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RECENT ADVANCES IN MILLIMETER WAVE INSTRUMENTATION FOR RADIO ASTRONOMY

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ABSTRACT

During the past few years major advances have been made in instrumentation for millimeter wave radio astronomy. Antennas have been built with large apertures and high precision and the sensitivity of receivers has improved greatly. This paper summarizes the more important of these advances.

Antennas

Over the past few years several new millimeter wave radio astronomy antennas have been constructed. These new antennas share many common features to such a degree that a standard design for large millimeter wave antennas appears to have emerged. Table 1 shows the largest major millimeter wave antennas in operation at the present time and several more are in the construction phase. All have been constructed within the past five years.

TABLE 1

The Major New Millimeter Wave Telescopes

Organization	Site	Diameter	Surface Accuracy	Reference
National Radio Astronomy Observatory (NRAO)	Kitt Peak Arizona	12m	70μm	Ref. 1
Institut de Radio Astronomie (IRAM)	Pico Veleta Spain	30m	85μm 70μm*	Ref. 2
Institute de Radio Astronomie (IRAM)	Plateau de Bure, France	15m	50μm	Ref. 3
Nobeyama Radio Observatory of the Tokyo Astronomical Observatory	Nobeyama Japan	45m	160μm	Ref. 4
J. C. Maxwell Telescope Royal Observatory Edinburgh	Mauna Kea Hawaii	15m	90μm 35μm*	Ref. 5

* Design Goal

The common features shared by these antennas are as follows:

1) Large - All the antennas are larger than 10^4 wavelengths in diameter.
2) Adjustable Panels - The preferred method of construction for the surface of the antennas is to mount many individual highly accurate panels to a stable back-up structure.
3) Homologous - Many of the antennas use the principle of homology to maintain an accurate figure while subjected to varying gravitational loads. The reflector structure is so constructed that deformations always result in only a change in the focal position for the parabolic reflector. The gain of the antenna may be held constant by moving the subreflector (or prime focus feed) in a programmed manner.
4) Cassegrain - The preferred optical arrangement is Cassegrain with a long effective focal length. The slowly converging beam that results from the long effective focal length has many practical advan- tages. Manipulation of the final tele- scope beam by "Quasi Optical" techniques and loose tolerances on the positioning of the feed system are probably the two major advantages.
5) Multiple Receiver Selection - The Cassegrain configuration permits multiple receiver mounting at the Cassegrain focus. In some instances simultaneous operation at two wavelengths is obtained by use of dichroic or polarization sensitive optics. Typically, four receivers covering the 3mm, 2mm, 1mm, and 0.8mm atmospheric windows may be permanently installed on the antenna.

Several of the antennas are sited in the open; others are enclosed. Of those in the open, one, the 30m antenna, has an active temperature control of the back-up structure. The 15-m IRAM telescope has a carbon fiber back-up structure to minimize temperature effects. All of the enclosures used may be opened during normal observing to permit unobstructed use of the telescope.

One of the more difficult tasks in building a large precision antenna is that of setting the panels of the telescope to the required accuracy. Microwave holography has emerged as the preferred method of measuring the surface of high precision antennas (6). The signal source for the holographic measurement may be a high frequency satellite or maser emission from a radio source. Measurement accuracies of 20μm have been reported using the LES-8 Lincoln Laboratory satellite transmitting at 38GHz and 5μm at the University of Texas using a 90GHz ground based transmitter.

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Interferometry

The past few years have seen the development of interferometers at millimeter wavelengths. Three interferometers are now operational, two in the United States and one in Japan (7, 8, 9). Angular resolutions of approximately 1 arc second are obtained using this technique. Very recently Very Long Baseline Interferometry (VLBI) techniques have been applied at millimeter wavelengths (10) and fringes have been obtained on unresolved radio sources with trans-continental baselines at a wavelength of 3mm. The corresponding angular resolution is approximately 10^{-3} arc seconds.

Receivers

1) Noise Performance

For the past ten years cooled Schottky mixers have been the mainstay of receiver systems for millimeter wave radio astronomy (11). Noise temperatures of around 200K SSB at a wavelength of 3mm, 500K SSB at 1.2mm, and 2000K SSB at 0.8mm are now routinely achieved. A major contributor to these performance figures has been the development of the low noise cooled GASFET amplifiers that are used as intermediate amplifiers in these receiver systems (12). A noise temperature of 10K at a frequency of 1.5 GHz is routinely obtained from these amplifiers and further improvements to about 2K have recently been demonstrated using HEMT devices (13).

Recently a great improvement has been obtained in the noise temperature of millimeter receivers by the application of superconducting devices. These devices, known as S.I.S. junctions (Superconductor-Insulator-Superconductor) are characterized by low temperature operation (4.2K or less), low noise, and quantum behavior (14).

When used as millimeter wave mixers, S.I.S. devices exhibit low noise, low conversion loss, and have a very low power local oscillator requirement. The first S.I.S. junctions for millimeter wave applications were fabricated from lead alloy and have the advantage of being relatively easy to fabricate but are delicate and easily damaged by static charge. The transition temperature of lead is 7.2°K and practical implementation of these devices requires a helium bath with reduced pressure to achieve a working temperature of 2.8K.

