Target Detection by GPS Forward-Scattering System

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***Abstract* — In this paper, we investigate the possibility of constructing a bistatic Radar system based on GNSS signals. The aim of the paper is to solve problems of detection of ground and air targets on their GPS radio shadows. The proposed system uses the effect of Forward Scatter (FS) of electromagnetic wave in bistatic configuration of the GPS transmitter and GPS receiver. The phenomena of diffraction in the near area is used for shadow target detection. The proposed algorithm is tested on real GPS records.**

Keywords—FSR; GPS; parameter estimation

I. INTRODUCTION

Using GPS, radio, GSM and other communication systems as a source of signals in the design of systems for secondary application of wireless technology is not a new task [1-10]. In [2], the authors used GSM signal to detect targets. In [3-8], there are applied GPS signals to detect moving targets using the principles of FSR. In [9], the authors proposed the usage of WiFi to detect moving targets by FS principles. Most of proposed technologies are used the principles of FS configuration or split receiver and transmitter and an object passing between them. In this configuration, the receiver signal is received as a result of the phenomenon of diffraction of electromagnetic rays. Depending on the distance of the object to the receiver, there are two diffractive zones, zone Fresnel and Fraunhofer zone [10]. When the object passes close to the receiver in the zone of Fresnel, the receiver falls into the radio shadow of the object and the received signal power sharply reduced. In the case where the object passes at a greater distance from the receiver, in the area of the Fraunhofer, then as a result of diffraction of the signal is obtained so-called FS effect and the received signal power is much higher than the case without the obstacle of the baseline [11]. This effect has been studied by many scientists and it is the basis for the creation of different radio barrier systems. Due to this effect, stealth technology is not invisible to the FSR systems.

This article will be tested algorithm for detecting various ground and air targets using GPS FS system, implemented by commercial GPS receiver and antenna. The proposed algorithm will be tested with real records of GPS signals and will be estimate a theoretical forward scatter cross section of different moving targets.

II. FORWARD-SCATTERING RADAR SYSTEM

Forward Scattering Radar (FSR) system is a special case of a bistatic radar system where the bistatic angle is about 180 degrees (Fig. 1). The mechanism of scattering and signal production is different than in the case of mono- and bistatic radars, it is not based on scattering off individual points on the target surface, but rather the signal is produced coherently by the whole geometrical shadow of the target, projected in the plane of movement with respect to the baseline [13].

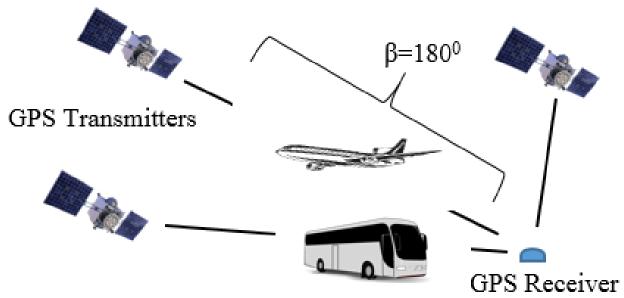

Fig. 1. Topology of Forward Scattering GPS system (β≈180°)

The shadow radiation, E_{sh}, is going to be represented as the reduction of the leakage radiation, i.e. the signal, E_i received in an absence of a target in the vicinity of the baseline [12]. Thus, the received EM field at the receiver point, according to Fig. 2, is going to be given by:

$$E_{Rx} = E_i + E_{sh} \tag{1}$$

Targets which are bigger than the wavelength have both self-scattering and shadow fields. But at bistatic angles very close to 180 degrees the main contributor in the scattering field is the shadow field. This region is specified as the forward-scattering (FS) field. In this region a real target can be considered to be an absolutely black body, allowing to neglect the effects of the currents on the surface of the target.

