Feasibility of Cosmic Object Detection Using a Solar FSR System

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***Abstract*—The article analyses the possibility of the forward scatter radar method for detecting large-sized cosmic objects when using emission of the Sun as probing signals. The method of the forward scatter radar is based on the phenomenon of a significant increase the bistatic target radar cross section when the probe signal is scattered forward, i.e. along direction of the principal beam of locator pattern.**

Keywords—diffraction, forward scatter effect, radar

I. Introduction

Forward Scatter Radar (FSR) radar belongs to the class of bistatic radar or spaced radar systems. Such a radar has a number of advantages in comparison with a monostatic radar, which consist in the possibility of implementing the method based on the Forward Scatter (FS) effect. This effect is that when any object is irradiated, the linear dimensions of which are several times more than the wavelength emitted by the transmitter, the energy scattered backward is several orders of more magnitude less than the energy scattered forward along the irradiation line, as a result, the effective scattering area (Radar Cross Section - RCS) of an object when observed in a bistatic FSR system is thousands of times greater than the RCS of the object in the traditional monostatic radar[1]. Over the last 10-20 years, space protection from asteroids and meteorites has been carried out by almost all developing countries using telescopes and radio telescopes. Unfortunately, there are many publications show that the preventive detection of large and small flying space objects with the available surveillance radars together with the radio telescopes is not effective enough, as about 30% of the alleged sites are detected. Recently, many authors have described FST systems, they are produced and sold in Russia to protect air, sea borders as well as for space surveillance [1-5]. One of the drawbacks of the FSR radar is the presence of a strong direct signal from the transmitter, which is necessary to be suppressed before the detection of the object. In order to increase this percentage of discoverable cosmic objects, we offer a new approach for space observation of small space objects based on bistatic FSR passive systems with different natural and artificial irradiators. In [2, 3, 4], it is proposed to use FSR systems, where the radio pulsars and satellites are used as an alternative sources of signals, to protect the Earth from unwanted space objects. The idea of this paper is to theoretically examine, by the Signal-to-Noise Ratio (SNR) criterion, the feasibility of detection of cosmic objects at far distances from the Earth, by the FSR system that uses solar radio radiation, using the star Sun for the irradiator in the visible frequency diapason (Fig. 1).

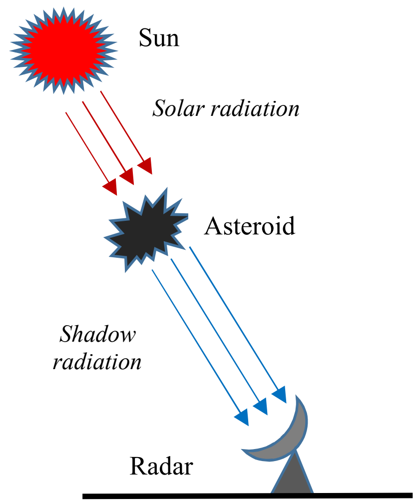

Fig. 1. Topology of a Solar FSR system

The use of the Sun as an irradiator has its additional advantages, for during the day, observations of space with such a FSR system can be made when telescopes can not watch it. The atmosphere of the Earth reflects, absorbs, or scatters most incoming electromagnetic radiation. There's a window in the visible range, some partial windows in the infrared, and a big broad window in the radio frequencies (including some frequencies that are classified as microwave). In between, there's a nice radio window that lets scientists see into space, and to see the Sun in radio frequencies (Fig. 2). The proposed FSR system exploits the Sun as a transmitter and a ground-based radio telescope as receiver. The feasibility of shadow target detection is estimated in terms of the magnitude of SNR at the input of the signal detector calculated depending on the size of cosmic objects and their distance from the radio telescope on the Earth, after compensation of the direct signal using signal generated by the direct signal model, time or frequency selection.

