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FAR INFRARED APPLICATIONS OF A LARGE MILLIMETER WAVE TELESCOPE

P. L. Richards

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FAR INFRARED APPLICATIONS OF A LARGE MILLIMETER WAVE TELESCOPE

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July 1975

In this memorandum we consider the benefits to be gained by locating a large mm-wave telescope at a high dry site so as to obtain useful atmospheric transparency in the far infrared (sub-mm) bands $10 \lesssim \nu \lesssim 30$ cm^{-1}. The telescope is assumed to have a diameter $D_L = 25$m, a mean square roughness $\sigma = 10^{-2}$ cm^2, and a circle of confusion of radius $\theta_c = 1.5 \times 10^{-4}$ rad.

Since this telescope will be incoherent in the far infrared bands, we will primarily consider incoherent receivers based on bolometer detectors. The assumption is made that the angular size of the image for $\nu \leqslant 10$ cm^{-1} is the geometrical circle of confusion of the telescope, despite the fact that the telescope is designed to be essentially coherent at $\nu = 7$ cm^{-1} with a much smaller angular resolution $(\nu D)_L^{-1} \approx 6 \times 10^{-5}$ rad. This circle of confusion analysis becomes more nearly justified as ν approaches 30 cm^{-1}.

Three receivers are considered with different spectral resolving powers $R = \nu/\delta\nu$. Each is assumed to have sufficient multimode throughput to accept the full circle of confusion of the telescope $A\Omega = \pi^2 D^2 \theta_c^2/4 = 0.35$ sterad cm^2, so that they can accept all of the power from a point source. The receiver parameters represent an estimate of of the best that can be built with <u>presently</u> <u>existing</u> technology.

The receivers contemplated for this application would be built around a confocal Fabry-Perot interferometer cooled to liquid helium temperatures for high efficiency and good dimensional stability. The high resolution interferometer would be followed by a grating or a second interferometer as an order sorter. The detector would be a bolometer similar to the one described in Appendix A. The thermal conductance and the heat capacity of this bolometer will scale as T^3, so that a dark optical noise equivalent power (NEP) of $\lesssim 10^{-16}$ $W/\sqrt{Hz}$ at the bolometer should be available at a bolometer operating temperature of $\sim 0.3°K$. The NEP of these bolometers will be limted by the fluctuations in the background radiation P_B passed by the wider band receivers. In order to compute this effect we must assume values for the atmospheric emission $\varepsilon(=0.5)$, the telescope feed efficiency $\alpha(=0.5)$, and the receiver transmission $\beta(=0.1)$. The background limited NEP_B is then

$$NEP_B = (2kTP_B)^{1/2} = (4\alpha\beta\varepsilon k^2 T^2 \nu^3 cA\Omega/R)^{1/2}. \qquad (1)$$

The optical NEP at the bolometer anticipated for each receiver is listed in Table I. The noise equivalent flux (NEF), as well as the noise equivalent temperature (NET) for an extended source which is large compared with the circle of confusion are also given in Table I.

For the case of a source small compared with the diffraction limit of either telescope, the NEP of the detector is converted to a noise

equivalent flux as follows

$$NEF = \frac{4\ NEP \cdot R}{\alpha\beta\varepsilon\pi D^2 c\nu}. \tag{2}$$

For an extended source, the power accepted by a system with throughput $A\Omega$ is given by the Rayleigh-Jeans law, so the noise equivalent temperature is

$$NET = \frac{NEP \cdot R}{2\alpha\beta\varepsilon k c\nu^3 A\Omega}. \tag{3}$$

The possibility exists of an improvement by a factor ~ 7 in the assumed performance of the receiver with $R = 10^5$, by cooling the bolometer with a ^3He - ^4He dilution refrigerator.

