MILLIMETER WAVE SOLAR OBSERVATIONS

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Abstract

Several categories of millimeter wave observations in the range between approximately 20 and 3 mm are considered. First, the general area of current observations conducted with small antennas of low resolving power and simple radiometric receivers is reviewed. The type of solar information derived and its application are discussed. The second area considered is that of current high-resolution solar investigations from antennas with beam widths as small as 1 minute of arc. Finally, future ultra-high resolution work (<10 arc seconds) by interferometer techniques and the need for such work are discussed.

Introduction

Millimeter-wave solar radio astronomy has assumed great importance with the advent of the space age. The general awakening to the effects of solar emission on communications and its relation to geophysical phenomena dictated the broadening of our knowledge of the sun to better cope with operational problems. Though the solar millimeter area had been largely neglected, improvements in components made millimeter monitoring with established techniques a routine accomplishment. Both optical and radio solar monitoring had been initiated on a large scale during the IGY. Nevertheless, radio surveillance was oriented toward longer wavelengths with hardly any work above 9000 MHz and few routine patrols above 3750 MHz. The weakness of our knowledge may be recognized by researchers erroneously setting the upper limit of the slowly varying component at 10 GHz. Nevertheless, scientists and operational groups were agreed that two kinds of information were required from an inadequately covered spectrum; that concerned with large flare-bursts (and associated particle activity) and that relating to solar active regions. For both, continuous monitoring was required.

Empirical knowledge of the flare-burst picture was reduced to reliable statistics from multi-frequency patrol programs such as conceived by the USAF in the early 1960's and placed in operation in 1965. Though proton-event warning signatures were derived from dm-cm measurements, several years of intensive observations were required to demonstrate clearly the need to expand coverage to the 20 mm region. This was accomplished in 1967. It then became apparent that bursts which had an increasing but flattening spectrum at 8.8 GHz generally attained a maximum below 15 GHz. The occasional burst observed with increasing flux density at 15 GHz dictated the need for later patrols at 35 GHz. The correlation of radio bursts with Hα, EUV and X-ray events could now be intelligently carried out. The marriage of observations and theory relating to emission mechanisms could be advanced.

In the high resolution domain, the Stanford and Fleurs brightness contour maps had become the basis for solar optical-radio distribution studies. New improvements in maintaining surface tolerance of large parabolic antennas and better pointing accuracy made possible the construction of high resolution antennas for solar studies at wavelengths as short as 3 mm which could view solar heights under 3000 km where flares, bursts, and X-ray activity originate. These data are used in the development of solar models and provide signature information from which the recurring longitudes of proton flare regions can be recognized for prediction purposes.

Solar Equipment/Measurement Considerations

In solar radio astronomy, source intensities are generally 10^4 or more greater than in non-solar work. The large signals obviate the need for ultra-low noise receivers. Receiver linearity, a serious problem at longer wavelengths because of the burst dynamic ranges encountered, is not a severe problem, at least in patrols (where the largest bursts are never more than 20dB above the quiet sun).

If the sun does not appear as a point source to the antenna, true flux density requires a correction factor which considers the beam shape and the source distribution. Ordinarily, in patrols the problem is avoided by reducing the antenna size to make the beamwidth at least 3 to 5 times the sun's diameter. At millimeter waves this becomes impossible because the ideal-beamwidth antenna has a collecting area much too small to provide a sufficiently large antenna temperature signal to overcome receiver insensitivity. Hence, somewhat larger dishes and appropriate data correction factors are dictated. The problem may be worsened in calibrating a burst occurring off the antenna-followed solar meridian.

In mapping, while the overall solar flux density increases with decreasing wavelength, the percent enhancement of active regions decreases, creating other problems of calibration. At millimeter wavelengths, the relation between the received flux density and that radiated must be derived from consideration of the varying atmospheric attenuation as a function of path length; it is usually convenient to use an average zenith-attenuation constant.

Low-Resolution Observations

Low-resolution whole-sun millimeter observations (λ < 20 mm) on a worldwide basis have been quite limited. Patrols have been carried out in the United States (15.4 and 35 GHz at Sagamore Hill Observatory), in Great Britain (19, 37, and 71 GHz by the Radio and Space Research Station at Slough) and in Japan (limited time-coverage observations at 17 GHz at Tokyo). A four-station worldwide Air Force solar radio patrol network has been established[1] to monitor the sun with a series of low-resolution, fixed-frequency radiometric systems. It is currently in the process of expansion in frequency coverage.

