Separation of GPS Signals in FSR System

H. Kabakchiev
Sofia University "St. Kliment Ohridski"
Sofia, BULGARIA
e-mail: ckabakchiev@fmi.uni-sofia.bg

V. Behar
Institute of Information and Communication Technologies
Sofia, BULGARIA
e-mail: behar@bas.bg

I. Garvanov
University of Library Studies and Information Technologies
Sofia, BULGARIA
e-mail: i.garvanov@unibit.bg

D. Kabakchieva
University of National and World Economy
Sofia, BULGARIA
e-mail: d.kabakchieva@unwe.bg

K. Kabakchiev
University of Birmingham,
Birmingham, UK,
e-mail: kalin.kabakchiev@gmail.com

H. Rohling
Technical University Hamburg-Harburg
Hamburg, GERMANY
e-mail: rohlingr@tu-harburg.de

K. Kulpa
Technical University,
Warsaw, Poland,
e-mail: kulpa@ise.pw.edu.pl

A. Yarovoy
Technical University,
Delft, Netherland,
e-mail: a.yarovoy@irctr.tudelft.nl

***Abstract*—An approach and algorithm are proposed for separating the useful signal from a moving cosmic target and the direct signal transmitted by GPS satellites, on the background of the receiver noise. The algorithms for separating the useful signal will be based on the principle of separation in speed of two GPS signal sequences, the first - with a satellite velocity (reference signal), the second - with the target velocity. We will evaluate their performance with computer calculation or simulation.**

Keywords—GPS, FSR, Signal Separation

I. INTRODUCTION

In bistatic radar, one of the factors affecting the signal strength at the radar receiver is the angle that the target makes to the transmitter and receiver, called the bistatic angle β. When the bistatic angle is equal or near 180° ($\beta \approx 180°$), the radar system is referred to as Forward Scatter Radar (FSR) system [1]. The forward scattering radar technology exploits the phenomenon of diffraction of electromagnetic waves in order to detect targets. The diffraction is observed when the wavelength of electromagnetic waves, incident on the target, is much less than the size of the target. The FSR technology actively exploits the diffraction of the transmitted electromagnetic waves in the far zone of Fraunhofer, when the target moves near the baseline "receiver - transmitter" and far from the receiver and the transmitter. In that case the Forward Scatter (FS) effect is observed, the most attractive feature of which is the drastic increase in the forward scattering radar cross-section, and therefore, the strong increase of Signal-to-Noise Ratio (SNR) of the received signal.

In last years, passive radar systems where GPS satellites are used as transmitters are becoming increasingly popular as an alternative to traditional radar systems. The GPS Forward Scatter Radar (GPS FSR) is a specific case of FSR, where GPS satellites are exploited as 'transmitters of opportunity'. In [2, 3] the authors consider the possibility to detect air targets in bistatic and forward scatter radar, which exploit GPS satellites as transmitters. These articles offer the theoretical analysis of possibilities to detect air targets [2] or sea targets [3] in bistatic radar systems, and also consider the difficulties in the practical implementation of such systems.

A possible algorithm for air target detection using GPS L5-based FSR system is described in [4], and the detection probability characteristics are analytically calculated in [5] for low-flying and poorly manoeuvrable air targets in the urban interference environment. In these two articles the authors have discussed the potential to increase the SNR to detect aircrafts with GPS L5-based FSR system, which are due to the increase in radiated power of GPS L5 signal and the maximum value of a forward scattering cross-section of the tested planes in the article.

In this article, the novelty are both the approach and the algorithm in GPS FSR for separating the useful signal scattered from the moving object and the direct GPS signal from a satellite on the background of the receiver noise.

In our case, due to the direct GPS signal and re-reflected GPS signals from the space objects, in order to perform a qualitative separation of the useful signal from the target, it is necessary in advance to accumulate signals in order to obtain the positive SNR values. These algorithms for separating the useful signal will be based on the principle of discrimination of two GPS signal sequences, one with a velocity of satellite - the reference signal, the other - with the target velocity. These algorithms will be a further development of the GPS signal algorithms, described in articles [4, 5].