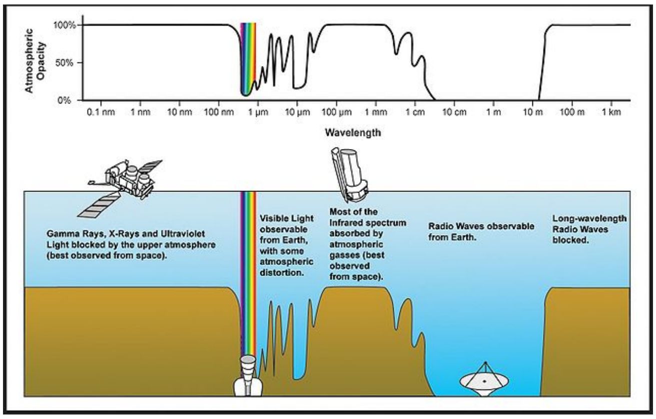

Fig. 2. From NASA public domain

II. Signal Processing

The general block diagram of the possible signal processing in a solar FSR system is shown in Fig. 3.

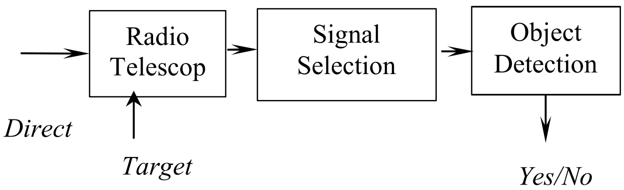

Fig. 3. General block diagram of signal processing

The use of the forward scatter effect initially suggests the location of the receiver (radio telescope) on the other side of the object relative to the transmitter (Sun). The FSR systems have a small area of coverage (in the vicinity of the baseline between the transmitter and the receiver) and a small delay of the scattered signal relative to the direct transmitter signal, which directly arrives at the receiver input. The main problem of the solar FSR system is a typical for the other FSR systems. It is the presence of a strong direct signal from the transmitter, which must be removed or compensated in the input signal from the object. In the FSR systems, unlike the bistatic ones, only one antenna is used. This is because only at very large bistatic angles, the difference in the distance of the shadow signal and the direct signal is very small, the propagation time is almost the same, and synchronic coherent processing between these signals and Doppler processing can be used. In this case we have a system with external coherence. The disadvantage of FSR systems is that they not have resolution on distance, but they as any coherent system have Doppler resolution and can resolve targets on speed when there is the necessary SNR for target detection. In our estimates, we consider the case where the FSR RCS of the target has the maximum, i.e. at very large bistatic angles (around 180^0). For extraction of the shadow signal from input signal, created by the object, can be used the compensation with signal generated by advance formed direct signal model, time and frequency selection of signals.

III. Power Budjet of a Solar FSR System

In a solar FSR system, the Sun is used as a transmitter and a radio telescope is used as a receiver. In the absence of the object on the baseline "transmitter-receiver", at the receiver input arrives a direct unobstructed signal from the sun $\mathbf{U}_{direct}$. However, if any object is located on the baseline "transmitter-receiver", the direct signal $\mathbf{U}_i$ is completely or partially blocked by the object (Fig. 1). In this case, this blocked signal at the receiver input $\mathbf{U}_{Rx}$ can be represented as a sum of the direct unobstructed signal $\mathbf{U}_i$ and the blocking shadow signal $\mathbf{U}_{shadow}$ [6-9]:

$$\mathbf{U}_{RX} = \mathbf{U}_{direct} + \mathbf{U}_{shadow} \tag{1}$$

According to the principle of Babinet, the direct incident radiation and shadow radiation, created by an opaque object, have opposite phases. Consequently, the envelope on the summed signal at the receiver input is determined as:

$$|\mathbf{U}_{RX}| = |\mathbf{U}_{direct}| - |\mathbf{U}_{shadow}| \tag{2}$$

According to the theory of physical optics, the exact mathematical description of the shadow field that creates the object can be made based on the diffraction of Kirchhoff-Fresnel [4]:

$$\boldsymbol{U}_{shadow} = \frac{j}{\lambda} \iint_Q U_{direct} \frac{\exp(-jkR)}{R} dq \tag{3}$$

In (3), Q is a silhouette area of the object, dq is a small part of the area of the object silhouette, R is a distance from that part to the receiver, and λ is the wavelength of emission (Fig. 4).

