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JPL PUBLICATION 85-10

(NASA-CR-175647) MICROWAVE BLACKBODIES FOR SPACEBORNE RECEIVERS (Jet Propulsion Lab.) 50 p HC A03/MF A01 CSCL 14B

N85-23068

Unclas
G3/35 14808

Microwave Blackbodies For Spaceborne Receivers

J.M. Stacey

MAY 1985
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March 1, 1985

NASA
National Aeronautics and
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Jet Propulsion Laboratory
California Institute of Technology
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FOREWORD

Microwave blackbody targets are very sophisticated thermal, electrical, and mechanical structures that simulate in the laboratory and in the thermal-vacuum chamber the temperatures of objects and gases in space, and in the atmospheres and on the surfaces of planets. During the calibration and testing of a spaceborne receiver, the radiating surfaces of blackbody targets are positioned to be viewed at the input ports of a receiver.

Cryogens are applied to the radiating surfaces of the targets to simulate the colder temperatures expressed by seawater, freshwater, iceforms, and even the Cosmic Background itself.

When heated, the radiative surfaces of blackbody targets also simulate the temperatures of deserts, mountains, and heavily foliated regions, like rain forests.

Considered in this report are the principles of operation of blackbody targets and the practices involved in their construction and application.

Problems that affect the accuracy of blackbody targets are discussed. Some new ideas are given for the construction of blackbody targets for use in both the laboratory and in the thermal vacuum chamber. Suggestions are given that will improve the accuracy and the practicability of blackbody target structures, and also circumvent some of the existing problems.

The structure and operating principles of variable-temperature, blackbody targets are described, mainly as they are applied to blackbody use in the thermal-vacuum chamber.

On space missions, or when in Earth orbit, spaceborne receivers carry blackbody targets for internal temperature standards. Corrugated-horn antennas are also carried as a receiver component for viewing the coldest space temperature of all--the Cosmic Background.

The community of workers who deal with, or who are concerned with, the application of microwave blackbody targets is small indeed--perhaps only two or three individuals in a large research organization. Moreover, the targets are used only briefly during the construction, testing, and calibration phases of a spaceborne receiver. To this extent, blackbody targets are used, typically, for only a few weeks in as many years--perhaps as infrequently as every five or ten years.

For this infrequent application, a great deal of manpower and money is expended to construct, test, and qualify a complex thermal-mechanical-electrical target structure that is comprised of many different materials and metals that must interact with a host of cryogens, heaters, and hot gases. Some targets must also be capable of producing blackbody radiation that is precisely and variably controlled and has extreme stability at any prescribed setting.

To produce a blackbody target structure that will operate with high accuracy in the thermal vacuum chamber, and especially one that must operate variably and precisely over a large temperature range, requires extraordinary skills that embrace thermal, mechanical, electrical, and RF engineering--all operating in consonance as a dedicated team.

The controller that circulates the cryogen through the radiative surfaces of the blackbody targets is an engineering development in itself and requires specialized skills and experience in its manufacture. The controller operates initially to set the radiative surfaces of the blackbody target to a prescribed temperature and to maintain it at that temperature for as long as is required. The controller circulates liquid nitrogen and heated nitrogen gas through the radiative surfaces of the blackbody targets.

The sponsoring organization for a spaceborne receiver development is importantly affected by the need to maintain, or to have access to, calibration facilities that involve the use of microwave blackbody targets. To this end, a large, highly specialized, and very expensive inventory of environmental test equipment, thermal-vacuum facilities, and cryogens and their dispensers must be maintained as well as personnel who are trained in its use.

It seems that no one person is ever really comfortable in dealing with the many and diverse technologies that are embraced by the use of blackbody targets, especially in an operation where high precision and great accuracy are required--even the most experienced worker feels, at one time or another, that his sphere of expertise has been exceeded.

When one considers that the operating requirements for a receiver calibration sequence involving microwave blackbody targets sometimes specify that the thermal gradients in a large radiating surface (e.g., 900 cm^2, or more) be maintained to less than 0.05 K at any specified temperature setting from 80 to 320 K, and with the expectation that a controller will circulate a capricious cryogen in both its liquid and heated gaseous phases in doing so, it is of little wonder that a truly successful calibration sequence is viewed by some technicians with considerable awe: Some feel that, at the very least, concentrated distillates of legerdemain, blackmagic, and witchcraft--arriving from somewhere--must have surely influenced the outcome.

ACKNOWLEDGMENTS

The construction and application of microwave blackbody targets used to test and calibrate spaceborne receivers are relatively new and truly esoteric technologies.

The few who use them in practice will agree that successful application is bounded mainly by hands-on experience.

It was long-term, hands-on experience, then, and the counsel of Jim (E.J.) Johnston, Pete (F.O.) Olson, Fred S. Soltis, and Richard S. Iwasaki that made this monograph possible.

ABSTRACT

The properties of microwave blackbody targets are explained as they apply to the calibration of spaceborne receivers. Also described are several practicable, blackbody targets used to test and calibrate receivers in the laboratory and in the thermal-vacuum chamber.

Problems with the precision and the accuracy of blackbody targets, and blackbody-target design concepts that overcome some of the accuracy limitations present in existing target designs, are presented.

The principle of the Brewster-Angle blackbody target is described where the blackbody is applied as a fixed-temperature test target in the laboratory and as a variable-temperature target in the thermal-vacuum chamber. The reflectivity of a Brewster-Angle target is measured in the laboratory. From this measurement, the emissivity of the target is calculated.

Radiatively cooled thermal suspensions are discussed as the coolants of blackbody targets and waveguide terminations that function as calibration devices in spaceborne receivers. Examples are given for the design of radiatively cooled thermal suspensions.

Corrugated-horn antennas used to observe the Cosmic Background and to provide a cold-calibration source for spaceborne receivers are described.

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INTRODUCTION

This report is concerned with the design and practical operation of microwave blackbody targets as they are applied to qualify, test, and calibrate spaceborne receivers.

Microwave blackbody targets are conceived as thermal-mechanical-electrical structures that conform to the requirements for blackbody radiation. In practice, blackbody targets are positioned at the input ports of receivers to simulate signals and to test input-output relationships.

The average power (flux) radiated by a microwave blackbody target is expressed by

$$\bar{P}_{Tar}(\nu,T) = \frac{h\nu}{e^{\frac{h\nu}{KT}} - 1}, \text{ W/Hz} \qquad (1)$$

where

h = 6.62520E-34 joules, Planck's constant.

k = 1.38046E-23 joules, Boltzmann's constant.

T = Temperature of the blackbody in kelvins.

ν = Frequency in hertz.

The flux radiated by a blackbody is a nonlinear function of its temperature. The deviation from linearity is expressed by the exp ($h\nu/kT$) term in (1).

A blackbody target that operates at 300 K (ambient temperature) radiates a flux level of 412.91 fW into a predetection bandwidth of 100 Mhz, which is centered at 37 GHz. At a target temperature of 77.36 K (liquid nitrogen), the flux level reduces to 105.57 fW. The nonlinearity is slightly less than 1% over this temperature range.

A trivial mathematical manipulation simplifies and reduces (1) to

$$\bar{P}_{var} \cong kT \text{ W/Hz} \tag{2}$$

for the case where $h\nu/kT$ is small, as it is in the microwave region.

Expression (2) is a very good approximation of (1). The importance of (2) is that it gives a simple, conceptual, operating relationship between radiated flux and blackbody temperature.

By the principle of reciprocity, blackbodies absorb and radiate microwave power. The emissivity is equal to 1. The radiated flux is randomly polarized.

The only natural blackbody is the Cosmic Background, whose measured temperature is 2.7 K with a 1-sigma uncertainty of 0.15 K (circa 1980).

One important application of the blackbody target, as it is used to qualify spaceborne receivers, is to produce a variable signal that moves over a prescribed interval of the dynamic temperature range of a receiver. Blackbody targets are sometimes used as signal sources to produce variable flux levels that are applied to the input ports of receivers. From the input-output responses of a receiver, the mathematical form of the transfer function may be derived.

Receivers produce internal noise waveforms whose statistical properties are characterized as stationary. That is, the mean and variance are significantly invariant with time. The signals that receivers must deal with, however, are characterized by nonstationary statistics; that is, the mean, standard deviation, and variance change with time depending upon the character and the pattern of the media being observed.

Noise waveforms with nonstationary statistics can be simulated in the laboratory by a blackbody target that radiates variable flux levels. For example, as the temperature of a blackbody target is lowered from 300 to 80 K, the mean and the variance of the radiated noise waveform decrease even as the process progresses. To this extent--albeit imperfect--a nonstationary noiselike signal is simulated.

Microwave blackbody targets importantly serve as secondary temperature standards for use in the laboratory; mainly, they are cooled by liquid nitrogen, solid carbon dioxide, and ice water. Where elevated emission temperatures are desired to produce higher flux levels, the radiating surfaces of targets are affixed with electric heaters. Alternatively, some are designed to circulate hot inert gases.

Typically, the emissive surfaces of targets are imbedded with very precise thermometers, such as platinum-resistance elements or thermisters.

Blackbody targets are frequently contained within the mechanical structure of a receiver to function as a stable reference temperature or an internal calibrator.

Variable-temperature blackbody targets are operated in a vacuum chamber to prevent icing and frosting of their emissive surfaces. In practice, variable-temperature targets are required where it is necessary to change the temperature of the emissive surfaces (e.g., from 80 to 320 K) and to accurately and stably set the operating temperature anywhere within a range. From this capability, the input-output transfer function of the receiver, or its linearity, may be determined.

Sometimes in the testing and verification of spaceborne receivers, blackbodies may, of necessity, have to interact with one another. This is especially true for blackbodies contained within a microwave structure, such as an RF modulator switch, or in any low-loss microwave cavity where blackbodies are inextricably coupled together by their electromagnetic fields. In particular applications, blackbodies may be in direct view of one another and in addition be coupled by their electromagnetic fields.

For these interactive situations, it is informative and useful to consider that blackbodies are controlled by the Laws of Thermodynamics in the manner in which they radiate and absorb blackbody radiation.

When two blackbody radiators are in thermal equilibrium with a third, they must also be in thermal equilibrium with each other. This is a consequence of the Zeroth Law of Thermodynamics. A practical manifestation of this law is suggested by the example of an RF modulator switch that contains more than one blackbody termination, with the expectation that all of the blackbodies are mutually coupled by at least their electromagnetic fields and some may also have a direct view of one another. If for any reason one or more of the blackbodies changes its temperature in any way, the temperatures of all other blackbodies will be ineluctably affected in a matter of degree. An actual example for this case is where solar irradiance propagated through an open-hole aperture of a waveguide section and caused local heating of one of the blackbody terminations in an RF switch. Because of this, the output response of the radiometer was affected in a spurious way by the corresponding change in temperature of a different blackbody termination within the body of the switch structure.

Microwave flux is transferred from a blackbody at a higher temperature to one at a lower temperature, and never the other way around. Flux that is intercepted by the lower-temperature blackbody can never return to the higher-temperature blackbody. This is a restatement of the Second Law of Thermodynamics as it applies to blackbodies. A practical example of this law is suggested when two reentrant-pyramid targets are oriented to face each other. If one target is elevated in temperature with respect to the other, the target at the higher temperature radiates flux--the lower temperature target absorbs it.

THE CRYOGEN-COOLED DEWAR TARGET

The most common laboratory target structure is the cryogen-cooled Dewar containing a microwave absorber as the blackbody radiator. See Figures 1 and 2. In this concept, the antenna, or, more typically, the feed aperture of the receiver, views the absorber through the liquid-nitrogen cryogen. The emission temperature of the blackbody radiator immersed in the liquid nitrogen is given by the boiling temperature of the liquid nitrogen, which is also affected slightly by atmospheric pressure:

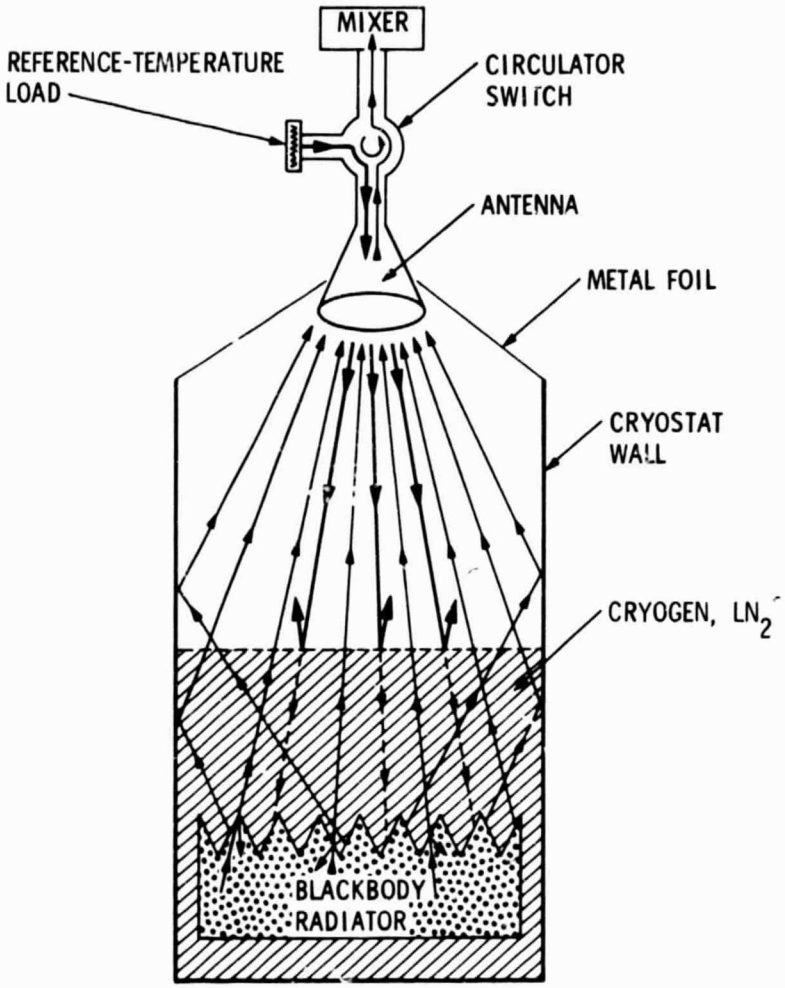

Figure 1. Cryogen-Cooled Target: Absorber Immersed in Cryogen

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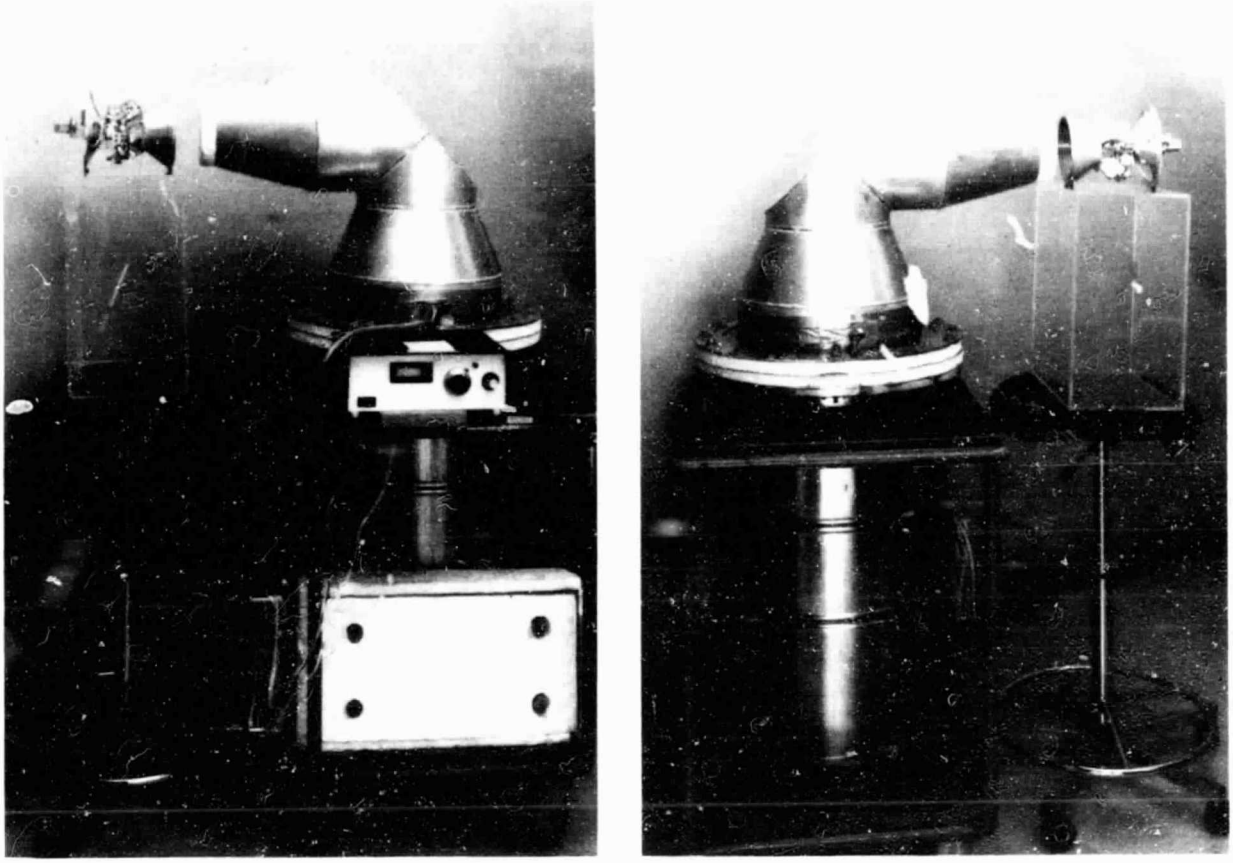

Figure 2. Dewar-Contained Blackbody Target

The practical embodiment of a cryogen-cooled (LN_2), microwave, blackbody target, as it is contained in a Dewar for general-purpose laboratory use.

A flat, blackbody target is positioned on the bottom of the Dewar where it is viewed by a feed horn (antenna). A ray passing between the blackbody target and the feed horn executes a 90-degree turn at the flat mirror and thereafter passes through the microwave-transparent, white-foam window.

The cylindrical diameter of the Dewar and the window diameter for the feed (in the frustrum of the cylindrical cone) are 50 and 18 cm, respectively.

On the lower deck of the table, and in the geometrical figure of a rectangular prism covered with white foam, is a chamber where the liquid nitrogen is heated to form a dry gas that continuously purges the volume within the Dewar above the level of the liquid nitrogen.

The electric, heat-controller unit for the purging nitrogen gas is shown on the top deck--it is set to maintain the temperature of the gas at approximately 268 K.

$$T_{LN2} = 77.36 + 0.011\ (P_a - 760),\ K$$

where P_a is the ambient pressure of the atmosphere in mm of mercury.

The accuracy of the cryogen-cooled, Dewar-type target is affected by several practical problems that diminish the target's general acceptability. The space above the liquid nitrogen must be free of all moisture to prevent the formation of frost and ice crystals on the surface of the liquid nitrogen and on the sides of the Dewar. In practice, it is constantly purged with dry, warm, nitrogen gas.

Another problem is that the emission from the reference-temperature load or other dissipative components in the front-end of the receiver is reflected from the dielectric boundary layer of the liquid nitrogen and reenters the receiver as an error contribution to the blackbody radiation from the absorber. This component is shown by bold arrows in Figure 1.

The dielectric constant of liquid nitrogen at microwave frequencies is 1.454.

The power reflected from a dielectric in air at normal incidence is given by

$$P_{refl} = \left| \frac{1 - \sqrt{\varepsilon}}{1 + \sqrt{\varepsilon}} \right|^2 \tag{3}$$

where

ε = the dielectric constant

The power reflection coefficient for liquid nitrogen at normal incidence is 0.0087, which produces an additive 2.5-K component to the nitrogen-immersed blackbody radiator, assuming that the temperature of the passive radiation element in the receiver is in thermal equilibrium at 290 K.

Another annoyance provoked by the reflection propensities of both the cryogen liquid[1] and the imperfect absorber is the incident local oscillator power emanating from the feed. Where local oscillator emissions and their harmonics are not effectively suppressed, or are internal to the receiver, or averted in some manner, the accuracy of the target becomes suspect.

Because of the problems associated with icing in the upper chamber area, dielectric reflections at the air interface, and the imperfect properties of flat absorbers, some investigators have abandoned the LN_2 cryogen-cooled target. Nevertheless, for purposes of setting gain-scale factors in receivers and for estimating temperature resolution, it is still retained as a practicable and low-cost embodiment of a cooled target.

LIQUID-NITROGEN-COOLED TARGETS WITH FOAM-LOADED RADIATING APERTURES

Two variations of the laboratory-type, cryogen-cooled, blackbody radiator (Figure 1) are shown in Figures 3 and 4. These target configurations have advantages, mainly because the air-dielectric interface is eliminated in the path between the blackbody radiator and the feed. The radiation from the reference-temperature load and the local oscillator in the receiver is also absorbed without reflection.

The reentrant-pyramid figure for the blackbody radiator is superior to flat radiators because surface reflections are importantly absorbed by multiple reflections.

The foam on the surfaces of the absorbers suppresses the formation of ice and frost.

---

[1]An innovative approach for the reduction of reflections from the dielectric, and for improving the transfer of power in the air-liquid nitrogen to the blackbody interface, is conceived by E. J. Johnston (JPL). In this concept, the surface of the dielectric is agitated with a periodic or aperiodic waveform to improve the impedance match at the air-liquid interface.

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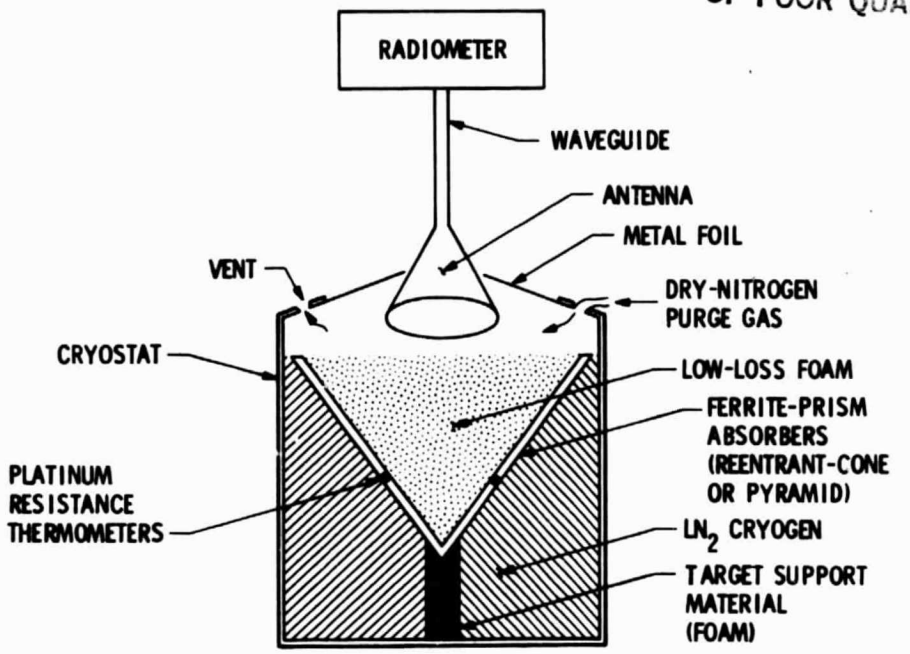

Figure 3. Cryogen-Cooled Target: Foamed, Radiative Surface

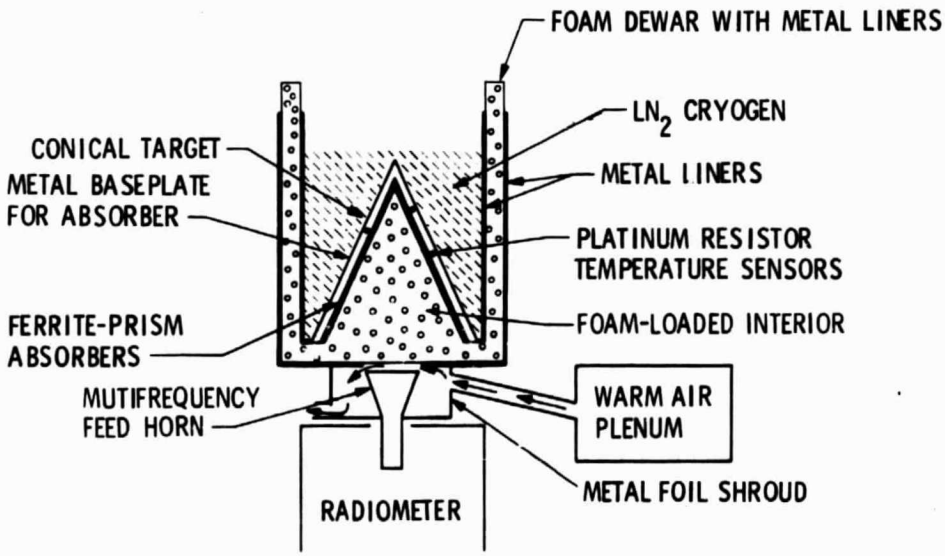

Figure 4. Blackbody Target (Zenith Viewing)

Both linear polarizations in a dual-polarized feed are absorbed by the reentrant pyramid design, albeit imperfectly and not identically. The reentrant pyramid is importantly adaptable to the principle of absorption at the Brewster Angle.[2]

The Brewster Angle is expressed by $\Theta_{BR} = \tan^{-1} \sqrt{\varepsilon}$. Notably, the Brewster-Angle absorption concept is implemented both in the prisms that are machined on the absorber surface and in the taper of the walls to the apex of the pyramid.

AMBIENT-TEMPERATURE BLACKBODY RADIATOR

A general-purpose blackbody target that is mainly intended to be viewed by a feed aperture for laboratory tests at ambient temperatures is shown in Figure 5.

The geometrical configuration of the target is a reentrant pyramid with ferrite-epoxy absorber elements serving as the emissive surfaces. Each absorber element that comprises the target area is individually shaped to absorb energy at the Brewster Angle. The dielectric constant of the material in this particular design is $\cong$ 20.

The walls of the pyramid are also fixed at the Brewster Angle with respect to the incident radiation to further enhance the absorptivity of the target on multiple reflections. The figure of a reentrant pyramid was chosen over a conical figure mainly for ease of construction and lower cost.

The Brewster-Angle absorber elements are moulded as ferrite prisms on aluminum plates to form a tile as shown in Figure 6. The tile dimensions are 10 cm on a side, as illustrated. The tiles are cut and fitted to form the

[2]The concept and development of the Brewster-Angle Reentrant-Pyramid Target, as shown and discussed here, is credited to R. S. Iwasaki (JPL).

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sides of the pyramid. Heavy copper plates form the sides of the pyramid and the absorber tiles are secured to them by machine screws. To improve the thermal contact between the aluminum baseplates of the absorber tiles and the copper walls, thermal grease is applied.

The tile structure, as shown in Figure 6, has been elaborately tested to survive repeated thermal cycling from 320 to 80 K. Very cursory tests also show that the tile survives repeated shock immersions into liquid helium without apparent damage to its physical structure. From these preliminary tests, the tile shows promise as a candidate absorber for a variable-temperature blackbody to operate at helium temperatures, i.e., 4.2 K.

Platinum resistance thermometers are imbedded into the apexes of the ferrite prisms to improve the measurement accuracy of the thermometric temperature of the ferrite material near the prisms' absorbing surfaces. The target may be adapted for operation at elevated temperatures by affixing heater elements to the copper faceplates.

The measured emissivity of this target is >0.9995 as based on VSWR measurements at both horizontal and vertical polarizations.

The power reflection coefficient is expressed by

$$P_{refl} = \left| \frac{VSWR - 1}{VSWR + 1} \right|^2 \tag{4}$$

where

VSWR is expressed by a number greater than 1.

Emissivity is defined by

$$E = 1 - P_{refl} \tag{5}$$

The emissivity is computed from a VSWR measurement of 1.05 at 6.6 GHz where the VSWR measurement was determined to be the residual VSWR measurement capability of the reflectometer.

