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EARTH-ROTATION SYNTHESIS OF THE RADIO SUN BY THE λ 8-CM RADIOHELIOGRAPH AT TOYOKAWA

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Abstract

Rotational synthesis method is proposed to make a two-dimensional map from one-dimensional fan beam scans by the λ 8-cm Radioheliograph at Toyokawa observatory. A preliminary map was synthesized using back projection method combined with CLEAN technique. S-components were successfully mapped but the quiet sun were not able to be restored by CLEAN technique. Some problems associated with rotational synthesis by a fan beam scanning instrument of the Sun are discussed.

1. Introduction

Two-dimensional distributions of the radio Sun were mapped by Cambridge group and by C.S.I.R.O. group using radio interferometers in early days. Both are based on Fourier synthesis technique and they mapped the quiet sun. Cambridge group(e.g. O'Brien, 1953) used a pair of interferometer. They changed the baseline length and orientation day by day by moving one of the areals and sampled necessary Fourier components. C.S.I.R.O. group (Christiansen and Warburton, 1954) used two one-dimensional grating interferometers: one is a east-west array and the other is a north-south array. It took several months to sample necessary Fourier components for both of them. For a study of slowly varying components (S-components), much faster mapping technique is necessary. Pencil beam forming technique was invented and applied at Fleurs, Stanford and Toyokawa observatories. Rotary phase shifters had been used to scan the pencil beam at Toyokawa observatory and they were replaced by digital phase shifters recently (Torii, 1983). Two microwave interferometers are in operation for solar observation at Toyokawa. One is at 3 cm wavelength and the other is at 8 cm wavelength. Both are similar systems and only the 8-cm interferometer (called λ 8-cm Radioheliograph) is mentioned here.

The λ 8-cm Radioheliograph is a T-shaped array and operates in various modes. In one-dimensional mode, the E-W resolution is 0.5 arc min. and the N-S resolution is 1 X SEC(Z) arc min. at local noon where Z is a zenith distance. In two-dimensional mode, the resolution is 2 X 2 SEC(Z) arc min.^{2} In the following, rotational synthesis technique is proposed to get higher resolution for two-dimensional observation and a preliminary result is presented.

2. Instrumentation and observation

The array configuration of the λ 8-cm Radioheliograph is shown in Figure 1. Detailed hardware configuration is in Ishiguro et al. (1975), Nishio (1980), and Nishio et al. (1984). This interferometer operates in various modes: grationg compound modes using 32 dishes in E-W and 16 dishes in N-S, grating compound modes using 2+32 dishes in E-W and 2+16 dishes in N-S, and two-dimensional pencil beam mode using 32 dishes(E-W) + 16 dishes(N-S). The spatial resolution of the one-dimensional mode is determined by the longest baseline which is 400 m in E-W grating compound mode and 200 m in N-S grating compound mode. The spatial resolution in two-dimensional mode is determined by the baseline length from the phase center of the array (the cross point of the two arms) to the end of the grating array (100 m).

Routine observation of the Sun has been carried out in grating mode in E-W and N-S, grating compound mode in E-W, and pencil beam mode. As the available backend receivers are only three, they are used by several mode on time sharing basis. Observing time is ± 2 hours from the local noon.

For the synthesis of the radio Sun by earth-rotation synthesis technique, we use one-dimensional E-W and N-S scans. E-W scans are done as the Sun drifts across the grating beams by its diurnal motion. In N-S direction, the Sun is swept by the grating beams which are controlled by the digital phase shifters. The data of the grating mode and also the grating compound mode can be used for the synthesis. In this paper we present the data taken by the grating mode, because the stability of the grating mode operation is better. For a higher resolution mapping, data of grating compound mode is necessary. This will be done in near future. Observing time is limited to ± 2 hours from the local noon by the driving system of the antennas. To extend the observing time, it is necessary to change the driving system which was carried out recently (Kobayashi and Yoshimi, 1984). Longer observing time is necessary for a better mapping. Here we use only 4 hour data and extend to 6 hours in near future.

