scaled horn configurations. Scaling of aerials is no novelty in radio engineering. It is possible to scale all geometrical dimensions. In our case it is even possible to scale resistivity by the use of mesh at lower frequencies. Two tests of horn scaling were carried out. Two small horns (aperture $2\lambda \times 1.5\lambda$) were tested at 9200 MHz and 3000 MHz. The far-field polar patterns of both horns were measured and found to give nearly identical directivity values. Near-field probing of the apertures of scaled horns was also performed. The Schelkunoff gain is computed on the assumption of the expansion of the $TE_{10}$ waveguide mode to the aperture. Uniform $E$-plane and a sinusoidal $H$-plane aperture fields are expected. An investigation of scaled horns (aperture $5.61 \times 4.2\lambda$) at 9200 MHz and 1420 MHz showed ripples in amplitude of up to 1.5 dB to be superimposed on the expected distributions. The amplitude of the ripple increased to 3 dB for a small horn (aperture $2.4\lambda \times 2.4\lambda$). The amplitude variation, dependent on horn geometry, must produce a reduction in the nominal horn directivity. Additional information on the horn geometry, must produce a reduction in the nominal directivity values are expected.

The actual directivity of a horn with nominal Schelkunoff gain near 22 dB can be assumed to be known within 2.5%. Scaled horns should give negligible differential directivity changes resulting in accurate spectra. Adoption of a 'standard gain horn' proposed in this communication should finally eliminate differences between observers in absolute solar calibrations.

The research described in this paper is a part of the research programme in radio astronomy in the School of Electrical Engineering, University of Sydney.

---

**A Simple Image-forming Technique Suitable for Radio Astronomy**

**M. M. KOMESAROFF**  
*Division of Radiophysics, CSIRO, Sydney*  
**AND**  
**J. E. B. PONSONBY**  
*Nuffield Radio Astronomy Laboratories, Jodrell Bank, U.K.*

This note describes a method of image formation which is applicable to radio astronomy. All the information simultaneously reaching an aerial array from an extended region is utilized to produce the image so that the maximum sensitivity is realized. The method is simple in principle and involves relatively few components. One stage of the data processing presents some technical difficulty, but it is believed that particularly for observations below about 50 MHz this difficulty can be met using available techniques. Application of the principle will be described first for a linear array and then for the more interesting two-dimensional case.

**A. ONE-DIMENSIONAL ARRAY**

Figure 1a represents a linear array consisting of $n$ identical aerial elements. Each element is connected to its own receiver, frequency converter and i.f. amplifier. Each aerial and receiver accept radio frequencies in the range $f_n \pm \frac{1}{2}Af$. The i.f. amplifiers are connected to a common i.f. channel by equal lengths of transmission line. The local oscillators all operate at the same frequency but the phase angle of the local oscillator signals increases linearly along the length of the array by $\phi$ radians from one mixer to the next. Thus the angle between the main response and the meridian plane of the array will be $\theta$, where in the small angle approximation $\theta$ radians is proportional to $\phi$.

---

**Figure 1.**  
(a) Linear array consisting of $n$ aerial elements each with its own receiver, mixer, local oscillator and i.f. amplifier.  
(b) Modulus of 'voltage spectrum' from common i.f. channel. (Only the positive frequency half of the spectrum is shown.) It is assumed that there is a frequency difference of $2Af$ between local oscillators.  
(c) Spectrum of square law amplifier output. (Only the positive frequency band near zero is shown.)

If now instead of a constant phase gradient a constant frequency gradient is introduced into the local oscillator signals, the response pattern of the whole array will move repeatedly across the response of a single element. The time for one such 'scan' will be $1/(b\phi)$, where $b\phi$ is the frequency difference between adjacent local oscillators. In order that the receivers should still continue to accept the same band of radio frequencies it will be necessary to retune the i.f. amplifiers. The frequency increment between adjacent amplifiers will need to be the same as that between the local oscillators, viz. $b\phi$ (for an 'up conversion').

If $b\phi$ is very much less than the radio frequency bandwidth $Af$, the system is essentially a time-sharing one since adjacent points in the brightness distribution are scanned sequentially and the full information-gathering capability of the array is not realized. However, if $b\phi \gg 2Af$, the whole brightness distribution encompassed by the primary pattern of one element will be sampled in a very short time interval during which the phases and amplitudes of the
individual radio frequency voltages do not change appreciably. In that case no information is lost and the full sensitivity of the system is realized. The price paid for achieving this is twofold. (1) The signal-to-noise ratio for a single scan will usually be very poor and many scans will need to be superimposed to produce an image of acceptable quality. (2) The common i.f. channel must now have a bandwidth not less than \((2n - 1)\Delta f\).

