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APPLICATION OF RECOVERING PROCEDURES TO RT-32 RADIO MAPS OF THE SUN

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The generalized maximum entropy method (GMEM) is proven to recover both positive and negative local microwave sources on the 2.7 cm maps of the Sun taken with the radiotelescope RT-32 of the Ventspils International Radio Astronomy Center (VIRAC). The maps of the Sun need to be recovered due to high intensity of the side lobes of the RT-32 diagram pattern − up to 30% at 2.7 cm. The presence of negative local sources associated with Hα filaments is inferred from the 2.7 cm maps of the Sun (RT-32) compared with the 1.76 cm maps of the Sun (Nobeyama Radio Heliograph).

1. INTRODUCTION

The observed radio map of the Sun can be represented as a true radio Sun image converted with the response function (diagram pattern) of a telescope and blurred by additive noise [1]. To evaluate the true radio map of the Sun the deconvolution problem should be correct, i.e. not amplifying additional noise and being solvable uniquely. Some additional information on the true radio map can convert the initial ill-posed problem of deconvolution to a correct one.

To obtain a clear picture, the blurred ("dirty") map of the Sun should be reduced to the map with the main lobe of a diagram pattern only. For this, two main nonlinear approaches exist: the first one is called CLEAN [2], and the second − the maximum entropy method (MEM) [1]. In the former, the algorithm of a clean image is generated from the dirty one as the sum of strong point sources until no more strong picks are left. It should be noted that the quiet Sun level poses a natural obstacle in this case. In the MEM procedure, the pixel radio intensities of the image are identified with individual probabilities, which are modified to provide the maximum of some "entropy".

The radiotelescope RT-32 of the Ventspils International Radio Astronomy Center (VIRAC) has an asymmetrical diagram pattern with some appreciable side lobes. To clear the solar radio maps an effective procedure is to be developed and adapted for the automated processing of a huge amount of the observational data. In this paper, some solar radio maps taken with the RT-32 are treated by three main approaches: the maximum likelihood (ML) method, the CLEAN and the MEM procedures. The reviewed results will help to specify the most appropriate method for recovery of the local solar sources.

The deconvolution of a radio image serves for correction of the instrumental effects and observation conditions (identification of local sources in a crowded field of the solar disk, removal of asymmetric diagram pattern artefacts, etc.). The observed image D is the convolution of true radio brightness I and diagram pattern A of a radiotelescope with some additive noise N:

$$D(x,y)=\int_{\Omega} I(x',y')A(x-x',y-y')dx'dy'+N(x,y)\,.$$

Usually, it is required to determine I knowing D and A values. The problem is generally ill-posed, i.e. not producing a unique and stable solution. To make the problem correct, we need some additional information to be added to the problem, e.g., by regularization [3]. The inverse problem involves difficulties arising from the additive noise and the spatial cut-off frequency of the diagram pattern. Within an apparently simple procedure of recovering the radio brightness I in the space of spatial frequencies with the help of inverse Fourier's transformation, $I(x,y) = F.T.^{-1}[\, F.T.[D(x,y)] \,/\, F.T.[A(x,y)]\,]$, the noise N cannot be neglected.

In this paper, we explore the widespread methods of deconvolution − the ML, MEM, and CLEAN, and verify the properties of the radio maps of the Sun taken with the RT-32 at the wavelength 2.7 cm, having applied more advanced versions (e.g. a generalized MEM [4, 5] and the method of inversed filtration [6]). The experience gained by the authors of [7] who employed the spatially-spectral MEM is also of great interest, as we are intending to make use of the information obtained at neighbouring frequencies using a new solar radio specropolarimeter at VIRAC.

2. SOLAR OBSERVATIONS WITH THE RADIOTELESCOPE RT-32

Among some tens solar maps we have sampled the one obtained with the RT-32 in September 12, 1999. Its parameters are: the rate of azimuth stripping − 3' per second, with the sampling rate of 0.2 s per point; the inter-strip interval − 2' in elevation, with a half-power beam width of the RT-32 diagram of about 3'.5 and the side lobes up to 30% at the wavelength of 2.7 cm (Fig. 1). The system temperature of the radiotelescope was about 100 K, with the recording time constant of 0.25 s. In view of gridding and centring of the scans with coordinates related to the solar disk centre, the points on the maps are taken to be 20" exactly.

