Passive Bistatic Radar for Helicopters Classification: A Feasibility Study

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***Abstract*—The alternative use of the Global Navigation Satellite System (GNSS) has recently initiated a number of studies that aim to exploit this system as an illuminator of opportunity for a passive radar system. In this paper a Passive Bistatic Radar configuration using a GNSS as illuminator in near forward scattering zone for micro-Doppler analysis is proposed. The received signal power is the main issue for this kind of passive radar, however it will be argued in the paper that the forward scattering enhancement can be exploited to cope with this issue. The analysis focusses on the case of helicopters rotor blades where the Doppler shift is very high and a large wavelength is useful in reducing the maximum Doppler shift. The power budget analysis for this kind of configuration and target is presented. The paper demonstrates the possibility of detecting these kind of targets and to measure their micro-Doppler signatures. The theoretical analysis demonstrates the effectiveness of the proposed configuration for micro-Doppler signature analysis.**

***Index Terms*—Passive Radar, GNSS, micro-Doppler analysis, forward scattering enhancement.**

I. Introduction

The study of possible secondary applications of the Global Navigation Satellite System (GNSS) has lead to several remote sensing applications [1], [2]. Interest in exploiting GNSS for remote sensing is growing recently due to the advantage given by its high coverage in time of the entire earth.

Exploitation of the GNSS for target detection has been reported in [3], [4], [5] and imaging [6], however the main limitation is identified in the very low power at the receiver. A possible solution to this issue is the use of high gain receiver antennas and a relatively big integration time [3] facilitating a good maximum operative range to be obtained.

In forward scattering the diffracted signal power may be many times higher than the backscattered signal [7]. This effect can be translated as an enhancement of the radar cross section, known as forward scattering enhancement. This effect can be exploited to cope with the very low power of the received signal in a GPS based Passive Bistatic Radar [2], [8] opening it to the use of a new family of PBR working in near forward scattering zone [9], [10].

Target micro-motions like vibrations due to the engine or a rotating antenna introduces micro-Doppler effect in the received radar signal [11], [12]. This effect is visible from both monostatic and bistatic radar providing some interesting advantages in the bistatic case [12], [13], [14]. Of particular interest in the paper is the analysis of the effect from the rotating rotor blades of an helicopter since the effect on the radar returns depends on the characteristics of the rotor like the blade rotating velocity, blade length and the number of blades [12], [15].

In this paper we investigate the possibility to exploit the GNSS signal in a Passive Bistatic Radar system when a target is in the near forward scattering zone for micro-Doppler analysis. We analyze the power budget of the received echoes to the receiver from this kind of target. The budget is presented and it is shown that exploiting the forward scattering enhancement will allow us to obtain enough forward scattered power to detect the echoes from the rotor blades within certain ranges.

The remainder of paper is organized as follows. Section II introduces the passive bistatic radar GNSS geometry and the signal model, section III introduces the forwards scattering enhancement concept with a particular attention to the case of the rotor blades, while in section IV is shown the budget analysis for the proposed system for different helicopters.

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II. Bistatic GNSS radar system geometry and signal model

The acquisition geometry is shown in Figure 1, the transmitter is one of the possible GNSS transmitters flying over the the receiver. R_T and R_R are the transmitter to target and the receiver to target ranges respectively. The angle β is the bistatic angle defined as the angle between the transmitter, the target and the receiver [8].
The principal transmitted signal from the GNSS satellite

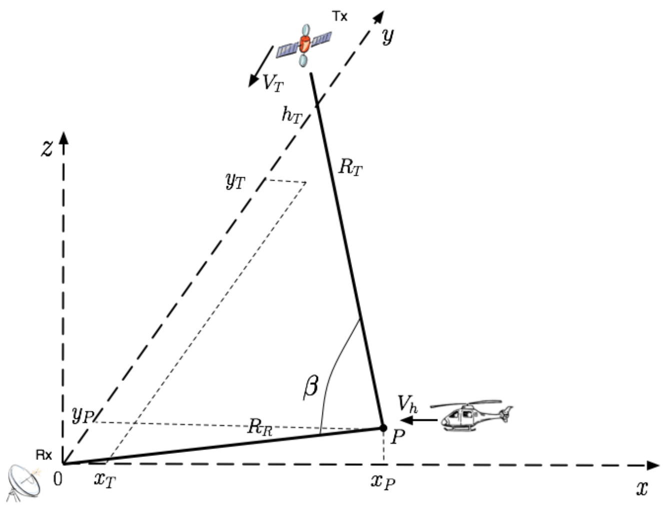

Figure 1: Proposed bistatic passive radar geometry with the GNSS illuminator.