In the article, will be chosen suitable algorithms for separating the signals in GPS FSR and will be determined their limitations, depending on the parameters of the GPS signals and the objects observed in the space. The study will be carried out using the simulation approach.

In the time domain, the direct signal is much more powerful than the radiated by the object, and masks it making the object impossible to be detected. 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 proposed algorithm includes: coherent integration, correlation, HF filtering for suppressing of the direct signal, and estimation of the meteorite velocity.

II. Separation of GPS Signals in FSR System

In the area of the FS effect, the GPS FSR receives at the same time the GPS pulse sequence emitted by the satellite and a GPS pulse sequence re-radiated by moving cosmic targets, on the background of the receiver noise. The GPS signals are coherent reference signals. In evaluating of the target detection possibility (air planes and asteroids) in GPS FSR system, we accept two important limitations [4 - 6]. The first of them is that a qualitative separation of the useful signal from the target and the direct signal from a GPS satellite (reference signal) is carried out. The second limitation is that the space object flies along the baseline during its flight, whereby it is possible to carry a fairly large signal accumulation. In practice, these two restrictions are very difficult to implement.

Therefore, in this article we will discuss in detail possible approaches and algorithms for separating GPS signals, and we will evaluate their efficiency using computer simulation.

Regarding the signal model, we assume that the re-radiation of the GPS signals from flying space objects does not change their form. They are modulated in amplitude and Doppler velocity relative to the receiver.

The Doppler velocity of signals depends only on the speed of the flying body and is linearly modulated from a minus maximum through zero to a maximum.

Regarding amplitude modulation, it is sufficiently depending on the distance to the target and the target RCS. In this case, the reference GPS signal from satellite is immersed in receiver noise of the order (-20÷-30 dB).

In a received mixture, the differences in SNR between the reference and the useful GPS signals will substantially depend on the forward scatter RCS and the difference in speeds between the satellite velocity of the target velocity and its distance to the receiver.

In our case, the evaluated parameter will be the target Doppler velocity for GPS L1 signal. This algorithm for separating the useful signal will be based on the principle of discrimination by speed of two GPS signal sequences, one - with the velocity of satellite (reference signal), the other - with the target velocity.

The proposed algorithm includes: coherent integration, correlation, HF filtering for suppressing of the direct signal, and estimation of the meteorite velocity.

For the study, it is necessary to estimate the SNR at the output of the GPS correlator of the signal re-radiated by the object.

III. SNR of the Direct and Irradiated Signals at the Detector Input

The power density (S_1) at the output of an omnidirectional antenna near the Earth's surface can be determined as follows:

$$S_1 = P_t / A_{omn}, \text{ where } A_{omn} = \lambda^2 / 4\pi \quad (1)$$

In (1), P_t is the power of the GPS L1 signal measured near the Earth's surface (-160 dBw), A_{omn} is the effective area of the omnidirectional antenna, and λ is the wavelength of the GPS L1 signal transmitted by a satellite. The power of the signal reradiated from a meteoroid with RCS σ in direction of the GPS receiver is:

$$P_{met} = S_1\sigma = 4\pi P_t \sigma / \lambda^2 \quad (2)$$

The FS effect is observed at distances (R_{met}) of more than D^2/λ, i.e. in the area of Fraunhofer diffraction. In case of the FS effect the meteoroid RCS in (2) is calculated as:

$$\sigma = \frac{4\pi A_{met}^2}{\lambda^2} \quad (3)$$

In (3) A_{met}^2 is the silhouette area of a meteoroid. If we approximate the meteoroid as a sphere with a diameter D, then the RCS in (3) can be rewritten as:

$$\sigma = \frac{\pi^3 D^4}{4\lambda^2} \quad (4)$$

The power density of the reradiated signal at the receiver antenna input (S_2) is:

$$S_2 = \frac{P_{met}}{4\pi R_{met}^2} = \frac{P_t \sigma}{\lambda^2 R_{met}^2} \quad (5)$$

