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HIGH ALTITUDE PARTICLE PHYSICS EXPERIMENTAL FACILITY

MEMO NO. 241
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SUBJECT "Aether Drift" and the Isotropy of the Universe: A Proposed Measurement Utilizing the Primordial Black-Body Radiation

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ABSTRACT:

We intend to search for large-angular-scale anisotropies in the primordial black-body radiation as small as 0.2×10^{-3} degrees Kelvin using a 33 GHz Dicke radiometer with a front end temperature of 300°K, flown at an altitude of 45,000 feet on the stabilized platform of the NASA-Ames C-141 airborne telescope. The experiment will be a sensitive probe of the Cosmological Principle as well as a search for an overall spin to the universe. In addition we should be able to detect motion of the earth with respect to the distant matter of the universe.

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Introduction

In earlier memos in this series (#236 and #239) we discussed in detail the state of the art in measurements of the anisotropy of the cosmic black-body radiation. In this memo we describe an experiment to improve on the present limit by better than a factor of ten by observing anisotropies in temperature as low as 0.2 m°K. We present below the results of our quantitative analysis of the backgrounds which limited the previous experiments. We then outline the arguments which have led us to propose the use of the NASA-Ames C-141 airborne telescope as a platform for our Dicke radiometer.

Motivation

The implications of the black-body radiation and its anisotropy for astrophysics and physical cosmology have also been described in the previous memos. The current limit for an anisotropic component (< 0.1%) is the strongest evidence cosmologists have in support of the Cosmological Principle, i.e. the isotropy and homogeneity of the universe. With the proposed measurement we should observe an anisotropic component due to the motion of the earth (called the "Aether Drift" experiment of Peebles). This motion should give a signal just below 2 m°K due to the rotation of the Milky Way galaxy and a signal of magnitude 0.27 m°K due to the motion of the earth around the sun. If the universe is rotating as a whole faster than once every 10^{14} years, we should detect an anisotropy resulting from the transverse Doppler shift. (See S. Hawking, Mon. Not.Roy.Astron.Soc. <u>135</u>, 413 (1967); also C. Collins and S. Hawking, Ibid., (1973).) We will be able to search for an anisotropic component to the Hubble expansion with a factor of ten more precision than previously possible. Dependent somewhat on theoretical models, we will also be probing the large-scale homogeneity of the universe (see memo #236). High precision data collected at various times of the year will be required to separate these various contributions.

