Feasibility of asteroid detection using pulsar signals

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Abstract

The feasibility of a Forward Scatter Radar (FSR) system, which exploits pulsars as opportunity transmitters, is examined. We provide a power budget estimate for asteroid detection using such a FSR system and assume the use of the higher-gain radio telescopes as the receivers. The numerical results are obtained for three types of pulsars and large asteroids, whose diameters equal and overcome 150m.

1 Introduction

Forward Scatter Radar (FSR) is bistatic radar where the directions “transmitter-target” and the “target-receiver” form the angle that is close to π. The FSR technology exploits the Fraunhofer diffraction of electromagnetic waves in order to detect targets. The Fraunhofer diffraction is observed when: (i)- the wavelength of electromagnetic waves, incident on the target, is much less than the size of the target; (ii)-the distances “transmitter-target’ and “target-receiver are much more than the size of the target. The Forward Scatter (FS) effect is observed when the target moves close to the baseline "transmitter-receiver" and so partially blocks the signal wave front from the transmitter. In case of the FS effect the target Radar Cross-Section (RCS) depends only on the target silhouette area and the wavelength of the electromagnetic field. The most attractive feature of the FS effect is the drastic increase of the target RCS, and therefore, the strong increase of Signal-to-Noise Ratio (SNR) of the received signal compared to traditional bistatic radar [1].

This paper focuses at the very important problem of the Earth protection from unwanted incident cosmic objects. At present, there are two program systems (SCOUT and SENTRY) used for detection of Near-Earth Objects and designed by NASA [2]. Their main task is to detect 90% of asteroids with the diameter of 140 meters and larger. The idea of this paper is to theoretically examine the feasibility of asteroid detection by using the FSR technology (Fig.1).

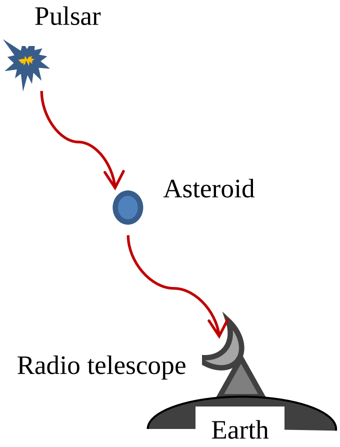

Figure 1: Topology of FSR system

The goal of this paper is to verify the ability to detect asteroids with the diameter of 150m and more at a height equal to four hours of the asteroid's motion to enter the stratosphere of the Earth. Bearing in mind that the speed of the asteroid is 30 km / s, the minimum height of asteroid detection is 460,000 km.

According to Fig.1, such a FSR system used for asteroid detection exploits pulsars as transmitters and the powerful radio telescopes as receivers. Pulsars are rotating neutron stars that periodically emit broadband electromagnetic pulses. The emission period of pulsar signals is the same as the rotation period of pulsars. Although individual pulsar pulses vary in strength and shape, the average pulse shape is stable and characterizes each pulsar.

Naturally, not all pulsars can be exploited as transmitters in FSR systems used for asteroid detection**.** It will be shown in this paper that only pulsars with high flux values and short periods of pulse repetition (less than 1ms) can be used in a FSR system for asteroid detection.

2 Signal processing

The block diagram of signal processing used for asteroid detection in the FSR system is presented in Fig.2.

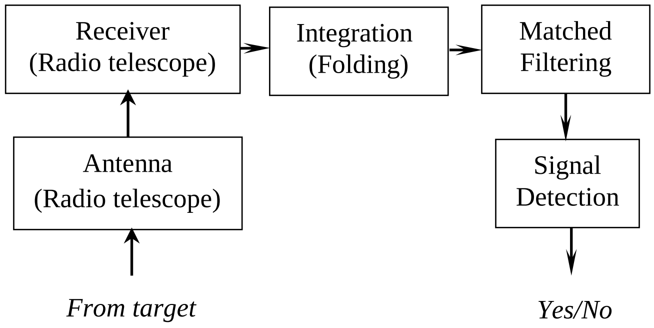

Figure 2: Block diagram of signal processing in FSR

The signal processing algorithm includes three main processing stages. They are non-coherent integration of the received pulses diffused by a target during repetition periods of the input data; matched filtering in the frequency domain with the impulse response according to a given pulsar template; adaptive signal detection. The main problem of the implementation of this algorithm is the need to pre-separate the signal diffused by an asteroid from the direct signal emitted by the pulsar.