The purposes of quantitative patrol observations are two-fold: to monitor the daily variations of the undisturbed sun at various frequencies and to give spectral and intensity-profile data of bursts. Centimeter undisturbed-sun data finds application in telemetry antenna calibration and atmospheric density modelling; however, millimeter data find little application in this regard since the slowly-varying component on a percentage basis at 15.4 or 35 GHz is relatively small compared to that at C-Band or S-Band.

As for bursts, we might divide observations into two categories of interest: (1) the peak flux density spectra of large numbers of solar bursts (most of which are of relatively small intensity but as a group might contain statistically significant information) and (2) the dynamic or time-varying spectra of a small number of large bursts (where the dynamic spectra might be used to determine the burst region parameters or the emission mechanisms involved).

In the first category, the addition of millimeter wavelength (15.4 and 35 GHz) patrols has paid important dividends. It has led to an improved burst spectral classification system, a significantly changed idea of centimeter-band spectral distribution of bursts, and an improved understanding of burst mechanisms.[2] Several days preceding the spectacular 2-7 August 1972 solar events (on 31 July 1972), a series of moderate-intensity bursts with unusual peak flux density spectra were observed at Sagamore Hill; radiation from these bursts was observed only at f > 10 GHz. The solar burst-region conditions responsible for this type of spectrum played a major role in the big August events that followed. Additional instances of series of bursts with similar spectra preceding major solar disruptions have been uncovered.

Regarding the second category, particular investigative emphasis has been directed toward the 7 August 1972 solar event because of the excellent microwave data up to 35 GHz from Sagamore Hill and the presence of other important corollary data. Good satellite measurements of hard X-rays and ejected particles were obtained. The event was observed in Hα and white light and was associated with an atmospheric ground-level event. The white light flare was probably caused by energetic particles being driven down into the photosphere. Figure 1 shows the time-varying spectrum of the 7 August 1972 event. The microwave parameter that is of prime importance is the slope on the high frequency side of the spectral maximum (f_{max}). The greatest spectral hardness (i.e., the flattest spectrum) above f_{max} occurs at 1518.0 UT, just after the greatest increase in the 35 GHz flux density; this abrupt increase could be indicative of particle injection and acceleration.

From the observed millimeter radiation spectrum during different times of the burst, the probable electron energy distribution can be obtained and can be compared with the spectra of energetic particles and hard X-rays. If consistent correlations can be obtained, ground-based millimetric patrol observations can be used to forecast the ionospheric effects caused by these emissions, instead of relying on discontinuous satellite data. For example, Figure 2 shows the strong correlation between the rate of change of ionospheric total electron content (TEC) and the burst flux density at 35 GHz during the 7 August 1972 event. The use of 35 GHz burst data to predict TEC during large bursts becomes important when the increased ionospheric D-region absorption caused by the burst makes conventional ionosonde measurements impractical.

High Resolution Observations

High resolution observations at mm wavelengths, begun in the Soviet Union in the early 1960's, are now carried out in the United States, Great Britain, Germany and the Soviet Union with pencil beam antennas and in France and Japan with interferometer systems. Resolution is significant because it allows investigation of individual active centers; mm wavelengths are significant because the emission observed in this range originates in the chromosphere, the seat of major evolutionary development of active regions as well as the seat of the majority of flare events. As a general rule, the shorter the wavelength of the radiation observed, the deeper its region of origin in the chromosphere.

Historically, high resolution observations have been performed on a sporadic basis due to limited observing time on the available telescopes. Areas of intensive investigation have been (1) quiet sun brightness distributions, (2) descriptive statistics (intensity, position, size, polarization) of the slowly varying component of active regions and (3) flare events. (An excellent summary of these investigations has been compiled by Schanda[3].) In contrast, regular observations of the solar brightness distribution have been carried out on an almost daily basis by: the Aerospace Corporation (λ3.2 mm); Air Force Cambridge Research Laboratories (λ8.6 mm); and Naval Electronics Laboratory (Corona), (λ8.6 mm, λ20.0 mm). Each of these facilities, with resolutions in the 2-4 arc-min range, generates a daily spectroheliogram which is made available on an international basis.

