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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Radiophysical Research Institute (NTRFI) as follows: The contractor will investigate techniques of high frequency solar radars and receiving antennas to detect mass motions in the solar corona such as solar mass ejections. Testing will be accomplished and solar data taken using the Sura Radar Facility and the UTR-2 Receiving Antenna as described in the proposal.

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"The Use of High Frequency (HF) Solar Radar to Detect Coronal Mass Ejections(CMEs)"

RRI Director, Dr. S.V.Polyakov

***1998**

1. Introduction.

It is recognized that coronal mass ejections (CMEs) at the sun can have deleterious effects on geosynchronous satellites, communications systems, and power grids. Such space weather effects on the earth's geospace motivate experiments to detect earthward-directed CMEs before they impinge on the earth [Rodriguez,1996].

The first experiments of the US Naval Research Laboratory (NRL), related to CMEs detection showed the real possibility of regular early warning of the geo-effective solar events. These experiments were carried out with the Russian HF radar SURA, located at Vasil'sursk, near Nizhny Novgorod (RRI) and with the Ukrainian Great Radiotelescope UTR-2, Grakovo, near Kharkov, Radio Astronomical Institute (RAI) [Rodriguez,1997; van't Klooster et al, 1997].

The experiments have motivated a new cycle of joint experiments for CMEs detecting in the summer 1997, which were entitled as the project "The Use of High Frequency Solar Radar to Detect Coronal Mass Ejections". The project is an extension of the first experiments on HF sounding of the sun. In this report we present the results which were obtained at the SURA facility (see a description in the preliminary report).

The most important requirements for investigation of CMEs is a development of adequate instruments, new methods for space plasma testing, and a regular monitoring of the sun with the appropriate technique and specially designed annual schedule. The experiments of 1997 year session as well of 1996 have been implemented during the quiet sun period, thus we have as a main objective the development of a reliable technique to detect reflections from the solar corona. As has been previously shown CMEs events would only increase the radar cross section, thus the technique developed will provide positive recognition. The information and experience gained by these experiments will be directly applicable to all future systems operating in the geospace environment and for the study of CME interaction with the interplanetary medium [Int.STEP Newsletter, vol 3, N3, Sept 1997].

During the project performance period the following basic results were implemented:

- the model of a back scattering of HF radar signals in solar corona for 9 MHz frequency vicinity has been developed *(section 2.1);*

- the statistics for interference levels at the frequency 9 Mhz for the Kharkov (Ukraine) region has been studied *(section 2.2);*

- technical parameters of coding for most reliable detection of radar signal reflected by solar corona as well as CMEs were developed *(section 3.1);*

- the interferometric technique for solar observations by the SURA radar at zenith angles more 40 degrees has been tested *(section 3.3);*

- data traces were provided to compare the single propagation paths "Earth (SURA) - Moon","Earth (SURA) - WIND", with the double propagation path "Earth (SURA) - Moon - Earth (UTR-2)". *(section 4).*

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2. The object and propagation media investigation.

In summer 1997, the 9 MHz solar radar tests were mainly to develope the technical parameters needed to allow investigation of:
- the physical conditions in solar corona and in medium of wave propagation for backscattered SURA signals;
- interferences levels in permitted frequency bands at the UTR-2 site.

2.1. Solar corona model.

After discussion with the Russian experts, it has been proposed that in the most cases, a volume scattering from the reflection layer R = 4-5 Rs will be most likely, because corona has complex structure, even in solar minimum [I.Chashey, V.Shishov, Radiotechnics & Electronics, (in Russian), 1992. v.37. No.4. p.612]. For R = 4-5 Rs in current phase of solar cycle the bulk velocity of solar wind is V = 50 km/s, which corresponds to Doppler shift df = +1.5 kHz; and the velocity of chaotic motion is Vt = 100 km/s, which corresponds to monochromatic signal broadening sf = 3 kHz. As a result of vector summation of these velocities the effective bandwidth for receiving of solar echoes can be estimated as 6 kHz, from -1.5 kHz up to +4.5 kHz relative the frequency of sounding. It is also possible that rare events (CME or others) will have V = 200-300 km/s and Vt << 100 kHz, so that df = 6-9 kHz, sf < df.

The same parameter range can be obtained if we analyse the experiments performed by James [1968], when the sun was sounded at the frequency 38 MHz. It is necessary only to scale the values of df and sf used by J.James to the frequency of operation of SURA and UTR-2. It has been assumed that the reflected signals (9 and 38 MHz) are formed in the same physical conditions in the middle part of solar corona, using a model density profile [Allen,1973]. So we expect the return pulse is spread in both Doppler and range.

These results led to the selection of:
- the radiated frequencies separation for the SURA signals;
- the appropriated UTR-2 receiving bands (see final report on the project would be performed by RAI).

