Interoffice

NATIONAL RADIO ASTRONOMY OBSERVATORY
TUCSON, ARIZONA

To: Dr. David S. Heeschen, Dr. William E. Howard, III,
Dr. Hein Hvatum, Dr. Sander Weinreb, Dr. E. K. Conklin.

From: John D. G. Rather

Subject: 1 Millimeter Status Report for 12/31/71 and Subsequent Developments.

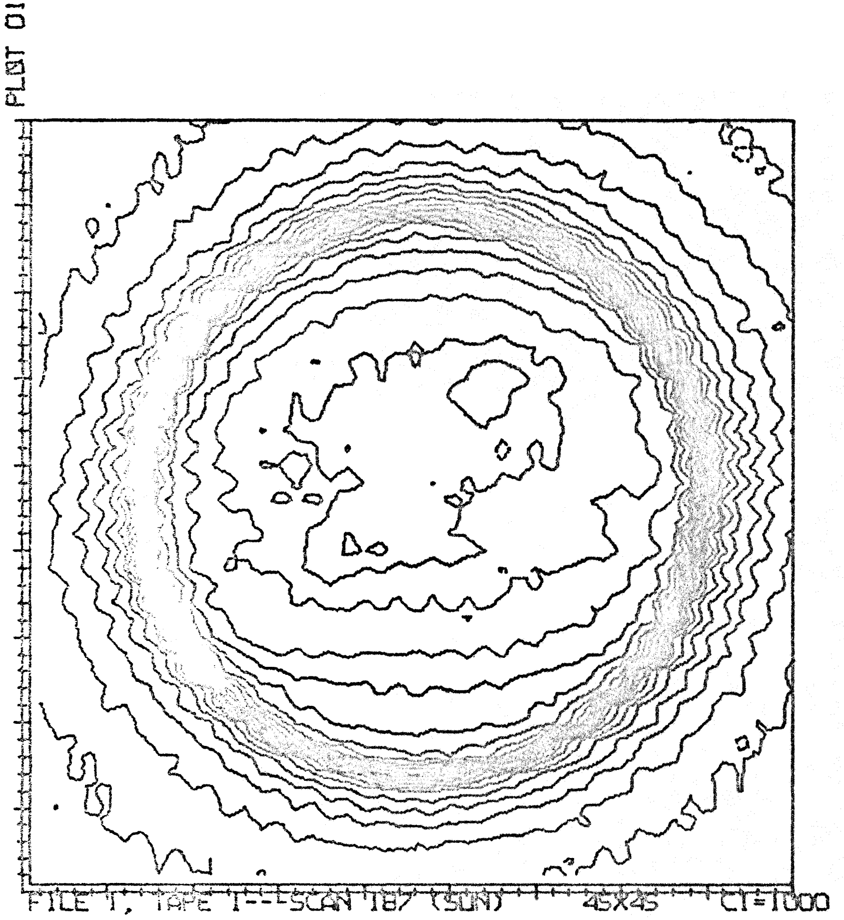
Attached is my much belated status report for the past year. Since the text was substantially completed we have had a very successful run (18-28 February, 1972) using an Indium Antimonide detector with mesh filters provided by Queen Mary College, London. The detector, built by John Bastin, Peter Clegg and Peter Ade of Queen Mary College, functioned perfectly as did all of the support systems. A large amount of data is in hand, and the results will be reported as soon as possible.

Enclosed are a sample sun scan, moon scan (showing temperature asymmetry), and some on-offs on Jupiter from the recent run.

John

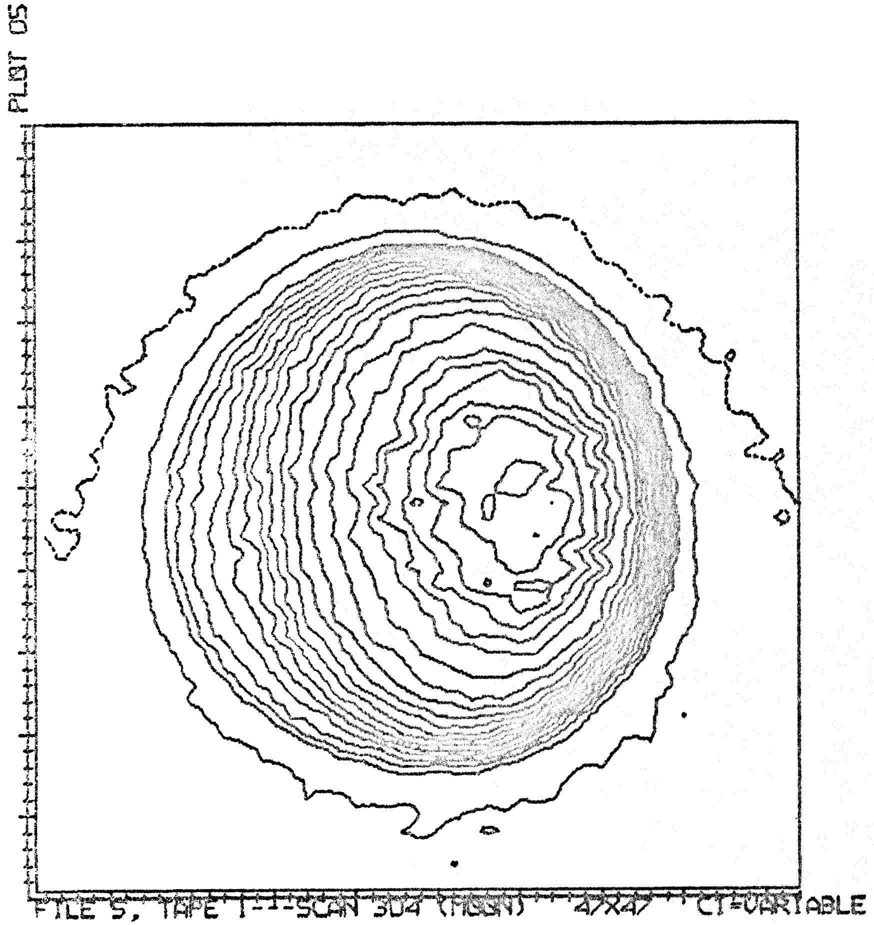
JR/g

3/23/72



SUN

(CONTOUR INTERVALS NOT OPTIMUM AND TRACKING ERROR NOT REMOVED. HOT SPOTS AGREE WITH SUN SPOT POSITIONS.)

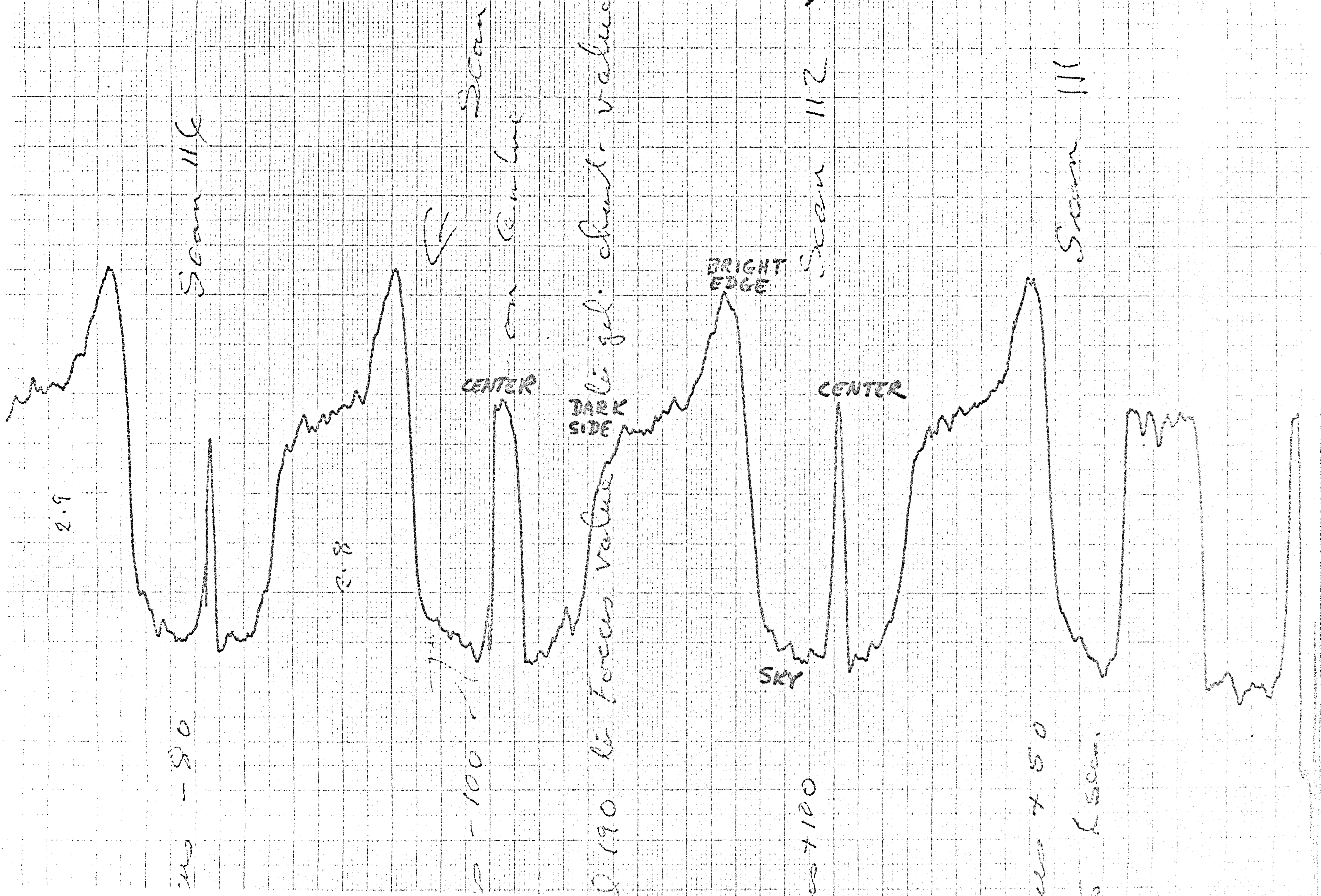


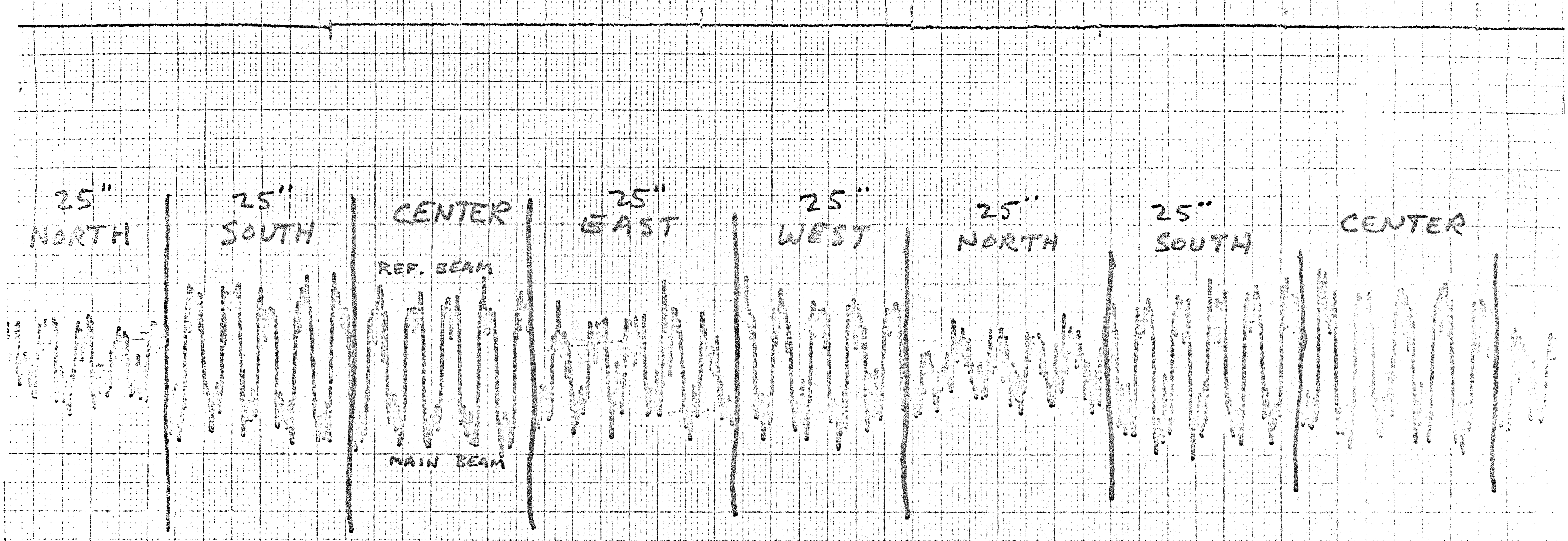
1ST. QTR. MOON
(CONTOUR INTERVAL
NOT OPTIMUM.)
NOTE DETAILS IN MARIA.

,25%

CRESCENT MOON SCANS

(MAPS SHOW DIFFERENCE BETWEEN MARIA AND HIGHLANDS.)





5 POINT DATA

JUPITER

1^s TIME CONST.

