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Radiometer System to Map the Cosmic Background Radiation*

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ABSTRACT

We have developed a 33 GHz airborne radiometer system to map large-scale angular variations in the temperature of the 3°K cosmic background radiation. A ferrite circulator switches a room-temperature mixer between two antennas pointing 60° apart in the sky. In forty minutes of observing, the radiometer can measure the anisotropy of the microwave background with an accuracy of ± 1 m°K rms, or about one part in 3000 of 3°K. The apparatus is flown in a U-2 jet to 20 km altitude where 33 GHz thermal microwave emission from the atmosphere is at a low level. A second radiometer, tuned to 54 GHz near oxygen emission lines, monitors spurious signals from residual atmospheric radiation. The antennas, which have an extremely low side-lobe response of less than -65 dB past 60°, reject anisotropic radiation from the earth's surface. Periodic interchange of the antenna positions and reversal of the aircraft's flight direction cancel equipment-based imbalances. The system has been operated successfully in U-2 aircraft flown from NASA-Ames at Moffett Field, California.

INTRODUCTION

We have developed and tested an airborne radiometer to detect and map anisotropy of the 3°K cosmic blackbody radiation on a large angular scale. This radiometer represents a state-of-the-art improvement of the basic twin-antenna Dicke radiometer used by several groups$^{(1-4)}$ to set previous limits on the anisotropy.

Anisotropy in the background radiation of a few milli-degree Kelvin (m°K) should result from the motion of the solar system with respect to the 3°K cosmic blackbody radiation.$^{(5)}$ In addition, the motion of the earth around the sun produces an annually varying anisotropy of 0.3 m°K. Anisotropies would also be expected from asymmetric expansion of the universe, large scale irregularities in the distribution of matter or energy, or various other dynamical effects important in the evolution of the universe.

Our radiometric system is designed to detect anisotropic radiation in the cosmic background with a sensitivity of a few tenths of a milli-degree Kelvin. The design incorporates several new features that reveal or cancel systematic effects. In this section we shall briefly describe the system operation. In the balance of the paper we expand on this description, detail the design criteria, and document the system's performance.

Two antennas that point 30° from the zenith and oppositely in azimuth collect the 33 GHz radiation (see Figures 1-3). Thus the sky provides both the source and the reference for differential detection of anisotropy. The 33 GHz frequency is in a 'window' where the sum of atmospheric and galactic microwave backgrounds is minimal. The antennas are dual-mode corrugated horns that reject side-lobe illumination from the direction of the earth by more than -65 db and thereby reduce signals due to anisotropic terrestrial radiation below the 0.2 m°K level.

A switching ferrite circulator, alternating between the antennas at 100 Hz, directs the radiation to a room-temperature mixer. Rapid switching between antennas reduces 1/f noise from the receiver. Two 1000 MHz bandwidth IF gain stages amplify the signal, and a lock-in amplifier analyzes the detected output for a component synchronous with the switching. Thus the radiometer detects <u>only</u> the difference in sky temperature, not its absolute intensity. The 33 GHz receiver rms sensitivity is 44 $m^\circ K/Hz^{1/2}$.

The equipment is carried on board a U-2 jet to 20 km altitude where atmospheric microwave emission is greatly reduced. Pointing the antennas at the same zenith angle cancels most of the remaining thermal emission from the residual atmosphere. Slight departures from level flight are the primary cause of the remaining imbalance in atmospheric radiation received by the antennas. A second radiometer, functionally identical to the primary 33 GHz radiometer measures these imbalances. This 'roll monitor' is tuned to 54 GHz, in a region near strong oxygen emission lines.

Two switching techniques cancel and detect equipment based imbalances. Periodic interchange of the antennas cancels insertion loss differences between the radiometer arms. The system is mounted in a bearing that rotates the radiometers 180° every 64 seconds. Periodic reversal of the aircraft flight path (about once per 20 minutes) detects asymmetries in the equipment correlated with rotation state.

The system incorporates thermal controls that regulate and monitor the temperatures of crucial components. All anisotropy, roll, and housekeeping data are recorded in flight on a magnetic tape cassette for later processing. The data collection is fully automated. Except for turning the equipment on, and initiating the rotation sequence at altitude, the pilot's primary responsibility is to orient the airplane according to the flight plan.

CHOICE OF FREQUENCY AND OBSERVING PLATFORM

In choosing a receiver frequency one must consider astrophysical backgrounds, emission from the atmosphere, and receiver sensitivity. Synchrotron radiation from the Milky-Way Galaxy places a fundamental limit on the sensitivity of any experiment which measures the anisotropy of the cosmic background radiation. At about 1 GHz the intensities of galactic synchrotron emission and the cosmic background are comparable. Fortunately, compared to the cosmic background, galactic synchrotron radiations falls off rapidly with frequency.

The antenna temperature(6) of typical galactic synchrotron emission is plotted as a function of frequency in Figure 4. This plot shows that by 20 GHz the magnitude of the extrapolated galactic background falls below 1 m°K. The thermal spectra of ionized hydrogen (HII) regions and dust clouds, which are mainly localized near the galactic plane, are also shown.

Also plotted in Figure 4 is our estimate of state-of-the-art room-temperature receiver sensitivity as a function of frequency for one hour of integration. The need to detect anisotropies on limited time scales constrains the choice of receiver frequency to frequencies where the expected anisotropy is on the order of a millidegree Kelvin or more.

Thermal microwave emission from the earth's atmosphere is an important background. Figure 5 is a plot of the expected zenith temperature due to atmospheric emission as a function of frequency and altitude. The oxygen spectrum is calculated using a standard model of the earth's atmosphere together with formulae that describe the microwave spectrum of O_2 as a function of temperature and pressure.(7) This plot shows that there are preferred windows - below 20 GHz, around 35 GHz and around 90 GHz - in which atmospheric effects are greatly reduced relative to the peaks. The choice of the 33 GHz receiver frequency was based on the above considerations. This is a frequency where the effects of galactic background and atmospheric emission are minimized, and where receiver performance and signal strength are adequate.

A high altitude platform is required for this measurement because fluctuations of precipitable water vapor do not allow a sensitive experiment to be done on the ground. Even at mountain-top altitude fluctuations of 20 m°K are common.(8) The experiment must be conducted at altitudes above 14 km, where all significant water vapor has been frozen out.(9) Pointing the antennas at nearly the same zenith angle can cancel the residual thermal radiation from the oxygen above this altitude.

There are several vehicles which could be used for altitudes of 14 km and above: satellites, balloons, and aircraft. Although a satellite experiment is potentially the most sensitive, having no atmospheric background and long integration times, it is also the most expensive. Such an experiment (the Cosmic Background Explorer) is now being planned, but it will not be flown for several years. The results from an airplane experiment will aid in the design and planning of the satellite experiment. Other anisotropy experiments sensitive to the milli-degree Kelvin range are currently being flown,(4,10) and use balloons to reach the necessary altitudes. The U-2 is a particularly good vehicle for this experiment because of its high (20 km) altitude, excellent roll stability, and quiet electrical and mechanical environment. The U-2 has the advantage over balloons of being piloted and less at the mercy of weather. Recovery of the instrument after a flight is straightforward.

RADIOMETER

Figure 6 shows a schematic drawing of the 33 and 54 GHz radiometers. Rapid switching between a source and a reference load is a standard technique used to reduce the effect of receiver gain fluctuations (1/f noise) in a microwave radiometer. We use a dual antenna configuration where the sky is both the source and the reference. Thus difficulties in monitoring the temperature of a reference load within a few tenths of a milli-degree Kelvin are eliminated. Radiation from the atmosphere is canceled by pointing the antennas at the same zenith angle. The primary components of the radiometers are the antennas, the ferrite ('Dicke') switch, the receiver, and the downstream electronics. A discussion of each of these components for the 33 GHz radiometer follows.

Antennas

The anisotropy in the blackbody radiation is minute compared to anisotropies in the radiation from the earth and aircraft. Thus a first requirement of the antenna system is that its side-lobe response reduce the differential emission from the earth and aircraft below the design sensitivity, about 0.2 m°K. Thus the integrated 300 °K signal from the earth must be reduced by a factor of about 10^{-6} compared to the main beam. Secondly, this performance must be achieved with a compact design. Mechanical and aerodynamic considerations make installation of antennas with large apertures, or ground shields impractical in the U-2. Thirdly a beam width of more than 1° is needed. A small beam-width would make the measurement susceptible to spurious signals from point-like astrophysical sources of radiation. Finally to eliminate potential systematic errors, the insertion loss of the antennas must be small, or comparable to losses of other components upstream of the receiver.