About 80 scans by E-W and N-S arms are shown in Figure 2. Total power of each scan is normalized using the independent total power observation at the same wavelength. In case of radio burst and noise, corresponding scans are deleted by inspecting the data which are displayed on a graphic terminal.

3. Principles of earth-rotation synthesis

The baselines of the E-W and N-S arms rotate as the earth rotates. The projected baseline vectors of the arms to the direction of the

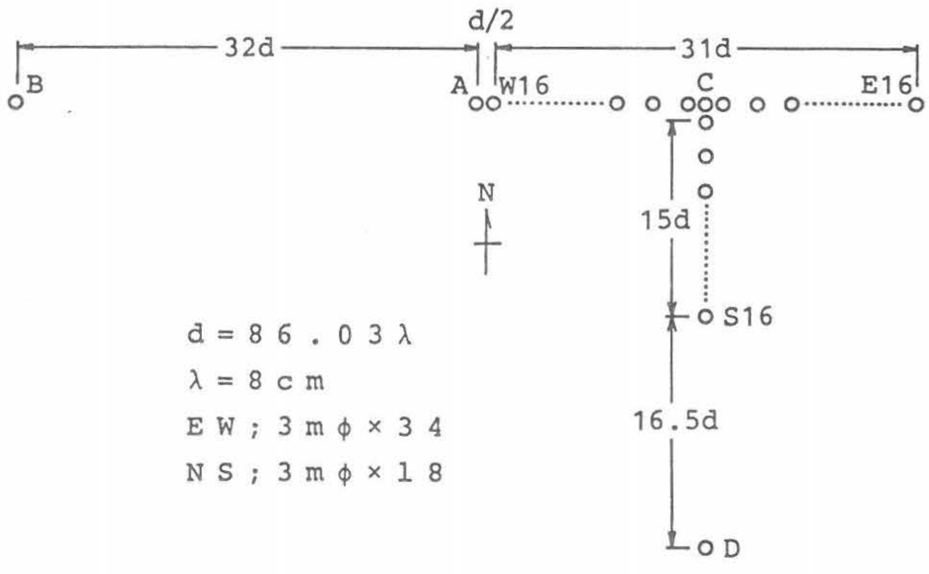
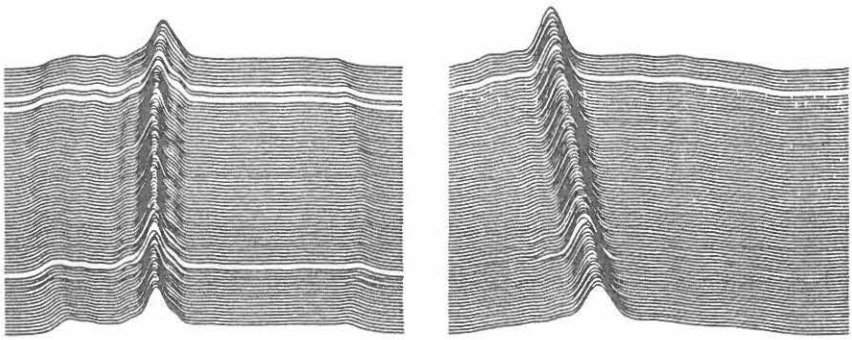
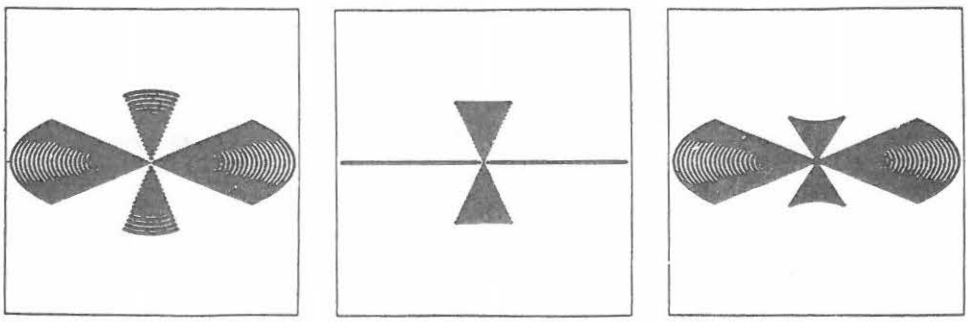