The signal power at the output of the receiver antenna depends on the effective area of the receiver antenna, i.e. the antenna gain:

$$P_{rec} = S_2 A_{omn} G_r = \frac{P_t G_r \sigma}{4\pi R_{met}^2} \quad (6)$$

The noise level N_r at the output of the RF front-end can be determined in terms of the equivalent noise temperature (T) and the receiver bandwidth (B):

$$N_r = kTB \quad (7)$$

In (7), k is the Boltzmann constant (1.38x10 in units w/K/Hz). For a GPS L1 receiver, the frequency bandwidth is 2 MHz, and the noise level N_r in decibels is nearly -141 dBw. Using (6) and (7), the signal-to-noise ratio at the RF front-end output of the GPS receiver can be written as:

$$SNR_{rec} = \frac{P_{rec}}{N_r} = \frac{P_t G_r \sigma}{4\pi R_{met}^2 N_r} \quad (8)$$

The signal to-noise ratio (8) could be improved by coherent integration over a detection time period $T_{\det}$. The maximal number of coherent samples is evaluated as:

$$N = T_{det}/T_{C/A} \quad (9)$$

The subsequent correlation processing includes circular cross-correlation. Therefore, the signal-to-noise ratio at the cross-correlator output is given by:

$$SNR_{cor} = SNR_{rec} G_{SP} = \frac{P_t G_r \sigma G_{SP}}{4\pi R_{met}^2 N_r} N \quad (10)$$

In (10), $G_{SP}=BT_{C/A}$ is the processing gain of the cross-correlator, and $T_{C/A}$ is the period of the C/A code of the GPS L1 signal.

We assume that the observation time is T_{det} = 0.01-0.02 seconds, taking into account the velocity of the falling cosmic object and the distance, which the object passes over that time. To achieve the FS effect, we assume that the cosmic object crosses the baseline at a very small deviation angle (1-2 degrees), or part of its trajectory is almost parallel to it (the deviation angle is almost zero).

IV. Modeling of Signal Processing in FSR System

In this article, we simulated the signal mixture at the output of the GPS correlator, containing the direct GPS L1 signal and the re-radiated by the meteorite, on the background of the receiver noise. In the time domain, the direct signal is much more powerful than the signal reradiated by the meteorite and masks it making the object impossible for detection. 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 filter.

The signal mixture at the correlator output is simulated as:

$$y[nT_s] = a_0[nT_s] + b_0[nT_s]\cos[2\pi f_{doppler} nT_s] + N[nT_s] \quad (11)$$

In (11), $y[nT_s]$ is the baseband signal sample, $N[nT_s]$ is the baseband noise sample and T_s is the period of sampling.

Coherent Integration

This procedure carries out a periodic integration of the input signal power during N sequential periods. When the number of integrated periods grows, the output signal-to-noise ratio also grows with each integrated period.

High frequency filter

After conversion to the baseband, the 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. The purpose of HF filtering is to pass signals at the frequencies higher the cut-off frequency. The output signal is formed as convolution between the input signal and the impulse response of the filter. The cut-off frequency of the high frequency filter must be more than a half of the bandwidth of the GPS L1 signal.

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:

$$f_d = argmax(P_{filtered}[f_n]) \quad (12)$$

Using (12), the estimate of the target velocity is computed as:

$$V = \frac{\lambda f_d}{2} \quad (13)$$

V. Numerical 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 4. In simulation of signals, the following parameters of the GPS L1 signal are used. They are: receiver gain in dB is Gr=20, transmitted power on the Earth in dB is Pt=-160, GPS receiver noise in dB is Nr=-141; number of integrated periods of the C/A code N=20; coherent processing time is P=0.001s., GPS receiver bandwidth is B=2 MHz, wavelength λ =0.19 m, sampling frequency is fs=10.B Hz, pulse width is W=4/B s, processing gain is Gsp=10log10(P.B) dB.