These criteria were met by corrugated horn antennas based on the work of A.J. Simmons and A. Kay(11). A matched pair of antennas with a beam width of 7° FWHM were built by TRG Division of Alpha Industries for this experiment. Each antenna is an aluminum cone with concentric grooves machined down the full length of the inside surface. The grooves force the electric field at the edges to zero, effectively apodizing the aperture. This effect is enhanced by the excitation of two modes in the antenna throat phased to cancel at the mouth of the antenna. At the throat end of the antenna a transition is made from circular to rectangular waveguide.

A sensitive measurement of the antenna beam patterns was made at the JPL-NASA test range of the Jet Propulsion Laboratory in Pasadena, California. Figure 7 shows the results of the experimental measurement along with the theoretical predictions of antenna patterns.(12) These results imply that the earth should contribute a total antenna temperature of no more than 2 m°K, and the airplane no more than 2.1 m°K into either antenna during level flight. Radiation from terrestrial surface features with different emissivity illuminating the side-lobes should result in differential reception between the two antennas of no more than 0.2 m°K.

The aircraft made 20° banks over the California coast to check the calculations. During the banks, terrestrial radiation illuminated the side-lobes of the lowered antenna to within 40° of the central beam axis. Systematic differences of <4 m°K out of the 22 m°K bank signal were observed as the lowered antenna swept over terrain of varying emissivity. This limit is in agreement with the predicted value calculated from convolving the antenna beam pattern with the varying thermal emission from the earth at 33 GHz.

Ferrite Switch

A latching ferrite circulator switches the input of the receiver between the two antennas at 100 Hz. The switch was manufactured by Electromagnetic Sciences Corporation of Atlanta, Georgia. The input ports are canted at ±30° so the antennas connect directly to the switch without any intervening waveguide. Small adjustable attenuation stubs in each port reduce the insertion loss imbalances between switch states to less than 50 m°K.

The switching is accomplished by reversing the magnetic field of a ferrite embedded in the circulator. If an interaction between the earth's magnetic field and the switch has a significant orientation dependence, then a signal synchronous with the antenna rotation may result: thus the earth's field is a potential background. To avoid this background we had the manufacturer shield the switch with mu-metal and we enclosed the switch in additional magnetic shielding. We tested the shielding by immersing the entire hatch in a periodically reversing 10 gauss field. Based on these tests, we conclude that an interaction of the earth's field with the switch results in a spurious signal of less than 0.1 m°K.

Receiver

A primary limitation in the measurement of differential signals of a few tenths of a milli-degree Kelvin is the noise added to the signal by the receiver. The sensitivity of a radiometric system is defined as the root-mean-square (rms) noise fluctuation in the power output of the receiver (referenced to the input port) and is given by the formula:(13)

$$\Delta T_{rms} = K \cdot \frac{(T_R + T_A)}{\sqrt{B \cdot \tau}}$$

T_R is the receiver noise temperature in degrees Kelvin, T_A is the antenna temperature for this measurement, B is the IF bandwidth, τ is the integration time, and K is a constant depending on radiometer design (1 for a total power radiometer, 2.2 for this configuration).

Our design goal was a system that would have an rms sensitivity of less than 1 m°K in one hour of integration time, and would operate at room-temperature while being rugged enough to perform satisfactorily in an aircraft environment.(14) These goals were met by a receiver based on a balanced mixer built by SpaceKom in Santa Barbara, California. The combination of a balanced mixer and IF pre-amplifier yielded an rms sensitivity of 35 m°K in one second of integration or 0.8 m°K in one half-hour. The device has a 26 db RF to IF power gain with an IF bandwidth, B, of 1000 MHz, and a double side-band noise temperature of 500°K. Figure 8 illustrates the components of this receiver. Including 0.7 db insertion loss from the upstream switch, isolator, and antennas, the system noise performance, ΔT_{rms}, at altitude is 44 m°K for one second of integration time, (T_R = 630°K) in agreement with measurements made in the laboratory.

Downstream Electronics

The 33 and 54 GHz radiometers use similar demodulation, integration and recording electronics. A narrow band amplifier tuned to 100 Hz filters the detected output of the radiometer. A lock-in amplifier demodulates the sine wave component in phase with the 100 Hz switching between the antennas. The resulting difference signal is integrated for two seconds in an 'ideal' integrator then sampled, digitized, and recorded on magnetic tape of processing after the flight.

As a diagnostic of equipment performance the phase of the square-wave that demodulates the 100 Hz component is switched by 180° every 12 seconds.

The difference of the signals between the phase states provides a monitor of the radiometer imbalance which is observed to be about 50 m°K for the 33 GHz radiometer. The average of the two signals is used to verify that the DC level of the system after demodulation is constant.

MONITOR FOR ATMOSPHERIC ANISOTROPY

Atmospheric microwave emission at 33 GHz can yield a spurious signal if the U-2 aircraft flies at a bank. A second twin antenna radiometer, of the standard Dicke design, operating at 54 GHz monitors this potential source of background. Its antenna beam widths are matched to those of the 33 GHz antennas. Figures 1 and 2 show the position of the radiometer in the airplane hatch. The 54 GHz radiometer has a double-sideband noise temperature of 1000°K, and a 500 MHz IF bandwidth, yielding an rms sensitivity of 100 m°K for one second of integration time. The choice of 54 GHz satisfies the requirements that the oxygen signal due to aircraft rolls be strong and easily monitored at the 20 km altitude, yet not be saturated on the ground, facilitating check out.

In several flights the U-2 performed a series of banks from 5° to 25° during which the 33 and 54 GHz radiometers measured the differential atmospheric emission. The results of these runs are shown in Figure 9 along with the predictions based on our calculations of atmospheric zenith temperature (Figure 5). Due to the small optical depth, atmospheric emission at this altitude varies approximately as the secant of the zenith angle. A 0.25 degree bank results in a differential signal of 0.2 ± 0.03 m°K at 33 GHz and 95 ± 5 m°K at 54 GHz, a ratio of 1 to 420. Thus in one second of integration the 54 GHz radiometer can measure the atmospheric contribution to the 33 GHz signal to ± 0.2 m°K rms.

In level flight the 54 GHz roll monitor indicates that the U-2 autopilot, a Lear 201 Automatic Flight Control System, maintains the aircraft at constant average bank angles of less than 0.25° for periods up to an hour. For departures from level flight of a few degrees or less, the average roll monitor signal is proportional to the average atmospheric signal at 33 GHz. Since a 0.25° roll yields a signal of only 0.2 m°K at 33 GHz, the subsequent corrections to the anisotropy data during post-flight analysis are small. As with the 33 GHz signal, the 54 GHz signal is integrated and recorded every two seconds. On this time scale the rms fluctuations about the mean bank in level flight are less than 1° in roll angle. The output of the roll monitor is displayed to the pilot, but the average bank is so small that there has been no need to make corrections to the attitude of the aircraft in flight.

U-2 AIRCRAFT AND ENVIRONMENT

The NASA-Ames Earth Survey Aircraft (U-2) is a single-seat aircraft designed as a high-altitude (20 km), long-range (2500 km), reconnaissance jet by Clarence "Kelly" Johnson of Lockheed Aircraft Company of California. In appearance the U-2 is like a glider with a single powerful jet engine. Our apparatus fits in a modified upper hatch replacing the standard access hatch above the equipment bay. It is located just aft of the cockpit and forward of the wings, Figure 3. The two radiometers and most of the accompanying electronics are sealed off from below by a pressure can which maintains the equipment bay atmosphere at 4 psia.

Twenty-eight volts DC supplied by the aircraft powers the equipment. The voltage is filtered against RF interference and regulated at 24 volts. All data are recorded on board; no telemetry is used. The pilot flies the aircraft on a predetermined path. Normally there is no communication to the ground during data taking.

The equipment is operated in a carefully regulated thermal environment. Due to the finite emissivity of the horn antennas, a 0.05°C physical temperature difference between the 33 GHz antennas would produce a 1 m°K signal. However there is considerable variation in the loss per unit length along the horn. In flared smooth-walled antennas each transverse section radiates power approximately in inverse proportion to its diameter. But in the dual-mode corrugated design, the greatly reduced fields at the surface of the antenna mouth result in correspondingly lower loss per unit length. In the 33 GHz antennas the power per unit length contributed by the mouths is only one three-hundredth that of the throats.

A 20 kgm aluminum block thermally shorts the throats together, and an aluminum bar shorts the midpoints of the antennas together. The temperature of the block, containing the antenna throats and the ferrite switch, is regulated at 26°C by embedded resistive heaters. The antenna mouths cool in the air-stream where they reach -35°C during the flight.

Silicon diodes used as temperature sensors monitor the absolute and differential temperatures of the antenna mouths and midpoints. Measurements made during the flight show the differential temperatures to be less than 0.05°C. Additional heaters maintain the 54 GHz ferrite switch at 35°C and regulate the digitizing and sequencing electronics at 25°C. Total heat dissipation through the antennas is about 70 watts from the electronics and 50 watts from the heaters. The equipment cools for 20 minutes after the rotation sequence is initiated at altitude,allowing the system to reach thermal stability. The aluminum block gradually cools an additional 1.6°C during the remainder of the flight.