2.2. Interferences.

A specific feature of radio waves HF band is a great level of interferences of natural and industrial origin. The problem of interference impact to S/N in radar experiments is important for the receiving (UTR-2) site. The SURA facility can simultaneously transmit a few frequencies to allow tests for selection of the frequency with the least interference. The priority in selection of radiated frequencies was in favor of the least noisy frequency at the receiving site, i.e. at UTR-2. Every day, before the starting of sounding, the interference levels were studyed at UTR-2 by means a spectrometer; and using a telephone "hot line" between UT-2 and SURA, the choice of the mostly "clear" frequencies for transmitting was made. The most often used frequency values were: 8913 kHz; 8926 Khz; however, as was proposed in our preliminary report; 8953 kHz also was used sometimes, when it was "clear" and was used to replace 8926 kHz.

3. Techniques of solar radar experiment.

3.1. Coding

In the current quiet sun period, to recognize echoes from solar corona, attention was paid mainly to the following calibration procedures.

Our evaluations show that the signal to noise ratio (Ps/Gs) is very small. This quantity was calculated for the spherical (R = 4-5 Rs) average radar cross section in quiet sun conditions, and it was estimated as a value 0.02 +/- 3 dB.

A coding method to increase the probability of recognizing reflected signals was was developed for the volume scattering model of corona.

As it follows from the modelled dimension of scattering layer, the duration of echo would be expected as a value of 10 - 20 s.

The phase modulation (PM) technique (which decreases the error probability by 4 times) would permit to use the pulse time durations near "n" ms only, because of the Rayleigh scattering referred to velocities near 100 km/s. Therefore the amplitude modulation (AM) technique was chosen.

It is known [Klovsky,1973] that the minimal error probability for the AM case depends on the argument **(Ps*T/Gn),** where **Ps** is the averaged power signal; **T** is the duration of integration, and **Gn** is the noise flux density.

The maximal integration time is limited by the value of Sun-Earth distance i.e. 16 min. James (1968) has used for his experiments a maximal length random coding. However, specific features of 9 Mhz frequency signal propagation produce signal fluctuations at time intervals near "n" min. Thus after total discussion with NRL (US), RRI (Russia), and RAI (Ukraine) project participants it was proposed to use coding frame lengths N similar to the time scale intervals.

Taking into account the arguments given above, the requirements of maximum autocorrelation peak/sidelobes ratio, and of minimum energy losses for every code frame, the Barker codes corresponding to N = 4 and 7 were selected as transmitted signal coding during the 1997 summer session. Nevertheless, we used also a greater size frame length corresponding to an N = 43 bits quasi-periodic random code.
The advantage of long code has been discussed above, but the disadvantage are the losses related to sudden breaks of signal records (from interferences or short wave fades, for example).

To compensate and to avoid an interference impact to signals received at UTR-2, the SURA facility radiated at two frequencies sequentially, i.e. one frequency is radiated, while the second one is switched off; after an interval corresponding to one bit of the code, the second frequency is radiated, and the first frequency is switched off, and so on. Thus a full power transmitted signal is always present.

3.2. Technical parameters of solar sounding.
The complete schedule of coding and frequencies used are shown in Table 1.

Table 1.

Date	f0F2(MHz)	Freq(kHz)	Power (kW)	Mode
19.07	4.4	8926	160 250 250	ON-OFF (17.2 s)
		8913	- " -	OFF-ON
20.07	4.7	8926	160 250 250	ON-OFF (17.2 s)
		8913	- " -	OFF-ON
27.07	5.0	8953	160 250 250	ON(29.7s, 4 bit code)-OFF
		8913	- " -	OFF-ON(29.7s, 4 bit code)
28.07	5.4	8953	160 250 250	4 bit (29.7 s)
		8913	- " -	
29.07	4.7	8953	160 200 250	43 bit code during the
		8913	- " -	session with 1 bit=21.6s
30.07	4.8	8926	160 200 250	4 bit (29.7 s)
		8913	- " -	
31.07	5.4	8926	160 200 250	4 bit (29.7 s)
		8913	- " -	
01.08	4.4	8953	160 200 250	7 bit (29.4 s)
		8913	- " -	
02.08	4.7	8953	160 200 250	7 bit (29.4 s)
		8913	- " -	
03.08	5.0	8953	160 250 250	7 bit (29.4 s)
		8913	- " -	
04.08	6.3	8926	160 200 250	43 bit (21.6 s)
		8913	160 250 250	
23.08	5.1	8916	- 230 250	beam steering (9.2 s)
24.08	4.7	8916	- 230 250	beam steering (9.2 s)
25.08	4.8	8916	- 230 250	beam steering (4.75 s)

The time of every sounding was selected to a condition when in the middle of transmission period (15.8 min) the sun would be in the maximum of antennas main beam. The radar beam is oriented in the plane of the Earth's magnetic meridian to zenith angles near 2-3 degrees above the sun's direction in order to take into account the ionospheric refraction. An exception are the experiments on the dates 23-25 Aug, when the sun's position was below the main beam orientation and the interferometric technique with beam steering was used to reach the sun (see below in the section "Interferometer").
Remarks: ON and OFF means a presence or absence of the frequency radiation.