3 Power budget

In radio astronomy one of the most important parameters, which characterizes every pulsar, is the spectral flux density (**S**). This parameter denotes the power in watts transmitted by a pulsar per square meter per hertz. The spectral flux density is measured in units of Jansky. The **Janski** (**Jy**) is a non-SI unit of spectral flux density and it is equivalent to 10^{-26} watts per square meter per hertz. In analogy to radar we assume that the peak spectral flux density is transmitted by a pulsar before being diffused by an asteroid to the radio telescope (in units of Jy). The spectral flux density available at the output of the radio telescope antenna with the effective area A_{eff} is [3]:

$$S_{rec} = S_{peak}\sigma A_{eff} /(4\pi R_t^2) \qquad (1)$$

In (1) the symbol σ denotes the Radar Cross Section (RCS) of a pulsar and R_t is the distance to the target. In radio astronomy the effective area of the radio telescope antenna is given by [4]:

$$A_{eff} = 2k_B G \qquad (2)$$

Where G is the radio telescope antenna gain (in units of K/Jy) and k_B is the Boltzman constant ($1.38\cdot10^{-23}$ W/Hz/K)

According to [1], the Forward Scatter effect is occurred when the target, i.e. asteroid, is located very close to the baseline between the radio telescope and the pulsar (as shown in Fig.2). In that case the RCS of the target, i.e. asteroid, can be expressed as:

$$\sigma = 4\pi A_{aster}^2 / \lambda^2 \qquad (3)$$

In (3) A_{aster} is the asteroid shadow area and λ is the wave length. If it is assumed that the asteroid is approximately spherical in shape with the diameter D, then (3) takes the form:

$$\sigma = \pi^3 D^4 /(4\lambda^2) \qquad (4)$$

After replacing σ in (1) by (4) the equation (1) takes the form:

$$S_{rec} = 2\pi^2 S_{peak} G k_B D^4 /(16 R_t^2 \lambda^2) \qquad (5)$$

Since the pulsar pulse period is very stable, the pulses transmitted from one pulsar can be integrated for hundreds of periods by summing the period to the accumulated stack and finally averaging it. If the noise is random it eventually cancels itself out. This operation is called epoch folding [4]. In result of epoch folding the received spectral density in (5) takes the form:

$$S_{rec} = \pi^2 S_{peak} G k_B D^4 \sqrt{n_p} /(8 R_t^2 \lambda^2) \qquad (6)$$

In (6) n_p is the number of integrated periods. According to [?], after the epoch folding process the spectral density of the receiver noise is evaluated as:

$$N_0 = 2k_B \cdot \Delta T_{\mathrm{int}} \qquad (7)$$

In (7) ΔT_{int} is the root mean square fluctuations in the system temperature $T_{\mathrm{sys.}}$, which is [4]:

$$\Delta T_{\mathrm{int}} = \frac{T_{sys} P}{\sqrt{t_{obs} BW(P-W)}} \qquad (8)$$

In (8), t_{obs} is the epoch folding time, B is the frequency bandwidth of the receiver, P is the repetition period of the pulsar and W is the pulse width. According to [4], the system temperature can be evaluated as:

$$T_{sys} = T_{rec} + \frac{f}{1GHz} \qquad (9)$$

For the cooled receivers, the receiver temperature T_{rec} is varied in the interval (20-30) K. In (9) f is the central frequency of the receiver. Taking into account (6), (7), and (8), the Signal-to-Noise Ratio (SNR at the antenna output can be expressed as:

$$SNR = \frac{S_{rec}}{N_0} = \frac{\pi^2 S_{peak} G D^4}{16 R_t^2 \lambda^2} \cdot \frac{\sqrt{t_{obs} BW(P-W)}}{T_{sys} P} \sqrt{n_p} \qquad (10)$$

The parameters n_p and S_{peak} in (10) can be expressed as

$$n_p = \frac{t_{obs}}{P}, \text{ and } S_{peak} = S_{ave} \cdot \frac{P}{W} \qquad (11)$$

Substitution of n_p and S_{peak} in (10) gives:

$$SNR = \frac{\pi^2 S_{ave} G D^4 t_{obs}}{16 R_t^2 \lambda^2 T_{sys}} \cdot \sqrt{\frac{B(P-W)}{PW}} \qquad (12)$$

In (12) S_{ave} is the parameter that characterizes the pulsar and it is given in each pulsar database. The equation (12) allows the calculation of SNR at the output of the radio telescope antenna. If will be taken into account the receiver gain (G_{rec}) and the processing gain (G_{SP}) , the SNR at the detector input can be calculated as:

$$SNR = \frac{\pi^2 S_{ave} G D^4 t_{obs}}{16 R_t^2 \lambda^2 T_{sys}} \cdot \sqrt{\frac{B(P-W)}{PW}} \cdot G_{rec} G_{SP} \qquad (13)$$