Teflon windows protect the mouths of the 54 GHz antennas. The windows are 1.9 mm thick, or 1/2 wavelength at 54 GHz, thereby minimizing reflections of an incoming signal. The emissivity of the windows is less than 1%. A physical temperature difference between the windows of a few degrees Kelvin results in a thermal signal of a few hundredths of a degree Kelvin. This is negligible compared to the 85 m°K signal generated at 54 GHz by the minimal roll to be detected, 0.2°. In contrast, at 33 GHz, windows with sufficient mechanical strength to withstand aerodynamic stress cannot be used. Differences in physical temperature of a few degrees Kelvin would produce spurious signals large compared to a few tenths of a millidegree Kelvin to be detected with this radiometer.

The entire assemblage is mounted on three vibration dampers that reduce potential microphonics due to aircraft vibration. The electronic components are packaged in modules that are shielded against radio-frequency interference and a double-shielded container encloses the entire assembly except for the actual antenna mouths.

Rotation System

As with previous anisotropy experiments, it is essential that the position of the antennas be periodically interchanged to cancel anisotropy inherent in the instrument. The main portion of the equipment is suspended on a 22-inch diameter bearing mounted in the U-2 hatch. A motor drives the bearing through a worm gear, a clutch, and a stainlesss steel chain. This system rotates the instrument 180° every 64 seconds to the alternate observing position.

A rotation takes 5 to 6 seconds during which the instrument is accelerated through a 90° turn and then de-accelerated until it coasts to rest against a positioning stop. The motor is shut off with a sensing microswitch. The design of the system insures proper alignment of the antennas in the observing positions to within 0.1°. A ten turn potentiometer and four microswitches measure the rotation angle to within 0.5°. Their outputs are recorded, and the analog rotation angle signal is displayed on the pilot's instrument panel.

During ascent and descent the equipment is rotated 90° away from the observing positions to protect the 33 GHz antennas from the external environment. In this 'stored' position, the 33 GHz antennas are positioned inside the hatch, and plugs, lined by brushes, seal the open ports.

Aircraft Reversals

A spurious anisotropy signal would appear if the output depended on rotation state or if the apparatus were not located symmetrically in the U-2 aircraft. We detect and cancel any such signal by taking data in pairs of 'legs' flown in opposite directions with respect to the ground and sky. During each leg the pilot flies the aircraft straight and level for 20 minutes. Six pairs of legs are flown in a typical flight. The final three pairs are usually flown in directions perpendicular to the first three.

DATA RECORDING AND ANALYSIS SYSTEM

The experiment is run in an automated mode. Controlling electronics, activated by the pilot at take-off, provide the necessary timing and sequencing signals to the equipment. A Datel LPS-16 Data Logger, a lightweight low power incremental tape recorder, digitizes and records four words of data per second on a magnetic tape cassette. Table I lists the quantities measured and recorded in an eight-second data cycle.

During post-flight analysis we use computer programs to display, edit, and average the measurements. The bulk of the editing consists of deleting data taken during banks and antenna rotations. The scatter of the edited data is generally consistent with a gaussian distribution, as expected for signals from a noise limited radiometer. On two occasions during data-taking flights transients occured that were inconsistent with statistical fluctuations about the mean. These points were removed, resulting in a loss of twenty seconds of data. Data taken during course corrections made by the pilot are deleted if the 54 GHz roll monitor indicates a bank of more than one degree. The cuts due to rolls and transients amount to less than six minutes out of 32 hours of data taken over nine flights.

The remaining data is grouped by 'legs' and averaged. The anisotropy is found in each 'leg' by subtracting the averages of data taken in one antenna orientation from the average of data taken in the other orientation. Corrections are applied to these averages for astrophysical, local, and equipment based backgrounds. Take II lists these corrections, and tabulates the 90 percentile limits on the magnitudes of the corrections that are applied to each 'leg'. The 90 percentile limits for the combined corrections applied to each 'leg' is 0.56 m°K.

RESULTS OF ENGINEERING AND DATA FLIGHTS

Three engineering flights were used to study the thermal environment of the equipment in the U-2 by monitoring the external temperatures and the heat flow through the antennas. During these flights the effect on the equipment of radio transmissions from the plane and engine re-start were checked and found not to cause significant interference.

The statistical and systematic properties of the 33 GHz signals in nine subsequent data flights were studied by a variety of methods. The data were auto-correlated, and signal-averaged at the rotation period. In the initial three data flights correlations were seen with time periods of 40 to 120 seconds, and amplitudes that varied from 10 to 45 m°K. After these flights we made a number of changes and improvements including the following: A parametric amplifier(14) was replaced with the SpaceKom mixer, and regulation of the temperatures of the aluminum block and the controlling electronics was improved. In the final six data flights no correlations were observed, nor anomolous effects in the signal averaged plots, down to sensitivities limited by statistics. Figure 10 shows a segment of data taken with the 33 and 54 GHz radiometers from the fifth data flight.

A spurious signal of about 2 m°K, of yet unexplained origin, is associated with the rotation state of the system. Reversing the heading of the aircraft measures this effect, and shows it is constant during a flight. This offset is subtracted from the data for later analysis. It may be inherent in the system, or due to an asymmetry in the way the equipment is mounted in the plane. This problem is being investigated.

Microwave absorbers maintained at room-temperature and at liquid nitrogen temperature are used in the laboratory as the primary calibrators of the 33 and 54 GHz radiometers. The equipment was also calibrated during pre-and post-flight checkout with a secondary calibrator. In several flights the moon provided a check of the calibration. The U-2 flew the equipment over a pre-determined location at the proper time and heading so that one of the antennas pointed at the moon to within 0.5°. The observed signals of 675 ± 25 m°K imply a surface temperature of 228 ± 12°K consistent with measurements made on the ground by us and others (15) at similar wavelengths.

During the flights the anticipated thermal, terrestrial, and atmospheric backgrounds were at the expected level. Data were accumulated for directions distributed over the northern hemisphere. Anisotropy in the cosmic background radiation has been detected in these data with an overall sensitivity of ± 0.6 m°K. Details are published elsewhere.(16)

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REFERENCES

1. R.B. Partridge and D.T. Wilkinson, Isotropy and Homogeneity of the Universe from Measurements of the Cosmic Microwave Background, Phys. Rev. Letters 18, 557 (1968).
2. E.K. Conklin, Velocity of the Earth with Respect to the Cosmic Background Radiation, Nature 222, 971 (1969).
3. P.S. Henry, Isotropy of the 3°K Background, Nature 321, 516 (1971).
4. B.E. Corey and D.T. Wilkinson, A Measurement of the Cosmic Microwave Background Anisotropy at 19 GHz, Bull. Am. Astron. Soc. 8, 351 (1976).
5. P.J.E. Peebles, Physical Cosmology, (Princeton, 1971), pp. 147.
6. Throughout this paper we shall refer to microwave intensities in the units of antenna temperature. The antenna temperature of a source is the temperature of a blackbody radiator filling the antenna beam, observed at a frequency ν in the Rayleigh-Jeans region that matches the power of the source. Degrees Kelvin can be converted to Watts/m^2Hz by multiplication by the coefficient which appears in the Rayleigh-Jeans blackbody formula: $(2k\nu^2/c^2)$. Here k is Boltzmann's constant, ν is the frequency, and c is the speed of light; at 33 GHz the coefficient is $2k\nu^2/c^2 = 3.3 \times 10^{-19}$. Watts/$m^2$Hz°K.
7. M.L. Meeks and A.E. Lilley, The Microwave Spectrum of Oxygen in the Earth's Atmosphere, J. of Geophys. Res. 68, 1683 (1963).
8. D.E. Burch, Absorption of Infrared Radiant Energy by CO_2 and H_2O.III. Absorption by H_2O Between 0.5 and 36 cm^{-1} (278 -2 cm), J. Opt. Soc. Am. 58, 1383 (1968).
9. P. Kuhn, M. Lojko, and E. Peterson, Infrared Measurements of Variations in Stratospheric Water Vapor, Nature 223, 462 (1969).

10. D. Meuhlner and R. Weiss, Infrared and Submillimeter Astron., Vol. 63, Astrophysics and Space Sciences Library, Ridel (1976).

11. A.J. Simmons and A.F. Kay, "The Scaler Feed - A High Performance Feed for Large Paraboloidal Antenna", IEEE Conf. Publ. 21, pp. 213-217, (1968).

12. P.D. Potter, "A New Computer Program for the Design and Analysis of High Performance Conical Feedhorns", in The Deep Space Network. Technical Report 32-1526, Vol. XIII, pp. 92-107, Jet Propulsion Laboratory, Pasadena, Calif. February 15, (1973).

