Separation of Pulsar Signals in FSR System

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***Abstract**: In this paper, one possible algorithm for target detection and velocity estimation in a pulsar FSR system is proposed. In this processing algorithm, two approaches for extraction of the target signal from the input mixture "direct pulsar signal + reradiated target signal" are studied and compared. The signal processing algorithm is evaluated by computer simulation.*

1. Introduction

Pulsars are neutron stars that periodically emit broadband pulses of electromagnetic radiation in radio, X-ray and optical ranges. Each pulsar has its own period of pulsations that lies in the range from 640 pulses per second to one pulse every 5 seconds. The repetition periods of most pulsars are very stable and often lie in the range from 0.5 to 1 s [1]. There are pulsars that generate signals every millisecond, making them ideal for navigation purposes - by measuring the differences between signals from several known pulsars, spacecraft can determine their location to within 5 km. The main limitations towards designing of detection algorithms are the very low input signal -to-noise ratio (SNR) of pulsar signals (between -40dB and -90dB) and the large time needed for their detection (typically more than 1-2 hours) [2]. The standard way to improve the SNR of pulsar signals often used in radio observatories is to integrate the power samples of the received pulsar signals taken from a large number of pulse repetition periods (epoch-folding) [1, 3]. Another approach to improve SNR is to add a matched filter after the epoch-folding performance before signal detection [4]. In this way it is possible to reduce the processing time at the stage of epoch-folding. In [5, 6] the authors propose the methodology for calculating of SNR at the detector input in various versions of Pulsar Forward Scatter Radar (Pulsar FSR) where the radio telescope is used as a receiver, for detection of asteroids and airplanes. However, the authors in these articles do not discuss the problem of separation of the useful signal, scattered by a target, from the strong direct signal, transmitted by a pulsar, and also signal losses due to the processing and propagation in the outer space when asteroids and air planes move in the stratosphere of the Earth. The results obtained in [5, 6] show that it is possible to observe space or flying objects at distances between 100÷1000 km. depending on their size (asteroids), flying vertically to the Earth near the baseline between a pulsar and a radio telescope. The possibilities of aircraft detection in these pulsar FSR systems are very limited because SNR is only a few dBs at distances between 3÷6 km. This is due to the fact that their trajectories cross the FS zone for a short time, i.e. the observation time is substantially less than that of the asteroids, and their size is substantially small. These results have also been confirmed in [7-10] for the case of a FSR network where it is shown that the simultaneous detection of the same target in different signal processing channels from different pulsars should increase the probability of target detection. In traditional FSR systems, the problem of separating of the weak target signal from the strong pulsar signal in the received mixture of signals on the background of the receiver noise remains unresolved. In the received mixture of signals, the differences in SNR between the direct and the target signals will substantially depend on the FSR RCS of the target and its distance to the receiver.

In this article, we investigate two possible approaches for separating of the useful signal scattered from the moving air target and the direct signal from a pulsar on the background on the receiver noise, which are used in the signal processing for detection and velocity estimation of the target. One of them is the high-frequency filtering of the received signal after frequency conversion to the baseband. The second approach is based on the principle of discrimination of two pulsar signal sequences, one - with a zero velocity (direct signal), the other - with the target velocity (MTI). In the signal processing algorithm for detection and velocity estimation is used the epoch-folding performance before signal separation in order to increase the SNR of signals. The detection and velocity estimation are realized in the frequency domain.

2. Signal Model in a Pulsar FSR System

It is known that in the area of the Forward Scatter (FS) effect the pulsar FSR receives at the same time the pulse sequence, emitted by the pulsar (direct signal), and the pulse sequence, re-radiated by moving cosmic targets (target signal), on the background of the receiver noise.

We assume that the pulse sequence re-radiated from the moving target does not change the pulse form and the repetition period. The received pulses from the target are modulated in amplitude and Doppler frequency. The Doppler frequency of signals depends only on the speed of the target. The amplitude modulation is sufficiently depending on the distance to the target and the target RCS.