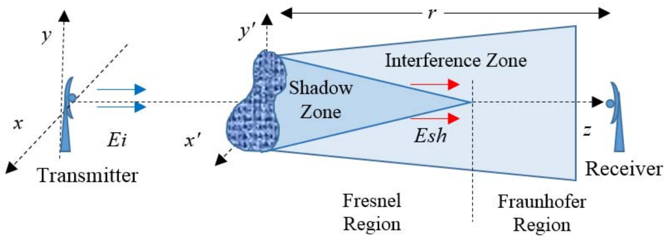

Fig. 2. Geometry of measuring of shadow radiation by an object sitting on the baseline, between transmitter and receiver

Taking into account the principle of Babinet, shadow radiation from an opaque object will have an opposite phase when compared to incident radiation. So due to the shadowing effect, the signals received in FSR are going to be defined as a reduction of a constant leakage, rather than the induction of a signal, as in traditional radars. The Physical Optics gives a useful approximation for shadow radiation E_{sh}^{F}, derived on the basis of Fresnel diffraction.

$$E_{sh}^{F} = \frac{-j}{\lambda} \iint_A E_i \frac{\exp(-jkr)}{r} dS \qquad (2)$$

where all terms have their usual meanings: λ is the wavelength, E_i is the incident wave on the target, and A is the projected shadow contour of the object on the observable plane integrated over the whole area of the target, dS is an infinitesimally small slice of the target total area and r is the range from that slice of area to the receiver, $k = 2\pi/\lambda$. According to [12], the radio shadow received from an object does not depend on the material or shape of the object, but depends on its geometry and size. This approximation can only be valid if the target is considered as an absolute black body, which is valid for the general radar target, i.e. ground and air target, which resolves the biggest advantage of FSR - the received signal is not affected by the scattering coefficients of the target and thus stealth coating or geometry do not reduce the FSCS. For greater distances between the receiver and the target silhouette, *Ei* can be considered to be constant and taken out of the integral, also $\iint_A dS = A$, thus the equation 2, can be rearranged:

$$E_{sh}^{F} = \frac{-j}{\lambda} E_i \frac{\mathrm{A} \exp(-jkr)}{r} \qquad (3)$$

For distances smaller than the area of the aperture, $r < A$, equation 2 can be approximated by the Fresnel diffraction integral. If a target lying on the baseline, can be represented in a Cartesian coordinate system x' and y', which is parallel to the signal source coordinate system. Then the shadow of the radiation, E_{sh}^{F} is given by:

$$E_{sh}^{F} \cong \frac{-jE_i}{\lambda} \frac{\exp(-jkr)}{r} \iint_A \exp\left(\frac{-j\pi}{\lambda r}(x'^2 + y'^2)\right) dxdy \qquad (4)$$

where it is considered that the illuminating field, *Ei* is uniform and *r* does not change much over the area of the aperture. The forward scatter cross section (FSCS), σ_{FS} of the object is defined by the distance between incident and shadow radiation [14]:

$$\sigma_{FS} = 4\pi \lim_{r\to\infty} r^2 \frac{|E_{sh}|^2}{|E_i|^2} \qquad (5)$$

The maximum of the FSCS of a target can be estimated then as:

$$\sigma_{FS}(180^0) = \frac{4\pi A^2}{\lambda^2} \qquad (6)$$

where *A* is the target plane shape (silhouette) and considers the case when the target is in the optical scattering regime, i.e. target area is much larger than wavelength λ.

Using Fresnel parameter $F = D^2/(4\lambda)$, we will consider scattering mechanism as a Fresnel diffraction in the case when ranges to/from target are smaller than *F*. The wavelength of the *L*1 signal λ = 0.19 m and the parameter *D* is effective size of target.

III. SIGNAL PROCESSING

The proposed signal processing algorithm originally combines some well-known approaches. The first of them is the recording of real GPS signals using the GPS recording system, which is proposed and developed in the Aerospace Department of the Colorado University, USA. This recording system receives and records the raw GPS data flow using the small commercial GPS antenna and the USB-based device. The recorded GPS signals are saved as binary files in the computer memory. The second approach is the software-defined GPS receiver developed in [13]. The software-defined GPS receiver contains a set of MATLAB programs for implementation of the main sequential stages of signal processing in the GPS receiver: acquisition, tracking and navigation. The next approaches are the integration of absolute values of the *Ip* component at the output of the Code & Carrier tracking block. The block-scheme of the proposed algorithm for target detection of GPS radio shadows of objects is shown on Fig. 3. According to this block-scheme, the signal processing implemented in MATLAB includes the following stages: acquisition and tracking of recorded GPS signals over their complete duration; transformation and filtering of the extracted navigation message; automatic detection of radio shadows; automatic estimation of radio shadow parameters.