is a Code Division Multiple Access code consisting of a Pseudo Random Noise sequence called C/A code. We will concentrate on the case of the GPS constellation and will consider the $L1$ signal at $1.5\ GHz$. Each satellite can be identified based on the specific C/A sequence which exhibits a very narrow cross-correlation function allowing the system to measure the time delay between the satellite platform and the GPS receiver.
The same principle can be exploited to perform target ranging when a target scatters the signal coming from the GPS satellite to a receiver located on ground or on an aircraft. The relative delay between the direct signal at the receiver and the scattered echo from the target can be estimated.
The received radar return after the cross correlation with the replica of the PRN signal can be modeled as [16]:

$$s_{rc}(\tau,\eta) = A_0 p_r \left(\tau - \frac{R_R(\eta)}{c}\right) \exp\left\{-j\frac{2\pi f_0 R(\eta)}{c}\right\} \tag{1}$$

where f_0 is the carrier frequency, c is the speed of light, $p_r(\tau)$ is the range envelope where the time reference is triggered to the direct signal received from the transmitter, A is the amplitude of the scattered signal, τ is the variable representing the *fast* time of the received signal, while η represents the *slow* time of the acquisition of the different echoed PRN sequences. This *slow* time is required because the dynamic of the micro-motion is slower than the dynamic of the signal used to perform ranging, this is also the reason why the cross-correlation of the C/A sequence can be performed without affecting the micro-Doppler analysis.

III. Forward scattering enhancement

The forward scattering enhancement occurs when the bistatic angle is large, i.e. near $180°$. In [17] it was shown that based on the physical optics the forward-scatter RCS for a target with silhouette area A is:

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

This is principally due to the Babinet's principle, which says that the diffracted wave from a perfect absorbing target is the same as that radiated from an aperture of the same shape and area A of the target. For the case in analysis the area A is the product of the blade length L_b and blade width W_b, then (2) becomes:

$$\sigma_{b_{peak}} = \frac{4\pi (L_b W_b)^2}{\lambda^2} \tag{3}$$

For example Figure 2 shows the bistatic RCS for a

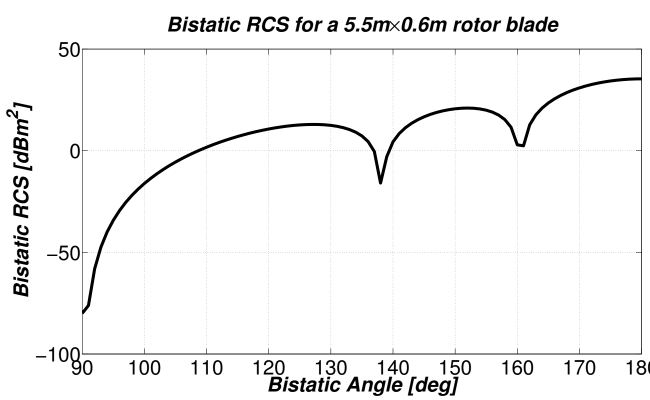

Figure 2: Bistatic RCS for a $5.5 \times 0.6m$ rotor blade.

rectangular shaped rotor blade sized 5.5m×0.6m, this bistatic RCS has been computed using the physical optics approximation provided in the POfacets tool for Matlab® [18]. The maximum $\sigma_{b_{peak}}$ is 35 dBsm, a very high value that can make possible the detection of this kind of target. For values of the bistatic angles between $165°$ and $180°$ the bistatic RCS results to be higher than 20 dBsm, that

is still a quite considerable value.
This condition can be achieved relatively easily considering that a certain area on the earth is continously covered by at least 3 (more often 4) GNSS illuminators at the same time. Under this assumption the case of a target crossing the LOS between the receiver and one of the illuminators is more probable.

IV. Budget analysis

In [3], [4], [5] the analysis of the bistatic GPS power budget was presented, in different conditions and with different (more or less optimistic) results. In this section the analysis is contextualized in the case of the helicopter rotor blades showing that they can be detected using an appropriate system configuration within an acceptable range. The power density that reaches the receiving antenna after the scattering from the rotor blades is given by [16]:

$$S_r = \left(\frac{P_t G_t}{4\pi R_T^2}\right)\left(\frac{\sigma_b}{4\pi R_R^2}\right) \tag{4}$$

where P_t is the transmitted power, G_t is the transmitter antenna gain and σ_b is the radar cross section of the rotor blade that in our case is increased by the forward scattering enhancement as explained in section III. From (4) the power at the receiver after the target reflection can be expressed as:

$$P_r = \left(\frac{P_t G_t}{4\pi R_T^2}\right)\left(\frac{\sigma_b}{4\pi R_R^2}\right)\left(\frac{\lambda^2 G_r}{4\pi}\right) \tag{5}$$