13. See for example, J.D. Kraus, Radio Astronomy (McGraw-Hill 1966), p. 251.

14. Originally, a low-noise room-temperature receiver based on a 33.5 GHz degenerate parametric amplifier was used in the engineering and initial data flights in 1976. The receiver built by TRG Division of Alpha Industries had a noise temperature in the lab of 250°K with IF bandwidth of 300 MHz, having a system sensitivity in one second of integration of 38 m°K. However gain stability was difficult to achieve in flight because its thermal gain coefficient was -0.4 db/°C. In 1977 the Space-Kom mixer became available and we use it because of its greater gain stability, its simplicity, and its equivalent sensitivity.

15. C.H. Mayer, Surfaces and Interiors of Planets and Satellites, (New York, Academic Press, 1970, ed. A. Dollfuss), pp. 180; T. Hagfors, Remote Probing of the Moon by Infrared and Microwave Emissions and by Radar, Radio Science 5, 189 (1970).

16. G.F. Smoot, M.V. Gorenstein, and R.A. Muller, Detection of Anisotropy in the Cosmic Blackbody Radiation, Phys. Rev. Lett. 39, 898 (1977).

TABLE CAPTIONS

Table I. The 28 analog and 4 digital words sampled in an eight second data cycle. The 33 and 54 GHz integrated signals are sampled and recorded once every two seconds during each cycle. The other signals, primarily monitors of equipment performance and environmental conditions, are sampled less frequently.

Table II. The 90 percentile limits on the magnitude of the corrections applied to data averaged over a leg. Most systematic corrections applied to the data are small compared to the integrated sensitivity of a flight, about 0.5 m°K.

TABLE I

Data Recorded

Analog	Number of times sampled in 8 seconds
1. 33 GHz radiometer signal	4
2. 33 GHz noise monitor	2
3. Atmospheric (54 GHz) monitor signal	4
4. Atmospheric noise monitor	2
5. Heater circuit current	2
6. Antenna orientation	2
7. Absolute temperature, antenna mouth	1
8. Differential temperature between antenna mouths	1
9. Absolute temperature at middle of antenna	1
10. Differential temperature across middle of antennas	1
11. Temperature of 33 GHz ferrite switch	1
12. Five temperatures of 33 and 54 GHz radiometer	5x1
13. Accelerometer output	1
14. Power supply voltage	1
Digital	
Universal time	2
Antenna position, status bits	2
	32 words

TABLE II

RESIDUAL SYSTEMATIC EFFECTS

EFFECT	90% of the corrections in each category result in change of less than: (m°K)
Galactic Backgrounds	
Synchrotron Radiation	0.32
Ionized Hydrogen (H II Regions)	0.01
Radio Sources	0.06
Dust	0.01
Atmospheric Anisotropy (Banks)	0.15
Antenna Side Lobes	0.20
Antenna Temperature Difference	0.27
Motion of Earth Around Sun	0.23
Jupiter	0.01
Combined	0.56

FIGURE CAPTIONS

Figure 1. Schematic layout of the radiometer apparatus in the U-2 equipment bay. The main electronics and mechanical components of the system are illustrated. The antennas are shown in the data taking position, with the direction of flight perpendicular to the plane of the drawing. Interchange of the antennas is accomplished by a periodic (once per 64 seconds) rotation of the equipment 180° about the vertical center-line.

Figure 2. The 33 and 54 GHz radiometers in the modified upper hatch of a U-2 jet. The RF shields and protective air cover have been removed to expose the horn antennas of the radiometer systems, the monitoring and demodulating electronics packages, and the outer bearing clamp and chain drive of the rotation system.

Figure 3. The forward section of U-2 jet with a 33 GHz antenna mouth and 54 GHz teflon window visible. The modified upper hatch, situated just aft of the pilots canopy, is easily removed from the U-2 equipment bay with the equipment installed, for checkout and testing. The top surfaces of the airscoops are 72° from the 33 GHz antenna beam axis.

Figure 4. Estimates of galactic radiation backgrounds as a function of frequency compared to a possible 'Aether Drift' signal. The large scale anisotropy of galactic microwave radiation is comparable to the absolute intensity of the sources. The dust and HII regions are concentrated in the galactic plane and tend to be greatest near the galactic center. An estimate of receiver sensitivity for one hour of integration is included.

Figure 5. An estimate of the zenith temperature due to atmospheric emission as a function of frequency and altitude, computed from the formulae of Meeks and Lilley.[7] We used these calculation in conjunction with other considerations described in the test to choose the 33 GHz observation frequency. Atmospheric emission at 54 GHz gives sufficient signal strength to monitor rolls at the U-2 altitude, but is sufficiently unsaturated on the ground to permit verificaiton of the predicted emission.

Figure 6. Components of the 33 and 54 GHz radiometers. The individual components making up the receiver section are shown in Figure 8.

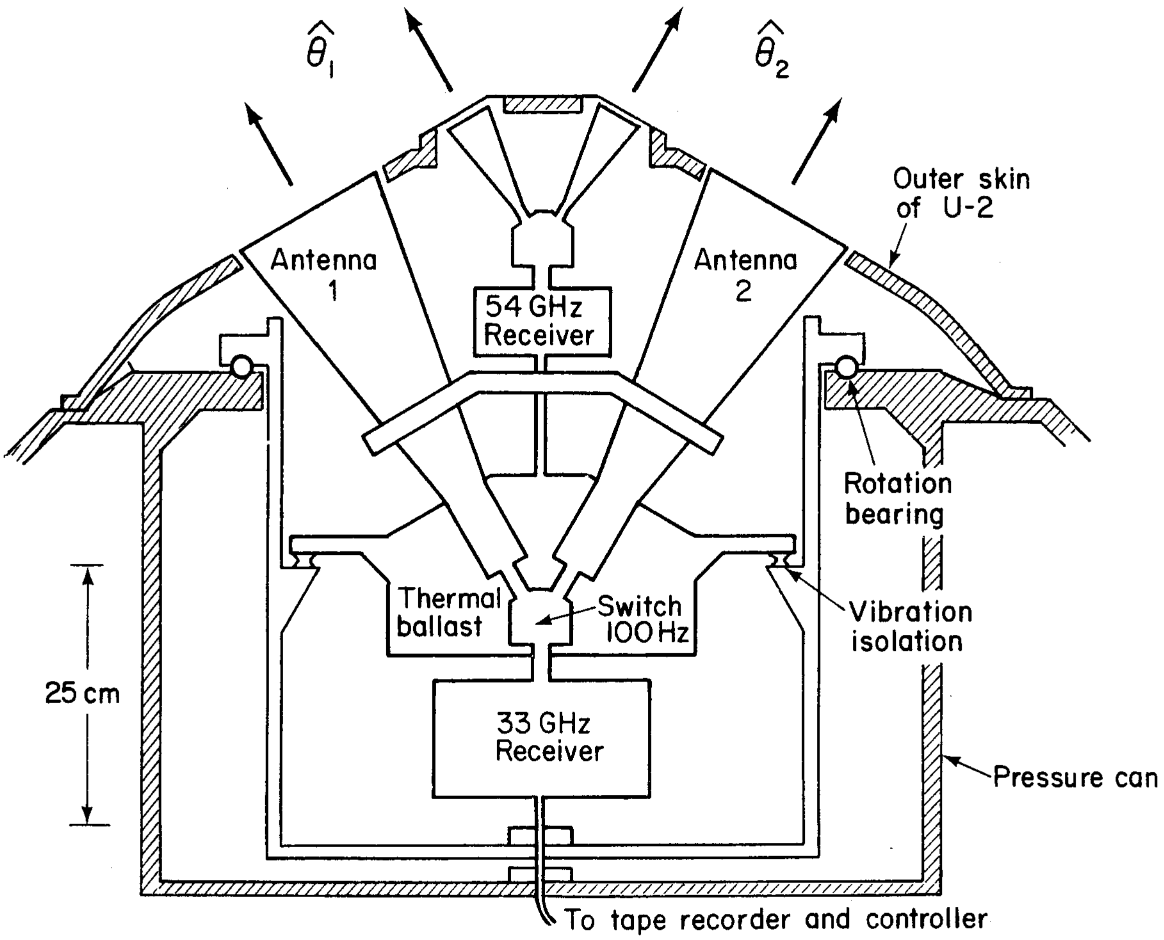
Figure 7. The E and H plane one-way power pattern of the 33 GHz corrugated horn antennas used in this experiment, as measured at the JPL test range. Low side-lobes are necessary to reduce anisotropic radiation from the earth and aircraft. The integrated power received from the earth is reduced by over 10^{-5} compared to the main beam.

Figure 8. The component layout for the 33 and 54 GHz receivers. In this standard super-heterodyne receiver a non-linear element, excited by a local oscillator, down-converts the signal to a intermediate frequency for further amplification. These receivers feature low-noise and wide bandwidth operation at room-temperature.

