Aircraft Detection at Short Distances by GPS FSR System

Christo Kabakchiev
Sofia University
Sofia, Bulgaria
e-mail: ckabakchievr@fmi.uni-sofia.bg

Ivan Garvanov
ULSIT
Sofia, Bulgaria
e-mail: i.garvanov@unibit.bg

Vera Behar
IICT-BAS
Sofia, Bulgaria
e-mail: vera.behar@yahoo.com

Dorina Kabakchieva
UNWE
Sofia, Bulgaria
e-mail: dkabakchieva@unwe.bg

***Abstract*—The paper considers the concept of a Global Position System (GPS) shadow Forward-Scatter Radar (FSR) for detection of air targets at short distances. This paper discusses the experimental results obtained after processing the GPS signals received near the airport in Sofia, Bulgaria. This research aims to demonstrate the ability to automatically detect low-flying aircrafts by a Forward Scattering GPS system. The other goal of this article is to study and estimate different types of GPS shadows created by aircrafts of different sizes and shapes.**

Keywords- Forward scattering radar (FSR); radio shadow.

I. INTRODUCTION

In recent years, passive radar systems where GPS satellites are used as transmitters have become 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 [1], [2], [3], [4] and [5], the authors consider the possibility of detecting air targets in bistatic and forward scatter radar, which exploit GPS satellites as transmitters. A possible algorithm for air target detection using GPS L5-based FSR system is described in [6], and the detection probability characteristics are analytically calculated in [7] for low-flying and poorly maneuverable air targets in the urban interference environment. In [6] and [7], the authors have discussed the potential to increase the Signal-to-Noise Ratio (SNR) to detect aircrafts with GPS L5-based FSR system.

Papers [5], [6], [7] and [8] are devoted to experimental measurements made by using the GPS L1-based FSR system and the Software-Defined GPS receiver, developed by the Aerospace Department at the University of Colorado [9], allowing to observe the geometric shadows (signal blocking) of ground objects of different sizes, mobile and stationary.

Our hypothesis was that, since there is a very weak signal on the surface of the Earth from a GPS L1-based FSR system, in order to register the radio shadow of some object, the object size must be large, and the distance from the receiver to the object must be small.

The purpose of our experiments was to clarify the real possibilities of the proposed system for recording radio shadows created by different objects - depending on the object's size, distance from the receiver to objects, speed of objects, and satellite constellation at the time of recording. Our GPS L1-based FSR system contained a Universal Serial Bus USB-based recording system with a small commercial GPS antenna, which recorded the GPS data flow and stored it as binary files in our computer, and a Software-Defined GPS receiver to process the recorded data in MATLAB [9]. The Software-Defined GPS receiver contains the Acquisition block to identify satellites, and the Code & Carrier Tracking block to form the navigation message. Next, the obtained navigation message was integrated within hundreds milliseconds in order to form the radio shadow of the object and the integrated message was used for further detection of the object based on its radio shadow. During the experiments, the choice of satellites to observe the deepest shadow from the object, the estimation of the type and parameters of radio shadows, were all carried out manually by the operator; they were not automated.

The purpose of this article is to explore different types of GPS shadows created by aircrafts of different sizes and shapes. This knowledge is necessary to extract the characteristic parameters of the radio shadows, which can be used for the further classification of different types of aircrafts.

The originality of the research is that we propose to use additional information derived from radio shadows of different aircrafts in order to improve the detection of low-flying aircrafts. The innovation is to develop new secondary applications of GPS technology.

The rest of the paper is structured as follows. Section 2 describes the principle of the diffraction in forward scattering radar system. The algorithm for signal processing is presented in Section 3. Section 4 discusses the experimental scenario and the experimental results. Finally, Section 5 draws conclusions based on the obtained results.

II. DIFFRACTION IN FORWARD SCATTERING RADAR

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.