2 mm PERCIP. H_2O

NRAO Internal Report

YEAR END STATUS REPORT ON
1 MILLIMETER PROJECT

John D. G. Rather
National Radio Astronomy Observatory
Tucson, Arizona

December 31, 1971

1. Introduction

The first status report, dated March 25, 1971, outlined the general problems which had been diagnosed in the operation of the 1 millimeter system which NRAO purchased in 1969 from the group headed by F. J. Low at the University of Arizona (Infrared Laboratories). Briefly, three primary problem areas were identified.

(1) A loss of some 30 db appeared to be taking place between the signal assumed available at the prime focus of the 11 meter dish and the power supposedly detectable by the germanium bolometer.

(2) The filters, incorporated into the system had such broad transmission that the bandpass included much of the opaque infrared radiation of the atmosphere.

(3) The cryogenic dewar containing the detector and the related vacumm systems had many deficiencies.

The months subsequent to the first report have resulted in the following responses to the above problems:

(1) An in-house capability for modifying and evaluating the internal optics and electronics of the system has been developed. This includes development of testing equipment and techniques, training of support personnel in the machine shop, welding shop and optical shop and familiarizing the people in our own electronics and operations groups with the specialized problems of the equipment.

(2) The cryogenic problems of the dewar have been understood and the troubles with the existing dewar have been fixed. A new and better dewar design is now under study.

(3) All vacuum systems both in the Tucson Laboratory and the 11 meter telescope have been completely rebuilt and de-bugged.

(4) The reasons for the great difference between available and detected power have been fairly well understood. A research program is under way to develop the best possible energy transfer system for the dewar by using a combination of light pipes and internal and external optics. The reason for the failure of the "Gregorian" system tried by Low in October, 1970, is understood. The problem of developing a "blacker" detector, more capable of responding to the radiation delivered to it is considered central to the success of the entire project. The present detector is thought to be at least 99% transparent to incident 1 millimeter radiation.

(5) The filtering problem will hopefully be solved by adopting a mesh type etalon now being built for us by D. H. Martin's group at Queen Mary College (hereinafter QMC), London.

(6) A lively exchange of ideas and knowledge about various types of detectors has been carried out with groups at various laboratories notably with:

(a) P. Clegg, Physics Dept., QMC, London, England (InSB Kinch-Rollin detectors and mesh filters.

(b) R. Waniek, Advanced Kinetics Corp., Costa Mesa, California (InSb Putley detectors)

(c) K. Jefferts, Bell Telephone Labs., Holmdel, New Jersey (Detector theory)

(d) M. Simon, Astronomy Dept., SUNY, Stonybrook, New Jersey (Cryo-optics, Germanium detectors and mesh filters)

Useful information has also been derived from visits with the following people:

(a) Grame Duthie, Physics Dept., U. of Rochester, New York (Josephson devices and cryogenic techniques)

(b) D. Mac Donald, NBS, Boulder, Colorado (Josephson mixers)

(c) R. Chiao and T. Ota, Physics Dept., Berkeley, California (weak-link Josephson detectors)

(d) B. Ulrich, Ecole Normal, Paris, France (Josephson junction detectors)

(e) P. Lena, Observatorie de Meudon, Meudon, France (Germanium and Josephson junction detectors)

(f) D. Crecraft, U. of Warwick, Coventry, England (Preparation of solid-state surfaces; welding and soldering techniques)

(7) One attempt has been made to use a Putley-type Indium Antimonide (InSb) detector on the 36' dish (May 12-18, 1971) The attempt failed because of unforseen vacuum and optical problems. Another InSb experiment is now being attempted using a Kinch-Rollin type detector. The superiority of InSb over doped Germanium has been proven in the laboratory but remains to be demonstrated on the telescope.*

(8) A five foot dish has been procured from Green Bank and recently made operational on the roof of the Tucson Laboratory. Secondary optics have been designed for the dish which will convert it to a 0.8 system to simulate as accurately as possible the operation of equipment on the 36 foot dish. This modification is now in the final stages. It is hoped that this facility will greatly improve our capability for proving out equipment before committing time on the 36 foot telescope.*

(9) A cryogenic laboratory and control room for the 5 foot dish has been designed and built on the roof.

Some of the details of this work will be discussed in the following pages. The present sense of the experiment is that the groundwork is now finished and that a much improved system should be achievable within the next few months.

* See attached letter

II. Comments on Detectors

During the past decade there has been a slow evolution in the state of the art of detector technology for the wavelength range near 1 millimeter. Traditional superheterodyne mixers thusfar have proven impractical because of many difficulties in fabricating low-loss components and reliable sources of local oscillator power. There are many ongoing experiments directed toward the development of coherent detectors which may eventually prove successful. Among these are cooled mixers, masers, weak-link Josephson devices, and bulk diode Indium Antimonide mixers (which potentially have Noise-Equivalent Power (NEP) of 10^{-18} $W/\sqrt{Hz}$ or better. The latter type device, originally proposed by Arams *et al*[*] and by Putley[**], was tried in November at 2 millimeters wave-length on the 36 foot dish by Jefferts and Phillips from Bell Laboratories. The experiment failed because lack of an adequate isolator permitted re-radiation of the local oscillator power to the dish, resulting in a giant interferometer for measuring deflections of the dish! The device, no doubt, has a great future for spectral line work and possibly even continuum work, but its adaptation for 1 millimeter will probably require at least another year or two.

At the present time it appears that incoherent detectors, rather than any of the aforementioned devices, hold out the most immediate promise for a workable 1 millimeter system which will produce interesting broadband astronomical results. Such devices borrow much of their technology from cryogenic detectors now in common use in the near and middle infrared, but they differ in certain important respects.

Let us digress to consider various modes of operation of the devices under study. In the near ($\lambda<10\mu$) and middle($10\mu<\lambda<100\mu$) infrared there are two modes of operation, characteristic of many semiconducting materials including doped Germanium and Indium Antimonide. These are easily understood. The valence electrons attached to the atoms in the crystal behave roughly as in the Bohr model except that the attraction between the

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[*] Proc. of IEEE,54, 612 (1966)

[**] Proc. of IEEE,54, 1096 (1966)

nucleus and the electrons is reduced by the dielectric properties of the crystal.

Hence direct photoionization of the atoms in the primary crystal lattice can occur, giving rise to intrinsic photoconductivity. Clearly the energy $h\nu$ of the absorbed photon must be greater than the intrinsic energy gap, ε, which separates the valance and conduction bands. Thus, there will be a long wavelength threshold given by:

$$h\nu \sim \varepsilon$$

or

$$\lambda_0 \varepsilon \sim 1.2$$

for typical materials, where λ_0 is the threshold wavelength in microns (μ) and ε is expressed in electron-volts. Thusfar it has proven impractical to develop intrinsic detectors for wavelengths much longer than 10μ.

If λ is to be longer than 10μ, ε must be smaller than 0.12ev. This is accomplished by doping the primary material of the crystal lattice with impurities from Groups III and V of the periodic table, such as Gallium. These impurities, in the presence of the electric fields associated with the primary crystal lattice, have well defined ionization energies as small as 0.01 ev. Hence, they can be directly ionized by photons with $\lambda \rightarrow 100\mu$, giving rise to increased conductivity due to impurity photoionization.

The efficiency of the impurity photoionization process, as in the case of the intrinsic photoionization, drops off rapidly for photons having energies corresponding to wavelengths longer than the lower energy threshold. How, then, can semiconductors be made to operate as photoconductors in the long wavelength range $100\mu < \lambda < 5\text{mm}$? There are two basic detection mechanisms available, if the crystal is cooled to very low temperatures, which we shall now consider. Both are called hot electron effects, but they are quite different in terms of modus operandi.

In both of the detection modes considered thusfar, the change in conductivity was effected by ionizing additional electrons into the conduction band. But conductivity is given by

$$\sigma \sim ne\eta$$

where n is the number of electrons, e is the charge, and η is the mobility (charges/second). Now, in the long λ regime which is of interest to us, it is possible to achieve a $\Delta\sigma$ in a very cold crystal either by changing n or by changing η. It turns out that doped Germanium bolometers ("Low detectors") still operate by changing n, whereas Indium Antimonide detectors change η. It will be seen that the latter should be much more desirable for our purposes.

The first question that arises is, "If impurity ionization in doped Germanium ceases at $\lambda > 100\mu$, how is it possible to increase n when photons of longer λ impinge upon the crystal?". In order to answer this, we must consider what is meant by the temperature of a crystal: Basically what we mean is that photons striking the crystal transfer momentum to the lattice. The resulting modes of vibration are quantized and are discussed in terms of phonons, (i.e. unit quanta of acoustical energy). It turns out that if several low energy phonons (excited by several photons of $\lambda > 100\mu$) exist in the crystal at a given time it is possible for them to combine to produce a phonon of high enough energy to eject an electron

$$\begin{tikzcd}
\text{Low E Phonon} \arrow[dr] & & \\
& \text{High E Phonon} \arrow[r] & \text{Free Electron} \\
\text{Low E Phonon} \arrow[ur] & &
\end{tikzcd}$$

But, as we continue to longer wavelengths, the statistical probability of this effect decreases monotonically. Hence, the crystal becomes more and more transparent to the incident radiation. Still more important, even if the crystal is coated with some sort of perfectly black material and equipped with perfect filters which allow only 1 millimeter radiation to impinge, the thermalized 1 millimeter "holraum" surrounding the crystal will still give a very low probability of producing a conduction electron. *Hence the quantum efficiency of a Gallium-doped germanium bolometer must remain very low at 1 millimeter within present understanding of its physics*.

To the extent to which I have been able to pursue this matter,(*1) the real mystery is why the responsivity does not drop essentially to zero for wavelengths longer than∿350μ. A guess has been made by Zwerdling (*2) who invokes, "a possible photon induced resonant transition process," to account for the absorption. The data which underlies such considerations seems to be taken either from Low's original paper (*3) or from a paper by Oka *et al* (*4). The latter paper is the only one which gives an experimental plot of spectral response versus wavelength, and we reproduce the plot on the next page. Although Oka's experiment as detailed in this paper eliminates several possible causes of the long wavelength behavior, it makes no positive contribution toward explaining it. We are left wondering about the overall calibration of the incident radiation which he uses as his input. The Low paper (*3) infers the response by demonstrating that the detector is operating in the Rayleigh-Jeans domain. He shows that the output of the detector increases linearly with increasing black-body temperature. The lowest calibration temperature used, however, was a black-body at 77°K, the peak of whose radiation should be at∿40μ. Hence,

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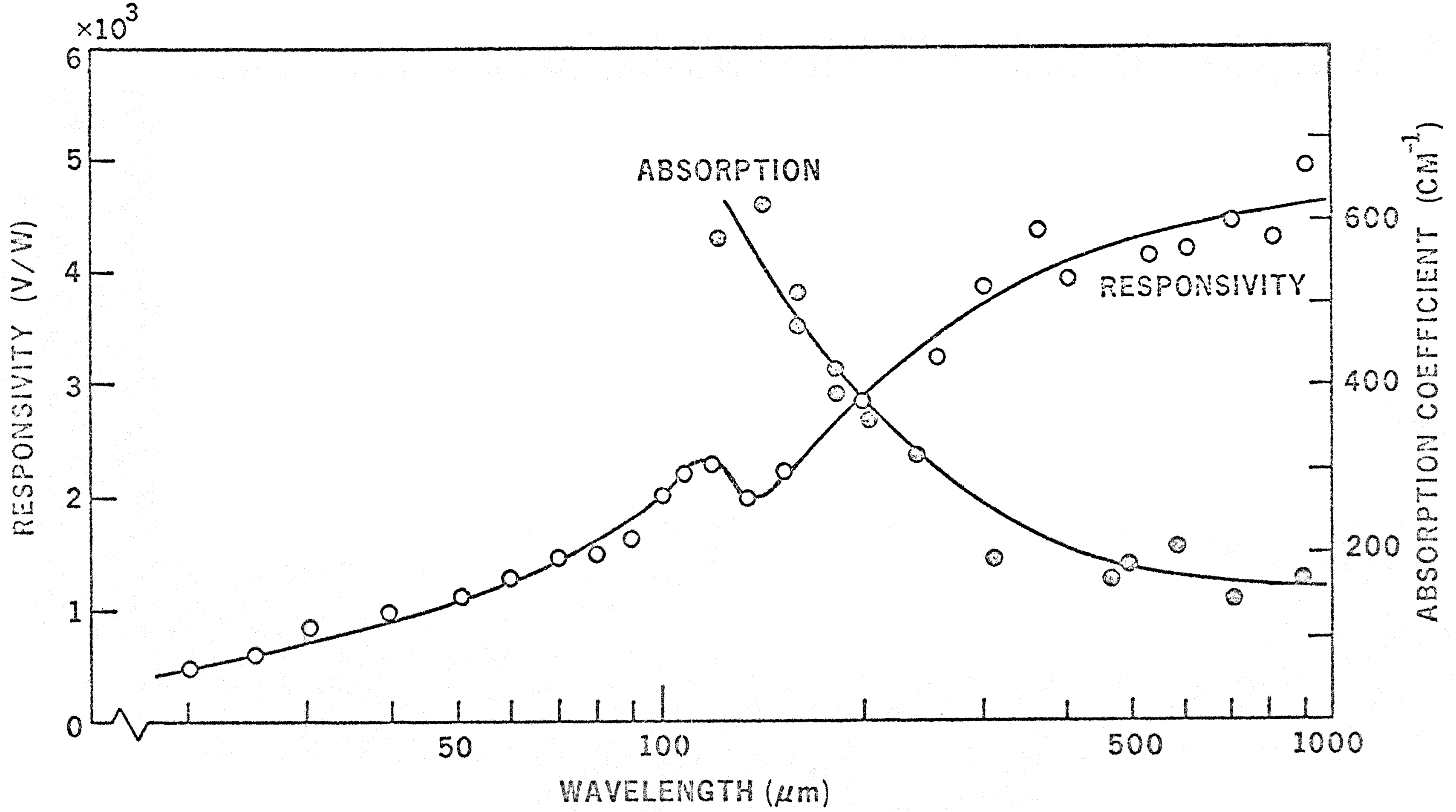
(*1) Published literature and private discussions with Jefferts and Phillips at Bell Labs., Ade and Clegg at Queen Mary College, and Smith and Werner at Berkeley.