Fig. 1. Array configuration of the λ 8 cm Radioheliograph



(a) (b)

Fig. 2. One-dimensional fan beam scans by the E-W arm (a) and by the N-S arm (b) of the λ 8 cm Radioheliograph with grating mode. Observing time is 4 hours and the time runs from bottom to top. East is to the left in (a) and south is to the left in (b). Bad scans are deleted.



(a) (b) (c)

Fig. 3. Projected baselines in U-V plane during 6 hour observation on the summer solstice (a), on the vernal and autumnal equinox day (b), and on the winter solstice (c). East is to the left and north is to the top.

solar disk center are calculated in the following way: for the E-W array,

$$U = L\cos(H),$$

$$V = L\sin(H)\sin(\delta),$$

and for the N-S array,

$$U = -L\sin(\gamma)\sin(H),$$

$$V = L(\cos(\gamma)\cos(\delta)+\sin(\gamma)\sin(\delta)\cos(H)),$$

where, U : E-W component of the projected baseline length in wavelength unit,

V : N-S component of the projected baseline length in wavelength unit,

L : baseline length of the interferometer in wavelength unit,

H : hour angle of the solar disk center,

δ : declination of the solar disk center,

γ : geographic latitude of the interferometer.

Figure 3 shows the coverage of the projected baselines in U-V planes in case of 6 hour observations on the summer solstice, on the vernal and autumnal equinox, and on the winter solistice using grating mode of E-W and N-S arms. Radial gaps are due to the lack of observing time. This makes the beam dirty. If the 12 hour observation can be done, E-W arm covers the whole position angle. Small coverage of the position angle by the E-W arm is partly supplemented by the N-S arm.

There are several methods to make a two-dimensional map from one-dimensional scans at various position angles. They are Fourier synthesis method, back projection method and so on. Two-dimensional image reconstruction from one-dimensional fan beam scans are reviewed by Bracewell (1979). To use Fourier synthesis method, first we do one-dimensional Fourier transform of each scans and put the complex Fourier components on the U-V plane along the projected baseline; and then we do the two-dimensional inverse Fourier transform of the U-V plane to get a map. It is necessary to grid the U-V plane when we use Fast Fourier Transform to save computation time of two-dimensional inverse Fourier transform. Gridding causes several effects on the final map and also it takes time. It is possible to bypass the gridding process.

Back projection method is one of the ways to make two-dimensional map without gridding. Each pixel value of one-dimensional scans is distributed evenly along the direction vertical to the projected baseline direction. The two-dimensional map completes when all the scans are added. If we use one-dimensional beam patterns instead of solar scans, we can get a synthesized beam. Principles of back projection method can easily be understood by principles of Fourier synthesis method. The difference is a weighting function in a U-V plane. There are also many modifications of this method. Wide coverage of position angle produces a better beam and a map. A dirty map due to a lack of position angle coverage can be restored by CLEAN technique (Högbom, 1974). In the present paper we use back projectin method combined with CLEAN technique because they are simple.