Direct signal

At the input of the pulsar FSR system, the direct signal from a pulsar, mathematically can be represented as convolution between the pulsar pulse shape function (pulse profile) *p(t)* and the Shah periodic function:

$$s_{direct}(t) = p_0(t)\cos(2\pi f_0 t) * \sum_{k=-\infty}^{\infty} \delta(t-kP) \quad (1)$$

In (1), f_0 is the central frequency of pulsar emission and P is the repetition period of pulsar pulses. According to the European Pulsar Network (EPN) the pulse profile *p(t)* can be approximately represented as a simple Gaussian pulse [11]:

$$p_0(t) = A_0 \exp(-\frac{2(t-t_0)^2}{W^2}) \quad (2)$$

In (2), A_0 is the maximum of the pulsar amplitude at time $t=t_0$, and W *is* the Gaussian pulse width determined at the level of $(A_0 * exp(-1/2))$. According to [1], the input signal-to noise ratio of the received direct signal is:

$$SNR_{direct} = \frac{S_{ave}A_{eff}}{2k_b T_{sys}}\sqrt{P/W} \quad (3)$$

In (3). k_b is the Boltzmann constant (k_b=1.38x10^{-23}WHz^{-1}K^{-1}), S_{ave} is the average pulsar flux density in units of WHz^{-1}m^{-2}, A_{eff} is the effective area of antenna aperture in units of m^2 , T_{sys} is the system temperature in Kelvin degrees.

Target signal

Assuming that the shadow signal from the target has the same structure as the direct signal from a pulsar, it can be represented as a power-attenuated and frequency-shifted copy of the direct signal:

$$s_{target}(t) = b_0(t)\cos\ [2\pi(f_0 + f_{doppler})t] * \sum_{k=-\infty}^{\infty} \delta(t-kP) \quad (4)$$

In (4) the impulse $b_0(t)$ is the power-attenuated copy of the pulsar pulse profile:

$$b_0(t) = k_{att} p_0(t) \quad (5)$$

where k_{att} is the power-attenuated factor. The input signal-to-noise ration of the received signal from the air target can be expressed as:

$$SNR_{target} = SNR_{direct}\frac{\sigma_{FSR}}{4\pi R_{target}^2} \quad (6)$$

where σ_{FSR} is the target RCS in FSR, and R_{target} is the distance to the target.

Input signal

The input signal is a sum of three signals - the direct signal, the target signal and the band-limited zero mean Gaussian noise of the receiver, power of which is σ^2:

$$y(t) = s_{direct}(t)) + s_{target}(t) + N(0,\sigma^2) \quad (7)$$

2. Signal Processing

The functional block-scheme of the studied signal processing used for target detection in pulsar FSR is shown in Fig.1

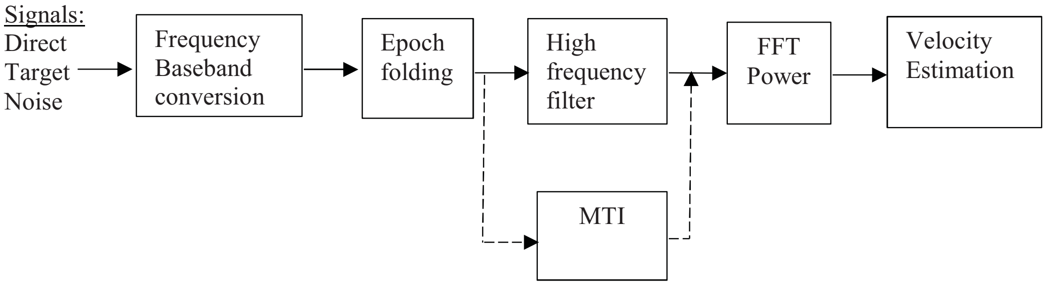

Figure 1. The studied signal processing

After frequency conversion to the baseband and sampling, the received signal in one repetition period can be approximately written as:

$$y[nT_s] = a_0[nT_s] + b_0[nT_s]\cos\left[2\pi f_{doppler} nT_s\right] + N[nT_s\ ] \tag{8}$$