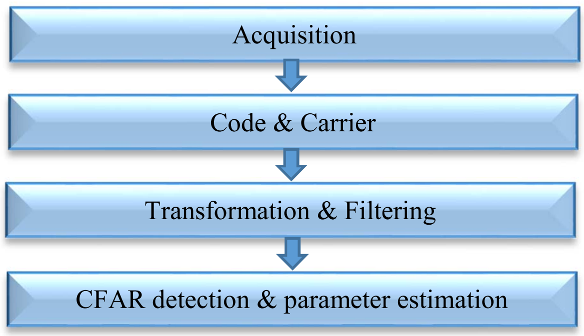

Fig. 3. Blok-scheme of signal processing

In order to meet the requirements for the appearance of GPS radio shadows of the object during the experiment, only signals from the visible satellites that are located close to the line “satellite-object-GPS receiver”. Upon the higher power of the received signal, the stronger effect of the formation of GPS radio shadow (falling of the signal) will be observed at the intersection of the line “satellite - object - GPS receiver”. To improve the radio shadow detection is desirable to increase the “shadow power” through a long-period non-coherent summation of received GPS L1 signals, i.e. by filtering of received signals. In practice, the long non-coherent summation of GPS signals in the software-defined GPS receiver is cannot be performed. For this reason we use the approach for non-limited integration of the bits of the extracted navigation message at the output of the Code & Carrier tracking block, after being transformed prior their negative values. We offer the inversion of the radio shadow to transform it into the traditional pulse signal.

This is done by a specific nonlinear transformation of the shadow by transforming it into a positive signal, normalizing and squaring him, i.e. transforming it into a signal power - suitable for automatic detection. In this article to improve the speed of signal processing closer to real time, we used the Moving Average Filter with Jumping Window (MAFJW) with the length of 200 ms. To perform automatic detection of the GPS L1 radio shadows of objects, we propose to use the Constant False Alarm Rate (CFAR) processor. The parameters of the detected radio shadows of moving objects are estimated using the algorithm for Automatic Rough Parameter Shadow Estimation proposed by us in [14].

IV. Results

The purpose of the experiments is to verify that GPS receiver with a small and omnidirectional GPS antenna and software-defined GPS receiver is possible to detect moving targets (car, van, bus and airplane). The location of the satellites is obtained by the GPS receiver (Antaris AEK-4R). Recording and storing GPS signals from visible satellites is obtained by the GPS receiver (GNSS_SDR) and laptop.

A. Power budget

The results of numerical calculations of Fresnel parameter (distance) and radar cross section of car, van, bus and airplane obtained for Fraunhofer diffraction are shown in Table 1.

TABLE I. Fresnel parameter and radar cross section

Target	*D*	*F*	σ_{FSR}
	M	m	dB
plane	38	1900	57
bus	12	190	47
van	6	47	41
car	4	21	37

B. Experimental results

The experimental results are obtained in the case when ranges to/from target are smaller than Fresnel parameter *F*. Topology of the experiment suggests the presence of the conditions of occurrence of the FS effect. This means that the GPS satellite, the object and the GPS receiver are nearly located on the same line, therefore the bistatic angle is close to 180 degrees. It is also assumed that the moving object crosses almost perpendicularly the line "satellite-GPS receiver". In this way the selected satellite meets the requirements for the occurrence of the FS effect.

- *Detection of moving targets*

The satellites position during the experiments is monitored with the AEK-4R GPS receiver and satellite constellation is shown in Fig. 4. Recording the raw data is obtained by the GPS receiver GNSS_SDR. The used GPS receivers are positioned on the sidewalk near to the moving vehicles. The distance between the GPS receiver and vehicles is about 4 m. The satellites that are located at low elevation angles and meet the conditions of the FS are selected for signal processing. The vehicles intersect the base line between the transmitter and the receiver and form a temporary GPS shadow over the receiver. As can be seen from Fig. 4, the most suitable satellite to obtain the FS effect is satellite number 6. In this case, the vehicles cross the baseline at an angle of 90 degrees.

