First Results from A Small Bolometer-Array on the IRAM 30-m Telescope at 250 GHz

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Abstract

Bolometers, cooled to temperatures below 1 K, are the most sensitive detectors of continuum radiation for mm- and submm-waves. The reason for their sensitivity is the virtually unlimited bandwidth that can be used. Processes involving continuum radiation give clues to a variety of important astronomical topics, such as star formation and active galactic nuclei. All large submm-telescopes are therefore equipped with bolometers for these studies. In a groundbased environment bolometers can be made to work close to the fundamental limit of the photon fluctuations of the thermal radiation of the atmosphere and the telescope. The same limit, at a lower level, will apply for space experiments involving passively cooled telescopes (SMIM, FIRST). In this situation further improvement of performance is possible, for the study of extended sources, by using bolometer arrays.

We report the first operation of a small bolometer array, cooled to 0.3 K, on the IRAM 30 m-telescope at a wavelength of 1.2 mm. Several observing strategies have been tried and evaluated. It is obvious from the raw data, that the noise in adjacent channels is partially correlated. This is to be expected if the noise is due to fluctuations of the sky emissivity (skynoise). One can take advantage of these correlations in order to reduce the noise of the raw data. In the near future we hope to apply these techniques to a large bolometer array for the 350 μm atmospheric window on the MPIfR/SO Submm-telescope which is under construction on Mt. Graham, Arizona.

Introduction

For the purpose of mapping extended sources, a bolometer array consisting of n elements should have an advantage of a factor of n in observing time over a single bolometer, if each array element is equivalent in performance to the single bolometer. If on the other hand, the average noise equivalent power (NEP) of the array bolometers were higher by a factor of n the array advantage would vanish. It is difficult to manufacture large numbers of bolometers of unformly high quality and to couple them efficiently to the telescope. Therefore, if some loss of performance of the individual array element is unavoidable one should favour a large number of elements. Mm/submm-bolometer systems on large groundbased telescopes are often limited by skynoise even at the best observing sites. Skynoise is that fraction of the fluctuations of atmospheric emission that remains even after sky-chopping and phase-sensitive detection. At submm-wavelengths atmospheric fluctuations are caused mainly by spatial and temporal variations of the concentration of water vapour. Work by other groups (Ref. 1) seems to indicate that skynoise is highly correlated across an array. Therefore in a skynoise limited situation even the smallest array (e.g. of two elements) could be advantageous.

The Instrument

We decided to investigate the properties of bolometer arrays experimentally with a small array of seven bolometers, arranged in a hexagonal grid with one central element. The array was designed to operate on the IRAM 30 m Millimeter Radio Telescope (MRT) in the 1 mm atmospheric window. This small array will serve as a prototype for future large arrays. The array of composite bolometers was fabricated at MPIfR, with thermometers made from NTD-germanium[1] (Ref. 2), and installed on He-3 "minifridge" (Ref. 3) on the cold surface of a standard HD-3(8) cryostat (Ref. 4). With a pumped He-4 bath the hold time of both the He-3 and He-4 stage are conveniently above 48 hours. A seven channel preamplifier with room temperature junction-FETs in the first stages is mounted on top of the cryostat. It provides a gain of 1000. As in our single channel bolometer systems (Ref. 5) each bolometer is designed to operate in the diffraction limited mode. In this way, the full spatial resolution of telescope is preserved and the array can thoroughly optimised for one wavelength. Each element of the array consists of three parts: the feed, a short length of waveguide and the bolometer cavity. In the diffraction limit the antenna theorem is valid for the feed

$$A\Omega = \lambda^2$$

and one can think of the system as a very simple waveguide receiver. The main difference to a coherent receiver is that the bolometer will accept both planes of polarisation. Unless one is interested in polarisation measurements, the feed and the waveguide should not be polarisation selective. We chose a circular waveguide with a diameter such that the cutoff frequency of the fundamental mode (TE 11) coincides with the desired long wavelength cutoff

$$\lambda_c = 1.706\ d$$

A circular waveguide allows about 30 % bandwidth of single mode propagation up to the cutoff wavelength of the next higher mode (TM 01).

