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The Radiometer and Polarimeters at 80, 35, and 17 GHz for Solar Observations at Nobeyama

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Abstract

An 80-GHz whole Sun radiometer with a new technique for reducing the atmospheric effect has been completed at Nobeyama. The radiometer has been proved to have the capability of detecting small bursts with the flux density of down to ~10 sfu (solar flux unit) under usual weather conditions; the detection limit has been lowered by one and a half orders of magnitude compared with that achieved with radiometers of a conventional type. The key point of the new technique is to cancel the quiet Sun component of large flux density (~10^4 sfu), which deteriorates the detection limit through atmospheric fluctuations, by correlating signals from two small antennas installed on a common equatorial mount with a separation of ~330 wavelengths. Owing to this new technique, it has been possible even for small flares to determine the microwave spectrum, in association with polarimeters operating at 17 and 35 GHz.

Key words: Solar millimeter-wave observations; Solar radiometers; Solar radio spectrum.

1. Introduction

Observations of solar flares at millimeter-wavelengths have long been needed to obtain precisely both the turn-over frequency and the high-frequency slope of microwave spectra both of which are crucial to infer the energy distribution of relativistic electrons produced in flares. In spite of their importance, millimeter-observations of solar flares are extremely few (Coates 1966; Croom 1970; Shimabukuro 1970). The reasons for this are as follows: First of all, the absorption of radio waves by the earth's atmosphere becomes increasingly severe with increasing observing frequency. Furthermore the flux density of the component steadily emitted from the quiet Sun increases with frequency. For example, at 80 GHz (λ=3.75 mm), it amounts to ~10^4 sfu (1 sfu=10^{-22} W m^{-2} Hz^{-1}). Then, the observed level of the quiet Sun fluctuates

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owing to time variations of the atmospheric absorption. The 10% fluctuation of the atmospheric absorption causes the fluctuation of ~1000 sfu at the observed level of the quiet Sun. Since the fluctuation of such an amount frequently occurs, it is difficult to detect an excess above the quiet Sun level due to a flare, unless it is greater than ~1000 sfu. Second, microwave spectra of nonthermal flares show the steep decline above the turn-over frequency which is usually at ~10 GHz. The flux density at 80 GHz is estimated to be one to two orders of magnitude smaller than that at 10 GHz. Large flares with the flux density of 10^4 sfu at 10 GHz are very rare. Hence it is expected that the probability of detecting bursts at 80 GHz with a conventional whole Sun radiometer is very small. Indeed, 2.5-yr observations at Slough recorded only seven bursts at 70 GHz (Croom 1970) and observations at 4 mm at Nagoya recorded only a few bursts (K. Kawabata and H. Ogawa, private communication).

To break through these limitations, we have developed a new technique which can reduce the effect of the atmospheric fluctuation by one or two orders of magnitude. By using this technique it has become possible to detect a much larger number of bursts at millimeter-wavelengths than those obtained with radiometers of a conventional type. We describe the design principle in section 2, its application to the 80-GHz radiometer in section 3, two polarimeters operating at 35 GHz and 17 GHz in section 4, and discuss the performance of these instruments inferred from some initial observations in section 5.

2. Design Principle

We considered three different methods for detecting small flares at millimeter-wave-lengths, among which the third method is original.

(1) *Use of a large antenna.* The simplest method is to use a large antenna. If the antenna beam is much narrower than the size of the Sun's disk, the received flux density of the quiet Sun component becomes small in proportion to the ratio of the solid angle sustained by the beam to that of the whole Sun, and hence the absolute value of the atmospheric fluctuation also becomes small in the same proportion. When an antenna with a diameter of 5 m is used at 80 GHz, the beam width (FWHM) is ~3′, which is comparable to the size of an active region. Then the received quiet Sun component is reduced by two orders of magnitude [$\sim(3'/32')^2$]. If we assume that the atmospheric fluctuation is ~10%, then we can detect small bursts of ~10 sfu. Thus radiometers with large antennas have an advantage in detecting small flares. However, the probability of recording bursts would become smaller by a factor of $\sim(32/3)^2$, unless the prediction of flare occurrence is well established.

