Air Target Detection With a GPS Forward-Scattering Radar

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***Abstract*—Forward scattering radar (FSR), as a specially configured bistatic radar, is provided with the capabilities of air target detection by using the GPS signal shadow. This paper discusses the experimental results obtained by GPS receiver near to Sofia airport. This research aims to demonstrate the feasibility of the Forward Scattering GPS system to detect air targets.**

Keywords—Forward scattering radar (FSR), radio shadow

I. INTRODUCTION (*HEADING 1*)

Forward scattering radar (FSR) is usually classified as bistatic radar for its separated transmitter and receiver and bistatic angles close to 180 degree. FSR is a special type of bistatic radar that operates in a relatively narrow scattering area along the transmitter – receiver baseline, where the effect of the Electro-Magnetic Wave forward scattering interaction with targets is dominant above other scattering mechanisms [1]. Due to the forward scattering effect, the Radar Cross Section (RCS) of targets extremely increases (by 2-3 orders) and mainly depends on the target's physical cross section and is independent of the target's surface shape and the absorbing coating on the surface. These special characteristics give FSR the potential to detect stealth targets [2]. FSRs are very attractive not only due to their inherit low cost, which derives from the absence of a dedicated radar transmitter, but also due to their wide range of applications.

Many published studies have applied FSR to air target detection [3], maritime surveillance [4-5], and target recognition and classification [6]. Aside from ground-based FSR, navigation satellites have also been used for bistatic remote sensing in the Forward Scattering (FS) region, such as remote sensing imaging and moving target detection [7].

There are some theoretical and experimental works done concerning the feasibility of forward-scattering Global Navigation Satellite System (GNSS). The advantage of considering GNSS satellites as transmitters of opportunity is the high availability that these satellites offer. Anywhere on earth, around eight Global Positioning System (GPS) satellites are continuously in view. This provides an optimum scenario for implementation of a GPS-FSR system.

The use of GPS signals as a passive radar system is becoming increasingly popular as an alternative to radar systems. The idea to apply a GPS L1 receiver to FSR for air target detection is discussed in [7]. Some experimental results of a GPS L1 receiver concerning the detection of air targets are shown and discussed in [8-9]. A possible algorithm for air target detection in a GPS L5-based FSR system is described in [10], and the detection probability characteristics are calculated in case of low-flying and poorly maneuverable air targets in the urban interference environment. GPS L1 FSR system is researched in [11-12] for detection of FSR shadows from stationary and moving ground objects. Target detection is indicated if the signal integrated from some satellites exceeds a predetermined threshold.

The paper focuses on scientific issues related to new application of GPS in radar networks using the effect of forward scattering of electromagnetic waves to detect ear target by their GPS radio shadows. The aim of the paper is to make experimental studies of GPS radio shadows of air objects and to propose algorithm for their detection.

This paper is organized as follows. In Section II, we describe the principles of forward scattering radar. Section III analyzes an algorithm for signal processing. In Section IV, we describe the experimental results. Finally, conclusions are drawn in Section V.

II. PRINCIPLES OF FORWARD SCATTERING RADAR

The FSR is based on the Babinet principle, which says that the shadow radiation in the optical case is completely determined by the size and geometry of the shadow contour. Thus scattering on the target with the rectangular cross-section is equivalent to the radiation by a rectangular aperture antenna. This principle is a theorem concerning diffraction, stating that the diffraction pattern from an opaque body is identical to that from a hole of the same size and shape except for the overall forward beam intensity. Diffraction of wave can be divided into two classes: Fresnel diffraction (when the target is close to the transmitter or the receiver) and Fraunhofer diffraction (when the target is far from the transmitter and the receiver).

In Fresnel diffraction, the size of the target is comparable with the Fresnel zones, which takes place when the target is relatively close to the receiver or the transmitter [7]. Here, the diffraction pattern varies from high intensities to low intensities as the targets cross different Fresnel zones. These variations will depend on the coverage percentage of one or more Fresnel zones. The parameters used to determine whether the target is in the Fresnel or Fraunhofer zone are defined as:

$$F = \frac{a^2}{D_r \lambda} \tag{1}$$

If $F << 1$, then Fraunhofer diffraction is considered; on the contrary, when F• 1, Fresnel diffraction dominates. In (1), a is the greatest dimension of the target, and D_r is the distance to the receiver or the transmitter (figure 1).

