A SIMPLE IMAGE FORMING TECHNIQUE SUITABLE FOR MULTIFREQUENCY OBSERVATIONS OF SOLAR RADIO BURSTS

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Abstract. A simple image forming system using a multielement interferometer for obtaining rapid pictures of solar radio bursts is described. A dispersive transmission line is used to feed the elements in series through directional couplers. Truly instantaneous pictures of solar activity can be obtained by placing a number of narrow frequency filters at the end of the I. F. amplifier in the main receiver, located at one end of the array.

The two dimensional extension of this principle is examined in some detail. Multibeaming in the two arrays of a crossed grating interferometer can be combined with fast phase-scanning in one of the arrays to produce rapid pencil beam pictures. If log-periodic antennas are used, observations can even be made at widely different frequencies simultaneously. For illustration, some important parameters for simultaneous observations at 60, 90 and 120 MHz are estimated for an interferometer assumed to be located at a latitude of 30° N. The main advantage of the proposed system is that high-resolution rapid pictures of radio bursts can be obtained simultaneously at a number of frequencies with modest effort.

1. Introduction

High-resolution fast-speed observations of radiobursts are of great importance in our understanding of the variety and complexity of solar phenomena, specially at meter wavelengths. This has been well demonstrated by observations with the Culgoora radioheliograph (Wild, 1967; Wild *et al.*, 1968; Wild, 1968) at a frequency of 80 MHz. We describe below in Section 3, a simple image forming technique by which two dimensional almost-instant pictures of burst activity can be realised at a number of frequencies simultaneously using a crossed-grating interferometer. The new method of image formation is based on the simple principle of frequency dispersion of a transmission line feeding in series the antennas of a multielement interferometer. A multielement interferometer working at a frequency of 610 MHz and incorporating a dispersive transmission line has been successfully operated at Kalyan near Bombay (Swarup *et al.*, 1966; Kapahi and Isloor, 1968). This array is first briefly described in Section 2. The new method of image formation is compared in Section 4 with the existing or proposed systems.

2. The 610 MHz Multi-element Interferometer at Kalyan

Thirty-two equatorially mounted parabolic dishes of diameter 1.7 m each are used to set up two independent arrays, one along the east-west direction and the other along the north south direction. A schematic of the two interferometers is shown in Figure 1.

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The east-west array (Figure 2) consists of 24 dishes spaced uniformly along a 631 m base line. This gives rise to fanbeams with half power beam width and separation of 2.3 and 61.4 min of arc respectively.

The north-south array employs 8 dishes spaced uniformly along a 256 m base line.

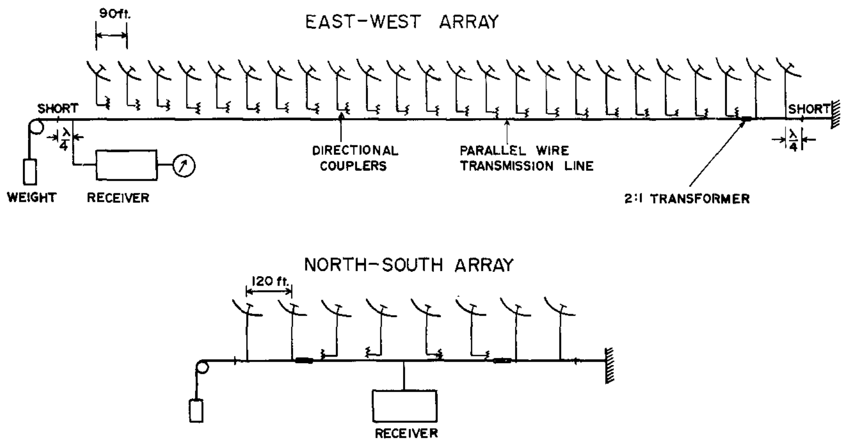

Fig. 1. Schematic of the feeder system for the east-west and north-south arrays at Kalyan.

