Feasibility of Air Target Detection using Pulsar FSR Net

Hristo Kabakchiev [1], Vera Behar [2], Ivan Garvanov[3], Dorina Kabakchieva[4], Avgust Kabakchiev[5], Herman Rohling[6], Mark Bentum[7], Jorge Fernandes[8]
[1]Sofia University, Sofia, Bulgaria
ckabakchiev@fmi.uni-sofia.bg
[2]IICT-BAS, Sofia, Bulgaria
behar@bas.bg
[3]ULSIT, Sofia, Bulgaria
igarvanov@unibit.bg
[4]UNWE, Sofia, Bulgaria
dkabakchieva@unwe.bg
[5]BULATSA, Sofia, Bulgaria
av_kab@abv.bg
[6]TU-Hamburg-Harburg, Germany
rohlingr@tu-harburg.de
[7]University of Twente, Netherlands
m.j.bentum@utwente.nl
[8]INESC-ID, Lisboa, Portugal
Jorge.fernandes@inesc-id.pt

***Abstract*—The feasibility of air target detection using the Forward Scatter Radar Net that exploits three pulsars as transmission sources is examined. We provide a power budget estimate for air target detection using such a FSR net with the higher-gain radio telescope used as a receiver. The numerical results are obtained for the known radio telescope Dwingeloo and three known pulsars.**

Keywords*—*forward scatter radar; pulsars; target detection

I. INTRODUCTION

The forward scatter effect observed in the far-field zone of diffraction (Fraunhofer zone) is exploited in Forward Scatter Radar systems (FSR) to detect the target when the target is near the baseline "transmitter-receiver" [1]. Most of traditional FSR systems use their own transmitters as in [2]. However, the role of the transmitter can also perform any independent sources of signals, for example, the satellites of GNSS [3]. In this paper, we suggest to use pulsars as transmitters in FSR systems (Fig.1). Pulsars are neutron stars, which in rotation periodically emit broadband electromagnetic pulses. The emission period of pulsar signals is very stable that is one of characteristics of each pulsar.

The aim this article is to study the feasibility to automatically detect air targets using a FSR net, in which each FSR system exploits pulsars as transmitters. The topology of such pulsar FSR net is shown in Fig.2. All FSR systems in this net exploit one common receiver (radio observatory), like a multi-radar system.

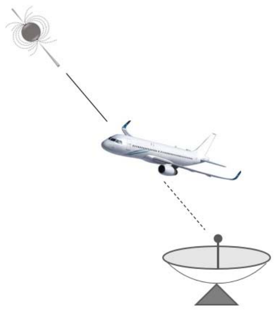

Fig.1 FSR system with pulsar as a transmitter

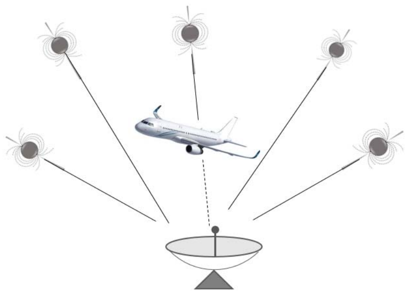

Fig.2 Topology of a pulsar FSR net

II. Signal Processing

The general flow-chart of the proposed algorithm for air target detection is presented in Fig.3.

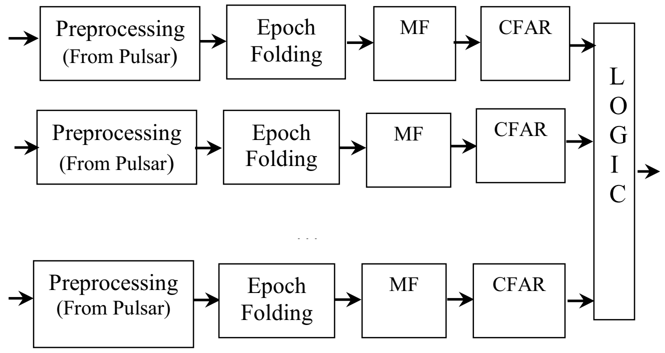

Fig.3 Flow-chart of signal processing

As can be seen, the algorithm for air target detection is multi-channel, and each channel extracts and performs the signal from only one pulsar. In each channel, the first very important task of signal processing is separation of the direct signal, received from a pulsar, and the radio shadow signal, incoming from the air target. Since the radio shadow from the target is very weak, its Signal-to Noise Ratio (SNR) can be increased by incoherent integration within very large number of pulse repetition periods. This operation is known as the epoch-folding procedure. It is well known that each pulsar emits the pulse having the original form (pulse profile). Therefore, this pulse profile can be used as the impulse response of the matched filter, the use of which can additionally improve the SNR of the signal before detection [5, 6]. The signal detection in the channel is carried out using the adaptive CFAR detector that maintains the predetermined probability of false alarm. For final target detection, we propose to use the simplest logical algorithm to combine the information from all channels. It can be based on the OR logic or the logic "K out of M".