The performance of these receiver -telescope combinations is compared in Table I with the same receivers on the next largest available high altitude telescope, which is assumed to have D_S = 3m and be coherent for $\nu < 30\ cm^{-1}$. For the purposes of the comparison of NET values, the beam diameter on the sky is assumed the same for both telescopes. This need not be quite true in actual use since the diffraction limit of the small telescope varies over $3.3 \times 10^{-4} \geqslant (\nu D_S)^{-1} \geqslant 1.1 \times 10^{-4}$ rad. compared with a circle of confusion of order $2\theta_c = 3\times10^{-4}$ rad. for the large telescope.

It is quite clear from Table I that a spectacular improvement is obtained by using the large telescope, with only a small sacrifice (near $\nu = 30\ cm^{-1}$) of spatial resolution.

Since coherent receivers are being developed for the far infrared band of interest here, it is useful to know the receiver noise temperature T_R which would have equivalent performance to each of the proposed incoherent systems operated on the large telescope. We assume that the coherent receivers are operated on the largest available coherent telescope which is again taken to have $D_S = 3m$.

For the point source

$$T_R = \frac{NEP}{2\beta k}\sqrt{\frac{R}{c\nu}}\left(\frac{D_S}{D_L}\right)^2. \tag{4}$$

For the extended source

$$T_R = \frac{NEP}{2\beta k\nu^2 A\Omega}\sqrt{\frac{R}{c\nu}}. \tag{5}$$

In each case we measure T_R at the input to the receiver. The atmospheric and telescope feed losses $\alpha\varepsilon$ are assumed to be the same as for the incoherent system.

From the results listed in Table II, we see that the incoherent receiver with $R = 10^5$ is just equivalent (at $\nu = 10\ cm^{-1}$) to a coherent receiver with $T_R = 3{,}000K$ which has a 100 channel

multiplex i. f. filter bank. For smaller values of R the incoherent receivers rapidly become more favorable. In fact it seems possible that the uncertainty principle limit $T_R = h\nu/k$ of an ideal coherent receiver which gives $T_R \gtrsim 1.4\nu$ (°K) would prevent any coherent receiver on the small telescope from equalling the performance of the wider band incoherent receivers on the large telescope.

One alternative to the above approach is to use coherent receivers on the large telescope. Because $D_S \ll D_L$, the usefulness of the large telescope for coherent receivers extends beyond $\nu = 10\ cm^{-1}$ even for point sources. Its effective coherent diameter $D_{eff} = D_L e^{-\sigma\nu^2/2} \approx 15m$ at $\nu = 10\ cm^{-1}$ and $D_{eff} = D_S$ at $\nu \approx 21\ cm^{-1}$. Consequently, if the coherent receivers of Table II are used on the large telescope, the values of T_R in the point source column are increased by a factor 25 for $\nu = 10\ cm^{-1}$. This improvement disappears when ν reaches $21\ cm^{-1}$. The values of T_R in the extended source column remain the same at all frequencies. The usefulness of coherent receivers for observing point sources in the range $10 \leq \nu \leq 21\ cm^{-1}$ strengthens the argument for locating the large telescope at a high site.

All of the numbers listed in Tables I and II were computed for $\nu = 10\ cm^{-1}$. Their frequency dependence is complicated and is quite rapid in some cases. In order to specify this dependence, the exponent of ν obtained from Eqs. (1-5) is given in parenthese in Tables I and II beside the corresponding quantity.

One other size of telescope may be of great interest. It appears to be feasible to construct a telescope with D = 10m which is coherent for $\nu < 30\ cm^{-1}$. Eqs. (1-5) can be used to evaluate the performance of this telescope with either type of receiver. This is most easily done if it is assumed that the solid angle on the sky is kept constant so that $A\Omega$ scales as D^2. For $R = 10^5$ so that background fluctuations are negligible, the values of NEF and NET in Table I scale as D_S^{-2}. In Table II, T_R for a point source scales as D_S^{2} and for an extended source as D_S^{o}. For R = 10 so that the bolometer is background limited, these factors became D_S^{-1}, D_S^{3}, and D_S^{1} respectively.

