A PROJECT OF MULTIPLE-ELEMENT SWEPT-LOBE INTERFEROMETER FOR THE STUDY OF SOLAR RADIO BURSTS*

Haruo TANAKA

Abstract

A project is proposed of a swept-lobe interferometer to observe a rapidly changing burst at microwave frequency region. The brightness distribution as well as the distribution of circularly polarized components can be observed. A frequency of 5 Gc/s and a bandwidth of 3 Mc/s are recommended. A 2.4-m-dish 32-element interferometer is considered to be suitable for the quick scanning. Additional 2 elements to compose a compound phase-switch interferometer will be useful for the high-resolution study of S-component. A heliographic scanning at a moderate speed is possible by adding 16 N-S elements. The scanning frequency is limited by S/N ratio, and the maximum one is once per 2 seconds for a fan-beam scan, and once per 3 minutes for a heliographic scan.

1. Introduction

The observation of active regions on the sun with the technique of multiple-element interferometer has been made extensively during the last solar cycle, but only a few observations of radio bursts have been made with the same technique. (1) (3) (5) However, the necessity of the precise observation of radio bursts has been increased with the rapid advance of space science. A motion-picture helioraph at a meter wavelength, which is being constructed by the Australian group, (4) is indeed the first step toward this requirement. But the precise observation of the burst on a microwave frequency region would have the same importance to study the complicated solar phenomena. The above 'precise observation' means the observations of position, movement and shape of the source of the burst and, what is more important, the observation of polarized components which is closely related to the magnetic field.

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These observations will supply us with fruitful materials for our better understanding of the mechanism of radio emission extended on a wide frequency range as well as the ejection mechanism of energetic particles. If this kind of interferometers were placed at 3 points on the earth for a continuous monitoring of radio spots and bursts, they will contribute much not only to the research of solar atmosphere but also to the progress of the space and earth sciences.

For these several years, we have made observations of bursts by our interferometer at 4 and 9.4 Gc/s. [2] [3] We have found already for example that the position of the source of bursts roughly coincides with that of the flares, [2] and that the source of a polarized component occasionally moves at a peculiar phase of the microwave-IV burst. [3] But an insufficient resolving power and a slow scanning speed have always prevented the precise discussions. Few information has been obtained on the M-burst or the initial phase of the large burst.

Though a couple of 2- or 3-element interferometers will be sufficient for only the position measurement of the gravitational center of the burst, a multiple-element swept-lobe interferometer is indispensable for the observation of the shape of the source or the origin of polarized components which might be the mixture of positive and negative senses. And this paper is a technical discussion on the possibility of realizing a quick scanning interferometer on a microwave frequency region.

2. Frequency

A frequency of 5 Gc/s is considered to be most suitable for the following reasons:-

(1) It is the gap of the existing or planned high-resolution interferometers. [4]-[16]

(2) A frequency band of 4990 - 5000 Mc/s is a band where radio astronomy service could be protected from harmful interference.

(3) The flux density of S-component is maximum at this frequency which is favorable to detect the active regions.

(4) It is the maximum frequency where a standard compound interferometer can be realized without difficulty.

(5) The cost of construction will rapidly increase as the frequency decreases below 5 Gc/s.

3. Arrangement of antennas

The source of a polarized component may have a size of the order of 1 minute of arc and a pair of these sources may exist a few minutes apart. Then a resolving power of about 1 minute of arc is desirable to resolve these sources.

Let us begin with a one-dimensional fan-beam interferometer. According to our experiance, it is again quite desirable to realize this resolving power by an adding-type interferometer; easy to adjust and free from negative side lobes. A 32-element interferometer with a spacing of about 86 wavelengths, which produces a series of fan beams of 1.1′ wide and 40′ apart, will meet this requirement. The length of the base line is 160 meters at 5 Gc/s. It is preferable to add a two-element interferometer of a 32-unit spacing to the east or west side of the 32-element interferometer so as to form a compound interferometer. A high-resolution drift scan with 0.35′ beam will then be possible by the addition of a small amount of cost.

If we want to make a heliographic scanning of the solar disk, the addition of 16 elements in the N-S direction to complete a T-shaped antenna may be the most economical solution. The half-power width of the beam will be then about 1.5′×1.5′ in a direction not far from the zenith.

