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FOCAL PLANE ARRAYS FOR MILLIMETER–WAVELENGTH ASTRONOMY

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ABSTRACT

Arrays of detectors in the focal plane offer a major avenue for increasing the data rate of astronomical observations of extended sources. While having had only limited use at centimeter and longer wavelengths, focal plane arrays are being intensively developed for use on millimeter and submillimeter telescopes. In this review I discuss some of the general characteristics of focal plane imaging systems and associated optics. Detailed discussion is focused on the two large millimeter–wavelength focal plane arrays presently in operation: the 8 element 1.3 mm wavelength NRAO array on the 12 m telescope and the 15 element 3 mm wavelength array on the FCRAO 14 m antenna. Other systems and relevant technology presently under construction or in development phase are briefly described.

IMAGING

Radio telescopes, as their optical counterparts, are capable of imaging, the process in which the radiation arriving from different directions is focused at different points away from the antenna axis. The beam scanning, or imaging properties of different types of antennas have been considered in the literature (*cf.* [1]–[3]). Most of this work has been restricted to conventional antenna configurations such as Cassegrain and Gregorian geometries.

The performance degradation for parabolic antennas is dominated by coma, which produces a sidelobe towards the antenna axis in the plane of the scan, as well as reducing the on–axis gain [1]. One criterion for the maximum off–axis scan angle is a 1 dB gain reduction, at which point the coma lobe is at $\cong -10$ dB relative to the main lobe. For an antenna with focal length to diameter (focal) ratio > 1, this occurs for a feed offset which corresponds to a number of full width to half maximum (fwhm) beamwidths given by [1]

$$n_{scan} = 22 \cdot (f/D)^2 \ .$$

The total number of beams on the sky is given by

$$n_{tot} \cong 1520 \cdot (f/D)^4 \ .$$

For typical Cassegrain systems with $f/D > 2$, the number of independent (fwhm separation) beams is obviously much larger than the number of elements in present or planned arrays. The above criterion is, however, overly generous for very high quality imaging. However, even based on a more conservative calculation [4], the limitation on the number of beams in a diffraction–limited radio wavelength focal plane imaging system is likely to be limited by receiver costs and other optical effects such as vignetting, rather than by the basic imaging capability of the antenna. The limited size of arrays considered to date at radio frequencies has not encouraged investigation of geometries developed at optical wavelengths to allow larger range of beam scanning, such as the Ritchey–Chretien design [5], but this issue is deserving of further consideration.

FEEDS

Of particular importance for understanding constraints on focal plane arrays for radio frequencies is the fact that at these wavelengths we are dealing with coherent detector systems which are coupled to single mode radiating systems (single mode in the sense of pattern solid angle times effective area product $A \cdot \Omega = \lambda^2$). Since we need to illuminate the main antenna with some reasonable edge taper, the solid angle of the feed element and thus its area is determined for a particular imaging geometry. The result is that the size of the array element and consequently the minimum spacing or sampling interval in the focal plane is determined. While different types of feed elements may be conceived, general principles limit the closeness with which they can be packed if excessive cross–coupling is to be avoided [6]. Various feed elements have been investigated to determine the optimum tradeoff between efficiency and spacing [7].

Additional insight into the issue of sampling by an array of feeds in the antenna focal plane can be obtained by considering the coupling of radiation from a plane wave incident on the antenna to a feed element in the focal plane. In the case of moderately large focal ratio ($f/D > 1$) the electric field distribution in the focal plane is given by the Airy pattern

$$E_a(r) = 2 \cdot J_1(\pi D r/\lambda f)/(\pi D r/\lambda f) \ .$$

Here, r is radial coordinate and J_1 is the first order Bessel function. The coupling between the electric field distribution E_f of the feed element and the Airy pattern gives the aperture efficiency of the antenna as illuminated by this feed. The coupling is given by

$$K = |\langle E_a^* \cdot E_f \rangle|^2 \ / \ [\langle E_a^* \cdot E_a \rangle \cdot \langle E_f^* \cdot E_f \rangle] \ ,$$