The simulation is carried out for a large meteoroid with a diameter of 50m that falls along of the baseline "GPS receiver – GPS satellite". As known, when the object moves along the baseline „ receiver- satellite" 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 by (4):

Figure 1 show the difference in SNR of the received direct signal and the re-radiated FS signal from the cosmic objects, depending on different diameters of meteoroids. It can be seen that this diffrence in SNR is directly proportional to the FS radar cross section (FS RCS) of the cosmic object, and inversely proportional to the square of the distance to the

object, and does not depend on the parameters of the GPS FSR system. These graphics are universal because they show the dependence of the difference in SNR between the direct and the redirected signal depending on the size of the falling objects and the distance to it, in FSR systems monitoring the space with different signal sources (satellites, pulsars, etc.).
The final SNR of cosmic objects (Fig. 1) and the GPS signal at the detector input, after coherent integration (N = 20) and correlation is calculated and plotted below for different diameters of meteoroids: D = 10, 30, 50 m (Fig. 2).

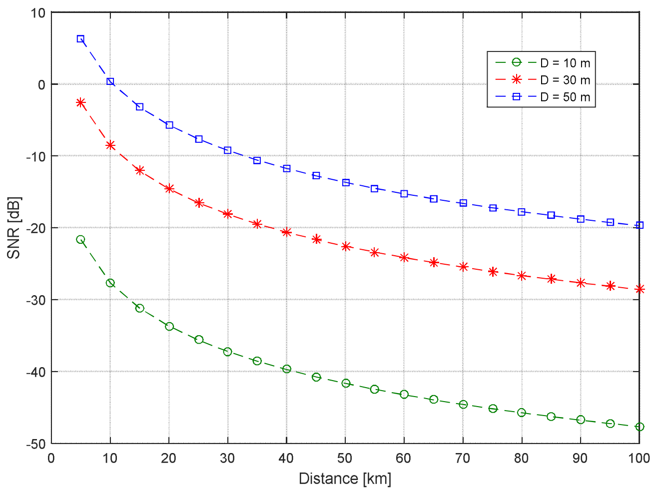

Figure 1. SNR of cosmic objects

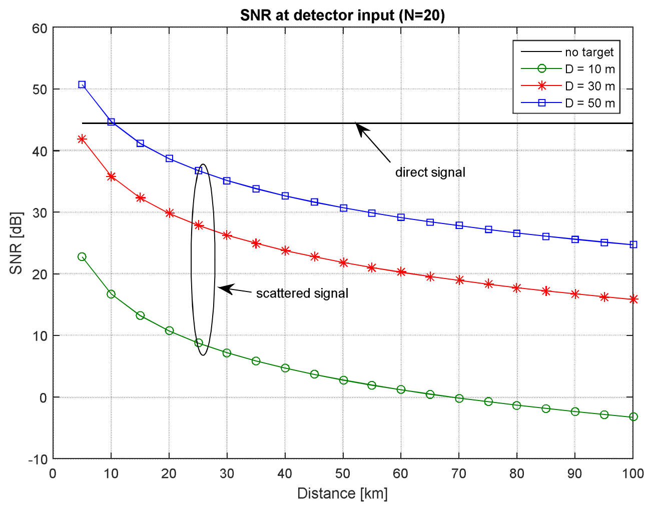

Figure 2. SNR of the direct and the scattered GPS signal

From the results in Fig. 2 follows that the direct GPS signal received by the receiver on the surface of the Earth has a constant magnitude and it is represented as a straight line. Naturally, the magnitude of the direct signal depends on the number of coherent integrations of the signal at the input of the correlator.
It is impossible to detect the meteorite signal in the time domain because it coincides in time with the direct signal. The power of the direct signal is much greater than that of the signal reradiated by the meteorite. The reradiated signal by the meteorite has a high Doppler velocity of 20-40 km/s. Then the signal selection can be performed in the frequency domain. In this article we accept that satellite signals have the zero Doppler frequency. This assumption is plausible because the speed of GPS satellites is much smaller than that of meteorites. The one-sided spectrum of the direct signal and the signal from the target that moves at a speed of 20 km/s is shown in Fig. 3.