In the past year niobium devices have been placed into service. These junctions are fabricated by a refractory process and are robust, stable and have a transition temperature of 9.3K. This higher transition temperature permits operation at 4.2K and either a helium bath or a closed cycle helium refrigerator may be used as a cooling system. At a frequency of 115 GHz noise temperatures for a complete receiver of less than 100K SSB have been reported and further reductions in this figure are virtually certain in the next few months (15). At a typical millimeter observatory, the measured antenna temperature on the sky at a frequency of 90 GHz is 65K of which 23K is the atmosphere. The emphasis in reducing system noise will now shift, as it has at centimeter wavelengths from the receiver system to the antenna system.

2) Local Oscillators

Reflex klystrons have been used as local oscillators in millimeter wave receivers for many years. During the past two years these devices have been replaced by Gunn oscillators. It is now possible to build a Gunn oscillator to cover the band 75-115 GHz with a power output of 10mW (16). This is more than adequate to pump a dual channel cooled Schottky mixer receiver. At higher frequencies a fundamental Gunn oscillator may be used to pump a varactor multiplier. For example, a quadrupler pumped by a 50mW source at 86 GHz will give an output of 2mW at 345 GHz (17). The tunability of such a system is such that a single quadrupler with two interchangeable Gunn oscillators can cover the frequency range 330-365 GHz. Phase locking may be simply achieved by varying the bias voltage on the Gunn diode.

3) Multiple Beam Receivers

As the noise temperatures of millimeter-wave receivers improve and approach the emission temperature of the atmosphere, other ways to improve the overall performance of the radio telescope system need to be employed. For measuring and mapping spatially extended radio sources, multibeam operation becomes an attractive possibility. Using conventional feeds displaced in the focal plane is the first obvious way to implement such a system and it may be shown that beam spacings in the sky of two beamwidths are possible using such an arrangement (18). The University of Massachusetts has a 3 x 5 array under construction for 115 GHz and the National Radio Astronomy Observatory is building a 4 x 2 array at 230 GHz. Both these arrays will use cooled Schottky mixers and solid state local oscillators. Such arrays will enable mapping of radio sources in both spectral line and continuum (broadband) emission. For continuum use only, arrays of bolometer elements are being developed. Cochise Instruments has developed a four element array operating at a wavelength of 1 mm and a physical temperature of 0.35K (19).

More compact arrays are under development and millimeter wave application of these ideas may be expected in the next few years (20, 21). A major problem to be faced will be the complexity and expense of the equipment associated with each receiving feed.

4) Spectrometers

Millimeter wave spectroscopy consists of observing narrow band emission contained within the broad band noise like signals emitted by radio sources. Since the discovery of emission from the carbon monoxide molecule in 1970, many other molecules have been discovered. The general method used in millimeter wave spectroscopy is to mix the RF signal down to an IF signal and to analyze the power spectral density of the IF signal. The RF signal typically lies in the range 70-400 GHz and the IF signal in the range 1-6 GHz. The intensity of the narrow band emission of interest may be very weak, less than 0.1K of antenna temperature, for example, so several hours of integration may be required to achieve a reasonable signal to noise ratio.

The narrow band emission from complex objects, such as other galaxies, will be broadened by the wide range of velocities within the object and, as the frequency of observation increases, so the range of velocities increase.

A typical requirement for a suitable spectrometer is 512 channels of 1 MHz bandwidth per channel for broad band work such as described above and 512 channels of 25 KHz bandwidth for high resolution observations within our own galaxy.

This requirement is replicated for each receiver channel so for a multibeam system the spectrometer and associated equipment become an expensive and complex undertaking.

The traditional solution to this problem has been to use a series of individual contiguous analog filters. Each filter is followed by a detector; the outputs of the individual detectors are read into a computer system where suitable signal processing is undertaken. This technique is costly and involves a large number of analog components, so reliability is a problem. Recently two alternatives to this approach have been developed.

a) The Hybrid Spectrometer

A hybrid approach to the problem of measuring the power spectrum of wideband noise-like signals has recently been developed (22). The system utilizes a comb-filter bank followed by digital-correlator processing of each filter output. Bandwidths narrower than the maximum bandwidth can be analyzed by a simple reassignment of the correlator channels in the system. The National Radio Astronomy Observatory is constructing such a system for use on the 12-meter radio telescope on Kitt Peak in Arizona. 2,000 points with a total bandwidth of 2 GHz are available with an option of dividing this total band among 2, 4, or 8 signals.

The system cost of this hybrid system is much lower than the cost of spectrometers which utilize either a filter-bank or a digital correlator alone.

b) The Acousto-optical Spectrometer

The principle of the acousto-optical spectograph has been known for many years and the last few years have seen its implementation as a high performance, relatively low cost spectrometer suitable for millimeter wave spectroscopy. The basic principle is simple. The signal to be analyzed is converted to an acoustic wave within a suitable crystal. This acoustic wave produces variations of refractive index within the crystal so producing, in effect, diffraction gratings within the crystal. A monochromatic light source is used to illuminate the crystal and is diffracted by the gratings within the crystal. Each frequency component of the input signal creates a grating of a different spacing and so diffracts the light at a different angle. The intensity of the light diffracted at a given angle is a measure of intensity of the input signal at that frequency.

The diffracted light is detected by an array of photodiodes; the charge accumulated on each of these diodes between readouts is a measure of the integrated light intensity which fell on the diode in that time. After a fixed integration time, the charge residing on each diode is read out.

Instruments of this kind have been refined into compact robust units and an instrument with 500 MHz and 1024 channels has been reported (23).

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