The first factor on the right side of (5) is the power density of the direct signal incident on the target and is termed S_{dir}. The noise at the output of the RF front-end is $N_0 = kT_{eff}BW$, where k is the Boltzmann constant, T_{eff} is the equivalent noise temperature and BW is the bandwidth. In this budget the losses due to processing L_{sp} and the processing gain G_{sp} are also required in order to obtain the final signal to noise ratio [4]:

$$SNR = \frac{S_{dir}\sigma_b \lambda^2 G_r G_{sp}}{(4\pi)^2 L_{sp} R_R^2 k T_{eff} BW} \tag{6}$$

Assuming a minimum SNR value to perform the target detection from (6) the maximum range can be obtained as:

$$R_{R_{max}} = \sqrt{\frac{S_{dir}\sigma_b \lambda^2 G_r G_{sp}}{(4\pi)^2 L_{sp} SNR_{min} k T_{eff} BW}} \tag{7}$$

The values to be used in (7) to obtain the maximum range for the analyzed case are given in Table I. These values differs from the one used in [4]. In that paper

Table I: Simulated parameters in the budget analysis.

Parameter	Value	Units
S_{dir}	39.81×10^{-15}	W/m^2
L_b	5.5	m
W_b	0.6	m
σ_b	379	m^2
SNR_{min}	8	dB
Bandwidth	2.046×10^6	Hz
T_{eff}	344	K
λ	0.19	m
G_{sp}	53.2	dB
L_{sp}	3.25	dB
G_r	35	dB
k	1.30×10^{-23}	
R_{max}	3920	m

a processing gain of 63 dB was assumed. This gain is not acceptable for the micro-Doppler analysis where the integration time is limited by the time coherence of the specific target. For this reason the 40 dB gain coming from the C/A code cross-correlation is used and 10.8 dB is added assuming a 21 ms integration time. The integration time is considered integrating the signal during the time-frequency analysis, allowing to increase the SNR without decreasing the number of useful gates to be exploited. Due to this decrease in the processing gain a 35 dB receiver antenna gain is considered as in [3]. The RCS of the rotor blade with blade length L_b and blade width W_b is considered to be ten times less than the peak RCS obtainable in the forward scattering situation from (3). From the parameters in Table I the maximum range is in the order of 4 km. This is a reasonable distance to have an effective near forward scattering configuration for this kind of PBR.
Further analysis are presented in this section, based on the rotor blades parameters given in Table II and the budget parameters (exluding the RCS) in Table I the maximum range for different helicopters has been computed.

Table II: Simulated helicopters and rotor blades features.

Model	# of blades	Blade length [m]	Blade width [m]
AW-109 Agusta	4	5.5	0.6
AH-64 Apache	4	7.3	0.6
UH-60 Black Hawk	4	8.18	0.6
MD 500E Defender	5	4	0.6

In Figure 3 the maximum range obtained for the four helicopters is shown, it can be seen that the maximum range increases as the bistatic gets closer to $180°$. It can be seen from Figure 3 that for smaller rotor blades,

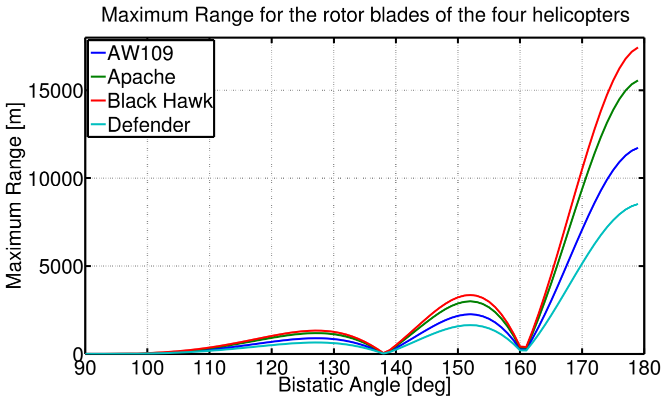

Figure 3: Maximum Range for the helicopters in Table II with the parameters in Table I.

like in the case of the Defender, the maximum range is smaller, while for bigger blades, like those of the Black Hawk, the maximum range becomes larger exploiting better the forward scattering enhancement. These results show that for many cases the micro-Doppler analysis of the rotating blades of an helicopter is possible from the power budget point of view.

V. Conclusions

This paper investigated the possibility of exploiting the GNSS signal in a Passive Bistatic Radar working when a target is in the near forward scattering zone for micro-Doppler analysis. The feasibility study has provided the budget analysis showing that by exploiting the forward scattering enhancement it is possible to obtain enough forward scattered power from the rotor blades of an helicopter.

The proposed PBR, deployed as a network of cheap sensors, is therefore a good candidate to be an alternative application of the GNSS signal and is useful for the analysis of the micro-Doppler signatures of helicopters and can find applications in areas such as borders or coastal surveillance. Problems such as the bury of the signal of interest by the strong main and side lobes of the direct signal must be considered and addressed with good micro-Doppler extraction and direct signal removal techniques.

The micro-Doppler signatures of different helicopters from this PBR will be analyzed in a future work.

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