III. Power Budget For one Pulsar FSR

As well-known from radio astronomy, every pulsar is characterized by the average spectral flux density (S_{ave}), which is measured in units of Jansky. In analogy to bistatic radar we assume that the peak spectral flux density (S_{peak}), received by the radio telescope, is emitted by a pulsar before being reradiated by the target to the radio telescope. The peak spectral flux density at the output of the radio telescope antenna depends on the effective area of the receiving antenna (A_{eff}) as [3]:

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

In (1), the symbol σ denotes the Radar Cross Section (RCS) of the air target and R_t is the distance from the radio telescope to the target. In the radio astronomy, the effective area of the radio telescope antenna is calculated as [4]:

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

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In (2), the radio telescope antenna gain G is measured in units of K/Jy, and k_B is the Boltzman constant ($1.38\cdot 10^{-23}$ W/Hz/K). According to [1], the FS effect can occur in case when the target crosses the baseline "pulsar - radio telescope" and the distance from the target to the pulsar and the distance to the radio telescope is much larger than the length of the target. When the FS effect appears, the RCS of the target depends only on the target silhouette area and the wave length of emission and can be expressed as:

$$\sigma = 4\pi A_{t\arg}^2 / \lambda^2 \quad (3)$$

After replacing σ in (1) by (3) the equation (1) takes the form:

$$S_{rec,peak} = 2S_{peak} G k_B A_{t\arg}^2 /(R_t^2 \lambda^2) \quad (4)$$

The standard way to improve SNR of pulsar signals before detection, which is often used in radio observatories, is to integrate the received pulsar pulses taken from a large number of pulsar pulse periods. This procedure accumulates the signal power during the long time interval providing the desired SNR. It is the epoch-folding processing, which usually requires much observation time [5]. After the epoch folding, the received peak spectral density in (4) takes the form:

$$S_{rec,peak} = 2S_{peak} G k_B A_{t\arg}^2 \sqrt{n_p} /(R_t^2 \lambda^2) \quad (5)$$

In (5) n_p is the number of integrated pulsar pulse periods. As shown in [4], after the epoch folding the spectral density of the receiver noise is evaluated as:

$$N_0 = 2k_B \cdot \Delta T_{\text{int}} \quad (6)$$

The parameter ΔT_{int} in (6) denotes the root mean square fluctuations in the system temperature $T_{sys.}$ that is [4]:

$$\Delta T_{\text{int}} = \frac{T_{sys} P}{\sqrt{t_{obs} B W (P - W)}} \quad (7)$$

In (7), t_{obs} is the epoch folding time, B is the frequency bandwidth of the receiver, P is the repetition period of pulsar pulses and W is the pulse width. Taking into account (5), (6), and (7), the SNR after the epoch-folding can be expressed as:

$$SNR = \frac{S_{rec,peak}}{N_0} = \frac{S_{peak} G A_{t\arg}^2}{R_t^2 \lambda^2} \cdot \frac{\sqrt{t_{obs} B W (P-W)}}{T_{sys} P} \sqrt{n_p} \quad (8)$$

The number of integrated pulsar pulse periods n_p and the peak flux density S_{peak} in (8) can be expressed as:

$$n_p = t_{obs} / P \text{ and } S_{peak} = S_{ave} P / W \quad (9)$$

The substitution of n_p and S_{peak} into the equation (8) gives:

$$SNR = \frac{S_{ave} G A_{t\arg}^2 t_{obs}}{R_t^2 \lambda^2 T_{sys}} \cdot \sqrt{\frac{B(P-W)}{PW}} \quad (10)$$

The pulsar parameters P, W and S_{ave} in (9) are available in all pulsar databases. Another approach to additionally improve SNR is to add the matched filter after the epoch-folding performance before signal detection [6]. The impulse response of the matched filter is the pulse profile of the corresponding pulsar. Taking into account the processing gain (G_{SP}) of the matched filter, the SNR at the detector input is calculated as:

$$SNR = \frac{S_{ave} G A_{t\arg}^2 t_{obs}}{R_t^2 \lambda^2 T_{sys}} \cdot \sqrt{\frac{B(P-W)}{PW}} \cdot G_{SP} \quad (11)$$