4. Problems associated with rotational synthesis

There are some problems to be solved to synthesize two-dimensinal map from one-dimensional scans using the λ 8-cm Radioheliograph. Phase stability of the total system is good enough for 4 hour observation and longer (Nishio et al., 1984). But the absolute position of an observed distribution cannot be determined because we use the redundancy of the antenna array for the phase calibration. There are 31 combinations of the shortest baseline length in E-W array. They are redundant and should produce the same phase and amplitude when observing the Sun. Differences are due to the phase and gain errors of each antenna. We can calibrate phase and gain of each antenna using this principle. But an absolute position of the Sun is lost in this method. We need an absolute position of the observed one-dimensional scans to use rotational synthesis. If the quiet sun is symmetrical and does not change we can determine the positional offset value by fitting a simple model of the quiet sun to the observed scans. But the quiet sun at 8 cm wavelength is not symmetrical and it is disturbed by such as coronal holes and limb brightening. We used the following principle to find the positional offset of one-dimensional scans. When we use scans which have distinct peaks of S-components with some positional offset, the positions of the peaks do not meet within a certain area rather make a circle around a real position as the position angle of the baseline rotates. In another word, the power does not concentrate to a certain area if there is a positional offset. So we calculated the peak values in the synthesized map by shifting the one-dimensional scans and searched the shift value which gives the highest peak value. This value have to be calculated independently using E-W arm and N-S arm. Motion of the S-component on the solar disk influences the result. So the motion of the S-component due to differential rotation of the Sun is subtracted before applying the above principle. Rough position of the corresponding active region on the solar disk is enough to calculate the motion of the S-component. If the source is near the solar limb, no correction is necessary. The obained positional offset value can be used for several months and longer if the system is stable.

5. Data on August 12, 1983

In this section, the actual data is presented which was obtained on August 12, 1983 and also the preliminary map is presented using the above mentioned method. One-dimensional scans by E-W and N-S arms are shown in Figure 2. The positional offsets are already removed and bad scans are deleted. The projected baselines are shown in Figure 4. Large gap in position angle coverage is due to the short observing time (4 hours). Before synthesizing the map, we applied inverse filter for each one-dimensional scans to make a flat weight in spatial frequency domain. The reason is that the higher spatial frequency components obtained by the grating interferometer are heavily tapered and this reduces the spatial resolution. The synthesized map and the beam pattern are in Figure 5. Both are heavily distorted by the small coverage of position angle. CLEAN technique is applied to restore the map. Figure 6 is a restored map with gaussian beam with the same half power beam width (HPBW) as the original beam. In the cleaning process,

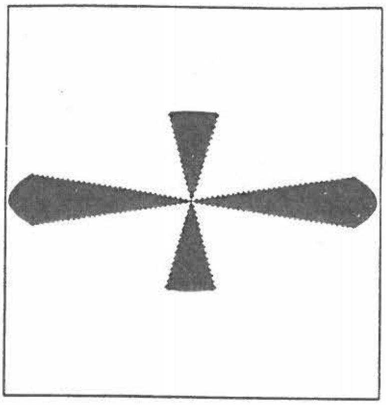
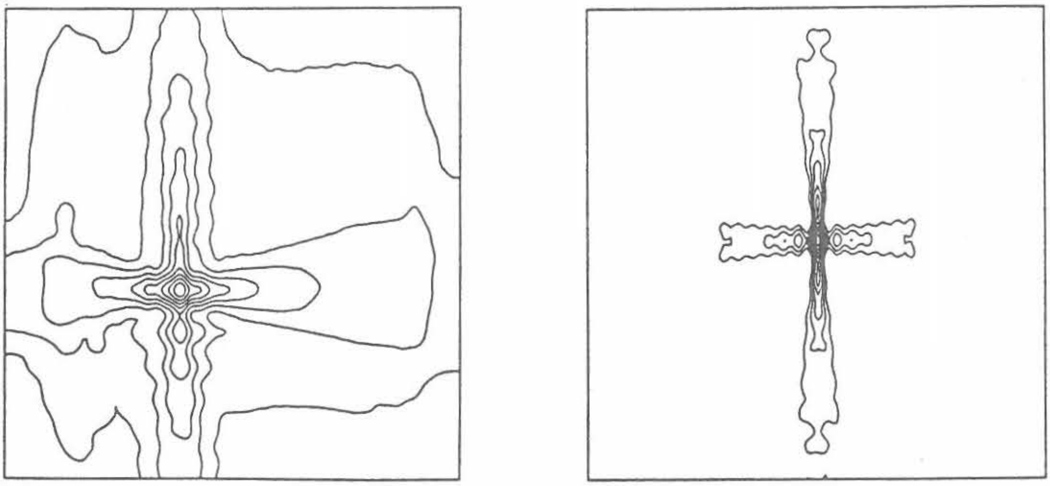