It appears from the analysis given here that a large mm wave telescope at a high dry site would provide a formidable tool for both spectroscopy and broad band radiometry in the frequency range $10 \leqslant \nu \leqslant 30\ cm^{-1}$. Only for the highest resolution spectroscopic applications could the projected 3m infrared telescope be competitive, and then only with the best mixers likely to become available.

TABLE I

Noise equivalent flux (for a point source) and noise equivalent temperature (for an extended source) for an incoherent receiver operated on the large D_L = 25 m and the small D_S = 3 m telescopes. The optical NEP at the bolometer which depends on the resolving power R because of background radiation fluctuations is also shown. The numerical values are computed for ν = 10 cm^{-1}. The frequency dependence is given in terms of a power of ν(in parentheses).

	R	NEP ($W/\sqrt{Hz}$)	NEF ($10^{-26} W/M^2 Hz^{3/2}$)	NET ($°K/\sqrt{Hz}$)
LARGE TELESCOPE	10^5	10^{-16} (0)	270 (-1)	1.4 (-3)
	10^3	2×10^{-16} (~3/2)	5.4 (~1/2)	0.03 (~-3/2)
	10^1	1.3×10^{-15} (3/2)	0.35 (1/2)	0.0017 (-3/2)
SMALL TELESCOPE	10^5	10^{-16} (0)	19,000 (-1)	100 (-3)
	10^3	10^{-16} (0)	190 (-1)	1 (-3)
	10^1	2×10^{-16} (~3/2)	3.8 (~1/2)	.02 (~-3/2)

TABLE II

Receiver noise temperature T_R of a coherent receiver operated on a coherent 3m telescope which would have the same performance as the incoherent receivers of Table I operated on the large telescope. Since there is a practical limit of a few GHz to the bandwidth of a coherent receiver the row labeled $R = 10^1$ compares an incoherent receiver with $R = 10^1$ to a coherent receiver with $R = 10^3$. The numerical values are computed for $\nu = 10\ cm^{-1}$. The frequency dependence is given as a power of ν(in parentheses).

R	T_R (°K) Point source		Extended source	
10^5	300	(-1/2)	600	(-5/2)
10^3	60	(~1)	120	(~-1)
10^1	4	(1)	8	(-1)

APPENDIX A

A SUPERCONDUCTING TRANSITION EDGE BOLOMETER*.

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Liquid helium temperature bolometers are widely used as detectors of broadband infrared and far-infrared radiation. Although most presently-used bolometers are made from semiconductors, superconducting bolometers, operated on the resistive transition, have been studied for many years.[1] Previous superconducting bolometers suffered from appreciable excess low-frequency noise. The recent discovery[2] that this low frequency noise can be greatly reduced if the film is strongly thermally coupled to its substrate has re-opened the possibility of making very sensitive superconducting bolometers.

In this article we briefly describe a superconducting bolometer which is designed around an Al transition-edge thermometer on a sapphire substrate. Measured values of the electrical noise equivalent power (NEP), time constant τ, specific detectivity $D^* = \sqrt{\text{Area}}/\text{NEP}$, thermal conductance G, and heat capacity C are shown in Table I.

Table I.

NEP	~~10^{-14} W/$\sqrt{\text{Hz}}$~~ 5×10^{-15} W/$\sqrt{\text{Hz}}$
τ	0.13 sec.
D^*	4×10^{13} cmW/$\sqrt{\text{Hz}}$
G	5×10^{-8} W/K
$C=G\tau$	6.5×10^{-9} J/K

The sapphire substrate on which the superconductor is deposited is coated with a Bi film to give a calculated coupling efficiency to far infrared radiation of 50 percent. This efficiency has been experimentally verified over a frequency range from 10 to 300 cm^{-1}. The electrical NEP is the best achieved with a superconducting transition edge bolometer, and is comparable to that of the best semiconducting bolometers. Because of the low heat capacity per unit area, the D^* is larger than is generally achieved with semiconducting bolometers. It is comparable in sensitivity to the SNS bolometer,[3] but considerably easier to construct and operate.

