle$. In our 7, 9, and 10 cm^{-1} filters, little signal should be present from either a $T_0 = 1.7 \text{ K}$ or $T_d = 0.3 \text{ K}$ blackbody. As T_{cal} is taken to zero, no signals are observed in the laboratory. The signal offsets are close to estimates of a T_0 plus T_d signal. If they

also change appropriately as T_0 and T_d vary in the lab, with $I(\nu, T_1)$ unchanging, we will finally conclude our leakage is unimportant.

A non-ideal laboratory calibrator would constitute another failure mode of sorts. In general, it is not possible to correct for this. Our solution is to use only ideal laboratory calibrators, black [$\epsilon(\nu) = 1$] and well-matched [$\Delta\tau(\nu) = 0$]. These properties will be checked by direct laboratory comparison to a warmer, large blackbody above the optics where it is easier to achieve $\Delta\tau(\nu) = 0$ and $\epsilon(\nu) = 1$. Also, the properties of our calibrators have been estimated in Section C and should suffice.

The problems created by a non-ideal calibrator can be understood using our model. If $\epsilon(\nu)$ and $\Delta\tau(\nu)$ of such a non-ideal calibrator were approximately constant within a filter pass-band, we could write $\epsilon(\nu) = \epsilon_0$ and $\tau(\nu) + \Delta\tau(\nu) = \bar{\alpha}\tau(\nu)$. Then at least the value of $\bar{\nu}$ would remain unmodified. Equation (28) would still be valid, but with $\langle t^{\text{cal}} \rangle \neq \langle t^{\text{sky}} \rangle$ and $\langle Z^{\text{cal}} \rangle \neq \langle Z^{\text{sky}} \rangle$. The experimental values of u and w could not then be used to infer $\langle t^{\text{sky}} \rangle$ and $\langle Z^{\text{sky}} \rangle$; they would each require a correction.

One correction, that for u , the ratio of the $\langle t \rangle$'s, is straightforward. A ratio of $\langle t^{\text{sky}} \rangle$ to $\langle t^{\text{lab}} \rangle$ can be obtained by comparing a hot, laboratory calibrator with a large, warm box, such as the room. In this limit, $\langle Z^i \rangle \ll \langle t^i \rangle B(\nu, T_i)$.

The correction to w , the ratio of the $\langle Z \rangle$'s, is more difficult. As implied by a comparison of Equations (17) and (22), this correction requires knowledge of both the distribution functions and any leakage present.

A final failure mode, easily imaginable, is a change in responsivity during flight. Gain changes, taking $R(\nu)$ to $\alpha R(\nu)$, have been suggested for other experiments (Weiss, 1980). As noted above in discussing Equation (33), this will not affect our measurement. While the fluxes predicted by Equations (35) and (36) will not individually match the appropriate Planck functions for each filter, we would find

$$\frac{F_{\text{amb}}(\bar{\nu})}{F_{\text{ical}}(\bar{\nu})} = \frac{B(\bar{\nu}, T_{\text{amb}})}{B(\bar{\nu}, T_{\text{ical}})}.$$

The characteristic signature of this equality would identify a gain change, and we could report the flux from Equation (33) with confidence.

3. APPLICATION TO OTHER EXPERIMENTS

Our algebraic model has allowed us to describe our calibration procedure and to discuss some of its possible failure modes. Other experiments to measure the spectrum of the cosmic background radiation in the same frequency range have previously been attempted and have similar calibration procedures. As noted above, the nature of the experiment requires a low-temperature spectrometer above much of the atmosphere. In all experiments so far reported, the fundamental calibrator has been a cold absorber in the neck of the antenna and has only been used in the laboratory. Our algebraic model can be applied to these experiments to examine their calibration procedures.

In particular, aspects of both the rocket-borne experiment of Professor Gush (Gush, 1981) and our group's earlier experiment (Woody and Richards, 1979, 1981) can be examined with this model.

The rocket-borne experiment has a flawed calibration procedure. First, there is evidence for significant leakage flux, $I(\nu, T_1)$. Also, the flight conditions were difficult to simulate in the laboratory during calibration. Most critically, the laboratory calibrator used was not ideal.