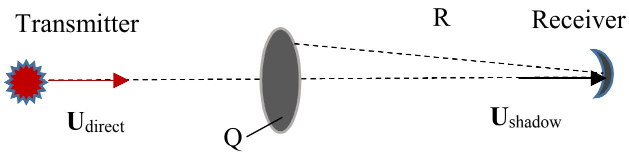

Fig. 4. Geometry of the shadow field

According to [5], a shadow field does not depend on the shape or material of the shadowing object but is entirely determined by the size and geometry of the object's silhouette. When the object is far enough away from the transmitter and receiver (far diffraction zone), it can be assumed that:

- the direct field $\mathbf{U}_{direct}$ from the sun is distributed evenly over the area of the object's silhouette;

- the value of R almost does not change with a change in the position of dq on the area of the object silhouette.

In the far zone of diffraction, the integral (3) takes the form:

$$\boldsymbol{U}_{shadow} = \frac{j\exp(-jkR)}{\lambda R} U_{direct} \iint_Q dq \quad (4)$$

After integration the equation (4) takes the form:

$$\boldsymbol{U}_{shadow} = \frac{j\exp(-jkR)}{\lambda R} U_{direct} Q \quad (5)$$

From (5) follows that the envelope of the shadow signal is:

$$|\boldsymbol{U}_{shadow}| = U_{shadow} = U_{direct} Q/(\lambda R) \quad (6)$$

Where U_{direct} is the envelope of the signal transmitted from the Sun and measured at the object. Taking into account the equations (2) and (6), we obtain the following expression for the envelope of the received signal:

$$|\boldsymbol{U}_{RX}| = U_{RX} = U_{direct}(1 - Q/(\lambda R) \quad (7)$$

From (7) follows the limitation for the far zone of diffraction:

$$Q/(\lambda R) \leq 1 \quad (8)$$

From (8) follows the further requirement for the distance R in the far zone of diffraction:

$$R > Q/\lambda \quad (9)$$

In the bistatic FSR system, for the detection of air objects is used the difference between the direct signal from the transmitter and the obstructed signal received from the object:

$$U_{detect} = U_{direct} - U_{RX} = U_{shadow} \quad (10)$$

The Signal-to-Noise (SNR) at the detector input can be approximately estimated as a ratio of the power the useful signal P_{detect} and the receiver noise power P_{noise}:

$$SNR = P_{detect}/P_{noise} \quad (11)$$

The power of the useful signal can be as:

$$P_{detect} = U_{detect}^2 = U_{shadow}^2 = U_{direct}^2 Q^2/(\lambda R)^2 \quad (12)$$

The equation (12) can be rewritten as:

$$P_{detec} = P_{direct}\sigma_{FSR}/(4\pi R^2) \quad (13)$$

In (13), $P_{direct}=U_{direct}^2$ is the power of direct signal from the sun incident on the object. The parameter σ_{FSR} is the bistatic Radar Cross Section (RCS) in the forward scatter radar, which is defined as:

$$\sigma_{FSR} = 4\pi(Q/\lambda)^2 \quad (14)$$

The power of the direct signal can be estimated using the flux density of the solar emission:

$$P_{direct} = SA_{eff}B \quad (15)$$

In (15), S is the flux density measured in terms of $\mathrm{wm^{-2}Hz^{-2}}$, A_{eff} is the effective area of the receiver antenna, and B is the frequency bandwidth of the receiver. The noise power of the receiver can be estimated as:

$$P_{noise} = kT_{sys}B \quad (16)$$

where T_{sys} is the system temperature of the receiver, and k is the Boltzmann constant. In result of combining the equations (13), (15) and (16), the expression for SNR takes the form:

$$SNR = \frac{SA_{eff}}{kT_{sys}} \cdot \frac{\sigma_{FSR}}{4\pi R^2} \quad (17)$$

It must be kept in mind that the expression (17) can be used to evaluate SNR it only if condition (9) is fulfilled.