If \(v(t)\) is the instantaneous voltage at the output of the common i.f. channel and \(\tilde{v}(f)\) is its Fourier transform, which we will call the ‘voltage spectrum’, then the modulus of \(\tilde{v}(f)\) has the form shown in Figure 1b. (Since \(|\tilde{v}(f)\)| is a symmetrical function of frequency, only the positive half of the frequency axis is shown.) In Figure 1b each peak represents the signal from one aerial element and the position of the peak along the frequency axis corresponds to the spatial position of the element. As the signals are separated in frequency they may be individually correlated. This is achieved by passing the broad band i.f. signal through a ‘square law’ amplifier.

The ‘voltage spectrum’ of the square law amplifier output is the autocorrelation function of \(\tilde{v}(f)\). Its modulus is shown in Figure 1c. (For positive frequencies near zero only. There will also be a high-frequency band extending upwards from \(f = 2f_0 - A\). Since this contains no additional information and is not required for image-forming, it has been omitted.) In Figure 1c successive peaks refer to successive aerial element spacings, with the amplitude of the zero frequency peak proportional to the sum of the powers from the individual elements. The complex amplitude of each of the other peaks represents the corresponding voltage correlation multiplied by the number of times the particular spacing occurs. Thus, apart from this weighting factor, each peak is proportional to one Fourier component of the observed brightness distribution. Clearly, by appropriate shaping of passbands, we could weight the Fourier components in any desired way. The information required to construct an image is contained in the narrow range of frequencies centred on each peak. Filtering this component from the remaining energy, which represents noise, is equivalent to superimposing many ‘scans’. Before discussing how this might be done we shall describe the two-dimensional application.

B. TWO-DIMENSIONAL ARRAY

We use a Tee array to illustrate the two-dimensional case although the application of the method is more general. There are assumed to be \(2n + 1\) elements in the E-W arm and \(n\) elements in the N-S, and again each element has its own receiver, frequency converter, local oscillator and i.f. amplifier. An example is shown in Figure 2 with \(n = 2\). Each arm has its own common i.f. channel and their outputs are combined in a correlator. The correlator output is a measure of the brightness temperature of a point at the intersection of the two fan beams. The angular co-ordinates \(\theta_0, \theta_N\) of this point are proportional to the phase gradients along the E-W and N-S arms respectively.

If the frequency interval between local oscillators in the E-W arm is \(\delta f_E\), the pencil beam scans the primary response of a single element from east to west in a time \(1/\delta f_E\). A similar gradient with frequency increment \(\delta f_N\) in the N-S arm causes a simultaneous sweep from north to south in time \(1/\delta f_N\). With \(\delta f_N = \delta f_E/n\), the pencil beam makes a ‘television scan’ of the primary response pattern, the ‘line frequency’ being \(\delta f_E\) and the ‘frame frequency’ \(\delta f_N = \delta f_E/n\).

Clearly, if we made a television display of the correlator output, we would have a two-dimensional image of the brightness distribution. In order to avoid loss of sensitivity it would be necessary to make the ‘frame frequency’ \(\delta f_N > 2\Delta f\). The ‘voltage spectrum’ for each common i.f. channel is shown in Figure 2 (for the case \(\delta f_N = 2\Delta f\)). The spectrum of the correlator output is also shown in the same figure. Each peak corresponds to a spacing obtained by combining a pair of elements, one from each arm, and therefore represents a two-dimensional Fourier component of the observed brightness distribution. The gaps in the sequence are due to the fact that the common aerial element has had its signal combined with that of the E-W arm only. The missing components could be obtained by squaring part of the output of the E-W i.f. amplifier and passing the squared voltage through a circuit which applied the inverse of a triangular weighting function. The resultant could then be added to the correlator output.

C. TECHNICAL PROBLEMS

The most immediate application of the principle is at frequencies below about 50 MHz. The prevalence of interference usually restricts observations to relatively narrow bandwidths, so that the requirements of the wide band correlator should fall within the limits set by current techniques. In addition, it is desirable at these frequencies to obtain an ‘image’ of a limited region in a time short compared with the period of ionospheric scintillations.

The construction of a filter which passes only harmonically related frequencies presents considerable difficulty. A simpler approach to the problem is to use the correlator
output to modulate the intensity of a cathode ray oscilloscope beam. If the horizontal and vertical time bases were synchronized with the two scanning frequencies of the array, this would provide a two-dimensional image which could then be ‘integrated’ photographically to provide the required signal-to-noise ratio.

