ANALOGUE PROCESSING METHODS FOR SYNTHESIS OBSERVATIONS

(Invited paper)

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1. INTRODUCTION

In aperture synthesis the formation of an image involves the two steps of spatial correlation across an aperture and transformation to the image. This is closely related to conventional imaging with a lens (Cole, 1977a), which Abbé interpreted as two successive transformations at the surfaces of the lens. With the simple lens the image is the light intensity in the output plane (Figure 1(a)). In aperture synthesis (Figure 1(b)) the image is the transform of the correlation but no detection takes place. The image corresponds to the 'light' amplitude rather than intensity.

The two classes of instrument, direct imaging and aperture synthesis, exist in radio astronomy but they are rarely as simple as depicted in Figures 1(a) and (b). Dilute aperture imaging arrays such as crosses or rings require processing in order to simulate an ideal aperture. One form of processing modifies the amplitude and phase distribution across the aperture by a filter. The corrected image is then the difference between images obtained when the aperture has been modified by each of two filter functions.

Similarly, in aperture synthesis the spatial correlation samples rarely have the distribution one would have from an ideal aperture. Correction in this case however is often achieved by a single weighting filter across the (spatial frequency) aperture as in Figure 1(d).

The similarities in Figure 1 form the basis of most of the analogue processing techniques to be discussed. The differences are however important, as will be seen.

2. AN APERTURE SYNTHESIS SYSTEM

A typical aperture synthesis system (Brouw, 1975; Fomalont and Wright, 1973; Pooley, 1976) and the stages involved in the processing

C. van Schooneveld (ed.), Image Formation from Coherence Functions in Astronomy, 123-141.

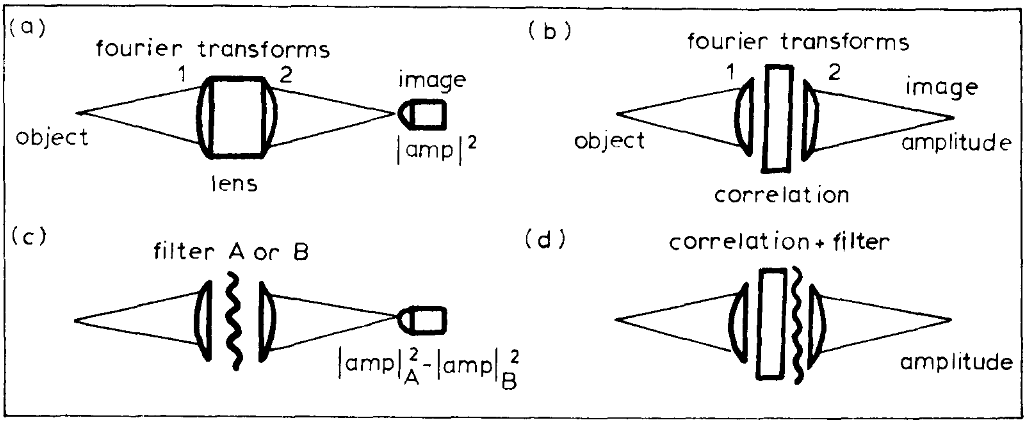

Figure 1. Conventional imaging with a lens (a) is diagrammatically compared with spatial coherence imaging (b). Processing for dilute apertures involves modifying the aperture with weighting filters and taking an image difference (c). Processing in aperture synthesis (d) involves a simple weighting filter.

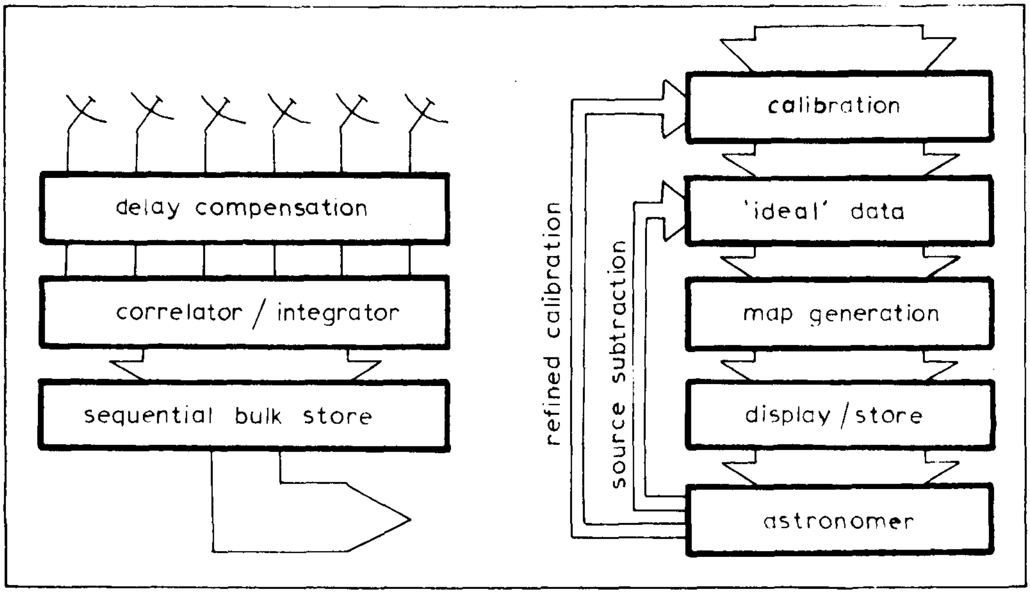

Figure 2. The basic steps in collection (left) and reduction (right) of aperture synthesis data involves several feedback loops.