(*2) S. Zwerdling, "Recent Advances in the Germanium Bolometer" Proc. of Colloquium on Cryogenics and IR detection held in Frankfurt-am-Main, West Germany, April 17-18, 1969, Boston Technical Publishers, Inc., p.54.

(*3) F. Low, Proc. IEEE, 53, 516 (1965).

(*4) Y. Oka, K. Nagasaka, and S. Narita, Japan, Journal of Applied Physics, 7, 611 (1968).



Spectral response and absorption coefficient curves for a compensated Ge bolometer element at 1.8°K used by Oka et al. Oka's measured NEP, derived from the expression NEP=Noise/Reponsivity, is found to be 10^{-11} W/$\sqrt{\text{Hz}}$. This is in accord with all other results: The Low detector works at 1 millimeter, but not with Low's load-curve-determined NEP of 10^{-14} W/$\sqrt{\text{Hz}}$.

Ref.: Y. Oka, K. Nagasaka, and S. Narita, Japan, "Journal of Applied Physics," 7, 615 (1968).

there is no contradiction with our continuing assertion that the claimed NEP of 1×10^{-14} $W/\sqrt{Hz}$ (cf. Low's NRAO quotation and attachments 2/18/69) applies to radiation in the neighborhood of 300μ. In addition to my own measurements, I have communicated directly with four other investigators* who have found measured NEP's in the range of 1 to 5×10^{-11} $W/\sqrt{Hz}$ at 1 mm and 800_μ. In summary, I therefore feel that it is very unlikely that a Germanium Bolometer system for the 1 millimeter region with an NEP much better than that of the present Low system can be devised within the confines of present experimental and theoretical evidence.

Let us turn now to a consideration of the Indium Antimonide "hot electron" photoconductor. As mentioned above, this device depends upon a change in electron mobility for its operation rather than electron number. The doping of the InSb is adjusted so that the wave functions of the impurity electrons overlap with each other and also with the bottom of the conduction band, thus forming an "impurity conduction band." At very low temperatures de-coupling between the impurity electrons and the InSb lattice occurs. This results in marked non-Ohmic behavior because, when an external electric field is applied to the crystal, the mean electron energy can rise well above its thermal equilibrium value before a steady state is set up. Since the electron mobility is governed by energy-dependent scattering mechanisms, the conductivity of the crystal becomes a function of the electric field. If various DC biasing currents are applied to the crystal a non-Ohmic current-voltage (I-V) characteristic curve is found for each lattice temperature. If radiant energy is then permitted to impinge upon a crystal having fixed temperature and DC bias, it will interact directly with the super-thermal electrons thus altering their equilibrium Fermi-Dirac distribution and hence changing their mobility. The system thus moves to a new point in the I-V characteristic, and the accompanying change in conductivity can be measured directly. The response time is

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* Clegg, Queen Mary College; Eddy, NBS, Boulder; Noyes, SAO, Harvard; and Simon, SUNY, Stonybrook.(All used bolometers purchased from Infrared Laboratories).

extremely fast, being simply the conductivity relaxation time ($\tau < 10^{-12}$ sec.).

It is emphasized that, unlike the situation in the Germanium Bolometer, which requires heating of the entire crystal by the impinging radiation to produce a change in conductivity, the In Sb crystal itself may be held at a fixed temperature. The In Sb crystal may be much larger than the 1 x 2 x 0.25 wavelength dimensions (i.e. 1 x 2 x 0.25mm) of the Low detector, thus facilitating much easier coupling to the impinging radiant power. It may also be mounted directly to the cold-work surface of the dewar, thus eliminating the microphonic response so frequently observed in the Low detector, which is suspended on two #40 wires which seldom come to just the right mechanical tension during cool-down.

The only difficult problem which is encountered in using In Sb detectors is that the intrinsic resistance of the detector element is too low ($\sim 10\Omega$) to match a low noise preamplifier such that amplifier noise does not dominate detector noise. There are two completely different solutions to this problem presently available.

1) The method of Kinch and Rollin*, which has been extensively developed at Queen Mary College, London, uses a tuned toroidal transformer, cooled to liquid helium temperature, to transform the chopped signal to a useful impedence level. The transformer has a turns ratio of >100:1 and is wound on a 3/4 inch diameter ferrite core. Its principal disadvantages are that it dissipates a small amount of power, thus shortening the helium hold-time, and that it limits the response time of the system, the latter being of no consequence for our 97 Hz chopping frequency. The high turns ratio of the transformer more than compensates for the low responsivity (i.e., low voltage response per incident watt) of the crystal, and NEP values of $< 10^{-12}$ $W/\sqrt{Hz}$ are readily attainable.

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* M. A. Kinch and B. V. Rollin, Brit. Journal Appl. Phys., 14, 672 (1963)

2) The Putley method[*1] uses an entirely different approach to the problem of raising the resistance of the InSb crystal. A uniform magnetic field of several thousand gauss is applied to the crystal through the agency of a superconducting coil immersed in the liquid helium. The magnetic freeze-out effect (Sladek[*2]) decreases the free electron concentration and the magneto-resistance effect reduces the electron mobility. (Basically this means that the number of available states is reduced and that the electron path length is greatly lengthened as it negotiates something akin to helical orbits through the crystal.) The net effect is to produce families of I-V characteristics such as those reproduced on the next page.[*3]

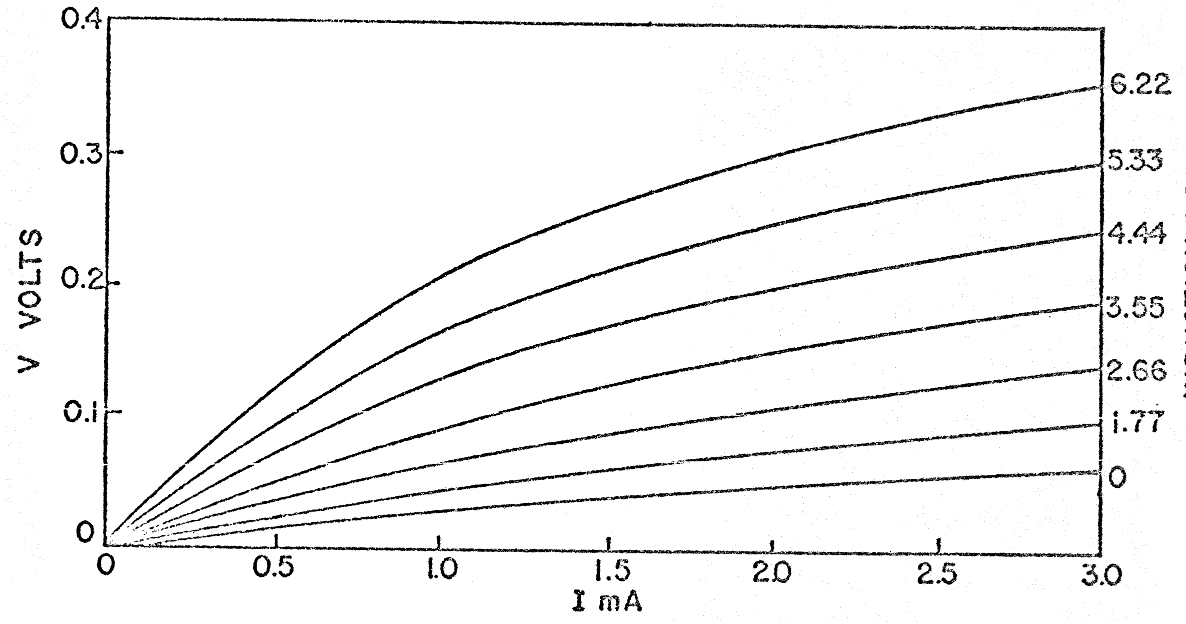
The basic advantage of the Putley detector is that it achieves a satisfactory match to the preamplifier without sacrificing response speed ($\tau \lesssim 10^{-9}$ sec.) This advantage is of great value for laboratory physics, but of no apparent use to us, unless we can devise a higher frequency chopping system to improve on the $1/f^n$ noise. (Present InSb chopping rate is 7x maximum for Germanium Bolometer). Disadvantages include the necessity for a much larger (7 liter) and heavier (100 lb.) dewar to accommodate the superconductivity coil, a long light pipe to reach the detector, very expensive electronics, and much more liquid helium consumption. (See accompanying illustration).

In spite of these handicaps, I decided in the Spring of 1971 to attempt an experiment on the 36 foot dish to test a Putley detector, primarily because I could borrow an entire system from my friend Ralph Waniek, president of Advanced Kinetics Corp. in Costa Mesa, California.

[*1] E. H. Putley, Phys. Stat. Solids 6, 571 (1964)

[*2] R. J. Sladek, Journal of Phys. Chem. Solids 5, 157 (1958)

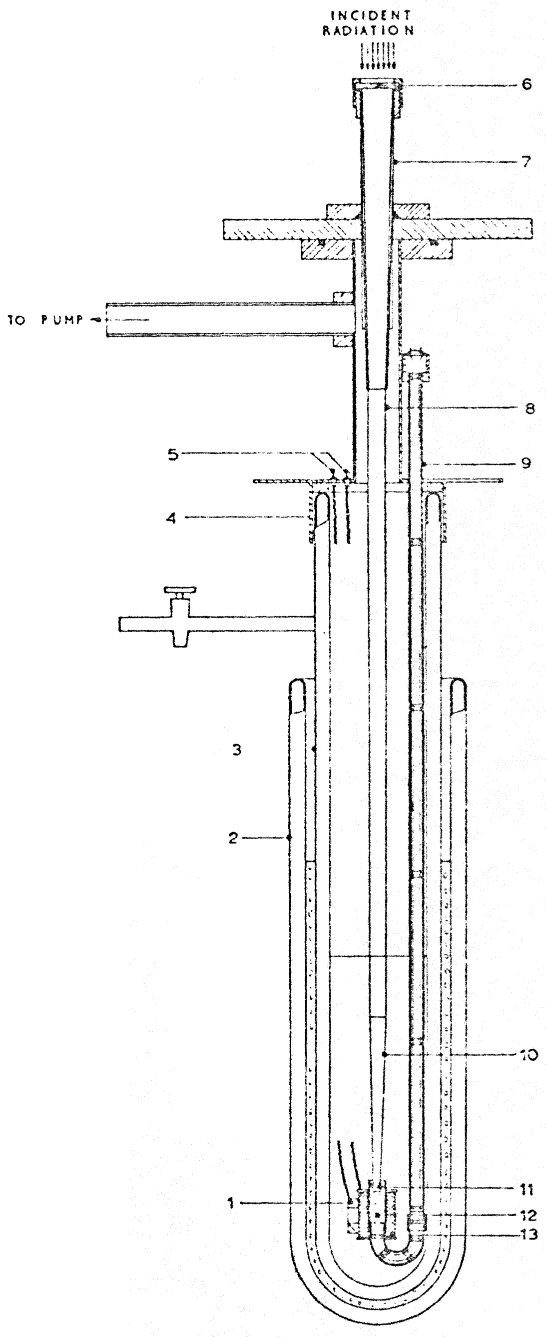
[*3] Additional strong cyclotron resonance responses can be generated in the middle IR ($\lambda < 100\mu$) by the magnetic field. We shall ignore such effects here.



NON OHMIC BEHAVIOR OF InSb AT 4.23°K

Note zero-field behavior as in Kinch-Rollin device (bottom curve).

REF.: E. H. Putley, Proc. of Colloquium on Cryogenics and IR Detection, Frankfurt-am-Main, W. Germany, April 17-18, 1969, Boston Technical Publishers, Inc., p. 148.



1. Quenching magnet.
2. Outer nitrogen dewar.
3. Inner dewar containing helium at 1.5 °K.
4. Dewar cap.
5. Leads to magnet and solenoid.
6. Polyethylene seal.
7. Copper tapered light pipe.
8. Cupro-nickel light pipe.
9. Screening tube containing low-capacity leads from detector.
10. Tapered copper light pipe.
11. Cooled filter.
12. Indium antimonide detector.
13. Superconducting niobium solenoid.

Fig. 4.4. Cryostat for a cooled detector (PUTLEY [1963]).