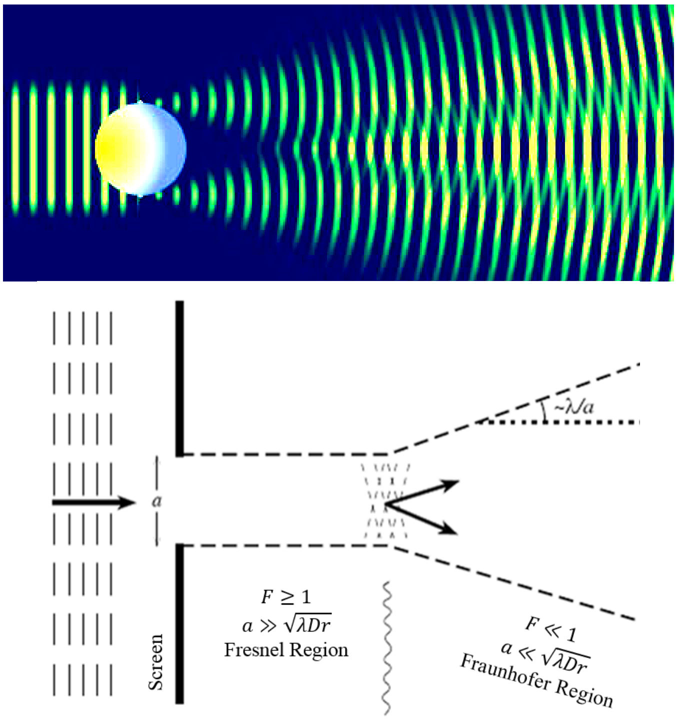

Fig. 1. Types of Diffraction

In Fraunhofer diffraction, as shown in [7, 8], the forward-scattering RCS is defined as:

$$\sigma_{FS} = \frac{4\pi A^2}{\lambda^2} \tag{2}$$

where A is the target's physical area and λ is the wavelength of the carrier signal emitted by satellites ($\lambda = 0.19$ m – for the C/A code). The width of the forward scatter beam is approximately expressed as:

$$\theta_{FS}(rad) \cong \frac{\lambda}{a} \tag{3}$$

where a is the target's length in the direction that the beam width is calculated. Subsequently, the following inequality determines the condition of being in FS region,

$$\beta \geq 180^0 - \frac{\theta_{FS}^0}{2} \tag{4}$$

where β is the bistatic angle (figure 2).

However, (2) and (3) are only applicable to Fraunhofer diffraction.

Equation (2) can also be written as:

$$\sigma_{FS} = GA \tag{5}$$

where $G = 4\pi A / \lambda^2$ is the peak antenna gain of the uniformly illuminated aperture having the area A. So, according to (5), it is obvious that σ_{FS} is greater than the geometrical area A by a factor of G. For example, if we assume that a target is a perfectly conducting sphere with radius, $r = 10\lambda$, the monostatic RCS and also bistatic RCS (for $\beta < 140°$-$150°$) is given by A, $\sigma_{MS} = \sigma_{BS} = 100\pi\lambda^2$. But for the forward scatter RCS, $\sigma_{FS} = 40000\pi^3\lambda^2$. This shows an increase of RCS by a factor of $400\pi^2$ (or ≈ 36 dB). So, forward scattering RCS enjoys the advantage of having a much larger RCS over backscattering RCS.

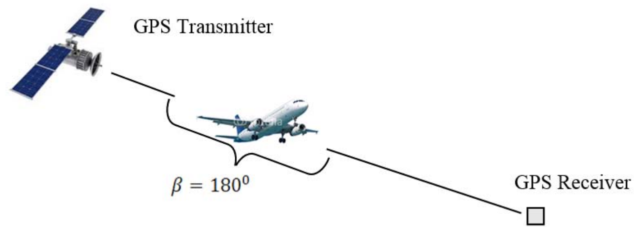

Fig. 2. GPS FS topology, i.e. when bistatic angle is ≈ 180°

III. SIGNAL PROCCESSING

The use of GPS signals as a passive radar system is becoming increasingly popular as an alternative to radar systems. The general block-scheme for target radio shadow detection using a Software-Defined GPS receiver [8] is shown in figure 3.