VARIABLE-TEMPERATURE BREWSTER-ANGLE BLACKBODY TARGET

A variable-temperature target configuration is adapted from the room-temperature target shown in Figure 5. The details of the structure, when affixed with cooling coils and when instrumented by platinum-resistance thermometers, are shown in Figure 7. Typically, about 16 platinum thermometers are imbedded near the apexes of the ferrite prisms, as shown within the pyramid structure. In practice, an equilibrium temperature is declared when the thermometers stabilize to less than 0.1 K of each other. The outside copper walls are affixed with coils for circulating nitrogen both in the liquid and heated-gas states. A key element in the variable target design is the servocontroller that regulates the temperature and the flow rate of the nitrogen through the coils. The controller permits a specified temperature to be set, and the platinum resistance thermometers that are imbedded in the prisms serve as the feedback element to stabilize the target at the prescribed temperature setting. Higher target temperatures are achieved by circulating heated nitrogen gas through the coils. Because of the thermal inertia of the target, an hour or more is required for the target to stabilize to a target-temperature change of 25 K in the thermal-vacuum chamber. The target, as shown, operates at any specified temperature from 80 to 325 K. The accuracy of the setting is determined by the platinum resistance thermometers operating as feedback elements.

The target operates in an air-evacuated (thermal-vacuum) environment to prevent frosting of the emissive surfaces.

The use of the variable temperature target is sine qua non for the measurement of subtle nonlinearities present in the signal transfer responses of microwave receivers.

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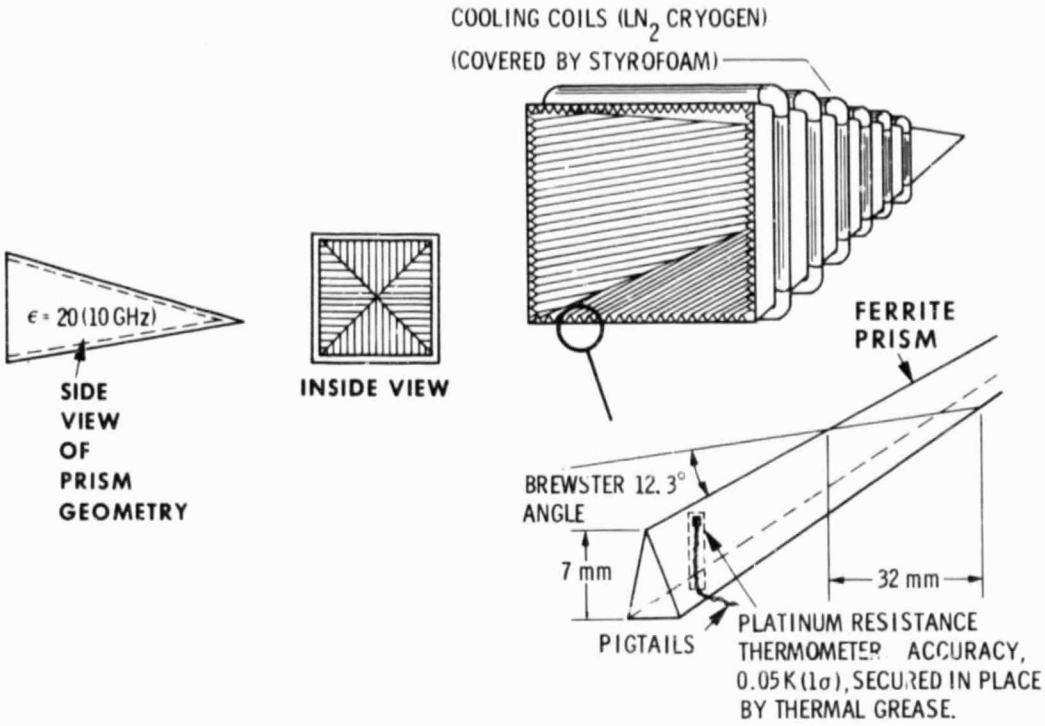

Figure 7. Microwave Blackbody Target: Reentrant Pyramid

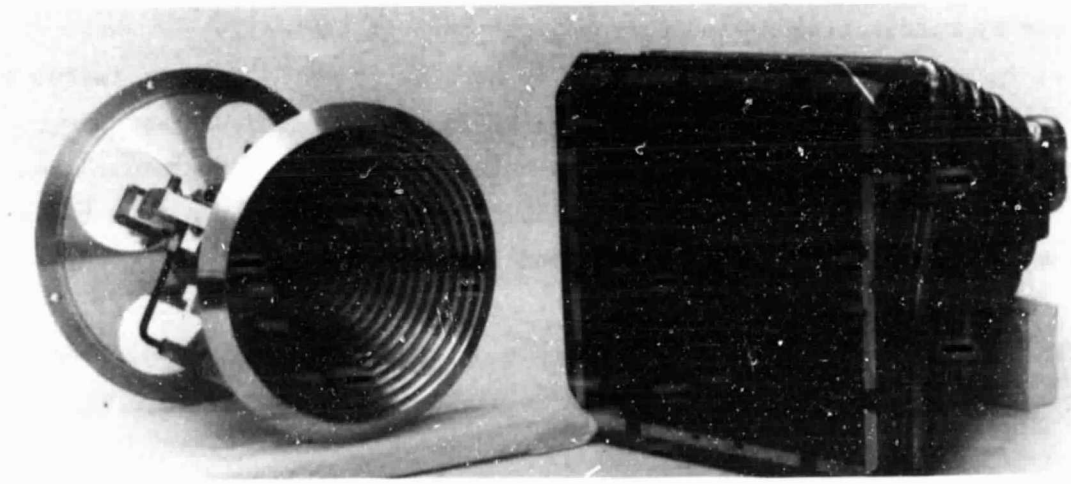

Figure 8. Variable-Temperature, Brewster-Angle, Blackbody Target With Cooling Coils Attached

Figure 8 depicts a multifrequency feed assembly that is positioned near the opening of a reentrant-pyramid blackbody target. The feed is wideband and operates over 2.5 octaves in frequency and at five discrete frequencies with both horizontal and vertical polarization at each frequency--basically, a ten-channel feed assembly. The figure illustrates the methodology for calibrating all ten channels of a spaceborne receiver, simultaneously, by using the variable-temperature blackbody radiator.

The temperature of the target is varied from 350 to 80 K by circulating liquid nitrogen gas through the coils that are affixed to the outside walls of the reentrant-pyramid target. The target is operated in the vacuum chamber where the temperature increments are changed (typically) in 25-K steps over the total temperature range of the target. For any particular temperature setting of the target temperature controller, the emissive surfaces of the target are declared to be in equilibrium when the platinum thermometers are within 0.1 K. The accuracy of the platinum thermometers is traceable to a primary temperature standard.

The emissivity of the absorptive surfaces of the target is greater than 0.9995 based on a 6.6 GHz measurement.

RADIATIVELY COOLED THERMAL SUSPENSIONS

The signal or antenna temperatures received by Earth-orbiting receivers commonly range from about 100 K when viewing smooth water surfaces to about 310 K when viewing hot land masses. To calibrate this range of signal temperatures, it is desirable to provide calibration temperatures that are within the same temperature range as the signal temperatures. In this way, extrapolation distances are minimized and the curvature in receiver input-output responses is more closely accounted for. The need then arises for a cold-calibration temperature that operates suitably within this range. The radiatively cooled blackbody target emerges as a candidate calibration source for the circumstances where calibration temperatures are satisfied within the range from 100 to 200 K. The radiatively cooled blackbody target

concept, as it is adaptable to serve the needs of a cold-calibration source, is illustrated in Figure 9. This is, in fact, an operational, radiatively cooled blackbody that is designed to cool several waveguide terminations. The waveguide termination sections are clamped to the aluminum plate (18 x 18 cm) that is in turn cooled by a radiative cooler (infrared radiation) in the form of a matrix of two-surface mirrors. The mirrors operate as a cooler to transfer heat in the infrared to the Cosmic Background by the principle of the Second Law of Thermodynamics.

The term "radiatively cooled" deserves more explanation. In the context that the term is used here, the heat in the metal plate (a thermal suspension) is transferred to the Cosmic Background by the principle of the Second Law of Thermodynamics. That is, the heat is always transferred from a warm to a cold body and never the other way around.

Stainless-steel waveguides are affixed to the waveguide terminations on the plate to minimize thermal conduction from the plate to the receiver chassis. The plate itself is supported by long thermal insulators in the form of fiberglass rods.

A more efficient design from the standpoint of providing lower operating temperatures is shown in Figure 10. In this concept, the radiatively cooled plate supports microwave targets that thermally equilibrate to the plate temperature. The important consideration illustrated here is that the waveguide transmission lines are not in physical contact with the plate or the cooled targets and the conductive thermal path is therefore eliminated. The plate can, therefore, be reduced to lower calibration temperatures. A variety of targets and target configurations can be affixed to the plate to accommodate several types of target-viewing antennas.

One interesting target configuration is illustrated in Figure 10; it is in the form of a reentrant cone with tapered prism corrugations that run longitudinally along the inside cone surface. The absorptive material in the target is machined to absorb the incident radiation at the Brewster Angle both

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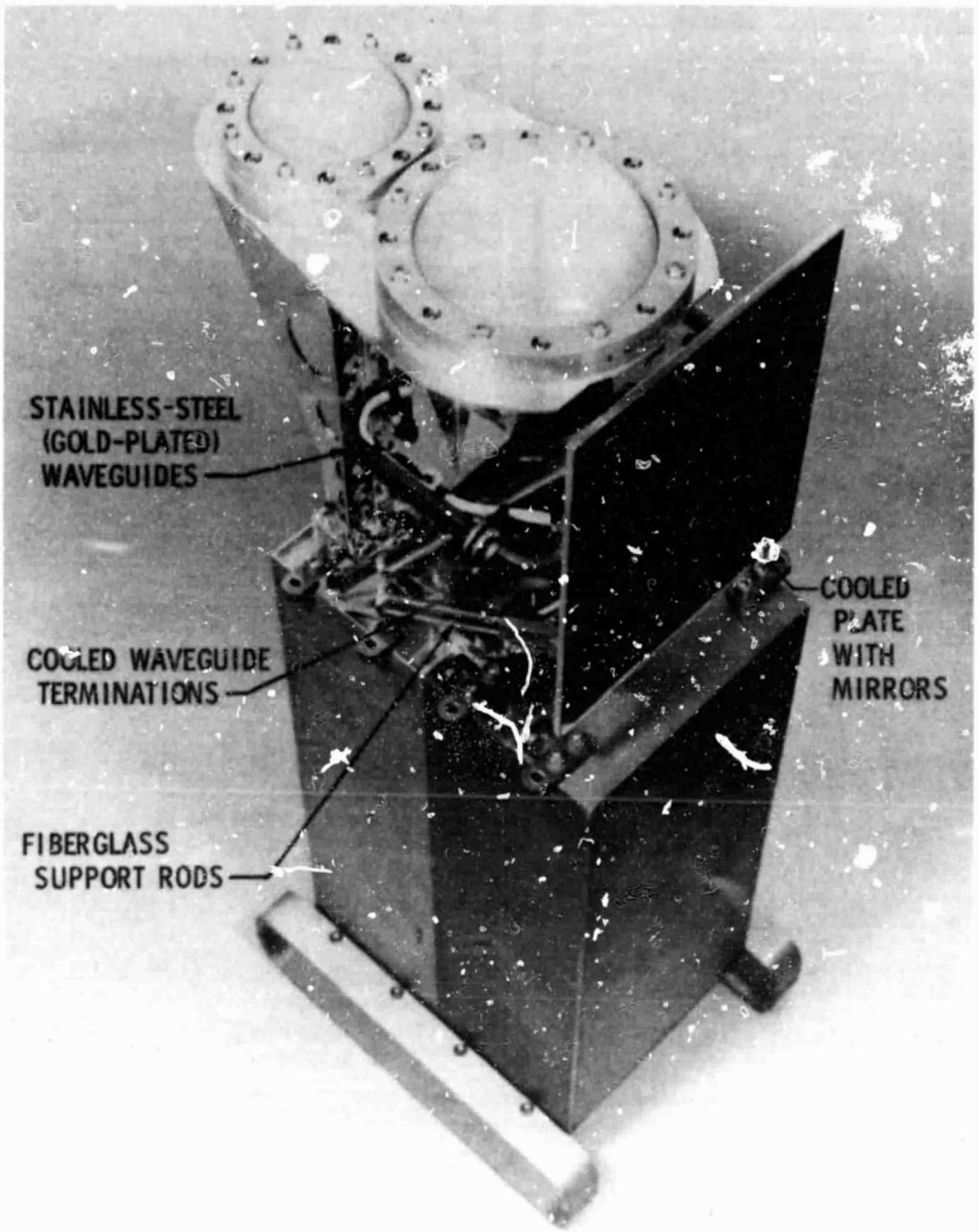

