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Airplane Detection by FSR using cosmic radio emissions

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***Abstract*—The paper analyses and compares the possibility for airplanes detection by a FSR system that exploits radio emission from such cosmic bodies as Moon, Sun and pulsars. This possibility is estimated as a magnitude of SNR at the input of the signal detector calculated depending on the frequency of reception, the size of airplanes, which are crossing the baseline of FSR at the approximately right angle and the distance from the receiver to airplanes.**

***Keywords* — FSR, Fraunhofer diffraction, forward scatter effect, target detection**

I. INTRODUCTION

Forward Scatter Radar (FSR) is a specific type of bistatic radar, named as a radio electronic barrier. The unwanted object is detected only in situation when it crossing the virtual baseline between the transmitter and receiver. The principle of operation of such radars is based on the Fraunhofer theory of diffraction of electromagnetic waves and the Babinet principle [1-5]. According to diffraction theory, when an unwanted object is near the baseline (a bistatic angle is approximately 180^0), the object generates a strong shadow field increasing the shadow Radar Cross Section (RCS) of the object [6,7]. 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 Forward Scatter Radar (FSR) technology use the Doppler radar approach, so called Zero-Beat Receiver approach. The target velocity is measured with the multi-channel algorithm for Doppler velocity estimation by the channel number with the strongest signal.

The FSR systems have some limitations - lack of resolution in distance, the target moves close to the baseline; the wave length is much less than the target dimensions, the distances “transmitter-target” and “receiver-target” are much more than the target dimensions.

In the last ten years, there has been a particular interest in these bistatic FSR systems, since they practically allow to observe stealth targets, which are invisible by conventional radar systems [1]. The practical use of FSR systems goes together with bistatic radar systems. The purpose is to take the advantages of the Forward Scatter effect on the one hand and to offset its disadvantages, in determination of the parameters of moving targets.

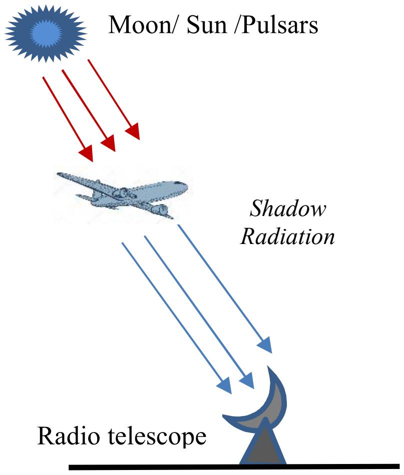


Fig.1 Topology of a FSR system that uses cosmic radio emission

In recent years, a number of variants of FSR have been proposed, which use signals from various modern communications sources (Secondary Application of Wireless Technology) [15]. Another possible way is the use of natural or GPS signal sources in the FSR systems for detecting unwanted objects [16].

Such natural sources of radio signals can be cosmic bodies emitting radio signals, which can be received by radio telescopes on Earth [8,9]. Although these cosmic radio signals are very weak, they can be efficiently processed in radio telescope receivers, which would not be possible with traditional radars. The standard algorithm for processing of pulsar signals implemented in the radio observatories usually includes epoch-folding. We present in [10, 11] signal processing algorithm for detection of pulsar signals using filtering approach. The other cyclostationary approach presented in [12, 13].

This article will discuss FSR systems that use natural sources of signals, such as Sun, Moon and pulsars. The novelty of this paper is to develop a methodology for calculation of the energy Signal-to-Noise Ratio (SNR) at the signal detector input and estimation of the time of contact of passenger airplanes with the receiving antenna in the FSR system in order to theoretically examine and compare, by SNR criterion, the possibility for detection of passenger airplanes by a FSR system that uses radio emission from Moon, Sun and pulsars (Fig.1). 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 (pulsar, Sun, Moon). In such a FSR system, the cosmic bodies (Moon, Sun and pulsars) serves as a source of radio emission in the visible radio frequency diapason and the ground-based radio telescope acts as a receiver. We consider the case where the FSR RCS of the airplane has the maximum, i.e. when the bistatic angles are very close to 180^0. For extraction of the shadow signal, created by the airplane, can be used, for example, the methods of time and frequency selection of direct and shadow signals. The possibility of airplane detection in these FSR systems is expressed as the magnitude of SNR calculated at the input of the signal detector depending on the size of airplanes, crossing the baseline between the Moon and the radio telescope, their distance from the radio telescope on the Earth, for two values of the frequency of reception. In this paper will be shown that the time of contact of the airplanes with the receiving antenna significantly affects the value of SNR at the detector input. This contact time depends primarily on the angular beamwidth of both the reception antenna and the airplane re-radiation, the velocity of movement of the airplane when crossing the baseline and also on the distance from the airplane to the radio telescope. The time of contact means the duration of the signal received from the airplane. This duration influences the time of signal integration in the receiver. For this aim we have developed a specific Matlab program to calculate this time.

