Statistical comparison of radio granulation and the calcium chromospheric network

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(Submitted June 9, 1988)

Astron. Zh. **66**, 822–831 (July–August 1989)

We present a statistical analysis of the results of simultaneous observations of radio granulation on the RATAN-600 radio telescope (wavelength 1.35 cm) and the chromospheric network (a birefringent filter at the K line of ionized calcium), carried out on July 21 and 28 and August 3, 1976, at an epoch of minimum solar activity. Structures of radio granulation with spatial scales of 44 and 122″ (i.e., 30 and 88 · 10^3 km) and of the chromospheric network with scales of 29, 44, and 74″ (i.e., 22, 30, and 53 · 10^3 km) are revealed by the method of autocorrelation spectral analysis. The two series of data are compared by the method of cross-correlation analysis. For the scales of 22, 30, and 53 · 10^3 km the coherence between the two series reaches 0.35, 0.80, and 0.75, respectively. These results confirm the earlier conclusion that radio granulation is related to the structure of the calcium chromospheric network. The presence of a period near 120″ only in the radio data, however, indicates that these two phenomena are not physically identical.

INTRODUCTION

Fluctuations in the distribution of radio brightness over the disk of the quiet sun, called radio granulation in Ref. 1, were detected in the centimeter wavelength range at the RATAN-600 radio telescope [2] and in the millimeter range at the RT-22 radio telescope during a transit of Mercury across the solar disk. [3] Observations in 1976 at the RATAN-600 with 9 × 50" resolution at 1.35 cm enabled us to identify individual elements of radio granules with corresponding bright and dark elements of the calcium chromospheric network. [4] Radio images of the quiet sun at 6 cm were obtained somewhat later by the method of aperture synthesis using the radio telescope at Westerbork[6] (WSRT) with a resolution of about 6", and a pattern similar in nature to the chromospheric network was obtained.

A statistical analysis both of radio observations of radio granulation themselves and of their relation to the corresponding optical structures of the chromosphere based on observations in the Hα hydrogen line and the K lines of ionized calcium has been carried out in a number of papers (Refs. 3, 5, and 6-11). Characteristic scales of radio granulation in the range from 15 to 280" were revealed in the process. Some (but not all) of the scales were also revealed in the optical chromospheric network.

In the present paper we continue the analysis of the 1976 solar observations at the RATAN-600 with the aim of a statistical determination of the characteristic sizes of radio granulation at 1.35 cm and its relation to the structure of the calcium chromospheric network based on photographs taken simultaneously by an expedition of the P. K. Shternberg State Astronomical Institute (SSAI) directly on the same observational field of the radio telescope. In the last part of the paper we compare these results with the data of other authors (in the range from 8 mm to 6 cm).

RADIO OBSERVATIONS

The simultaneous optical and radio observations of the sun that we carried out on 21 and 28 July 1976, were described in Refs. 4 and 7. In the present paper they are supplemented by the results of 3 August, presented in Fig. 1. A trace of the radio emission, obtained by scanning the sun with the beam pattern of the RATAN-600 antenna, is shown in this figure against the background of a filtergram in the Ca II K line.

Dashed lines outline the strip on the solar disk scanned at 1.35 cm by the main lobe of the beam pattern at the half-power level. Here the brightest features at the center of the disk correspond to weak flocculi, clearly displayed in the optical and radio ranges. In the rest of the curve one can trace the correspondence between features of the radio image and the clearest structural elements of the chromospheric network, including both light and dark features, analogous to what was done in Ref. 4.

The observations were carried out on the northern sector of the RATAN-600 radio telescope at λ = 1.35 cm. At a solar elevation of 65° this observing mode corresponds to a calculated beam pattern at the half-power level 9" (E—W) × 54" (N—S). A single pass of the sun through the antenna beam, set in advance at the calculated angle of passage of the center of the solar disk, was recorded. The central part of the disk was recorded using a rapidly-switched noise generator for signal calibration, and at higher gain, since the signal fluctuations due to radio granulation are small and comprise tenths of a percent of the antenna temperature of the sun. The radio signal was recorded on paper tape along with special time markings, from which the scale of the radio trace along the scanning direction was determined. Here the calculated time of passage of the center of the solar disk was noted.