Figure 9. The measured atmospheric signal at 33 and 54 GHz as a function of aircraft bank angle. Data taken during banks of the aircraft show the magnitude of the atmopsheric signals to be in reasonable agreement with predic-

tions based on the work of Meeks and Lilley.[7] Both sets of data can be empirically fit to a secant(θ) law with zenith temperatures of 38 ± 2 m°K at 33 GHz and 16.1 ± 0.2 °K at 54 GHz. The 33 GHz data is expected to include a contribution to the bank signal from differential earth-shine in the back antenna lobes as indicated.

Figure 10. The 33 and 54 GHz data from the fifth data flight. (a) Each point is the measured anisotropy at 33 GHz averaged for 56 seconds during successive antenna orientations. The data is combined from both phase states of the 100 Hz demodulating wave form. The error bars are the computed rms fluctuations of the two second data divided by the square root of the number of measurements. (b) The corresponding 54 GHz data, where no averaging has been done, show the scatter for two seconds of integration, and the roll signal during 20° banks of the aircraft. There is more oscillation about the mean in legs flown north (e.g. 3:41 to 3:55) than in alternate legs flown south. This effect is produced by an interaction between the aircraft's magnetic heading sensor and the auto-pilot. Averaging the data shows that only the amplitude, not the mean, of the roll oscillation is affected.



XBL 776-1228A

Fig. 1

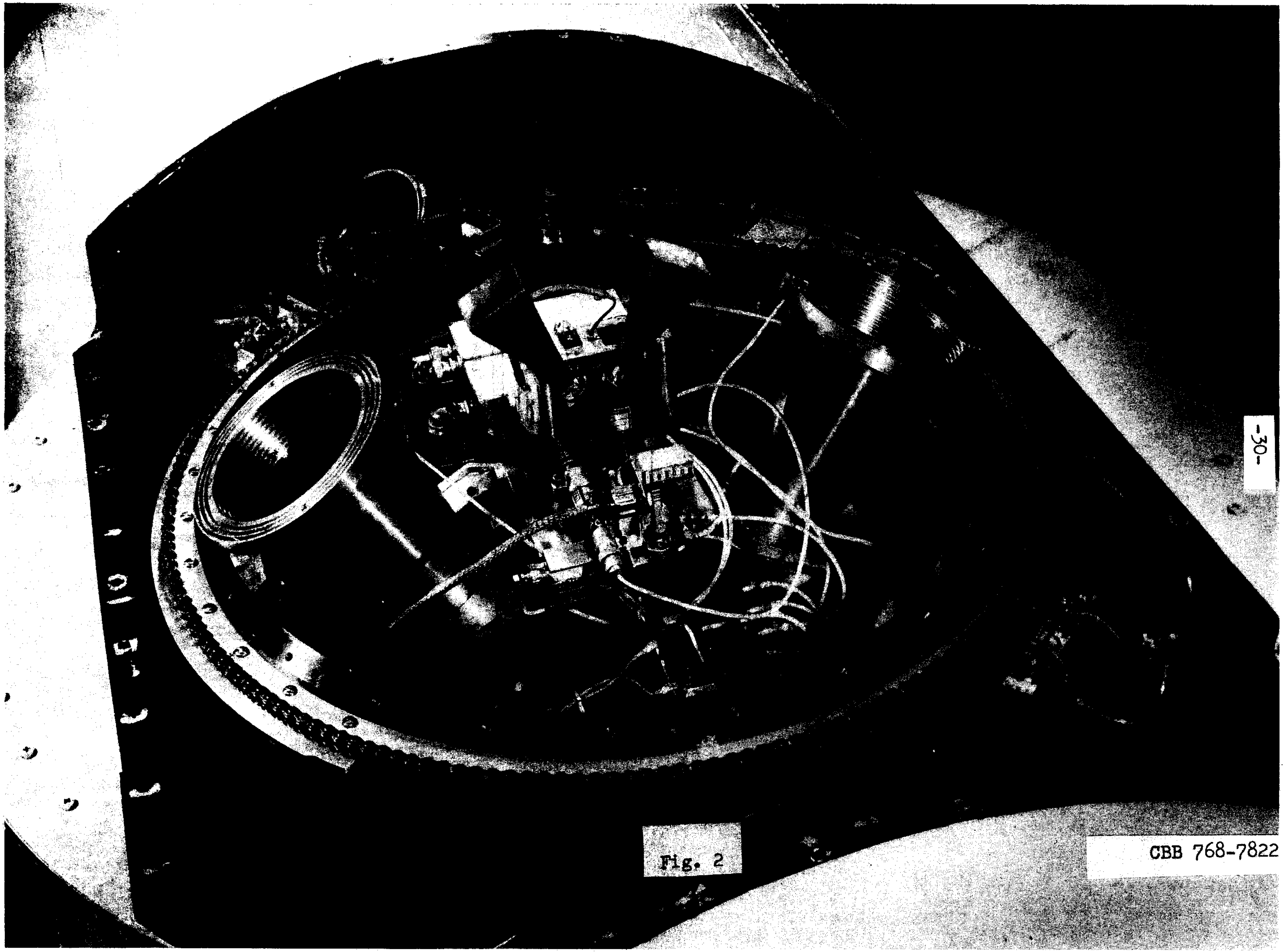
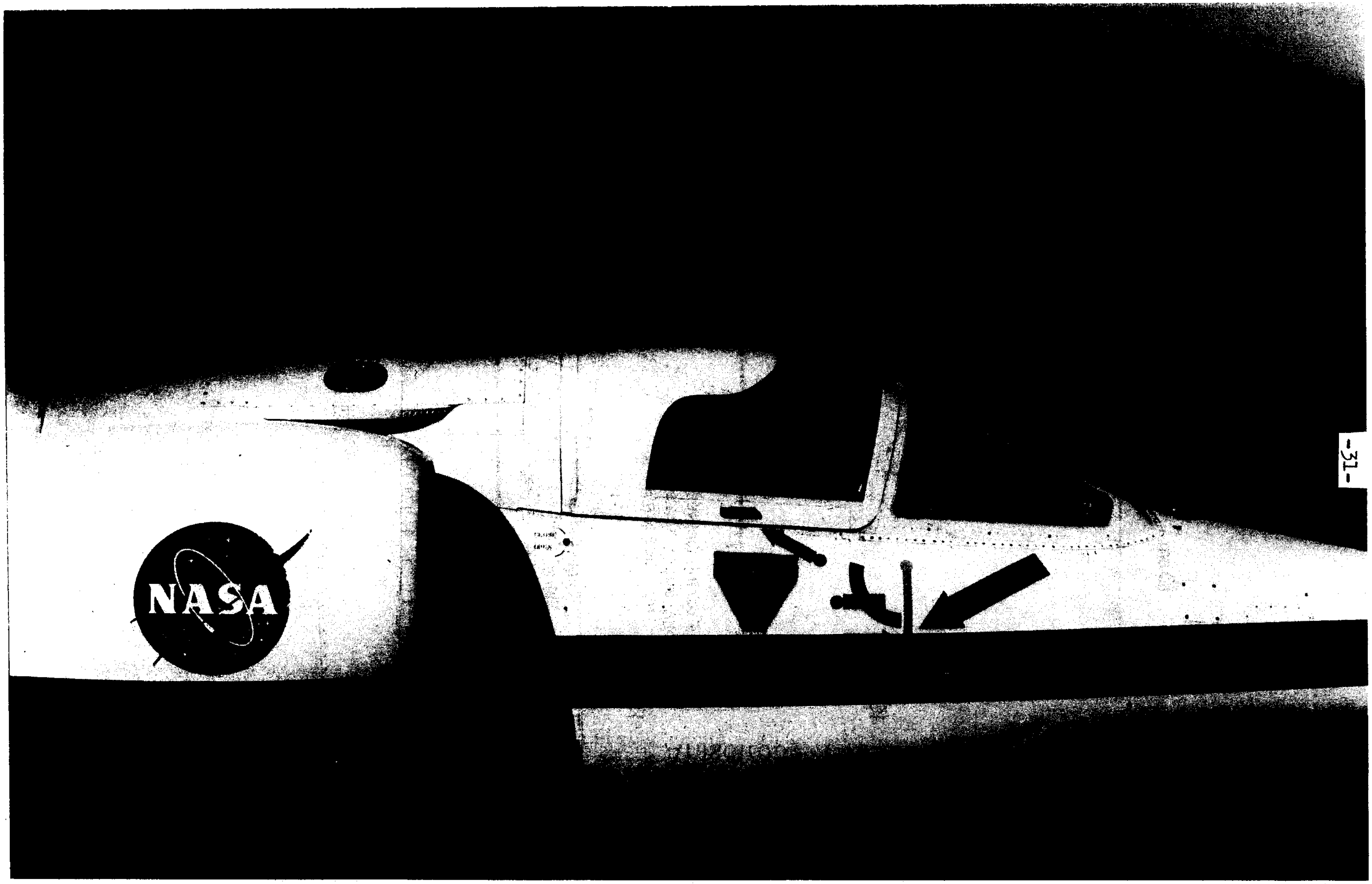