IV. Numerical Results

In our solar FSR system, we consider the radio telescope with an antenna, the diameter of which is 25m, as a receiver, the Sun as a transmitter, and the cosmic object as a target of detection. The spectral frequency density (flux) of solar radio radiation depends on the frequency, at which the receiver receives the solar radio radiation. The values of the solar flux (1 SUF is equivalent to 10^{-22} watts per square meter per hertz) are given in Table1. in dependence with the receiver frequency. The receiver frequency bandwidth is assumed to be 60 MHz. The system temperature of the receiver is assumed to be 150 K. As an example, the envelope values of the direct signal arriving at the receiver input directly from the Sun (U_{direct}) and the envelope values of the shaded signal received by the receiver (U_{RX}) are shown in Fig. 5 depending on the distance from the receiver to an asteroid with a diameter of 10 m.

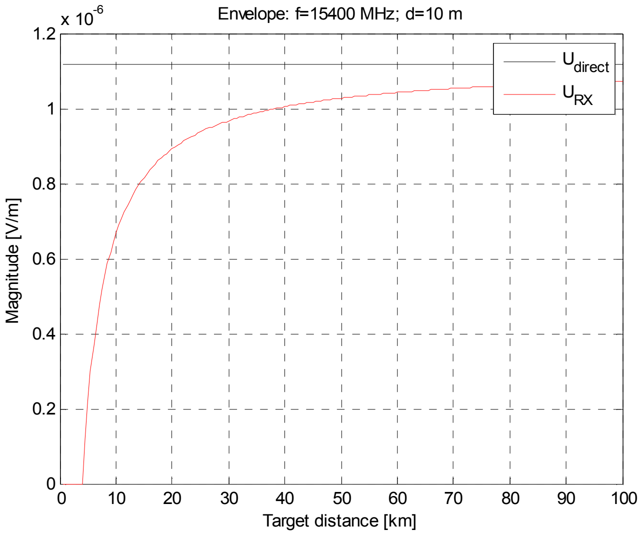

Fig. 5. Envelopes of the direct signal and the shaded signal

TABLE I.

f MHz	245	410	610	1415	2695	4995	8800	15400
Flux SUF	10	26	36	45	70	110	220	530

The values of envelopes U_{detect}, used for object detection and calculated according to (10), are shown in Fig. 6 as a function of the distance between the receiver and the object.

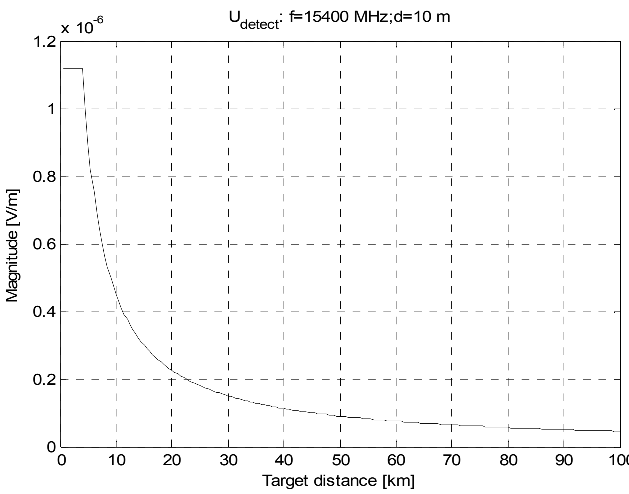

Fig. 6. Envelope U_{detect}, used for object detection

As an example, for calculating of SNR at the detector input we consider three types of large asteroids with the following diameters: 50m; 100m and 200m. The values of SNR calculated for these asteroids, depending to the distance between the receiver (radio telescope) and the corresponding asteroid, are plotted in Fig. 7. In order to show how the detection range of asteroids depends on the operating frequency of the receiver, in Fig. 8 are shown the values of SNR calculated for the operating frequency of 410 MHz.