In the figure, the peak radio brightness of the microwave local sources (LSs) *A– D* is $1.9–5.9\cdot10^3$ K above the quiet Sun level, which is some tens times higher than the variance of the radio signal at the quiet Sun level of about 150 K. The peak brightness of LS is determined by referring it to the radio brightness at the centre of solar disk (11400 K at 2.7 cm [1]). The apparent dark sources *a–c* on the disk (which somehow correlate with the quiet Hα filaments) seem to be reliable.

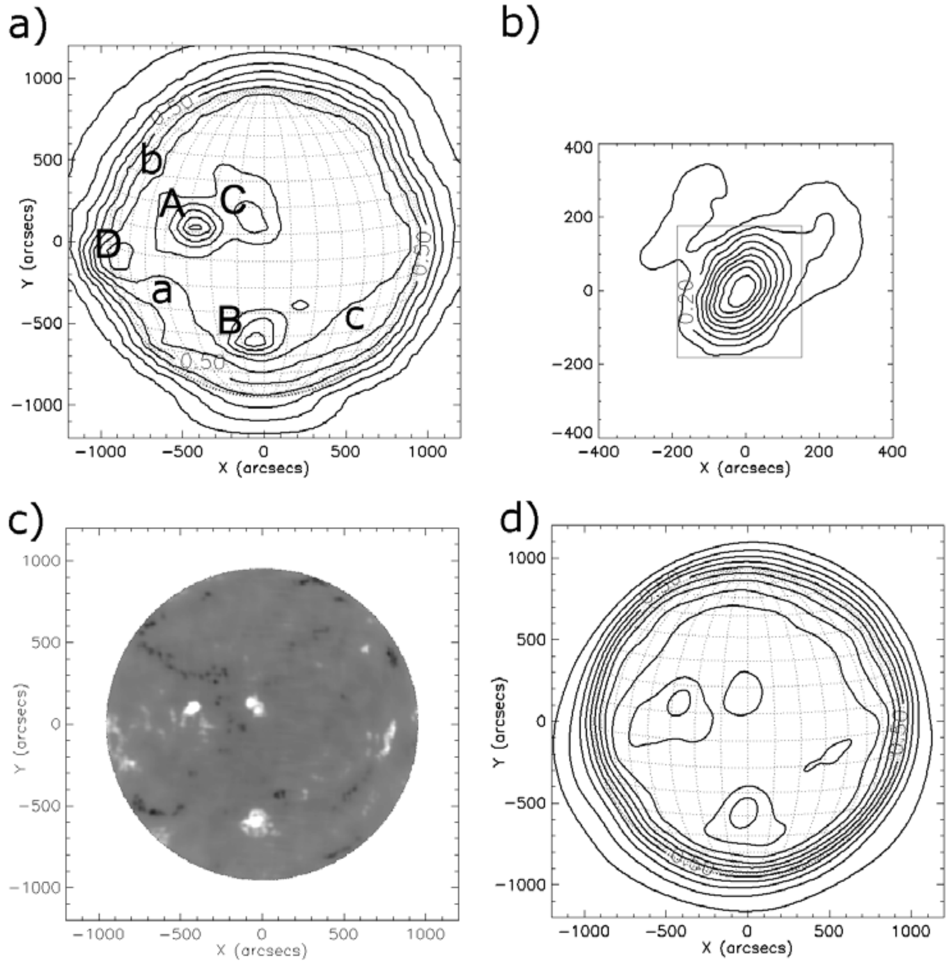

Fig. 1. The maps of the Sun (Sept. 12, 1999).

(a) The RT-32 2.7 cm map with the step of 0.1 for radio brightness levels and the horizontal direction toward the radio stripping.