In (8), $y[nT_s]$ is the baseband signal sample, $N[nT_s]$ is the baseband noise sample and T_s is the period of sampling. The input signal-to-noise ration (SNR_{input}) of the received signal can be expressed as:

$$SNR_y = SNR_{direct} + SNR_{target} \tag{9}$$

Epoch folding

Because the repetition period of pulsar pulses is very stable, the input SNR_y can be further improved using the *epoch folding* procedure [3, 5]. This procedure carries out a periodic integration of the input signal power during K sequential periods. When the number of integrated periods grows, the output signal-to-noise ratio also grows with each integrated period. In result of epoch folding, the output signal y_{fold} at time discrete n is formed as:

$$y_{fold}[nT_s] = \frac{1}{K}\sum_{k=1}^{K} y[nT_s, k] \tag{10}$$

Where k is the current integrated period. According to [1], after epoch folding the signal-to-noise ratio can be calculated as:

$$SNR_{y,fold} = SNR_y\sqrt{K} \tag{11}$$

High frequency filter

After conversion to the baseband, the frequency spectrum of the direct signal is centred at the zero frequency. However, the spectrum of the signal reradiated by the target is centred at its Doppler frequency. If the speed of the target is large enough, then the Doppler frequency will also be quite large. In this case, the signal from the target can be separated from the direct signal by means of a high frequency (HF) filter. The purpose of filtering is to pass signals at the frequencies higher the cut-off frequency. The output signal is formed as convolution between the input signal (y_{fold}) and the impulse response of the filter (h_f).

$$y_{filtered}[nT_s] = y_{fold}[nT_s] * h_f[nT_s] \tag{12}$$

The cut-off frequency of the HF filter must be more than a half of the bandwidth B of the pulsar pulse. Taking into account that the pulsar profile has the Gaussian form and W is the pulsar pulse width, the cut-off frequency of the high frequency filter can be chosen meeting the following condition:

$$f_{cut} > B/2 \tag{13}$$

Direct-signal compensation (MTI)

The direct signal can be cancelled using the MTI approach. According to this approach the direct signal can be removed using the simple “inter-period subtraction” algorithm.

$$\boldsymbol{y_{filtered}[nT_s] = y_{fold}[(n+1)T_s] - y_{fold}[nT_s]} \tag{14}$$

Target velocity estimation

The target velocity is evaluated through the estimate of the target Doppler frequency. The estimate of the target Doppler frequency is found as a frequency, at which the filtered power spectrum has the maximum value:

$$\boldsymbol{\overline{f_d} = \arg\max\{P_{filtered}[f_n]\}} \tag{15}$$

Using [12], the estimate of the target velocity is computed as:

$$\boldsymbol{\overline{V} = \lambda\overline{f_d}/2} \tag{16}$$

3. Simulation Results

The study is carried out using the computer stimulation approach. The signal processing algorithm, described in Section 3, is tested according to the simulation models of signals, described in Section 2. In simulation of signals, the parameters of the radio observatory Westerbork, the Netherlands are used. They are: radio telescope antenna gain -2.5K/Jy; system temperature – 150 K; central frequency- 400 MHz. The parameters of pulsar B0833-45 are taken from the EPN database for simulation of the integrated pulsar pulse and the pulse reradiated by the meteoroid. The pulsar parameters are: flux at frequency of 400 MHz – 5Jy; pulse width after epoch-folding – 0.0021s; repetition period- 0.089328s. The simulation is carried out for a large meteoroid with a diameter of 30m that falls along of the baseline “radio telescope-pulsar”. As known, when the object moves along the baseline „ receiver- pulsar” the FS effect appears at distances to the target more than R_{FSR}. In this case the radar cross section of the meteoroid is calculated as:

$$\sigma_{FSR} = \frac{\pi^3 D^4}{4\lambda^2} \tag{17}$$

In (17), *D* is the target diameter, and λ is the wavelength that corresponds to the frequency of 400 MHz. The distance R_{FSR} is calculated as:

$$R_{FSR} = 4D^2/\lambda \tag{18}$$

For the meteoroid with a diameter of 30 m, the distance R_{FSR}, calculated by using (18) is 4800 m. The values of SNR for the target signal after the epoch-folding are presented in Fig.2 and Fig.3 depending on the distance to targets. The results in Fig.2 correspond to the case when the number of integrated periods in the epoch folding is 500. Analogically, the results in Fig.3 are obtained for 1000 integrated periods.