3.3. Radar interferometer.

During the summer 1998 radar test it has been suggested to use a technique with steering of interferometer beam. The steering is provided by a small difference of signal frequencies radiated by neighboring sections of SURA array.

It is easy to show that in an interferometer consisting of two elements with the baseline separation **"B"**, and with a small difference of frequencies radiated by the elements, the interferometer output will be modulated in amplitude. The modulation period is given by the inverse of the difference of frequencies.

The steering angle **"Delta (Z)"**, where **Z** is the zenith angle, can be determined from the: finite increment of interferometric phase, as shown by the expression:

$$\mathrm{Delta}(Z)*B*2*\pi*\cos(Z)=\pi.$$

For our experiments, the baseline B can be either 100 m or 200 m (corresponding to one or two section dimensions of the SURA array), resulting in a steering angle of +/- 10 degrees.

The advantage of the technique is that greater Z angles can be reached by the SURA array, permitting tilts of the main beam up to 40 degrees. This technique was used in August when the sun could be seen at Z=45 degrees. We propose to continue a studying of the technique for its promising possibilities to prolong the season of radar tests.

4. The lunar sounding

As it has been preliminarily reported [van't Klooster et al., 1997], in 1996 for the SURA/UTR-2 joint experiments the moon echoes received at UTR-2 were at 30 dB average above background signals.

In order to help calibrate the characteristics of the SURA/UTR-2 bistatic radar configuration for the 1997 solar radar tests, moon sounding tests were done on dates shown in the Table 2.

On July 29 and 30 the WIND spacecraft was in a suitable position near the Moon's vicinity, to permit detection of moon echoes by the receiver RAD-2. Simultaneous signal/noise ratios measured at the WIND and UTR-2 receivers would permit us to compare propagation traces losses for the Kharkov site. Pulse widths and periods were selected for separation of signals reflected from the Moon, which must be distinct at the both WIND and UTR-2 receivers (see Table 2).

Table 2.

Date	UT	foF2(MHz)	Freq(kHz)	Power (kW)	Mode
29.07	05:00-05:40	4.5	8925	160 250 250	T=455,tau=84 ms
30.07	05:55-10:35	4.6	8925	160 200 250	T=463,tau=84 ms
01.08	07:33-08:13	4.4	8913	- 210 -	T=10.388,tau=0.2 ms
			9210	- - 250	
02.08	08:22-09:02	4.6	8953	- 200 -	T=5,tau=1.2 s
			8913	- - 250	
04.08	09:54-10:34	5.3	9210	- 240 -	T=5,tau=1.2 s
			8913	- - 250	
25.08	03:00-03:40	4.5	8916	- - 250	T=1,tau=0.2 s
26.08	03:50-04:30	4.6	8916	- - 250	T=1,tau=0.2 s

5. The WIND spacecraft as a calibrator.

On July 19 and 20 and on August 24 and 25, the apparent position of the WIND spacecraft was near the sun's apparent position. Continuous wave (CW) signals from SURA were radiated and received at RAD-2, which operated in fixed-frequency mode on special requests to NASA.
An analysis of signals received provides a study of the ionosphere propagation losses of signal transmissions during sounding of the sun.

A difficulty we met in this study was a high input temperature of the RAD2 receiver: the observed background level was more than cosmic background. To investigate this problem special experiments of common calibration of the RAD1 and RAD2 receivers at the range of 1-1.4 MHz were organized by RRI with GSFC NASA (December 1997 - January 1998). Our estimates shown that the calibration level of the RAD2 is near +8 dB above RAD1 in the common frequency range. It is suggested that for our usual set of sun sounding frequencies (near 9 MHz) the same difference for observed background level is present.

To assume this result implies that the main loss factor of solar soundng signal in the path "SURA-WIND" is ionospheric wave absorption. Under the noontime conditions when the solar sounding experiments were performed the trace losses were near 3 dB.

6. Sun activity monitoring.

During the 1997 session good support for monitoring of sun's activity was the SOHO s/c data from LASCO instrument which was available via INTERNET (http://sohowww.nascom.nasa.gov). For example, the 43-bit code was used accordingly to the SOHO forecast was for "quiet" sun conditions.

7. Resume

The schedule of tests planned in preliminary report was realized successfully at the frequency range of 9 MHz with the effective power 120 MW. The ionospheric cut-off frequency did not exceed 5.5 MHz. The main loss factor was the ionospheric traces losses which were less than 3 dB for the operating frequency.

Non-linear effects related to the great power transport through the ionosphere were not evident. New techniques, which were based on the solar corona model and the statistics of interferences in the Kharkov region, have been developed.

A new interferometric technique to prolong the SURA operating season of the sun radar tests has been suggested. A method of control of the sounding signal by means of s/c WIND has been improved.

Solar activity will start to increase as the solar cycle advances. The CME phenomena could be well resolved in the current period, when there are not too many active solar events, but nevertheless, occurring frequently enough. Thus it would be the most suitable time to continue the project of CME detection with the background of methods and techniques which have been developed.

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