II. FSR SIGNAL PROCESSING

The Earth's atmosphere disturbs most types of electromagnetic radiation from space from reaching the surface of the Earth. Only parts of the radio range and visible light reach the surface of the earth. There is a large wide window in radio frequencies (including some frequencies that are classified as microwave), which allows scientists to look into space and see cosmic bodies (the Moon, the Sun and pulsars) at radio frequencies. The photo below shows the possibility of observing the shadow of an airplane against the background of the moon's radiation in a bistatic system (Moon - camera.) The photo was kindly provided by the Rozhen Observatory, Bulgaria.

Fig.2. The airplane shadow on the background of Moon

In FSR systems that exploit natural sources of radio signals (pulsar, Sun, Moon) as transmitters, the radio telescopes are used as receivers. In the absence of an airplane on the baseline "transmitter-receiver", a direct unobstructed signal $\boldsymbol{U}_{\mathrm{direct}}$ arrives at the receiver input from the transmitter.

However, in a case when any airplane moves very close to the baseline "transmitter-receiver", the direct signal $\boldsymbol{U}_{\mathrm{direct}}$ is completely or partially blocked by the airplane. Then the signal $\boldsymbol{U}_{\mathrm{RX}}$ at the receiver input can be represented as a sum of the direct unobstructed signal $\boldsymbol{U}_{\mathrm{direct}}$ and the blocking shadow signal $\boldsymbol{U}_{\mathrm{shadow}}$ [5]:

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

According to the principle of Babinet, the direct incident radiation $\boldsymbol{U}_{\mathrm{direct}}$ and shadow radiation $\boldsymbol{U}_{\mathrm{shadow}}$, created by an opaque airplane, have opposite phases. According to the theory of physical optics, the exact mathematical description of the shadow field that is created by the airplane is based on the diffraction of Kirchhoff-Fresnel integral [5,6]:

$$\boldsymbol{U}_{shadow} = \frac{j}{\lambda}\iint_Q U_{direct}\frac{\exp(-jkR)}{R}dq \tag{2}$$

In (2), Q is a silhouette area of the airplane that depends on the movement direction, dq is a small part of the area of the airplane silhouette, R is a distance from that part to the receiver, and λ is the wavelength of emission. As can be seen, a shadow field does not depend on the shape or material of the shadowing airplane but is entirely determined by the size and geometry of the airplane silhouette. When the airplane is far enough away from the transmitter and receiver (far diffraction zone), it can be assumed that: (i) - the direct field $\boldsymbol{U}_{\mathrm{direct}}$ from the transmitter is distributed evenly over the area of the airplane silhouette; (ii) - the value of the distance R almost does not change with a change in the position of dq on the area of the airplane silhouette. In that case After integration the equation (2) takes the form:

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

As follows from (3) the envelope of the shadow signal can be expressed by the following equation:

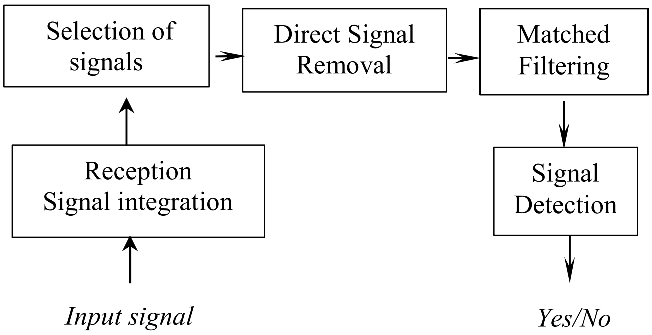
$$|\boldsymbol{U}_{shadow}| = E_{shadow} = E_{direct}Q/(\lambda R) \tag{4}$$

According to the Babinet principle, 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:

$$E_{RX} = E_{direct} - E_{shadow} \qquad (5)$$

From (5) follows that the shadow signal E_{shadow} can be considered as a reduction (leakage) of a direct signal E_{direct}, received in a FSR system. Hence, will have the following inequality:

$$E_{shadow} \leq E_{direct} \qquad (6)$$



Taking into account (4) and (6), we can conclude that the calculation of SNR at the detector can be performed only for distances (R) to airplanes satisfying the following inequality:

$$R \geq Q/\lambda \qquad (7)$$

This means that the estimation of the signal-to-noise ratio at the detector input in the FSR system can be performed only for distances (R) satisfying the inequality (7).