of the data are illustrated in Figure 2. The antenna structures, and in many cases the feed lines, the delay compensation, and the correlators, are analogue devices, but from there on the data are almost invariably digitized. In an extreme case digitization could occur at the intermediate frequency right at the antenna elements of the array, and this will probably be the future trend. Only for observing bandwidths of hundreds of megahertz or more will analogue systems be used.

The sequentially stored data are processed in several stages. Calibration observations determine the fixed deviations in amplitude, phase and position of the array. The measurements are corrected to those which would have come from an array more nearly 'ideal'.

A map is obtained by transformation and is both stored and displayed. A number of options are then open. Calibration errors and deviations from ideal behaviour during the measurements can often be discerned in the point source responses in the map. Corrections to calibration can then be re-applied before making a more ideal map.

Sidelobes and grating responses occur in the response from even an ideal array. Strong sources in the map can therefore confuse weak ones with their (accurately predictable) sidelobes and grating responses. The most accurate way to remove the effects of strong sources is to subtract from the spatial frequency data. A new map would then have a lower peak value and show the weak structure more unambiguously.

In practice these two processing loops of calibration correction and source subtraction could be repeated many times before all the information in the data is clearly available in maps. Spectral line observations differ only in increasing the complexity of reduction by a factor which is somewhat larger than the number of frequency channels.

An important consideration emerges from this description. So long as one can repeat the map-making process the accuracy of the generated map need not be high. With sidelobes and grating responses usually 5% or more of the peak response one requires an accurate source subtraction step in order to see detail much weaker than 5%. But as one subtracts sources the dynamic range of the map decreases. It would be uncommon to require a dynamic range in the map-making stage of better than, say, 100:1, even though the original data might have a much higher accuracy.

Two approaches can be compared. Current practice, and as far as I understand it the projected routine practice for the Very Large Array (VLA), is to produce an accurate map of a field and the 'ideal' beam. Processing such as 'cleaning' (Hogböm, 1974) is then done in the map plane. But if one has multiple access to the (u,v) plane data, subtractions are more accurate, and it is then quite sufficient to generate maps of only 1% or 2% accuracy.

I want to concentrate on alternative means of generating maps from the spatial frequency plane data with an accuracy of 1%. If it is possible to do this quickly and economically, then truly interactive data analysis is possible. The quest for high dynamic range will force one to this interactive approach. It is not possible in all cases to produce a map which is strictly the convolution of the true distribution of the sky and a single, ideal beam. The variation of the beam shape across the map will form a fundamental limit to processing when only the map is available.

3. HYBRID RATHER THAN ANALOGUE

To generate the map from spatial frequency data I will consider special-purpose hardware rather than the various software approaches.

Software processing is very flexible. Programs can be quickly modified, and at the expense of speed and at a price the result can be obtained with as many significant figures as one wishes. However, the digital computer load of these methods is becoming too great.

In a special-purpose device, flexibility is sacrificed. There is a trade-off of flexibility (and perhaps accuracy) for economy and/or speed. Processing steps which are rigidly defined, and which are repeated many times, are the ones to implement in hardware. From Figure 2 the data reduction after the calibration correction contains just such steps.

The input and output to the special-purpose device is therefore seen to be digital. It is almost always in the form of a serial access to magnetic tape, disc or memory.

Special-purpose digital hardware can be devised and several approaches are discussed by other speakers at this meeting. Instead, we shall consider analogue components.

The antenna elements, like any analogue component, have fixed errors (of amplitude, phase and position) which can be calibrated and corrected for in the digitally recorded data. They also have variable errors which limit the accuracy of the final map.

Optical systems, ultrasonic, electron beam or co-axial systems are all analogue, with basically identical accuracy limitations and characteristics. A special-purpose analogue system is an assemblage of these analogue devices which performs the required mathematical processing. Analogue processing would convert the digitized spatial frequency data to light, sound, electric charge and so on, and generate the desired image as a distribution of light, sound or electric charge. The problem is to identify the mathematical analogues, study the generation and detection of the analogue, and compare accuracy, speed and cost.

The analogue device will have fixed errors which can be compensated for digitally. The input and output will usually be digital. Therefore the special-purpose device may be considered as a hybrid - that is, as an analogue peripheral to a digital computer.