The construction of the bolometer is straightforward, and closely follows the technique used for the SNS bolometer.[3] Four indium contacts are evaporated onto the corners of a 4×4×0.125mm sapphire substrate. An aluminum strip is evaporated across one pair of contacts and a bismuth strip is evaporated across the other pair. An additional layer of indium, about 3μm thick, is then evaporated onto the contacts. Two 15μm diameter parallel nylon threads are glued to a brass ring; the segment of the ring to which each thread is attached is electrically isolated from the remaining segments. Each thread is coated with an indium film about 1μm thick, except for a region 2mm long at the mid-point. The threads are gently pressed against the indium contacts on the substrate so that the indium films cold-weld. This procedure produces a support for the substrate that is mechanically reliable and whose thermal conductance to the ring can be adjusted to the optimum value. Electrical connection to the aluminum thermometer and to the bismuth heater is available through the appropriate pair of indium-coated threads. The brass ring is mounted inside a vacuum can immersed in liquid helium. The temperature of the ring can be raised above that of the bath by means of an electrical heater.

Changes in the resistance of the aluminum thermometer are measured as follows. A series resonant circuit, consisting of a capacitor and a superconducting coil, is connected across the thermometer leads. An ac current connected across the capacitor excites the tank circuit at its ~15kHz resonant frequency. The amplitude of the ac voltage across the capacitor is then inversely proportional to the resistance of the thermometer. This voltage is amplified by a room temperature FET preamplifier with a noise temperature of about 2K, and detected by a diode in its linear range. The bolometer is calibrated by passing a known current through the bismuth heater. The measured parameters of a typical bolometer operated at the ~1.5K transition temperature of the aluminum film are shown in Table I. The calculated heat capacity of the sapphire substrate and indium films is about 5×10^{-9}J/K. The achieved NEP is a factor of about 3 above the noise limit imposed by thermal fluctuations, $\sqrt{4kT^2G}\approx3\times10^{-15}W/\sqrt{Hz}$. The source of this excess noise is being investigated.

The design of this bolometer can be improved in a number of ways to obtain either faster response or smaller NEP. The volume of the indium contacts which presently contribute about 40 percent of the total heat capacity

can be reduced. The heat capacity of the substrate can be reduced by making it smaller in area, or by using diamond in place of sapphire. Either the NEP or the τ can be reduced in proportion to C, depending on the value of G chosen.

The bolometer is made sensitive to infrared radiation by coating the reverse side of the sapphire substrate with a thin bismuth film. The absorption of radiation by a thin conducting layer on a dielectric can be calculated from Maxwell's equations. The result depends on whether the radiation is incident upon the conducting layer from the vacuum or the dielectric side. The absorption, A, is greater for the latter case, and is then given by

$$A = \frac{4nZ_o/R_\square}{(1+n+Z_o/R_\square)^2}$$

for normal incidence. Here, n is the refractive index of the dielectric, Z_o is the impedance of free space, and $R_\square$ is the surface resistance of the conducting layer.

The infrared transmittance of sapphire substrates coated on one side with bismuth films 300 to 4800Å thick was measured over the frequency range 10 to 300 cm^{-1}. The observed transmittance exhibited oscillations with a period of 12 cm^{-1} due to Fabry-Perot interference of radiation reflected from the two surfaces of the substrate. The reflectance was calculated from the magnitude of these oscillations and the absorptance obtained by subtracting the transmittance and reflectance from unity. The maxima and minima of the Fabry-Perot oscillations in the absorptance are plotted in Fig. 1 vs the surface resistance of the films. The experimental points shown were measured at 100cm^{-1}, but the results were essentially independent of frequency over the range of the measurement. For spectroscopic applications it is convenient to choose a film with surface resistance $R_\square = 2Z_o/(n+1)$ to avoid the Fabry-Perot fringes in the absorptance.

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* Work supported by the U.S.E.R.D.A.