The aim of this investigation is to find at what minimal velocity of the target it can be detected upon the very low SNR when one of the approaches to suppress the directed signal is used, the HF filter or the „inter-period subtraction”.

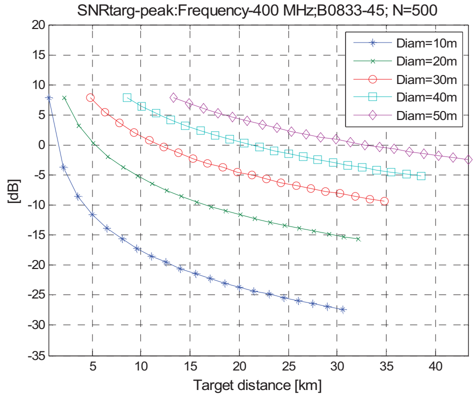

Figure 2. Number of integrated periods -500
(epoch folding time is 44.5 s)

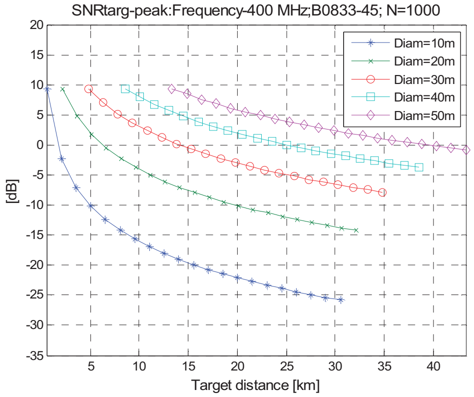

Figure 3. Number of integrated periods -1000
(epoch folding time is 89s)

For example, from Fig.2 follows that the value of SNR for the target distance of 8000 m is 3.4 dB when 500 integrated periods are used in the epoch folding. From Fig.3 follows that for 1000 integrated periods the value of the target SNR for the distance of 8000 m is 4.9 dB. In this article we carried out all simulations for this value of the target SNR. Using the large number of simulations we found that the minimal target velocity when the target can be reliably detected at the distance of 8000 m and its velocity can be estimated is the velocity of 1.5-3 km/s if the HF filter is used for removing of the direct signal. For the target velocity of 3 km/s, the simulated signal mixture containing the direct signal and the target signal is shown in Fig. 4. The value of SNR of the direct signal is 23.5 dB. The Doppler frequency that corresponds to the target velocity of 3 km is 8 kHz. The noised mixture (direct signal + target signal +noise) is shown in Fig.5. The sampling frequency chosen for simulation is about 100 KHz.

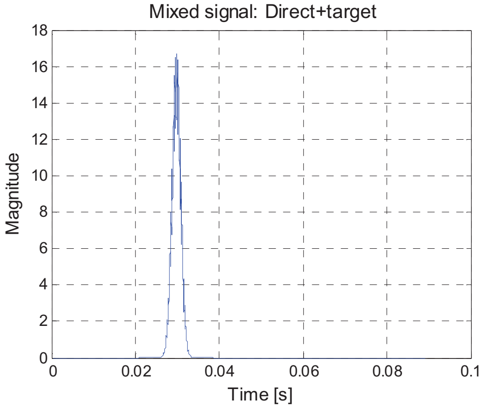

Figure 4. Mixed signal (direct + target)