For detection, we are interested in finding the maximal distance to the detectable asteroid, which corresponds to the minimal SNR needed for detection with the predetermined probability of detection:

$$R_{t,\max} = \sqrt{\frac{\pi^2 S_{ave} G D^4 t_{obs} G_{rec} G_{SP} \sqrt{\frac{B(P-W)}{PW}}}{16\, SNR_{\min} \lambda^2 T_{sys}}} \quad (14)$$

4 Results

Currently more than 1820 pulsars have been discovered but naturally not all these pulsars are suitable for asteroid detection by using a FSR system. To show that, for example, three pulsars, B0329+54, B0833-45 and B1937+21, with different parameters have been selected for the study (Table 1). The purpose of this research is to determine such a pulsar that is most suitable for the detection of asteroids and also to determine the optimal frequency of reception of its signals. The other goal of the study is to show that it is possible to detect large asteroids at a distance of four hours before its entry into the Earth's stratosphere. When the speed of the asteroid is 30 km / s, this distance is about 460,000 km.

Pulsar Name	Period (P) (s)	Width (W_{50}) (ms)	S_{ave} 400MHz (mJy)	S_{ave} 1400MHz (mJy)
B0329+54	0.714520	6.600	1500	203.0
B0833-45	0.089328	2.100	5000	1100.0
B1937+21	0.001558	0.038	240	13.20

Table 1: Pulsar parameters (from European pulsar database)

To solve this problem, we have calculated SNR at the detector input for each pulsar, depending on the distance to the asteroid and the asteroid's diameter. The values of SNR were also calculated for two frequencies of reception of signals from the pulsar - 400 Hz and 1400 Hz. The other parameters used in calculation of SNR are presented in Table 2. As shown in Table 1, we calculated SNR for four large asteroids with diameters of 150m, 300m, 500m and 800m. For comparison, the integration time of the received signal is chosen to be one hour for all pulsars and asteroids. Previous studies, made for pulsar B0329+54, have shown that the improvement in SNR at the output of the matched filter is about 10 dB for the receiver bandwidth of 30MHz [5]. The gain of 20K/Jy given in Table 2 corresponds to the five-hundred-meter aperture of the world's largest radio telescope in China [6].

Parameters	Units	Values
f	MHz	400 and 1400
B	MHz	30
G	K/Jy	20
G_{rec}	dB	130
G_{SP}	dB	10
t_{obs}	s	3600
D	m	150; 300; 500; 800
Rt	km	From 200000 to 8000000

Table 2: Parameters used in calculation of SNR

The values of SNR vs. distances to the asteroid are plotted on Fig. 3 and Fig. 4- for pulsar B0329+54; on Fig.5 and Fig.6 – for pulsar B0833-45, on Fig. 7 and Fig.8 – for pulsar B1937+21.