Figure 9. A Two-Channel Receiver With Radiatively Cooled Waveguide Loads

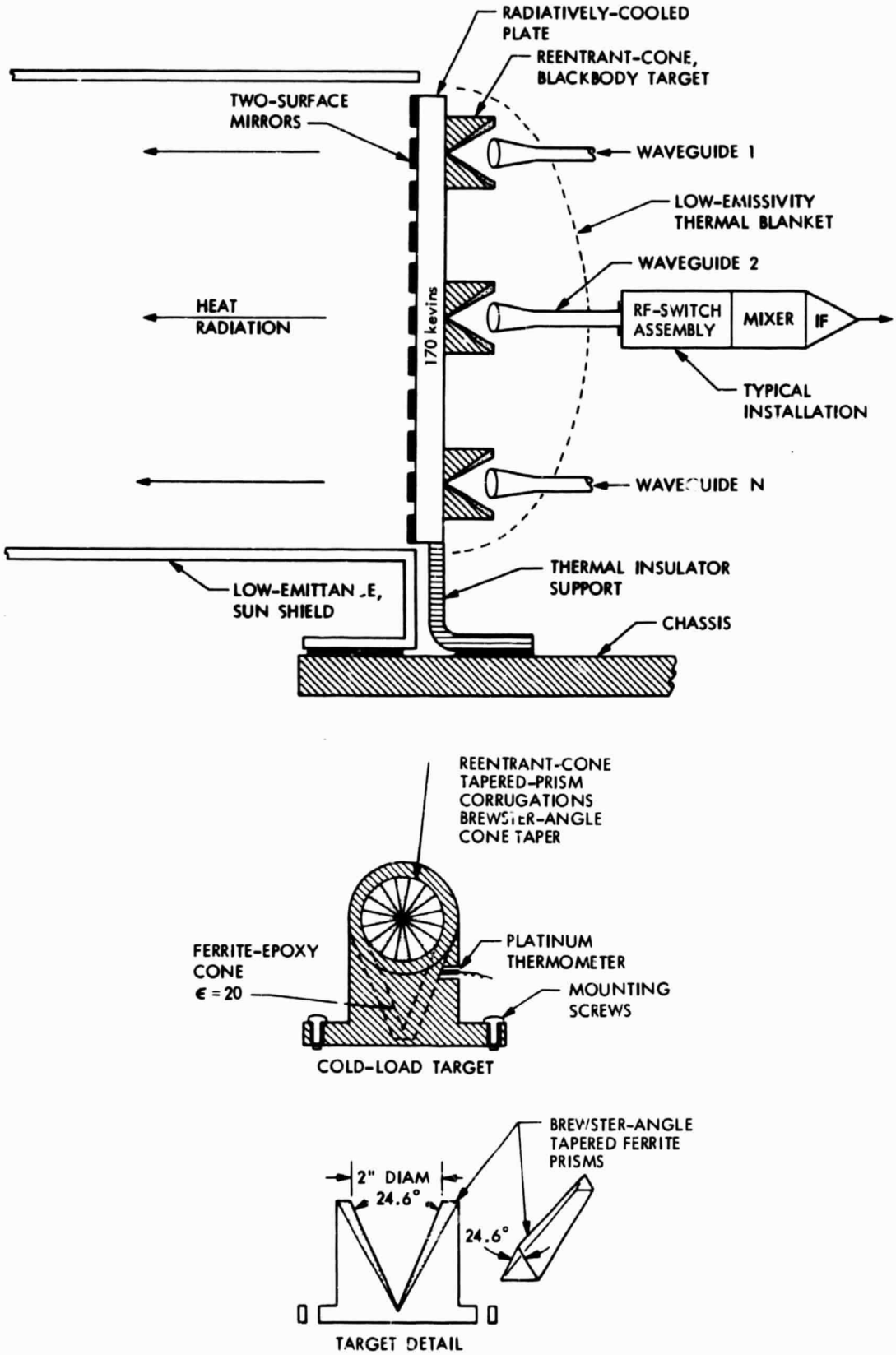

Figure 10. Radiatively Cooled Target Concept

in the cone angle and in the apex angles of the prisms. Alternatively, where a less-efficient target is tolerable, flat prism sections as shown in Figure 6 are simple and sometimes suitably efficient. By expectation, the conical target configuration can provide emissivities greater than 0.999 in the microwave region. The flat target is considerably less absorptive and is more polarization sensitive.

A low-emittance sunshield is required to direct the infrared radiation from the mirrors in a preferred direction to avoid intercepting the infrared irradiances from structures on the spacecraft and to minimize the occurrence of solar irradiance on the cold plate itself.

The radiatively cooled blackbody target concept, as shown in Figure 10, may provide cold-calibration temperatures in the range from 150 to 200 K.

Actually, the radiatively cooled target is somewhat resistant to solar irradiance because the two-surfaced mirrors offer high reflectivity to incident sunlight, when and if this may briefly occur in a given orbit. Even so, if the solar irradiance is sustained uniformly on the mirrors for a length of time, the temperature of the targets will be affected.

The radiatively cooled blackbody target is invulnerable to manmade radio-frequency interference arising from its companion spacecraft sensors or from ground-based transmitters. This is a considerable advantage and may importantly influence the adoption of this class of calibration device in certain applications.

A critical design consideration in the construction of any cooled suspension (plate) is to ensure that the thermally conducting paths from the plate to the instrument chassis are minimized. In fact, it is this very feature that controls the minimum temperature that can be achieved by the plate.

The radiatively cooled plate[3] shown in Figure 9 is severely penalized for achieving a temperature lower than about 200 K because the large stainless-steel waveguides that interconnect the plate with the chassis conduct an undesirable amount of heat into it. Also, the long fiberglass rods that provide mainly the thermal insulation are cumbersome and undesirable because they adversely affect the vibration properties of the cooled structure.

THERMALLY ISOLATED SUSPENSIONS

A superior design[4] for a radiatively cooled plate is shown in Figure 11. The cooled plates (thermal suspensions) are shown suspended by monofilament fiberglass bands, which provide the thermal isolation from the base mounting. When the bands are firmly tensioned, the plates become a very stiff mechanical structure. It is stable in six dimensions and will qualify for the most stringent shake and vibration tests. Actually, this particular suspension has been environmentally qualified and flown in space with thermoelectric coolers.

In the practical implementation of the thermally isolated suspension, one side of the plate is cooled by either a thermoelectric device or by radiation to the Cosmic Background by the principle of the Second Law of Thermodynamics. Second-law coolers operate in the infrared. When second-law coolers are attached, they must also be supplied with a sunshield and properly oriented so that the radiation from the cooler is not obstructed by spacecraft structures.

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[3]The radiatively cooled thermal suspension (plate) shown in Figure 9 is credited to James W. Stultz (JPL). This device cools waveguide terminations on a multichannel spaceborne receiver that has been in orbit for over a decade; it has consistently maintained a waveguide termination temperature of 200 K $\pm$1 K (3 sigma).

[4]The radiatively cooled thermal suspension as it is illustrated in Figure 11 is credited to Robert M. Bamford (JPL).

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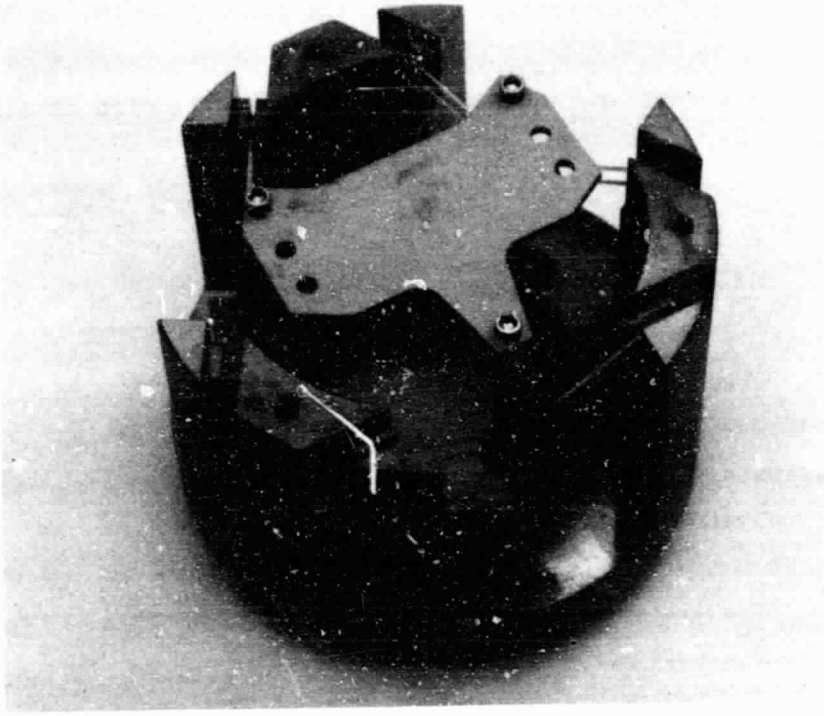

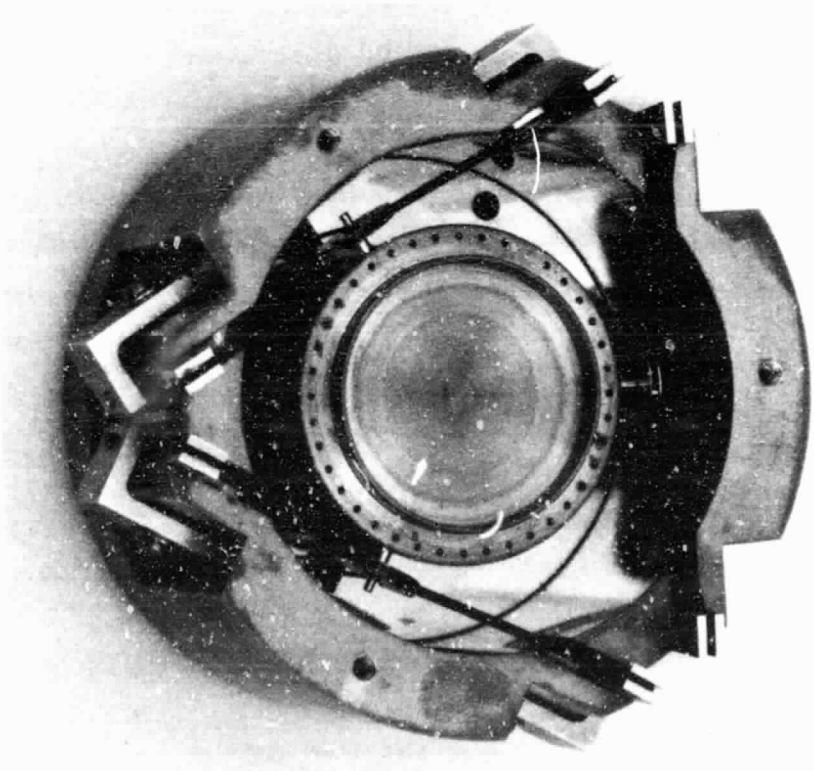

Figure 11. Thermally Isolated Suspensions

Thermally isolated suspensions and their associated cooler mechanisms are capable of producing stable temperatures in the range from 100 to 200 K depending upon a host of factors such as the size of the targets to be cooled, the type of cooler mechanism, and even the way the suspension itself is fitted to the instrument that carries it.

COSMIC BACKGROUND CALIBRATION HORNS

The Cosmic Background calibration horn is manifestly the most widely used of all cold-calibration devices as evidenced by its prevalent usage on spaceborne receivers. The mechanical structure of the horn is simple and it possesses the additional attributes of low weight, low volume, and in a relative sense as compared to other cold-calibration devices, low cost.

Because the temperature of the Cosmic Background is so low (2.7 K), the dissipative losses within the calibration horn and the transmission components that follow it importantly determine the magnitude of the calibration temperature as it is introduced into the input terminals of the spaceborne receiver.

As an example, consider a Cosmic Background calibration horn that is connected to the input terminals of a spaceborne receiver through a short length of waveguide. If the dissipative losses of the horn and the waveguide are both only 0.2 dB, and if they are maintained at a temperature of 300 K, the 2.7-K temperature of the Cosmic Background appears as a cold-calibration temperature of 29 K at the input terminals of the spaceborne receiver.

One disadvantage of using the Cosmic Background as a calibration source is that the 2.7-K temperature is cumbersome and expensive to simulate in the laboratory, or in the thermal vacuum chamber--and especially if a variable-temperature target is used. Liquid helium is required to produce a 2.7-K temperature in the test chamber.

In practice, because of the technical difficulties and costs of simulating the Cosmic Background temperature in the laboratory, it is typically not done. Liquid-nitrogen temperature targets (80 K) are substituted as the lowest calibrated temperature with the expectation that the spaceborne calibration accuracy of the receiver is compromised to some indeterminate degree.

In the practical installation of the cold-calibration horn on the spacecraft, considerable attention is given to maintain its field of view in a preferred attitude that sustains an unobstructed view of the Cosmic Background. This requirement is more easily achieved if the calibration horn projects a very narrow beamwidth. Further, the sidelobes and backlobes of the horn must be extremely low to prevent spurious radiation from the spacecraft and the Earth from entering the calibration horn.

The corrugated horn feed meets all of these requirements well. An improvement on the conventional corrugated horn is an extension to the corrugations around the feed aperture; this extension sustains the length of the corrugations and operates as an RF choke section to further reduce surface currents. See Figure 12.

The choke sections, in combination with a compatible design for the feed and its internal corrugations, operate to drastically reduce the sidelobe levels, especially at the far-angle sidelobes. This is of considerable importance in the cold, calibration-horn application to minimize spurious emissions and radiations from the spacecraft, the earth, and from the sun. The calculated and measured antenna patterns (Ref. 1) for the corrugated horn (Figure 12) show sidelobe levels (Figure 13) that reduce to -80 and -90 dB at off-axis angles exceeding 90 degrees.