If the distance from the receiver to the target (R_t) is comparable to the size of the object (D), then the target creates the “geometric shadow” of electromagnetic waves incident on the target. In the zone of “geometric shadow”, act the laws of geometrical optics, i.e., electromagnetic waves spread straightforward. In that zone, the distance from the transmitter to the target meets the inequality R << D2/λ where λ is the wavelength. In the near diffraction zone, i.e., Fresnel zone, the diffracted electromagnetic waves mutually interfere, and the approximate inequality R ≤ D2/λ holds for the distance between the receiver and the target. In the far zone of diffraction, i.e. Fraunhofer zone, the distances from the transmitter to the target and from the target to the receiver are much larger than the size of the target. In this area, the inequality R >> D2/λ holds. The diffraction of light passed through the circular aperture is shown in Figure 1.

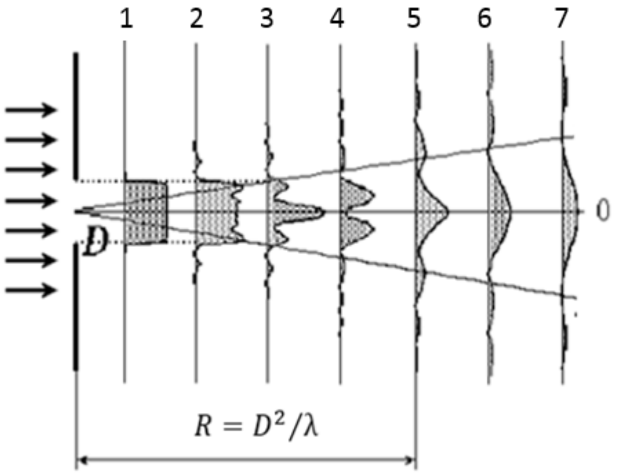

Figure 1. Diffraction of light passed through the circular aperture (1–zone of geometric shadow; 2 to 5 – Fresnel zone; 6, 7 –Fraunhofer zone)

The diffraction of light on the disc is shown in Figure 2. According to the Babinet’s principle, the diffracted signal in this case only changes the sign compared to the diffracted signal passed through the circular aperture.

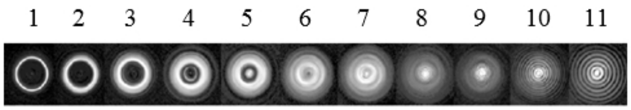

Figure 2. Diffraction of light on the disc (1, 2 – zone of geometric shadow; 3 to 7 – Fresnel zone; 8 to 11 – Fraunhofer zone)

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. 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.

This paper considers the case when a target fully blocks the signal from the GPS satellite (geometric shadow), Figure 3. This way, the formed GPS radio shadow can be used for target detection, estimation and classification.

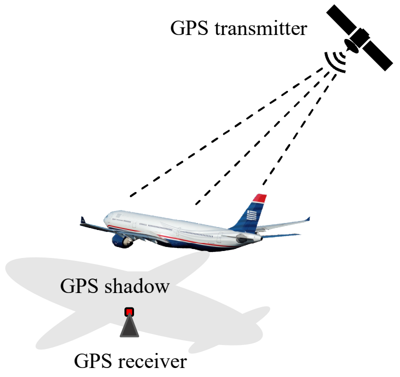

Figure 3. FS GPS Shadow

III. SIGNAL PROCESSING

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 [3] is shown in Figure 4.

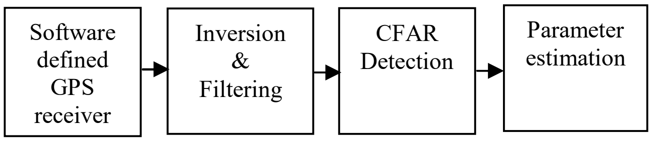

Figure 4. Block-scheme of signal processing

According to Figure 4, in the software-defined GPS receiver, the message is obtained in result of execution of a set of program files for acquisition and tracking, presented in [5]. The message is further inverted as follows:

$$y = [(x - \max(x)]^2 \text{, where } x = abs(I_P) \tag{1}$$

where I_p is the component at the output of the Code & Carrier tracking block, x is the absolute value of I_p, y is the inverted signal x.