When the airplane crosses the baseline "pulsar - radio telescope", the silhouette target area A_{targ} in (11) can be calculated through the target's length (l) and height (h):

$$A_{t\arg} = hl \quad (13)$$

According to the principle of Fraunhofer diffraction, the target is seen from the receiver at Θ angle:

$$\theta = 2\lambda / l \quad (14)$$

When the air target moves at velocity V perpendicularly to the baseline "receiver-pulsar", the observation time t_{obs} in (11) corresponds to the time of the target visibility and can be determined as:

$$t_{obs} = 2\lambda R_{tg} /(lV) \quad (15)$$

Since t_{obs} in (15) is the integration time of pulsar pulses within a certain number of repetition periods of the pulsar, so it should be more than at least one pulse repetition period. The distance to the target in this case must meet the following restrictions:

$$R_t > PlV /(2\lambda) \quad (16)$$

However, it should be recalled that the forward scatter effect is observed at distances of more than l^2/λ, in the area of Fraunhofer diffraction. Hence the expressions (8, 10, 11) for calculation of SNR should be used when:

$$R_t > l^2 / \lambda \quad (17)$$

Combining limits (16) and (17), we conclude that the distance to the target must satisfy the following condition:

$$R_t < \max\{PlV /(2\lambda); l^2 / \lambda\} \quad (18)$$

IV. RESULTS

It has now been found more than 1800 pulsars. For example, three of them, B0329+54, B0833-45 and B1937+21, with different parameters have been selected for this study (Table I).

TABLE I: PULSAR PARAMETERS (FROM EPN)

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

The first goal of this study is to show whether it is possible to detect air targets using pulsar FSR net that exploits pulsars as transmitter sources. The other goal of this research is to determine what is the optimal frequency of reception of pulsar signals. To solve these tasks, we have calculated SNR at the detector input for each pulsar given in Table I, depending on the distance from the radio telescope to the air target. The ditance to the target satisfies the requirement (18). The values of SNR are calculated for two frequencies of reception of pulsar signals: 400 Hz and 1400 Hz. The other parameters used in calculation of SNR are presented in Table II.

TABLE II: PARAMETERS USED IN CALCULATION OF SNR

Parameters	Units	Values
f	MHz	400 and 1400
B	MHz	30
G	K/Jy	0.18
G_{SP}	dB	10
T_{sys} f=400 MHz	K	75
T_{sys} f=1400 MHz	K	30
Boeing: l x h V	m km/h	70.7 x 19.4 900
Rt	m	From 100 to 10000

As shown in Table II, we calculated SNR in case when the air target is the aircraft Boeing with dimensions: length – 70.7m and height -19.4m that crosses the baseline „radio telescope – pulsar" at velocity of 900 km per hour or 250m per second. The integration time (t_{obs}) is calculated using (15) in accordance with the distance to the target. 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]. For comparison, the values of SNR are calculated for three pulsars B0329+54, B0833-45 and B1937+21. The radio telescope Dwingeloo, whose parameters are given in Table II, is used as a receiver.

The values of SNR calculated as a function of distances to the Boeing are plotted in Fig.4 – for the reception frequency of 400 MHz and in Fig.5 – for the reception frequency of 1400 MHz. In case, when the reception frequency is 400 MHz, the air target can be stably detected by the three FSR systems "Radio observatory –Target- Pulsar" at distances more than 6000m according to the restriction (18). However, it can be seen that the reception frequency of 1400 MHz is less appropriate for air craft detection because the distance to the target must be more than 20000m.

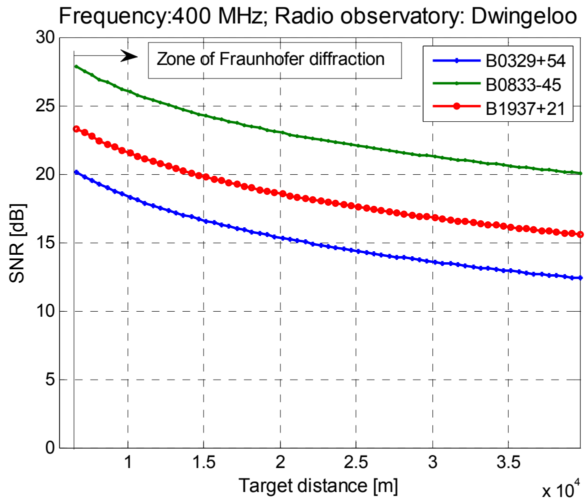

Fig.4: SNR vs. Rt (f=400 MHz)

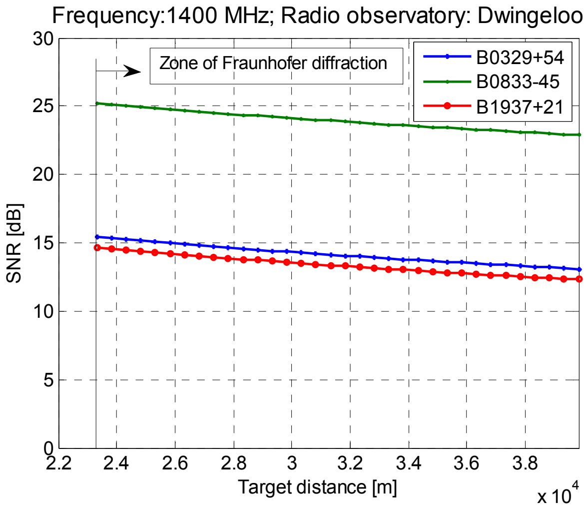

Fig.5: SNR vs. Rt (f=1400 MHz)

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