(2) *Compensation of the absorption of the quiet Sun by atmospheric emission.* Let us denote the antenna temperature of the quiet Sun without the atmospheric absorption T_Q, and the temperature and optical depth of clouds T_C and τ, respectively. Then, if the Sun is covered by clouds with uniform temperature and thickness, the antenna temperature T_A is expressed by

$$\begin{aligned} T_A &= T_Q \exp(-\tau) + T_C[1-\exp(-\tau)] \\ &= (T_Q - T_C)\exp(-\tau) + T_C \ . \end{aligned} \quad (1)$$

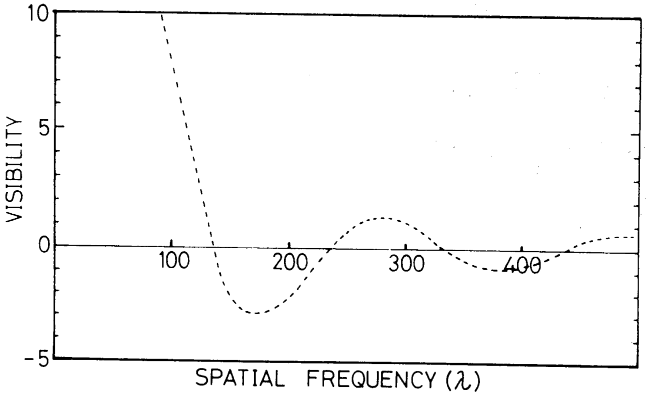

Fig. 1. The visibility function of the quiet Sun at 17 GHz obtained with the east-west interferometer. The abscissa is the spatial frequency in wavelengths. Note that the visibility becomes zero at discrete values of spatial frequency.

If T_Q is approximately equal to T_C, the received level of the quiet Sun is almost free from fluctuations due to the change in τ; the amount of absorption is compensated by the atmospheric emission. Then the excess temperature due to a flare T_B is calculated from the ratio of $T_B \exp(-\tau)$ to $T_Q \exp(-\tau)$. The condition of $T_Q \fallingdotseq T_C$ can be satisfied by choosing the diameter of the antenna.

(3) *Canceling the quiet Sun component by correlating singals from two separated small antennas.* The visibility function of the quiet Sun measured with the 17-GHz one-dimensional interferometer (Nakajima et al. 1980) is shown in figure 1. Here the abscissa is the antenna spacing or the spatial frequency. The visibility function crosses zero at discrete values of spatial frequency. When two antennas are separated, for example, by 330 wavelengths, the correlation output of the two antennas is zero for the quiet Sun, whereas it has almost the full sensitivity to a burst originating in a region much smaller than the whole Sun. As a result we can reduce to a large extent fluctuations which are mainly caused by the large flux density contributed from the whole Sun component. Thus we can detect a small burst wherever it occurs on the Sun using two small antennas whose beams cover the whole Sun. However, if each antenna is mounted separately, the effective antenna spacing varies with the Sun's hour angle. It is therefore essential to install the two antennas on a *common equatorial* mount.

We have decided to apply the new technique described in (3) to the 80-GHz radiometer, and the method (2) to the 35-GHz polarimeter.

3. 80-GHz Radiometer

A general view of the 80-GHz radiometer is shown in figure 2, where the antenna at the middle of the same equatorial mount is for the 35-GHz polarimeter. Two parabolic antennas with Cassegrain feeds are installed on a common equatorial mount. The diameter of each antenna is 25 cm. The beam width of each antenna is ~65′, which is much larger than the angular size of the Sun's disk. The separation between the two antennas, adjustable between 320 and 350 wavelengths, was fixed to 330 wavelengths to minimize the quiet Sun component.