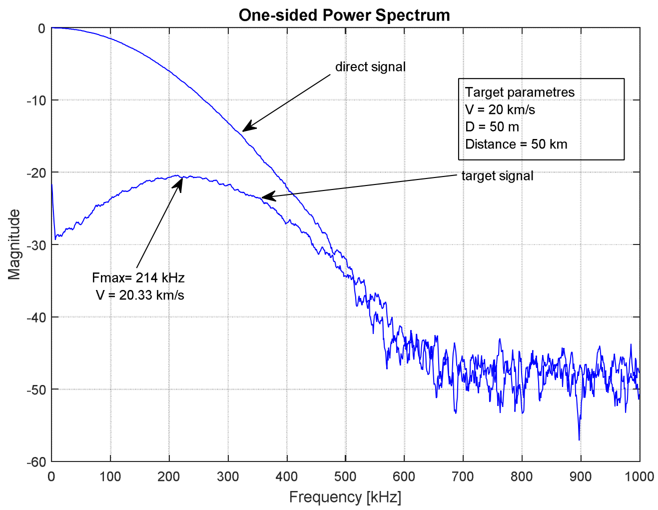

Figure 3. On-sided spectrum of direct and target signals (V=20 km/s)

From Fig. 3 follows that the spectra overlap and the detection of the meteorite signal is difficult. If the meteorite moves at a speed of 40 km/s its spectrum is outside the spectrum of the direct signal (Fig. 4 and Fig. 5).

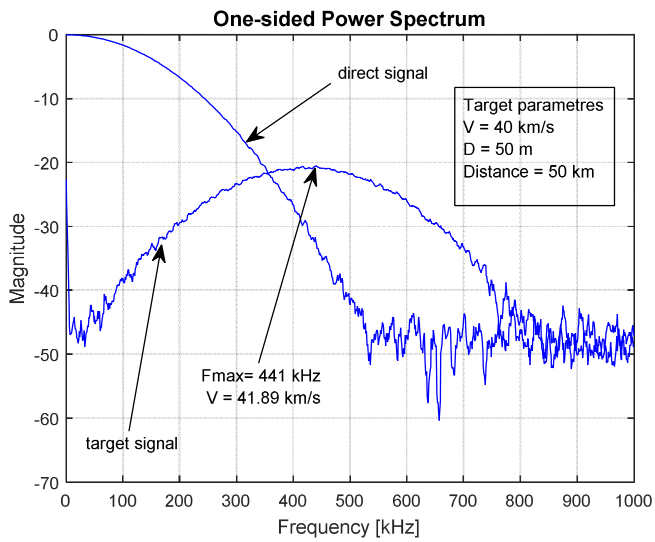

Figure 4. One-sided spectrum of direct and target signals (V=40km/s)

To separate the two signals, we used a high-frequency filter that suppresses the direct and powerful GPS signal, and thus allows a target to be detected at speeds greater than 20 km/s.

