SINGLE DISHES: THE POTENTIAL OF PRESENT-DAY BIG DISHES AND THE PROMISE OF THE LMT

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1. Introduction

Single dish antennas are familiar facilities at all millimeter wave astronomical observatories, whether as stand-alone instruments or parts of interferometers. Baars (1983) and an issue of the *Proceedings* of the IEEE (Imriale & Thorburn 1994) contain summaries of many aspects of modern radio astronomical single dish antennas. Filled-aperture instruments are only one possible form for antennas, and many other types are important at radio astronomy facilities. At millimeter waves, however, the only other principal configuration is the aperture synthesis interferometer, the subject of Jack Welch's talk (Welch 1995) and the excellent book by Thompson, Moran, and Swenson (1986). Some analysis of the relative strengths and limitations of these instruments is an essential preliminary to properly speculating on their potential best uses. The critical areas for comparison between the two types of instruments are sensitivity, imaging properties, and spatial resolution.

2. Sensitivity and Imaging

2.1. POINT SOURCE SENSITIVITY

The simplest sensitivity comparison is to find the time that both instruments need to detect the same point source. Solving for the same S/N ratio for the same source flux, the integration time ratio is

$$\frac{\tau_I}{\tau_S} = \left(\frac{1}{K} \frac{T_{\mathrm{rec},S}}{T_{\mathrm{rec},I}} \frac{\eta_{A,S}}{\eta_{A,I}} \frac{A_S}{A_I \sqrt{n(n-1)}} \right)^2 \frac{\Delta\nu_S}{\Delta\nu_I}, \tag{1}$$

for n identical elements each with area A_I in the interferometer, a single dish with area A_S, aperture efficiencies η, receiver temperatures $T_{\rm rec}$, $\Delta\nu$ detection bandwidths, K an efficiency term about $\sqrt{2}$ to 2 for conventional observing modes, and S and I subscripts denoting terms corresponding to the single-dish and interferometer. Since the interferometer's total area is $\sqrt{n(n-1)} \sim n$ times the area of an individual element, the required time scales approximately as the square of the total area and linearly with bandwidth. In the case of spectral line observations, the line's width defines the bandwidth $\Delta\nu$. Expanding the bandwidth can bring a large increase in S/N for observations of sources with wideband continua, however.

The rising spectrum of dust and falling spectrum of free-free emission cross in the millimeter band; dust continuum tends to dominate emission at wavelengths shorter than a few millimeters, with emission from hot plasmas dominating at longer wavelengths. In the case of dust, Figure 1 shows that a wavelength near 1 mm is optimum for survey work. For the 50-m telescope (Fig. 1*a*), the peak signal-to-noise ratio lies at about 260 GHz (1.1 mm). Increasing dust emissivity (dust flux scales as $\nu^2 B_\nu$ in Fig. 1) and a more accurate surface shift the peak to about 860 GHz for a precision telescope in excellent weather (Fig. 1*b*). The higher frequency atmospheric windows close faster than the lower frequency windows, however, and the peak lies near 260 GHz for all conditions but those with very low water vapor.

Direct detectors can be substantially more sensitive than heterodyne receivers for wideband signals. Figure 1*c* shows the relative S/N for a coherent detector. Figure 1*d* gives the ratio of S/N for the incoherent to coherent detectors. Near 260 GHz, where the two systems' sensitivities peak, the incoherent system has a factor 7 better signal to noise than the heterodyne system. The heterodyne system's signal-to-noise ratio will always be a factor of about two or more lower than the incoherent system's.

Single dishes can easily accommodate direct detectors, but interferometers require a rather cumbersome optical beam combination to use incoherent detectors. Especially at submillimeter and longer wavelengths, coherent techniques will dominate interferometry, and this will limit instantaneous bandwidths to a few GHz; single dish instruments will support bandwidths that cover entire atmospheric windows.

2.2. EXTENDED SOURCE SENSITIVITY

One approach for sensitivity comparisons for extended sources is to find the time ratio necessary to fully map the area contained by the primary beam of a smaller interferometer antenna with a larger single dish. Comparing

Figure 1. S/N ratios for 15 K dust from a point source, observed with an incoherent detector on a *(a)* 50-m diameter telescope with a 70 μm rms surface, in a radome, and *(b)* a 15-m telescope with a 20 μm surface and no radome. The three curves in each panel are for different atmospheric optical depths corresponding to about 1, 4, and 8 mm of precipitable water along the line of sight. Panel *(c)* is the S/N ratio for the 50m telescope but with a coherent detector with a bandwidth of 5 GHz. Panel *(d)* is the ratio of incoherent and coherent detection S/N ratios with the 50-m telescope. The signal-to-noise scales are arbitrary but consistent from one figure to another. The incoherent detector is background-limited and single mode with a 50 GHz FWHM Gaussian bandpass; the heterodyne receiver has a 5 GHz rectangular bandwidth and noise temperature $3h\nu/k$. The radome has 20% transmissive loss, scattering 80% of this power onto the sky and 20% onto ambient.