The values of the radio brightness were calculated from the tape every 0.25 sec of time, which corresponded to a spatial interval of 3".5 on the sun for 21 July and 3".6 for the other two days.

The data were fed into the BÉSM-4M computer of the SSAI for further analysis. The smooth variation of the signal (trend) due to the passage of the sun through the antenna beam pattern was eliminated by subtracting a sliding weighted mean through the formula

$$I(x)=I'(x)-\int I'(x+\tau)\,W(\tau)\,d\tau \Big/ \int W(\tau)\,d\tau, \qquad (1)$$

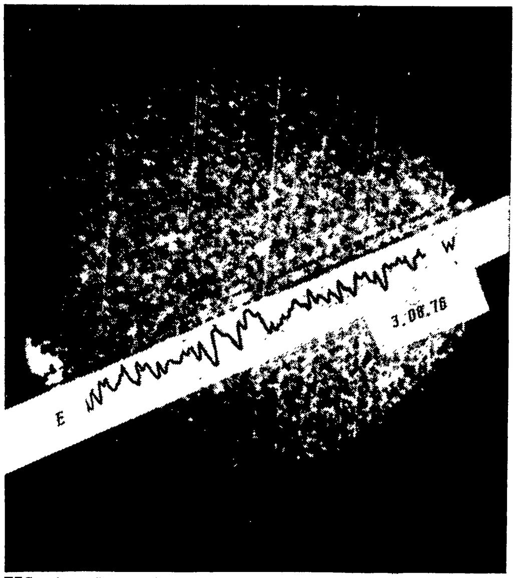

FIG. 1. Comparison of radio granulation at 1.35 cm with a filtergram of the sun in the Ca II K line from observations of 3 August 1976.

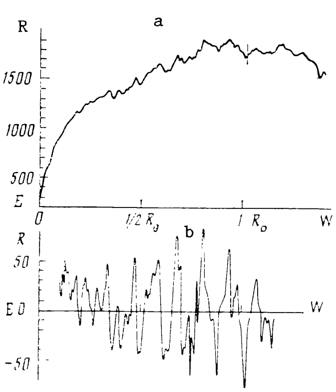

FIG. 2. Trace of solar radio emission at 1.35 cm obtained on 21 July 1976 (a), and the same trace after baseline subtraction: elimination of the limb-darkening effect (b). R is in arbitrary units.

where I'(x) is the observed brightness, I(x) is its value after eliminating the trend, and $W(\tau)$ is the weight function, taken in the Gaussian form $W(\tau) = \exp(-\tau^2/\sigma^2)$ with a width σ. It turned out that with $\sigma = 100''$ the drop in the trace of the quiet sun near the limb is eliminated fairly well, with the high spatial frequencies characteristic of the radio granulation pattern being conveyed without significant distortion. This drop in the signal is associated with the exit of the sun from the system of side lobes of the beam pattern, which includes more of the effective area of the antenna for radio telescopes with an unfilled aperture (such as the RATAN-600). A trace of solar radio emission for 21 July 1976, before and after the application of this baseline subtraction procedure is given in Fig. 2 as an example.

OPTICAL OBSERVATIONS

The sun was observed in the optical range directly in the field of the radio telescope. The basis of the integral horizontal solar field apparatus was a chromospheric telescope with a birefringent filter of the Halle Co. at the λ 3933 (Ca II K) line [12]; the filter passband was 1.2 Å wide.

The diameter of the solar image on the photographic film ranged from 18.33 mm on 21 July to 18.99 mm on 3 August. The resolution of the optical image was determined from photometry of the limb of the solar disk and averaged 4". The optical filtergrams were analyzed on the digital microdensitometer of the Main Astronomical Observatory, USSR Academy of Sciences (MAO).[13] An equatorial zone of width 310" along a diurnal parallel (X axis) was scanned; the accuracy in determining its position was 2". The microdensitometer slit scaled to the celestial sphere corresponded to a rectangle of size 4" (E–W) × 10" (N–S). Densitometric scans were made every 5" and readings along the scanning line were taken every 1".55. The densitometric results together with data for determining the characteristic curve were also fed into the BÉSM-4M computer of the SSAI, in which the subsequent joint analysis of the results of the optical and radio measurements was performed.