The design of this experiment differs from our experiment in several details. First, there is no chopper. Rather, the spectrometer is a rapid-scan, interference modulator. This interferometer thus combines the frequency-selective role of our filters with the chopping necessary for bolometric detectors. While eliminating the chopper and filter wheel shafts, this design requires a mirror drive. Like our apparatus, the rocket-borne instrument uses a bolometric detector at ~ 0.3 K, but the temperature of its spectrometer is higher, 3.3 K.

Professor Gush's instrument was calibrated in much the manner of our model. A low-temperature calibrator was placed in the antenna, and its spectrum was measured. An internal absorber could be moved to fill the beam and so could play the role of our internal calibrator. The first flaw, the presence of leakage flux, can be inferred from the published data. Spectra of the laboratory calibrator at various temperatures are reproduced in our Figure 23 (Gush, 1982). The different curves, a to k, correspond to different calibrator temperatures, ranging from 4.215 K for a to 1.812 K for k. The apparatus was at 4.2 K for these measurements. The curves show negative response. This is due to a large positive signal when the spectrometer is most reflective. This corresponds to our "chopper closed" condition. We believe

Fig. 23. Calibration Spectra from Gush's Instrument.

this negative response is due to leakage radiation filling much of the throughput of the detector in this condition. A warm neck in the antenna could provide such a source, particularly with the reflective calibrator used (see below, page 102). Also, such radiation could enter the spectrometer along drive shafts or wiring tubes. Leakage radiation would naturally provide a spectrum with significant power above 10 cm^{-1} .

More spectra are presented in the next figure. The measured sky spectrum, the shaded area, and the final calibration spectrum, the dashed line, are plotted in Figure 24 (Gush, 1982). The instrument was at 3.3 K. Professor Gush writes, "Note that this curve [the calibrator spectrum] bears little resemblance to a Planck curve, because the detector signal arises only because of differences in emissivity of the various optical components in the interferometer, and the calibrator" (Gush, 1982).

Such an interpretation, i.e., without leakage, requires peculiar performance of the interferometer. To give a large negative signal requires much of the throughput of the detector to originate at the highest temperature, T_0 , when the interferometer is most reflecting, yet originate at a much lower temperature, presumably $T_d \sim 0.3\text{ K}$, when the interferometer is transmitting. Most interferometers do the opposite. That is, the throughput of the detector would normally be most filled by the detector itself, seen in reflection, when the interferometer just above it is most reflective. Furthermore, this strangely-distributed throughput would need to be larger than that originating at the calibrator to produce Figure 24.

Fig. 24. Calibration and Sky Spectra from Gush's Instrument.

A final indication of leakage flux comes from comparing these two figures, assuming their vertical scales to be similar. Spectrum a in Figure 23 and the spectrum of the 3.3 K calibrator in Figure 24 both show the same detector response around 18 cm^{-1} . Yet T_O and T_{cal} were 4.2 K in Figure 23 and 3.3 K in Figure 24. The brightness of a black-body at 18 cm^{-1} falls by over a factor of 5 as the temperature goes from 4.2 K to 3.3 K. Another source of radiation is needed to keep the detector response constant.

Any such leakage flux is particularly bad in a rocket-borne experiment because of the second flaw; the flight conditions were not simulated in the laboratory. The rocket flight first heats the bath by vibration, then spins it during free fall, while venting it to zero pressure. Not only is T_O a rapidly changing function of time, but the new distribution of cryogens could change $I(\nu, T_1)$. Even if $Z^{\text{sky}}(\nu)$ could be obtained for laboratory conditions, it could be expected to change during the flight. Measurements of the internal calibrator during flight could, in principle, be used to check this.

The final flaw is the use of a non-ideal laboratory calibrator. In Gush (1982), the calibrator is said to fill the beam [$\Delta\tau(\nu) = 0$], but to have an emissivity of 0.61 [$= \epsilon(\nu)$]. Accepting these estimates, the calibrator is non-ideal. To understand the effect of this, we must understand Professor Gush's calibration procedure; that is, we must know what he assumes fills the reflected throughput. The fundamental equation he uses (Gush, 1982) becomes in our notation

$$S^{\text{sky}}(\nu) = t^{\text{sky}}(\nu) F^{\text{sky}}(\nu) + S^{\text{cal}}(\nu) - t^{\text{sky}}(\nu) B(\nu, T_{\text{cal}}). \quad (37)$$

To apply our model to this calibration procedure, our Equations (8) and (9) need not be integrated over frequency. We assume here all functions are essentially constant over the resolution of this instrument, so that Equations (8) and (9) can be directly used.