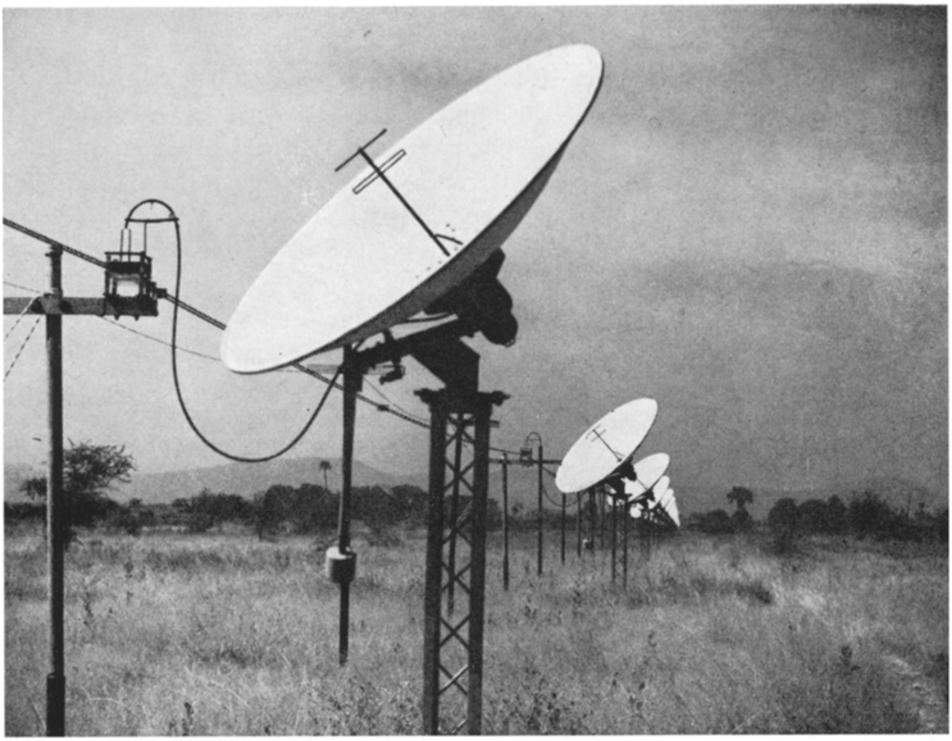

Fig. 2. East-west array of 24 dishes of 1.7 m diameter at Kalyan.

The half power width and separation of fan beams for this arrangement are 5.2 and 45.8 min of arc respectively.

A novel feature of the arrays is the series feeder system shown in Figure 1. A single parallel wire transmission line is used to connect the 24 dishes of the east-west interferometer to a Dicke-switched receiver at the east end. The dishes are coupled to the transmission line through quarter wave directional couplers (Oliver, 1954) and the couplings suitably graded along the array in order to feed the dishes uniformly. If α is the loss factor of the transmission line between adjacent elements, the required power coupling at the nth element, K_n ($n=1$ corresponding to the element farthest from the receiver) is given by $K_n=(\beta-1)/(\beta-1)$; where $\beta=1/(1-\alpha)$. Each directional coupler is supported on a pair of teflon insulators mounted on wooden poles so as to be fixed with respect to ground. As the copper conductors (of diameter 7.6imm) of the parallel wire line expand or contract due to variations in ambient temperature, they can slide through the teflon insulators. The heavy weight at one end keeps the length of transmission line between adjacent elements constant. The phases along the array have been checked and adjusted by the modulated reflection method of Swarup and Yang (1961). The feeder system has been observed to be phase-stable over fairly long periods.

Apart from its simplicity and much lower cost as compared to the conventional branching arrangement of transmission lines, this highly dispersive system of a single transmission line can be used with advantage to realize instantaneous pictures. A number of fan beams displaced with respect to each other are obtained by making observations at slightly different frequencies. At the different frequency, the phase gradient along the array is no longer the same. In the small angle approximation, this shifts the direction of beam maxima by an amount proportional to the difference between the two frequencies. To get instantaneous radio picture of the sun one could place a number of frequency-filters at the end of the I. F. amplifier of the main receiver in Figure 1. The detected outputs from the filters can be suitably displayed, say on an intensity modulated oscilloscope (Wild, 1967) or a solid state device (Vinokur, 1968) to record the pictures.

A possible two dimensional extension of this multiple beaming principle which appears to be quite simple for making high resolution instant observations of solar bursts at meter wavelengths will now be described.