In an FSR system, the power of a shadow signal is used to detect an object. However, the direct signal power is much stronger than the shadow signal. Therefore, when processing the input signal, it is first necessary either to somehow remove the direct signal from the input signal, or to separate the direct and shadow signals by frequency and then use the amplitude (power) of the shadow signal to detect the object. As shown the main problem of the implementation of FSR signal algorithm is the need to separate the shadow signal created by the airplane from the direct signal from the cosmic radio emissions, however, in our article we do not focus on this problem, assuming that it has been solved in advance. To ensure high sensitivity, radio astronomy receivers (radiometers) should have bandwidths of hundreds of megahertz or even several thousand megahertz and increase the accumulation (integration) time of the signal. The gain of the signal (q) at the output of the radio astronomy receiver due to the integration of the received signal can be expressed as [5]:

$$q = \sqrt{\Delta f t_{cont}} \qquad (8)$$

In (8), Δf is the frequency bandwidth of the receiver and t_{cont} is the aircraft contact time with receiving antenna. The contact time is calculated as:

$$t_{cont} = \max\{\lambda/_{l}, \lambda/_{d}\} R/V \qquad (9)$$

where λ/d is the angular beamwidth of the radio telescope antenna, λ/l is the angular beamwidth of the shadow radiation from the airplanes, V- is the aircraft velocity, λ is the wavelength, and R_t is the distance to the aircraft. In other words, we assume that this is also the duration of the noise signal (from the Sun and the Moon) re-emitted from the object that has to be detected. In the case of pulsed FSR, this is the length of a series of pulses re-emitted from the target, the number of which is:

$$N = t_{cont}/P \qquad (10)$$

In (10), t_{cont} is the aircraft contact time with receiving antenna, and P is the repetition period of pulsar pulses. It is known that the energy SNR at the input of a signal detector realized in the LF domain (eg CFAR) depends on both the energy SNR at the receiver input and the parameter q of the receiver [7]. In the next paragraph, we will present a methodology for calculating this important parameter - energy SNR at the signal detector input for different space emitters (Pulsar, Sun and Moon). Usually in such FSR systems, there are two antennas arranged in different directions. One antenna is basic for target detection and is source (pulsar, Moon, Sun) oriented. The other antenna is for the formation of a reference signal from the source that is being subtracted from the main input signal (for Direct Signal Removal), however, in our article we do not focus on this problem and assume that such a system is built.

The general block diagram of signal processing used for detection of airplanes in the pulsar/solar/lunar FSR system is presented in Fig.3.

Fig.3 General block diagram of signal processing in a pulsar /solar/lunar FSR

The shown on Fig.3 signal processing algorithm in the solar or lunar and pulsar FSR system includes four main processing stages. The first of them is reception and selection signals. At the second stage, the direct signal from the signal source (pulsar, Moon, Sun) is removed, and the third stage is the matched filtering of the power of a shadow signal. The final stage is the adaptive signal detection.

III. POWER BUDGET IN A FSR SYSTEM

A. Pulsar FSR

One of the very important parameters of pulsars, which are usually given in each pulsar database, is the average power spectral flux density *Sav*. This is the average power in watts transmitted by a pulsar per square meter per hertz. The spectral flux density is usually expressed in units of Jansky. The power of one Jansky (Jy) is equivalent to 10^{-26} watts per square meter per hertz. The peak power spectral flux density transmitted by a pulsar can be evaluated using the basic pulsar parameters:

$$S = S_{av}P/W \qquad (11)$$

where the parameters P and W denote the repetition period and the pulse width of the pulsar radio emission. According to (4), the power peak spectral density of the shadow signal received from an airplane with the silhouette area Q by the radio telescope antenna having the effective area A_{eff} can be expressed as:

$$S_{ant} = S_{av}PA_{eff}Q^2/(\lambda^2 R^2 W) \qquad (12)$$

However, using the concept of Radar Cross Section (RCS), in conditions of the Forward Scatter effect, the equation (12) can be rewritten as:

$$S_{ant} = S_{av}PA_{eff}\sigma/(4\pi R^2 W) \qquad (13)$$

In (13), the parameter σ is the Radar Cross Section (RCS) of an airplane expressed as:

$$\sigma = 4\pi Q^2/\lambda^2 \qquad (14)$$

As can be seen, the RCS of an airplane depends only of the airplane silhouette area and the wave length of the pulsar radio emission. In radio astronomy the effective area of the radio telescope antenna is given by:

$$A_{eff} = 2k_B G \tag{15}$$

Where G is the radio telescope antenna gain (in units of K/Jy) and k_B is the Boltzman constant ($1.38 \cdot 10^{-23}$ W/Hz/K).

In case of airplane detection, when the airplane crosses the baseline "pulsar-radio telescope" at an almost right angle, we assume that the silhouette of the airplane is approximately equal to a rectangle with a length l and width h. Then (15) takes the form:

$$\sigma = 4\pi(hl)^2/\lambda^2 \tag{16}$$

The spectral density of receiver noise of the radio telescope can be approximately evaluated using the receiver system temperature T_{sys} as:

$$N_0 = k_B T_{sys} \tag{17}$$

Taking into account (13), (15) and (16), the Signal-to-Noise Ratio (SNR) at the antenna output can be expressed as:

$$SNR_{ant} = \frac{2S_{av}PG(hl)^2}{\lambda^2 R^2 W T_{sys}} \tag{18}$$

According to Fig.3, the SNR in (18) can be improved by the further signal processing. The signal processing that improves SNR includes three stage: (*i*) - signal integration in the receiver that is characterized by the gain q defined in (8); (*ii*) - epoch folding, i.e. the accumulation of the pulses transmitted from one pulsar for N pulse repletion periods defined in (10) that is characterized by the improvement factor $\sqrt{N}$ and (*iii*) – matched filtering of the accumulated signal that is characterized by the processing gain G_{match}. In result of this signal processing the SNR at the signal detector input can be evaluated as:

$$SNR_{det} = \frac{2S_{av}PG(hl)^2}{\lambda^2 R^2 W T_{sys}} q\sqrt{N}\, G_{match} \tag{19}$$

B. Solar/Moon FSR

The solar radiation spectrum covers all frequencies from the radio diapason to the optical one. The solar radiance is a function of the wavelength. In the optical range, the Sun can be considered as a blackbody with a constant temperature of about 6000 K. The radiation flux is quite stable, with very small deviations over the solar cycle. However, in the radio frequency diapason, the radiance of the Sun is different from that in the optical range. For that reason, daily observations of the Sun's radio emission at a wide visible radio frequency diapason are conducted by different radio telescopes in the World. The solar observations (S) are presented as the power spectral flux density in solar flux units, where one solar flux unit (SFU) is 10^{-22} $\mathrm{Wm^{-2}Hz^{-1}}$ or 10^4Jy.

The radio emission of the Moon is purely thermal. The moon re-emits the energy of solar radiation incident on it. The brightness temperature of radio emission (T_B) for a point on the lunar equator in the centre of the visible disk of the Moon depends on the phase of the moon and the wavelength of radio emission. At frequencies from the range (400MHz÷ 1400MHz), the brightness temperature of the Moon is about 240 K. This temperature can be used to calculate the power spectral flux density of radio emission (S). This is the power in watts transmitted by a transmitter (Moon) per square meter per hertz. Based on the Rayleigh-Jeans approximation for blackbody radiation at radio frequencies, the power spectral flux density can be approximately expressed as:

$$S = 2k_B T_B \pi\left(\frac{\alpha\pi}{180}\right)^2 \lambda^{-2} \tag{20}$$

Where α is the angular radius of the Moon in degrees (α = 0.25 deg).

In case of the airplane detection, the value of SNR at the detector input of a solar/lunar FSR system can be expressed by analogy with a pulsar FSR system as:

$$SNR_{det} = \frac{2SG(hl)^2}{\lambda^2 R^2 T_{sys}} q \tag{21}$$

The expressions (19) and (21) are used for calculation of SNR in the next Section.

IV. NUMERICAL RESULTS

The purpose of this study is to evaluate and compare the capabilities of three types of FSR systems (pulsar, solar and lunar) that exploit natural sources of radio radiation (Sun, Moon and pulsar). To do this, we will calculate the signal-to-noise ratio at the detector input when detecting airplanes with the same dimensions, at the same frequency of radio emission, with the same parameters of the receiver and receiving antenna.