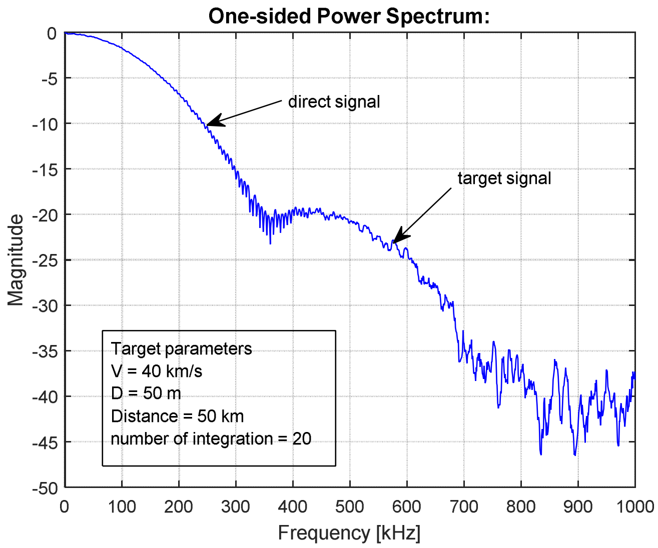

Figure 5. One-sided spectrum (direct + target)

The result after filtration is shown in Fig. 6. The maximum frequency is 490 Hz, which corresponds to 46.5 km / s.

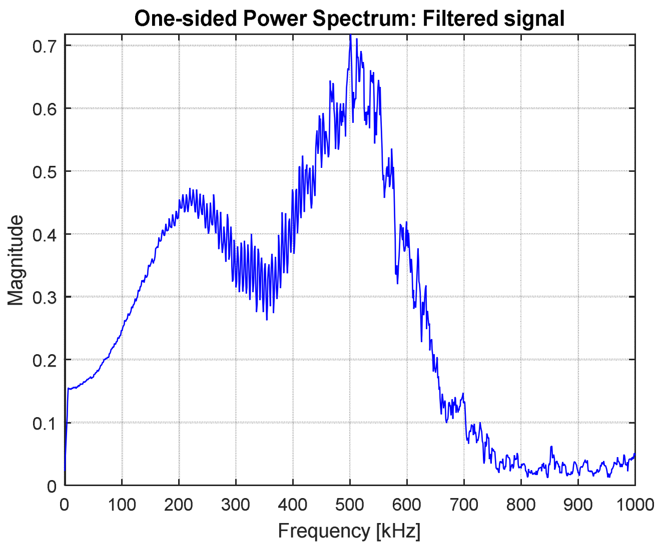

Figure 6. One-sided spectrum after HF filter

VI. Conclusions

The article shows the possibility of separating the direct powerful GPS signal from the useful but very weak signal reradiated by the meteorite. Separation of signals is possible when the velocity of the meteorite is greater than 20 km/s. This limitation is imposed by the bandwidth of the GPS L1 signal (2 MHz). The detection of the target is easier when the SNR is large and when the meteorite's dimensions are large and when the distance from the receiver to the meteorite is less.

Acknowledgment

This work is financially supported by the Bulgarian Science Fund, grand DFNI-T 02/3 from 12.12.2014.

References

[1] Cherniakov, M., (ed.): Bistatic Radar: Principles and Practice, Wiley & Sons, (2007).

[2] Glennon E.P., A.G. Dempster , and C.Rizos: Feasibility of air target detection using GPS as a bistatic radar, Journal of Global Positioning Systems, vol.5, no.1-2, (2006), pp. 119-126

[3] Clarizia M. P., P. Braca, C. Ruf, and P. Willett: Target Detection Using GPS signals of opportunity, 18th International Conference on Information Fusion, (2015), pp. 1429-1436.

[4] Behar, V., Chr. Kabakchiev: Detectability of Air Target Detection using Bistatic Radar Based on GPS L5 Signals, International Radar Symposium, Leipzig, (2011), pp. 212-217.

[5] Behar, V., Chr. Kabakchiev, H. Rohling: Air Target Detection Using Navigation Receivers Based on GPS L5 Signals, ION GNSS, Portland OR, (2011), pp. 333-337.

[6] Garvanov, I., Chr. Kabakchiev, V. Behar, M. Garvanova: Target detection using a GPS Forward-Scattering Radar. IEEE Pros. of the Second International Conference “Engineering & Telecommunications – En&T 2015”, Moscow-Dolgoprudny, Russia, (2015), pp. 29-33.