3. Proposed Two-Dimensional Array for High Speed Observations of Radio Bursts

Figure 3 shows a schematic of two linear arrays of N elements each in the east-west and north-south directions. The elements of each array are coupled to a parallel wire transmission line through quarter wave directional couplers. The two arrays are combined through a phase switch to operate as a crossed grating interferometer. The system is essentially similar to the conventional crossed grating interferometers (Christiansen *et al.*, 1961; Bracewell and Swarup, 1961) except for the dispersive transmission lines instead of the branching system. If now the reception band is sub-divided into a number of uniformly spaced frequency bands or channels, each array of the cross will give rise to a set of multiple fan-beams, which are angularly displaced in the sky with respect to each other for different channels. When the two arrays are correlated or phase-switched as in a Mills-cross, the directivity pattern of the system would consist of a number of closely spaced pencil beams at the intersection points of the series of fan beams of the two arrays. The set of pencil beams corresponding to the different frequency channels would lie along diagonals as shown

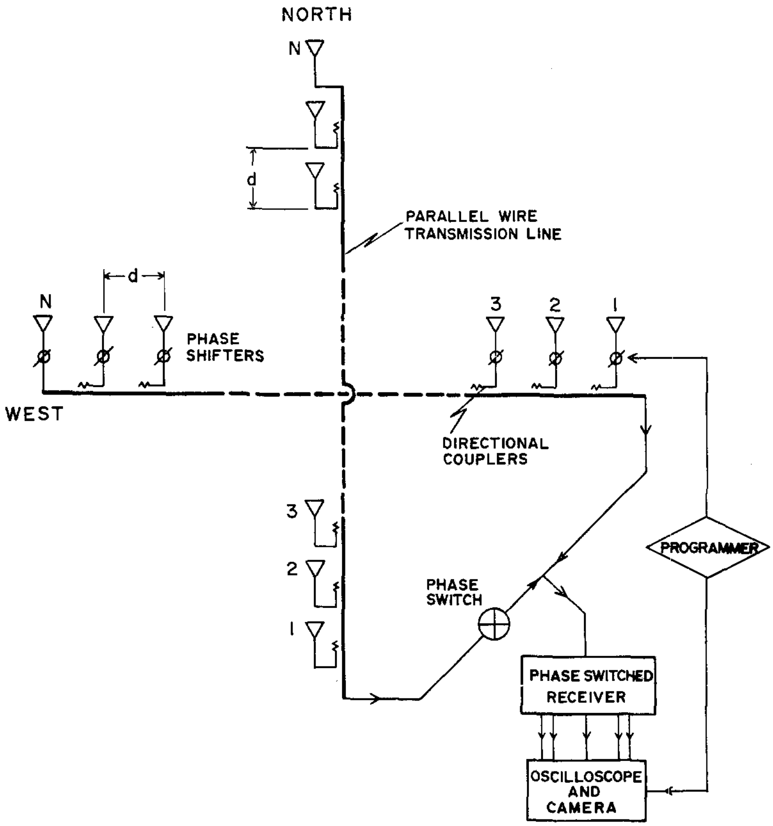

Fig. 3. Schematic of proposed crossed-grating interferometer with the dispersive feeder system.

in Figure 4. By introducing appropriate phase shifts in each antenna, say of the east-west array, in a step wise manner, the set of pencil beams lying along the diagonal can be made to scan the sun as shown in Figure 4, to obtain a complete two dimensional picture. With fast-switching phase-shifters the speed at which one picture can be completed should depend only on the desired signal to noise ratio. Although the complete picture is synthesized from information obtained at slightly different frequencies, the distortion would be small as the total bandwidth required (about 2.75 MHz for a meter-wavelength array, as shown later) is smaller than the instantaneous bandwidth of solar radio bursts.

If log-periodic antennas are used as the individual elements of the two arrays and the directional couplers are made sufficiently wide band, two dimensional pictures of solar activity can be obtained simultaneously at several widely different frequencies. For illustration some important parameters for simultaneous observations at 60, 90 and 120 MHz are estimated below. From considerations of the resolution desirable and the size of the radio sun at meter wavelengths we suggest that there be 40 elements in each array with a uniform spacing of 100 m giving total base lines of 3.9 km. For