The SNR of the signal y is further improved by filtering using the Jumping Average Filter. The Neyman–Pearson algorithm for signal detection can be used for testing a simple hypothesis H_1 (target is present) against a simple alternative H_0 (target is absent):

$$\begin{array}{ll} H_1 : if \max\{y_f(n)\} \geq T_{fa} \cdot \sum_{l=1}^{L} y'_f(l) & \\ H_0 : & otherwise \end{array} \tag{2}$$

where $y_f'(l)$ is 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.

The registered GPS radio shadows are characterized by the following parameters:

1) The length of a target shadow, obtained by the FS GPS system can be approximately related to the physical size of the object. The length of the target shadow (dT) in seconds is estimated as:

$$dT = T_2 - T_1 \tag{3}$$

where T_1 and T_2 are the beginning and the end of the target shadow in the time domain, which are estimated manually by the operator when processing the experimental records of the target shadow in MATLAB.

2) The peak signal-to-noise ratio (SNR_{peak}) is estimated as the difference between the average noise power in dB and minimal value of the radio shadow in dB, found in the interval [T_1, T_2].

$$SNR_{peak}[dB] = mean(P_n) - \min(P_s) \tag{4}$$

In (4), P_n is the noise power in dB and P_s is the power of the target shadow in dB.

IV. EXPERIMENTAL RESULTS

In this experimental study, the GPS L1-based recording system (1575.42 GHz) consists of two types of GPS receivers and a GNS 5490 ADS-B receiver for verification of measurements (Figure 5). The first GPS receiver (Antaris AEK-4R) is used to determine the location of the satellites over the horizon, while the other software GPS recording system (GNSS_SDR) is used to record and store GPS signals from different targets.

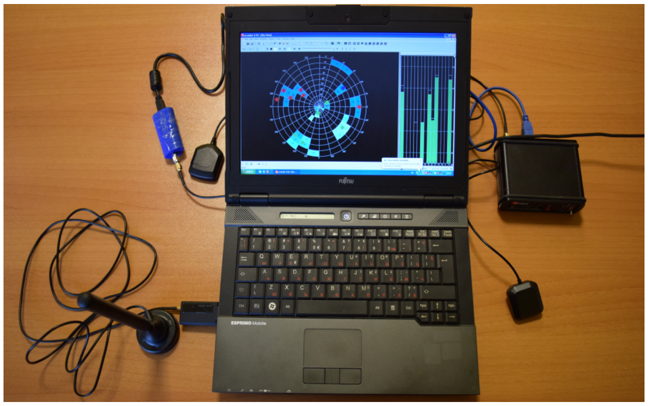

Figure 5. Experimental equipment

The GPS receiver GNSS_SDR was proposed and developed in the Aerospace Department of the Colorado University, USA [9]. This recording system receives and records the GPS data flow using a small commercial GPS antenna and an 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 the experiment obtained from the GPS receiver "Antaris AEK-4R" is shown in Figure 6.

In our experiment, only signals from visible satellites that are located close to the line "target-receiver" at high elevation angles, are recorded for further processing. The air target crosses the baseline "satellite-receiver" and forms GPS geometric shadow, (falling of the received signal) which is observed as a deep "hole" in the received signal.

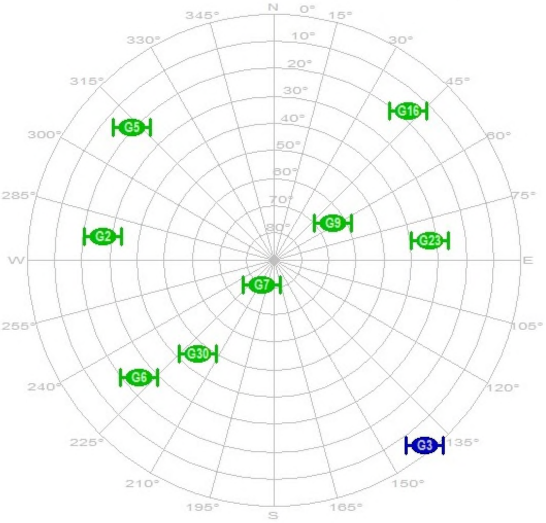

Figure 6. Satellite constellation during the experiment

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 (Figure 7). During the experiment, the length of the airplanes is about 30-40 m and the distance from the airplane to the receiver is about 80 m.