Many of the features cited in the literature can be seen in the λ8.6 mm spectroheliogram shown in Figure 3. For example, in limb brightening investigations it is the fall off of intensity at the edges that is of prime concern. The observed decrease may be due to instrumental smoothing rather than chromospheric structure. Active region investigations would concentrate on the feature in the upper center of Figure 3 in order to catalogue its maximum intensity, size and position. Typical features exhibit enhancements of 10% above the background while the most intense are as much as 20% above the background. Although Figure 3 shows only one major region, at times as many as 3 major and 6 minor features are discernable. Since these features overlie optical counterparts (sunspots, plages, filaments, etc.) the central issue of much research has been the relation of the one to the other. Statistics are often employed to determine the correlation of the observed mm intensities with various parameters of the optical region. A different statistical approach has been to assemble the available radio spectrohiliograms over a multi-year period and examine active regions simultaneously observed at many radio wavelengths.[4] The mean flux spectrum of a population of 700 regions observed from λ9.1 cm to λ3.2 mm is shown in Figure 4. This spectrum may be regarded as that of a fictictious "average region". This spectrum exhibits a long wavelength hump characteristic of gyrobremsstrahlung processes and a distinctive rise as λ^{-1} in the mm range which is related to the temperature gradient in the chromosphere. Studies such as this are currently being employed to "filter" newly observed active regions according to possible proton production since regions exhibiting levels of enhancement factors of 2 or 3 above this mean have been sources of past proton events. Current efforts are concerned with setting usable thresholds for prediction criteria such as this.

In spite of the progress made in the 15 years since the early Soviet investigations, the limitation of present instruments has been dramatically demonstrated by recent ultra-high resolution observations in the centimeter wavelength range. In particular, employing interferometer systems with 9 arc-second and 3 arc-second resolutions, Kundu[5] has found a wealth of structural detail in the coronal portion of active regions which had been totally blurred at previous resolutions of a few arc minutes. In order to probe the chromospheric microstructure to this scale, CESRA, the Committee of European Radio Astronomers, has proposed the construction of an ultra-high resolution instrument with two dimensional resolution of 5 arc seconds or less over the entire wavelength range from λ6 cm to λ3 mm! This instrument (Schanda, 1973) would provide the first observation of the radio properties of granulation patterns, dark and bright mottles, oscillatory motions and the magnetic field configurations in both quiet and active regions. Thus, the goal of future instruments is to provide the resolution needed to relate optical and radio microstructure in order to observe and identify the physical processes controlling solar radiation processes.

References

1. J.P. Castelli, J. Aarons, D.A. Guidice and R.M. Straka, Proc. IEEE, 61, p. 1307 (1973).
2. D.A. Guidice and J.P. Castelli, High Energy Phenomena on the Sun, Symp. Proc., NASA X-693-73-193, p. 87 (1973).
3. E. Schanda, ed., Scientific Motivations for a High Resolution Microwave Heliograph, Joint Interferometer Project, CESRA (1973).
4. P.M. Kalaghan, 140th Meeting AAS, Columbus, Ohio (1973).
5. M.R. Kundu, IAU Symposium No. 56, Australia (1973).

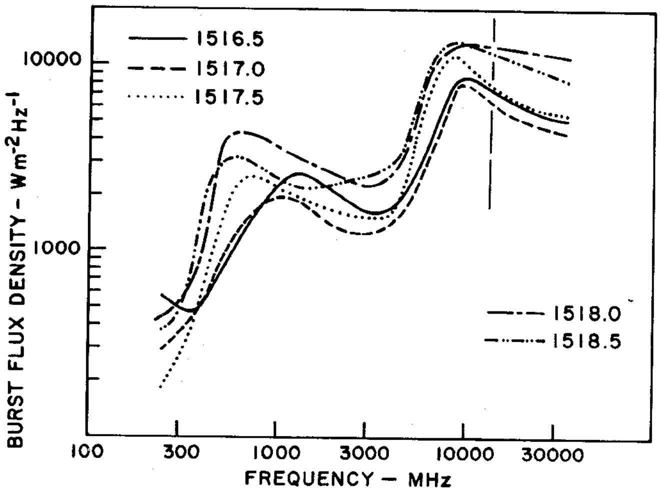

Fig. 1. Time-varying spectrum of the 7 August 1972 event. Greatest spectral hardness (i.e., flattest spectrum) above f_{max} occurs at 1518.0 UT, just after the abrupt increase in the 35 GHz flux density.

