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Optical Design and Performance of the BIMA Interferometer

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ABSTRACT

The Berkeley-Illinois-Maryland Association millimeter wave interferometer has a very clean and simple optical design. Each antenna holds one dewar which houses mixers for 4 frequency bands; the feed horns for the 4 frequency bands are located slightly off the telescope axis and look directly at the subreflector without any intervening transfer optics. To change frequency bands, the telescope pointing is offset slightly. The feed horn to antenna coupling is frequency independent; aperture efficiency is measured to be 75% at 100 GHz and is expected to be greater than 71% up to 270 GHz. Main beam efficiency is about 83% at 100 GHz. The total antenna surface error is 30 μm rms, corresponding to $\lambda/100$ at 100 GHz. By extrapolating a tipping curve to zero airmass, the residual telescope noise temperature is found to be 3 to 5 K, in good agreement with calculations. Teflon (PTFE) lenses, serving also as windows in 50 K and 10 K radiation shields, provide excellent blockage of infrared radiation but very low loss at millimeter wavelengths.

INTRODUCTION

In recent years, as SIS mixer noise temperatures have steadily improved, the noise from receiver optics, the telescope itself, and the atmosphere have become major contributors to the system temperature of many millimeter and sub-millimeter wave telescopes. Complex optical designs are often chosen for these instruments, perhaps in an effort to achieve great versatility. However, these complicated optical trains very often negate much of the sensitivity gain due to improved receivers. The Berkeley-Illinois-Maryland Association millimeter wave interferometer (BIMA) is designed with the simplest possible optical train to minimize its contribution to the system noise temperature and to maximize the coupling of the receiver to the dish. This paper describes the optical design and performance of the BIMA interferometer.

OVERVIEW OF THE BIMA ARRAY

The Berkeley-Illinois-Maryland array[1] is a millimeter wave interferometer consisting of six 6.1 m antennas located at Hat Creek, California at an altitude of 1030 m. Expansion of the array to 11 elements is in progress, with a 9 element array expected operational by fall 1995. Baselines of up to 300 m are currently available. Two new stations will provide North–South baselines of up to 825 m in the near future. Several additional stations are to be built which will give baselines over 1 km providing up to ~ 0.3 arcsecond resolution at 100 GHz.

Receivers for each antenna consist of a single dewar containing up to 4 SIS mixers to cover the 70–90, 90–115, 130–170, and 210–270 GHz frequency bands. The mixers are a single polarization, fixed tuned, waveguide design[2,3] and are fed by corrugated scalar horns[4]. They utilize a series array of 4 niobium-aluminum oxide-niobium SIS junctions made at the U. Illinois. The lowest receiver noise temperature obtained so far is 45 K near 78 GHz; noise temperatures are typically 60 - 85 K over a 75 to 115 GHz band. Gunn diode local oscillators[7] are coupled quasi-optically.

The mixers are cooled to $\sim$ 3.2 K by a single 3 stage Gifford-McMahon cycle refrigerator. The coldhead is a CTI Cryogenics, Inc. model 1020 which is modified by the addition of a third stage utilizing an Er_3Ni regenerator[5–6]. Compared to the more conventional Gifford-McMahon/Joule-Thomson hybrid refrigerators, these refrigerators are more compact, less prone to clogging by contaminants, and require only a single helium compressor. The refrigeration capacity is about 50 mW at 3.5 K, with loads of about 300 mW on the 2nd stage and about 6 W on the 1st stage.

Telemetry to each antenna monitors of over 100 analog voltages and numerous digital levels every 10 msec; it provides remote control of all antenna and receiver functions and allows monitoring of nearly any quantity of interest.

TELESCOPE OPTICS

The dewar is mounted at the Cassegrain focus of the telescope, with each mixer feed located about 65 mm off the telescope centerline, but looking directly at the subreflector. The only intervening optics between the front of the receiver and the subreflector are a thin membrane window at the front of the receiver cabin and quarter-wave plates if polarization measurements are being made. No movable mirrors are used to direct the telescope beam into a particular frequency band's mixer; instead the telescope pointing is offset slightly when changing frequency bands. Coma due to the off axis feed location is less than $\lambda/550$ even at 270 GHz.

The telescope primary mirror consists of 84 cast aluminum panels, the largest being about 75 cm by 75 cm. The panels are intentionally machined with a scalloped surface to scatter visible sunlight, allowing solar observations without overheating other telescope components. With an amplitude of 5 μm rms, the scallop contributes negligibly to the total surface error budget of 30 μm rms. Panels are unpainted, which minimizes radiative cooling and the possibility of condensation of water vapor. Using a remote transmitter 5 km east of the site, all antenna surfaces have been set to better than 30μm rms, corresponding to $\lambda/100$ at 100 GHz. One antenna has been set to a total surface accuracy of less than 20 μm rms, and after 14 months of use shows no measurable change.