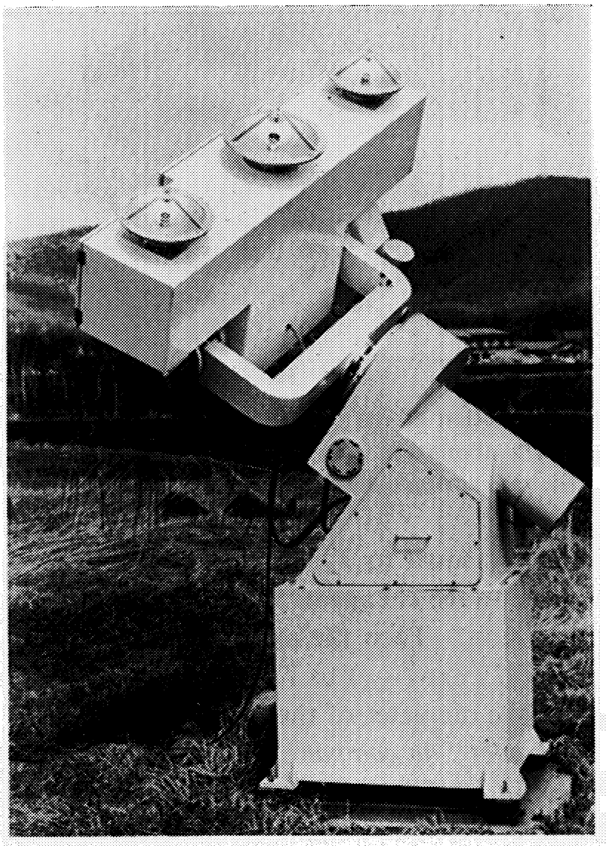

Fig. 2. The 80-GHz radiometer and the 35-GHz polarimeter at Nobeyama. Two small antennas with a diameter of 25 cm (on both sides) are installed on a common equatorial mount. The separation between the two antennas can be adjusted between 320 and 350 wavelengths. The antenna at the middle is for the 35-GHz polarimeter.

The block diagram of the receiver system is shown in figure 3. The 80-GHz signal is fed through a horn to a mixer placed immediately below each antenna, where the signal is converted to the first IF of 1.5 GHz with the bandwidth of 400 MHz (the 77.0-GHz signal is rejected by a filter). The receiver noise temperature is ~3000 K, which corresponds to the minimum detectable flux (5 times rms fluctuation) of ~15 sfu for the integration time of 0.2 s. The first IF is converted to the second IF of 300–700 MHz and then transmitted to the observing room. The second IF is divided, further converted to 0–200 MHz (DSB; double side bands), and then correlated. The pair of correlators on the left-hand side correlate two signals from the east and west antennas in phase (cosine correlator) and those on the right-hand side correlate the two signals after inserting the phase difference of 90° to one of the two signals (sine correlator). A pair of correlators are used for each of the sine and cosine correlators not to reduce the signal-to-noise ratio of the DSB signal. The output of the correlators (amplitude and phase) together with the output of a square-law detector (SQD) are recorded on magnetic tapes as well as on chart recorders.

The calibration of the flux density is carried out once every hour during 120 s by the following procedure. For the first 60 s of the calibration mode, the signal from the west antenna only is divided and fed to the correlators and also to the SQD. The

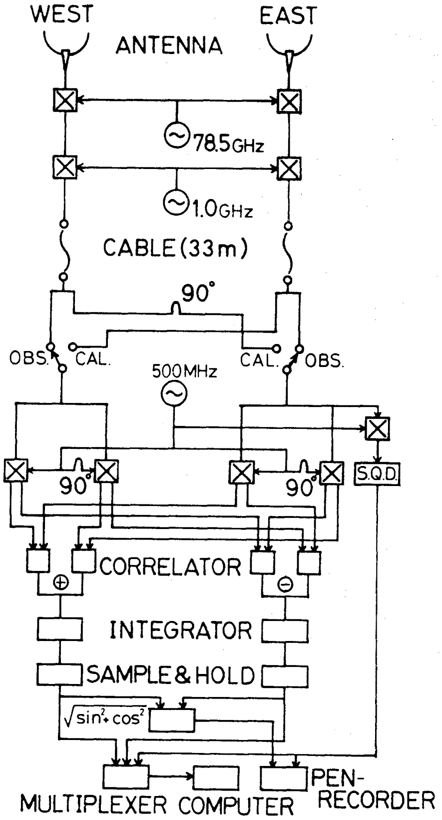

Fig. 3. A simplified block diagram of the receiver of the 80-GHz radiometer.

outputs are measured successively for the Sun and the sky. The outputs are the sum of the integrated flux over the whole Sun, the emission from the earth's atmosphere, and the receiver noise when the antenna is pointed to the Sun, and only the latter two contributions remain when the antenna is off the Sun. Then the difference in the outputs between the Sun and the sky is proportional to the flux density integrated over the whole Sun. Since the signal from the west antenna is fed to the "east" part of the system through an additional path of 90°, only the sine correlator has an output. For the next 60 s the same procedure is carried out for the east antenna. In this case there is no additional path so that only the cosine correlator has an output.