(b) The point radio source Cyg *A* is used as the RT-32 diagram pattern (the radio flux ratio "side lobes /main lobe" is 0.39:0.61).

(c) The NoRH 1.76 cm map is adjusted to the time of RT-32 radio observations (11:24 U.T). (*d*) The NoRH map of the Sun is convolved with the RT-32 diagram pattern.

In our observations we have faced a problem of determining the shape of the quiet Sun. It is a difficult task to reveal the constant level of the quiet Sun if the rotational asymmetry of the observed maps does not keep constant from map to map. The problem is to be solved in the future with a more exact position obtained for radio strips of the Sun. The diameter of the Sun equal to 34'.75 observed at 2.7 cm is about 1.5 angular minutes wider than the diameter of 33'.25 restored (see [1]) and convoluted with the RT-32 diagram (Fig. 2). We suggest that the widening was due to the near-limb activity observed in September 1999. In this paper, we use the circular symmetrical shape of the quiet Sun [1] to add it to the recovered LSs on the solar disk.

The 1.76 cm solar emission is known [8] as optically thin or optically thick gyroresonance or bremsstrahlung radiation originating from the outer chromosphere of the quiet Sun or from the chromosphere-corona transition region above large solar sunspots. As for dark Hα filaments, it has a negative contrast at the shortest microwaves and merges with the quiet solar chromosphere at some cm long wavelengths. Despite such differences, we have taken the Nobeyama Radio Heliograph 1.76 cm maps as reference to compare with the RT-32 2.7 cm maps shown in Fig. 1. Rather a good correlation could be noticed for the maximum radio brightness of bright sunspot-associated *A–D* sources at 2.7 cm and the peaks at 1.76 cm, provided that the 1.76 cm radio map is adjusted to the time of RT-32 radio observations with the help of IDL Mapping Software [9] (Fig. 1*d*). Some filament-associated 1.76 cm sources are supposed to be identified with the *a–c* sources on the 2.7 cm maps.

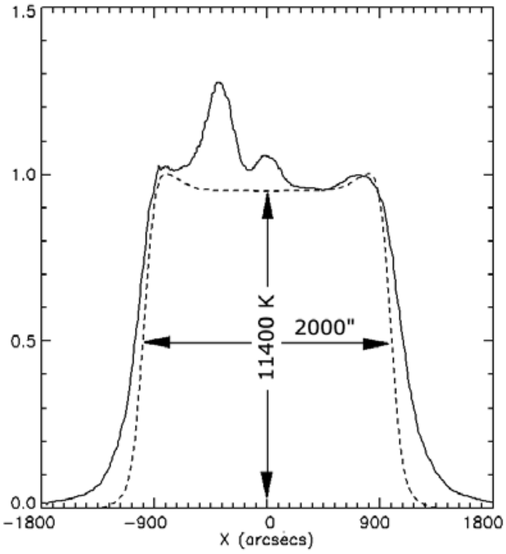

Fig. 2. The central scan of the radio map of the Sun taken with the RT-32 at 2.7 cm on 12 Sept., 1999 (dashed line in Fig. 1*a*) overlaps the quiet Sun contour ([1], dashed line) convolved with the main lobe of the RT-32 diagram. The central scan is normalized to the radio brightness of 11400 K in the centre of the solar disk.

3. RECOVERY PROCEDURES

Recovery procedures are supposed to reform the microwave solar maps taken with the poorly formed diagram pattern of the RT-32 and to provide the recovered large-scale structures on the solar disk. Apart from that, they are meant to condense the observed data volume and to make the maps in Stokes I and V commensurable.

The subtraction of the quiet Sun before recovery is considered advisable (despite our poor knowledge of the quiet Sun). An appropriate microwave model for the quiet Sun is found to be a nearly uniform disk with a limb brightening [1].

The comparative approaches to a true (adequately recovered) radio map of the Sun can be characterised as follows.