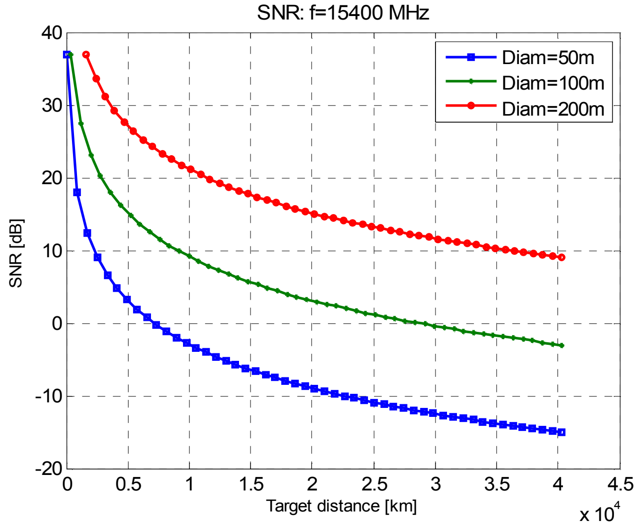

Fig. 7. Values of SNR (f=15400 MHz)

As follows from Table I, the spectral density of the emission from the Sun at this frequency is twenty time smaller than that at the frequency of 15400 MHz. As a result, it can be seen in Fig. 8 that the detection range of asteroids at the operating frequency of 410 MHz is much less than that at the frequency of 15400 MHz.

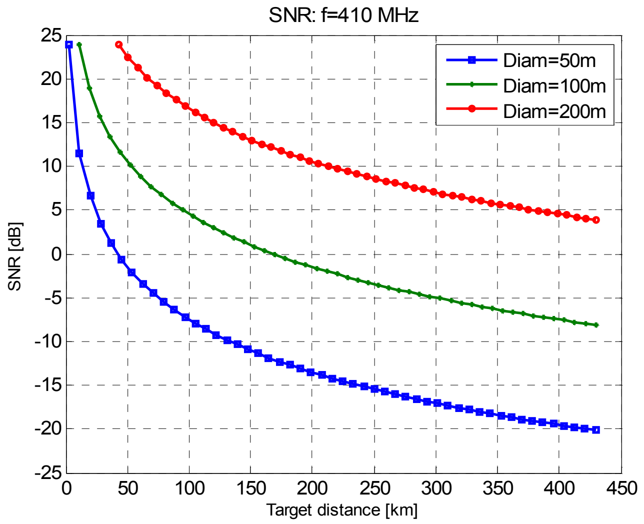

Fig. 8. Values of SNR (*f*=410 MHz)

If we assume that to detect an asteroid, it is sufficient to have a level of SNR equal to 10 dB, then from the graphical results in Fig. 7 it follows that an asteroid with a diameter of 50 m can be detected at a distance of 2000 km, with a diameter of 100 - at a distance of 8000 km, and with a diameter of 200 - at a distance of 35000 km.

V. Conclusions

The main idea is to using Sun as alternate transmitters in a FSR system for the purposes of cosmic target detection. The results obtained in this study show the theoretical energetic capabilities of a Solar FSR system to detect different cosmic targets, with solar radio radiation in the visible frequency diapason. It is shown that the detection capabilities depend on the values of the solar flux, asteroids diameters and also the reception parameters of the used radio telescope. It must be noted that the solar flux density radiation in the radio range is more intensive than the flux density radiation of pulsars, which is makes more usefully to use solar FSR systems for target detection in spite of pulsar FSR systems.

Acknowledgment

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