where the brackets denote integrals of the appropriate

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combinations of electric fields. We have evaluated the coupling coefficient for two feed types for illustration. The first is an ideal Gaussian with $E_f = \exp[-(r/r_0)^2]$ and the second is a scalar feed horn assumed to have a field distribution $E_f = J_0(2.405r/r_0)$ for $r \leq r_0$ and $E_f = 0$ for $r > r_0$ (r_0 is the radius of the feed horn). The results are shown in Figure 1, where we have defined $A = \pi D r_0/\lambda f$. For the Gaussian feed we find $A_{opt} = 2.25$ and $K_{max} = 0.82$, while for the scalar feed $A_{opt} = 3.65$ and $K_{max} = 0.84$. The optimum value of A is equivalent to $r_0 = 0.72 \cdot f\lambda/D$ for the Gaussian feed, which is the same result as found from analyzing the coupling in the aperture plane of an antenna with Gaussian illumination [8]. For the scalar feedhorn we find that the optimum radius is equal to $1.16 \cdot f\lambda/D$, which is very close to that of the first zero of the Airy pattern. Thus, while perfect coupling (100 % aperture efficiency) can only be obtained with a feed element that has an aperture field distribution given by the Airy pattern, such a feed is particularly impractical for array applications. We see that moderately good coupling is achieved by matching only the central lobe of the Airy pattern, which is done quite well by a scalar feedhorn.

Although focal plane array systems are most effectively used for observations of extended sources, the preceding analysis of feed parameters for maximizing aperture efficiency is still relevant, in that we wish to maintain high sensitivity to small–scale structures. In addition, achieving a high beam efficiency generally will require a greater edge taper and consequently a *larger* feed element than that required for maximizing aperture efficiency. The beamwidth of an antenna with Gaussian illumination has been analyzed [8], and for the 10.9 dB edge taper required for maximum aperture efficiency we find $\Delta\theta_{fwhm} = 1.17 \cdot (\lambda/D)$. The diameter of the scalar feedhorn found above thus indicates that the minimum angular separation between beams of an array of scalar feedhorns is $\delta\theta_{min} \cong 2 \cdot \Delta\theta_{fwhm}$. Other types of feed elements having more nearly uniform aperture field distributions can achieve closer packing, but generally at the expense of lower antenna illumination efficiency [9], [10].

Operational focal plane array systems to date [11], [12] have utilized scalar feedhorns to achieve high antenna efficiency even at the expense of relatively poor sampling of the focal plane. In fact, this is less of a problem than may first appear, since many objects of interest are spatially extended on scales larger than the footprint on the sky of plausible arrays, and consequently multiple antenna pointings are required to make complete maps of these sources. With a less than fully sampled array, these pointings must be interleaved to achieve complete sampling of the the focal plane field distribution, which can be extended to full Nyquist sampling, if desired.

OPERATIONAL FOCAL PLANE ARRAYS

Focal planes that have achieved operational status necessarily represent compromises in terms of number of elements, driven in part by the cost and complexity of millimeter–wavelength frontend electronics, and to a significant extent by these same issues relative to the spectrometer system for each pixel which is required for spectral line observations which at present dominate observational astronomy in this wavelength region. The two systems described below give a feeling for the present state of the art.

NRAO 1.3 mm Wavelength Array

This array, which has eight elements in a 4 x 2 arrangement, covers the 220 – 230 GHz frequency range. Schottky diode mixers cooled to 15 K are employed as front end elements. The large f/D = 13.8 focal ratio of the 12 m telescope requires relatively large element feeds which in this case are scalar feedhorn–lens combinations. Individual quasioptical diplexers are used to inject local oscillator into each feed element, and the space required, combined with that for the lens feed systems, results in an element spacing of 85 arcseconds, which is approximately 3.5 times the FWHM beamwidth at 230 GHz. The local oscillator for all elements is derived from a single Gunn oscillator followed by a frequency tripler for each 4 element subarray. Aligning and tracking the array footprint in parallactic angle is accomplished by mechanical rotation of the entire receiver. Having demonstrated satisfactory operation on the telescope, this array is currently being refitted with superconductor – insulator – superconductor (SIS) mixers to improve its sensitivity.