1. The approach of the CLEAN procedure assumes that the image is composed of point sources. To decompose the image (a dirty map) into a set of Dirac's delta functions this procedure iteratively finds the largest brightness point, subtracting the dirty beam scaled down to the product of the radio intensity at that point and the loop gain. The residual map is used to repeat the iterative process, which is stopped when some specified limit is reached. The convolution of the delta functions with an ideal main beam plus the residual is taken as the recovered image (a clean map). Such solution presumes no large-scale structures within an initial image.

2. The maximum likelihood (ML) solution maximizes only the conditional probability density of the observed map (data) for a given recovered image. The probability density of the observed image is considered as a constant which does not affect the maximization. If the prior probability of the restored image is considered uniform, we are dealing with the ML method.

The maximum entropy method (MEM) differs from ML in deriving the probability of the restored image from its entropy. Several entropy functions are in use [10]; in this paper the Shannon entropy function $S(n) = \sum n \ln(n)$ is employed.

It is generally accepted that the recovering methods like MEM and ML work better than the CLEAN method for extended structures as the last is insensitive to the size and position of the extended faint sources. In turn, the CLEAN deals with the exact maxima of the local sources and preserves the positions. To find the difference we started with the ordinary form of the above procedures.

As all sources brighter than a quiet Sun are subtracted, no sources darker than this level can appear on the recovered solar maps (Fig. 2). Thus, the negative microwave sources associated with the filaments (*a, b, c* in Fig. 1) are missed.

When divided by variance σ^2 (as a measure of the measurement errors), the residuals turn to be less profound. Nevertheless, the sources with significant radio brightness should be eliminated from the residuals to emerge in the recovered image of the local sources on the Sun.

We have tested the NoRH image (normalized to the maximum radio brightness of the RT-32 map) as an initial guess on the clear image in the first run of ML procedure. The resulted map is similar to that with the averaged data in the framework of the initial guess.

3. The MEM procedure provides the closest positions of the maxima of local sources with regard the NoRH map (r.m.s. displacement of 35″). The MEM accuracy differs only slightly from those of the initial RT-32 map (r.m.s. displacement of 42″) and the CLEAN map (45″). The corrected radio brightness and size of the local sources are assumed to provide an improved radio flux at 2.7 cm.

4. The modern developed procedures that deal with negative sources are of especial interest for our purposes. Figure 4 shows two versions of a detailed structure for both the positive LSs and the negative filament-associated sources on the Sun (cf. Fig. 1*c*). Finally, two numerical methods are taken to be the best approach to the solar map recovering, namely the GMEM and the inverse filtration. Both the positive and the negative microwave sources, as regards the quite Sun level, are taken into account in the Generalized MEM method [4, 5] and in the inverse filtration. While the GMEM separately represents the radio brightness of positive and negative sources, the inverse filtration benefits from an additional positive term in the denominator. The additional term of 10^{-4} in the denominator of the inversion filter improves the resolution by reducing the effect of side lobes.

These procedures, which are adjusted to the RT-32 maps, seem to provide a complete and detailed recovery of all the microwave local sources on the Sun (Fig. 4) and thus should be chosen for the future analyses.