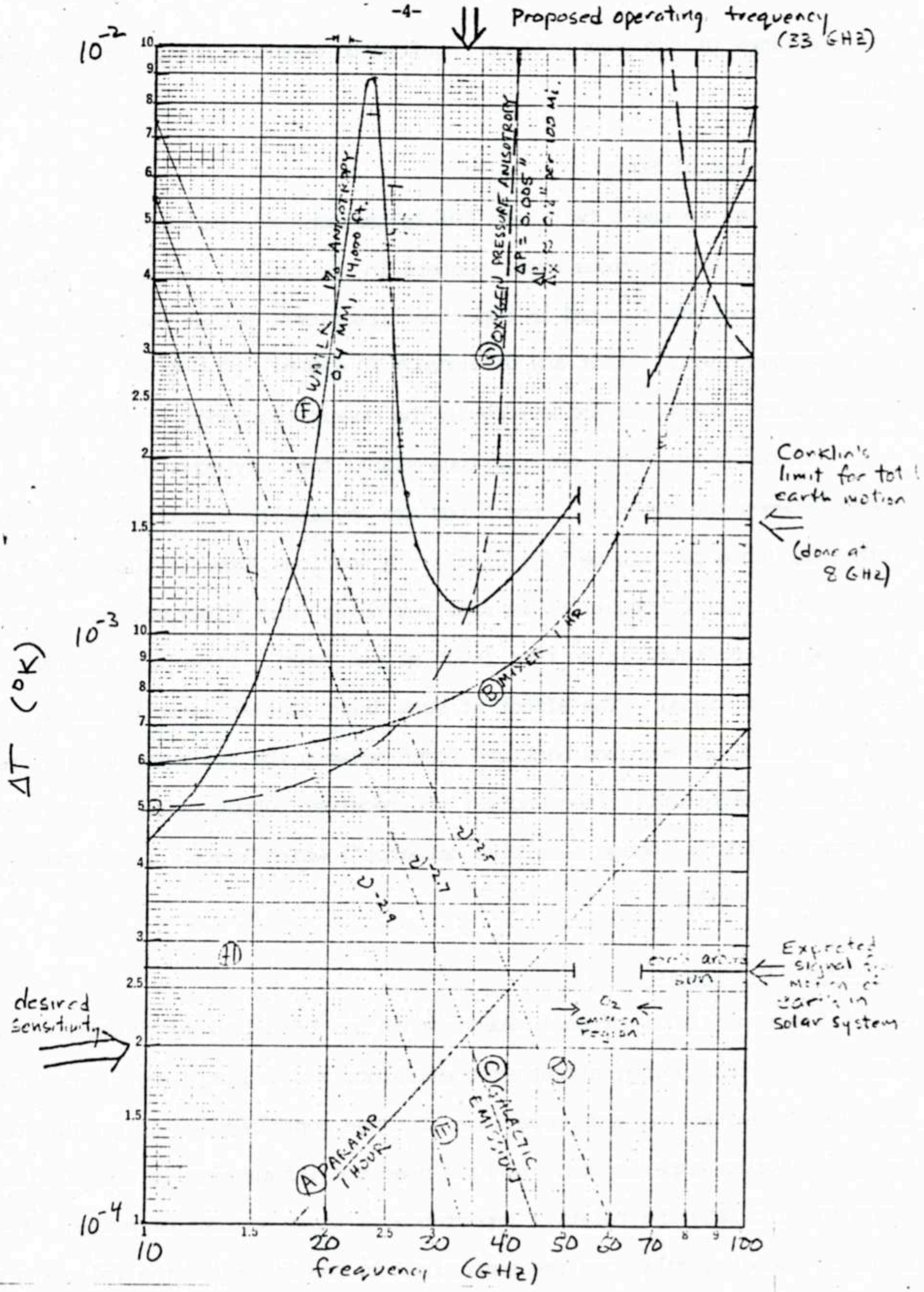
Basic Experimental Setup

We plan to use a twin horn "Dicke radiometer" similar in concept to those used by the previous experimenters in the field. Two nearly identical microwave horns are pointed in opposite directions, but at the same zenith angle. The experiment will detect any difference in signal received by the two horns due to an anisotropy in the cosmic black-body radiation.

In order to cancel any spurious signal that may come from slight differences between the two horns, the horns are physically interchanged at periodic intervals (once per minute is typical). A spurious signal could also arise from statistical fluctuations in receiver noise; such fluctuations are reduced by using a long integration time (such as one hour). Likewise, receiver drift could yield a signal. The effect of such drift is eliminated by using a single receiver which is switched back and forth between the two horns with a frequency rapid compared to drift frequencies; the receiver output is fed into a second detector (called a "phase sensitive detector") which looks for a signal synchronous with the switch.

Sources of Background

The sensitivity of past measurements has been limited by various combinations of detector noise, atmospheric emission, and galactic emission. Thus, a detailed understanding and comparison of these contributions is crucial to the design of future experiments. We have used the information in the previous memos to calculate the relative importance of these sources of noise. The results of these calculations are summarized in the figure on the following page. The vertical axis represents the signal difference of the two horns, measured in degrees Kelvin. The curves have been normalized assuming state of the art


Proposed operating frequency (33 GHz)
10^{-2}
10^{-3}
10^{-4}
ΔT (°K)
10
20
30
40
50
60
70
100
1.5
2.5
frequency (GHz)
Ⓕ WATER 1% ANISOTROPY 0.4 MM, 14,000 ft.
Ⓖ OXYGEN PRESSURE ANISOTROPY ΔP = 0.005" ΔP/ΔX ≈ 0.2" per 100 mi.
Ⓑ MIXER 1 HR
Ⓐ PARAMP 1 HOUR
Ⓒ GALACTIC EMISSION
Ⓔ
Ⓓ
Ⓗ
$\nu^{-2.9}$
$\nu^{-2.7}$
$\nu^{-2.5}$
Conklin's limit for tot l earth motion (done at 8 GHz)
earth around sun
O2 emission region
Expected signal for motion of earth in solar system
desired sensitivity
LOGARITHMIC 358-103 KEUFFEL & ESSER CO. MADE IN U.S.A. 2 X 1 CYCLES

electronics, and atmospheric emission for a mountain-top experiment. The important features of this plot are as follows (for details, see memo #236):