When the calibration horn suffers an exposure to solar irradiance at some time in the orbit, it requires elaborate protective measures. Ultraviolet-visible-infrared (UVI) irradiances produce extraordinary heating and thermal gradients in the machined surfaces of the feed. Ultimately, by thermal conductivity, heat is transferred into the waveguide structures and RF switches

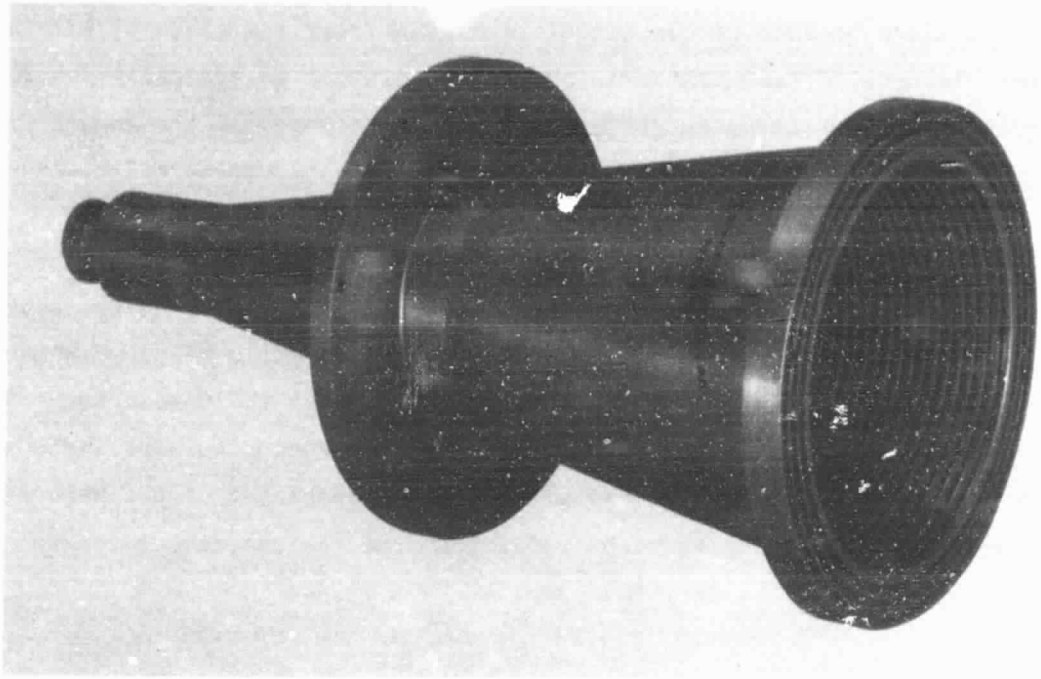

Figure 12. Corrugated Horn Feed With Extremely Low Sidelobes and Backlobes

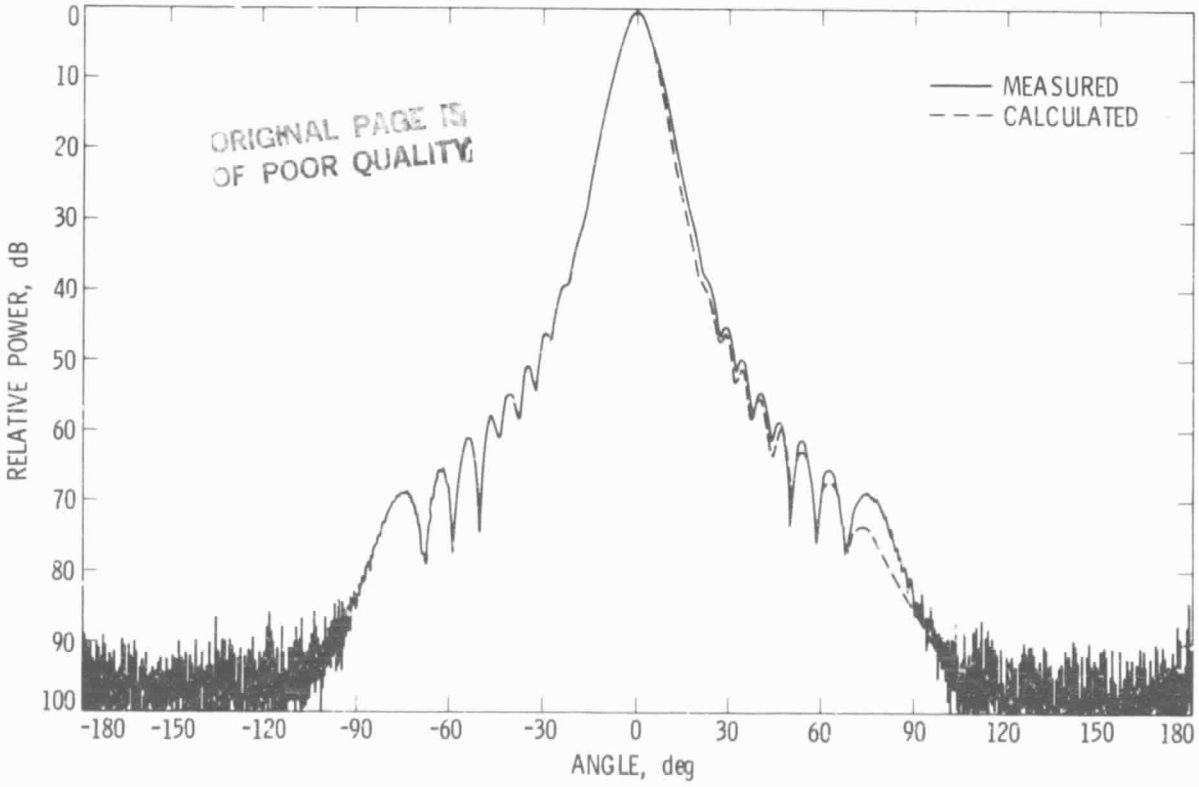

Figure 13. Corrugated, Conical Feed-Horn Pattern (Low-Sidelobe Sky Horn)

that control calibration and signal intensities. UVI irradiances that enter the collecting cone of a machined aluminum horn may increase the surface temperature by several tens of degrees in a few minutes of time. In addition, UVI irradiance may propagate down the infrared reflective inside walls of the waveguides and affect the temperatures of waveguide terminations and RF switch elements. All of these effects militate to degrade the calibration accuracy and to vitiate the measurement of signal temperatures.

The vulnerability of the cold-calibration horn to UVI irradiance is eliminated by the installation of a UVI-dome as shown in Figure 14.

Dome structures are fabricated from materials that are transparent to microwaves and resist the penetration of UVI. Notably, and importantly, the UVI-dome covers all metallic surfaces of the sky horn and the signal feed.

Multichannel receiving systems that require individual cold-calibration horns can add considerable complication to the RF section of the instrument. Figures 15 and 16 illustrate the microwave component interactions of the cold calibration horns, their attaching waveguides and coaxial cables, and the multifrequency signal horn. In this multifrequency receiver application, five frequencies are serviced by three cold-calibration horns. Several of the horns combine two frequencies.

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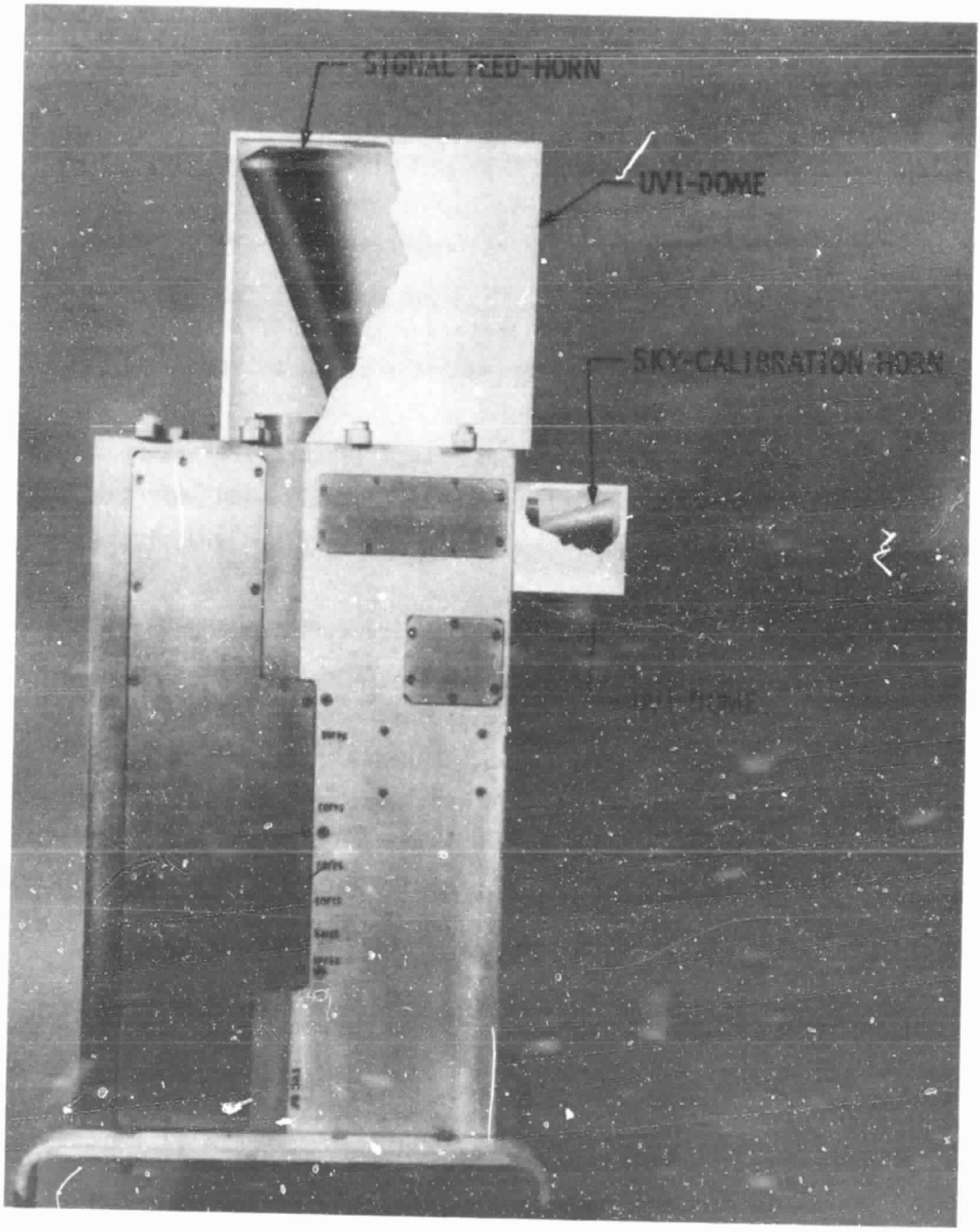

Figure 14. Receiver Instrument With UVI Domes

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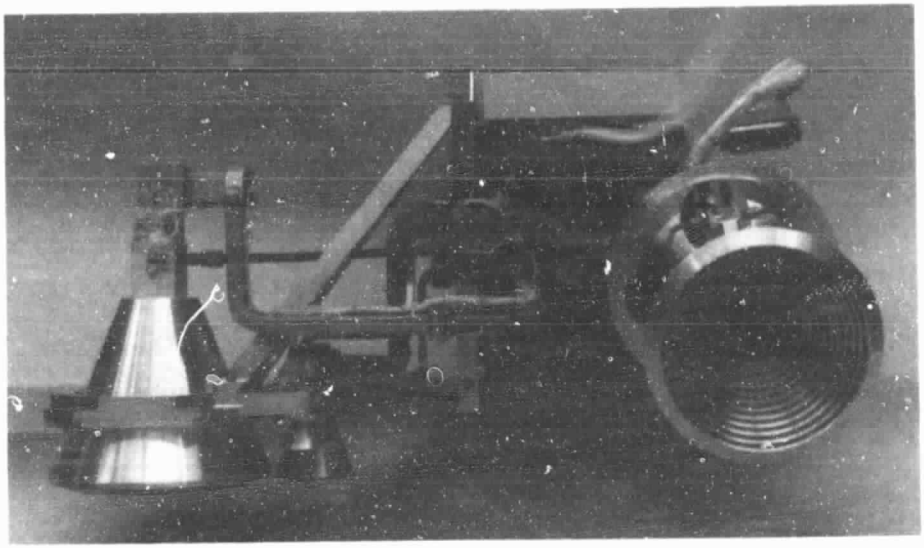

Figure 15. A Cluster of Three Cosmic Background Calibration Horns are Shown on the Left. The two large horns each operate at two frequencies. The multifrequency feed that illuminates an offset parabolic antenna is shown on the right.

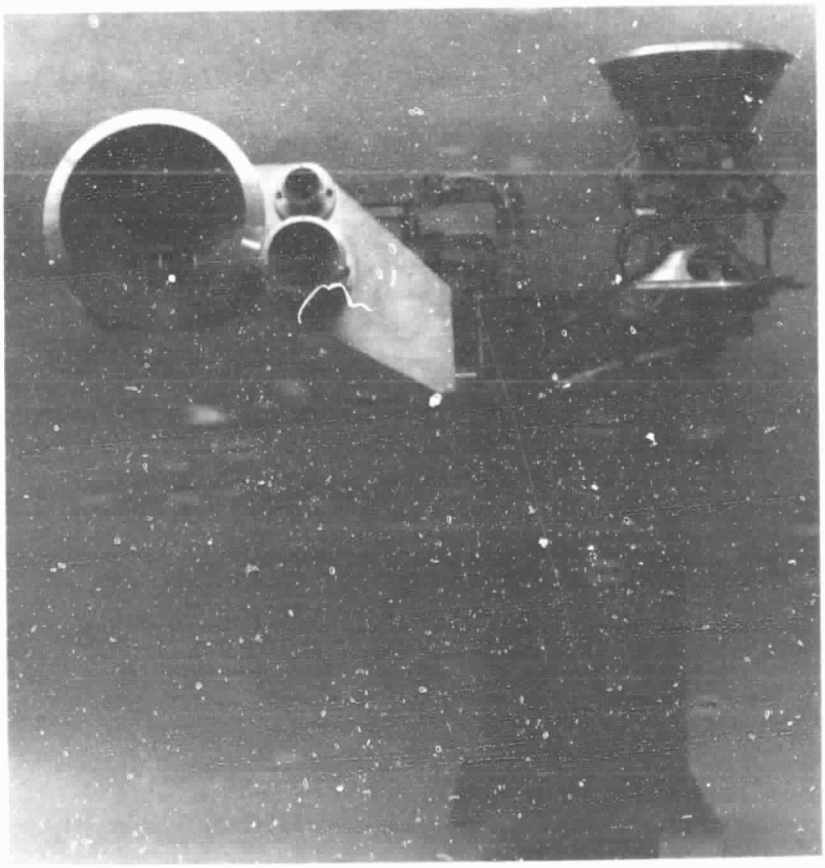

Figure 16. A Facing View for the Cosmic Background Calibration Horns

REFERENCE

1. M. A. Janssen, S. M. Bednarczyk, S. Gulkis, H. W. Marlin, and G. F. Smoot, "Pattern Measurements of a Low-Sidelobe Horn Antenna," IEEE Transactions on Antennas and Propagation, Vol. AP-27, No. 4, July 1979.

APPENDIX A

THE PRACTICE AND THE HARDWARE

Blackbody targets, radiatively cooled thermal suspensions, and antennas that view the Cosmic Background (sky horns) serve to calibrate spaceborne receivers.

In practice, blackbody targets are generally cooled; occasionally they may serve as reference-temperature standards that operate at ambient or at elevated temperatures.

Depending upon the need, blackbody targets may be located either within the spaceborne receiver, as a component, or externally where they are viewed, on command, by an articulating antenna.

This appendix shows actual applications of blackbodies where they serve as calibration devices and operate in the environment of space.