solid angles on the sky, there are

$$N = \frac{\Omega_P}{\Omega_S} = \frac{\lambda^2 A_S}{\lambda^2 A_I} = \left(\frac{D_S}{D_I}\right)^2 \tag{2}$$

single dish beam solid angles Ω_S within the interferometer's primary beam solid angle Ω_P. The primary beam response modulates the signal by a factor of two from center to half-width edge; the average factor of $2\ \ln(2) \sim \sqrt{2}$ for a Gaussian beam is a representative correction. The time ratio for the same S/N ratio for a given average signal level is

$$\frac{\tau_I}{\tau_S} = \left(\frac{2\ \ln(2)}{K} \frac{T_{\mathrm{rec},S}}{T_{\mathrm{rec},I}} \frac{\eta_{B,S}}{\eta_{B,I}} \frac{A_S}{\sqrt{n(n-1)}A_I} \right)^2 \frac{\Delta\nu_S}{\Delta\nu_I} \frac{M_S}{4\ M_I}. \tag{3}$$

Multiple receivers or polarizations are accommodated by factors of M_S for an M_S element focal plane array on the single dish and M_I at each interferometer antenna. The difference in sampling the power and the field accounts for the factor of four. This comparison contains the implicit constraint, through Eq. 2, that the number of interferometer antennas n must be within a distance equal to the diameter of the single dish to weigh in with full efficiency.

This time ratio again scales as the square of the total collecting areas and linearly with bandwidth. Eq. 3 confirms an intuitive feeling that instruments with comparable numbers of equal receivers, and comparable areas contained within a given diameter, will have very similar sensitivities: differences will derive more from switching strategies, illumination, packing, and other details that are not fundamental to either type of instrument. The main practical difference is that interferometers can be spread over large areas to produce much higher spatial resolution maps than single dishes can obtain. The price for an interferometer's higher resolution is lower sensitivity to extended emission and more complex imaging characteristics.

2.3. IMAGE FORMATION AND SPATIAL FREQUENCY RESPONSE

The differences in imaging characteristics are easiest to see in the spatial frequency plane ((u,v) plane), which closely approximates the Fourier transform of the image plane. A single dish equipped with a power detector has a spatial frequency response given by $g \star g$, where g is the field "grading," or distribution, across the aperture and the star denotes autocorrelation. (Bracewell & Roberts (1954) contains the definitive discussion of this topic). Radiation temperatures across a map are the convolution of the true brightness distribution of the source with the autocorrelation function of the field grading (the power beam distribution):

$$T_{\mathrm{map}} = T_{\mathrm{source}}\ *\ (g \star g). \tag{4}$$

Figure 2*a* is the radial spatial frequency response for a circular antenna. This instrument has a centrally peaked frequency response that is most sensitive to large spatial structures (components of structures with low spatial frequencies). Although it is hard to see at the plot's scale, the edge of the dish forces a hard cutoff for spatial frequencies greater than D/λ, where D is the antenna diameter. This cutoff is the origin of the sampling theorem's $\lambda/2D$ minimum angular spacing requirement.

Careful design can produce blocked, axis-symmetric apertures with performance that approaches the clean spatial frequency response of unblocked designs. For instance, Lawrence et al. (1994) report a series of measurements on their 5.5 m antenna, which is designed for continuum measurements of the cosmic background. They adopted the secondary support scheme developed for the BIMA antennas to achieve a reduction of differential elevation-dependent pickup from 4.3 mK to 0.14 mK.

Figure 2. Difference in spatial frequency response for single dishes and interferometers with same field grading g: a 10 dB power edge taper and 10% radial central blockage.

Interferometers retain field amplitude and phase information rather than power intensity alone, and produce maps that are the convolution of the true brightness distribution of the source with the field grading g itself,

$$T_{\text{map}} = T_{\text{source}} \ * \ g. \tag{5}$$

The effective grading, and therefore the spatial frequency responses, depend on the locations of the antennas in the array. At any instant the interferometer is sensitive to points in the (u,v) plane corresponding to the antenna separation (Fig. 2*b*), at one spatial frequency and one angle on the sky. Unless the antennas can overlap, this distance is necessarily greater than the antenna diameters. The best known effect of the lack of short projected spacings is the central "hole" in interferometers' spatial frequency responses. Interferometers consequently produce maps with complicated spatial and spectral distortion when the sources have spatial extent comparable to the primary beam or larger. Wilner and Welch (1994) give a clear analysis of this effect for Gaussian and disk sources. Such spatial frequency filtering is sometimes useful, for instance in removing extended emission to emphasize compact structure. Although far from a fundamental issue, this can also add to the complexity of interpretation.