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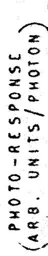
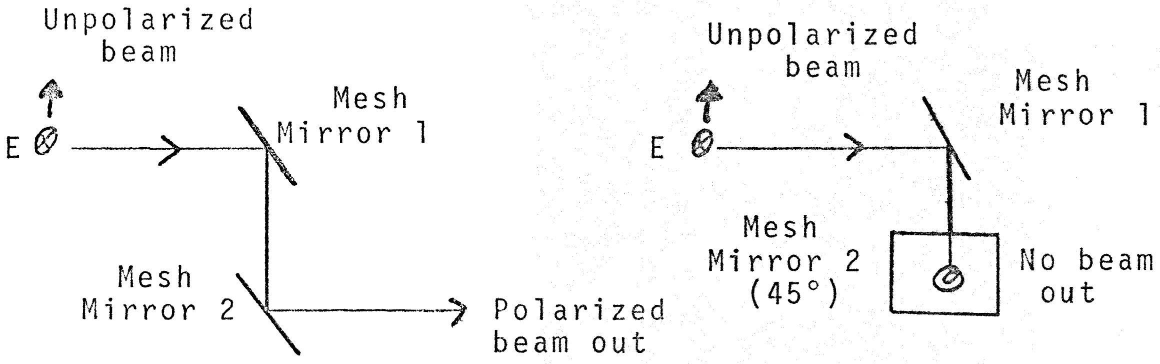


F

Typical Putley detector. Interior of Waniek dewar is very similar. Note 3 foot length of light pipe which carries radiation to InSb crystal.

Ref.: D.H. Martin, Spectroscopic Techniques, North Holland Pub. Co., Amsterdam, 1967.

Dr. Waniek brought some $20,000 worth of equipment to Kitt Peak which was used on the telescope from May 12 to 18, 1971. The experiment is described in detail in the report appended at the end of this paper. It failed primarily because of inadequate pumping capability (See Section IV below), and secondarily because of unforseen problems of low dish illumination resulting from the very long light pipe which had to be used (See Photo at end of report). The actual f/D turned out to be $>$ 2.0 rather than the $\sim$ 0.8 value measured in the lab. The problem is mostly traceable to the fact that the double 90° bend used produces different loss at different angles due to favorable or unfavorable Brewster angle polarization. This may be seen schematically from the following illustration:



(3dB loss of one component)

(Loss of both components)

(This diagnosis was made after Waniek's report was written.) The problem could unquestionably be solved if there were sufficient justification for use of a Putley type system.

Positive results of this experiment were the demonstration of easy helium serviceability on the telescope and stable operation of the superconducting magnet and electronics under actual observing conditions. The most valuable spin-off, however, came from better understanding of the vacuum system and also from much experience with low power-level ground loop problems which must be solved for use of InSb detectors.

(Note added in proof: This experience with ground loops proved to be the salvation of the very successful Kinch-Rollin detector run in February, 1972. The experiment will be described in detail in a forthcoming report.)

III. Portable High Vacuum System

The first status report illustrated a portable service cart designed to facilitate convenient testing of the dewar and to provide for pumping to reduce adiabatically the temperature of the liquid helium. Since it soon became apparent that any reasonable developmental program would require: (1) a readily available capability for pumping out the high vacuum isolation region between the inner and outer parts of the dewar, and (2) a sensitive helium leak detector, it was decided to retain the portable feature by building as much of the needed equipment into the same cart as possible. A valving system was designed to permit the existing cart pump (inherited from Infrared Labs.) to serve both as a helium pump and as a forepump for the 4 inch high-vacuum diffusion pump donated by the Kitt Peak optics lab. (value about \$550). A closed-cycle circulating oil cooling system for the diffusion pump was designed by Neil Albaugh and fabricated by him from surplus aircraft and automotive parts for less than \$100. Capital equipment purchased to complete the system included a thermistor vacuum gauge for the range from atmospheric pressure to 10^{-3} Torr (\$150) and an ionization gauge for the range from 10^{-3} to 10^{-10} Torr (\$1700 with ion tubes and adapters).

The system was tried at first without a liquid nitrogen cold trap. The base pressure (of 4×10^{-5} Torr) was rather disappointing. The problem was traced to the somewhat higher than nominal equilibrium temperature of the portable cooling system ($\sim$37°C). Since it was clear that greater benefit would be realized from the addition of a LN_2 cold trap than could possibly be achieved with an improved oil cooling system, an additional \$500 was spent on the cold trap. This resulted in a rapidly achievable base pressure of 8×10^{-7} Torr, which is entirely satisfactory for all foreseeable needs.

A final component essential for evaluation of any high vacuum system is a highly sensitive leak detector. The standard device for this purpose is the helium leak detector, which is basically a small mass spectrometer, tuned for atomic mass 4, which can be valved into the system under test. The system is then searched with a hypodermic probe from which a light flow of helium gas is allowed to emerge. Since helium diffuses through minute channels faster than any other gas, it is very rapidly detected by the masss spectrometer if any leaks exist. It is readily feasible to detect leaks of 10^{-9} cm ^{3}/sec with such a system.

The need for such a system is nowhere more important than in testing a liquid helium cooled cryogenic vacuum device. The contraction and expansion incurred in cycling the equipment from 300°K to 2°K is very detrimental to solder joints and welds between dissimilar metals such as the stainless steel casing and copper work surface of the helium chamber. Moreover, at 2°K the materials are exceedingly brittle and sensitive to fracture. The coup-de-gras is administered by the ability of superfluid liquid helium to flow readily through a fracture only a few atoms wide. (Such a failure ended my March observing run after 40 hours of operation).

For the above reasons it was deemed necessary to have a helium detector available at all times. Attempts to make-do by borrowing Kitt Peak's only leak detector proved very frustrating because (1) it was usually on the mountain looking for problems with the various vacuum systems at the solar telescope and 150" telescope sites, and (2) it was usually so badly contaminated with dirt from poor vacuum technique that maintenance of the detector itself bacame a serious issue.

Although it would have been convenient to include the leak detector on the cart with the rest of the vacuum equipment, this was discouraged by expert counsel since the pumping speed of the main vacuum system varies with the external load (e.g. the leak rate); and hence, the calibration of the leak detector is very difficult to maintain. This problem is circumvented by having a separate high vacuum pump for the leak detector itself. The detector, when valved into the system under test is very loosely coupled through a small throttling orifice.

It would have been possible to try the former approach (using a common high vacuum system) for a cost of $2800, covering the mass spectrometer and associated electronics only. By a fortunate coincidence, however, I was able to procure a complete used NRC-Varian Model 925-20 leak detector with its own pump from Varian Corporation for $3000. The new price of the same unit would have been $4200. The detector, obtained in October, completes all anticipated dewar high vacuum requirements.

In summary, I wish to point out the following relevancies:

1) We now have a completely portable capability for pumping high vacuum or liquid helium. The system can be taken to the mountain and, in fact, permitted me to learn far more from the recent observing run* than would have otherwise been possible. Typical turn-around time for opening the dewar and returning it to the telescope was 4 hours rather than 1 day as in January and March.

2) The superior high vacuum achievable with this system will materially reduce the noise level of any detector by reducing the frequency of collisions of ambient gas particles with the detector surface. It also minimizes the freezing out of outgassed contamination of the cold surfaces (including the detectors).

3) The helium leak detector will permit development of leaktight high vacuum systems which should give long term service without attention. A particularly nice feature of the present combination of pumping systems is that the dewar can actually be tested at 2°K, since the leak detector, of course, detects any helium

*November 3-9,1971

passing through from the liquid helium chamber as well as from the outside hyperdermic probe.

The pump cart and leak detector are shown in Photo #1.

IV. New Vacuum Manifold on 36 Foot Dish

One of the first questions that arose about the old operating system for the bolometer on the 36 foot telescope was the efficiency of the extremely long pump line. About 130 feet of 3/4 inch hose and 1 inch plastic tubing were required to connect the Heraeus E-70 pump to the dewar at the Stirling mount. Furthermore, the throttle valves and gauge were located very near the pump, thus reducing the pumping speed at the most critical point. Since acceptable performance of the system had been previously claimed, however, it was decided to postpone modification of it until more evidence was in hand that it was inadequate. My fears were confirmed with a vengence during the May test of the indium antimonide Putley detector.

As the pressure on the pump line is decreased, the mean-free-path of the gas molecules increases and the number of collisions with the tube walls increases proportionately. Hence, the viscosity becomes greater at lower pressures, and a larger pressure differential exists between the pump and the gas source.

Since the temperature-resistance characteristic of the Advanced Kinetics InSb detector was well known, and since the temperature of the liquid helium is directly proportional to the pressure, it was possible to follow the behavior of the pressure differential during the pumpdown with considerable accuracy. The large (7 liter) dewar required for the superconducting bias coil of the Putley-type detector evolved so much gas that it was impossible to reduce the temperature to the Lambda point of liquid helium (2.2°K). The liquid, never reaching this stable condition, was constantly boiling, and the performance of the detector was badly impaired. Detailed discussion of the problem is included in the appendix written by R. Waniek.

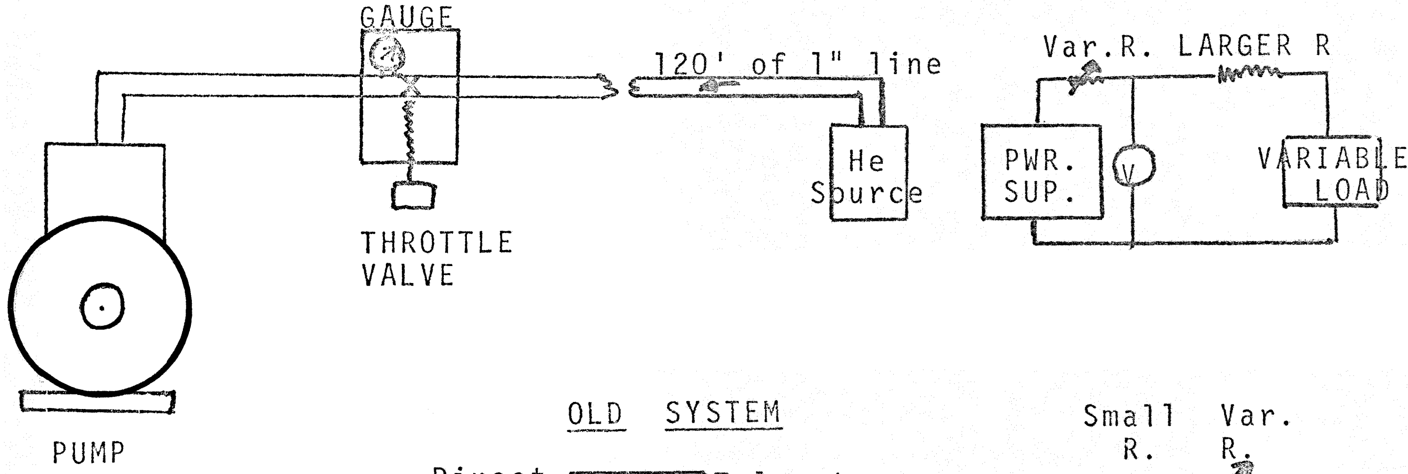
While no good measurements of the pressure differential were made with the Low bolometer mounted on the telescope, it is clear that the old practice of inferring the temperature of the detector from a pressure reading made at the bottom of the pump line was much in error. This, no doubt, has some bearing on the problem of unaccountably low sensitivity discussed in the first status report.

To end the problem with finality, it was concluded that a pump line should be installed which could handle any reasonable gas load. During the May run with Waniek we moved the pump to the platform just behind the left elevation bearing in a desperate attempt to shorten the line (figs.~~9~~11&10).This location of the pump has been adopted for the new system. The 1 inch plastic tubing has been replaced by rigid 3 inch tubing all the way to the Stirling mount. Since the pumping speed is proportional to the fourth power of the tube diameter and inversely proportional to the length, the new arrangement provides an improvement of 160X over the old.

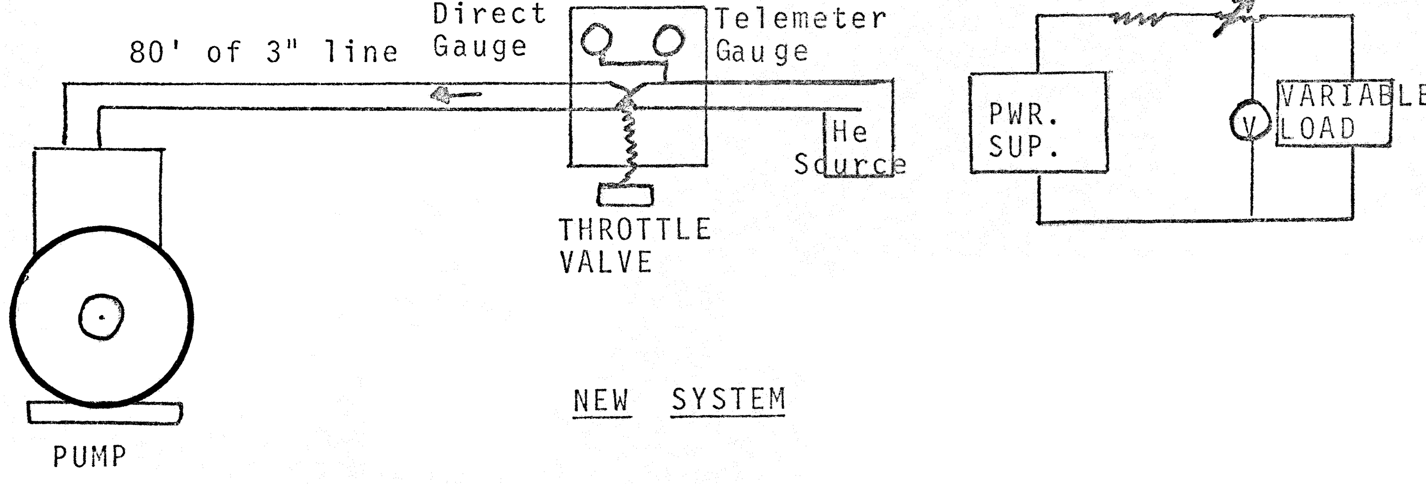
Another major improvement is the relocation of the valving and metering to the feed support just adjacent to the Stirling mount. This is, of course, now feasible because the air operated throw-out device permits the dewar pump-down to be accomplished in the normal service position. Thus there is no high impedance in series with the line far from the load. The arrangement also includes a pair of very accurate Heraeus gauges, one of which reads directly at the feed support and the other of which telemeters the pressure to the control room. The total distance between the throttling valves and the dewar is now 4 feet instead of the former 120 feet.