1. Curves (A) and (B) represent residual detector noise after one hour of integration, assuming two types of detectors. Curve (A), the parametric amplifier, allows a sensitivity of 0.2 m°K to be reached in one hour of integration. Sensitivity increases as the square-root of the integration time for both detector types.
2. Galactic emission falls off very rapidly with frequency, but with a spectral index that varies from position to position in the sky from 2.5 to 2.9 (lines C, D, E); this presently unmapped variation precludes us from doing accurate galactic background subtraction. As can be seen in this plot, the level of the best experimental limit so far, that of Conklin (1.6 m°K) corresponds very closely to the uncertainty in the galactic emission at the frequency at which he operated (8 GHz). To improve on Conklin's limit requires operation at higher frequencies. At 33 GHz the uncertainty in Galactic Emission is approximately ±0.16 m°K. This uncertainty is what will limit the accuracy of the experiment proposed here.
3. Assuming that we must operate above 30 GHz because of galactic emission, atmospheric emission (curves F and G) precludes an experiment with the desired sensitivity from being accomplished at a mountain-top altitude, unless both water vapor and oxygen anisotropies are monitored and can be subtracted. Because of large anisotropies expected for water vapor (the conservative value of 1% was plotted) the subtraction is probably impossible

even with monitoring.

4. Note that by flying several times during the year we may be able to observe the signal due to the motion of the earth around the sun, indicated by H.

To summarize the experimental problems: we cannot operate at low frequencies at which galactic emission is intense, anisotropic, and unknown. At higher frequencies, atmospheric emission poses similar problems, even at mountain-top altitudes. We believe, therefore, that the only way to do an experiment of the required sensitivity is to go to altitudes higher than those of a mountain top. The existence of parametric amplifiers (curve A) means that we can consider airplanes and balloons, where the measurement time for a single experiment is measured in hours. A satellite experiment could make use of the noisier detectors (such as diode mixer, curve (B) because of the availability of longer integration times.

Atmospheric Emission at Higher Altitudes

By going to higher altitudes, we reduce the level of curves (f) due to water vapor, and (G) due to oxygen. Let us consider experiments done at a balloon altitude (say 100 kft), and at airplane altitude (45 kft). The amount of oxygen at balloon altitude is only 2% of that at mountain top level; at 45k ft it is 25% that at a mountain top. Water vapor falls off with altitude more rapidly than does oxygen: NASA measurements indicate the residual water vapor at 45 k ft is 2-3μ precipitable, a factor of 500 times lower than at White Mountain (P. Kuhn, M. Lojko, E. Petersen, Nature <u>223</u>, 462, 1969).

Oxygen anisotropies at airplane altitudes are still sufficiently serious (amounting to approximately 0.25 m°K on the average) that they cannot be ignored completely; however if we were careful to avoid flying in regions where weather maps indicated large pressure gradients, their effect could be reduced to well below the desired measurement sensitivity of 0.2 m°K so that no subtraction would be necessary.

Leveling Requirements

An additional source of error arises if the instrument is not precisely leveled: even if there were no pressure gradient, there would be a variation of the emission of oxygen with zenith angle (proportional to the secant) that comes from the variation of the optical depth of the atmosphere with that angle. If the two horns in our apparatus operate at the same zenith angle, the atmospheric emission would cancel. Any error we make in leveling the apparatus means that the horns would have different zenith angles, and therefore would lead to an apparant anisotropy. Let us assume that each of our horns point 30° down from the zenith; then one can show algebraically that the temperature difference dT observed by the two horns, assuming the apparatus is tilted an angle $d\theta$ with respect to the normal, is given by $dT/d\theta = (4/3)T$. At balloon altitudes T is 130 m°K due to oxygen; at airplane altitudes it is 840 m°K. If we now require that dT be no more than 0.2 m°K, we get that $d\theta = 1.2 \times 10^{-3}$ radians = 4 minutes of arc at balloon altitudes. At airplane altitudes, the requirement is more severe: $d\theta = 0.18 \times 10^{-3}$ radians = 37 seconds of arc.