Fig. 4. Projected baselines in U-V plane during 4 hour observation on August 12, 1983.



(a) (b)

Fig. 5. Synthesized map (a) by back projection method using one-dimensional fan beam scans in grating mode after applying inverse filter, and synthesized beam (b) on August 12, 1983. Contour interval is 10 % of the peak value and the lowest contour level is 10 %. Angular dimension of the map is 40 X 40 arc min.^{2}

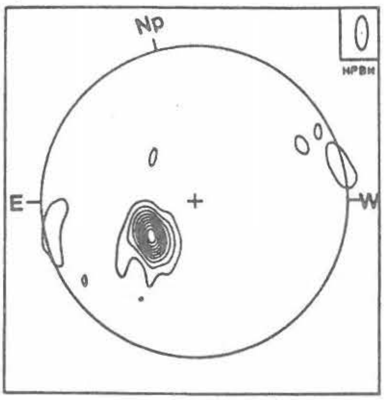


Fig. 6. Restored map of Figure 5(a) by CLEAN technique. Contour levels are the same as in Figure 5.

gain factor of 0.25 is used and 240 components were found. Cleaning process was stopped when the maximum value in the residual map was less than three times the standard deviation of the residual map.

6. Discussion

The HPBW of the synthesized beam in E-W direction is abou the same as that of the inferred HPBW from the longest baseline. But the HPBW in N-S direction is about 50 % larger than that of the inferred HPBW from the longest baseline. The reason is the lack of position angle coverage. This can be seen in the contour display of the synthesized beam in Figure 5(b). Wider coverage of the position angle can be obtained by extending the observing time and by observation when the declination of the Sun is far away from zero.

The restored map (Figure 6) does not contain the quiet sun component, although the original map contains it. The reason is that we stopped cleaning when the maximum in the residual map was less than three times the standard deviation of the residual map. It is very difficult to clean extended source. Practical way to restore the quiet sun may be a model fitting to the residual map after cleaning S-components. The restored map is overlaid in Figure 7 on the sunspot sketch obtained by Tokyo Astronomical Observatory on the same day. A strong radio source coincides with a sunspot group. Higher resolution

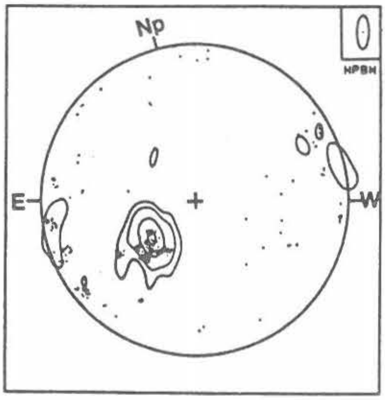


Fig. 7. Restored map of Aug. 12, 1983 is superposed on the sunspot sketch (courtesy of Tokyo Astronomical Observatory). Contour levels are 10, 20, 50 and 90 % of the peak value.

is necessary for detailed study. To get higher resolution, we extend observing time from 4 hours to 6 hours and use data of graing compound mode as a next step.

The solar observation by the λ 8-cm Radioheliograph has been carried out by the technical staffs of the Toyokawa observatory. Sunspot sketch was supplied by Tokyo Astronomical Observatory. This study is supported by Scientific Research Grant in Aid of Ministry of Education (57420004).

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