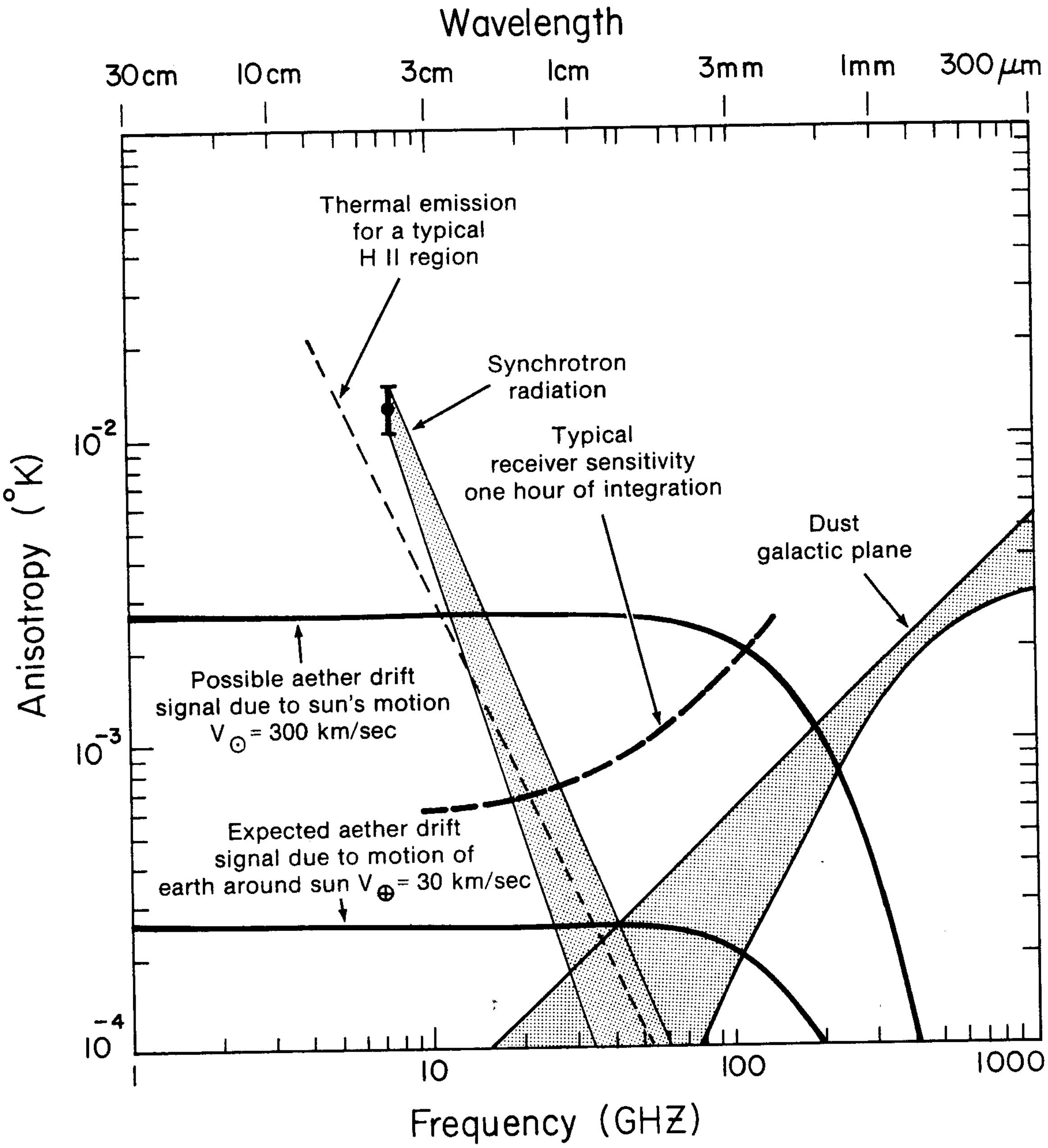
Fig. 2

CBB 768-7822



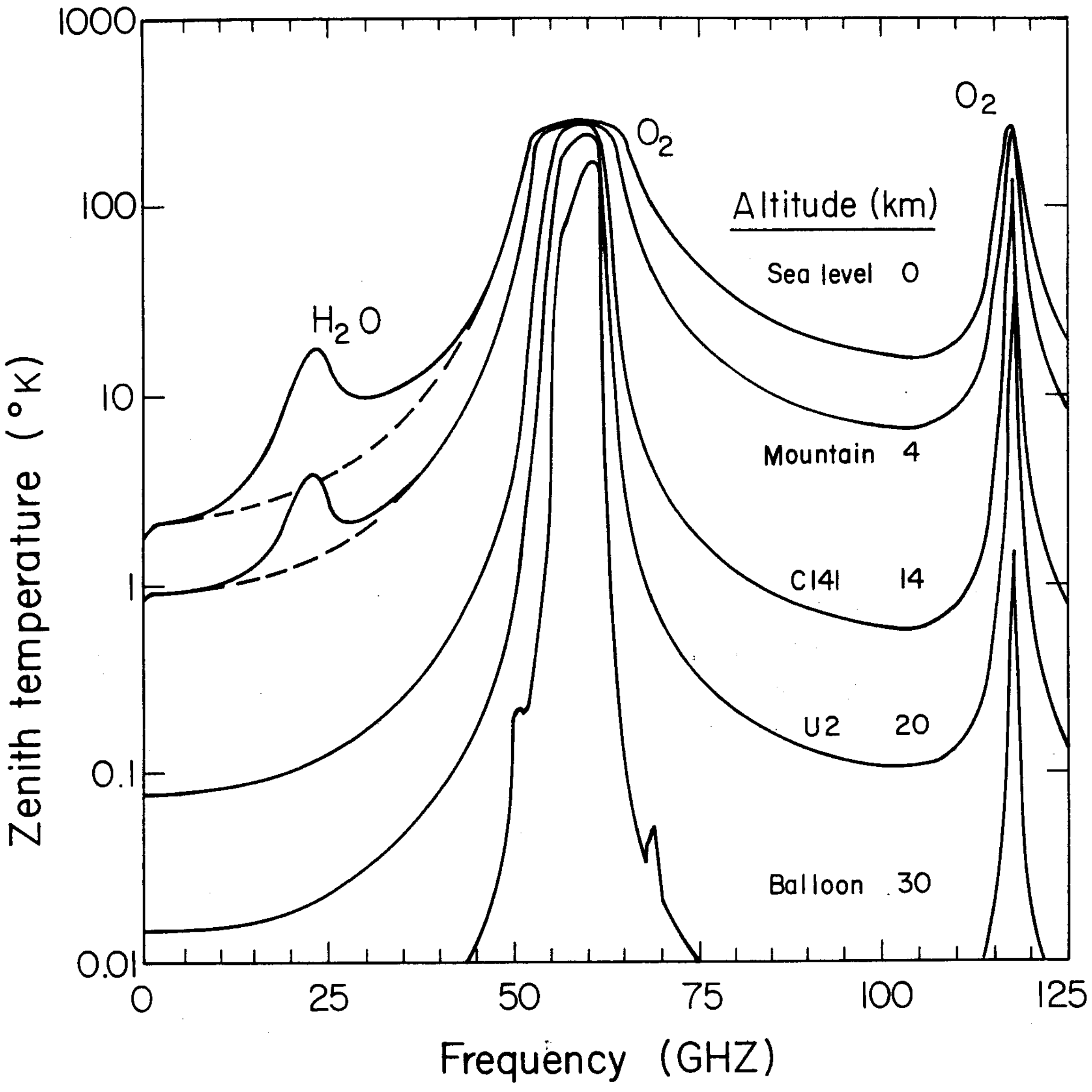
CBB 779-9349

Fig. 3



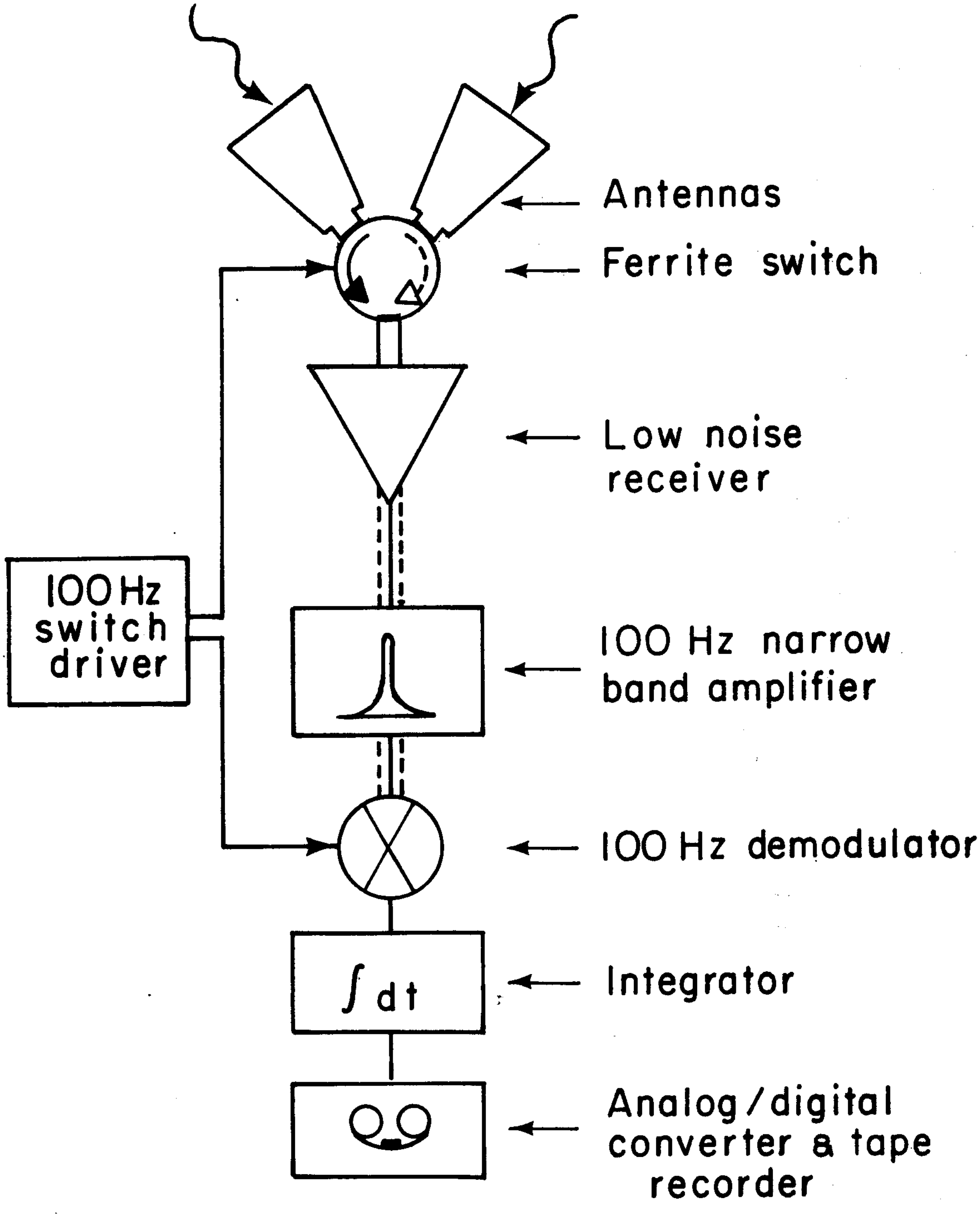