Another telescope design feature which minimizes its background noise contribution is the placement of the subreflector support legs outside the edge of the primary mirror. With this geometry large shadows cast by the support legs are avoided.

Because of its clean, simple optical design, the telescope noise contribution is very small. Extrapolation of a tipping curve to zero airmass gives a residual noise temperature of only 6 to 8 K. This measurement is in good agreement with the 6.2 K noise that is expected from the sum of the 2.7 K microwave background radiation, plus a 1.5 K contribution from the 75 μm thick teflon cabin window, 0.5 K from rearward spillover due to off axis illumination, and a 1.5 K contribution from subreflector support leg scattering to the ground.

FREQUENCY INDEPENDENT COUPLING

Padman, Murphy, and Hills[8] have investigated the general problem of maximizing the coupling of a corrugated scalar horn to a telescope aperture with a central blockage. They demonstrate

Table 1: Aperture Efficiency

	dish area	100 GHz	230 GHz
spillover, taper, central blockage		0.83	0.84
feedleg blockage	1.43%	0.971	0.971
gap between panels	0.32%	0.994	0.994
panel adj. screws	0.58%	0.988	0.988
surface roughness (30 μm)		0.984	0.919
total		0.77	0.73

that placing the horn aperture at an image of the telescope primary not only provides a frequency independent coupling, but it gives the highest possible coupling efficiency without use of "shaped" optics. This frequency independent, high aperture efficiency design has been chosen for the BIMA antenna optics.

As a compromise between peak aperture efficiency and having a larger primary beam with lower sidelobe levels, we use a more tapered illumination than the peak aperture efficiency design. This decreases the coupling efficiency due to taper, spillover, and a 1% (of the dish area) central blockage from .85 to about .83 to .84. The overall surface roughness of 30 μm contributes a factor of .98 at 100 GHz decreasing to .92 at 230 GHz. All other contributions are quite small, resulting in a calculated aperture efficiency of 77% at 100 GHz and 73% at 230 GHz, as shown in Table 1.

Single dish measurements give aperture efficiencies of about 75% near 100 GHz. Self–cal gains give aperture efficiencies of about 70% on short baselines decreasing to 50% to 60% on long baselines in average atmospheric conditions, consistent with an aperture efficiency of about 75% given a perfect atmosphere. Our calculated main beam efficiency is 83% at 100 GHz.

The BIMA antennas currently do not employ shaped optics, although that option remains open. Our present design achieves a good balance between high main beam efficiency and high aperture efficiency, so the primary goal of a shaped system would be to reduce spillover, which is currently about 5%.

A very versatile and general package of computer programs called Geebeams has been written by Jerry Hudson (U. C. Berkeley) for gaussian mode analysis of optical systems. It models the distribution of the electric field pattern through any arbitrary series of lenses. It is very useful for calculating the effects of truncation of the beam by finite sized apertures or for optimizing the performance of systems with shaped optics, for example.

RECEIVER OPTICS

Like the rest of the telescope optical system, the receiver itself has a minimal number of optical elements: 2 radiation shield windows, a dewar window, and the beamsplitter for coupling the local oscillator. Two teflon (PTFE) lenses are used to couple each feed horn to the telescope. The first lens forms an image of the telescope primary mirror at the feed horn aperture and also serves as the pressure window of the dewar. A second and much smaller lens is located just in front of the feed horn aperture and matches the curved wavefront of the feed to the flat image of the telescope. It too performs a second function, serving as the window in the 10 K radiation shield. A planar teflon slab is used as a window in the 50 K radiation shield.