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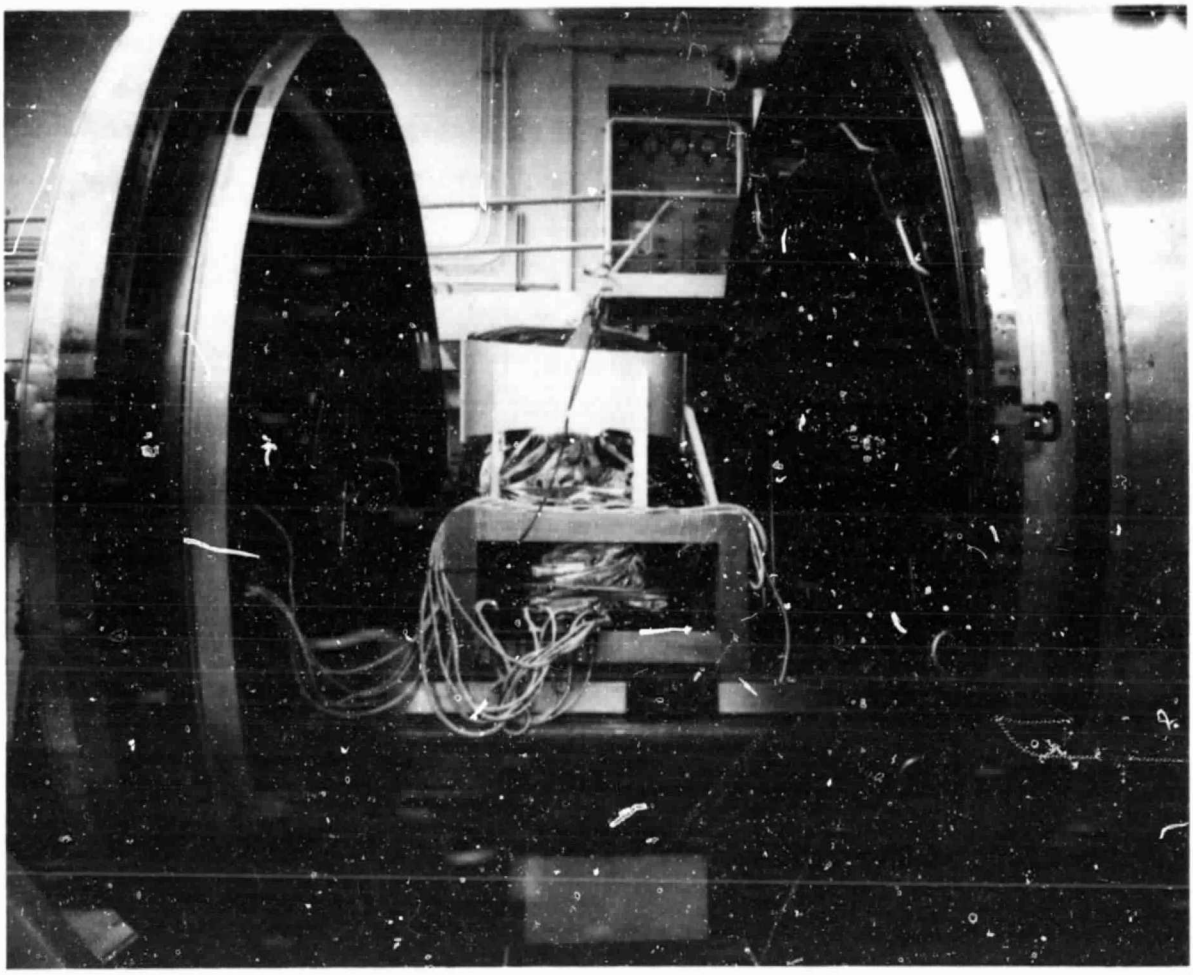

Figure A-1. One Type of Thermal-Vacuum Chamber.

In principle, the thermal-vacuum chamber simulates the vacuum and thermal environment of space as it will be experienced by an instrument on a spacecraft.

The thermal-vacuum chamber shown here is a cylinder with discoid-type end caps. The caps are attached to the body of the cylinder by steel rods. The rods slide into cylindrical bores within the body of the cylinder and permit the end caps to be retracted for access to the chamber or closed to seal it off.

This chamber is 3 m in diameter and 3 m long. It is regarded as intermediate in size. The test instrument mounted on the platform will be positioned within the chamber when the end cap is closed. Coils that circulate a liquid cryogen are secured to the inside body of the cylinder.

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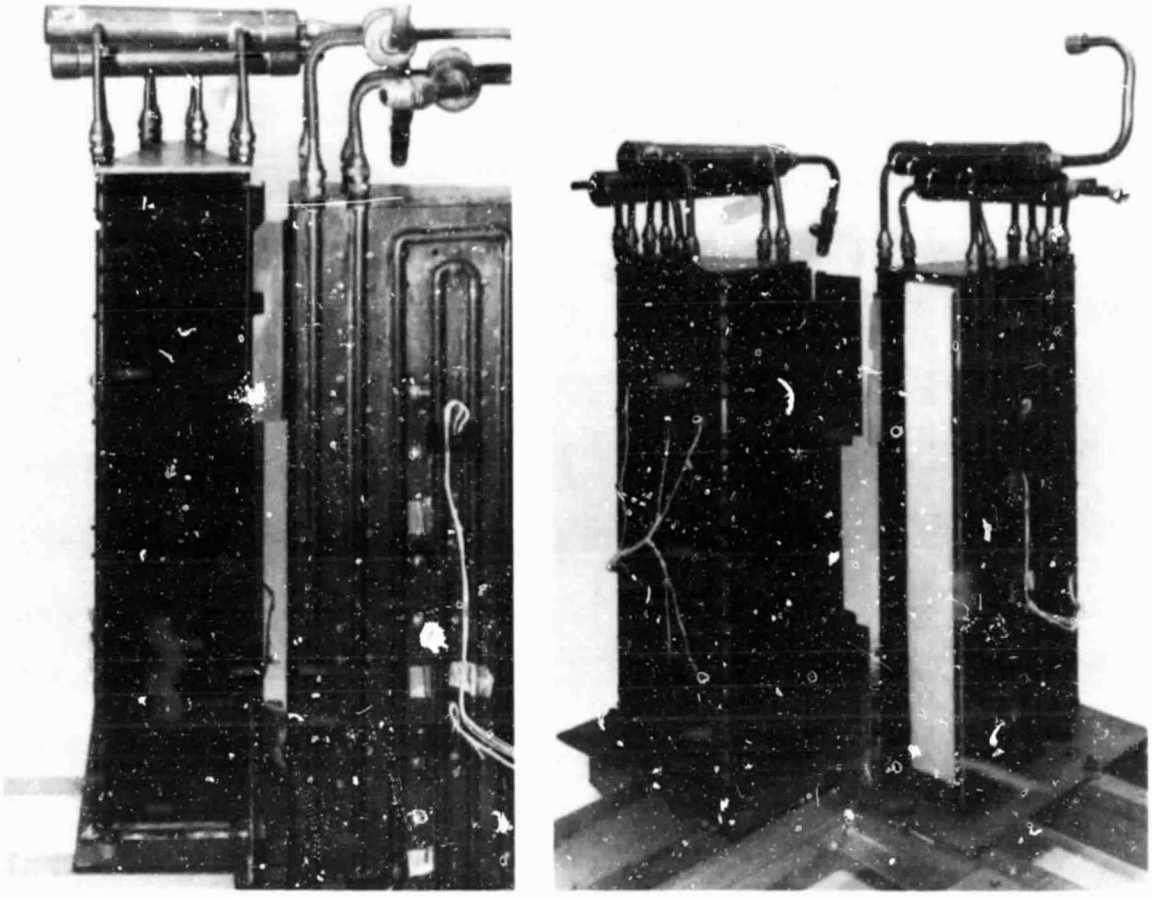

Figure A-2. Reentrant Blackbody Target in the Geometrical Figure of a Wedge.

The target is an adaptation of the reentrant pyramid. The advantage of the wedge is that is extends the blackbody surfaces especially in one dimension so that many feeds or antenna assemblies that occur in a line array or in clusters may view the same target simultaneously.

The absorptive surfaces of the reentrant wedge target are constructed from ferrite-loaded-epoxy prisms oriented to intercept the incident microwave radiation at the Brewster Angle. The entire aperture of the target is filled with a white foam that is transparent to microwaves. The foam prevents frosting of the absorptive surfaces and also keeps them clean.

The apex angle of the sides of the wedge is also formed at the Brewster Angle. The reentrant wedge--similar to the reentrant pyramid--has the advantage of absorptive properties that are improved by multiple reflections within the wedge.

Coils are attached to the outside copper surfaces of the target for the circulation of nitrogen in both its liquid and gaseous states. The absorptive surfaces of the target may be varied in temperature from 80 to 320 K.

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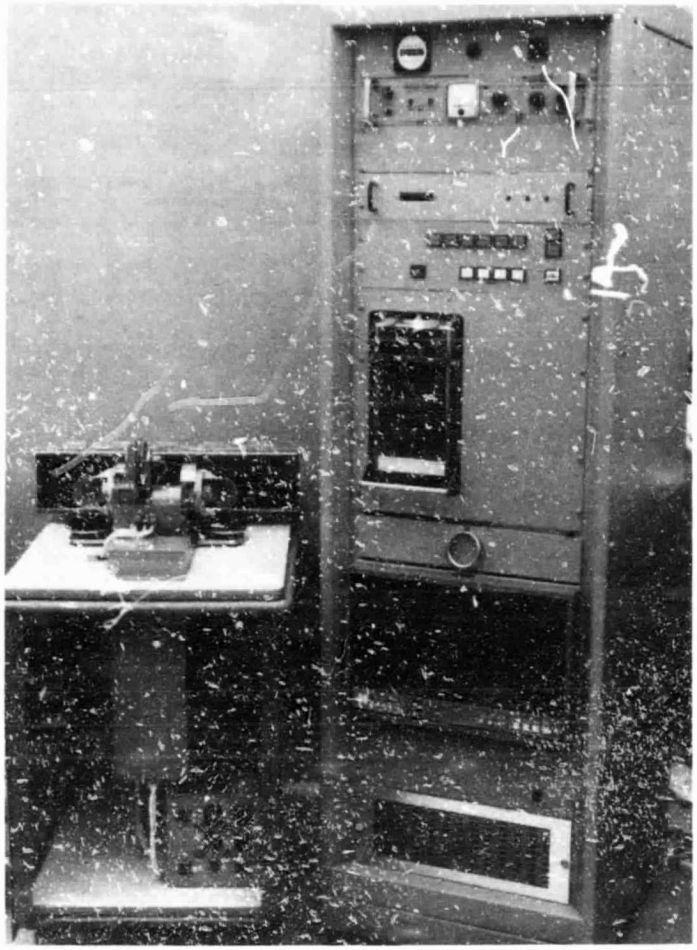

Figure A-3. A Reentrant-Wedge Target (Laboratory Model).

The small target is shown on the top deck of the table where it is part of a laboratory test; it is viewed by a receiver with two synchronized and offset antenna assemblies. The antennas are affixed to each side of the receiver. The hyperbolic offset reflectors direct the blackbody radiation from the reentrant-wedge target into the corrugated horns when the antennas are oriented to view the wedge. When the antennas are rotated to view the flat blackbody targets that are mounted directly below the reflectors, the ambient temperature radiation from the flat targets is directed into the corrugated horns. The flat-disk targets are integral components of the instrument design--they are affixed with platinum-resistance thermometers and serve as the ambient-temperature calibration function for the instrument.

Electric heaters are mounted on the copper sideplates of the wedge to elevate the temperature of its radiative surfaces.

The ferrite-epoxy prisms that form the absorptive surfaces of the target and the copper side plates are both set at the Brewster Angle.

The instrument calibration is performed at two different target temperatures: ambient temperature (290 K) when the flat targets are viewed by the antennas, and 325 K when the wedge is viewed.

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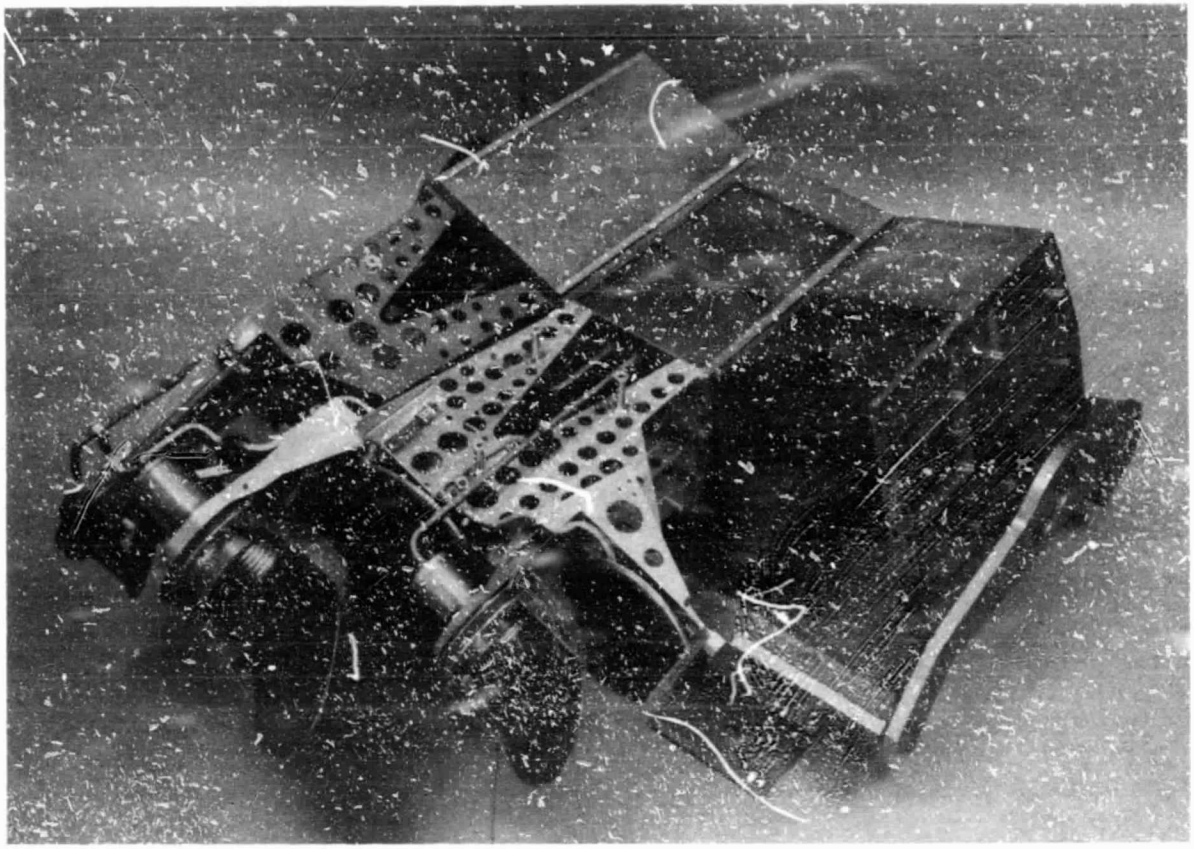

Figure A-4. Articulated Antenna Assemblies With Blackbody Targets.