4. Bandwidth

From the point of S/N ratio, bandwidth should be taken as wide as possible. However, the correlation between the noise signals received at 2 points of different path length from the source diminishes as the path difference becomes large. Let the difference of travelling time be t for a band width B, then the correlation becomes null at $Bt=1$.[12] For two extreme antennas of a distance D, $t=(D\sin\theta)/c$, where θ is an angle of arrival from the meridian plane and c is the light velocity. If we want to make observations of the sun for 4 hours around the local noon, the maximum value of θ is about 30°. *Then* $t_{max}=2.7\times10^{-7}$ for $D=160$m. The correlation between the two extreme signals disappears for a bandwidth of 3.75 Mc/s.

In conclusion, the bandwidth should be less than about 3 Mc/s for a 4-hour observation by the 32-element interferometer. The observing time will be limited to 2 hours for the compound interferometer of double base line. It is to be noted that an effective taper feed is realized spontaneously at a large value of θ even for a compound interferometer, which broadens the beam and reduces the unwanted side lobes.

5. The size of dishes

If the antennas follow the sun continuously, the scan curve corresponds to the source distribution multiplied by the directive pattern of each antenna. Therefore, as the beam produced by each antenna becomes sharp compared with the size of the source, the sensitivity near the solar limb falls off considerably. In the case of a drift scan, this effect can be partly avoided by stopping the antennas at the peak of the interference pattern during each scan. This 'step-drive system,[14] however, cannot be applied to the swept-lobe interferometer, so that the size of the antennas must be limited to a certain value. If we confine the weighting value at the limb to 95 %, the beam width is limited to approximately 2°. This in turn corresponds to the diameter of 2.4 meters at 5 Gc/s.

Another limitation on the size of the dish arises from a simple geometrical relation. Since the unit spacing of the antenna is 5.16 meters, the diameter of 2.4 meters is also considered to be maximum to compose the cross or *T* or the standard compound interferometer.

6. Transmission lines

According to our experiance, a single branch-line system is considered to be most desirable; simple, highly reliable and convenient for using an elaborate low-noise receiver. For the observation of circularly polarized waves, a combination of circular horn feed, quarter-wave plate and ferrite switch may be convenient. Also it is desirable to use rotary joints, magic T's and low-loss circular waveguides; the loss of the WC-10 circular waveguide will be about 0.008 db/m, about 1/6 of that of the WR-5 rectangular waveguide.

If these transmission lines are all similar to those of our 9.4-Gc/s compound interferometer at Toyokawa, as shown in Fig. 1,[14] the loss and the collecting area can be estimated without difficulty. They are shown in Table 1.

Table 1. Estimation of the transmission loss and collecting area

Number of 2.4—m dish	Loss of transmission lines in db				Collecting area in M^2		
	WR—5 and circuits	WC—10 and circuits	Pol. sw.	Total	Geo-metric	with loss	as compound
32 (EW)	2.1	1.4	0.8	4.3	144.8	53.8	28.2
2 (EW)	1.6	1.5	0.8	3.9	9.0	3.7	
16 (NS)	2.1	1.4	0.8	4.3	72.4	26.9	(as T) 75.3

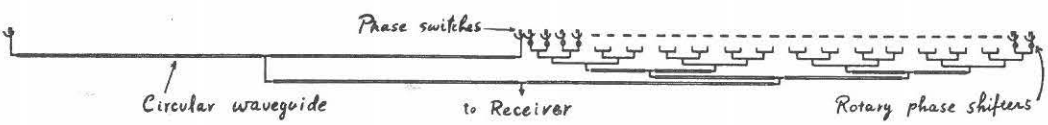


Fig.1. Arrangement of 32+2 antennas and feeders

7. The method of quick scanning

To shift the interference pattern, it is necessary to change artificially the phase of the output of each antenna in proportion to the distnce from the phase center. If the beam were single, it would be necessary to change the phase in a saw-tooth or triangular form. But in our case, an ideal saw-tooth scanning can be realized by the use of endless phase shifters, as shown in Fig. 2. because the beam returns to its initial state every time when the beam is shifted by a unit spacing. And for this purpose, a rotary phase shifter is considered to be most suitable for its simplicity, linearity, reliability and low loss. According to our experiment, it is not difficult to make the VSWR less than 1.05 for all angles of rotation.