4. THE CLASS OF PROBLEM

One of the difficulties of hybrid processing is in choosing the optimum implementation for the particular aperture synthesis system. I identify three broad classes of aperture synthesis system, whose common basis is a Fourier transformation and, equally important, a coordinate transformation from the essentially polar coordinates of the measurements to the rectangular coordinates of the map. The differences between the systems will imply that the optimum processing is different for each application. The conclusion will be reached that the most desirable hybrid systems involve optical processing.

4.1 The VLA-type system

The most general Earth rotation aperture synthesis system is the Very Large Array (Heeschen, 1975).

With north-south components to the baselines, the spatial coherence function is sampled in a three-dimensional (u,v,w) space. This and the varying height along the arms of the array produce a complex grating structure which varies markedly with source position. This will make it difficult to detect calibration and other errors by eye, will restrict the use of map plane subtraction, and will probably limit the dynamic range. However, the instrument has the distinct astronomical advantage of almost equal resolution over the major part of the sky.

The mathematical description of the array requires a three-dimensional Fourier transformation of the data. An alternative analysis approach would be to project the data on a number of two-dimensional planes appropriate to small sub-sections of the field of view and to perform two-dimensional Fourier inversions for these sub-sections.

In either case the software approach would need to weight the measurements for a reasonable beam, convolve the data to a grid, and use the fast FFT algorithm. However, the optimum weighting varies across the field because of the differing projections.

The general geometry of the VLA places enormous loads on the data processing if conventional, linear methods are to be used and high accuracy is demanded.

4.2 The east-west array

In contrast, Earth rotation synthesis with east-west baselines samples a two-dimensional spatial frequency plane along concentric ellipses. The data are therefore recorded in polar coordinates as sequential sets of samples along a radial line. A two-dimensional transformation produces a map in which the beam varies by the simple scaling sec δ with declination (δ). The usual software approach is to apply a weighting, convolve to a grid, and use the FFT. The symmetries of the spatial frequency sampling make it easy to distinguish by eye features due to real sources from elliptical or radial artefacts due to calibration or other errors. The result is a system in which high dynamic range is possible but which cannot effectively map low declination regions.

4.3 The Culgoora array

The middle ground between the two previous extremes is epitomized by the Culgoora array (Labrum et al., 1975) with 96 elements around a 3-km-diameter circle. The elements are in a plane although the plane is tilted with respect to the equatorial plane. In Earth rotational synthesis this makes the beam and the grating responses position-dependent. The circular symmetry is a powerful factor in simplifying the description of the spatial frequency sampling. The 96 elements are sufficient to form an image at each instant, and indeed in the solar application up to about 20 images per second might be produced. Rotational synthesis could therefore be processed as the sum in the map plane of sub-images produced at different times of the synthesis. Geometrical symmetries will be seen to make this approach attractive. However, the complicated grating responses due to the north-south components and the limited antenna tracking range will make high dynamic range difficult, while the relatively wide bandwidth will restrict the field of view and thereby simplify processing.

5. SOME APPROACHES OTHER THAN OPTICAL

I will concentrate on just three general approaches in this section. All of them could perform the processing required in aperture synthesis. But their disadvantages illustrate the major factors involved in a desirable hybrid system.

5.1 Ultrasonic imaging

A piezoelectric transducer readily converts a radio signal to an ultrasonic wave in the radio frequency region. An array of such transducers can generate waves which on propagation to the acoustic far field yield a Fourier transform image. The ultrasonic imager has been described by McLean and Wild (1961), analysed by Oliver and Billingham (1973), and used by Briggs and Holmes (1973). In the spatial frequency application, pairs of transducers generate spatial frequencies in the output plane and arrays of transducers in that plane measure the acoustic image amplitude. The problem is that detector arrays are rather limited in both number of elements and to the extent that each element must be connected to its own amplifier chain. There are developments in the medical field, but for parallel processing, ultrasonic imaging is still badly limited in its scope.

5.2 Radio frequency imaging

There are a number of forms of the radio equivalent of a lens. One is a free-space propagation system similar to the ultrasonic system (Oliver and Billingham, 1973) but this suffers, as do all the other radio frequency systems that follow, in the complexity of the detector system at each output point.

Radio frequency lenses can compress the size of such an imager but the most highly developed lenses are only one-dimensional and are limited in the number of input and output ports (Rotman and Turner, 1963).

Co-axial cable systems, such as Butler matrices (Shelton and Kelleher, 1961) and branching networks, perform the required transformation between aperture and image plane. The 96 × 48 cable system at Culgoora (Fourikis, 1967) probably represents the practical limit of a cable system.

5.3 Electron beam processors

A somewhat more attractive processor uses stored charge as the output parameter and electron beams to both form and read the charge distribution. In the charge storage tube electrons can be deposited at any of up to about 1000 × 1000 locations and the charge distribution can be progressively integrated. The device is readily interfaced to a computer and is basically a coordinate converter in which polar data can be recorded and integrated before being read-out in rectangular coordinates (Silver and Luedicke, 1971).