The signals from the rocket-borne instrument are then

$$S^{\text{sky}}(\nu) = t^{\text{sky}}(\nu) F^{\text{sky}}(\nu) + Z^{\text{sky}}(\nu) \quad (38)$$

and

$$S^{\text{cal}}(\nu) = t^{\text{cal}}(\nu) B(\nu, T_{\text{cal}}) + Z^{\text{cal}}(\nu). \quad (39)$$

The key issue in comparing Equations (37) and (38) is Professor Gush's form for $Z^{\text{sky}}(\nu)$.

To analyze his $Z^{\text{sky}}(\nu)$, we first interpret Figure 23 using Equation (39). Since curve a, with both the calibrator and apparatus at 4.2 K, is not identical to zero, we can immediately conclude that a single-temperature model can not apply. Some temperature difference must exist to produce a signal. This is confirmed by the calibrator spectrum in Figure 24, with both calibrator and apparatus at 3.3 K. Equations (38) and (39) can still apply, but for t and Z we must use a multi-temperature model.

As we have seen in our discussion of a non-ideal, laboratory calibrator as a failure mode of our experiment, two corrections are now needed. The correction taking t^{cal} to t^{sky} can be developed, since $\epsilon(\nu)$ and $\Delta T(\nu)$ are known. Presumably that was done in his estimation of $t^{\text{sky}}(\nu)$ in Equation (37). The intercept correction, taking Z^{cal} to Z^{sky} , is harder; knowledge of both new distribution functions and leakage is required. The limit of these spectra in Figure 23, as T_{cal} goes to zero, toward k , is a plot of Z^{cal} versus ν (σ in these plots).

This signal intercept, Z^{cal} , is large and negative, and so can not be ignored. Without knowledge of what sources fill the fraction $(1-\epsilon)\tau$ of $4\pi A$ in Equation (22), the fraction reflected by the calibrator, the change from this Z^{cal} to Z^{sky} can not be derived.

Professor Gush's procedure, our Equation (37), assumes

$$Z^{\text{sky}}(\nu) = S^{\text{cal}}(\nu) - t^{\text{sky}}(\nu)B(\nu, T_{\text{cal}}) \quad (40)$$

where $T_{\text{cal}} = T_0 = 3.3$ K. In terms of our model, he is assuming the distribution functions for this fraction $(1-\epsilon)\tau$. Specifically, our Equations (16), (17), and (20) show he is assuming

$$B(\nu, T_{\text{cal}}) = n_0(\nu)B(\nu, T_0) + n_d(\nu)B(\nu, T_d) + n_l(\nu)I(\nu, T_l). \quad (41)$$

These n_i are the distribution functions for the fraction $(1-\epsilon)\tau$ of $4\pi A$. Since $T_{\text{cal}} = T_0$, Professor Gush's procedure is equivalent to assuming $n_0(\nu) = 1$ and so $n_d(\nu) = n_l(\nu) = 0$.

This distribution is true in a single-temperature system, but as we have seen, the rocket-borne instrument is a multi-temperature system. Moreover, the deviations from a single-temperature model, as indicated by the 3.3 K calibration spectrum, are comparable to the measured sky signal. Finally, the reflected fraction, $(1-\epsilon)\tau$ of $4\pi A$, is comparable to $4\pi A\tau$. The total deviation from a single-temperature model should be significant. The contrary assumption that $n_0(\nu) = 1$ needs justification.

Professor Gush seems to be aware of this problem. In Gush (1982), he writes, "The above equation [our Equation (38)] would be invalidated if the spectrum of the known source contained a contribution of reflected radiation from the interferometer itself, which the unknown spectrum did not contain." We feel it indeed must contain such flux.

The enormous effort represented by this single-handed experiment must be admired. However, we do not feel its results can be accepted. Only with an ideal laboratory calibrator and the elimination of leakage radiation, can Professor Gush's experiment produce the first measurements of the cosmic background radiation above 10 cm^{-1} .

The calibration of our group's earlier experiment can also be examined with this model. The earlier experiment had a Martin-Puplett interferometer instead of our filter wheel. The polarizing chopper took the place of our Mylar chopper. The same detector and antenna structure were used.