During the recent experimental run (November 3 through 9) the behavior of the cryogenic pumping system was faultless. The dewar was repeatedly opened to atmosphere, evacuated, cooled, and pumped back to a stable pressure of 2.5 Torr, corresponding to a helium temperature of 1.4°K. This compares with the previous minimum pressure of 10 Torr metered at the bottom of the pump line, which probably implied a temperature of at least 2.4° at the dewar. The NEP resulting from this improvement should have been better by at least a factor of 3. The highly repeatable pumpdown rate was particularly satisfying since oscillations and unexplained sudden losses of helium had been very characteristic of the old system.

The schematic below shows the comparison between the old and new systems, together with an electrical analog.



OLD SYSTEM



NEW SYSTEM

The new valving manifold with its direct reading and telemetering gauges is shown in Photo #2

I am pleased to note that Stellar Division of Kitt Peak has adopted my system for the 50" telescope pumping scheme, with similar improvement in the performance of their 10 μ Low bolometer.

V. Summing Up

Wisdom accumulates slowly, particularly in the 1 millimeter trade. Several small, but important matters have become clear in the course of other work. One interesting example is the reason why the rocking Gregorian secondary system tried by Low in the Fall of 1970 did not work:

In a Gregorian system the image size scales as (M+1), where M is the magnification. Since the Low system converted the f/D = 0.8 main beam of the 36' dish to an effective f/D of 4.0, (M+1) = 6.0. Hence, in an ideal system we would simply expect a diffraction-limited focal spot of six times greater diameter. At 1 millimeter (and shorter λ), however, we have ample evidence that the focal spot at the prime focus of the 36' dish is definitely not diffraction limited. It turns out that nearly all of the various types of aberration which affect a Gregorian system appear as terms which enlarge the energy distribution in the focal spot by $(M+1)^n$, where n is the an integer >1. In particular, simply rocking the axis of the Gregorian system with respect to the main optical axis of the primary enlarges the non-diffraction limited spot from 3 mm to $3(M+1)^2 \approx 108$ millimeters diameter!*

It is worth noting that in a Cassegranian system the aberrations are proportional to M^n rather than $(M+1)^n$. Thus, the system would have scarcely been better if it had had the same magnification in a Cassegrainian configuration. For this reason it is doubtful that the system presently being constructed for the 36 foot dish will be usable at 1 millimeter unless the error pattern of the dish can be improved by mechanical modifications.

Another matter which cannot be ignored is the sad lack of observational data from the November run. The best thing that can be said for it is that it turned out to be a glorious debugging session; everything which had not previously given trouble failed. The bolometer mounting wire broke, requiring

---

* I. Ghoziel and J. E. Simmons, Advanced Programs and Technology Division, Kitt Peak. (Private discussion).

replacement with another bolometer which proved to be very microphonic. The new Adkin F-60 low-noise preamplifier, having >300 hour battery life compared with the 30 hour life of the batteries in the Low preamp and a 5 x better noise figure, shorted an output capacitor due to a ground loop in the ne~~ar~~wly installed tri-ax cable circuit. The old preamp was pressed into service since the Adkin unit was a potted module. An attempt to cool all the filters to 2°K backfired: few people know that black polyethylene becomes increasingly transparent at low temperatures. This would have been readily apparent if the 5' dish had been operational before the run, because I would have identified it from atmospheric tipping. It took me three days to identify this problem, in the course of which I discovered that the NEP of the Low bolometer is indeed about 10^{-13} at $\approx 200\mu$ as advertised. Finally a problem of serious spillover in the dish illumination pattern was recognized. This led to some experiments with dewar focussing and external "light-funneling" which are continuing.

On the positive side, all vacuum and cryogenic systems worked perfectly. Thanks to the portable service cart it was unnecessary to return to Tucson at all, and much more was fixed in the time available than would have otherwise been possible.

The coming months will see a shift of emphasis from peripheral systems to the matter of detector sensitivity and bandwidth. I am looking forward with much interest to the trial of the InSb Kinch-Rollin detector from Queen Mary College in February, 1972. This will involve for the first time the use of capacitive mesh filters, which should give a much better understanding of the actual 1 millimeter behavior of the dish. The 5' dish is now operational on the roof of the Tucson lab., and detailed preliminary tests will be possible for all future systems to be tried on the telescope.

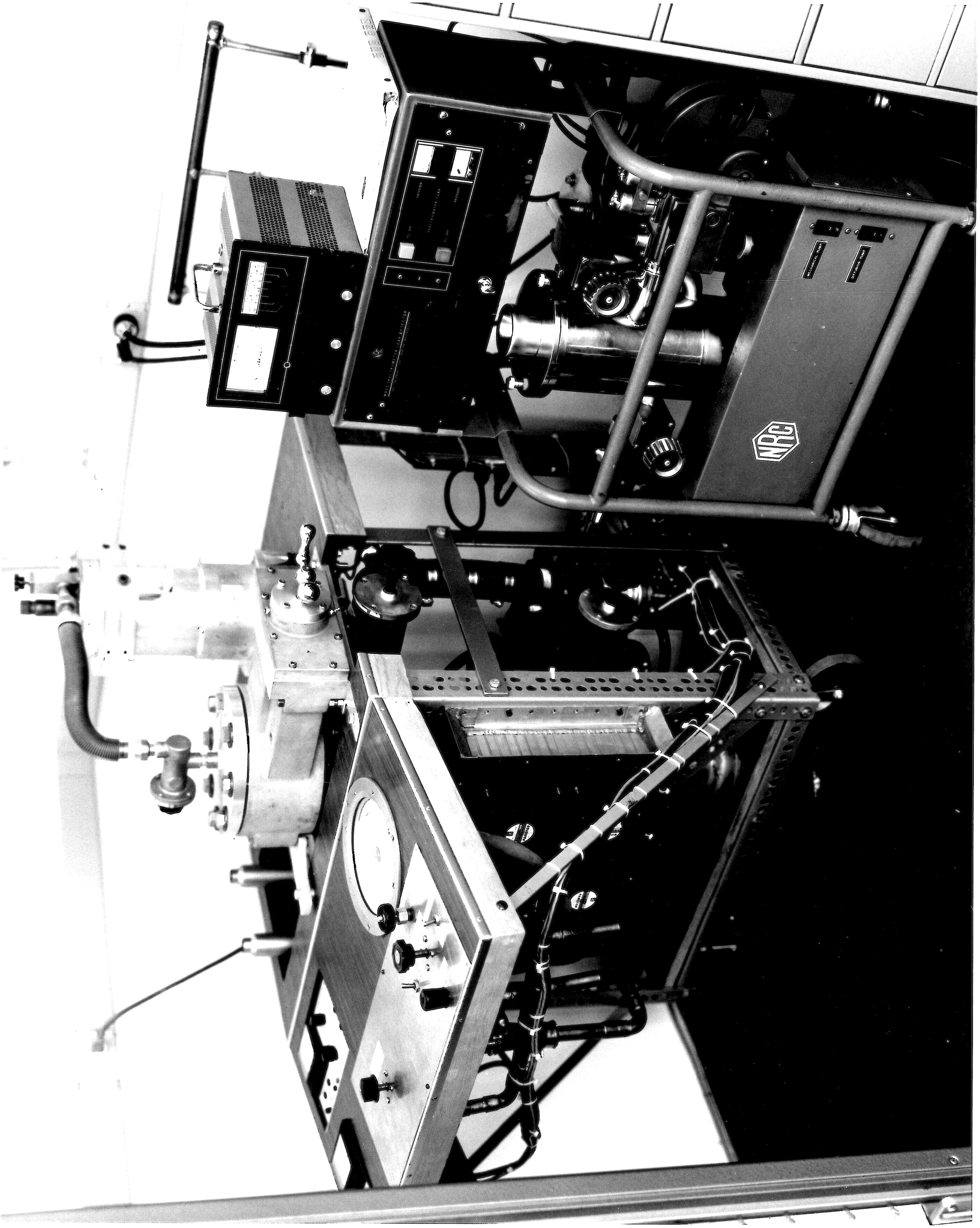


PHOTO I Vacuum service cart at left shows dewar being pumped to high vacuum. Helium leak detector is at right.

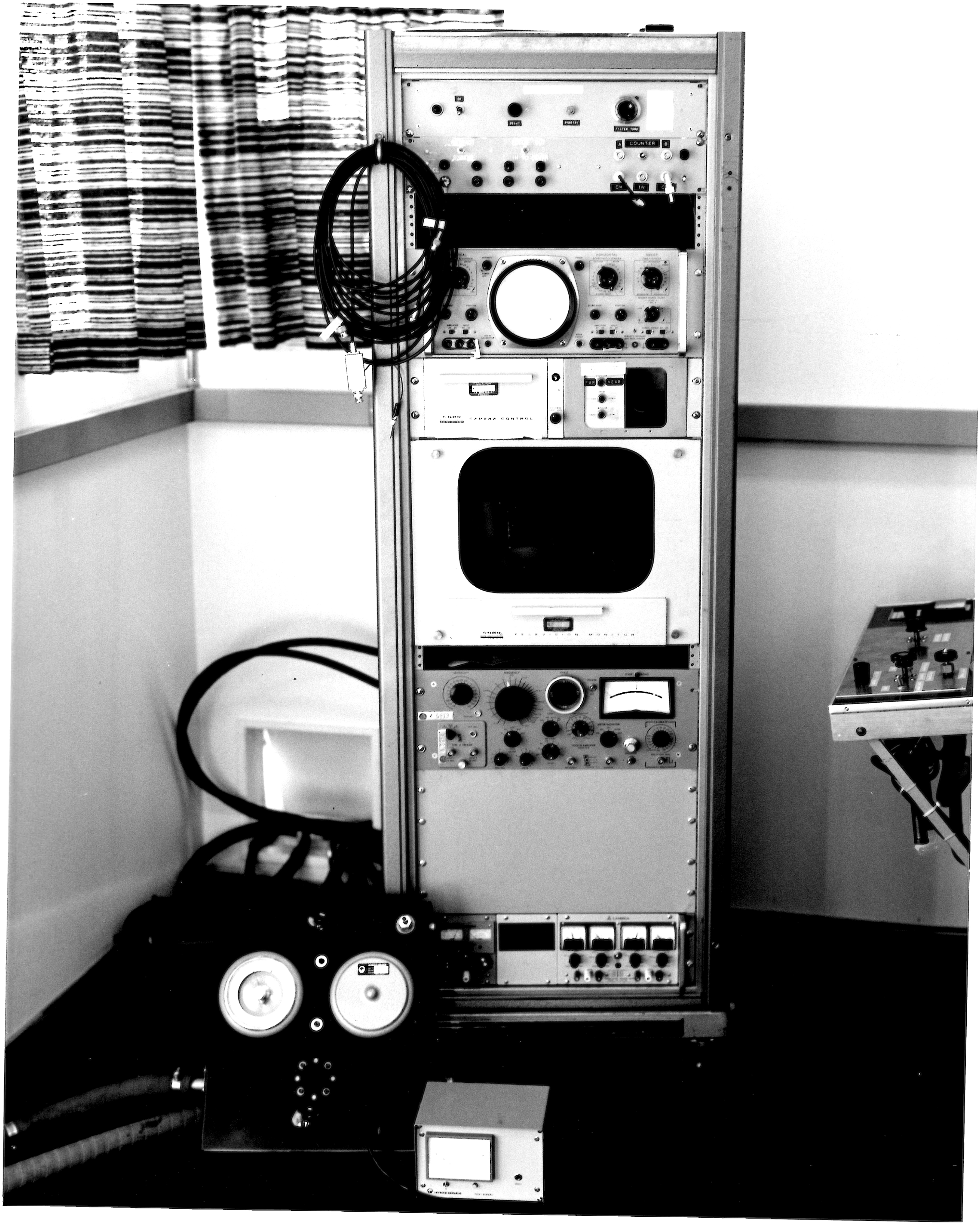


PHOTO 2

Relay rack contains all of 1 millimeter back-end and support electronics. TV measures dewar retraction accuracy and insures proper operation of chopper and iris.
New Vacuum pumping manifold with control valves and gauges.
Direct reading gauge at left, remote gauge at right.