There is no Fourier transform performed in the device so that integration must be of data already processed in the computer. For individual spatial frequency samples, the processor would generate the corresponding fringe pattern. Strip scans could be produced by the digital one-dimensional Fourier transform of radial lines of spatial frequency samples and processing via strip scans simplifies the source subtraction step. The charge storage tube would integrate these with the correct orientations and scale. In the more general array geometries instantaneous maps could be integrated. In all cases, the final, integrated distribution would be read back to the computer.

The major restriction of the device is its inability to write negative as well as positive values. Two solutions are possible. Either the values are floated around an offset bias charge or two sequential integrations are performed, one for positive and one for negative values. In either case a subtraction is needed for the final map, but the latter, the sequential approach, is clearly far superior. The final subtraction removes effects of fixed background variations due to leakage current and a maximum dynamic range is achieved. One notes however the restriction that the electron beam writes point by point. The painting of the whole screen could take several milliseconds if one assumes 2 μs per line and 1000 lines to the fringe or strip scan.

Typically one could then expect to complete a picture within 1 s each for positive and negative or 2 s for the complete 512 × 512 or more picture. At 2 μs per line, the required data rate of 500 kHz would probably be limited by digital disc transfer rates.

Linearity and dynamic range need still to be determined but experiments are taking place in the medical computerized tomography (CT) imaging field as well as in the radio field at Dwingeloo. The electron beam approach is, to my mind, the best of the non-optical approaches, even though it requires data to be transformed to strip scans or sub-images.

6. INCOHERENT OPTICAL PROCESSING

Optical processing of information has been discussed, analysed, and in some cases applied for a number of years (Tippett et al., 1965; Preston, 1972; Stroke, 1972). Its appeal lies in the availability of a wide range of optical components, light sources, light modulators and light detectors. A more subtle appeal is the possible speed of processing. An optical image can contain millions of picture points to be transformed by lenses in parallel and in nanoseconds.

For aperture synthesis processing it is not difficult to envisage an incoherent optical implementation of the charge storage tube processor described above. In this case a two-dimensional, optical, integrating detector (discussed below) accumulates sub-images generated by scanning a light source modulated by the digital data.

Other incoherent approaches could be derived (Cole, 1976), but all would suffer from two basic drawbacks. Offset light levels are needed, and to avoid diffraction effects, picture elements need to be much larger than the wavelength of light. This limits the processing capacity while the almost inevitable inclusion of mechanical movement in the processor can be a limit to speed. Their redeeming characteristics are probably cost, combined with a simplicity of design when compared with the use of coherent optics.

7. THE COHERENT OPTICAL PROCESSOR

The principles of coherent optical processing are now well established (e.g. Goodman, 1968) and some radio astronomy applications have been discussed (McLean and Wild, 1961; McLean et al. 1967; Cole, 1975). The processing relies on the Fourier transform properties of a lens. Near the optical axis where $\sin\theta \approx \theta$, the light amplitude distribution across an input aperture one focal length from a convex lens is Fourier-related to the light amplitude distribution across the output plane, one focal length on the other side of the lens.

Variations of the basic approach include cascaded transforms, where the input can be recovered after modification of its Fourier transform in the intermediate plane. Cylindrical lenses permit parallel transformation of a number of one-dimensional light distributions. Lasers and lenses are readily available. Lens accuracies can be one-twentieth of a wavelength or better r.m.s. and processing accuracies of better than 1% are common (Preston, 1972).

The implementation of a coherent optical processor for aperture synthesis data is now clear. From the computer-stored data, one needs to modulate the laser light distribution across the processor input plane. A simple lens provides a Fourier transform of this distribution. But from Figure 1(b) we realize that the light amplitude in the output plane needs to be measured. Detectors measure intensities, so that the amplitude needs to be determined by a further two-stage process somewhat akin to holography. As outlined by Bulabois (1976), a uniform reference light beam (R) firstly in-phase and then out-of-phase with the signal light amplitude distribution (S) in the output plane would give intensity distributions $|S+R|^2$ and $|S-R|^2$. On expansion of these terms and formation of the difference between them, we have 4RS, proportional to the desired amplitude S.

The practicality of the processor depends critically on the light modulators and detectors. They can be assessed in relation to several broad classes of configuration. The input and output digital stores are serial devices whereas the optical processor is parallel. A two-dimensional light modulator presents a two-dimensional output to be read either line by line with a linear detector array or in parallel by a two-dimensional detector array. The use of a two-dimensional integrating detector array will be seen to permit the sequential use of a one-dimensional modulator. In most cases however one is limited by the speed of serial access to digital stores and the optimum configuration depends critically on the detector and modulator.

8. LIGHT DETECTOR ARRAYS

Light detector array technology is advancing rapidly and a number of suitable components exist. The most studied one-dimensional array is the sensitive, accurate and reliable solid-state, self-scanned photodiode array (Fry, 1975; Vogt et al., 1978). With up to 1800 or so photodiodes delineated on a silicon substrate, incident light is integrated as stored charges to be read out on a single video output line by shift registers and control circuitry integrated on the silicon chip. The response is linear, and low-noise processing of the output produces a dynamic range between light saturation and r.m.s. readout noise of typically one or two thousand to one. To achieve this performance one removes fixed effects of leakage currents and fixed patterns by image subtraction.