The three assemblies are offset from their respective corrugated-horn feeds, and their hyperbolic reflectors rotate around the periphery of the feed aperture. The flat, blackbody targets operate at the ambient temperature of the instrument.

When operating in space, the antennas are positioned by rotation to view the Cosmic Background; this technique provides a cold-calibration temperature for the receivers.

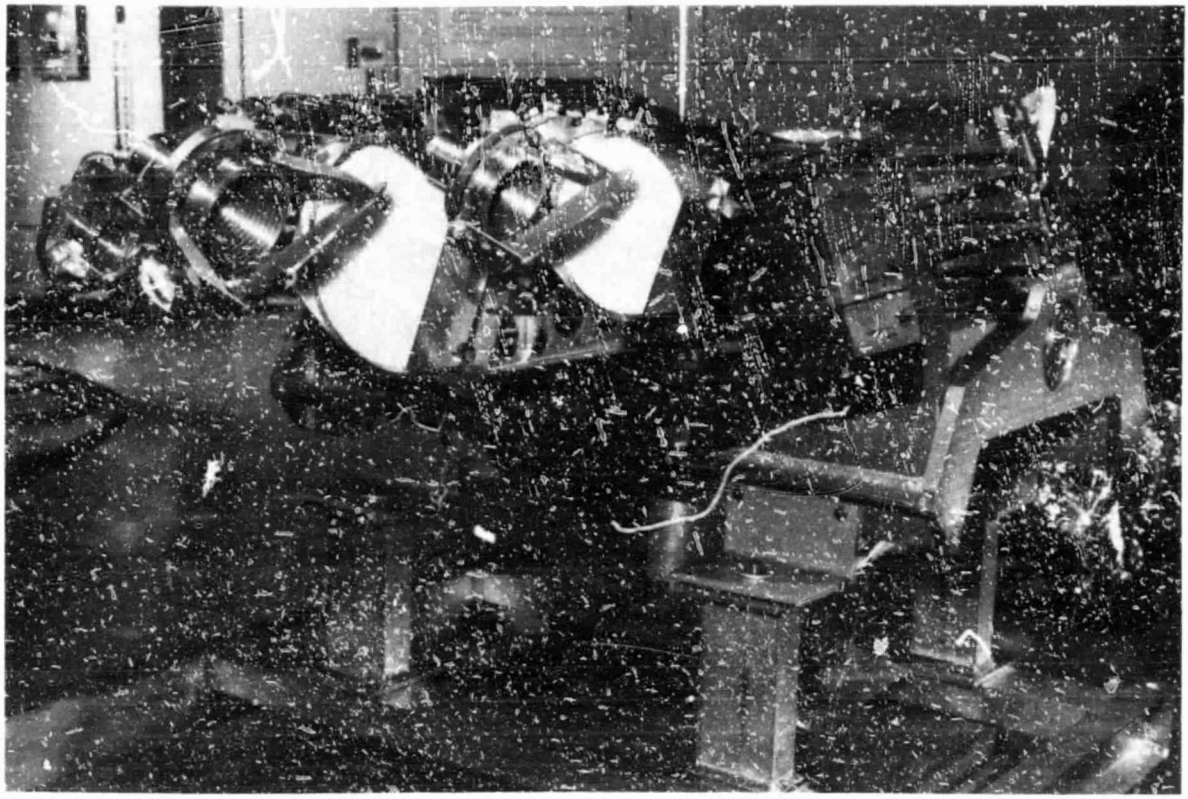

Figure A-5. A Multichannel Receiver on a Fixture Prior to Test in the Thermal-Vacuum Chamber.

The receiver is shown with three separate reflectors that functionally rotate around their respective corrugated feeds. The white-foam material protects the absorptive surfaces of the targets from solar irradiance.

The blackbody targets are affixed with a multiplicity of platinum-resistance thermometers to accurately monitor the temperature of the absorptive surfaces and the thermal gradients as they may occur.

When spaceborne, the reflectors rotate to allow viewing of the Cosmic Background; from this view, the receivers are provided two calibrated temperatures: 290 and 2.7 K.

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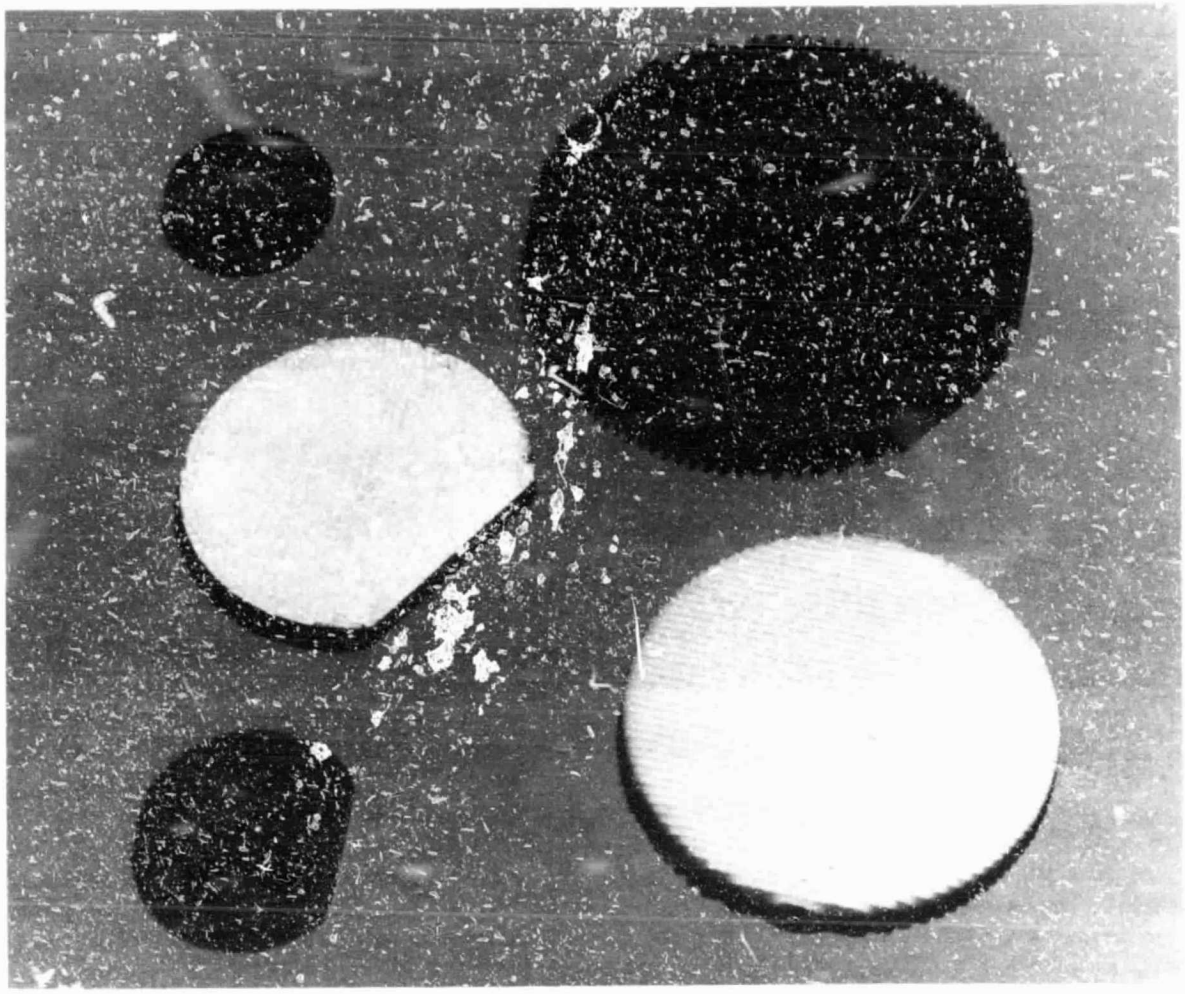

Figure A-6. Blackbody Targets With a Flat Figure and Absorptive Prisms Machined on Their Surfaces at the Brewster Angle.

Two of the blackbodies are covered with a white, low-loss, protective cover (expanded polystyrene) to protect the prisms from solar irradiance and to keep them clean. One target is shown without the Brewster-Angle prisms.

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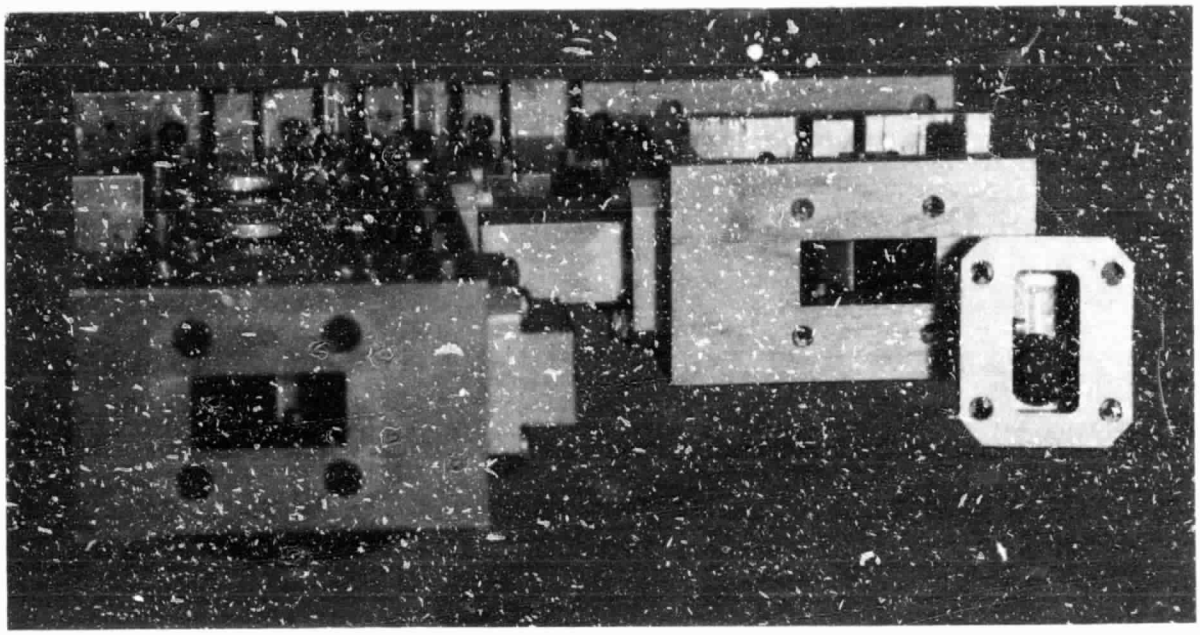

Figure A-7. Microwave Blackbodies Disposed as Waveguide Terminations.

The geometry of a blackbody structure is shown as it functions as a waveguide termination in an RF switch. The blackbody is the disk-cylinder in the end of a waveguide section that has been unbolted from the body of the modulator switch for the purpose of viewing it. This particular blackbody termination, as shown, functions as the reference-temperature load (RTL) in the modulator switch as it is applied to the needs of a modulated radiometer. An identical blackbody structure--again in the form of a waveguide termination--provides an internal calibration temperature.

Small variations in the temperatures of these blackbodies critically affect the performance of a radiometer. For this reason, platinum-resistance thermometers are imbedded within the absorptive surfaces of the blackbody through a hole drilled in the metal wall of the waveguide. Sometimes the thermometers are cemented directly to the outside wall of the waveguide opposite the blackbody.

The open waveguide section on the left side of the switch shows the signal-input port.

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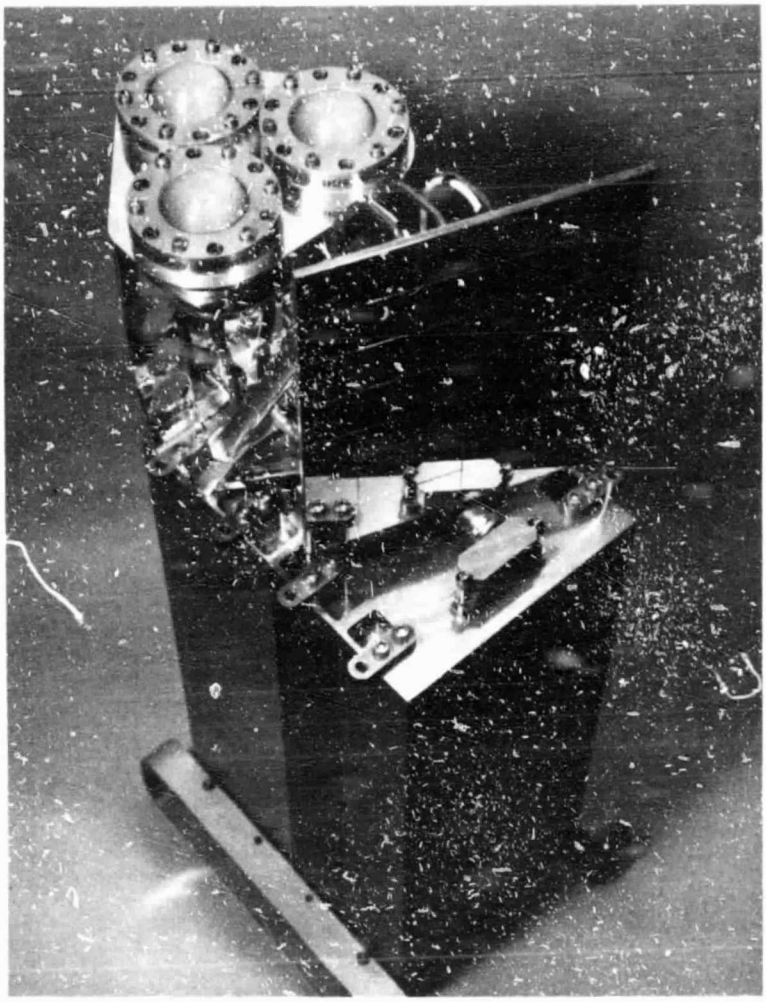

Figure A-8. A Three-Channel Receiver With a Radiatively Cooled Thermal Suspension for Cooling Blackbody Targets.