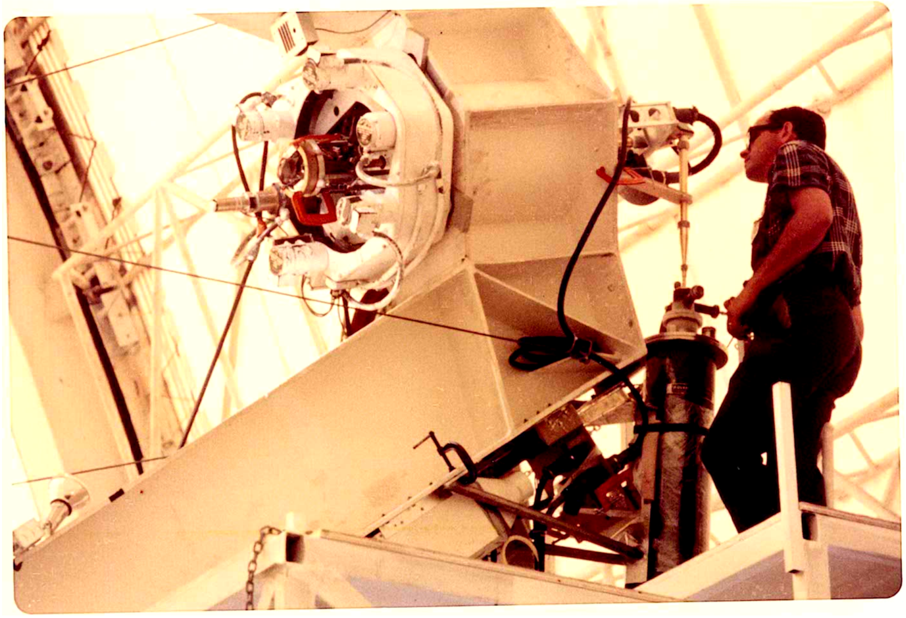
PHOTO 3 New roof lab with 5 foot dish; 1 Millimeter equipment shown installed. New secondary optics to produce f/D=0.8 beam not shown.

PUTLEY DETECTOR EXPERIMENT ---- Waniek and Rather

PHOTO 4

7-liter helium dewar with light pipe.
Note meter stick held against light pipe on left. Also note double right-angle bend at top. (See text)

PUTLEY DETECTOR EXPERIMENT----Waniek and Rather



Experimental setup. Chopper head at left; light pipe makes bend to enter dewar, bottom right.

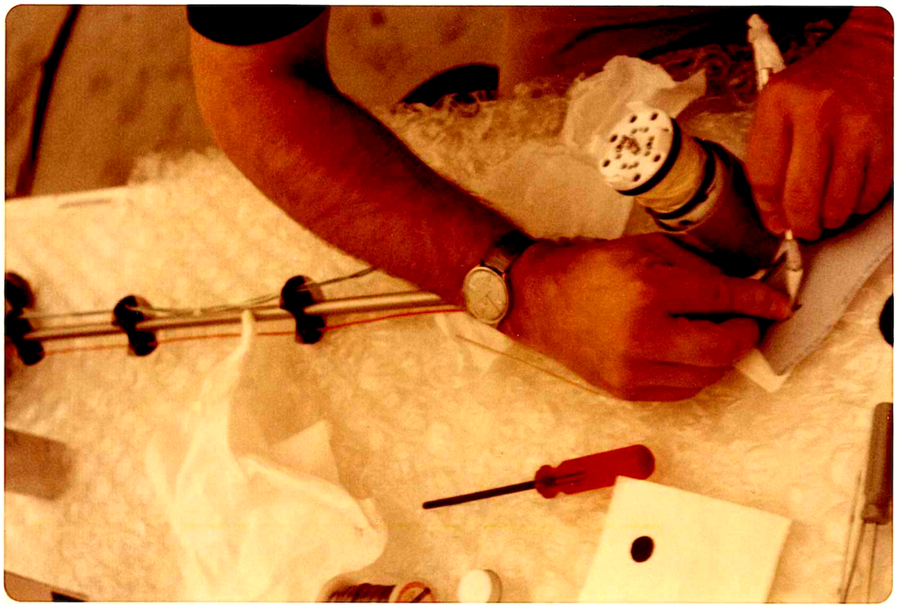
PHOTO 5

PUTLEY DETECTOR EXPERIMENT---Waniek and Rather

R. Waniek and C. Lipscomb transferring liquid helium into 7 liter dewar containing Putley detector at floor level.

PHOTO 6

PUTLEY DETECTOR EXPERIMENT----Waniek and Rather



Indium Antimonide detector is mounted at top of 20 kilogauss super-conducting coil shown. Stainless steel light pipe which carries radiation to detector is shown at left.

PHOTO 7

PUTLEY DETECTOR EXPERIMENT---Waniek and Rather

Servicing helium dewar in place on feed support.

PHOTO 8

<u>PUTLEY</u> <u>DETECTOR</u> <u>EXPERIMENT</u>----Waniek and Rather

Illustrating how dewar supported at 45° does not spill liquid Helium even at high elevation angles.

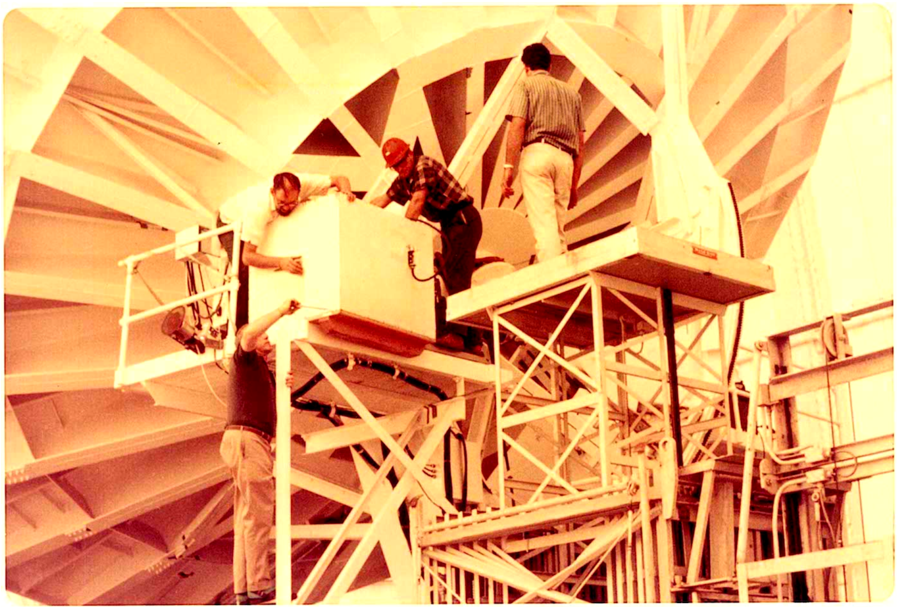
<u>PHOTO 9</u>

PUTLEY DETECTOR EXPERIMENT---Waniek and Rather

Temporary relocation of old vacuum line---a vain effort to improve pumping speed during the run.

PHOTO 10

<u>PUTLEY DETECTOR EXPERIMENT</u>----Waniek and Rather



Relocating 300 pound vacuum pump to platform behind dish. Pump is in white box.

PHOTO 11

ADVANCED KINETICS

ANALYSIS OF THE MILLIMETER WAVE EXPERIMENT

Submitted to

NATIONAL RADIO ASTRONOMY OBSERVATORY
KITT PEAK
TUCSON, ARIZONA

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Figure 4 Signal Amplitude with Eccosorb at Room Temperature

Figure 5 Comparative Signal between Eccosorb (~ 285°K) and Sky Background

Figure 6 Scan Across Moon

ADVANCED KINETICS

ANALYSIS OF THE MILLIMETER WAVE EXPERIMENT CONDUCTED WITH THE NRAO RADIOTELESCOPE AT KITT PEAK OBSERVATORY

(May 12 - 18, 1971)

During the period May 12 - 18, 1971, we have carried out a number of tests to determine the feasibility of operating an ADKIN millimeter wave photoimpurity detector in conjunction with the 36 ft NRAO radiotelescope. We shall summarize here briefly the problems encountered and the preliminary results obtained. Several suggestions are presented to improve the performance of the system for future runs.

1) INTERFACING PROBLEMS

Some problems were anticipated in interfacing the detector system with the existing focussing and modulator arrangement and with the support platform of the 36 ft telescope. Instead, this part of the system was made operational with only minor modifications in less than one day. The interfacing scheme adopted comprised a sliding lightguide, a dual 90° joint, providing the necessary motion in two perpendicular planes and two lengths of straight lightguide. The attenuation for this input portion of the system was determined to be approximately 6 db for radiation collected with a f:3 mirror. The acceptance angle of the detector and lightguide system is computed to be approximately 30°. Thus, the detector is fully matched to a collecting antenna of f:2, whereas with the NRAO telescope a loss factor of 6.25 (16 db) is encountered because of finite interception.

II) PERFORMANCE OF DETECTOR

The detector used for this experiment is an ADKIN model IRD-4. The detection mechanism is based on the decrease in the resistance of an InSb crystal when millimeter wave radiation is absorbed by free carriers. The sensitivity of the crystal improves by orders of magnitude as the temperature is decreased below 4°K and at high magnetic fields. A typical responsivity curve versus temperature is illustrated in Figure 1. For these reasons, the crystal is immersed in a LHe reservoir which must be pumped on and it is also placed in the magnetic field provided by a superconducting coil.

A) MINIMUM DETECTABLE POWER

The performance of the detector may be computed theoretically and checked by measurements. The figures agree well. For instance, the optimum responsivity S_o may be estimated from

$$S_o(V) = \frac{R(V) \cdot V \cdot \gamma(V)}{1 + 2\gamma(V)V^2} \qquad (1)$$

where γ is the non-linearity coefficient in the V-I curve

$$\gamma(V) = \frac{1}{\sigma}\frac{d\sigma}{d(E^2)} \qquad (2)$$

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$$\gamma(V) = \frac{1}{\sigma}\frac{d\sigma}{d(E^2)} \tag{2}$$

Here R = crystal resistance, V and E are the applied voltage and the electric field, σ is the conductivity of the material. For the crystal used in this run, and by introducing actually measured parameters, we obtain

$$S_o \approx 2 \cdot 10^3 \text{ v/w} \qquad (3)$$

By broadband calibration with a blackbody in the interval between 0.5 - 2 mm we obtain an average responsivity of $1.75 \cdot 10^3$ v/w, which is well in line with the above figure. This parameter refers to responsivity at the crystal.

In order to compute the minimum detectable power at the input to the lightguide, attenuation losses and the noise voltage should be taken into account. We obtain a noise equivalent power of

$$\text{NEP} = \frac{3 \cdot 10^{-8}}{1.75 \cdot 10^3} = 1.7 \cdot 10^{-11} \text{ w}/\sqrt{\text{Hz}} \qquad (4)$$

for a modulation frequency of 100 Hz and referred to the lightguide input. For a modulation frequency of 1 kHz, the NEP is improved by nearly one order of magnitude. The noise spectrum of the crystal is presented in Figure 2 for two levels of magnetic field.

The minimum detectable power obtainable in connection with the 36 ft radiotelescope is estimated to be

$$\Delta W = \frac{NEP}{AB\sqrt{\tau}} = \frac{1.7 \cdot 10^{-11}}{20 \cdot 6 \cdot 10^{11}\sqrt{\tau}} = 4.7 \cdot 10^{-25} w/m^2 Hz \qquad (5)$$

$$= 47 \text{ flux units}$$

We assume here $A = 20\ m^2$ as the appropriate fraction of the disc subtended by the f:2 aperture, $B = 600$ GHz is the present effective bandwidth with the cold filters used and $\tau = 10$ sec is the integration time of the phase rectified signal.

B) OPERATION OF DETECTOR

The detector performance parameters as measured at the ADKIN testing laboratory are summarized in Figure 3. A blackbody radiator at 500°K at the input of the lightguide represents a signal of approximately 130 µv, whereas a room temperature blackbody gives rise to 55 µv. The parameters characterize operation at 2°K, which is below optimal performance (usual operating temperature 1.5° - 1.6°K).

During the operation at Kitt Peak the detector was checked periodically against a stabilized mercury arc lamp with an effective temperature of 2800°K at 1 mm. The highest signal attained under "best" pumping conditions was approximately 240 µv. The reason for this disparity in response performance is attributable to the temperature attained during the pumping operation. From the response of the detector, from the data on crystal resistance and from the suction impedance of the system, we estimate here that the lowest temperature reached was around 3°K. The actual performance under these conditions is degraded by a factor between 30 and 40 with respect to that at 1.6°K.

From the viewpoint of cryogenic performance, the detector has exhibited excellent holding time of the cryogen, even under extreme tilt angles and high speed sweeps of the dish. In addition, one problem area has never materialuzed: the superconducting magnet maintained persistent magnetic fields in excess of 12 kOe without one single normal transition. Elevation angles up to 75° corresponding to tilt angles of the dewar up to 55°, have been covered during this phase of the operation.