Two classes of device exist. On one the photodiodes are sampled sequentially by switching each to the output video line. In the other all diodes are sampled at the same instant and read-out along an analogue charge coupled device (CCD) shift register. This second approach is preferred, since lower output video line capacitance and on-chip preamplifiers should give lower readout noise while the simultaneous sampling more closely matches the processing problem of comparing consecutive images. The so-called CCPD combines photodiodes (P) and CCD technology (Reticon, 1977).

In two dimensions CCD arrays already exist, and again those arrays which simultaneously sample all photodiodes are preferred (Barbe and Campana, 1977). Commerically available devices include the 120 × 150 point CCD camera from GEC currently being used at CSIRO. Laboratory devices exist with 10 or more times as many picture points.

Amongst the more traditional image detectors the silicon vidicon stands out as offering a very large number of output points and (with care) a high dynamic range (McCord et al., 1975). However, all the vidicon-type devices suffer in readout speed. The electron beam readout is sequential and must be complete before the next image can be displayed for integration.

The literature contains reviews and discussion of performance of most of these devices. There is however one point which needs to be stressed.

All of the detectors use stored charge as the parameter representing integrated light energy. Each storage area has a maximum charge typically of the order of 10^6 electrons. One has to consider the effects of shot noise, which for 10^6 electrons has an r.m.s. value of 10^3 electrons or one part in one thousand for the saturation charge. The other source of noise is readout noise, which is independent of the charge amount being read-out and which can be made much less than 10^{-3} of saturation charge. If the image being read-out is of low contrast (and it will usually be in optical processing), then shot noise will become the dominant source of processor noise. If a dynamic range of more than 30 or 33 dB is needed, then care is required in choice of detector.

For high-contrast images, dynamic range is determined by readout noise and could approach 40 dB. One notes however that this is up to 10 dB worse than might be achievable in a radio-frequency square-law detector!

Nevertheless, there is available a range of suitable detectors matched to the optical processing problem, especially where processing involves forming the difference between two images.

9. LIGHT MODULATORS

For speed the light needs to be modulated across an input plane. Therefore only those modulators which are multi-channel will be considered. Table I summarizes their properties.

Device type / Parameter	Elastomeric		Pockels effect	
	Oil film	Thermoplastic	Optically written	Electron-beam written
Aperture size (mm^2)	25 x 25	50 x 50	25 x 25	50 x 50
Limiting resolution (line pairs/mm)	50	50	80	30
Space-bandwidth product	$< 10^6$	10^6	10^5	$10^5 - 10^6$
Cycle time	30 ms	>0.5 s	10 ms	30 ms
Storage time	∿100 ms	Months	Minutes to hours	Minutes to hours
Erasure time	∿100 ms	∿1 s	∿1 ms	<1 ms
Lifetime	∿3000 h	∿10^5 cycles	Long	Long

Table I. General characteristics of some current spatial coherent light modulators.

The most traditional modulator is the silver-halide photographic transparency. Varying density distributions modulate the transmitted light amplitude. In order to cope with negative values the modulation function needs to be floated about a bias (grey) level. In order to modulate light phase more complex arrangements are needed. The most usual is to employ a spatial frequency carrier so that each element of the input distribution is in the form of a diffraction grating. The phase of the light diffracted from this grating element depends on the relative position of the element centre and the grating maxima.

Photographic modulators of a million or more picture elements are possible but in practice they have great drawbacks. Accurate exposure of the modulating pattern is difficult, especially in the aperture synthesis case, where a large peak occurs at low values of spatial frequency. Surface irregularities on the film require compensation. Chemical development and the non-reusable nature are further drawbacks. The main positive factor is the 'low technology' content.

As an alternative I wish to summarize developments in three broad classes of modulator; elastomeric, Pockels effect, and electro-optical.

The elastomeric modulator (Thomson, 1977; Casasent, 1977) relies on the deformation of the surface of a layer through which, or reflected from which, the light passing is to be modulated. The surfaces include thermoplastics or oil films and the required pattern is formed by writing an electrical charge distribution with an electron beam. The general properties of several elastomeric devices are listed in the table and a number of disadvantages emerge. In general they are expensive and of limited life. The decay time is either too slow or too fast. The optical quality is not always high, and like photography, these devices require a bias level and spatial carrier for complex light modulation.

A more attractive class of modulator relies on the Pockels effect whereby the linear polarization angle of the light is locally rotated by a charge distribution across an electro-optical substrate (Marie et al., 1974). Crossed polarizers convert the rotation to an amplitude modulation.

With 1000 × 1000 points or more, up to one hour storage of pattern, less than 1 ms to erase, long life, and high optical quality, the devices are very attractive. They do require a bias level and a spatial frequency carrier but the required modulating pattern is written either by a scanned electron beam or by a modulating blue light. The commercial development of these devices is sure to continue.