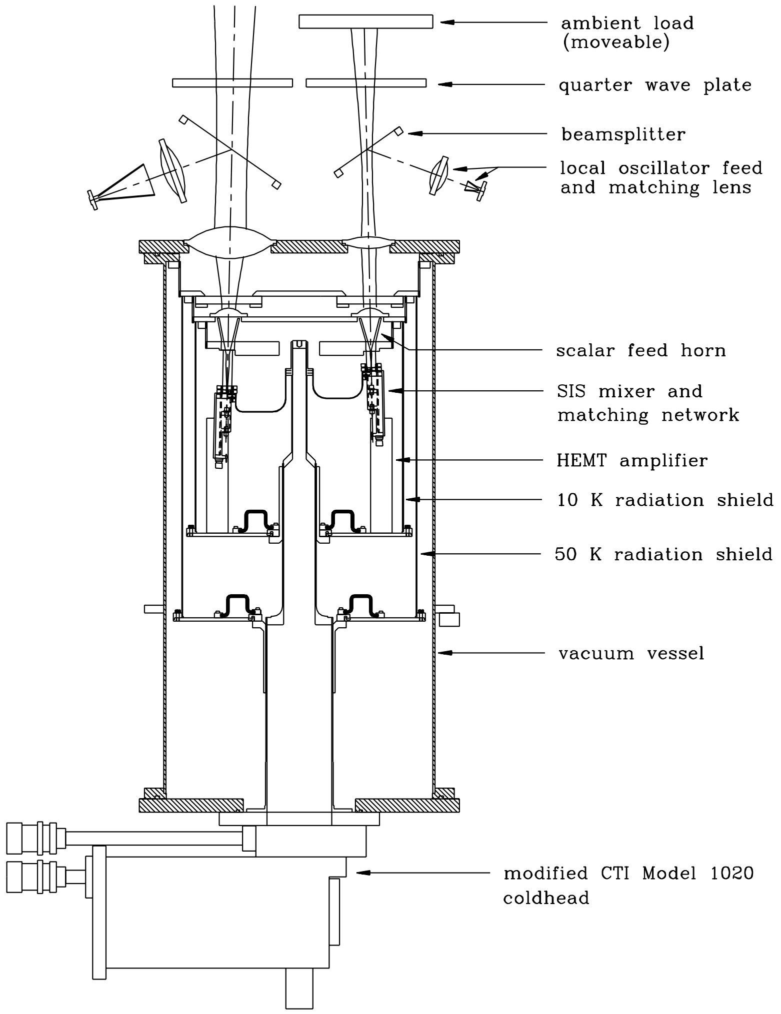

Figure 1. The BIMA receiver. Only two of up to 4 frequency bands are shown. Not shown are the 2 local oscillator assemblies which mount along the sides of the dewar to provide LO for the 4 bands. The CTI model 1020 coldhead is modified by the addition of a third stage utilizing an Er_3Ni regenerator.

Lens shapes were determined using geometrical optics to achieve the wavefront curvatures determined from the gaussian mode analysis. Each surface of a lens was treated individually (this is similar to the classical "thick" lens treatment; diffraction is sufficiently less in teflon than in free space to cause significant errors if using a thin lens treatment for lenses thicker than about 1 cm). The larger lenses are quite aspherical and are "bent" to minimize the angles of incidence. Lenses which operate cold were designed using the index of refraction at the cold temperature, then all dimensions scaled up the appropriate amount for room temperature manufacture. They are mounted so as to remain centered as they shrink. All of the teflon optical elements have quarter wavelength deep rectangular grooves to minimize reflection losses, which we estimate to be less than .5% per surface. Attenuation of the radio frequency signal in teflon is negligible.

Dewar Design

The layout of the dewar is indicated in Figure 1, which shows a cross section containing a high frequency and a low frequency band. The dewar is about 25 cm diameter and 55 cm long. A