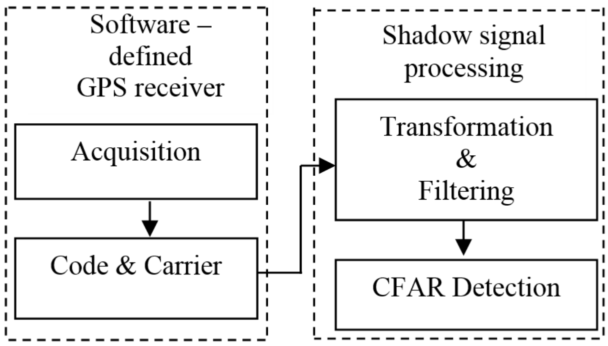

Fig. 3. Block-scheme of signal processing

According to figure 3, in the software-defined GPS receiver, the inphase quadrature component of the signal at the output of the Code&Carrier block (I_p) is obtained in result of execution of a set of program files for acquisition and tracking, presented in [10]. The signal I_p is further transformed (inverted) as follows:

$$y = [(x - \max(x)]^2, \text{ where } x = abs(I_P) \qquad (6)$$

This transformation is necessary for further signal detection by CFAR detector. The SNR of the signal y is further improved by filtering using the Moving Averaging Filter. According to the CFAR detection approach based on the criterion of Neyman–Pearson, the following algorithm can be used for testing a simple hypothesis H_1 (target is present) against a simple alternative H_0 (target is absent):

$$\begin{aligned} &H_1 : \textit{if} \ \max\{y_f(n)\} \ge T_{fa} \cdot \sum_{l=1}^{L} y_f^{'}(l) \\ &H_0 : \qquad\qquad\qquad\qquad \textit{otherwise} \end{aligned} \qquad (7)$$

In the decision rule (7), $y_f'(l)$ are the values of the filtered signal within the reference window of size L needed for power noise estimation. The scale factor T_{fa} is determined in accordance with the probability of false alarm P_{fa}, which should be maintained by the detection algorithm.

IV. Experiment description

In this experimental study, the GPS L1-based recording system consists of two types of GPS receivers. The first GPS receiver (Antaris AEK-4R) is used to determine the location of the satellites over the horizon (fig. 4, left), while the other software GPS recording system (GNSS_SDR) (fig. 4, right) is used to record and store GPS signals from different targets.

Fig. 4. Experimental equipment

The GPS receiver GNSS_SDR is proposed and developed in the Aerospace Department of the Colorado University, USA [13]. 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 position of the satellites at the time of experiment obtained from the GPS receiver "Antaris AEK-4R" is shown in figure 5.

At the center of the image is located our GPS receiver – it is our location at the time of the experiment. In order to meet the requirements for the appearance of GPS radio shadows of air targets during the experiment, only signals from such visible satellites that are located close to the line "target-receiver" at high elevation angles, are recorded for further processing. When the air target crosses the baseline "satellite-receiver" the formation of GPS radio shadow (falling of the received signal) will be observed as a deep "hole" in the received signal.