That experiment also relied on a laboratory calibrator in the antenna, but had no calibration during flight. The interferometer used was effectively a single-temperature instrument. Although it also had the 0.3 K detector, the low efficiency of the interferometer insured $f_0(\nu) = g_0(\nu) = 1$, reducing the multi-temperature model to a single-temperature one. In this limit, Equation (6) again applies, rewritten here as Equation (42)

$$S^{\text{cal}} = 4\pi A R_e [\tau + \Delta\tau] [B(T_{\text{cal}}) - B(T_0)]. \quad (42)$$

Now, $T_0 \approx 1.7 \text{ K}$. Again, we assume here that all the functions of ν are averaged over the resolution of the instrument, but that, keeping this in mind, Equation (42) directly applies.

Figure 25 is reproduced from Woody and Richards (1981). As with the rocket experiment, the solid-line spectra are measured calibrator signals. Here, though, there is no evidence of any leakage flux. In fact, the dashed-line spectra are predicted curves, calculated using

Fig. 25. Calibration Spectra From Woody and Richards's Instrument.

Equation (42), with the 20.14 K curve determining $4\pi AR\epsilon[\tau + \Delta\tau]$. No evidence of a multi-temperature system can be seen.

Still the possibility remains that the calibrator is non-ideal. This was discussed above as a failure mode for our current experiment. Here it is equivalent to misestimating $t^{\text{sky}}(\nu)$. Notice that it is not possible to estimate $\frac{\epsilon[\tau + \Delta\tau]}{\tau}$ from these spectra alone; the development claiming this in Appendix A of Woody and Richards (1981) is incorrect (Woody and Richards, 1982).

The ideality of a laboratory calibrator should be checked by comparing it to a calibrator known to be both black and well-matched. The match between the laboratory calibrator and the antenna was compared to the match of the sky and antenna by using the surrounding room to simulate the sky. The resulting instrumental response spectra are shown in Figure 20, page 71 (Woody and Richards, 1981). Their detailed similarity in fine structure strongly indicates that $\Delta\tau(\nu)$ can be assumed to be zero to an accuracy of a few percent; the same modes filled by the room are filled by the laboratory calibrator. Furthermore, their similar overall shapes indicate no large frequency dependence in $\epsilon(\nu)$, i.e., $\epsilon(\nu) = \epsilon_0$. Unfortunately, they cannot be used to determine the value of ϵ_0 . The large correction for the change in detector response when viewing the 300 K room is too uncertain.

As the earlier experimenters have pointed out, a constant percentage change in this response curve during flight would allow their data to fit a 2.79 K blackbody (Woody and Richards, 1979). This fit

would also be obtained if the laboratory calibrator had an $\epsilon(\nu) = \epsilon_0 \approx 0.79$. They have estimated this emissivity. Their calculation provides an estimate of $\epsilon(\nu)$ very near unity throughout this spectral range.

No direct experimental verification of this calculation is available. Indirect support is provided by the overall close agreement between the measured and the calculated atmospheric O_2 line spectra (Woody and Richards, 1981). The O_2 lines are used to provide a calibration during flight, checking the emissivity of the laboratory calibrator. Unlike the continuum calibrations we have discussed previously, these lines are very narrow, with widths less than 0.001 cm^{-1} , and so probe $t^{\text{sky}}(\nu)$ on a much finer scale than the 0.13 cm^{-1} instrumental resolution. It is thus difficult to determine the true t^{sky} , averaged over the line width, from the measured $t^{\text{cal}}(\nu)$, with its coarser resolution. Consequently, the O_2 line spectra cannot be considered a definitive calibration.

Recent measurements of the pressure-broadening of O_2 (Pickett, Cohen, and Brinza, 1981) do not affect the above arguments. If used to calibrate the instrument, the measurements imply $\frac{\epsilon[\tau + \Delta\tau]}{\tau} \sim 1.11$ at the line positions. This ratio would further increase the discrepancy between the reported sky spectrum and a $\sim 2.7 \text{ K}$ blackbody.

The value, 1.11, is approximate. The precise correction depends on the method of combining the pressure-broadening and Zeeman splitting effects. All simple approximations to this combination, even the

extreme case of neglecting the Zeeman splitting entirely, increase the discrepancy.