FCRAO 3 mm Wavelength Array

This 15 element array was designed to cover a relatively broad (86 – 115 GHz) frequency range with minimum number of mechanical adjustments, while retaining high efficiency and good focal plane sampling [12]. Fixed–tuned Schottky diode mixers are employed, with integrated HEMT IF amplifiers; RF and input optics components are cooled to ≅ 20 K. Local oscillator injection is via a nonresonant multiport directional coupler, and the single sideband filter is common to all array elements. The beams of 3 x 2 and 3 x 3 element subarrays are interleaved by polarization rotation and diplexing, resulting in an array footprint on the sky which has beams spaced by 1 FWHM beamwidth (45 arcsec) in 1 direction by 2 FWHM beamwidths in the orthogonal direction. As with the NRAO receiver, the entire array is rotated for parallactic angle tracking. Single sideband receiver noise temperatures are 300 K over an IF bandwidth of approximately 400 MHz. In use on the 14 m telescope in the Quabbin reservoir watershed (whence the acronym QUARRY), this system has already provided more than 500,000 spectra for a number of large–scale astronomical projects. The significant increase in data rate has allowed mapping of molecular clouds on a large scale with high angular resolution and good sampling. In turn, this has helped reshape notions of the structure of these objects and of effects of newly formed stars on their placental environment.

Spectrometers available for use with the QUARRY array at the present time include filter bank systems for studies of galactic molecular clouds and external galaxies. The cost and complexity of such devices has restricted the number of channels available with various frequency (Doppler velocity) resolutions, and thus the range of astronomical problems that can be addressed. To remedy this situation, a powerful autocorrelation spectrometer system is being constructed which will have 1024 spectral channels for each of the 15 pixels [13]. The autocorrelator is based on chip and circuit board designs developed for radio astronomical applications [14]. With this versatile spectroscopic system, QUARRY's capabilities will be enhanced to include studies of dark clouds, molecular outflows, and Galactic structure.

DEVELOPMENTS AND FUTURE DIRECTIONS

Focal plane arrays have begun to make an impact on radio astronomy – even though the number of pixels in present arrays is miniscule compared to CCD devices used at optical wavelengths ($\approx 10^6$ pixels) and also to the relatively more modest infrared arrays ($\approx$ 3600 pixels). However, the heterodyne signal processing employed in radio wavelength systems gives them very powerful spectroscopic imaging capability; with the autocorrelation spectrometer the output of each integration of QUARRY will be a not unimpressive 1.5×10^4 spatial x spectral pixels.

The status of millimeter systems makes an interesting comparison with those at far–infrared wavelengths, where broadband, direct detection array systems with modest numbers of elements have been in use for some time, but imaging arrays giving real spectroscopic capability are a relatively recent development. The 25 element FIFI system uses photoconducting detectors in conjunction with a scanning Fabry–Perot interferometer [15]. The fact that these detectors are much smaller in size than a wavelength necessitates a type of coupling arrangement quite different from that used for coherent millimeter–wavelength detectors. The interesting question of coupling to different types of detector system and relevant optics for far–infrared systems are discussed in [16] and [17].

A number of other focal plane array systems in addition to those mentioned above are in various stages of development. A four element array for the Nobeyama 45 m radio telescope will cover 103 – 110 GHz using tunerless SIS junctions. HEMT IF amplifiers cover the 5 – 7 GHz range allowing simultaneous observation of interesting molecular species. This system has the unusual feature of adjustable beam separation—between 15 and 45 arcsec (K. Sunada, private communication). Other focal plane arrays will have more pixels. A 16 – 25 element array for the Onsala Space Observatory 20 m telescope will operate in the 3 mm range using SIS mixers fed by slot antennas. Extensive quasioptical input signal processing will be used for rotation of the array footprint and local oscillator injection (J. Johansson, private communication). The Cavendish Laboratory 64 element heterodyne array for the 345 GHz frequency range will use SIS mixers and planar feed elements. The local oscillator will be injected quasioptically to all array elements (R. Padman, private communication). Low local oscillator power is an important ingredient in being able to expand the number of pixels in an array if a mixer is the first element of each radiometer. This aspect of SIS mixers is particularly advantageous for use in focal plane arrays.