To match the resolutions of the two series of observations, the optical data, clearly obtained with a higher resolution than the radio measurements, were averaged. After averaging over three readings, the step size of the optical measurements was 4".65. Spline interpolation was used to obtain readings with the same step size as the radio data. The common zero point of the coordinate system for all densitometric observations was found by matching the maxima of the respective mutual correlations. The correlation method of comparing the optical and radio observations was checked in the east–west direction by matching the centers of the optical and radio images of the sun, the accuracy of which was one step along the X axis, i.e., about 3".6. As we noted above, the center of the solar disk

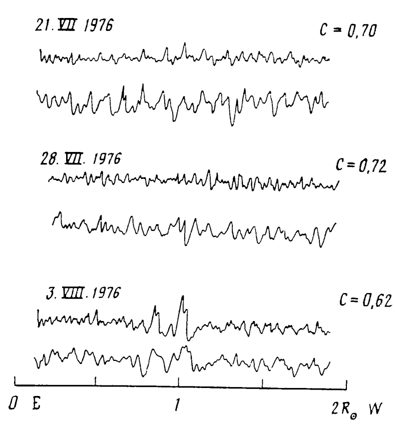

FIG. 3. Comparison of radio granulation and the calcium chromospheric network based on observations of 21 and 28 July and 3 August 1976. In each pair of curves the upper trace is in the Ca II K line and the lower trace is at λ 1.35 cm for each day, respectively; C is the value of the correlation coefficient.

TABLE I

Investigated ranges	Spatial frequencies of maxima of the power spectra				
Ca II K (PW)	–	74″	53″	(44±3)″	(29±2)″
1.35 cm (PW)	(120±2)″	–	–	(44±3)	(29±2)
Ca II K (Ref. 14)	–	–	(53±8)	–	(26±4)
Hα (Ref. 14)	–	–	(50±6)	–	(27±3)
Maximum coherence between Ca II K and 1.35 cm	–	0,75	–	0,80	0,35
Size, km	88 000	53 000	37 000	30 000	22 000

Note. (PW) means the present work.

TABLE II. Results of Studies of Brightness Fluctuations of Solar Emission

No.	Investigated ranges	Spatial periods of maxima, arcsec		References
		coherence spectra	power spectra	
1	2–4 cm	42–82, 102–156, 190–280		5
2	2,8 cm	50		8
3	0,85 cm	30–40		9, 10
4	1,35 cm	29, 44, 120		PW
5	3933 Å	29, 44, 53, 74		PW
6	6 cm 3933 Å		15, 44	6
7	6563 Å, 3933 Å		27, 53	14
8	1,35 cm, 3933 Å		29, 44	PW

on the radio scan was determined from its time of passage through the meridian of the observing site. There was no such check in the north–south direction because of refraction and the radial error in mounting the feed. In this case, correlation of the radio and optical scans enables us to estimate and eliminate the corresponding elevation error in setting the antenna. For the first two days of observations the correlation turned out to be highest for optical scans passing 30" to the north of the center of the visible image of the sun, and only for 3 August did the profile passing through the center of the radio image of the sun turn out to have the maximum correlation, so on this day the elevation pointing error of the RATAN-600 antenna did not exceed 5" and no corrections were introduced. The possible nonparallelism of the optical and radio scans was monitored by the same method, for which we calculated the correlation for the east and west halves of the scans separately. The nonparallelism did not exceed 10'.

COMPARISON OF OPTICAL AND RADIO OBSERVATIONS

Using the foregoing procedure, for each of the three days of observations we obtained values of the radio brightness R_i with a uniform step size along the X axis at points X_i. For the same coordinates X_i, i.e., with the same step size, we found values of the optical brightness I_i for all the scans ($n = 1, 2, \ldots, 62$) with a 5" step in the orthogonal N–S direction, i.e., over 310" of latitude within the equatorial zone on the sun. This strip corresponds to about three half-widths of the beam pattern to the south and three to the north from the diurnal parallel passing through the center of the solar disk. Thus, to compare the radio and optical measurements it was necessary to average the latter over the beam pattern of the RATAN-600 antenna.