There is also an electro-optical modulator specifically derived in response to the aperture synthesis processing problem. It is an advance on acousto-optical light modulators for antenna array processors (Lambert et al., 1965), which are difficult to arrange in large numbers. The new device is a variation of the total internal reflection electro-optical modulator (Scybor-Rylski, 1977, 1974). An interdigitated metal finger pattern is deposited on a suitable substrate surface from which light is internally reflected (Figure 3(a)). For electro-optical and piezo-electric materials such as lithium niobate a voltage across the fingers can produce a combined surface deformation and electro-optical effect which phase-modulates the reflected light distribution. Some light is diffracted from the main beam by the applied voltage (several tens of volts) and both positive and negative amplitude modulation is possible.

General phase modulation requires a more complex electrode pattern (Cole, 1978a,b). As shown in Figure 3(b), the pattern contains two electrodes whose modulation is 90° apart in phase. These COSINE and SINE electrodes permit fully complex light modulation at megahertz rates. The deposition of a number of such patterns permits the optical simulation of an antenna array (Cole, 1978a), as shown in Figure 3(c).

With standard microcircuitry techniques up to a hundred or so patterns could be accurately deposited on a polished substrate. Their use in the aperture synthesis problem is discussed below.

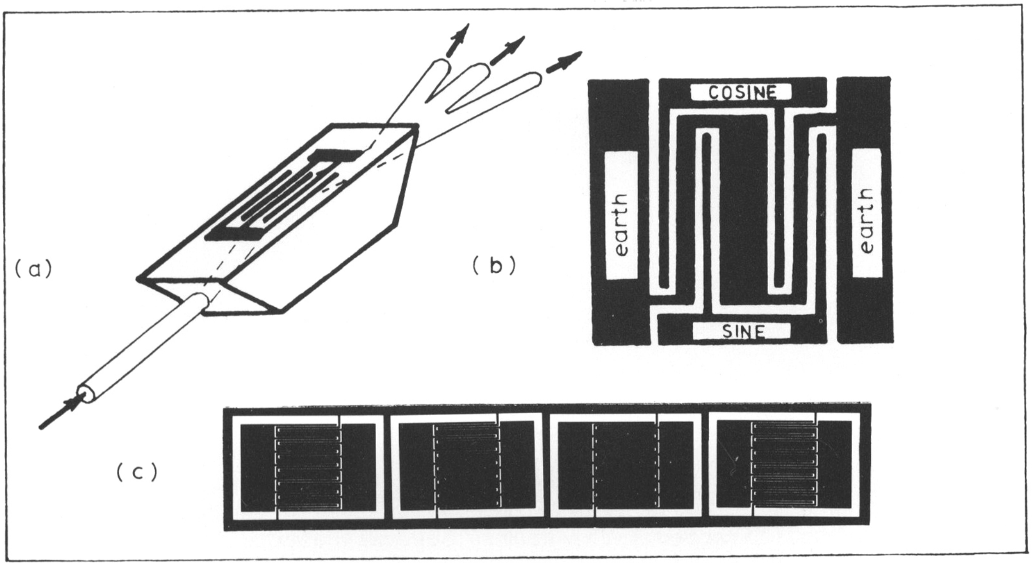

Figure 3. The total internal reflection electro-optical light modulator (a) uses interdigital metal finger patterns on lithium niobate. The light is reflected internally and the modulation diffracts light from the main beam. To modulate phase as well as amplitude a more complex pattern (b) with in-phase and quadrature elements as well as earth common is needed. A number of such modulators (c) forms an array processor.

10. SOME SYSTEM DESIGNS

Having defined the problem and assessed the components available for its solution we can consider those solutions. I concentrate on three systems. The first, the computer-generated hologram, is the most general, and in many ways the least attractive. The other two exploit the symmetries of particular antenna geometries.

10.1 The computer-generated hologram

The optical system can be required to fulfil only the Fourier transform function. A photographic transparency of the spatial frequency plane samples, suitably modulated on a spatial carrier and suitably embedded in a refractive index matching oil, forms the input, and photodiode arrays read the output distribution (Figure 4). The use of a switched reference light beam extracts the light amplitude (Somers and Burns, 1976; Bulabois, 1976; ERIM, 1977; Cole, 1977b, 1978c).