It is apparent that that the effort required per pixel must be reduced if millimeter–wavelength arrays are to expand to recover a significant fraction of the readily available information available in the focal plane of a large radio telescope. While considerable effort has been focused on arrays of feed elements (*cf.* [18]), there will have to be progress in making complete radiometers far less expensive and time consuming to construct, test, and adjust. This work should combine the best aspects of monolithic and hybrid technology. The development of low noise transistor amplifiers at frequencies up to 100 GHz is extremely promising both in terms of performance and likely ease of replication and operation of this type of front end.

In parallel with these efforts, we will need significant development of "backends" for spectral analysis which also greatly reduce cost and complexity in order to permit replication for, ideally, hundreds or more pixels. Probably the most promising avenue is the further development of digital correlation spectrometers [19], [20]. In view of the significant recent progress and exciting potential for future development, there is reason to hope that radio astronomers will soon think of the limited view provided by single pixel receivers as an historical curiosity.

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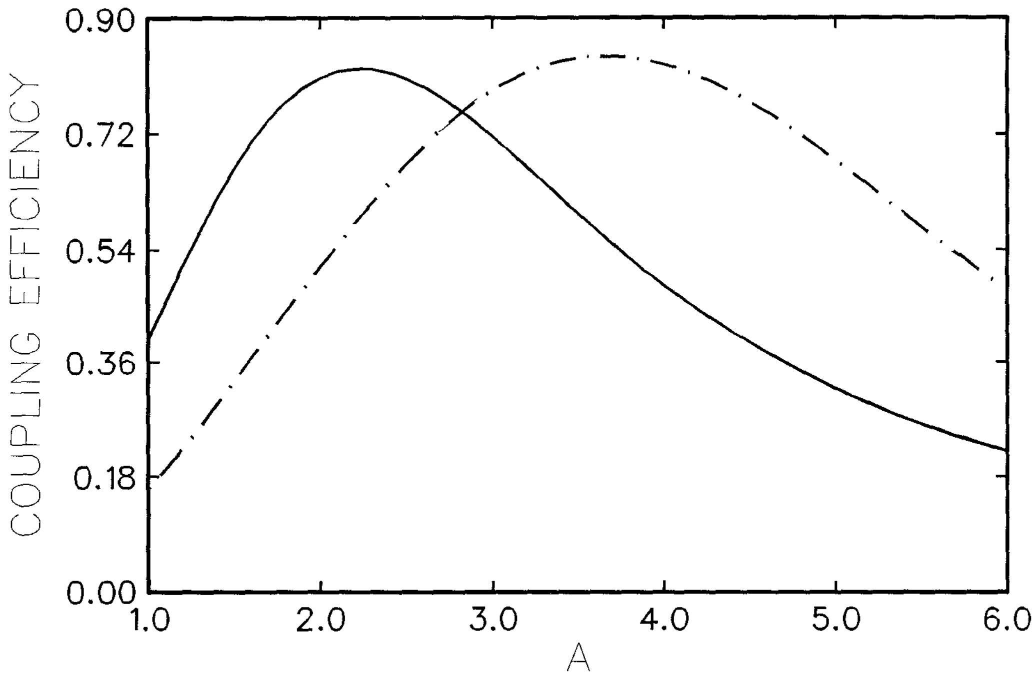

FIGURE 1. – Coupling efficiency of two types of feeds to antenna with moderately large focal ratio ($f/D \geq 1$). The solid curve is for a Gaussian feed and the broken curve for a scalar feed. The coordinate of the horizontal axis gives the feed size relative to the Airy diffraction pattern of the antenna and is defined by $A = \pi D r_0/\lambda f$, where D is the antenna diameter, f is its focal length, λ is the wavelength of the radiation, and r_0 is the Gaussian feed waist radius or the scalar feed horn radius. Optimum coupling efficiency occurs when the field of the feed most nearly matches the diffraction pattern that the antenna produces when illuminated by a plane wave.