$$\lambda_c = 1.307\ d$$

The waveguide can be very short (~ 2 d), because the very steep drop in transmission beyond cutoff provides an almost ideal high pass filter (Ref. 6). The definition of the system passband is completed by the addition of a low pass filter, mounted in front of the feeds. The low pass property of the filter is determined by a stack of capacitive meshes that are embedded in polyethylene (Ref. 7). These filters have to be combined with bulk absorbing materials in order to achieve the wideband blocking properties required by the bolometers. Of all possible waveguide feeds, corrugated horns have the highest efficiency, as they launch an almost ideal fundamental Gaussian mode. They would be the ideal choice for single channel diffracation limited systems, if it were not for the difficulty of manufacturing them for very high frequencies. For arrays one also has to consider the sampling efficiency. Feeds of different types have different minimum spacings in the focal plane which means that on the sky the spacing between the beams, relative to their widths is different. If for example the area to be mapped is of the same size as the array and if it is the aim to sample that area completely, then that type of feed that can be packed most densely is the best choice (Ref.

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[1] Neutron-Transmutation-Doped germanium

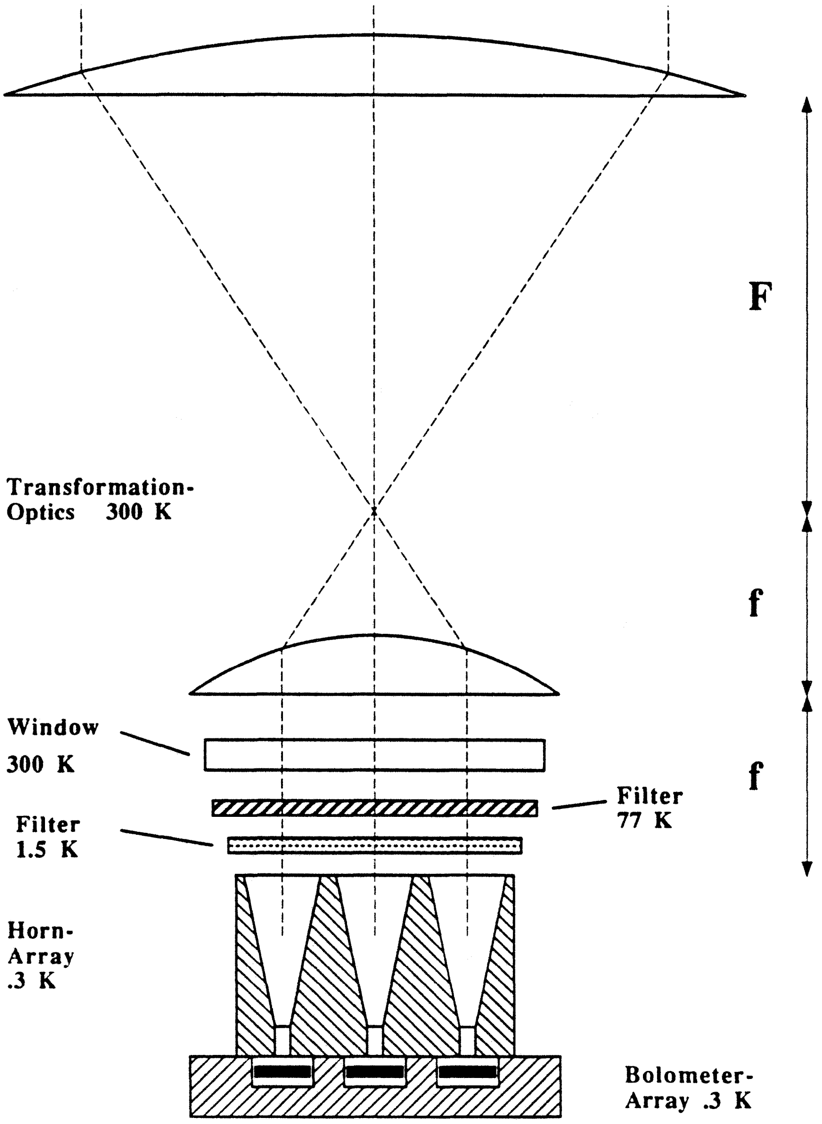

Figure 1 Schematic view of the seven element bolometer array

9). Corrugated horns, especially those of the wideband variety (Ref. 10) that would be required for bolometers, use a lot of space. For that reason a compromise between single beam efficiency and sampling efficiency is necessary. Without having done a detailed optimisation, the ease of manufacture led us to choose conical horns. The horns were made elong enough so that the maximum gain for the given aperture diameter is reached (Ref. 11). The 30m-MRT has a secondary focal ratio of