Thus, we have overcome the anticipated complexities of hoisting at the antenna focal point a dewar of nearly 85 lb weight with a high field persistent magnet operating at temperatures below 4°K. The holding time of the cryogen has been between 12 - 20 hours, depending on the time history of the attitude angle.

III) DISCUSSION OF PUMPING SYSTEM

The main problem area encountered during this operation is related to the performance of the pumping system. The task of reducing the vapor pressure in a cryogenic container at a distance of approximately 40 meter is not a trivial one. The requirements imposed entail a mechanical pump of high suction capacity and a line of sufficiently large diameter to minimize the existing pressure gradient.

The mechanical pump available at the radiotelescope satisfies the first requirement. However, the ducting to the focal point of the antenna represents a serious impediment to the gas flow.

The situation has been analyzed in some detail to obtain indicative figures which may be summarized as follows:

i) The flow regime in the duct is characterized by Reynolds numbers in the vicinity of 300 - 500. Thus, the flow is not turbulent and viscous flow regime dominates

ii) The nominal suction capacity of the Heraeus pump E-70 is 70 m^3 /hr for air at STP. This figure should be corrected for the difference in viscosity between air and helium. For helium, the final suction speed is about 17 liter/sec.

iii) The conductance of the line under an assumption of $L = 30$ m and $D = 15$ mm (under compressed conditions) results in 5 liter/sec. It should be stressed that for Poiseuille flow the dependence of conductance on the diameter is steep $\propto D^4$. Thus, the effective speed of the system is only 3.8 liter/sec.

iv) Unfortunately this is rather marginal because the evaporation and cool-down losses of the reservoir impose a requirement of at least 2.5 - 3 liter/sec.

v) Moreover, the flow impedance generates a pressure drop which limits the attainable vapor pressure in the container and hence the minimum operating temperature. A good guideline for the pressure drop in the viscous approximation is

$$\Delta p \approx 6 \cdot 10^{-3} \; \frac{S_p L}{D^4} = 6 \cdot 10^{-3} \; \frac{17 \cdot 30 \cdot 10^2}{1.5^4} = 60 \text{ torr} \qquad (6)$$

This pressure drop would result at best in a temperature of 2.5°K at the LHe reservoir. In practice, this temperature has never been reached during the run. Paralleling of two lines improves the suction speed. However, it does not eliminate the basic problem of pressure drop in each line.

vi) In order to eliminate this suction impedance, a tube diameter of approximately 2 inch is required to allow operation at 1.5°K. Adoption of such a line would be a substantial asset to the operation of the radio-telescope in connection with cryogenic detectors. Operation in a Cassegrainian configuration would clearly eliminate the majority of these problems.

vii) These figures indicate clearly that operation of the detector below the lambda point of LHe (2.18°K) has not been achieved.

IV) DISCUSSION OF MEASUREMENTS

The signal collected from the detector crystal after injection of the required biasing current is initially preamplified at a location close to the antenna feed mount. By introducing a completely triaxial line, which is featured in all the ADKIN detector and processing equipment, we have been able to carry signals from the feed mount to the control room at the microvolt level without too strong interference. However, at times some leakage of 120 Hz pulses of unknown origin was noticed.

Three modes of operation have been attempted. The first method involves direct feeding of the signal to the PAR lock-in preamplifier. The second mode entails amplification with one low-noise preamplifier ADKIN model F-60. The amplification factor is 60 db and the noise at the chopping frequency of 100 Hz is 17 nv/Hz. The third mode combines two such units with a gain factor of 120 db and a noise voltage of 27 nv/Hz. A length of 150 ft of triaxial cable is used to connect the detector and preamplification stage to the lock-in amplifier in the control room. The additional capacitive loading has no attenuation effect at the modulating frequency. The gain-bandwidth of the system with the triaxial cable has been measured to exhibit a 3 db point at approximately 50 kHz, instead of the usual 500 kHz location for the unloaded output.

There are two serious drawbacks about operation of the detector above 2°K. First, the loss in responsivity decreases the available signal. Second, the relatively low detector resistance makes the coupling to the preamplifier stage more difficult.

For optimal conditions appropriate matching of the noise (temperature) contours is required.

A typical example of performance of the detector is illustrated in Figure 4. A piece of Eccosorb material (emissivity at 1 mm ~ 0.9) was exposed to the input lightguide of the detector with the chopper energized at 100 Hz. The experiment was performed with the detector operational on the feed mount and the signal was fed to the control room. The ambient temperature was approximately 285°K. A similar piece of Eccosorb was then dipped in LN, allowed to thermalize and then brought rapidly in front of the aperture. The discernible difference between the two inputs is 300 ±50 nv. The signals are at the level of 1.5 μv. The estimated temperature of the Eccosorb was in excess of 150°K because of convective heat exchange with the surrounding air.

An example of the comparative signal levels between Eccosorb calibrator (285°K) and sky background is presented in Figure 5. The difference here is 200 ±50 nv and the signals are acquired at the level of 2 μv after optimization of bias current through the crystal.

The search for signals from planets was seriously hampered by this lack of detector sensitivity. Some indication of signals from Jupiter and Mars is perhaps available but at a level too marginal for being convincing. One pass across the moon after optical pointing illustrates roughly the situation (see Figure 6). The step signal between sky background and the lunar location is approximately 30 nv.

V) SUMMARY AND RECOMMENDATIONS

During this first run of a millimeter wave detector of the photoimpurity type in conjunction with the NRAO radiotelescope appreciable experience has been accumulated. Among the positive achievements should be listed the feasibility of interfacing the large detector dewar with the feed mount and the operability of cryogenic system and superconducting magnet with only minor deterioration of holding time.

On the other hand, the restriction imposed by the long vacuum ducting has appreciably impaired the sensitivity of the detector to the point where acquisition of signals from planetary sources has not been successful.

The steps to improve the situation are evident. Foremost is the installation of a vacuum line satisfying the requirements for a pressure drop not to exceed 2 - 4 torr. This line will open new possibilities in the application of cryogenic detectors at the radiotelescope. A second target covers the narrowbanding of the spectral acceptance of the detector system. During this run a new semiconductor filter has been adopted whose transmission is computed to fall to 10% at 20 cm^{-1}. This performance must still be tested and improved on.

The situation concerning modulator configuration and input lightguides should also undergo further design improvements and testing.

The paint material used for the surface of the reflector dish should be carefully spectrum analyzed as to its emissivity in the waveband of interest.

Finally, the electronic circuitry used for processing the signal can still be improved, although signal transmission at the microvolt level has been proven feasible both with and without preamplifier stage.