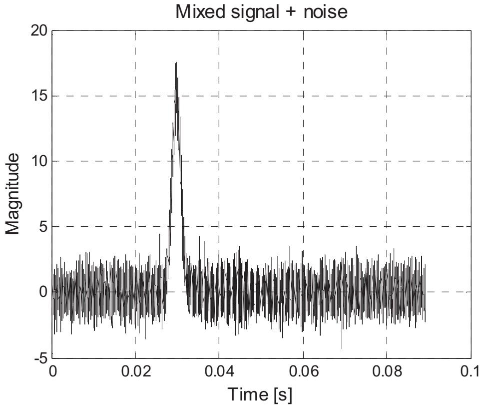

Figure 5. Noised input signal

The corresponding two-sided frequency spectrum of the noised mixture is shown in Fig.6. Figure 6 shows that the frequency spectrum of the direct signal is concentrated at the zero frequency while the frequency spectrum of the target signal is concentrated at the Doppler frequency of 8 kHz. The frequency spectrum in Fig. 5 also shows that a high-frequency (HF) filter can be used to separate the target signal from the direct signal. The cut-off frequency of this HF filter should be greater than a half the frequency bandwidth of the direct signal. In our case the frequency bandwidth of the pulsar pulse is 4 kHz. We chose the cut-off frequency of the HF filter to be 2.5 kHz. The frequency response of the used HF filter is shown in Fig. 7, where the normalized cut-off frequency of the filter is 0.05.

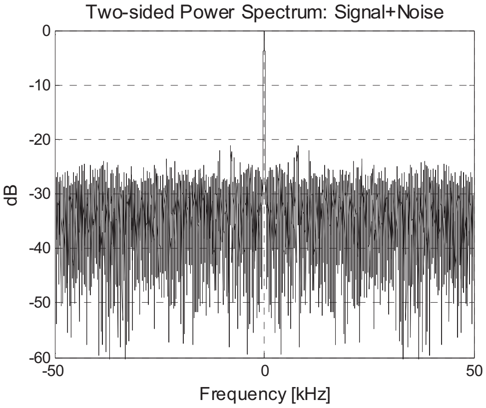

Figure 6. Two-sided spectrum of the noised signal

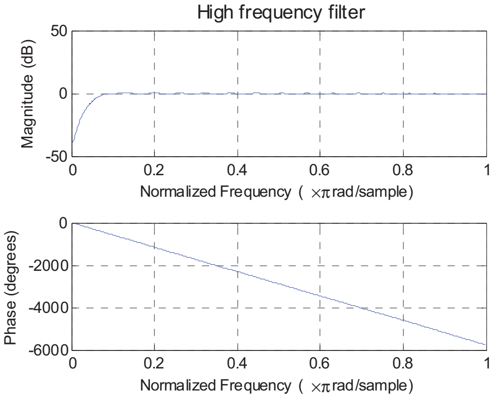

Figure 7. Frequency response of the HF filter

The output signal of the HF filter is shown in Fig. 8. The corresponding one-sided frequency spectrum of the output signal of the HF filter is shown in Fig.9. It can be seen that the output signal of the HF filter does contain the direct signal and that is clearly seen in Fig.9. The estimated Doppler frequency is 8.03 kHz, and the estimated target velocity is 3.02 km/s.