$$F/D = 9.73$$

Horns for this focal ratio would be too large and heavy to mount on the He-3 refrigerator that is used to cool the bolometers. Feeds with a small focal ratio are compact and light. They have the additional advantage of requiring only a small window in the cryostat, thereby reducing the radiative heat load. It is most convenient to fabricate both the bolometer- and the horn-arrays in a planar configuration, which means that the axes of the horns are parallel to each other. An optical system is then needed that can transform the beams to the telescope focal ratio, while maintaining the parallelism of the beams. This cannot be done with a single optical element. The solution is to use two optical elements (lenses in our case) with positive focal lengths in a telecentric configuration, i.e. with a common focal point between them (Fig. 1). In the Gaussian approximation a beamwaist in one focal plane of a single lens is transformed into a waist in the other focal plane independently of the wavelength. The ratio of the waist diameters still depends on wavelength (Ref. 12) and is given by

$$w_2 = \lambda f_1/\pi w_1$$

For the telecentric lens system if follows that

$$w_3 = f_2\, w_1/f_1$$

This means that in this configuration not only the positions of the waists are frequency independent, but also the ratio of the waist diameters. This is the principle of a Gaussian beam telescope (Ref. 8).

We use aspherical lenses, corrected for spherical aberration and machined from PTFE. The lenses have to be fairly large in order to satisfy both the Gaussian beam approximation and the field of view requirements (f_1 = 250 mm, f_2 = 50 mm). At shorter wavelengths, where there are no low loss, machinable dielectric materials one might have to use offaxis mirrors. Their design will require careful raytracing over the whole field of view and the alignment will be critical.

Results

During a test run February 1992 the array cryostat and the transformation optics were installed in Nasmyth focus of the IRAM 30 m MRT. Sky chopping in azimuth direction was done with the subreflector at 2 HZ and a throw of 30". Because of the Nasmyth configuration the beams of the array rotate around the central beam with any change in elevation. The center beam is used for pointing. This rotation occurs in addition to the usual rotation caused by the altazimuth mounting. Keeping track of each individual beam during any type of observation is therefore somewhat involved. Beam patterns obtained with the array on the planet Uranus (Fig. 2) show satisfactory beamshapes and good coupling to the