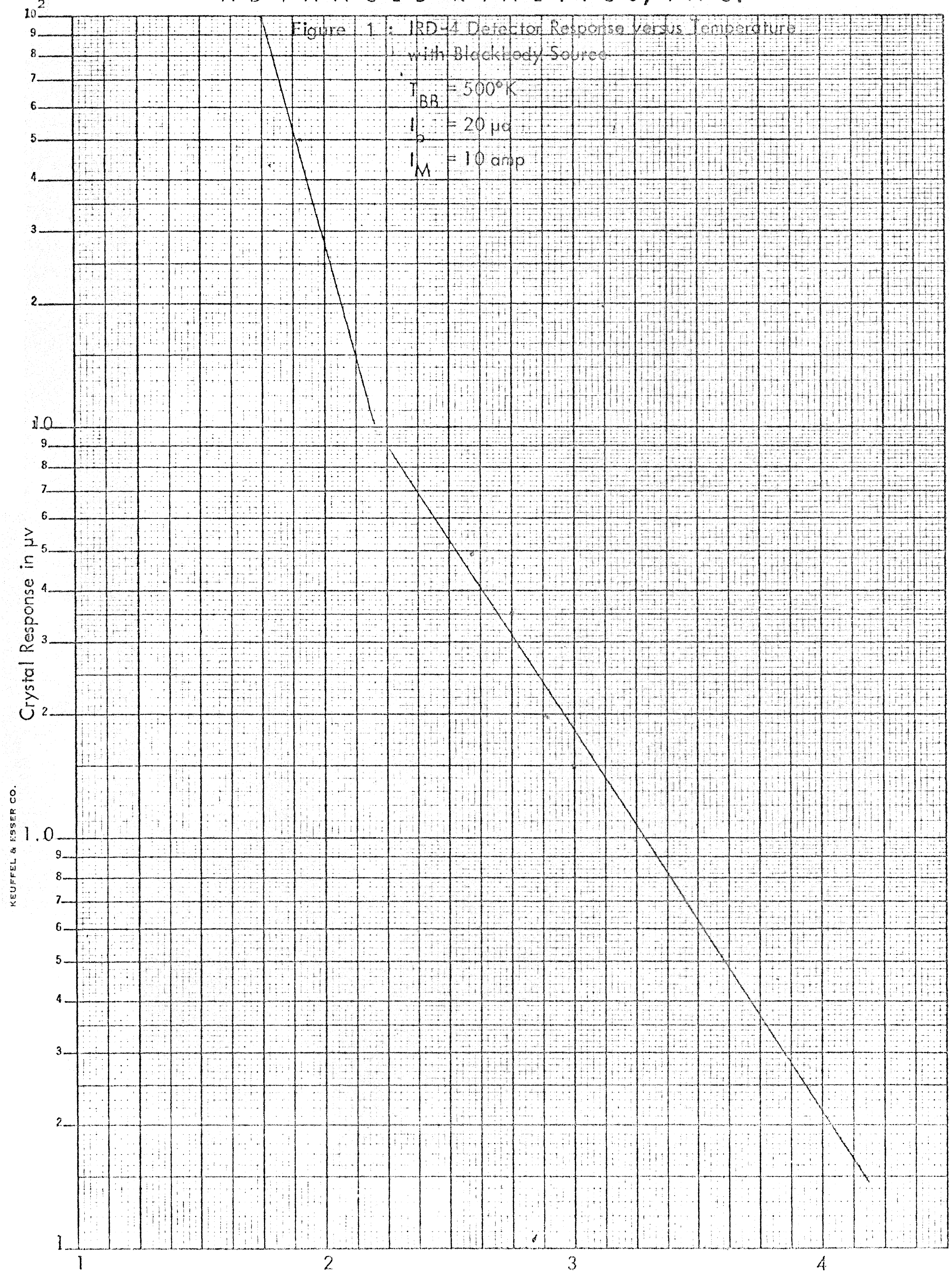


Figure 1: IRD-4 Detector Response versus Temperature with Blackbody Source

$T_{BB} = 500°K$

$I_b = 20\ \mu a$

$I_M = 10$ amp

Figure 23 Typical InSb Crystal Noise Voltage vs Frequency

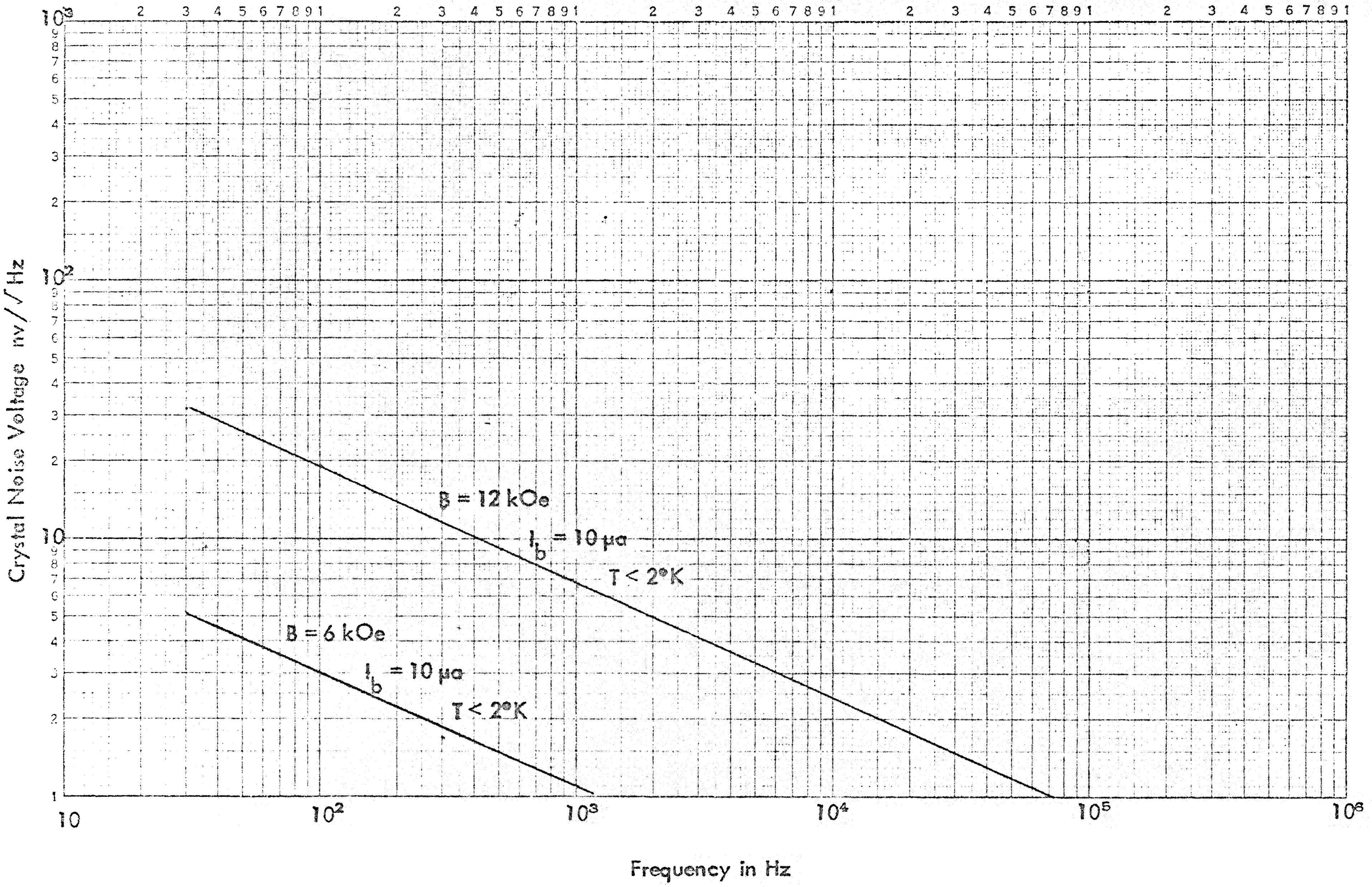
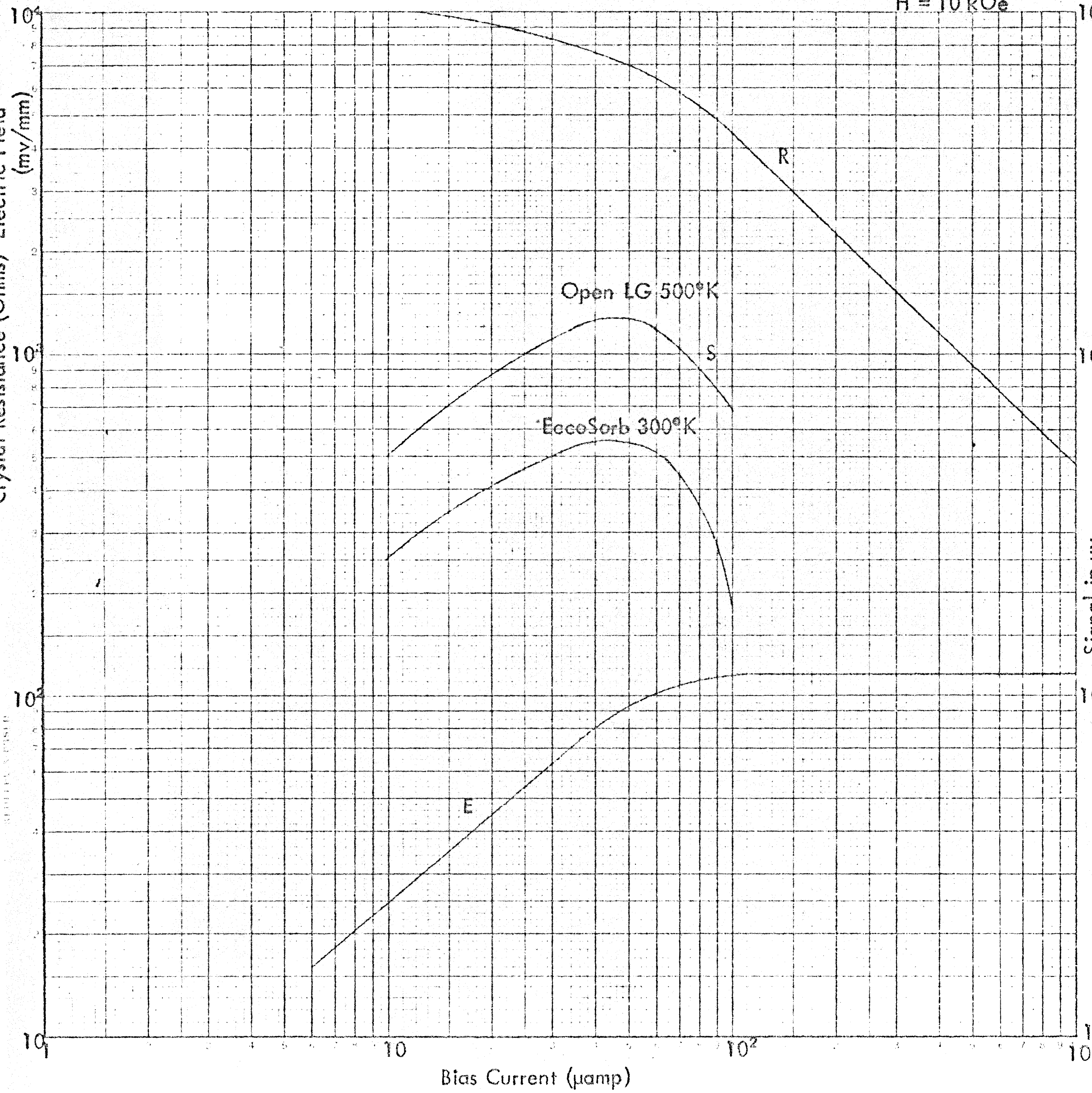


Figure 3: InSb Operating Parameters

T = 1.9°K
H = 10 kOe



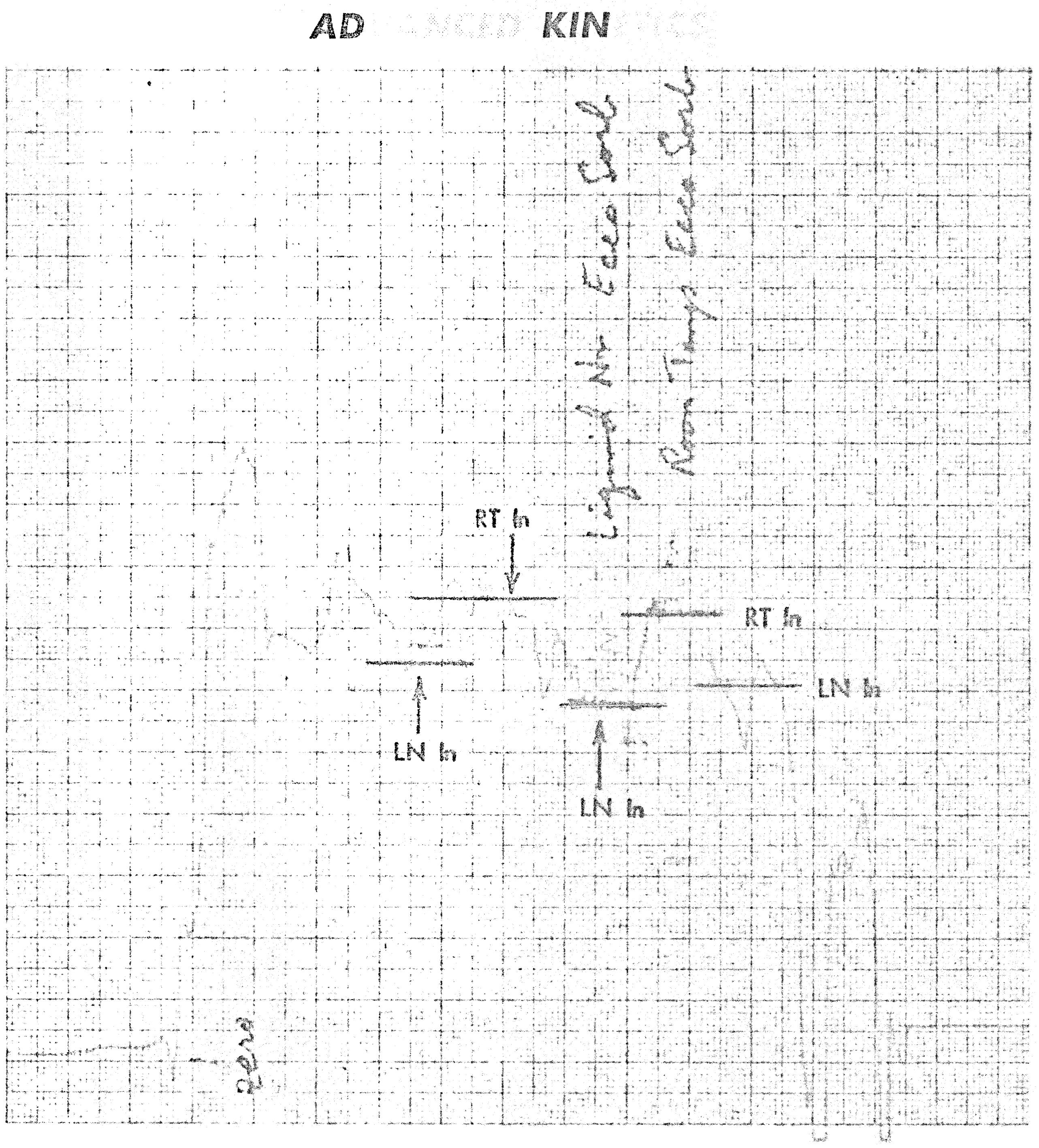


Figure 4: Signal Amplitude with Eccosorb at Room Temperature (~ 285°K) and Cooled by Immersion In LN (~ 150°K)

Full Scale 5 mv with G = 60 db
Actual Signal 200 nv/cm
V_1 (~ 285°K) ≈ 1.5 μv
V_2 (~ 150°K) ≈ 1.2 μv

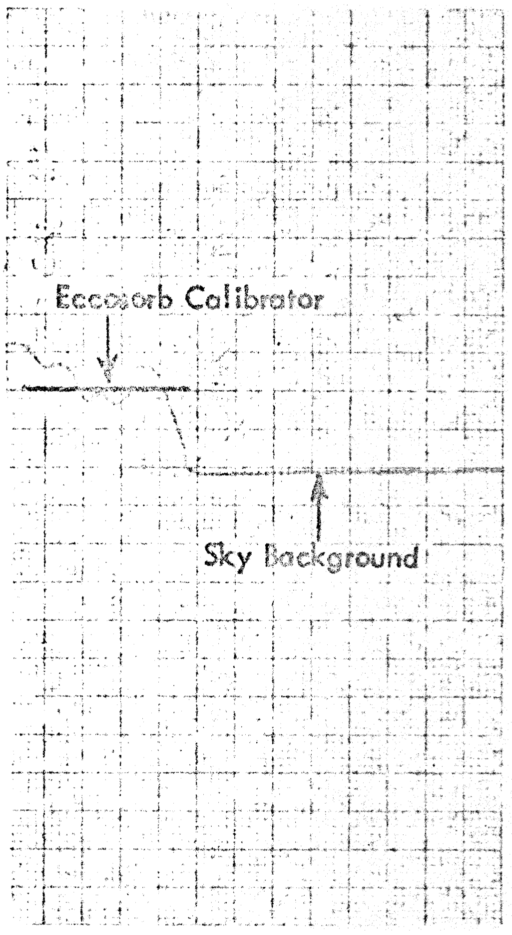


Figure 5: Comparative Signal between Eccosorb (~ 285°K) and Sky Background

Scale Sensitivity 200 mv/cm
RC = 30 sec
V (Eccosorb) ≈ 2 μv
V (Background) = 1.8 μv
Dish Elevation γ = 75° 25'

AD KIN

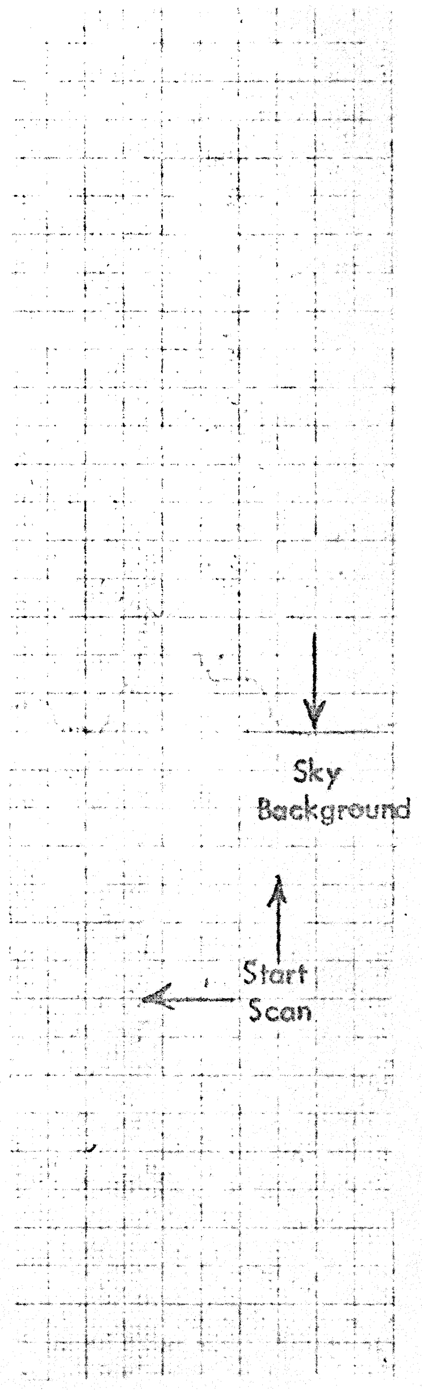


Figure 6: Scan Across Moon

Scale Sensitivity 20 nv/cm
RC = 10 sec