To accomplish this averaging we used the same baseline subtraction procedure as we used to eliminate the radio trend through Eq. (1). We first averaged along one scan in the east–west direction with a weighting function of width $\sigma = 9''$. For the averaging between densitometric scans, i.e., in the north–south direction, the width of the weighting function was varied from 0 to 120" and we chose the value for which the maximum correlation with the radio data was reached. It turned out that the maximum correlation between the optical and radio data is reached for $\sigma = 15\text{-}25''$.

In Fig. 3 the baseline-subtracted traces of radio granulation (lower curve for each day) are compared with densitometric scans in the Ca II K line, averaged by the procedure described above, for all three days of observations. The correlation coefficients C are given with confidence intervals at the 0.95 significance level: $C_1 = 0.70 \pm 0.04$ for 21 July; $C_2 = 0.72 \pm 0.04$ for 28 July; $C_3 = 0.62 \pm 0.04$ for 3 August. These curves permit a direct identification of most structural elements common to the optical and radio traces.[4] The correlation for 3 August is considerably lower than for the other two days, which may be related to the fact that for the floccular component that appeared on August 3 the correlation between the fluxes of optical and radio emission is different from that for radio granulation. At the same time, the flocculi of 3 August are the structural elements of the optical and radio images that are the most reliably identifiable in brightness and size.

On the whole, the comparison of data on radio granulation and densitometry of calcium filtergrams confirms the conclusions of Ref. 4 that most of the bright features of the radio granulation correspond to bright nodes of the chromospheric network, although the reverse is far from always being true: many bright features on the filtergrams in the Ca II K line do not have clear analogs on the radio traces. On the other hand, the most obvious dark

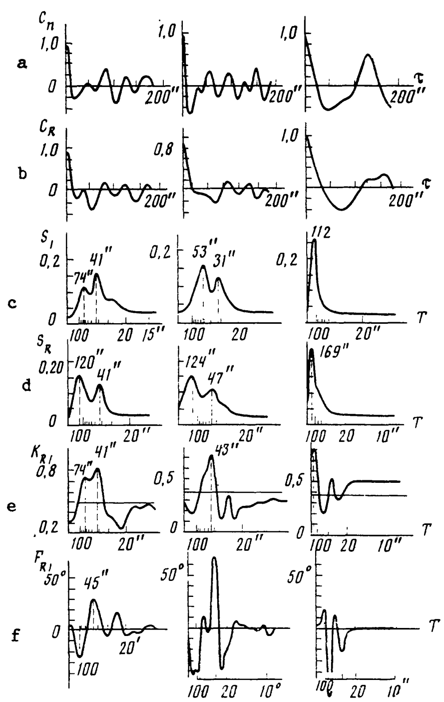

FIG. 4. Comparison of radio and optical observations processed by the method of correlation spectral analysis for each day of observations: a, b) autocorrelation functions for the corresponding optical and radio series of observations; c, d) spectral densities of the optical and radio observations; e) coherence spectra of the optical and radio observations; f) phase spectra of the optical and radio observations. The horizontal lines on the coherence graphs are the 95% significance level.

features of radio granulation practically always correspond to clear cut dark (internal) regions of the chromospheric network.

Besides this attempt to identify features of the optical and radio images, we compared them by methods of the theory of random functions. The results of the statistical analysis used for this comparison are given in Fig. 4. Of the three days analyzed, the third day (3 August 1976) again drops out, which in this case is apparently related to the dominant role of two floccular features at the center of the disk. Therefore, we confine ourselves here to a discussion of the curves for the first two days of observations.