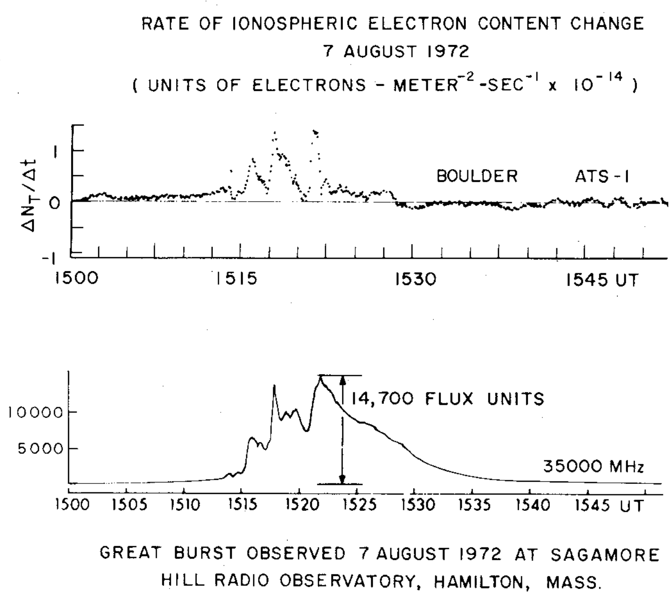

Fig. 2. Remarkable correlation of the rate of change of ionospheric total electron content and the solar flux density at 35 GHz, showing the possibility of using millimeter radio patrol data to forecast ionospheric variations.

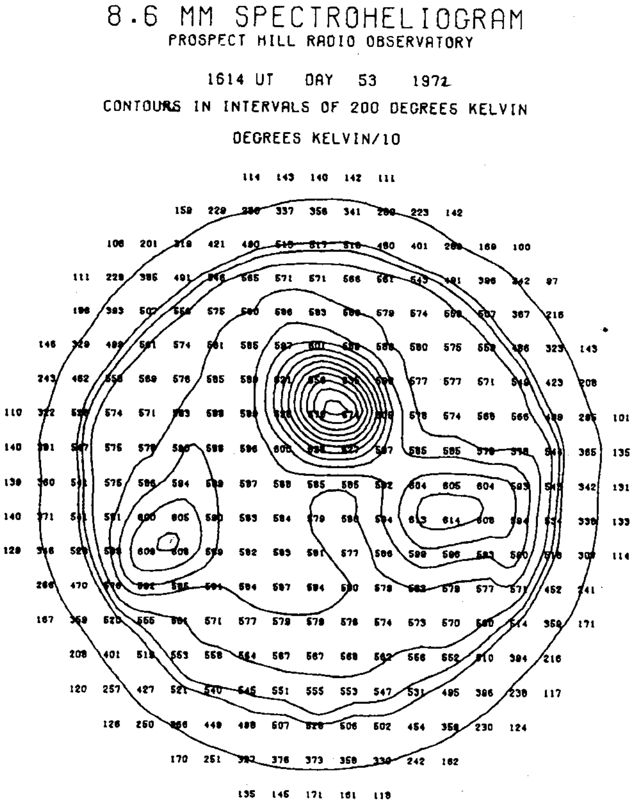

Fig. 3. Solar intensity distribution on 22 February 1972 at λ8.6 mm. Array value of 600 is equivalent to black body temperature of 8500°K.

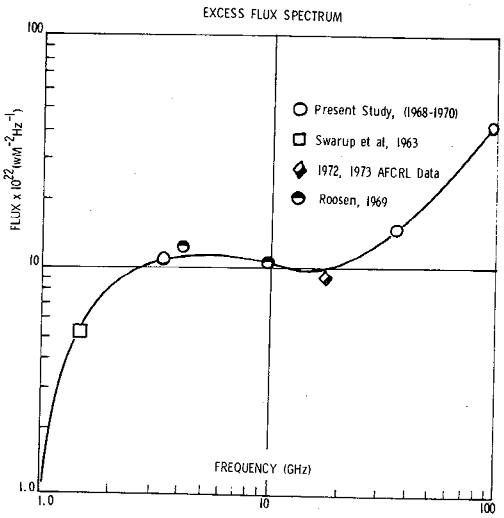

Fig. 4. Active region flux spectrum. Circles correspond to mean values (700 regions) observed in 1968-1970. Means from other surveys of large numbers of regions are included to confirm trend of the spectrum.