The phase which must be shifted for 1 scan is from π to 31π for the nearest and farest signals from the center. Therefore, a scanning frequency of 1 c/s corresponds to the maximum speed of a rotary phase shifter of 465 rpm, which can be realized without difficulty.

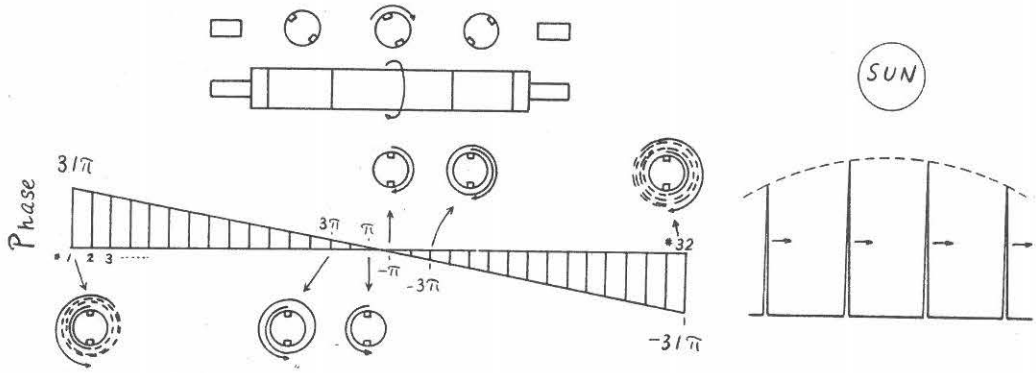


Fig. 2. Left : Rotary phase shifters and their arrangement. The spirals show how the rotor rotates in proportion to the distance from the phase center. One rotation corresponds to the phase shift of 4π.
Right : The beams flow continuosly in one direction.

8. Scanning frequency and S/N ratio

Since it is the purpose of this project to observe the burst of a short duration, the scanning frequency should be as high as possible. However, as the S/N ratio will become small in inverse proportion to the square root of the time constant, we must look for a good compromise between the two.

Now let the equivalent rms noise fluctuation σ at the output be $T_e/\sqrt{\tau B}$, where T_e is the equivalent noise temperature at the input of the receiver, τ is the time constant and B is the receiver bandwidth. T_e is roughly the sum of the receiver noise, the noise from transmission lines and the noise from the sun T_s, which varies during the course of scanning. The receiver noise of the order of 600 °K could be attained without difficulty and the noise from transmission lines is approximately 200 °K. B cannot be increased more than 3 Mc/s for the reason mentioned in Sec. 4. If τ is allowed up to 1/4 of the transit time of half-power width, $\tau=1/(160\mathrm{F})$, where F is the scanning frequency in c/s. Then,

$$\lambda = T_e/\sqrt{\tau B} = 7.3\times10^{-3}(800+T_s)\sqrt{F}.$$

The actual peak-to-peak fluctuation is roughly 5 times that of the rms value so that 5σ should be taken as N in S/N ratio. The estimated values are shown in Table 2.

Since the S/N ratio of the order of 20 is desirable, a scanning frequency of 0.5 c/s is considered to be maximum for an active region or burst of flux more than 10 units. It should be noted here that S/N ratio can not be improved more than $\sqrt{\tau B}$ /5, because T_s largely controls the noise level at a large value of T_s.

For a compound interferometer, τ should be reduced to 1/3. The S/N ratio can be calculated in a similar way, which is shown in Table 3. From this Table, it may be seen that the scanning speed must be reduced down to once per 15 seconds to get

Table 2. The relation between scanning frequency and S/N ratio (32 elements)

		Amplitude or height of peak in °K	T_s in °K	σ in °K	S/N
Quiet sun (center)		560	560	$9.9\sqrt{F}$	$11.3/\sqrt{F}$
Point source of flux dens.	1 unit*	125	685	$10.8\sqrt{F}$	$2.3/\sqrt{F}$
	10 units	1,250	1,810	$19.1\sqrt{F}$	$13.1/\sqrt{F}$
	100 units	12,500	13,060	$101.2\sqrt{F}$	$24.6/\sqrt{F}$

* 1 unit $=10^{-22}\mathrm{WM}^{-2}\ (\mathrm{c/s})^{-1}$

Table 3. The relation between scanning frequency and S/N ratio (compound)

		Amplitude or height of peak in °K	T_s in °K	σ in °K	S/N
Quiet sun (center)		93	520	$16.7\sqrt{F}$	$1.1/\sqrt{F}$
Point source of flux dens.	1 unit	65	590	$17.6\sqrt{F}$	$0.7/\sqrt{F}$
	10 units	650	1,190	$25.2\sqrt{F}$	$5.2/\sqrt{F}$
	100 units	6,500	7,200	$101.2\sqrt{F}$	$12.8/\sqrt{F}$

a satisfactory value of S/N ratio.