Figure 7. Receiver scenarios

During the experiment, airplanes that take off from the west fly over the GPS receiver. The visible satellites shown in Figure 6 are: 2, 5, 6, 7, 9, 16, 23, and 30. The filtered signals from all visible satellites are shown in Figure 8. It can be seen that the signal from satellite 7 was blocked by the airplane.

As shown on Figure 8, the deepest "hole" in the signal strength is created by the airplane in case of the satellite 7.

The detection sensitivity depends on the satellite position. The detection probability is a function of the signal-to-noise ratio. In our case, the highest signal to noise ratio is achieved when the air target is located near the baseline “satellite-receiver”, which means that the bistatic angle is close to 180 degrees.

Assessing the shadow parameters of two types of aircraft, it was found that the parameters were very sensitive to the geometry of the experiment. The position of the satellite is very important. The biggest shadow comes from the satellites located 90 degrees above the horizon. When using the same GPS satellites for detecting an aircraft, it was found that the distance from the airplane to the receiver strong influenced over the GPS shadow.

After the preliminary analysis of data, the filtered data has been statistically processed in order to calculate the statistical parameters of all shadow parameters. The mathematical expectation and the standard deviation of all measured parameters have been calculated for each aircraft (Table 1). The goal of this statistical processing is to check the possibility of using the resulting parameters for classification of targets by means of a statistical approach.

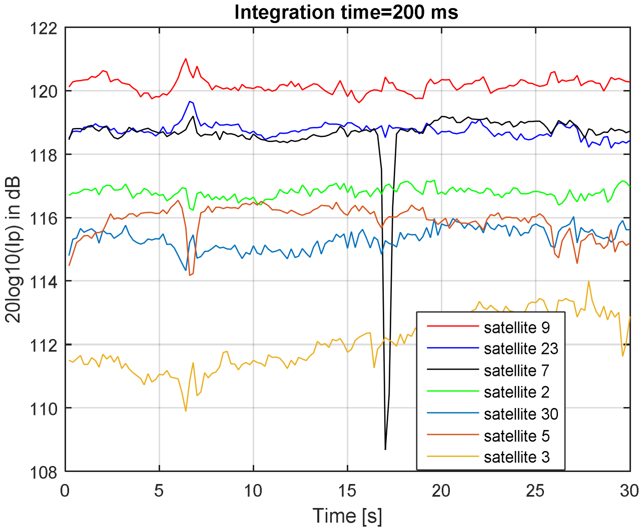

Figure 8. Filtered signals from all visible satellites

The duration of the target shadow (dT) in seconds is estimated as the difference between the beginning and the end of the target shadow in the time domain. The peak signal-to-noise ratio (SNRpeak) is estimated as the difference between the average noise power in dB and the minimal value of the GPS shadow in dB.

TABLE I. MATHEMATICAL EXPECTATION AND STANDARD DEVIATION OF SHADOW PARAMETERS FOR A320 AND ERJ-175

Targets	**Length/ Height (m)**	**Estimation**	***dT* [s]**	***SNR peak* [dB]**
Airbus A320	37.57/ 34.1	**Mean**	2.75	11.33
		STD	0.32	3.91
Embraer ERJ-175	31.68/ 26	**Mean**	2.29	10.12
		STD	0.52	5.34

In Table 1, the results are obtained by statistical processing of 7 records for Airbus A320 and 5 records for Embraer ERJ-175. The geometry of the scenarios was constant in all experiments for correct comparison of the obtained results. All experiments were conducted when the airplanes were taking off, the flying speed was about 300 km/h and the distance from the airplane to the receiver was about 80 m.