This is essentially the proposed optical processor for the VLA. I do not intend to go into great detail, but several comments are appropriate. The undesirable photographic input could be changed to

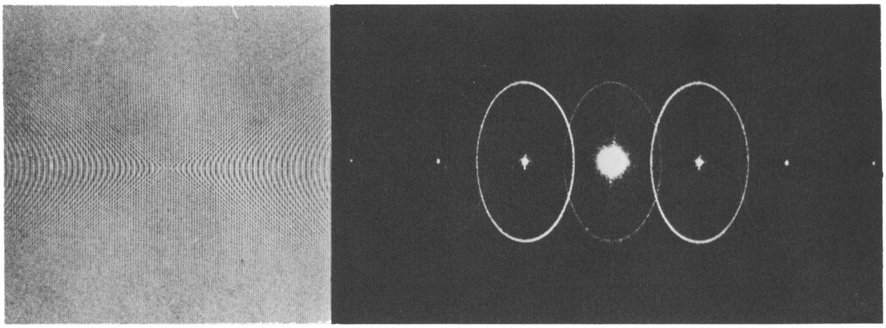

Figure 4. A computer-generated hologram of the Westerbork antenna beam in (a) can be optically transformed as in (b) to two images displaced about the undiffracted light beam. Several defects are discernible in the reconstruction (see Cole, 1978c).

any of the two-dimensional continuous modulators discussed in Table I. The approach is general in that any geometry can be processed as transformations of planes of spatial frequency samples. However, a not insignificant load is presented to the host computer because of the VLA geometry. The data would probably be placed on a grid (although not strictly necessary), the optimum taper would need to be applied, and most importantly, the data would need to have been projected to a plane. The north-south geometry strictly requires a number of planes for subsections of the field of view. The processor is not called upon to transform the entire field of view. The high parallel processing speed of the optics is not fully utilizable in the VLA optical processor.

However, it is clear that the system would work and produce outputs with 1% accuracy or better. It is not clear though that it could form part of a fully interactive data reduction system. Its generality is probably a disadvantage when compared with systems exploiting symmetries in the spatial frequency sampling. At best, the holographic approach could process east-west array data by recording along concentric ellipses for which the weighting factor is constant. This would greatly ease the load on the host computer and avoid aliasing due to gridding.

10.2 Strip scan processing

Earth rotation aperture synthesis with an east-west array measures sequential, radial lines of spatial frequency samples. The Culgoora array spatial frequency sampling can also be described in polar coordinates (see below). In these situations the transformation is describable as the sum of the one-dimensional transforms (or strip scans) of the properly weighted, radial lines of samples. A two-dimensional integrating array is required as the output plane.

An optical strip scan processor would use a two-dimensional detector and an effectively rotating, one-dimensional input system of light modulators.

Two-dimensional detectors exist. The one-dimensional modulator array is easily within current technology. In all antenna arrays there is only a finite number of spacings. For example, at Westerbork the minimum spacing increment of 18 m implies 167 or so possible spacings over 3 km. The rigid geometry of Culgoora also strictly defines the possible spatial frequency sampling. Therefore, it is feasible to contemplate individually addressed modulators aligned with a spacing pattern which closely matches the array whose data is to be processed.

For example, I would contemplate a one-dimensional line of total internal reflection modulators as in Figure 5. Each is addressable via a multiplexer and charge-hold circuit from the computer. At each hour angle the data are loaded and the two-dimensional strip scan is integrated on the output plane. The particular geometry of Culgoora requires one to use two types of radial sampling patterns (Figure 6(a) and (b)). In all cases one must determine light amplitude by a process of image differencing between outputs with two states of a reference beam. It is easy to insert a reference modulator at the spatial frequency origin. (One also notes that with careful control of the reference phase, it is possible to transform just the positive half of the spatial frequency plane. This eases modulator design and speeds processing.) The requirement to subtract in a two-pass imaging system not only obtains light amplitude but also cancels fixed irregularities in the detector.

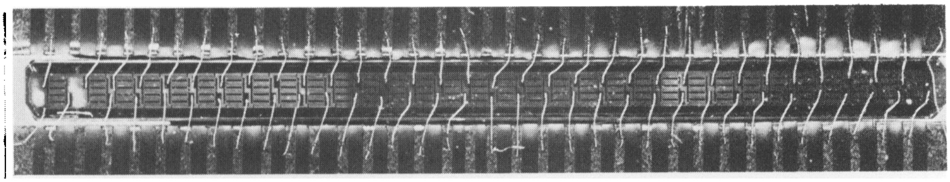

Figure 5. A complex internal reflection modular array with the geometry of one central arm of the Fleurs array is shown in the centre. The finger widths are 10 μm and the 33-element array measures 25 × 1 mm.

The processing speed would now be limited by the computer. The total internal reflection modulator responds at megahertz rates. At, say, 20 μs per strip scan, picture processing rates of many tens of pictures per second appear not unreasonable. The use of the fast, re-usable, solid-state modulators completely alters the processing