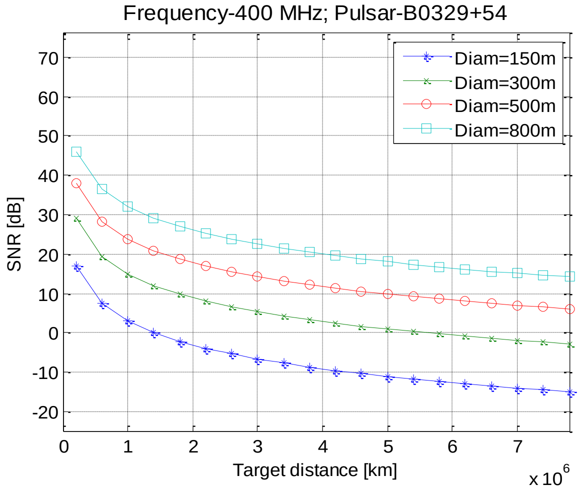
Frequency-400 MHz; Pulsar-B0329+54

Figure 3: SNR vs. distances R_t

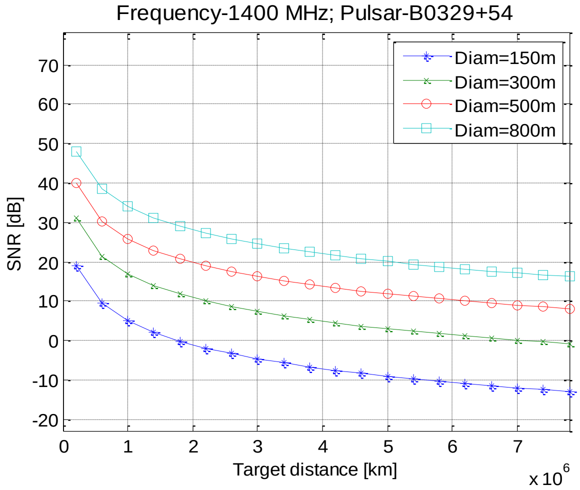
Frequency-1400 MHz; Pulsar-B0329+54

Figure 4: SNR vs. distances R_t

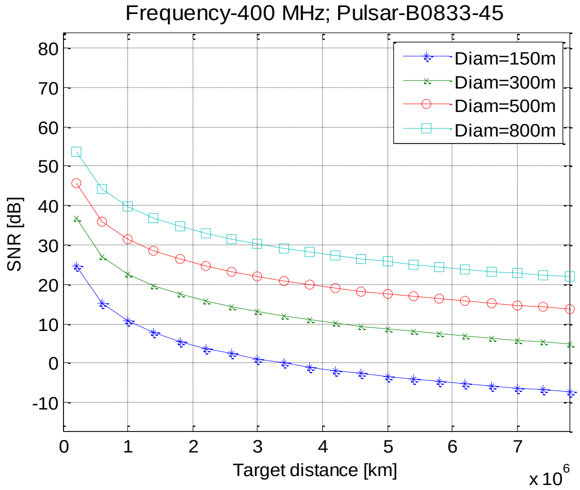
Frequency-400 MHz; Pulsar-B0833-45

Figure 5: SNR vs. distances R_t

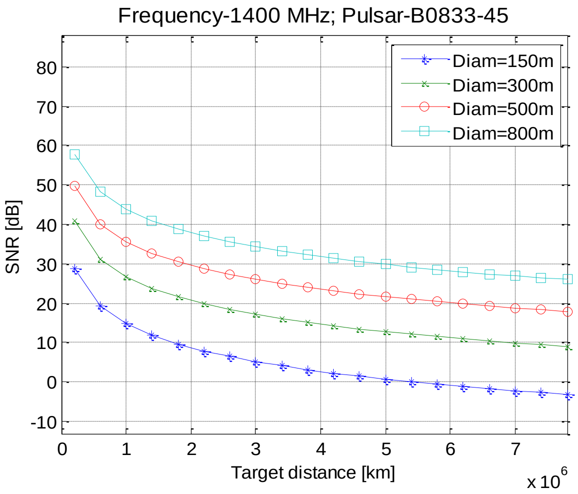

Figure 6: SNR vs. distances R_t

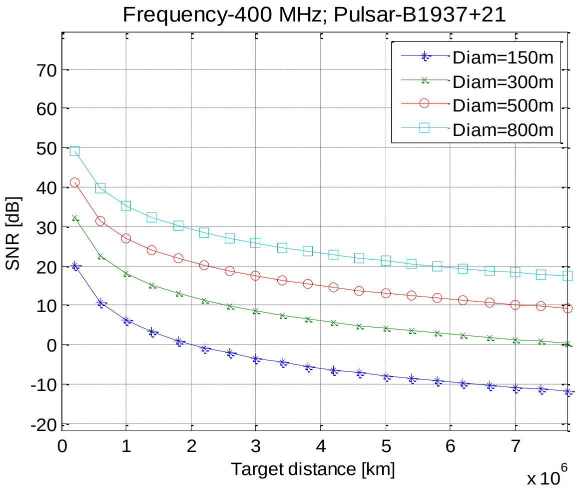

Figure 7: SNR vs. distances R_t

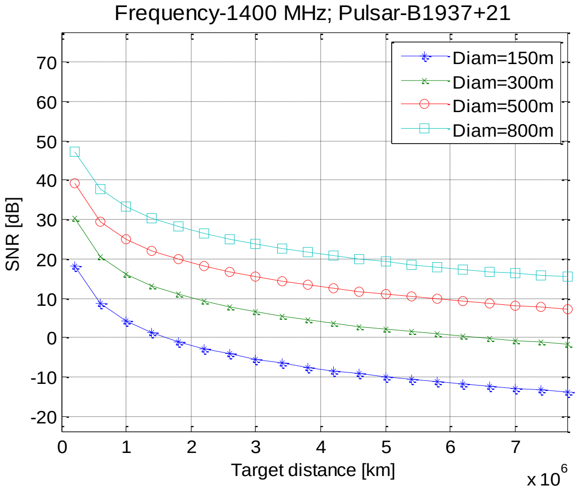

Figure 8: SNR vs. distances R_t

From the analysis of graphical result follows that the pulsar B0833-45 is the most suitable for the asteroid detection using the FSR system and the frequency or 1400 MHz is optimal for reception because they allow detecting the smallest asteroid with diameter of 150 m at the distance of 460000 km. In this case, the SNR at the detector input is about 10dB.

5 Conclusions

The results obtained in this study show the theoretical energetic capabilities of a pulsar FSR system to detect asteroids of large sizes asteroids at a distance of four hours before their entry into the Earth's stratosphere. It is also shown that the detection capabilities depend on the type of pulsars, the size of asteroids and also the reception parameters of the used radio telescope. The results are obtained for the five-hundred-meter aperture of the world's largest radio telescope in China.

Acknowledgements

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