The aluminum plate (18 × 18 cm) mounted on the top of the receiver chassis is radiatively cooled by the two-surface mirrors affixed to one of its surfaces. The mirrors radiate infrared heat from the plate to the Cosmic Background by the Second Law of Thermodynamics. To facilitate this function, the plate is a thermally isolated suspension: it is supported by fiberglass rods to minimize heat conduction.

Waveguide sections with blackbody terminations are clamped to the reverse side of the plate--they serve as a cold-calibration temperature for each of the three receivers. Stainless-steel waveguide sections are used to minimize heat conduction from the plate.

This particular thermal suspension maintains the temperature of the blackbody terminations in the waveguides at 200 K $\pm$1 K while operating in space.

The antenna apertures use fixed hemispherical lenses to shorten the focal length of the antennas, thereby reducing the volume of the receiver. The boresight for the antennas is fixed at the nadiral path of the spacecraft.

An internal waveguide termination in an RF switch within the receiver provides an ambient-temperature calibration.

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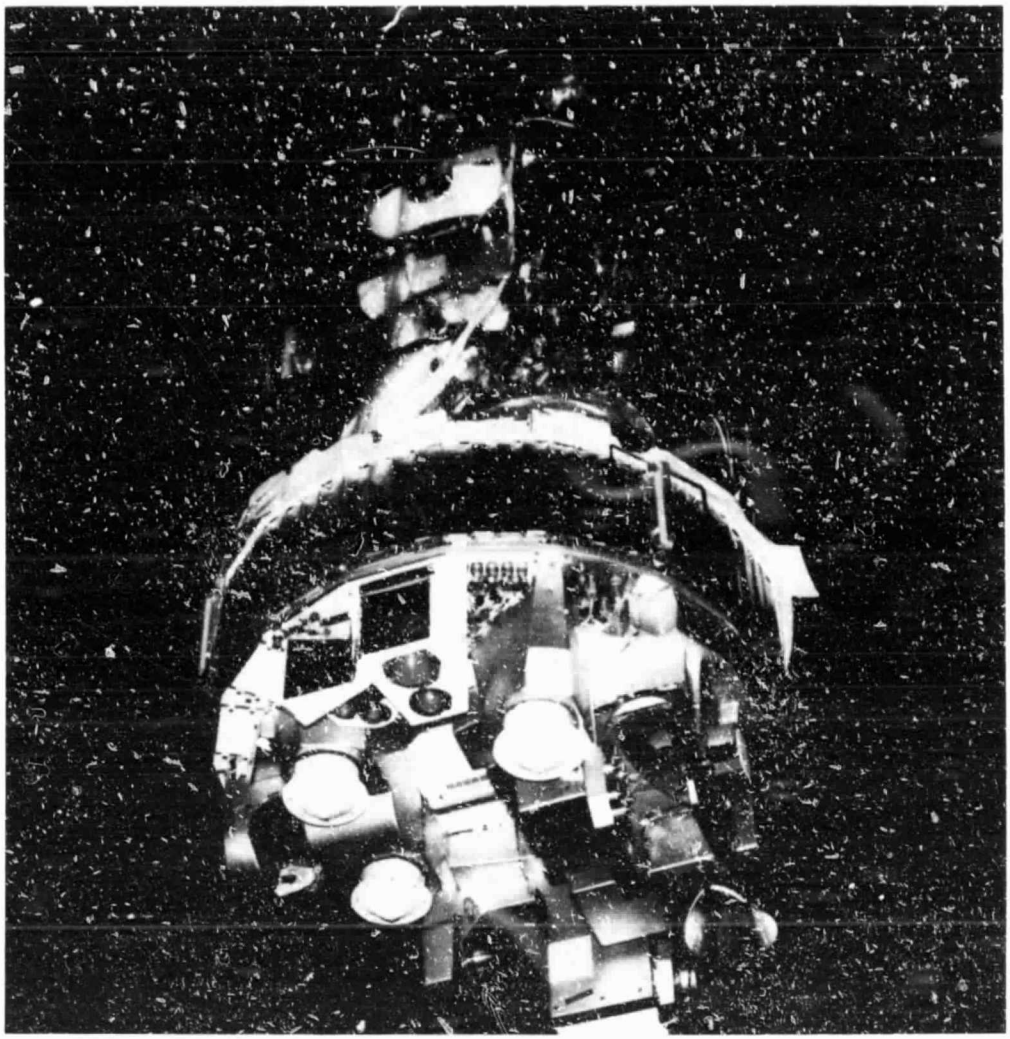

Figure A-9. Deployment of Radiatively Cooled Thermal Suspensions.

A Nimbus spacecraft is shown suspended from an overhead beam in a spacecraft test-and-assembly area. On the underside of the spacecraft is the instrument complement in the launch configuration.

Near the outer periphery of the central band of cooling-louver panel sections, slightly to the left of center and on the underside, are two spaceborne receiver modules. One module has two hemispherical lens antennas and the other has three.

The radiatively cooled thermal suspensions for the two receiver modules are shown as black rectangles. They are positioned immediately outboard, and adjacent to the receiver modules. From this coign of vantage, the Cosmic Background is viewed without physical obstructions.

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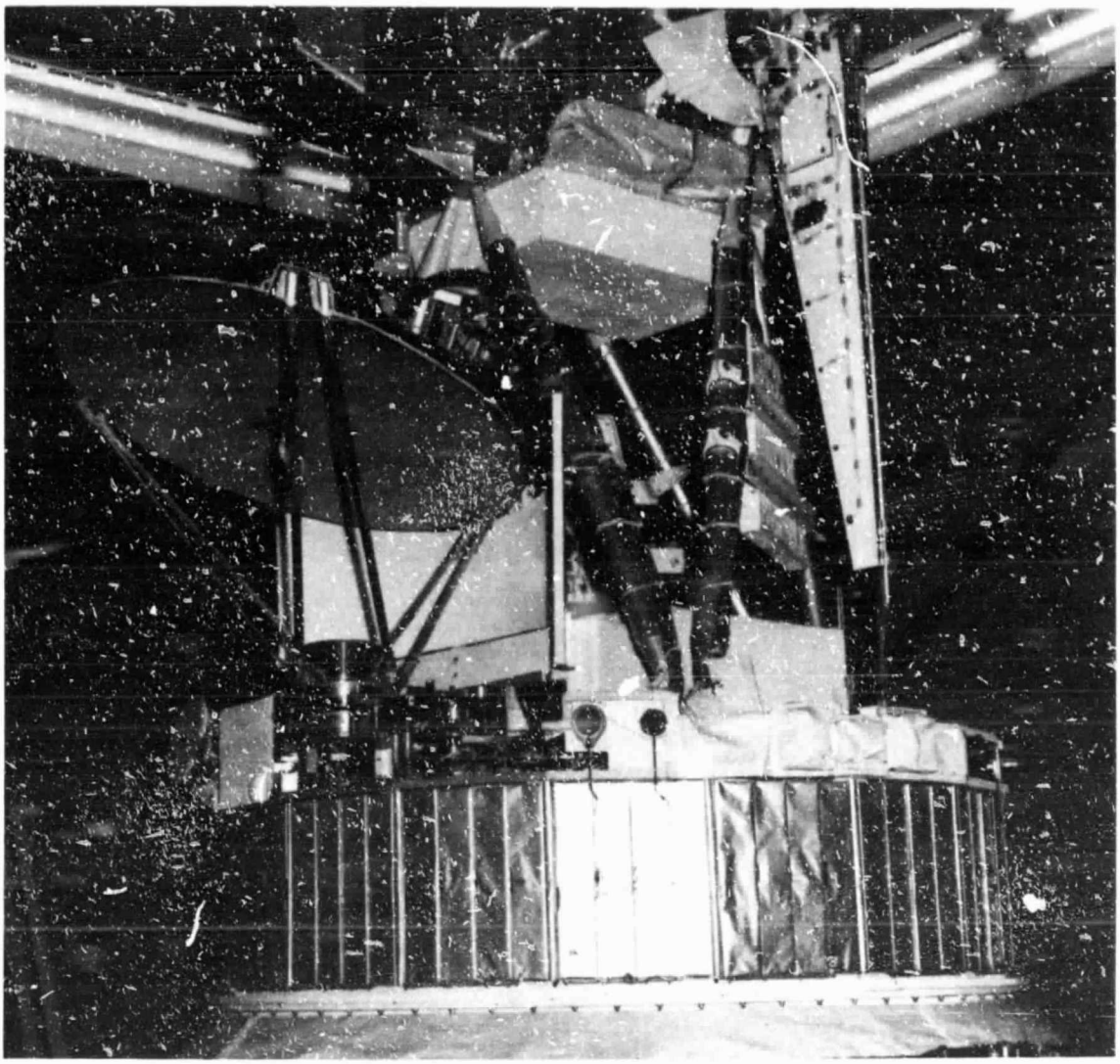

Figure A-10. Cold-Calibration Horns Assembled on a Multichannel Receiver With an Articulated Antenna.

The figure displays a portion of a Nimbus spacecraft. Slightly to the left of center is a multichannel microwave receiver module with an articulated, parabolic reflector attached to its scanning mechanism by pods.

A cluster of corrugated-horn feeds are seen on the extreme left edge of the receiver. The collecting apertures of the feeds are covered with white, disk-shaped, plastic covers that are removed prior to launch.

The cold-calibration horns are positioned for an unobstructed view of the Cosmic Background when in Earth orbit.

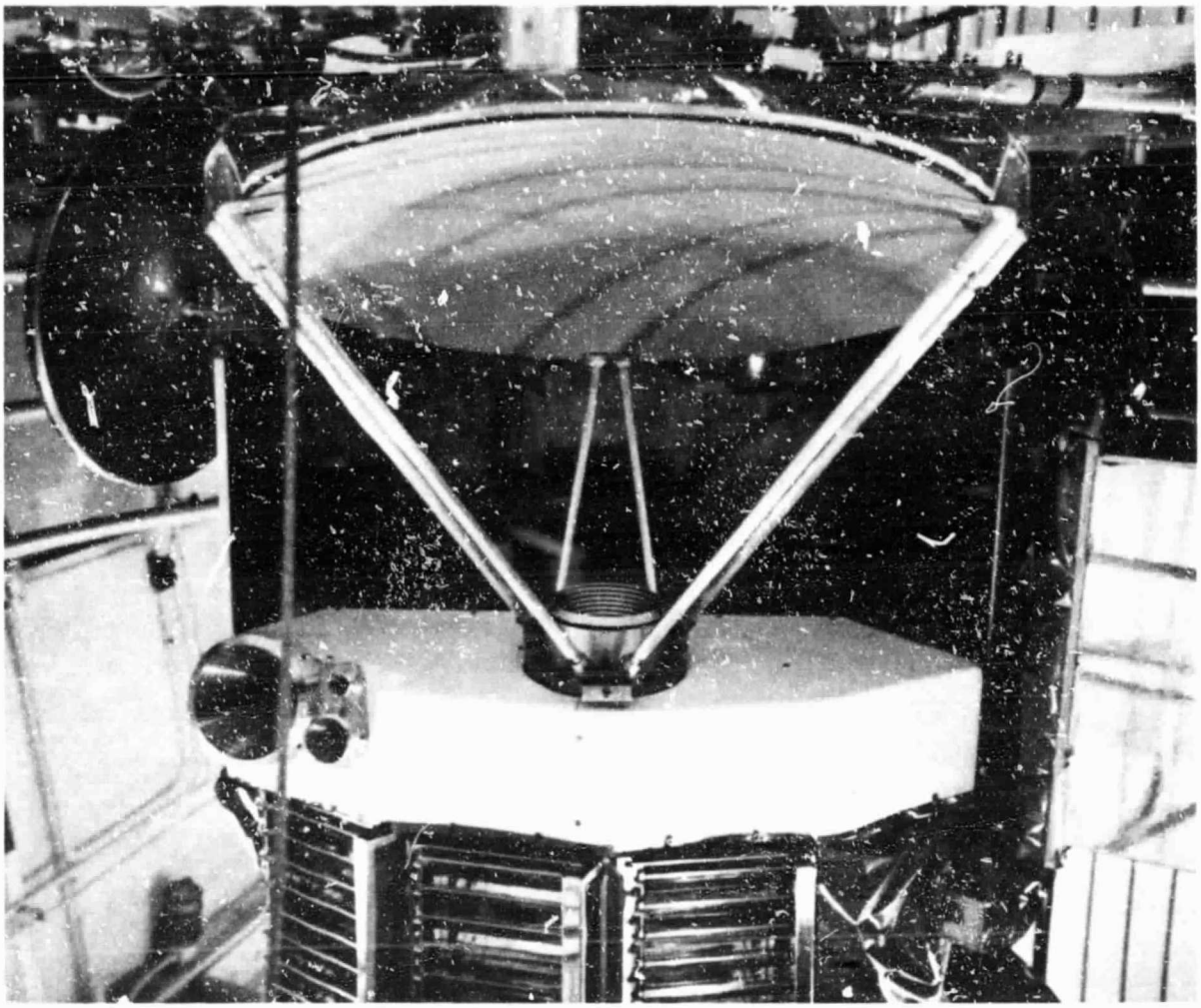

Figure A-11. A Cluster of Cold-Calibration Horns Deployed and Ready for Launch.

A multichannel microwave receiver with an articulated antenna system is shown in its launch configuration. This is the same receiver shown in the previous figure, but mounted on a different spacecraft. The receiver section is located in the lower center of the figure where it is oriented within the shroud of the spacecraft.

The multifrequency feed assembly projects through a thermal blanket (painted white) where it illuminates the articulated collector. Affixed to the front of the receiver module are cooling louvers for the entire receiver module. To the left of center is a cluster of cold-calibration horns oriented to view the Cosmic Background from orbit.

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