Very Narrow Band Interference Filters

J. V. RAMSAY

Division of Physics, CSIRO, Sydney

In solar physics a need exists for filters which have very narrow passbands, ~0.01 nm or less. While Lyot-Ohman birefringent filters have been used particularly for investigations at the Hα line, the limited availability of the raw materials, especially calcite, have usually restricted these filters to passbands of ~0.025 nm or more. A possible alternative type of filter consists of a number of Fabry-Perot interferometers mounted one behind the other.

The spectral transmittance of a single Fabry-Perot interferometer consists of a series of narrow maxima separated by broad regions of low transmittance, the separation and position of the maxima being determined by the spacing of the plates. For use as a filter it is necessary to select one of the transmission maxima and reject the others. This may be done by adding more interferometers whose spacings are such that over a broad spectral region there is only one common transmission maximum. If this range is sufficient, the other common transmission maxima may be rejected by an ordinary interference filter with a moderate passband.

For satisfactory operation of a Fabry-Perot interferometer the plates must be very flat, be coated with highly reflecting coatings having low absorption, and be maintained accurately parallel and at a precise spacing. Recent developments in the Division of Physics1 have led to means for producing optical flats of 75 mm diameter having flatness errors less than λ/120. In addition, automatic methods of control have enabled the parallelism and spacing to be controlled to this order of accuracy, to a large extent independently of environmental changes such as temperature.2,3,4

Interferometers embodying these principles have been constructed with finesse of 30 (the ratio of the separation of the transmitted maximum to its width at half peak intensity), peak transmittances greater than 0.6 and usable apertures of about 52 mm diameter.

For satisfactory spectral performance in an interferometer having a finesse of 30, the tolerance on plate flatness is usually quoted as λ/60. However if high spatial resolution is required in the image the tolerance is more stringent. For example, if the criterion adopted is that the central intensity of the Airy disk should not fall below 0.8 of its theoretical maximum, the tolerance becomes λ/120.5,6

The total usable angular field 2θ of an interferometer is determined by the allowable shift Δλ in the wavelength for peak transmittance across the field, and is given by

$$\theta = \left(2\Delta\lambda / \lambda \right)^{1/2} \text{ radians}$$

for an interferometer normal to the optical axis. If Δλ = 0.005 nm and λ = 600 nm, the semi-field has angle θ = 15′ arc. This is of the same order as a simple (i.e. uncorrected) birefringent filter.

When several interferometers are used in series as a filter, difficulties are experienced with interreflections between the interferometers. In order to avoid these embarrassing interreflections and to obtain the maximum usable angular field, the interferometer with the largest spacing (i.e. the one with the highest spectral resolution) should be placed normal to the incident beam and the preceding interferometers tilted so that these reflections are well separated in the image plane. This necessitates using the interferometers in a collimated beam. While the filter may be used in front of the objective lens, this restricts the lens diameter and hence the spatial resolution. More generally, it may be mounted behind a telescopic system and followed by a secondary objective which then produces an enlarged image of the object in light transmitted by the filter. The theoretical spatial resolution R in the image is given by

$$R = \frac{0.61 \lambda}{N \sin \alpha}$$

where N is the refractive index and α is the semi-angle which the secondary objective subtends at the image. Assuming N = 1 and α is small the resolution in the final image is 1.22 fsλ/ds (or in angular measure 1.22fsλ/ds), where fs and ds are respectively the focal length and diameter of the secondary objective. When used with a telescope system of magnification M preceding the filter, the angular resolution in the object is effectively increased by the same factor, with, however, a proportionate decrease in the angular field of view. The illumination in the image plane is independent of the magnification provided that the numerical aperture, N sin α, remains constant throughout the system.

We have recently constructed a filter of aperture 48 mm. Whilst the available aperture in our interferometers is 52 mm, the available interference filter has a usable aperture of only 48 mm. The filter comprises an interference filter of passband approximately 2 nm followed by three automatically controlled interferometers having spacings respectively of 28 μm, 103 μm and 750 μm. The passband of the filter is about 0.01 nm at 656.3 nm. The filter can be tuned to transmit any wavelength in the range 480–700 nm. Alternative interference filters are necessary to cover this range but this presents no undue difficulties. The filter has been tested without a preceding telescopic system, the focal length of the objective following the filter being approximately 180 cm.

Figure 1 shows the complete filter and Figure 2 shows some results achieved. Diffraction-limited optical performance would give a resolution of approximately 3′ arc. When photographing the Sun with a 16 mm image diameter on IV E film, we have resolved something in the region of 5–7′ arc under good seeing conditions.

Many people have been associated with this project including H. Kobler, R. G. Giovanelli, E. G. V. Mugridge and G. Otte. The project has been supported in part by the National Aeronautics and Space Administration under Contract No. NAS-208.

---

6 Ramsay, J. V., 'Optical Imagery through Fabry-Perot Interferometers'. To be published.