Since Woody and Richards's balloon-borne experiment could not be calibrated during flight, any constant factor change in $R(\nu)$ by $\sim 30\%$ would also allow the data to fit a blackbody. In Equation (42), describing this single-temperature instrument, a change in $R(\nu)$ or $A(\nu)$ is equivalent to using a non-ideal calibrator. The possibility of such an unexplained and unexpected change can only be experimentally tested by the O_2 line strength arguments sketched above.

Our model has allowed us to critically examine not only our calibration, but also that of similar experiments. In a sense, this calibration model only applies the basic principles of radiometry to this experiment. William L. Wolfe has written of radiometry,

A calibration is usually a measurement made under known and controlled conditions. The first rule of measurement is to make it under conditions as much like those of the calibration as possible. The next is similar: Account for the differences. A radiometer used for a radiometric measurement in general is affected by the position of focus on the detector; the angle from which it comes; the temporal, spectral, spatial, and polarization properties of the radiation; the nature of the background; the temperature of the instrument; and in some cases the phase of the moon. Certainly atmospheric transmission can have a profound effect. As many of the parameters and variables as possible should be eliminated by calibration and the effects of the rest should be considered very carefully.

(Wolfe, 1981)

The value of our treatment lies in the resulting emphasis on using only ideal calibrators and on eliminating any leakage radiation, that is, any radiation which may vary irreproducibly during the measurement. Only if those requirements are satisfied, does a successful experiment seem possible.

E. ATMOSPHERIC SUBTRACTION

The calibration procedure, described in the previous section, converts the signal of the detector to an equivalent brightness flux. That is not yet a measurement of the flux of the cosmic background radiation. The contribution of the atmosphere is significant and must be removed.

An estimate of the atmospheric contribution to our signal has been made (Bonomo et al., 1982). The atmospheric model from our previous experiment was used (Woody, 1975). Table III lists the atmospheric flux for each filter band as a fraction of a 3 K blackbody. These signals should be proportional to the column density of molecules and so to the secant of the zenith angle, since most of the atmospheric lines are unsaturated. A few partially-saturated O_2 lines do contribute, and the signal from these would vary somewhere between $\sec \theta$ and $\sqrt{\sec \theta}$. These contribute at most only 0.02 of the flux of a 3 K blackbody. Such small resulting curvature in a plot of signal versus secant θ would not be detectable in our experiment.

Our atmospheric subtraction procedure is to fit the fluxes obtained from equation (33) for each filter to

$$F_i^{sky}(\bar{v}) = C(\bar{v}) + B \sec \theta_i \quad (43)$$

where the index i runs over the set of zenith angles used. The intercept, $C(\bar{v})$, is the signal at zero air mass. That signal is our measurement of the flux from the cosmic background radiation.

Table III.

Center of filter band	Expected atmospheric signal as a fraction of the flux from a 3 K blackbody
3 cm^{-1}	0.01
5 cm^{-1}	0.02
7 cm^{-1}	0.07
9 cm^{-1}	0.31
10 cm^{-1}	0.47

F. ERROR ANALYSIS

In Section B, Experimental Design, we stated that a new measurement of this spectrum needed an accuracy of a few percent to be significant. Although the experiment remains to be done, we can make a realistic estimate of our accuracy.

Our approach to this estimate uses standard techniques (Bevington, 1969). If we desire an estimate of some quantity, x , which is a function of random variables $u, v, \dots$, where $x = f(u, v, \dots)$, then for our estimate, $\bar{x}$, we take $\bar{x} = f(\bar{u}, \bar{v}, \dots)$. For estimating the error in $\bar{x}$, we approximate its variance, σ_x^2 , by

$$\sigma_x^2 = \sigma_u^2 \left(\frac{\partial f}{\partial u} \right)^2 + \sigma_v^2 \left(\frac{\partial f}{\partial v} \right)^2 + 2\sigma_{uv}^2 \frac{\partial f}{\partial u} \frac{\partial f}{\partial v} + \dots$$

Here, σ_u^2 is the variance of u , σ_v^2 , of v , and σ_{uv}^2 is the covariance of u and v . Most of our covariances are zero. The variances are estimated from the standard deviations of sample populations.