For the *SNR* calculation, the following parameters of the radio observatory are used: the radio telescope antenna gain is 0.18K/Jy that corresponds to the antenna diameter of 25m; the system temperature is 150 K; the central frequency is 1400 MHz; the receiver frequency bandwidth is 100 MHz. In calculation of SNR are used the observation data of the spectral flux density prepared by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction Center, 23 July, 2018 (Table I).

TABLE I

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

The spectral flux density of radiation from the Moon is calculated using (20) in the assumption that the brightness temperature of the Moon is 240 K.

The parameters of pulsar B0833-45 are taken from the EPN database: the spectral flux density at frequency of 1400 MHz is S_{av}=1.1Jy; pulse width after epoch-folding is W=0.0021s; repetition period is P=0.089328s.

Three types of aircrafts with different dimensions were selected for study, small – Gripen JAS-39 (h= 2m, l=8.4m), medium - Lockheed C-130 Hercules (h= 4m, l=40.4m), large - Boeing – 747 (h= 6m, l=68.5m).

The radiation from the Sun and Moon is broadband and noise-like. In that case the contact time is used as the integration time for calculation of the receiver gain q using (8). In contrary to the Sun/Moon radiation the pulsar emits a pulse consequence. So in case of pulsar radiation, the contact time is used for calculation of the number of the pulse repetition periods using (10), necessary for the folding. The integration time needed for calculation of the receiver gain q is assumed to be 0.01*P*. The processing gain of the matched filter is assumed to be 10dB.

For comparison, in Table II is shown how the forward scatter RCS (FS RCS) of airplanes depends on the reception frequency.

TABLE II

f **{MHz}**	**FS RCS [dB]**		
	JAS-3S	*C-130*	*Boeing-747*
400	38.0	57.7	65.8
1400	48.9	68.5	76.7

For comparison, in Table III are shown the values of the angular beamwidths (λ/*l*), reradiated by aircrafts selected for study.

TABLE III

f **{MHz}**	***λ/l***		
	JAS-3S	C-130	Boeing-747
400	0.0893	0.0186	0.0109
1400	0.0255	0.0053	0.0031

The beamwidth of the radio telescope antenna (*λ/d*) with the 25m-diameter in radians is equal to 0.0298 – for 400 MHz, and 0.0085 – for 1400 MHz.

The SNR values calculated for the three types of radiation (pulsar, Moon and Sun) are plotted in Figs (5-7).

Graphic results are obtained for distances in the range from $R_{\min}$ to $R_{\max}$, where the minimal distance to an airplane is calculated according the limitation (7). This means that the minimal distance is calculated as $R_{\min}$=Q/λ where Q is the airplane's silhouette area.

The maximal distance of calculation is determined as follows: $R_{\max}=50R_{\min}$ –for pulsar FSR, $R_{\max}=100R_{\min}$ – for lunar FSR and $R_{\max}=200R_{\min}$ – for solar FSR