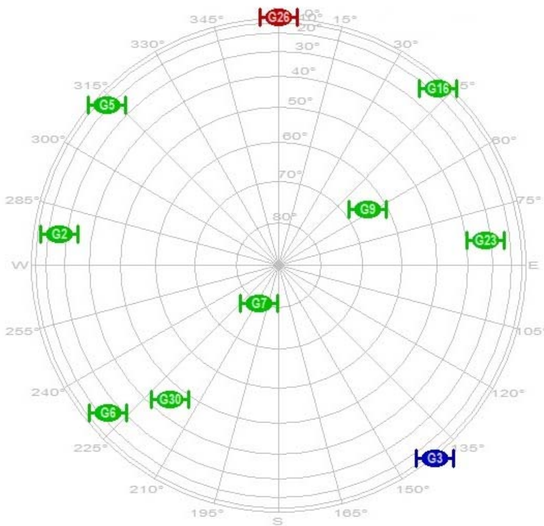

Fig. 5. Satellite constellation during the experiment

During the experiment, the two GPS recording systems are connected to a laptop which records and stores the raw data. The two recording systems use the same GPS antennas mounted on the roof of a car, which was stopped 900 meters from the start of the runway of the Sofia airport (fig. 6). During the experiment, the greatest dimension of the target (plane) is about 30 m and the distance to the receiver is about 80 m. Using equation (1), we calculate F=59.21, ($F \geq 1$) or the experiment is conducted in the Fresnel Region.

Fig. 6. Receiver scenarios

The figure 6 is positioned relative to the direction of the ground (right is east, left is west). During the experiment, airplanes that take off in the west fly over the GPS receiver. In conducting experiment, the visible satellites are with the following numbers: 2, 5, 6, 7, 9, 16, 23, and 30. According to the signal processing algorithms, the filtered and signals from all visible satellites are shown in figure 6. The signals of only one part of visible satellites were blocked by the airplane. These satellites have the numbers 2, 5, 6, and 7.

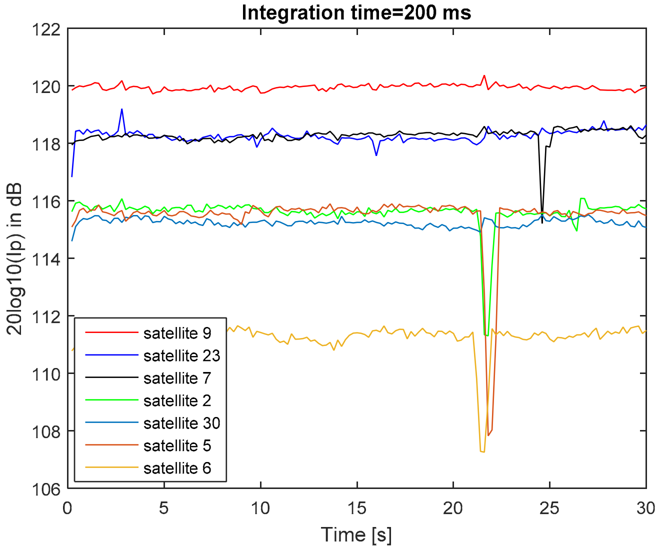

Fig. 7. Filtered signals from all visible satellites

From figure 7 follows, that the deepest "hole" in the signal strength is created by the airplane in case of the satellite having the number 5. The airplane shadow from this satellite is inverted and processed with the CFAR detector (fig. 8). As shown in the figure, the inverted signal from satellite 5 is successfully detected.

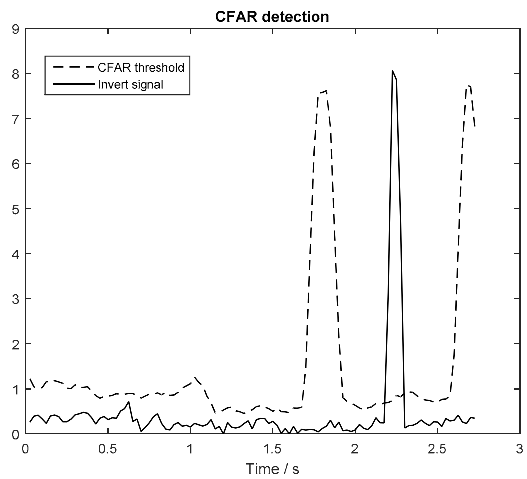

Fig. 8. Inverted signal (shadow) from satellite 5 with the CFAR threshold

V. Conclusions

The paper shows that the experiment is conducted in the Fresnel Region. By using a small omnidirectional commercial GPS antenna and GPS recording system developed by the Colorado University we can detect air objects on their GPS radio shadows. Topology of the experiment carried out close to Sofia airport. During the experiment, the air target is located near the baseline "satellite-receiver", which means that the bistatic angle is close to 180 degrees. For target detection, the inverted signal with maximal value of SNR is chosen.

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