This estimate of errors naturally divides into two parts: one involving the conversion from the measured signal to flux using Equation (33), and the other, the atmospheric correction of Equation (42). This latter may be quickly found, if we accept the method of least squares in fitting Equation (42). If we assume each point has the same signal variance, σ_c^2 , we find the variance of $C(\bar{v})$, σ_C^2 , is

$$\sigma_C^2 = \sigma^2 \frac{\sum_i (\sec \theta_i)^2}{N \sum_i (\sec \theta_i)^2 - (\sum_i \sec \theta_i)^2} + \sigma_{IJ}^2 \left\{ 1 - \frac{\sum_i (\sec \theta_i)^2}{N \sum_i (\sec \theta_i)^2 - (\sum_i \sec \theta_i)^2} \right\}. \quad (44)$$

The sums are over all observed θ_i , and σ_{IJ}^2 is the covariance for each pair of observations, which is assumed to be constant.

To evaluate this expression, we need to know the range of zenith angles. We choose here $\theta \geq 25^\circ$, to avoid emission from the balloon, and $\theta \leq 55^\circ$, to avoid earthshine. The secant then spans the range 1.1 to 1.75. If we further assume only the two end points are measured, Equation (43) becomes

$$\sigma_C^2 = 10.11 \sigma^2 - 9.11 \sigma_{IJ}^2. \quad (45)$$

The covariance, σ_{IJ}^2 , should be approximately equal in magnitude to σ^2 , since our errors are predominantly systematic, not statistical.

The interpretation of the minus sign in Equation (45) is straightforward; if $\sigma_{IJ}^2 = \sigma^2$, the measurements are positively correlated and would shift up and down together for different experiments in the ensemble of all possible experiments. Since that would not change the slope, the intercept $C(\bar{\nu})$ would have $\sigma_C^2 = \sigma^2$. If $\sigma_{IJ}^2 = -\sigma^2$, which is the other extreme, then $\sigma_C^2 \approx 20 \sigma^2$. In this case, the two measured fluxes shift oppositely as we explore the ensemble of experiments. This pivots the line and greatly increases the variance of $C(\bar{\nu})$, in this example by a factor twenty. Here, we will pessimistically assume this latter case.

Reducing this factor of twenty is certainly desirable. This estimate of σ_C^2 is not substantially affected if three zenith angles are measured. To reduce the numerical factor significantly requires extending the range of $\sec \theta$. While the available range of zenith angle is limited, Equation (42) is properly a fit versus air mass. We could vary the altitude of the balloon so as to expand the range. If the effective range could be expanded to the equivalent of a secant range from 1.1 to 4, then the two end points fix $\sigma_C^2 = 3.1\sigma^2$.

The difficulty with this procedure is in varying the altitude of the balloon slowly. If the internal temperatures of the instrument are varying with pressure, and thus altitude, while a single measurement is being done, then the conversion of the signal to flux is confused. This probably rules out measurements during the ascent. During the floating period near maximum altitude, a slow fall in altitude could significantly extend the range, but will require a change in flight procedure at the balloon launching facility.

Another possibility has been suggested—ignore the extrapolation to zero air mass, at least for the filters at 3, 5, and 7 cm^{-1} , where little atmospheric signal should be seen. While plausible, and probably accurate, our experiment then becomes dependent on the atmospheric model of our previous experiment.

In the worst case, the extrapolation to zero air mass would multiply our variance by twenty. That increases our probable error by a factor of $\sqrt{20} \approx 4.5$. An estimate of σ is needed to see if the accuracy we wanted could then be reached.

That decision requires an error analysis of Equation (33), here rewritten as Equation (46)

$$F^{\text{sky}}(\bar{v}) = \frac{B(\bar{v}, T_{\text{amb}}) - \frac{w}{u} B(\bar{v}, T_{\text{ical}})}{\langle S^{\text{amb}} \rangle - w \langle S^{\text{ical}} \rangle} [\langle S^{\text{sky}} \rangle - w \langle S^{\text{ical}} \rangle] + \frac{w}{u} B(\bar{v}, T_{\text{ical}}) \quad (46)$$

To apply the method to Equation (46), we need the partial derivative of $F^{\text{sky}}(\bar{v})$ with respect to each random variable and an estimate of the value and variance of each variable. The random variables for each filter are $\langle S^{\text{sky}} \rangle$, $\langle S^{\text{amb}} \rangle$, $\langle S^{\text{ical}} \rangle$, T_{amb} , T_{ical} , $\bar{v}$, u , and w .