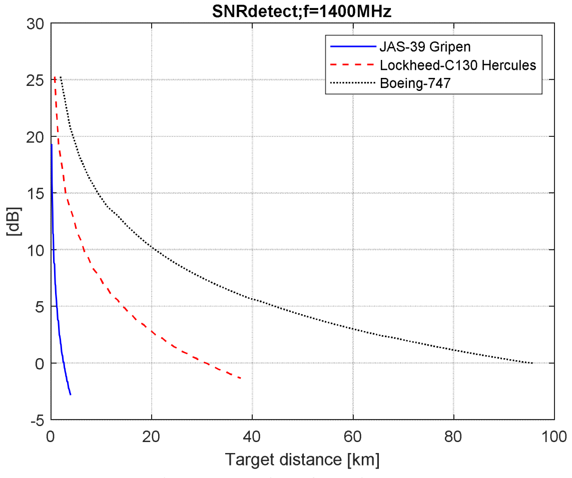


Fig.5 SNR values for pulsar FSR

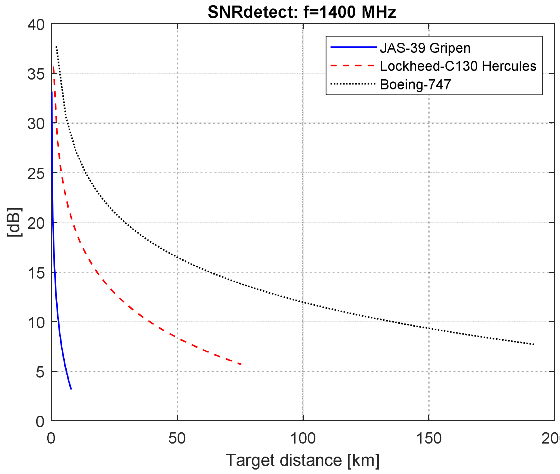


Fig.5 SNR values for lunar FSR

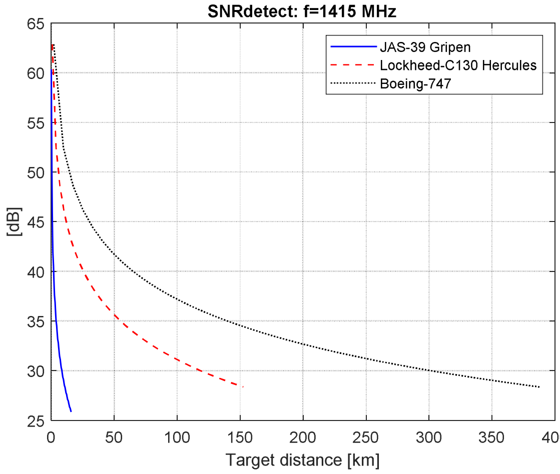


Fig.5 SNR values for solar FSR

To obtain the required magnitude of the energy SNR at the signal detector, for example above 5 dB. (to reliably detect the object in FSR) , the necessary amplification of the receiver must be selected and all possibilities for increasing the energy SNR at the receiver input should be sought.

The receiver amplification (*q*) mentioned in section III depends on the frequency bandwidth of the receiver (Δ*f*) and the time of contact of the target with the receiver antenna (t_{cont}). For this reason, the receiver frequency bandwidth is chosen to be 100 MHz. However, with a fixed antenna of FSR, we cannot essentially control (increase) the aircraft contact time with receiving antenna. The contact time depends on the beamwidth of the receiver antenna, on the re-radiated beamwidth of the airplane in conditions of the FS effect (Table III) and also on the airplanes parameters: velocity and distance. The calculations showed that the contact time almost linearly increases with the increase by a distance to airplanes.

The increase in the energy SNR at the input of the receiver (19 and 21) due to the increase of airplane RCS in the conditions of the FS effect according to (16) essentially depends on the magnitude of the frequency of radio emission (Table II).

For that reason, for calculating of SNR is chosen the reciver frequency of 1400 MHz. -for pulsar and lunar radio emission and 1415 MHz - for solar radi emission, which give more higher values of FS RCS for all given airplanes (Table II).

The solar flux density of radio emission is chosen according to the receiver frequency 1415 MHz (Table I).

For calculation of SNR in pulsar FSR is chosen the pulsar B0833-45 with the high repetition frequency of pulses emitted by this pulsar (the repetition period is P = 0.089328s), which implies a greater number of accumulated pulses (*N*) according to (10) for the time of contact with the target. However, the radiated energy of this pulsar in this frequency range is not great (Sav = 1.1Jy).

From the graphical results showen on Figs. 5, 6, and 7 for the three FSR system s (pulsar, lunar and solar) can be seen the high values of SNR especially for Boeing. However, the results obtained difficulty to compare with the same results of the classic radar systems (with backscatter).

These moving FSR systems have very short lifetimes - tens of minutes when the Sun, Moon and pulsar are very low above the horizon. In these specific time situations, conditions arise for the formation of the FS effect between the transmitter and the radio telescope when crossing the flying planes on the baseline between the receiver and the transmitter. Only in this case can be analized the results obtained for the SNR values for the different aircrafts.

ACKNOWLEDGMENT

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Conclusion

The novelty of this paper is a methodology for calculating the energy SNR at the signal detector input in a non-stationary FSR systems for detection passenger planes using solar, lunar and pulsar radio emissions. The goal is theoretically to examine and compare, by the Signal-to-Noise Ratio (SNR) criterion, the possibility for detection of modern passenger airplanes by a FSR system that uses radio emission from Moon, Sun and pulsars. The results obtained indicate a higher prospect for the use of such FSR systems with the Sun emitter. Such FSR systems do not need necessarily to use radio telescopes. They can work well with low-cost radar receivers but they need low-cost middle or large antennas.

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