Autocorrelation functions for the optical and radio scans are presented in Fig. 4a and b, respectively, and the power spectra calculated from these are presented in Fig. 4c and d. The period 120-124", fairly stable on a scale of a day, and the period 41-47", coinciding reasonably on the two days of observations, turned out to dominate in the spectrum of the radio image. In the calcium line the period of about 120" is not found at all. Spectral maxima near 74 and 41" appeared on the first day and at 53 and 31" on the second day of observations. From this it is clear that the radio granulation and the calcium chromospheric network are not at all identical formations (incidentally, this also followed from a direct identification of features of the optical image with those of the radio trace). To clarify the nature of the correlation between these structures, we performed a cross-correlation analysis, for which we calculated the cross-correlation and quadratic spectra, from which we then found the coherence spectra K_{RI} and the phases F_{RI}, presented in Fig. 4e and f, respectively. These curves show the definitely significant coherence of the optical and radio images at the periods 41 and 43", apparently corresponding to the second (higher-frequency) maximum in the spectra of the radio scans. Thus, the latter represents the part of the radio granulation that is physically related to the chromospheric ("optical") network. On the coherence spectrum for 21 July 1976, the maximum with a period 74" is also significant, and on the corresponding K_{RI} curve for 28 July a shorter-wavelength part is noted in addition to the 43" maximum. Thus, the 74 and 53" low-frequency maxima in the power spectrum of the calcium scans for the two days, respectively, also appear in the radio emission, although less clearly. At the same time, the periodicity near 120" turns out to be inherent only to the radio, and characterizes its lower-frequency structure. It should be recalled that lower-frequency scales that may be present in the scans are excised in our method of analysis by baseline subtraction performed with σ = 100", which cuts off frequencies at more than 160".

The foregoing gives the impression that characteristic periods of radio granulation and of the optical chromospheric network exist which vary with time (at least over about a day — the period over which a specific grid structure usually changes completely). Certain periods of the network structure (120" in the radio and 41-43", a period common to both ranges), however, apparently are more stable.

DISCUSSION

A comparison of the parameters of the structure of the solar atmosphere based on observations in different spectral ranges makes it possible to bring out the change in physical conditions with height, as well as to study the fields of variation of different parameters (such as fluctuations of temperature, density, velocity, etc.). In the optical range such an analysis has been carried out, for example, on the basis of simultaneous observations in the hydrogen H α line and the K line of ionized calcium.[14] It has been found that a common scale of 53" is present in both lines, which coincides with our results based on the Ca II K line and confirms the commonality of the procedure used in the two papers. Our results and those of Ref. 14 are presented in Table I. The spatial frequencies of maxima of the power spectra based on the results of the 1976 observations at $\lambda\lambda$ 3933 Å and 1.35 cm are given in the first and second rows of the table. The spatial frequencies of the power spectra at 3933 and 6568 Å from Ref. 14 are given in the third and fourth rows of the table, respectively. The maximum values of the coherence at the corresponding frequencies obtained in our work are given in the fifth row. The sizes of the spatial frequencies expressed in km are given in the last row.

It is seen from Table I that the spatial size 30" (the internal size of the cells; the dark elements on filtergrams in the Hα and Ca II K lines) appears in all three ranges investigated, but with a low coherence (0.35). For the emission ranges in the

Ca II K line and the radio a high degree of coherence (0.80) is displayed at spatial sizes (44 ± 3)", which can be considered to be the distance between the centers of cells of the chromospheric network, assuming a wall thickness of about 5-7". A configmation of the latter conclusion is the fact that the maximum coherence between the structures in the H α and the Ca II K lines in Ref. 14 was established in the size range (50 ± 8)", in which the spectral maximum of radio granulation at 44" falls. Hence it follows that the vertical structure in the vicinity of the chromosphere—corona transition layer largely coincides with the structure of the middle chromosphere, and hence the main "hot" elements have a predominantly vertical geometry, i.e., their temperature and density depend mainly on height.

In Table II we present the results of studies of brightness fluctuations of solar emission carried out by various authors and our own results. Fluctuations of radio brightness with a characteristic scale of 50" were studied[8] on the basis of radio observations at 2.8 cm, and fluctuations with scales of 30-40" were studied [9,10] at 0.85 cm. Attempts to compare H α spectroheliograms and radio images of the sun [11] did not reveal any significant correlation. Kundu et al., [6] using a two-dimensional cross-correlation analysis, showed that elements of the structure of the undisturbed part of the solar disk at 6 cm are statistically related to the supergranulation visible on a filtergram in the Ca II K line. The size of the boundaries of supergranules in the radio images was 15", and the distance between the centers of adjacent cells was 44". In Ref. 5 three groups of characteristic sizes of radio granulation were found at 2-4 cm: 42-82, 102-156, and 190-280". In comparing the results of these papers with ours, we can talk confidently about the general nature of brightness fluctuations of solar emission in two ranges — optical and radio — at spacing of 30 and 44".

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Translated by Edward U. Oldham