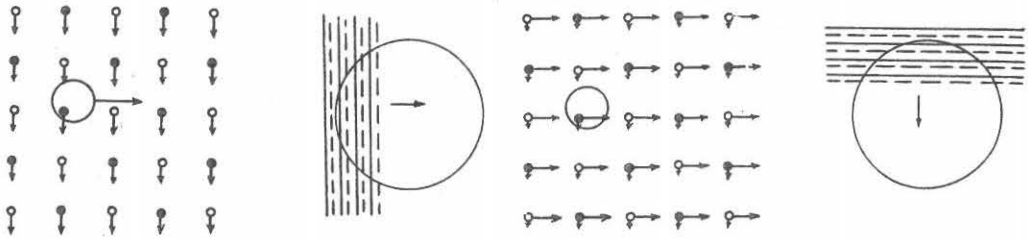
9. T-shaped antenna

When 16 dishes are added in the N-S direction, a heliographic scanning can be made by a pencil beam of about 1.5 minutes of arc. This time again, let us examine the relation between the scanning frequency and S/N ratio. The result of estimation is shown in Table 4.

If we choose the same scanning frequency as in the case of a fan-beam scan, i. e. F=0.5, We can expect a good S/N ratio for an active region or burst with a flux density of more than 10 units, though the quiet sun can just be recognized above the noise level.

At this speed, a heliographic scanning can be made simply by flowing the beam continuously in the N-S direction in the same way as described in Sec. 7. As shown in Fig. 3(a), the E-W scanning is automatically made by the drift of the sun every 0.5 minutes of arc, which interval is just sufficient for the beam-width of 1.5 minutes of arc.

Alternatively, if we flow the beam quickly in EW direction and slowly in NS



(a) Flow the beam quickly in NS, and the sun drifts in EW directions, then the sun is scannd vertically.

(b) Flow the beam quickly in EW, and slowly in NS directions, then the sun is scanned horizontally.

Fig. 3. How the sun is continuously sanned (a) vertically or (b) horizontally

Table 4. The relation between scanning frequency and S/N ratio (T-shaped)

		Amplitude or height of peak in °K	T_s in °K	σ in °K	S/N
Quiet sun (center)		54	560	$8.6\sqrt{F}$	$1.3/\sqrt{F}$
Point source of flux dens.	1 unit	175	650	$9.2\sqrt{F}$	$3.8/\sqrt{F}$
	10 units	1,750	1,500	$14.5\sqrt{F}$	$24/\sqrt{F}$
	100 units	17,500	9,960	$68.0\sqrt{F}$	$51/\sqrt{F}$

direction, then the sun is scanned in a conventional way as shown in Fig. 3(b) at any desired speed.

However it is clear that the maximum picture-speed of one per 3 minutes is far from our requirement of observing a rapidly changing burst. For this purpose, quick scannings in the E-W and N-S directions should be conducted separately if it is allowed to prepare an additional receiver. In this case, however, a cross-shaped antenna may be preferable to T from the standpoint of resolving power and sensitivity.

10. Conclusion

(1) A frequency of 5 Gc/s and a bandwidth of 3 Mc/s is desirable.
(2) Quick scanning in the E-W direction at a rate of once per 2 seconds by a 1.1′-beam 32-element interferometer is possible with a reasonable sensitivity and with the ability of observing circularly polarized components.
(3) By adding an N-S 16-element interferometer, a heliographic scanning of once per 3 minutes is possible. It can be used for the observation of a gradually changing burst. For the observation of active regions, the scanning speed should be much slower from the standpoint of sensitivity.
(4) Quick scanning in two dimensions of a rapidly varying burst should be made by using the E-W and N-S elements separately with an additional receiver.
(5) For a high-resolution study of S-component, it is desirable to add 2 elements to compose a compound interferometer.

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