XBL 777-1412

Fig. 2



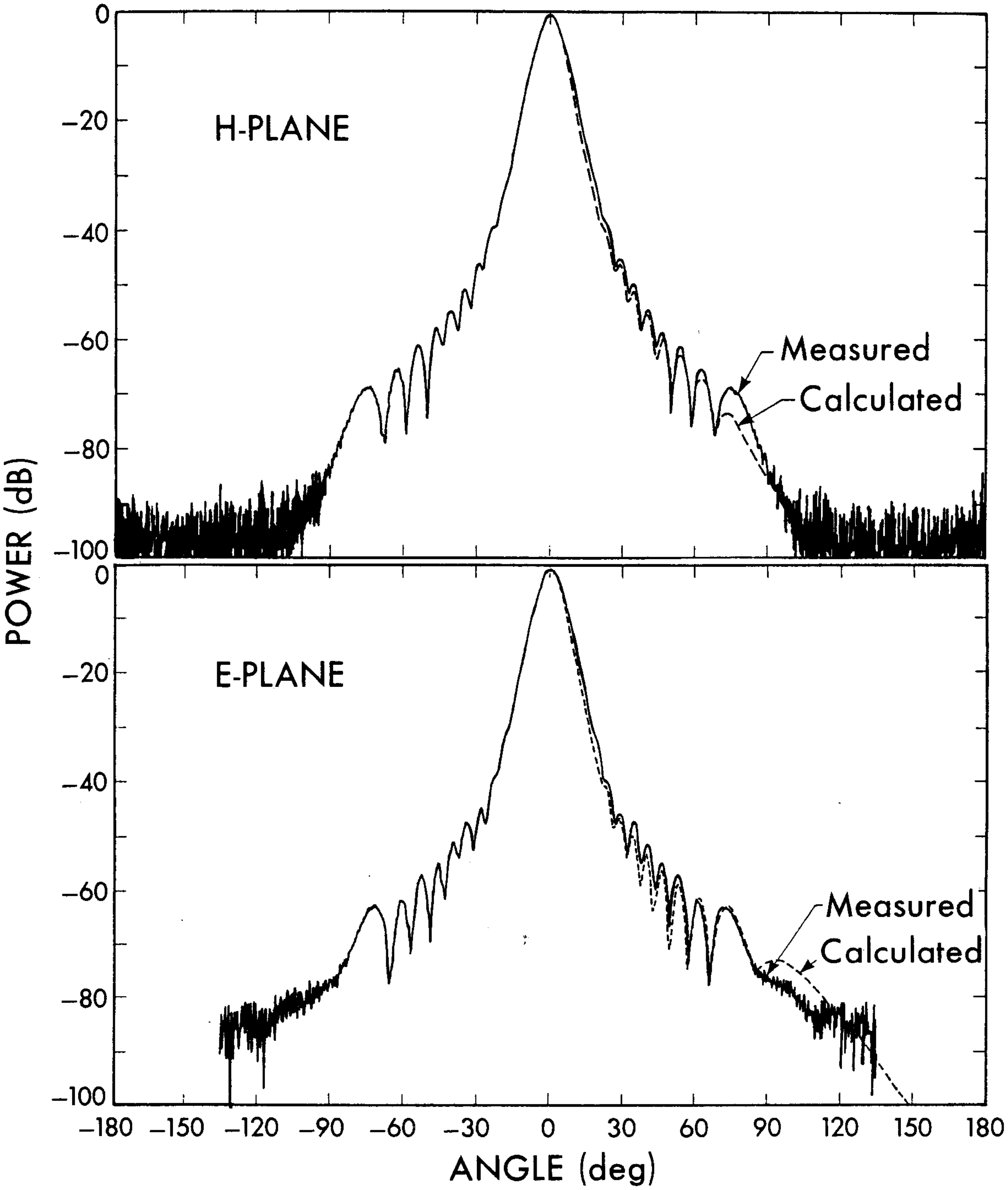
XBL 777-1413

Fig. 5



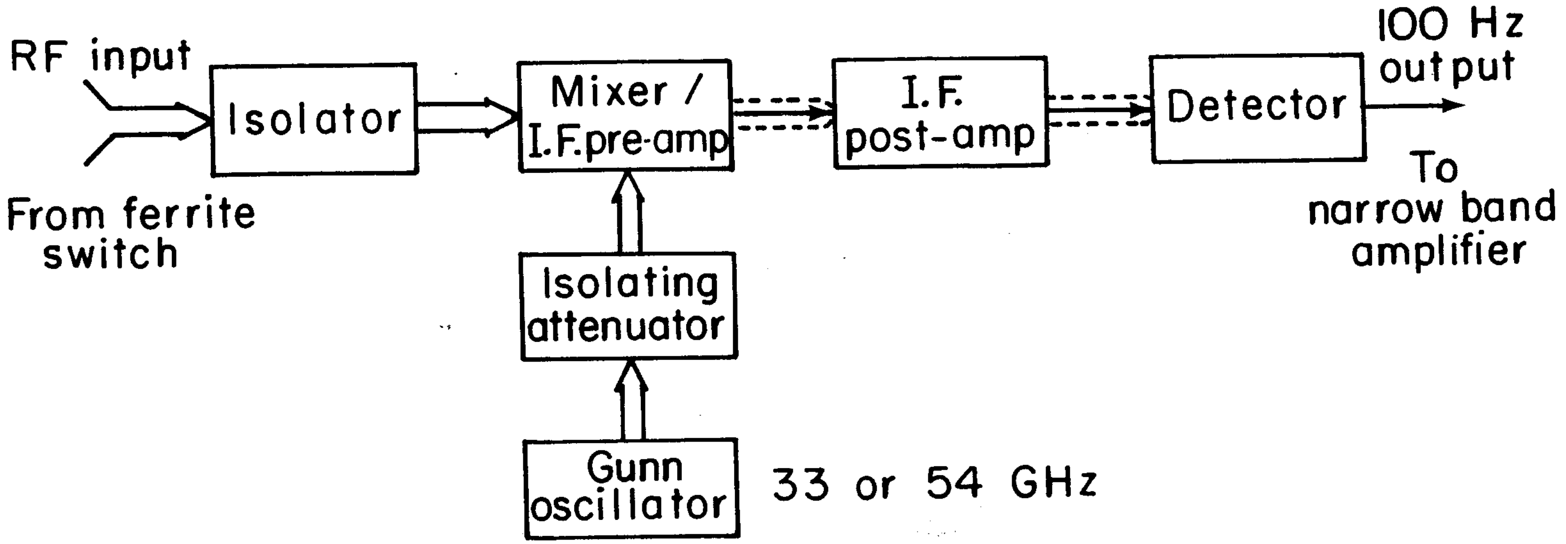
XBL 776-1338

Fig. 6