Either a balloon or airplane experiment would be difficult to do without expensive automatic leveling equipment. In principle, one might use microwave techniques to monitor the oxygen anisotropy (by operating simultaneously at 50 GHz, for example) and then attempt a subtraction. Such a subtraction would be very difficult: balloon gondolas swing typically by 1°; the oxygen anisotropy that one would have to subtract out would amount to 3 m°K, a factor of 15 larger than the desired accuracy. However, it is unnecessary to take this difficult (but perhaps feasible) approach, because the NASA Ames Research Center is about to begin operations of an airplane-borne research facility that incorporates a platform with sufficient stability for our needs!

The NASA-Ames C-141 Airborne Telescope

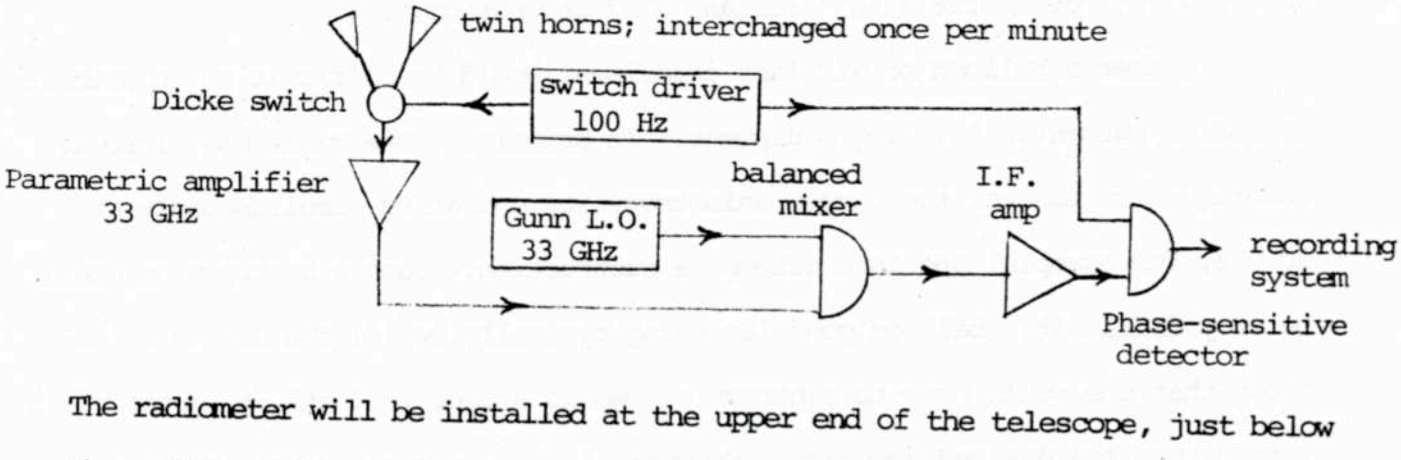
The features of this system are described in a series of Information

Bulletins available from the NASA AMES Research Center, Moffett Field, Calif. 94035, and in an article by R. Cameron, M. Bader and R. Mobley (Applied Optics, 10, 2011, 1971). The abstract from that article describes the basic system:

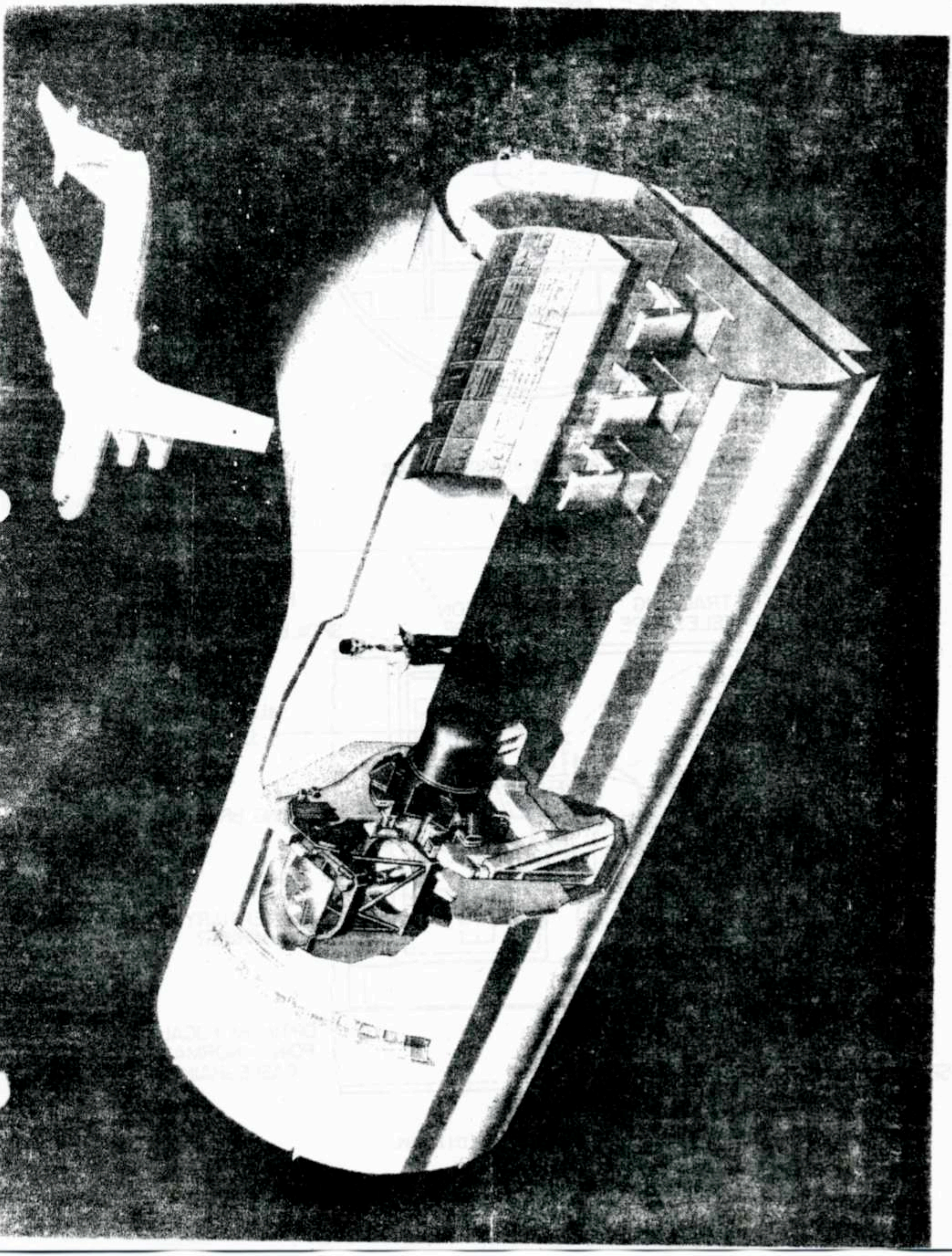
> A 91.5-cm aperture telescope is being built for ir and submillimeter observations at altitudes of 12 km to 14 km aboard a StarLifter (Lockheed C-141A) aircraft. The main optics will be totally reflecting, and aerodynamic boundary layer control will permit *open-port* operation (no material window). The elevation will be adjustable in flight between 35° and 75°. Westward flying will permit several hours' observation of an object near transit at constant bearing (azimuth) and with little change in elevation. An air bearing support with inertial stabilization and star tracking will give a net line-of-sight stability of better than 2-sec of arc rms in the open-port mode.

An artists drawing of the telescope system appears on the next page, followed by two more detailed line drawings.