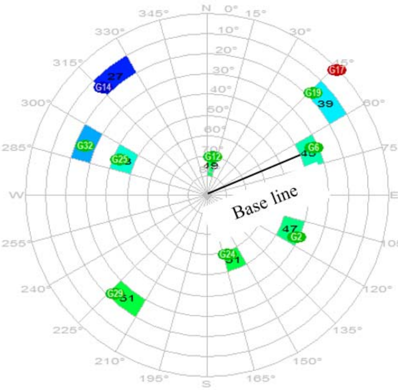

Fig. 4. Satellite constellation during the experiment

After applying of signal processing in the software receiver and moving average filter with jumping window with an interval of integrating 200 ms we obtained the results which are shown on Fig. 5. As shown in the figure, different vehicles form different GPS shadows with different parameters (depth and length of the shadow). Under the same conditions of movement (the same speed and the uniform distance to the receiver) it is possible to classify the vehicles from the received information.

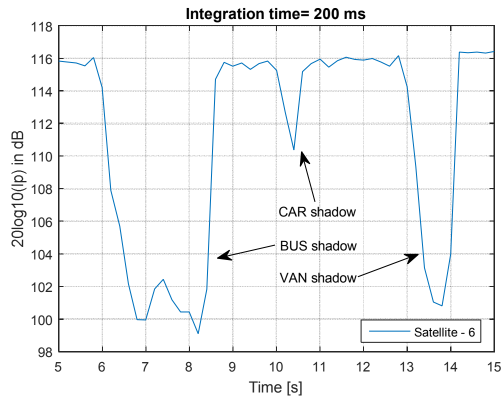

Fig. 5. Signal (shadow) from satellite 6

- *Detection of flying targets*

GPS recording system is mounted about 900 m from the start of the runway at the Sofia airport (Fig. 6).

Fig. 6. Position of the receiver near to runway

During the experiment, Airbus A320 is landing. Using equation for Fresnel parameter (the greatest dimension for Airbus A320 is about 38m), we calculate F=1900 m or the experiment is conducted in the Fresnel zone. The aircraft flew over 80 meters over the GPS receiver and blocked signals from the GPS satellites. The location of the GPS satellites during the experiment is shown on Fig. 7.

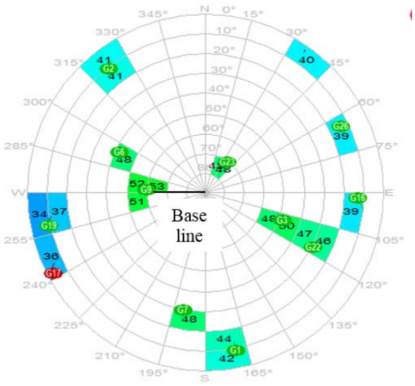

Fig. 7. Satellite constellation during the experiment

The signal from satellite 9 were blocked by the airplane and formed GPS shadow as shown on Fig. 8. The shadow parameters of the plane are similar to those of the vehicles although the size of the aircraft is much larger than the vehicles because the distance to the receiver is greater and the speed of movement is higher.

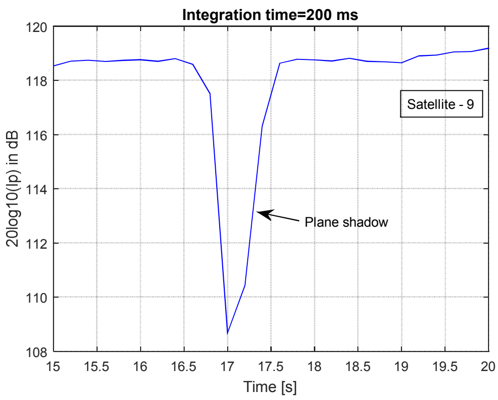

Fig. 8. Integrated satellite signal when crossing an airplane (Plane shadow)

V. Conclusions

In the paper, we studied algorithm for detection of ground and air targets through their GPS shadows, obtained in the Fresnel zone. The results are derived from experimental data conducted with cheap, small-size and commercial technique. The raw data are obtained from a GPS software receiver developed by the Colorado University [13].

During the experiments, the targets cross the baseline between the receiver and the transmitter or the base angle becomes 180 degrees and a FS configuration is obtained.

The parameters of the target shadow (length and depth) depends on the speed, dimensions of the target and from distance between the target and the GPS receiver.

If the distance between the target and the receiver is short and/or the dimensions of the target are large then the depth of the shadow is large. If the dimensions of the target are large and/or the speed is slow then the length of the shadow is large.

The probability of target detection is a function of the signal to noise ratio, which depends on the target size, the distance to the receiver, the wavelength and other.

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