From the above procedure we can obtain the gain difference between the east antenna and the west antenna through the common SQD, and at the same time the gain difference between the sine correlator and the cosine correlator. Then using the integrated flux of the Sun, we can calibrate on the absolute flux scale an excess of the correlator outputs due to a burst measured in the observation mode.

The flux density of the quiet Sun is estimated from the previously measured values at 50 GHz and 90 GHz [see Kuseski and Swanson (1976) and references therein]. The value of 9700 sfu is obtained at 80 GHz from the interpolation of those values. Since the antenna has a beam width of $\sim 65'$, the gain decreases by $\sim 15\%$ at the solar limb. Correcting for this effect, the value of 9000 sfu is used for the calibration described above.

The 80-GHz radiometer started regular observations in February 1984.

4. Two Polarimeters Operating at 35 GHz and 17 GHz

Two polarimeters have been working on a routine basis at Nobeyama: the 35-GHz polarimeter has been operating since 1983 and the 17-GHz one since 1978. Here we describe briefly these two polarimeters.

4.1. 35-GHz Polarimeter

The antenna of the 35-GHz polarimeter, 30 cm in diameter, is installed at the middle of the same equatorial mount (figure 2). The effect of the earth's atmosphere is still severe at this frequency; it is far above the minimum detectable flux determined by the receiver noise. It is therefore necessary to use one of the methods described in section 2 for reducing the atmospheric effect in order to discriminate small bursts from the fluctuating quiet Sun level. As mentioned previously we have applied method (2) to the 35-GHz polarimeter; the decrease in the antenna temperature of the quiet Sun T_Q due to the atmospheric absorption is compensated by the atmospheric emission by equalizing T_Q to the cloud temperature T_C. This condition has been achieved by choosing the antenna diameter of 30 cm. Then the calculated antenna temperature T_Q is ~250 K. If the difference between T_Q and T_C is less than 50 K, the fluctuation of the antenna temperature T_A is less than ~5 K, even when the atmospheric absorption varies by ~10%. This value of 5 K corresponds to 40 sfu, much smaller than 10% of the integrated flux over the whole Sun. Hence the fluctuation is expected to be reduced by a factor of ~6.

The excess above the quiet Sun level due to a burst can be converted to the flux density by using an estimated flux density of the quiet Sun. Here we have used the value of 2400 sfu as the flux density of the quiet Sun at 35 GHz. This value has been estimated from the extrapolation of the values measured at around 35 GHz (see Kuseski and Swanson 1976). The minimum detectable flux determined by the receiver noise (5 times rms fluctation) is ~10 sfu for the integration time of 0.2 s and the bandwidth of 1 GHz.

The right-handed (R) and left-handed (L) circular polarizations are alternately received through a polarization switch. The accuracy of the polarization measurement is less than a few percents.

4.2. 17-GHz Polarimeter

The 17-GHz polarimeter is a revised version of the previous 17-GHz polarimeter (Tsuchiya and Nagane 1965; Shibuya and Nakajima 1980). Unlike the 80-GHz radiometer and the 35-GHz polarimeter we have used no special technique to reduce the atmospheric effect. The antenna with a diameter of 85 cm is used, the beam width being ~100′. The minimum detectable flux density is ~10 sfu for the integration time of 0.3 s and the bandwidth of 20 MHz. The calibration of the absolute flux density has been made by using a conical horn.

5. Performance of Millimeter-Wave Instruments Inferred from Observations

An example of 80-GHz observations of small bursts is shown in figure 4. The small impulsive burst at 02h 49m 40s (UT) on April 29, 1984 was detected with a satis-