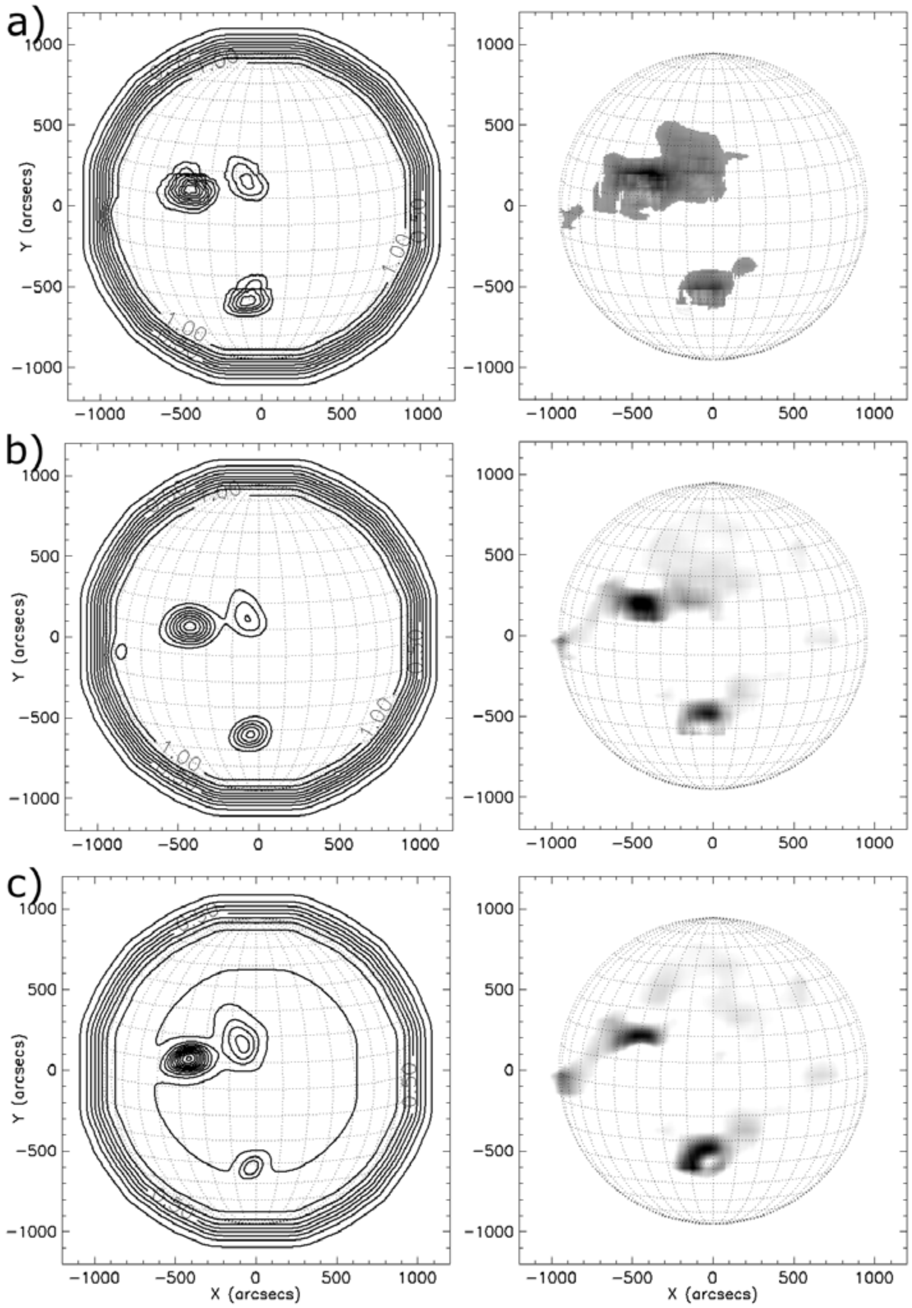

Fig. 3. The maps recovered from the RT-32 map of the Sun (Sept.12, 1999, Fig. 1*a*) and the residuals:

(a) CLEAN procedure: $\gamma = 0.37$, iter = 60; the quiet Sun model and the recovered local sources are convolved with the main beam of the RT-32 diagram pattern separately; the total radio flux of LSs is conserved; residuals are in the range –0.07–0.24;

(b) ML procedure: residuals are in the range 0–0.19;

(c) MEM procedure: residuals are in the range 0–0.24.