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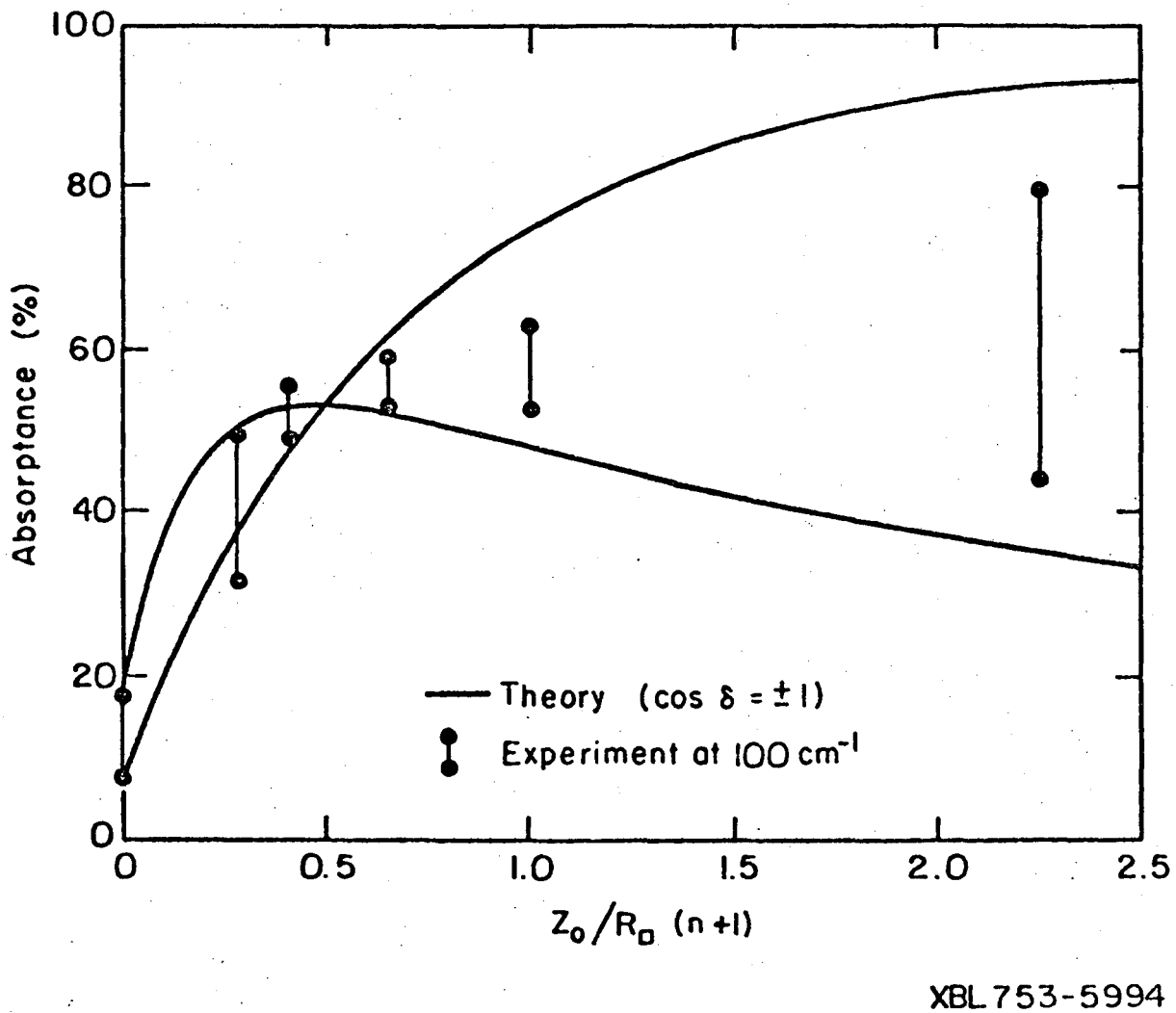

Fig. 1. Absorptance of bismuth-coated sapphire substrates (maxima and minima of Fabry-Perot fringes) as a function of the surface resistance, $R_\square$, of the film.

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