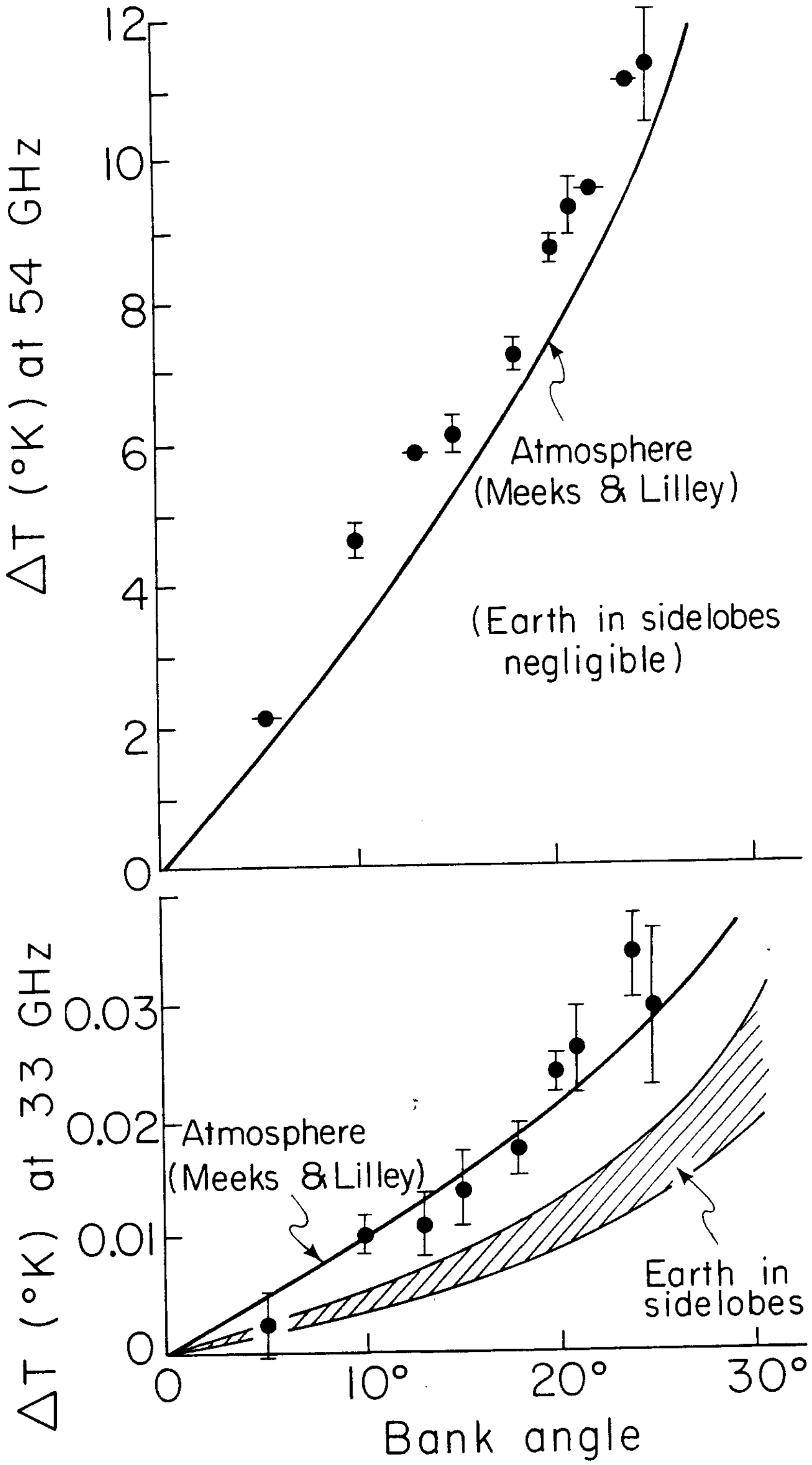
XBL 778-1809

Fig. 7



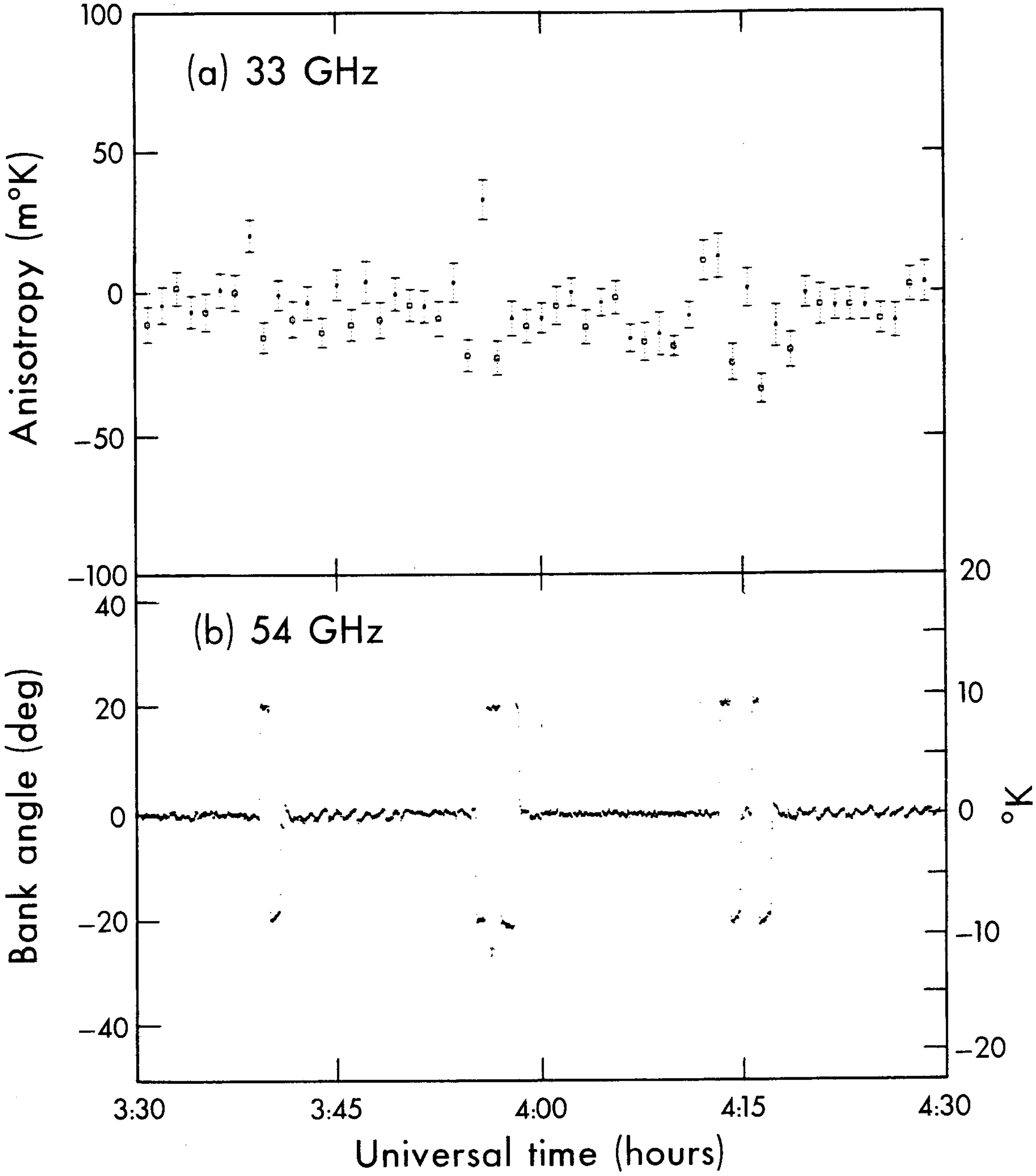
XBL776-1339

Fig. 8



XBL 776-1337

Fig. 9



XBL 778-1810

Fig. 10