Fortunately, the covariances of these quantities are generally negligible. This point needs some discussion for $\langle S^{\text{amb}} \rangle$, $\langle S^{\text{sky}} \rangle$, and $\langle S^{\text{ical}} \rangle$. An uncertainty in our gain, causing a change of $R(v)$ to $\alpha R(v)$, would effect these in a highly correlated manner. We do not include such effects in their variances. If we did, covariances would be needed, but they would only cancel the contributions from this effect, much as the minus sign in Equation (45) can cause a cancellation there. This is due to the independence of Equation (33) on gain, as is discussed in Section D.

The partial derivatives are straightforward. Let us define two ratios

$$Q = \frac{B(\bar{v}, T_{\text{amb}}) - \frac{w}{u} B(\bar{v}, T_{\text{ical}})}{\langle S^{\text{amb}} \rangle - w \langle S^{\text{ical}} \rangle} \quad (47)$$

$$q = \frac{\langle S^{\text{sky}} \rangle - w \langle S^{\text{ical}} \rangle}{\langle S^{\text{amb}} \rangle - w \langle S^{\text{ical}} \rangle} \quad (48)$$

Then we find

$$\frac{\partial F^{\text{sky}}}{\partial S^{\text{sky}}} = Q \quad (49)$$

$$\frac{\partial F^{\text{sky}}}{\partial S^{\text{amb}}} = Qq \quad (50)$$

$$\frac{\partial F^{\text{sky}}}{\partial S^{\text{ical}}} = -wQ [1 + q] \quad (51)$$

$$\frac{\partial F^{\text{sky}}}{\partial T^{\text{amb}}} = q \frac{\partial B(\bar{v}, T^{\text{amb}})}{\partial T^{\text{amb}}} \quad (52)$$

$$\frac{\partial F^{\text{sky}}}{\partial T^{\text{ical}}} = \frac{w}{u} [1 - q] \frac{\partial B(\bar{v}, T^{\text{ical}})}{\partial T^{\text{ical}}} \quad (53)$$

$$\begin{aligned} \frac{\partial F^{\text{sky}}}{\partial \bar{v}} &= q \frac{\partial B(\bar{v}, T^{\text{amb}})}{\partial \bar{v}} + \\ &+ \frac{w}{u} (1 - q) \frac{\partial B(\bar{v}, T^{\text{ical}})}{\partial \bar{v}} \end{aligned} \quad (54)$$

$$\frac{\partial F^{\text{sky}}}{\partial u} = -\frac{w}{u^2} [1 + q] B(\bar{v}, T^{\text{ical}}) \quad (55)$$

and

$$\frac{\partial F^{\text{sky}}}{\partial w} = \frac{1}{u} [1 - q] B(\bar{v}, T^{\text{ical}}) - [1 + q] Q \langle S^{\text{ical}} \rangle. \quad (56)$$

To apply these expressions, we need to calculate the variances σ_u^2 and σ_w^2 . Again, applying Equation (43) to Equations (31) and (32), which define u and w , we find

$$\sigma_u^2 = \left(\frac{\sigma_{t \text{ sky}}}{\langle t^{\text{ical}} \rangle} \right)^2 + \left(\frac{u \sigma_{t^{\text{ical}}}^{\text{ical}}}{\langle t^{\text{ical}} \rangle} \right)^2 \quad (57)$$

$$\sigma_w^2 = \left(\frac{\sigma_{z \text{ sky}}}{\langle z^{\text{ical}} \rangle} \right)^2 + \left(\frac{w \sigma_{z^{\text{ical}}}^{\text{ical}}}{\langle z^{\text{ical}} \rangle} \right)^2. \quad (58)$$

Our narrow spectral band-passes have simplified these equations.

Ordinarily, the averaging that produces $\bar{v}$ would require us to explicitly include the dependence of $\bar{v}$ on the assumed spectral shape. In our case, that would produce a dependence of $\bar{v}$ on T . But, this dependence disappears quickly enough as the filter band becomes narrower that we may neglect this effect.

This is not yet a complete error analysis. Some effects remain unmeasured: the dependences of u and w on zenith angle, and the saturation correction when viewing the ambient calibrator. The errors associated with these, if any, must be included in the final analysis.

The definite measurements of all these quantities will be made after the apparatus is in its final configuration. Preliminary results allow us to estimate these quantities in Table IV. Only the 7 cm^{-1} filter is presented for simplicity. The sky signal, $\langle S^{\text{sky}} \rangle$, has been assumed identical to $\langle S^{\text{ical}} \rangle$.