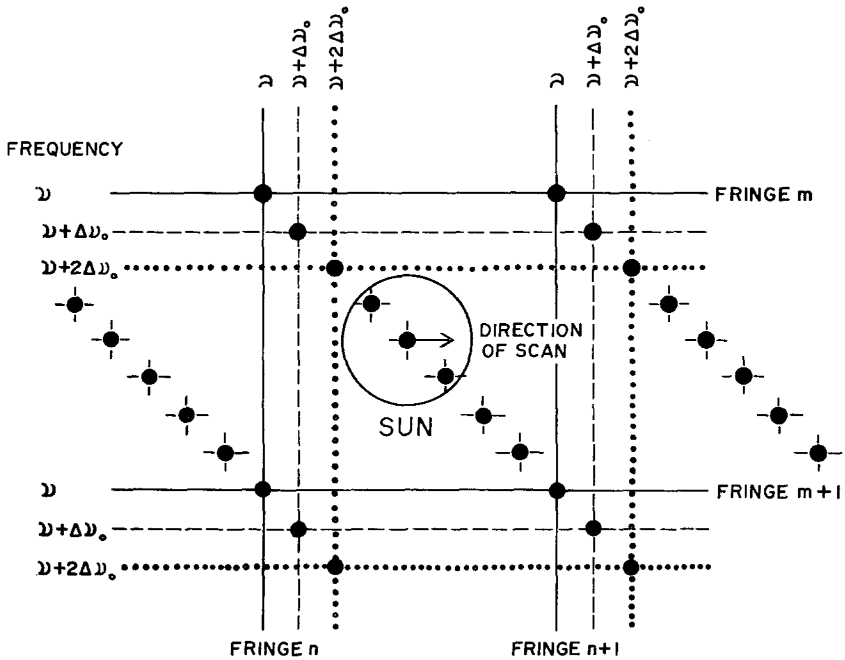

Fig. 4. Illustrative arrangement of 'dispersive' and 'main' beams for making rapid pencil beam scans of solar activity.

a non-tapered illumination of the arrays, one would have near the zenith a resolution of 5.2, 3.4 and 2.6 min of arc and a beam separation (picture field) of 2°86, 1°91 and 1°43, at 60, 90 and 120 MHz respectively. In case the arrays are tapered to suppress negative lobes, the value of beam widths will be wider to that given above by a factor of about 1.3. Each element of the arrays can be single or a group of log-periodic antennas with *H*-plane kept in the east-west direction to provide a sufficiently wide beam width so that no steering is required for observations of ± 2 hours around the meredian.

A. FREQUENCY DIFFERENCE BETWEEN ADJACENT 'DISPERSIVE BEAMS'

If it is proposed to scan the sun in an east-west direction it is necessary to choose the separation of the channels so that the north-south separation of adjacent pencil beams be less than or equal to the peculiar interval. Assuming that the receiver is connected at the south end of the north-south array as shown in Figure 3, the shift in declination of a beam $\Delta\varepsilon$ on the meredian plane, due to a shift in the reception frequency $\Delta\nu$, can be expressed as (Appendix 1).

$$\Delta\delta = \left\{\frac{1 + \sin(\Lambda - \delta)}{\cos(\Lambda - \delta)}\right\}\frac{\Delta\nu}{\nu} \tag{1}$$

where ν is the frequency and Λ is the latitude at which the array is located. It can be seen from Equation (1) that the shift in declination $\Delta\delta$ for a given change in frequency $\Delta\nu$ increases as one goes to more negative declinations, because the signal path-length difference to the receiver from adjacent elements of the north-south array increases with lower declinations. Therefore, the frequency increment $\Delta\nu_0$ between adjacent filters, in order that the adjacent dispersive beams are located *less than or equal to* the peculiar interval apart at all declinations between $+23.^\circ5$ and $-23.^\circ5$, is determined by the peculiar interval at $\delta = -23.^\circ5$. The peculiar interval for a cross with uniformly illuminated elements is given by $\lambda/Nd\cos(\Lambda - \delta)$. Assuming a value of $\Lambda = +30°$ it can be estimated from (1) that the desired separation of frequency channels for parameters suggested in the last section, is

$$\Delta\nu_0 = 42\ \text{kHz}.$$

This value of $\Delta\nu_0$ is independent of the frequency of operation ν.

B. NUMBER OF DISPERSIVE BEAMS

At a given δ, the minimum number of dispersive beams required is given by $\Delta\theta/\Delta\delta_0$, where $\Delta\theta$ is the separation between adjacent 'main beams' or fringes of order n and $(n+1)$ at frequency ν, and $\Delta\delta_0$ the separation between adjacent 'dispersive beams' of same order n but at frequencies of ν and $\nu + \Delta\nu_0$. In order that the dispersive beams cover an angular distance equal to or more than the separation between adjacent main beams at all declinations, the minimum number of required dispersive beams, K, should be determined by $\Delta\theta$ at $\delta = +23.^\circ5$, since $\Delta\delta$ increases faster than $\Delta\theta$ with decreasing declination. At smaller δ, these dispersive beams would cover more than the separation between main beams; the redundant ones may be rejected in the display if necessary. It is estimated that 64 dispersive beams are necessary if $\Lambda = +30°$ requiring 64 filters at each of the three main frequencies (60, 90 and 120 MHz). The centre frequencies of the 64 filters should be separated from the main frequencies in steps of 42 kHz. A total bandwidth of about 2.75 MHz would therefore be required at the I.F. amplifiers.