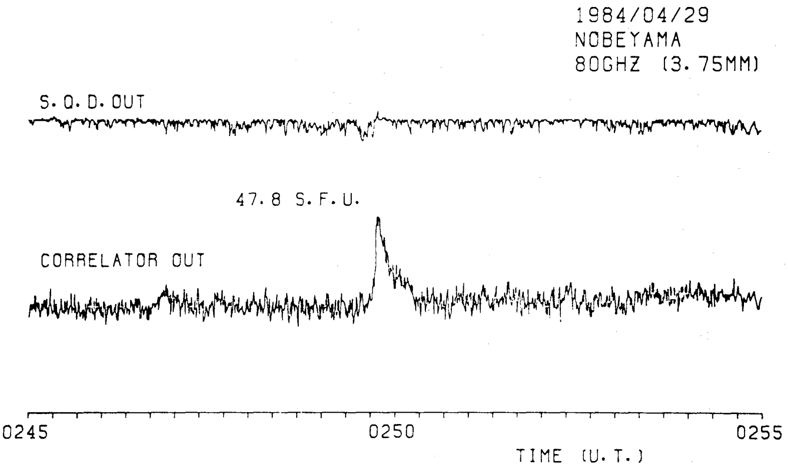

Fig. 4. 80-GHz records of the square-law detector (upper) and the correlator (lower) for a small burst.

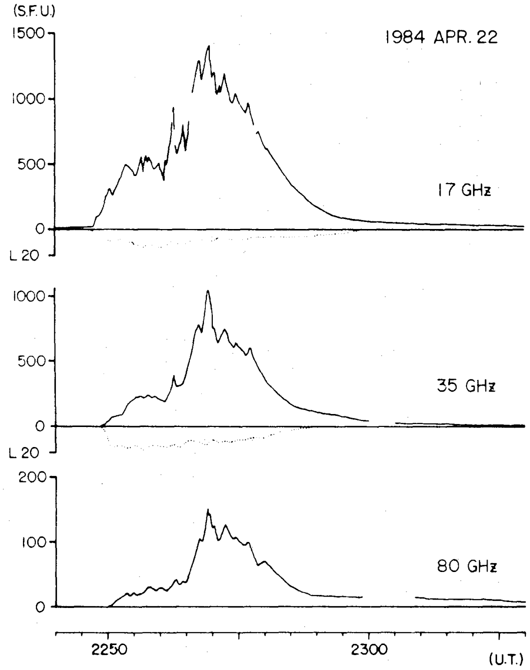

Fig. 5. Three-frequency (80, 35, 17 GHz) observations of a moderately strong burst followed by a weak post-burst increase. The 80-GHz time plot is reproduced from the correlator output. Solid and dotted curves are respectively for the sum and the difference of the right-handed and left-handed circular polarizations. No polarization measurement is made at 80 GHz.

factorily good signal-to-noise ratio on the record of the correlator (lower). Its peak flux density is calculated to be 48 sfu. However, no burst is seen on the record of the SQD (upper), which is connected with one of the two antennas. Peak-to-peak fluctuations of the correlator output are ~15 sfu, comparable to the minimum detectable flux determined by the receiver noise. Even in rainy weather when the SQD is almost useless, the correlator output shows peak-to-peak fluctuations of ~50 sfu. Relatively large fluctuations in unstable weather are caused by irregular thick clouds which cover part of the Sun. This is the only case where the cancellation of the quiet Sun component does not work properly.

The above values of fluctuations are one and a half orders of magnitude lower than those obtained with radiometers of a conventional type. Indeed, Croom (1970) reported the minimum detectable flux at 70 GHz to be 370 sfu in clear sky and 750 to 1500 sfu under usual weather conditions.

Simultaneous observations at 80, 35, and 17 GHz of a moderately strong burst followed by a weak post-burst increase are shown in figure 5. The time plot at 80 GHz is taken from the correlator. The peak flux density is ~150 sfu at 80 GHz. However, the burst is hardly detected on the record of the SQD. Fluctuations of the undisturbed level are ~10 sfu, ~15 sfu, and ~10 sfu at 80 GHz, 35 GHz, and 17 GHz, respectively. Fluctuations at both 80 and 35 GHz are comparable to the minimum detectable flux determined by the receiver noise.

From 80-, 35-, and 17-GHz observations together with 1 to 9-GHz observations at Toyokawa (Torii et al. 1979), it is now possible to determine the microwave spectrum even for small bursts with flux density less than 10 sfu at 80 GHz. For example, we will obtain spectra of GRF bursts or post-burst increases of thermal origin, which have not been known precisely. It is more important to know the slope of the spectrum above the turn-over frequency for bursts of nonthermal origin; this is crucial to estimate the energy distribution of *relativistic* electrons accelerated in flares. The high-frequency slope has not been determined so far except for a few extremely large bursts, because the flux density at millimeter-wavelengths is usually smaller than the detection limit determined by the atmospheric effect.

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