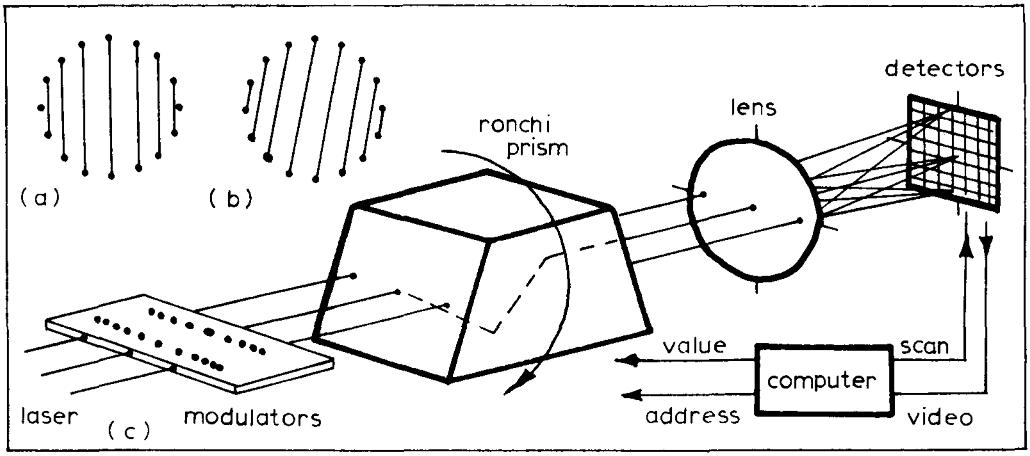

Figure 6. For the Culgoora array, those spatial frequency samples with the same orientations are shown in (a); (b) for a 16-element array. Two sets (odd and even) emerge with an almost twofold redundancy. In (c) is sketched one form of coherent optical processor for Culgoora (or east-west) spatial frequency data. The ronchi prism rotates the transformed image of the modulators on the two-dimensional detector array.

concept. To rotate the strip scans on to the detector a simple Dove prism system suffices (Figure 6(c)). With such a prism (or mirror equivalent) system, the image rotates twice as fast as the prism (or mirrors) so that mechanical constraints are not high.

10.3 Integration of instantaneous images

Strip scan processing for east-west arrays is a special form of a more general approach. Aperture synthesis is merely the summation of images obtained at a number of sequential times. The only requirement is that the spatial frequency sensitivity of the sub-images match the requirements of the complete, synthesized, spatial frequency sampling. A general case is Culgoora, capable of imaging a region of sky at any instant. Indeed, in its solar application, one is interested in producing up to 20 images per second. Earth-rotation aperture synthesis is therefore the addition of a large number of images which have been appropriately rotated and scaled to match the array rotation and foreshortening due to Earth rotation.

Similar arguments apply to the VLA, except that the VLA is not exactly in a plane. Simple rotation and foreshortening of a rigid planar array therefore do not exactly match the VLA behaviour. Nevertheless a device for generation of instantaneous images from the current samples of the spatial frequency plane could form the basis of a synthesis processor.

Without going into details, we can say that a two-dimensional distribution of light modulators in the same pattern as the array can be used to generate fringes appropriate to each measured spatial frequency (Cole, 1976). Acousto-optical and total internal reflection modulators could be used. However, it is difficult to see any advantage when this use is restricted to processing spatial frequency plane measurements from east-west arrays and from Culgoora. For these, strip scan processing appears simpler.

11. CONCLUSIONS

Undoubtedly, hybrid processing could undertake much of the repetitive digital processing stages in Earth rotation aperture synthesis. It has a distinct role in interactive reduction systems where the 20 dB or so limit to dynamic range is not itself a limitation. Hybrid processing is somewhat more attractive in those situations where it can perform the major part of the reduction. That is, those geometries for which weighting, coordinate conversion and transformation can be performed in the analogue components are more relevant than those for which only the Fourier transformation is performed.

As a result, the choice of processing depends critically on the antenna geometry. I would, in fact, prefer to see the reverse occur: where the processing would influence the initial antenna design. If this had occurred I am sure that several present arrays would have been constructed slightly differently.

The basic components of hybrid systems have all been studied, often in great detail. What then is the inhibiting factor to their use? The main problems appear to me to be human. So often it appears as an 'easy option' to just buy more digital computing power and take a software solution. Hybrid systems break interdisciplinary ground and do have accuracy limitations. Few of the traditional radio astronomy centres have the people prepared to face up to the challenge and possible risk. But if careful consideration is given to the computations to be done and careful selection made of the special purpose implementation, there is a significant role to be played by faster and cheaper hybrid processing in Earth rotation aperture synthesis.

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DISCUSSION

Comment J.P. HAMAKER
I want to put on record that, following Trevor Cole's original idea, we are constructing a storage tube-based Fourier transform machine of the type he just described, for getting a quick-and-dirty look at Westerbork maps. Results on its performance are not yet available.

Comment R.H. HARTEN
Isn't the whole idea of an interactive system dependent on the response time of the user (astronomer)? This is much slower than any disk head movement or I/O access time.
Also, the implemention of the 'digital' corrections to the data is the biggest problem: every data point must be handled, and at its observed coordinates, not at the gridded ones. This does not lend itself too well to special purpose devices.
Reply T.W. COLE
I consider one to ten seconds per cycle as matching the user response time and this probably matches the imaging systems under discussion. Digital correction is not as big a problem as you intimate when the antenna geometry is symmetric. Then it exactly matches special purpose devices.