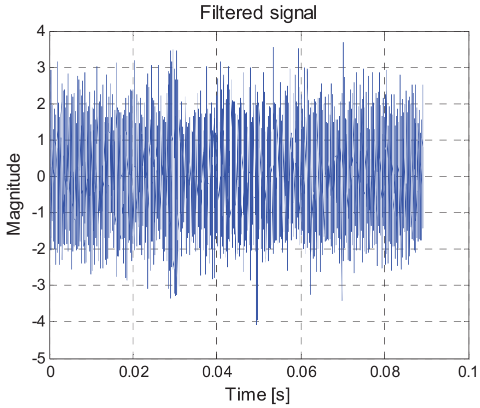

Figure 8. Signal after high-frequency filter

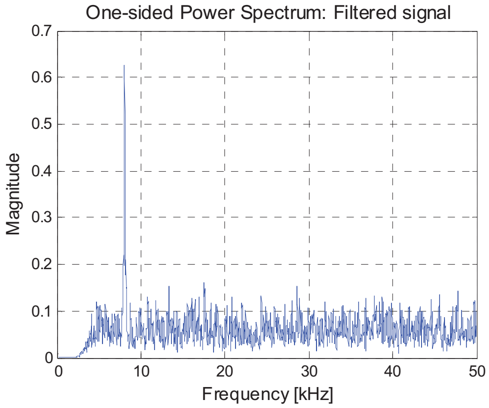

Figure 9. On-sided spectrum after HF filter

The alternative way to separate the target signal from the direct signal is to use the compensation of the direct signal in the time domain by means of the algorithm “inter-period subtraction” (MTI) according to (14). The one-sided frequency spectrum of the output signal after “inter-period subtraction” for the target velocity of 3km/s is shown in Fig. 10. It can be seen that at the Doppler frequency of 8 kHz the frequency spectrum has the peak, but this peak is not unique. It means that this Doppler frequency of 8 kHz does not automatically detected and estimated after the “inter-period subtraction”. Using the large number of simulations, we found that the minimal target velocity that can be reliably detected and estimated at the output of the “inter-period subtraction” is 10 km/s. The Doppler frequency that corresponds to the target velocity of 10 km/s is 26.667 kHz. The one-sided frequency spectrum at the output of the “inter-period subtraction” when the target velocity is 10 km/s is shown in Fig. 11. It can be seen that the highest peak of the frequency spectrum corresponds to the estimate of Doppler frequency - 26.7 kHz. The estimated target velocity in that case is 10.1 km/s. Comparing Fig. 10 and Fig.11 it can be concluded that if we previously know the range of the estimated velocities, then the additional HF filter can be used after the ‘inter-period subtraction” in order to remove the signal at the higher frequencies which appear in result of the “inter-period subtraction”.

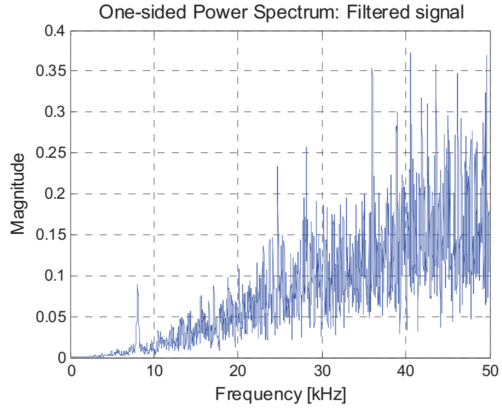

Figure 10. One-sided spectrum after MTI (V=3km/s)

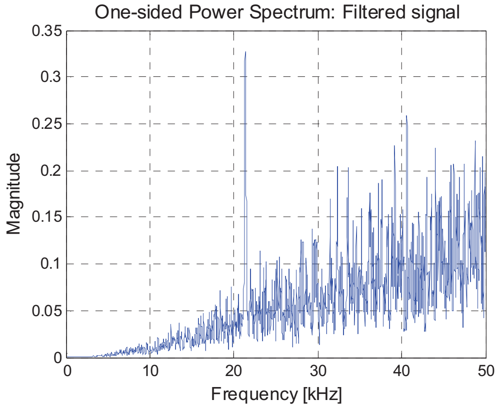

Figure 11. One-sided spectrum after MTI (V=10km/s)

4. Conclusions

Two approaches for removing the direct signal from a pulsar in a pulsar FSR system are considered in this paper. The results obtained show that when we do not know previously the range of the estimated velocities, the use of the HF filter is more preferably than the use of the algorithm "inter-period subtraction". It can be noted that the estimation errors depend on the appropriate choice of the cut-off frequency of the HF filter, which can limit the lower bound of the range of the estimated Doppler frequency. Therefore, the choice of the cut-off frequency of the HF filter should be a result of a compromise between the lower bound of the range of the estimated velocities and the accuracy of the estimates obtained.

Acknowledgment

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