V. CONCLUSION

The purpose of the article was to demonstrate the ability to automatically detect of low-flying aircrafts by Forward Scattering GPS system. The other goal of this article was to study and estimate different types of GPS shadows created by aircrafts of different sizes and shapes. The recordings were made both with commercial and with non-professional equipment. The topology of the experiments was the same as that used in the FSR systems. The statistical processing of the resulting estimates of GPS shadow parameters shows that the selected aircrafts create GPS radio shadows with different parameters. From the results, it is evident that we can apply a statistical approach for the classification of aircrafts from their radio shadows. The quality of the classification depends on the size and shape of targets.

The proposed approach and results can be used in various systems for security and surveillance facilities. In addition, the proposed technology can be used to create a passive GPS radar network for detection of air targets based on their GPS radio shadows. The advantage of the proposed GPS FSR system is that it is cheap and costs less than $ 1,000. It is also a passive system using signals from available GPS satellites that cover the entire globe with a signal. Thus, the proposed FSR system can be used around the world.

ACKNOWLEDGMENT

This work was supported by Bulgarian Science Foundation, the project DFNI-T 02/3/2014.

REFERENCES

[1] E. Glennon, A. Dempster and C.Rizos, “Feasibility of air target detection using GPS as a bistatic radar”, *Journal of Global Positioning Systems*, vol.5, №1-2, pp. 119-126, 2006.

[2] M. Clarizia, P. Braca, C. Ruf and P. Willett, “Target Detection Using GPS signals of opportunity”, *18th International Conference on Information Fusion*, pp. 1429-1436, 2015.

[3] V. Koch and R. Westphal, “New approach to a multistatic passive radar sensor for air/space defense”, *IEEE AES Systems Magazine*, pp. 24-32, 1995.

[4] I. Suberviola, I. Mayordome and J. Mendizabal, “Experimental results of air target detection with GPS forward scattering radar”, *IEEE Geoscience and Remote Sensing Letters*, vol. 9, № 1, pp. 47-51, 2012.

[5] I. Garvanov, C. Kabakchiev, V. Behar and P. Daskalov, “Air target detection with a GPS forward-scattering radar”, *19th International Symposium on Electrical Apparatus and Technologies (SIELA)*, Burgas, Bulgaria, pp.1-4, 2016.

[6] V. Behar and C. Kabakchiev, “Detectability of Air Target Detection using Bistatic Radar Based on GPS L5 Signals”, *12th International Radar Symposium*, Leipzig, Germany, pp. 212-217, 2011.

[7] V. Behar, C. Kabakchiev and H. Rohling, “Air Target Detection Using Navigation Receivers Based on GPS L5 Signals”, *ION GNSS*, Portland OR, pp. 333-337, 2011.

[8] L. Changjiang, H. Cheng, Z. Tao, W. Li and L. Teng, “Signal modeling and experimental verification in GNSS forward scatter radar”, *17th International Radar Symposium*, Krakow, Poland, pp.1-6, 2016.

[9] K. Borre, D. Akos, N. Bertelsen, P. Rinder and S. Jensen, “A Software-Defined GPS and Galileo Receiver: Single-Frequency Approach”, Birkhäuser, Boston, MA, 2006.

[10] I. Garvanov, C. Kabakchiev, V. Behar and M. Garvanova, “Target detection using a GPS Forward-Scattering Radar”, *IEEE Second International Conference “Engineering & Telecommunications – En&T 2015*”, Moscow-Dolgoprudny, Russia, pp. 29-33, 2015.

[11] I. Garvanov, Chr. Kabakchiev, V. Behar and M. Garvanova, “The Experimental Study of Possibility for Pulsar Signal Detection”, *The Second International Conference “Engineering & Telecommunications – En&T 2016*”, Moscow-Dolgoprudny, Russia, pp. 68-72, 2016.