TARGET DETECTION PERFORMANCE ANALYSIS FOR AIRBORNE PASSIVE BISTATIC RADAR

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1. INTRODUCTION

For the passive bistatic radar, its performance is very dependent on the geometrical configuration and the non-cooperative signal attributes. Target detections are realized by acquiring the direct path signal from the line-of-sight non-cooperative transmitter and echoes signal off the targets and applying the cross-ambiguity coherent processing. The concept may seems straightforward, however, technical difficulties concerning strong direct path signal and multipath interferences makes target detection a very big challenge. Furthermore, the influence of the non-cooperative signal properties (bandwidth, power, modulation, etc.), which is another issue that needs to be addressed altogether for the passive bistatic radar to be practical. This paper presents the target detection analysis on the power budget of the radar ambiguity function for predicting the level of performance required to achieve ground and air moving target detections using the passive signal from the non-cooperative transmitter. Thus, this study is based on a 3-dimension bistatic geometry where the non-cooperative transmitter is ground-based and the passive bistatic radar being airborne but stationary. Accordingly, theoretical analyses and simulations are carried out to envisage the requirements to achieve target detections (maximum) in a typical environment, using the parameters of the non-cooperative transmitter and considering their transmit signal attributes.

2. MATCHED FILTER RECEIVER AND AMBIGUITY FUNCTION

The signal received by the airborne passive bistatic radar receiver is the sum of the direct path signal from the non-cooperative transmitter and multipath signals due to the propagation effects in the environment and receiver noise. Most of the multipath will arrive by reflection and scattering from the local terrain and fixed objects (buildings, foliage, etc.), while some may come from ground and/or moving targets. Given that there exist N targets in the region of interest, accordingly, this received signal can be expressed as

$$s_r(t) = \sum_{n=1}^{N} \alpha_n s(t-\tau_n)\, e^{-j2\pi f_n t} + \sum_{k=0}^{K} a_k s(t-\tau_k) + n(t)$$

where $s(t)$ is the non-cooperative transmitted signal. The target's signal coefficeints α_n, τ_n and f_n represent its amplitude, time delay and Doppler frequency respectively. K is the index for the clutter component where a_0 and

τ_0 is the amplitude and time delay of the direct path signal and the clutter's signal coefficients a_k and τ_k (for $k = 1, \dots, K$) represent its amplitude and time delay respectively. $n(t)$ is the thermal and receiver internal noise contributions. It is desired that a matched filter be used by the airborne passive bistatic radar; a filter which optimally detects the transmitted signal in the presence of $AWGN$. Suppose there exists a single target ($\alpha_n = \alpha_t, \tau_n = \tau_t, f_n = f_t$) in the region of interest, the output of the matched filter receiver and square law device is

$$|M(\tau, f)|^2 = \left| \frac{1}{T} \int_0^T \left(\alpha_t s(t - \tau_t) e^{-j2\pi f_t t} + \sum_{k=0}^{K} a_k s(t - \tau_k) + n(t) \right) s^*(t - \tau) e^{-j2\pi f t} dt \right|^2$$

$$= |\alpha_t|^2 |\chi(\tau - \tau_t, f - f_t)|^2 + |a_0|^2 |\chi(\tau - \tau_0, f)|^2 + |a_k|^2 \sum_{k=1}^{K} |\chi(\tau - \tau_k, f)|^2 + \eta(\tau, f)$$

Where $\chi(\tau, f)$ is the time-frequency autocorrection function and $\eta(\tau, f)$ is the cross ambiguity function of $n(t)$ and (t) . $|\alpha_t|^2$, $|a_0|^2$ and $|a_k|^2$ can be expressed as the target power P_t, direct path power P_d and clutter power P_c respectively. For a passive signal of duration T and bandwidth B, it can be deduced that the individual term in the above equation produce an ambiguity function containing a pedestal $1/TB$ lower than its corresponding peak value.