For our experiment, we will make use of the telescope tracking and stabilization system, but not of the main telescope optics. We will use a two horn Dicke radiometer with a (low noise) room temperature parametric amplifier (300 MHz bandwidth) immediately following the Dicke switch, in order to achieve a front-end temperature of about 300°K at 33 GHz:



The radiometer will be installed at the upper end of the telescope, just below the orifice. We could operate as part of the normal experiment schedule, or when the telescope mirror has been removed for repair. We would make use of the raster-scan mode in order to keep the telescope pointed at the vertical: the design stability in this mode ("hands off") is 6 arcsecond peak-to-peak for 30 minutes;more than sufficient for our requirements (previously calculated to be 37 arcseconds RMS).



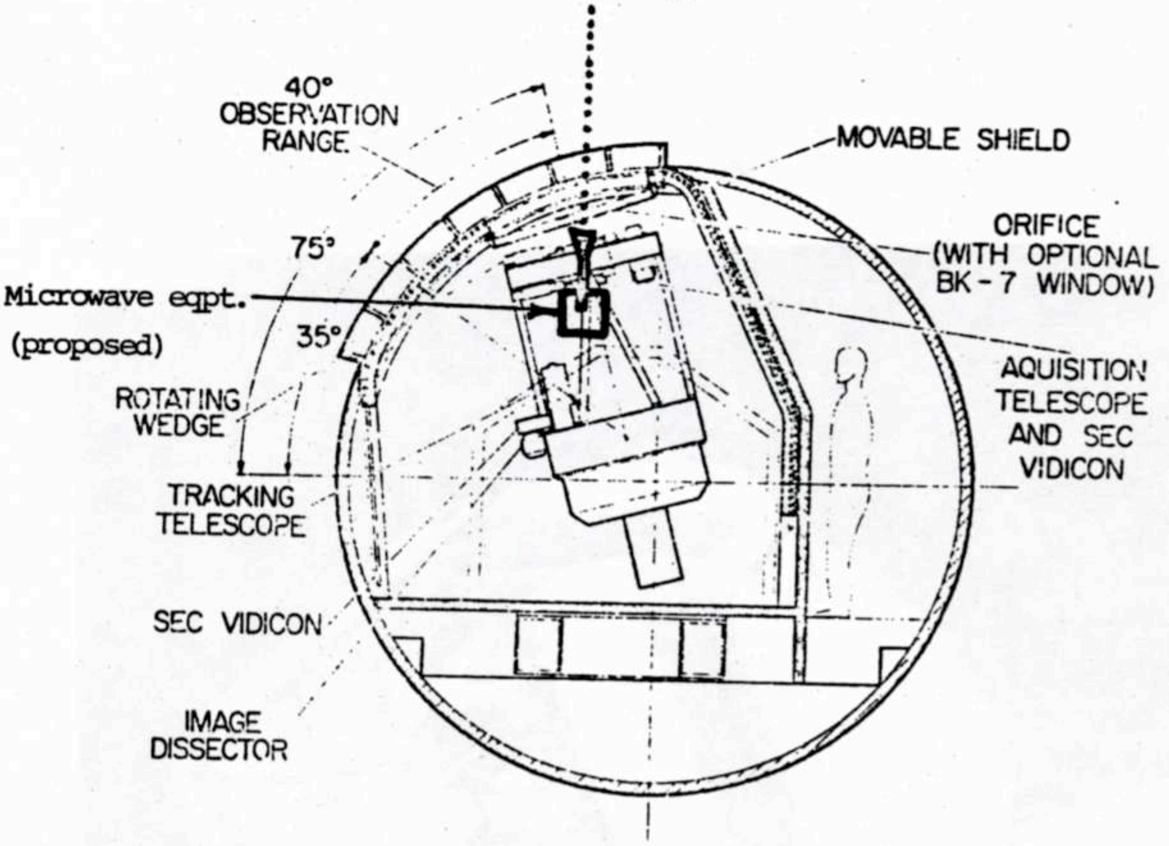


FIGURE 2: AIRBORNE 91.5-CM TELESCOPE

View Forward

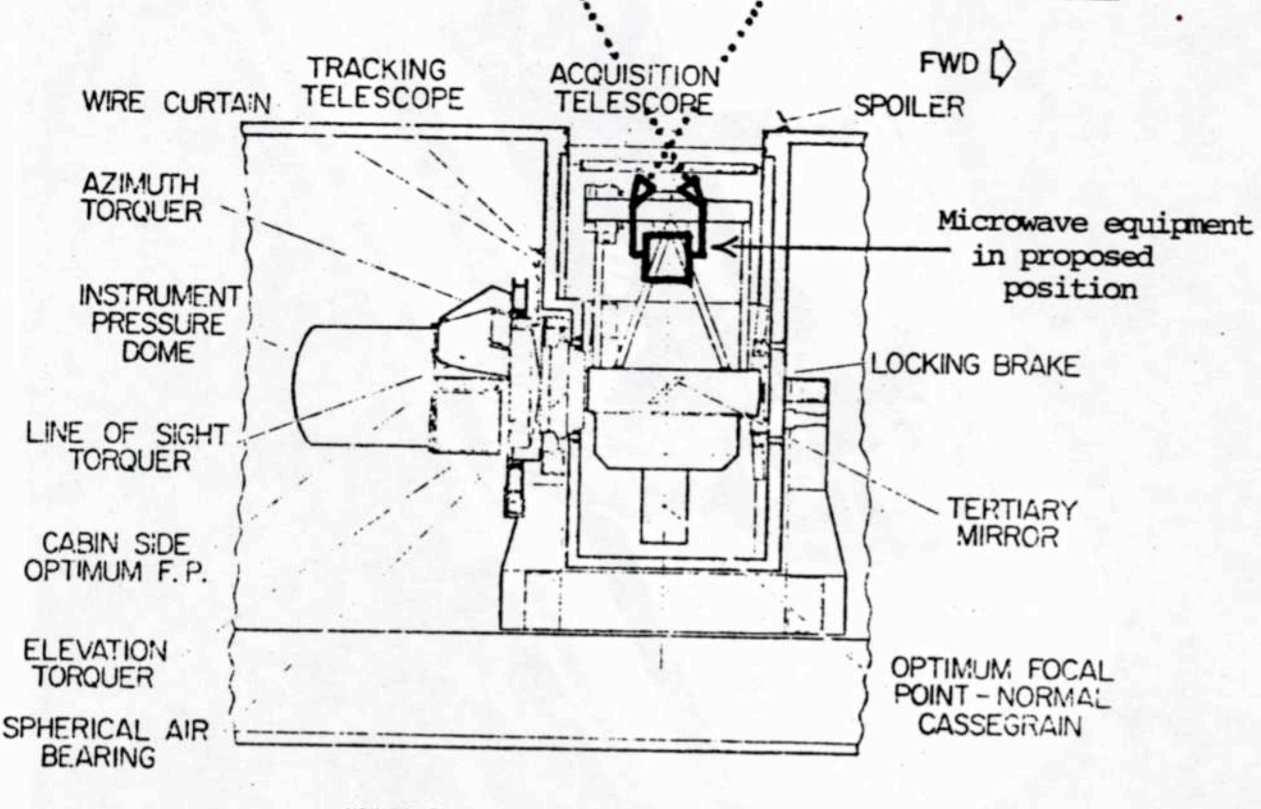


FIGURE 3: AIRBORNE 91.5-CM TELESCOPE

View Outboard

A potential new source of systematic error might be the slip-stream in the vicinity of the plane: differences in pressures arising from the flow of air over the surface of the plane could yield a systematic effect. However, the telescope was placed near the front of the C-141 in order to minimize the effect of the slip-stream and boundary layer on the system: at the telescope aperature the air should be disturbed significantly for only about six inches, according to Bob Cameron at Ames. Six inches of air contribute only 15 micro-degrees of background emission, so background noise contributed by this region is negligible.

Future improvements

The $3^{\circ}K$ black-body radiation is the only direct probe we have of the early stages of the Big Bang. If an anisotropy is discovered, we will want to study it in detail, and if no anisotropy is observed (except for the Aether drift component) it will be worth while improving further on the upper limit obtained. At 33 GHz our limit will be set by galactic background; the only way to improve upon this limit will be to operate at higher frequencies. Because both amplifier noise and atmospheric emission increase with frequency, we believe that future experiments will require operation from a satellite.