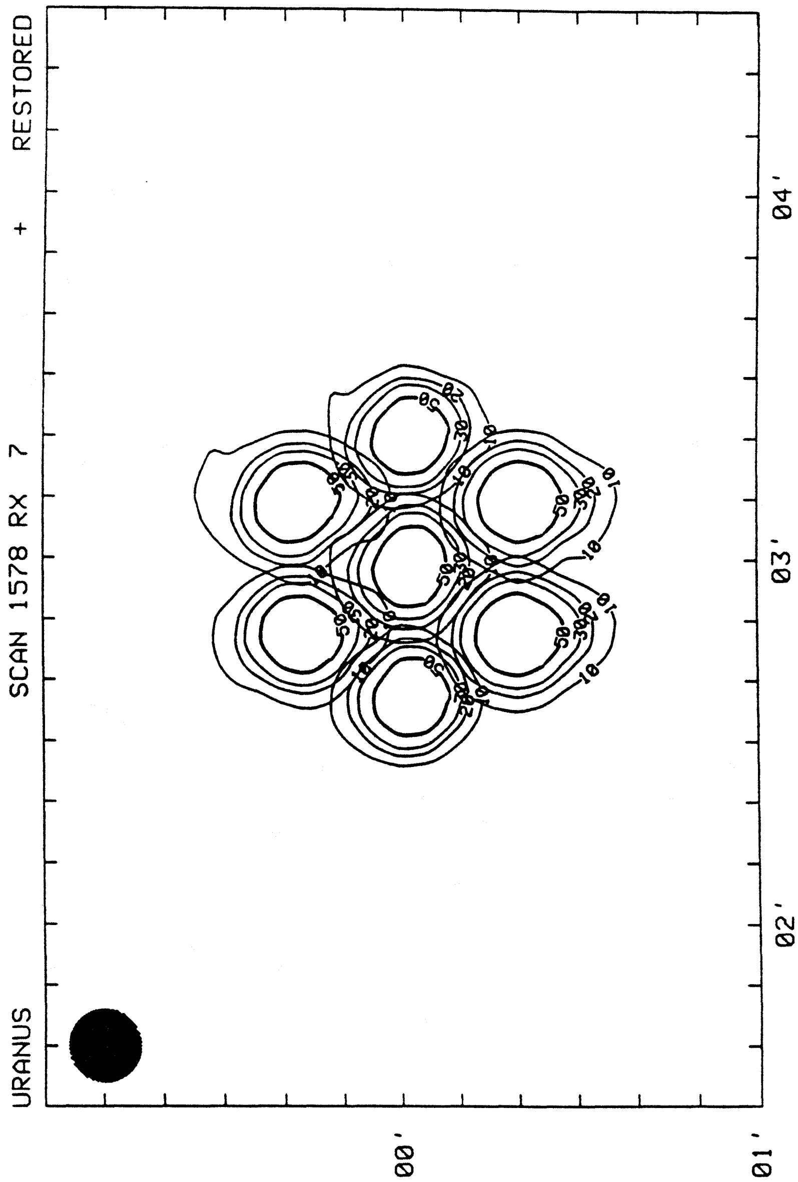

Figure 2 Beam pattern of bolometer array obtained on Uranus with the 30 m-MRT. Contour levels are in percent of peak intensity

telescope. The variation of the sensitivity among the beams is within 10 %. The average beamwidth (FWHP) is 12" at a spacing of 22" corresponding to an undersampling factor of about 5. The limiting flux density is about 50 mJy/ Hz (in perfect weather conditions), which is similar to the performance of single beam systems on this telescope.

The seven-element array has been used again extensively in Feb/March 1993 on the 30 m-MRT for different kinds of astronomical programs. The following advantages were obvious:

a) Skynoise filter algorithms are effective both for continuous mapping modes and for ON-ON observations of point sources.

b) The seven maps produced in the mapping mode have precisely known position offsets from each other. This is not necessarily true when seven coverages with a single beam system are done sequentially.

c) In deep ON-ON integrations on point sources with the central beam, the six surrounding beams can serve as control fields to check for spurious signals.

The last two advantages might also apply for space applications.

A 19-beam bolometer array for 250 GHz is nearing completion. We plan to build 37-element arrays at 250 GHz and 860 GHz for the 30 m-MRT and the 10 m-SMT (MPIfR/Steward Observatory) respectively.

References

1. Hildebrand, R., private communication
2. Haller, E.E. et al. (1984) Proc. 4th Neutron Transmutation Doping Conference, New York, Plenum Press, 21-36
3. Torre, J.P. & Chanin, G. (1985) Rev. Sci. Inst., 56, 318-320
4. Infrared Laboratories, Tucson
5. Kreysa, E. (1990) Proc. 29th Liège Int. Astrophysical Colloquium, ESA SP-314
6. Marcuvitz, N., Waveguide Handbook, MIT Radiation Laboratory Series 10, McGraw-Hill, New York, 1951
7. Whitcomb, S.E. & Keene, J. (1980), Appl. Optics, 19, 197-198
8. Goldsmith, P. (1982) Infrared and Millimetre Waves Vol. 6, N.Y. Academic Press, 277-343
9. Yngvesson, K.S. (1988) IEEE Trans. on Antennas and Propagation, AP.36, 1637
10. Thomas, B.M. (1978) IEEE Trans. on Antennas and Propagation, AP-26, 367
11. Hansen, R.C. (1988) Microwave and Optical Technology Letters, 1, 386
12. Kogelnik, H. & Li, T. (1966) Appl. Optics 5, 1550