3. DIRECT PATH, TARGET, NOISE AND CLUTTER POWER

The airborne passive bistatic radar geometrical model is developed in the 3-dimensional rectangular coordinate system with a stationary airborne passive receiver and a non-cooperative ground-based transmitter. The direct path power from the non-cooperative transmitter can expressed as

$$P_d = \frac{G_{tx}(\theta_{tx}, \phi_{tx}) G_{rx}(\theta_{rx}, \phi_{rx}) P_{tx} \lambda^2}{(4\pi)^2 R_{tr}^2}$$

where θ_{tx}, ϕ_{tx} and θ_{rx}, ϕ_{rx} is the elevation and azimuth angle of the transmitter antenna and receiver antenna respectively, $G_{rx}(\theta_{rx}, \phi_{rx})$ is the gain of the transmitter antenna and receiver antenna respectively, P_{tx} is the non-cooperative transmitter transmit power, λ is the transmit signal wavelength and R_{tr} is the baseline range. The received target power received is given by

$$P_t = \frac{G_{tx}(\theta_{tx}, \phi_{tx}) G_{rx}(\theta_{rx}, \phi_{rx}) P_{tx} \sigma_{B(t)}(\theta_{tx}, \phi_{tx}, \theta_{rx}, \phi_{rx}) \lambda^2}{(4\pi)^3 R_{ts}^2 R_{sr}^2}$$

where $\sigma_{B(t)}(\theta_{tx}, \phi_{tx}, \theta_{rx}, \phi_{rx})$ is the target bistatic radar cross section, R_{ts} is the distance between the transmitter and the target and R_{sr} is the distance between the target and the receiver. Thermal noise is usually the fundamental limitation on minimum detectable target signal and in practical receiver, it is normally expressed as $P_N = FKT_0 B_N$, where F is the receiver noise figure, T_0 is the reference temperature (290 Kelvins), K is the Boltzmann constant and B_N is the effective receiver bandwidth. The received bistatic clutter power is given by

$$P_c = \int_{A_c} \frac{G_{tx}(\theta_{tx}, \phi_{tx}) G_{rx}(\theta_{rx}, \phi_{rx}) P_{tx} \sigma_{b(c)}(\theta_{tx}, \phi_{tx}, \theta_{rx}, \phi_{rx}) \lambda^2}{(4\pi)^3 R_{tx}^2 R_{rx}^2} dA$$

where $\sigma_{b(c)}(\theta_{tx}, \phi_{tx}, \theta_{rx}, \phi_{rx})$ is the bistatic radar cross section of the ground clutter, R_{tx} is the distance between the transmitter and the ground clutter differential patch and R_{rx} is the distance between the ground clutter differential patch and the receiver. The value obtained for $\sigma_{b(c)}$ is directly related to the physical dimensions of the clutter patch where $\sigma_{b(c)} = \sigma_{b(c)}^0 A_c$. $\sigma_{b(c)}^0$ is the scattering coefficient occupying a clutter cell area A_c. In general, two measurement sets are of interest: in-plane and out-of-plane. For in-plane geometry, bistatic ground clutter data can be divided into three regions: low grazing, specular ridge and bistatic scatter region.

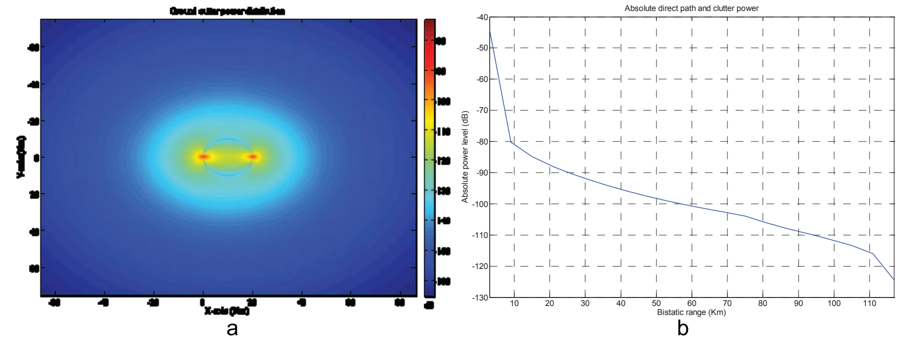

Figure 1: (a) Absolute ground clutter power distribution, (b) Summation of the absolute direct path and clutter power