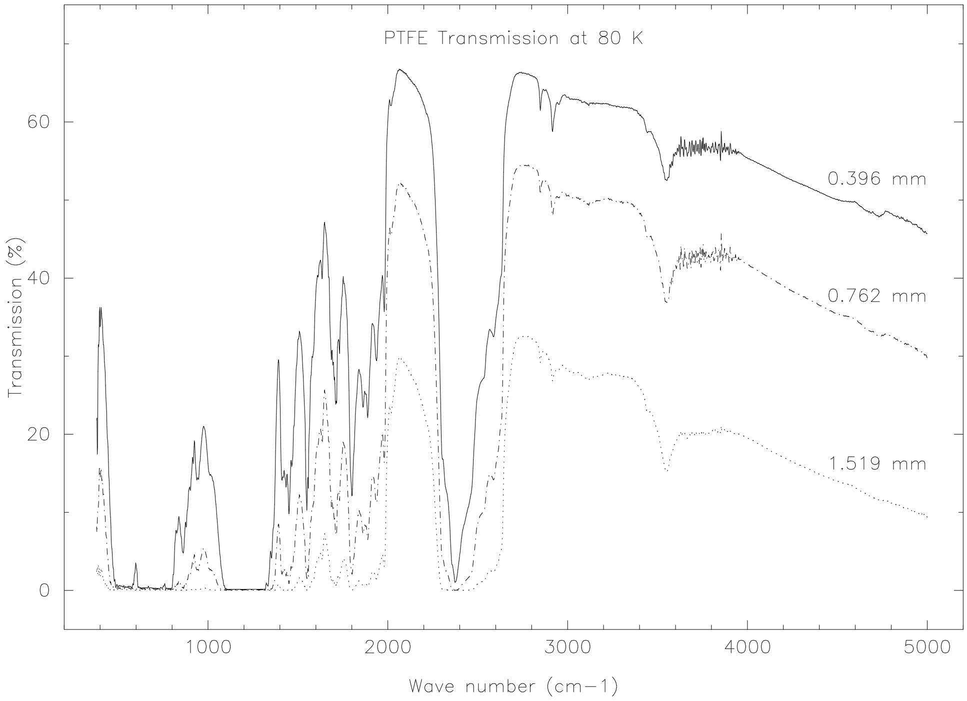

Figure 2. Transmission of PTFE at 80 K.

complete receiver including the refrigerator coldhead and local oscillators weighs about 60 kg. The receiver hardware and software is very modular; for example, local oscillator assemblies are easily interchanged. A receiver can be installed in an antenna by 2 people in about an hour.

The configuration of our antennas favors placement of the refrigerator coldhead and the feed horns at opposite ends of the dewar, which causes some difficulty in the mechanical design of the dewar. The lenses and horns must be accurately and rigidly located relative to each other and to the vacuum vessel, yet the lengths of the refrigerator cold finger and radiation shields shrink by 1.5 mm when cooled. The precise optical alignment is accomplished by supporting all optical elements and radiation shields by a series of G-10 fiberglass tabs from the front of the vacuum vessel. The lenses and feed horns are mounted near the front of the dewar such that their geometry does not change significantly upon cooling. The fiberglass tabs are configured to allow shrinkage of cooled components, but acting together define a single point on each temperature sub-assembly to remain fixed in space as that sub-assembly is cooled. Flexible copper heat straps are connected to the coldhead; these allow for thermal shrinkage and providing loose support when the dewar is partially disassembled.

Teflon Lenses as Infrared Radiation Shields

The infrared transmission spectra from 2 to 27 μm wavelength of 3 thin samples of teflon (PTFE) cooled to 80 K are presented in Figure 2. In the thicknesses required for our lenses, teflon is more than adequate to block 300 K blackbody radiation using our combination of a 50 K plus a 10 K window. The actual limitation on the window thickness is the low thermal conductivity of teflon. The center of our 50 K window operates about 30 K warmer than its heat sunk perimeter. The 10 K window is heated little.

Teflon is a good choice as a material for an infrared-blocking window. Compared to fluorogold, teflon has the advantage of being isotropic and easily machinable. Compared to quartz, the low index of refraction of teflon makes anti-reflection coating a much smaller concern. The machinability of teflon is important, allowing grooved surfaces for very effective anti-reflection coating and allowing manufacture of windows shaped to have optical power, functioning also as lenses.

The load on the 50 K refrigerator stage is estimated to be about 6 W, mostly from the radiation load on the outer shield and on the 50 K teflon windows. The load on the 10 K stage is about 300 mW, mostly from the HEMT amplifiers which are mounted on the inside of the 10 K radiation shield. The total heat load on the 3 K third stage is less than 9 mW, determined by measuring the temperature difference across a heat strap while various heater loads are applied, then extrapolating back to zero temperature difference.

By measuring the third stage heat load with a 10 K window covered, and comparing to the uncovered case, the 3 K heat load due to infrared radiation leaking through the teflon windows was determined to be 0.3 to 0.5 mW per window. A single teflon window in the 10 K radiation shield has a clear aperture of 5.1 cm^2 and one in the 50 K shield has 15 cm^2 aperture. The average thickness of a 10 K window is about 4.3 mm and that of a 50 K window 7.6 mm. Viewed from a 10 K window, a 50 K window subtends a few steradians. With this particular geometry, only about 0.03% to 0.05% of the 46 mW cm^{-2} heat load of a 300 K blackbody leaks through both of these windows, making them more than adequate infrared blockers.

Many engineers and scientists at U. C. Berkeley, U. Maryland, and U. Illinois have contributed to the development of the BIMA array. Many of the innovative design features of the antennas are due to Jack Welch. I am grateful to Rachael Padman for illuminating discussions on several occasions. I thank the Institute for Astronomy, U. of Hawaii for allowing me to use their FTIR to measure the spectra presented here.

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