With these assumptions $q = 0$, so that our formal dependence on $\langle S^{\text{amb}} \rangle$ disappears. This does not effect our use of this signal to check failure modes in Section D; it is rather a consequence of our overdetermined model. With actual values for these parameters, $q \ll 1$, but finite. Entering numbers, we find that the remaining contributions are

Table IV.

Variable	Estimated Value	Estimated Variance
$\langle S^{\text{sky}} \rangle$	2.720 μV	$(0.01 \mu\text{V})^2$
$\langle S^{\text{amb}} \rangle$	1730 μV	$(3 \mu\text{V})^2$
$\langle S^{\text{ical}} \rangle$	2.720 μV	$(0.05 \mu\text{V})^2$
T_{amb}	250 K	$(2 \text{ K})^2$
T_{ical}	3 K	$(0.01 \text{ K})^2$
$\bar{\nu}$	7 cm^{-1}	$(0.03 \text{ cm}^{-1})^2$
w	1	$(0.01)^2$
u	1	$(0.01)^2$

$$\begin{aligned}
\sigma_F^{\text{sky}^2} = & 3.30326 \cdot 10^{-23} \left(\frac{\text{Brightness}}{\mu \text{ Volt}} \right)^2 \left(\sigma_{S^{\text{sky}}}^2 + \sigma_{S^{\text{ical}}}^2 \right) \\
& + 2.95359 \cdot 10^{-22} \left(\frac{\text{Brightness}}{\text{K}} \right)^2 \sigma_{T^{\text{ical}}}^2 \\
& + 9.90085 \cdot 10^{-25} \left(\frac{\text{Brightness}}{\text{cm}^{-1}} \right)^2 \sigma_{\frac{2}{v}}^2 \\
& + 2.20820 \cdot 10^{-22} (\text{Brightness})^2 \sigma_u^2 \\
& + 5.9090 \cdot 10^{-25} (\text{Brightness})^2 \sigma_w^2
\end{aligned} \tag{59}$$

$$\text{or } \sigma_{F^{\text{sky}}} = 2.364 \cdot 10^{-13} (\text{Brightness}) . \tag{60}$$

Brightness here is in units of $\text{W}/(\text{cm}^2 \text{ sr cm}^{-1})$. The limiting contributions to $\sigma_{F^{\text{sky}}}$ are $\sigma_{T^{\text{ical}}}$ and σ_u , the uncertainties in our internal calibrator temperature and in our ratio of $\langle t \rangle$'s. Since $F^{\text{sky}}(\bar{v}) \approx B(\bar{v}, T_{\text{ical}})$ by our assumptions, this fixes

$$\frac{\sigma_{F^{\text{sky}}}}{F^{\text{sky}}} = 0.016 . \tag{61}$$

We now must apply our extrapolation to zero air mass from Equation (45), making our predicted error $\sim 7\%$. If the performance in Table IV can be reached, our experiment can achieve the needed accuracy.

IV. CONCLUSION

Two different projects in far-infrared astrophysics have been described in this thesis. The first, the mountaintop photometer, aimed at expanding the range of objects studied in submillimeter astronomy. The other, the balloon-borne experiment, is meant to test the reported spectral deviations in the cosmic background radiation. These scientific aims are still of interest.

Only one is now being pursued in our group. Submillimeter astronomy from White Mountain did not offer our group a chance to rapidly advance the field. Apparently, other groups have had similar experiences and have reached the same conclusion. Future broad-band, submillimeter photometry should be done from airborne platforms. In contrast, the spectroradiometer experiment is still proceeding. Until the Cosmic Orbiting Background Explorer satellite is operational, a balloon remains the preferred platform for this measurement.

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The mountaintop photometer project was made possible by Dr. David Cudaback. Without his enthusiasm, the project would never have been begun.

The spectroradiometer project has been a group effort. Professor Thomas Timusk began the reconstruction and developed the filters. Jeff Peterson has done much subsequent work. The ideas and effort they provided have been essential to the progress of this experiment.

The actual writing of this thesis owes much to two other individuals. Audrey Richards supplied a much needed impetus. I thank her both for her careful advice and for her concern. Finally, I thank my wife, Janet Wainwright, for the patient backing I needed.

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