For the airborne passive bistatic radar, the coherent integration time (CIT) is an important parameter which sets the amount of processing gain on the signal due to coherent integration and CIT_{max}, without inducing target range and Doppler cell migration respectively, can be expressed as $CIT_{max} < min\left(c/(2Bv_{max}), \sqrt{\lambda/(2a_{max})}\right)$, where v is the bistatic velocity vector of the target and a is the radial component of the target acceleration along the bistatic range. Figure $1(a)$ illustrates the absolute ground clutter power distribution for a non-cooperative transmitter and stationary airborne passive bistatic radar at an altitude of $200\ m$ (coverage radius of about $60\ km$ due to $4/3$ Earth model) and $500\ m$ respectively, and with a ground baseline of $25\ Km$ where both antennas pattern are assumed to be omnidirectional. Parameters replicating FM transmissions with a operating frequency of $98\ MHz$, effective radiated power of $250\ KW$, passive signal bandwidth of $50\ KHz$ and in additional, for a rural area, normalized reflectivity parameter of $-16\ dB$ and RMS surface slope of $0.17\ rad$ are used in the simulations. Figure $1(b)$ depicts the summation of the absolute direct path and clutter power for the given geometrical configuration. In addition, the thermal noise power $(F = 25\ dB)$ is calculated to be $-132\ dBW$.

4. POWER BUDGET ANALYSIS WITH AMBIGUITY FUNCTION

To investigate the effects of geometrical configuration and the passive signal properties on the detection performance of the airborne passive bistatic radar, a random $FMCW$ signal $(B = 50\ KHz, T = 0.5\ s)$ is generated where its ambiguity function has a noise pedestal of $-44\ dB$. Consider a $100\ m^2$ target with a Doppler frequency of 50 Hz and a bistatic range of 60 Km away from the airborne passive bistatic radar, the direct path to target ratio is $-88\ dB$. Collectively, together with the direct path and clutter scenario as in the preceding section, the output of the match filter and square law device for the airborne passive bistatic radar with a random $FMCW$ waveform as the waveform of opportunity is depicted in Figure $2(a)$. The target at bistatic range of 60 Km and Doppler frequency of 50 Hz cannot be detected because of the pedestal of the strongest (direct path) signal, which is $-44\ dB$ lower than its normalized peak value of $0\ dB$.

In order for the target to be visible, considerable attenuation must be provided to lower the pedestal of the ambiguity function of the interfering signals, the most significant of which is the direct path signal. Assuming a total attenuation of 65 dB and 35 dB for the direct path and clutter power respectively is made possible by means of combination of different cancellation methods and techniques, the output of the match filter and square law device for this new scenario is depicted in Figure $2(b)$. As shown, the target at bistatic range of 60 Km and Doppler frequency of 50 Hz can now be prominently seen at a level of 21 dB above the pedestal.

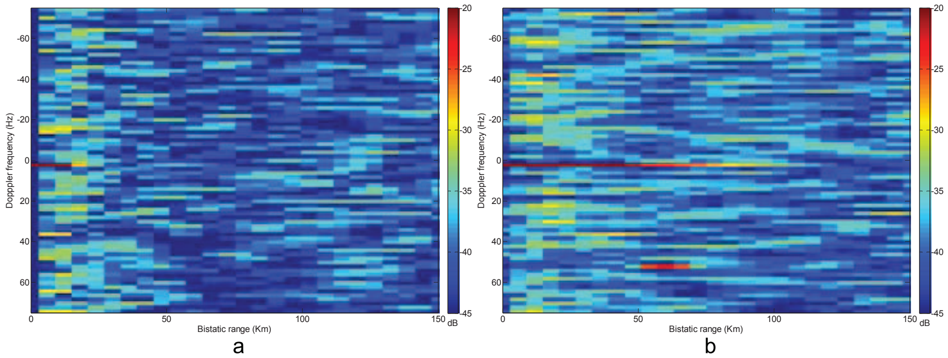

Figure 2: Output of the match filter and square law device for simulation example (a) without direct path and clutter attenuation, (b) with direct path attenuation of 65 dB and clutter attenuation of 35 dB

5. CONCLUSION

For the 3-dimension airborne passive bistatic radar scenario, it has been shown that the target detection performance is very dependent on the geometrical configuration. In comparison to the direct path power, the bistatic ground clutter power is significantly lower. Thus, the main challenge would be to suppress this strong direct path coupling signal. For the radar to perform satisfactory, attenuation must be provided for the direct path and strong ground clutter signals, which corresponds to increasing the height of the target peak on the overall ambiguity function pedestal. In addition, the strong direct path coupling signal also greatly reduces the dynamic range of the passive radar receiver and significantly degrades the weak target detection performance. Techniques that are able to mitigate this problem includes physical shielding, high gain antennas, adaptive beamforming, adaptive filtering, etc. With this issue properly addressed, there is no doubt that the airborne passive bistatic radar could provide a valuable alternative covert and low-cost surveillance system.