Mapping an extended source with a single dish samples larger spatial frequencies to fill in detail near the center of the (u,v) plane. The spatial frequency filter function $g \star g$ does not severely attenuate below $\sim D/2\lambda$, but there is no information at all past D/λ. Combination of single-dish and interferometer data profits from large single dishes whose edges are as far out in the (u,v) plane as possible, with good response at the interferometer's shortest spacings.

3. Reflector and Phase Front Tolerances

The chief size—and therefore spatial resolution—limit on single dishes is the requirement of high mechanical precision needed to maintain phase coherence across the antenna. The strength of materials gives a semi-fundamental limit to the size of conventional steerable telescope structures of about 680 m (von Hoerner 1969), but flexure rather than strength is the practical limit on large antennas. Scaling small, stiff structures to much larger size becomes impractical: the deflection of one dimensional structures, such as struts, scales as length cubed, and two dimensional structures scale as radius squared. These considerations limit steerable cm-wave antennas to diameters of order 100 m and mm-wave antennas to about half that.

Perhaps the most germane measure of precision is the on-axis gain, or coupling to a point source. For a single mode, diffraction limited system random errors in the surface reduce the gain by a factor $\exp(-4\pi\delta/\lambda)^2$, where δ is the rms deviation of the surface from a perfect parabola and λ is the wavelength (Ruze 1966). It is interesting to note that the usual requirement, $\lambda/20$, corresponds to an efficiency of only 67%. The remainder of the power scatters into a wide angle "error beam" with size λ/l_c, where l_c is the correlation length characteristic of the distance between surface errors. An incoherent system does not necessarily suffer as large a degradation in gain as do the phase-coherent systems because it can accept multiple modes and collect some power from the error beam.

3.1. COMPENSATION FOR NON-IDEAL EFFECTS

It is rare to find a modern single dish antenna that does not surpass its surface accuracy design goals. An important element of this has been developing methods to accurately measure, and then set, the surface. Baars (1983) reviews many of these methods. Opto-mechanical methods are accurate to a few hundred microns and are essential for initial surface adjustment. Purely optical methods have been developed to bring the surface to its final accuracy (e.g., Morris et al. 1988; Rogers et al. 1993; Serabyn et al. 1991).

Once set to high accuracy, the surface must compensate for a variety of mechanical and thermal effects that conspire to distort the surface. Compensation falls into four categories: none at all, passive open-loop, active open-loop, and active closed-loop compensation. A very familiar form of compensation is the "homologous" mechanical design, a passive open-loop design in which the surface deforms with changing elevation but maintains a parabolic form (von Hoerner 1967). Telescopes with homologously deforming surfaces need an active open-loop control of the secondary mirror's position to compensate for focal length and optical axis shifts. Pointing models and systems that appropriately deform secondary mirrors to compensate for large-scale distortions in the primary mirror (e.g., Ingalls et al. 1994) are other active open-loop compensation schemes.

Clever structures and construction can passively eliminate many problems for small antennas, but the trend is to increase the number of active control systems as telescopes increase in size. A relatively new and promising use of active closed-loop compensation is to precisely control to the primary surface shape. This technique has been proven by the Keck telescope at optical and infrared wavelengths (Mast & Nelson 1985). Cortés-Medellín & Goldsmith (1994) have investigated the optical properties of a segmented mirror that operates in the diffraction-limited mode to prove its feasibility and investigate allowable errors at millimeter wavelengths. The 100 m Green Bank Telescope will adjust its surface periodically to maintain accuracy, and the planned 50 m Large Millimeter Telescope (Schloerb et al. 1995) is designed to have a surface with an "update" rate of a few Hertz.

4. Conclusion

Sensitivity and imaging considerations indicate that single dish antennas with focal plane arrays will remain the most efficient way to map sources with resolution to $\sim \lambda/D_{\rm dish}$, while interferometers will be capable of imaging at much higher spatial resolution. Total area and bandwidth will determine which instrument is more sensitive for detecting point sources. Especially at wavelengths near and shorter than 1 mm, single dishes' wideband optics will permit very sensitive continuum detections with broadband direct detectors. Very large aperture single dish instruments will rely heavily on active measurement and control systems to keep the surface sufficiently precisely shaped. Both types of instruments borrow heavily from each other's successful technologies (e.g. antenna design, correlation techniques, focal plane arrays, on-the-fly mapping, and seeing correction schemes) and this healthy exchange will doubtless continue.

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