C. BANDWIDTH OF EACH FILTER

A disadvantage of the dispersive system as compared to the branching system is that the correlation of signals for the maximum path lengths from the farthest antennas sets a stringent limit to the maximum band width possible. For the maximum path difference of ~ 6 km at $H = 30°$, the maximum bandwidth for each filter in the present case is limited to about 12 kHz for a 90% correlation between signals from the farthest antennas. This narrow bandwidth should however provide sufficient sensitivity for observation of bursts.

D. PHASE SHIFTERS

The phase shift required in the signal from each antenna increases linearly along the length of the array. If an extra path length of Δp is introduced between adjacent antennas from east to west, the shift in hour angle of the beams can be expressed to a first approximation by (Appendix 2)

$$\Delta H = \sec H \sec \delta (\Delta p / d) . \tag{2}$$

For a given path length gradient Δp, the change in hour angle ΔH, is maximum at $\delta = \pm 23\overset{\circ}{.}5$ and $H = \pm 30^\circ$ and is independent of the frequency ν. In order to shift the hour angle by an amount equal to or less than the peculiar interval at all hour angles and declinations and at the three main frequencies, the incremental path length gradient, Δp_0 is determined by the peculiar interval at the highest frequency viz. 120 MHz. The number of phase steps necessary in order to cover the gap between the main beams is determined by the main beam spacing at $H=0$ for the lowest frequency viz. 60 MHz. It can be estimated that

$$\Delta p_0 = 0.0577 \text{ m}$$

and the number of phase steps is 87. For a picture per second with 87 phase steps, a time constant of about 0.01 sec is required. It is easy to do the phase shifting at this speed by means of switching diodes or transistors. It is preferable to put the phase-shifters between log-periodics and directional couplers and to do the switching in binary steps.

4. Comparison with Other Systems

The one-dimensional form of the dispersive array described here provides truly instantaneous fan-beam pictures similar to the multi-beam system of Vinokur (1968) or the image-forming technique described by Komesaroff and Ponsonby (1967). One can also obtain almost instantaneous pictures using a fast phase-scanning technique, such as that of Takakura *et al.* (1967). For a complete picture every one second with k picture points between adjacent main beams (k is given by beam separation divided by peculiar interval), the sensitivity of a phase-scanning array is $\leqslant 1/\sqrt{k}$ times that of multi-beam or Komesaroff and Ponsonby type array, since the time constant τ of the receiver has to be $\leqslant 1/k$. For the one-dimensional dispersive array the time constant is the same as the speed at which a picture is made, but the bandwidth is narrower as pointed out earlier. Thus the sensitivity of the dispersive array is also reduced by a factor of about $1/\sqrt{k}$ to that of a multi-beam system, as the bandwidth of the latter would be restricted to less than 1 or 2 MHz in most practical cases.

For getting instantaneous two-dimensional radio pictures, only 3 possibilities have been suggested; (a) two-dimensional multi-beam array; (b) Komesaroff and Ponsonby technique and (c) McLean and Wild (1961) technique. No such instantaneous image-forming arrays have however been built because of considerable practical difficulties. The only instrument built for taking rapid radio pictures of the sun is the Culgoora Radio-heliograph which combines multi-beaming and phase-scanning techniques. The sensitivity of this instrument is $1/\sqrt{k}$ of that possible if two-dimensional multi-beaming was used. In the dispersive array proposed here, multiple pencil beams produced along a line are phase-scanned in the perpendicular direction to record rapid pictures. Because of the restricted bandwidth and time constant, the sensitivity of the system is of the order of $1/k$ of that of a full multi-beam system. This reduction in sensitivity is the principal disadvantage of the dispersive array. The proposed array has to be in the form of a Mills cross or a tee. The Culgoora instrument uses a circular array which has the advantage that spurious sidelobes are more randomly distributed compared to a cross or a tee-array in which case they are distributed along rectangular grids in the sky. Crossed arrays with low side lobes have however been built. The number of elements for the same resolution and grating responses are similar, being $4/\pi$ and $3/\pi$ respectively for cross and tee-arrays to that of circular array.