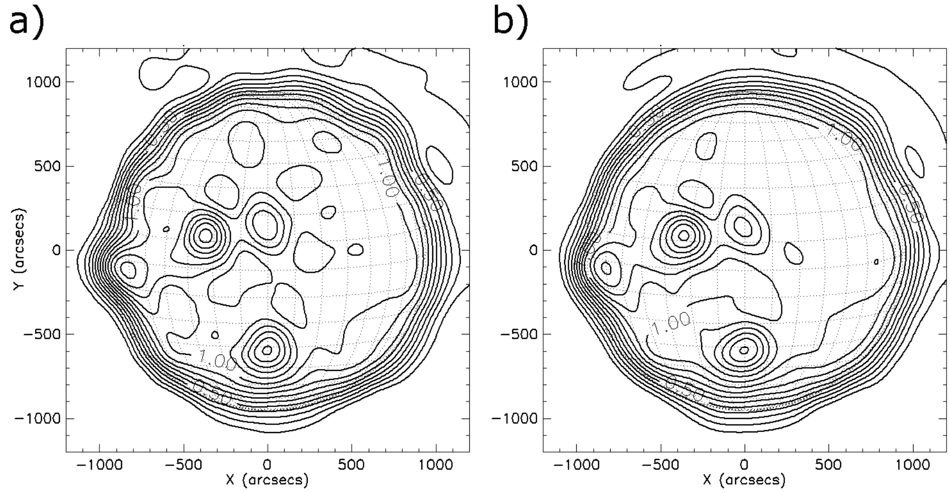

Fig. 4. The maps recovered from the RT-32 map of the Sun (Sept.12, 1999, see Fig. 1*a*) by two developed procedures:
(*a*) GMEM procedure: $\alpha = 10^5$, iter = 100. Model Quiet Sun and local sources are convolved with the main beam of the RT-32 diagram pattern separately.
(*b*) Procedure of inverse filtration.

4 CONCLUSIONS

1. All the procedures (CLEAN, ML and MEM) make the bright microwave local sources associated with sunspots more contrast on the solar disk. The roughly approximated images of these sources are obtainable by any of these procedures.
2. The comparison of the RT-32 map of the Sun obtained at 2.7 cm with the 1.76 cm NoRH map being convolved with the RT-32 diagram pattern (Fig. 1) makes the negative local sources on the solar disk clearly discerned. The early version (Fig. 3*c*) of recovering procedures cannot restore the negative sources that are below the quiet Sun level and are associated with dark Hα filaments. Thus, the initial "dirty" maps are much more informative than those recovered by the known CLEAN, ML and MEM procedures (Fig. 3).
3. The routine of stripping the Sun with the RT-32 beam should be optimised.

   Since the acquired maps of the Sun are rare stripped over a too short distance, the inter-strip distance should be halved to keep all the accessible information in the case of 2.7 cm solar observations. The stripping rate should be adjusted to the width of the RT-32 beam. It is suggested that our early trial to subtract the quiet Sun level failed due to an unidentified cause.
4. The correlation of the 2.7 cm RT-32 maps of the Sun with corresponding 1.76 cm NoRH maps is evidence for the reliable images of the 2.7 cm RT-32 local sources on the Sun. The 3σ noise level is about 3–5 times lower than in the case of bright local sources.
5. The modern procedures of the Generalized MEM and the inverse filtration (with an additional term) are taken as those capable of recovering all the reliable local sources of the solar radio maps acquired with the RT-32 [4, 5]. In these cases the recovered maps conserve the negative microwave sources

associated with Hα filaments on the solar disk, with the adequate positions of all local sources. Therefore the modern procedures of the GMEM and the inverse filtration can successfully be applied in these cases.

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ATJAUNOŠANAS METODES PIELIETOŠANA RT-32 SAULES MIKROVIĻŅU KARŠU NOTĪRĪŠANAI

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K o p s a v i l k u m s

Parādīts, ka vispārinātā maksimālās entropijas metode ļauj izdalīt un konstatēt gan pozitīvus, gan negatīvus lokālos mikroviļņu avotus ar Ventspils Starptautiskā radioastronomijas centra (VSRC) radioteleskopu RT-32. Tā kā RT-32 sānu lapu ieguldījums uztvertajā starojuma plūsmā sasniedz 30%, ar tā palīdzību iegūto Saules karšu tīrīšana ar skaitliskām metodēm ir nepieciešama. Salīdzinot RT-32 2.7 cm kartes ar Nobeyamas radioheliogrāfa 1.76 cm kartēm, parādīts, ka negatīvie lokālie avoti ir saistīti ar Hα šķiedrām.

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