5. Conclusion

A powerful technique of obtaining rapid pictures of solar burst activity has been described. For the suggested crossed-grating of 40 log-periodic elements in each array joined by a parallel wire transmission line of loss about 5 db/km similar to that used in the Culgoora instrument (Labrum and McAlister, 1967), the sensitivity for a signal to noise ratio of 5:1 is about 2×10^{-21} Wm^{-2} Hz^{-1} for the required bandwidth of 12 kHz and $\tau=0.01$ sec. This sensitivity is sufficient for studying solar bursts of medium or strong intensity. The transmission line could be made to run cross-country at heights of say 15 ft. It can be shown that the phase length of the line remains almost independent of temperature if the wires are clamped to insulators at each pole. The sensitivity of the array can be improved by using higher gain elements and/or by introducing preamplifiers at each element; but this would add to complexity. The main advantage of the proposed instrument is that high resolution pictures can be obtained at a number of frequencies with modest effort.

Appendix 1

A. NORTH-SOUTH ARRAY; RECEIVER AT SOUTH END

It is assumed that ϕ, the angle between a direction in the sky and a plane normal to the array axis, is measured towards north (Figure 5), and the length of transmission line between adjacent antennas in the same as the distance between them, equal to d. The angular direction of fringes is given by

$$\sin\varphi = \sin\delta\cos\Lambda - \cos\delta\sin\Lambda\cos H = 1 - \frac{m\lambda}{d}, \tag{A1}$$

where m is an integer and the fringe $m=0$ corresponds to the north horizon. Differentiating equation (A1) with respect to frequency, and substituting for $m\lambda/d$ from Equation (A1), one obtains

$$\frac{d\delta}{d\nu} = \frac{1}{\nu}\left[\frac{1 + \cos\delta \sin\Lambda \cos H - \sin\delta \cos\Lambda}{\cos\Lambda \cos\delta + \sin\Lambda \cos H \sin\delta}\right]. \tag{A2}$$

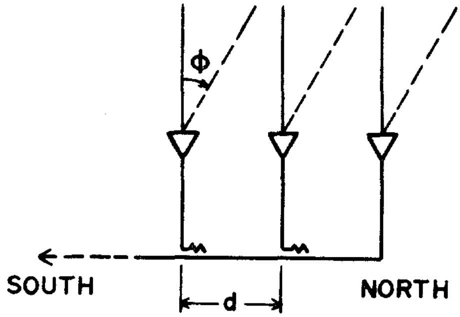

Fig. 5. North-South array.

On the meredian plane ($H=0$), the shift in declination $\Delta\delta$ of a fringe, due to a shift in frequency $\Delta\nu$ can therefore be written as

$$\Delta\delta = \left[\frac{1 + \sin(\Lambda - \delta)}{\cos(\Lambda - \delta)}\right]\frac{\Delta\nu}{\nu}. \tag{A3}$$

Appendix 2

A. EAST-WEST ARRAY; RECEIVER AT EAST END

If p is the extra path length introduced between adjacent antennas from east to west (Figure 6), the angular direction of fringes is given by

$$\sin\theta = \sin H \cos\delta = 1 + \frac{p}{d} - \frac{n\lambda}{d} \tag{A4}$$

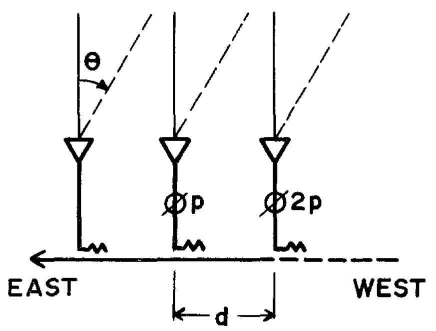

Fig. 6. East-West array.

where n is an integer and the fringe $n=0$ corresponds to the west horizon. Differentiating Equation (A4) with respect to ν and assuming $\partial\delta/\partial\nu=0$, to a first approximation one can write the shift in hour angle ΔH of a fringe as

$$\Delta H = \sec H \{(1 + p/d) \sec\delta - \sin H\} \frac{\Delta\nu}{\nu} \tag{A5}$$

similarly, differentiating Equation (A4) with respect to p,

$$\Delta H = \sec\delta \sec H \left(\frac{\Delta p}{d}\right). \tag{A6}$$

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