Toward the Detection of Bioparticles by Radar in the THz Region

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Abstract – A first-pass analysis is carried out of a 421-GHz *coherent* radar to detect the presence of a bioparticle cloud at a stand-off of 1 km. Compared to the *incoherent* radar performance under identical field conditions, the coherent system achieves a post-demodulator signal-to-noise ratio roughly 300 times higher and far superior probabilities of detection and false alarm.

I. Introduction

Recent measurements of the electromagnetic transmission through bacillus subtillus, an anthrax surrogate, has revealed absorption signatures at sub-THz frequencies. The physical origin of these signatures still being investigated, but from the measured absorption strength one can estimate the detectability in a remote sensor. In a previous study, an incoherent differential-absorption radar was modeled at the B. Subtillus signature around 421 GHz where the atmospheric attenuation is only ~6 dB/km. The DAR was found to provide a signal-to-noise ratio (SNR) around 1.0 at a transmit power of 1 mW and a range of 1 km through a bioparticle cloud of 10^3/cm^3 concentration and 10-m thickness [1]. Unfortunately an SNR of ~1 is of marginal value, yielding probabilities of detection (P_d) of ~0.5 and probabilities of false-alarm (P_{fa}) of ~0.1, depending on the receiver (Rx) threshold. In this work the analysis is extended to a *coherent* DAR system where the Rx operates by homodyne down-conversion.

II. Active Sensor Design and Performance

Because of the strong attenuation and high background temperature of the atmosphere at THz frequencies, remote detection of any species by *passive* means is difficult, so an active sensor is advisable. Because the absorption signatures of bioparticles are broad, a differential-absorption radar (DAR) modality is preferred, as shown schematically with a coherent Rx in Fig. 1. Whether an incoherent or coherent Rx is used, the DAR transmits alternately at two or more frequencies that span across the absorption signature. The simplest configuration is two frequencies, one at the center of the absorption signature and the other at the edge. It is assumed that the DAR transmits through the bioparticle cloud to a corner-cube mirror that retroreflects the power back through the cloud to the Rx co-located at the transmitter. The transmitter is amplitude modulated while hopping between the specified frequencies, and synchronous demodulation occurs in the Rx after THz-to-low-RF down-conversion.

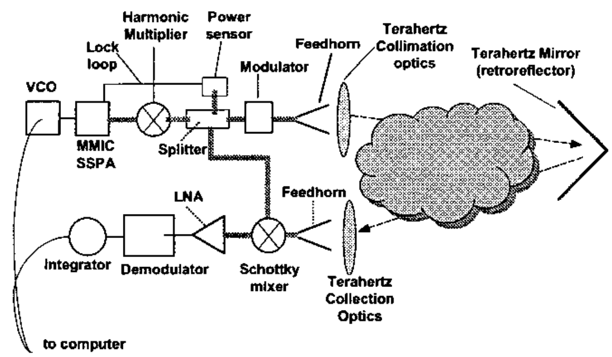

Fig. 1. Block diagram of 421-GHz coherent radar.

In the *coherent* DAR the received power is multiplied against a portion of the transmitted power on a Schottky-diode mixer. This portion of transmitted power plays the traditional role of a local oscillator (LO). Aside from any small Doppler shift caused by the bioparticles, the LO and signal should have the same frequency, so the mixing process produces a difference-frequency (DF) power spectrum centered at dc. Hence this process, commonly called *homodyne* down-conversion, displays at least two important distinctions relative to an incoherent Rx. First, the multiplication amplifies the signal strength relative to the noise floor, generally yielding a superior SNR compared to the incoherent Rx. Second, because the phase of the received signal coheres to the demodulator input, the detection statistics are different.

Analysis of the difference-frequency SNR, SNR_{DF}, in bioparticle DAR after the low-noise amplifier (LNA) leads to the curves shown in Fig. 2. The transmit power is assumed to be 1 mW and the mixer is assumed to be driven hard enough (~1 mW) so that the noise-equivalent power (NEP) is limited by LO-shot noise and coupling losses to a value of $hf/\eta = 5.6\times10^{-21}$ W/Hz ($h \equiv$ Planck's constant) for f = 421 GHz and η = 5%. The DF bandwidth is assumed

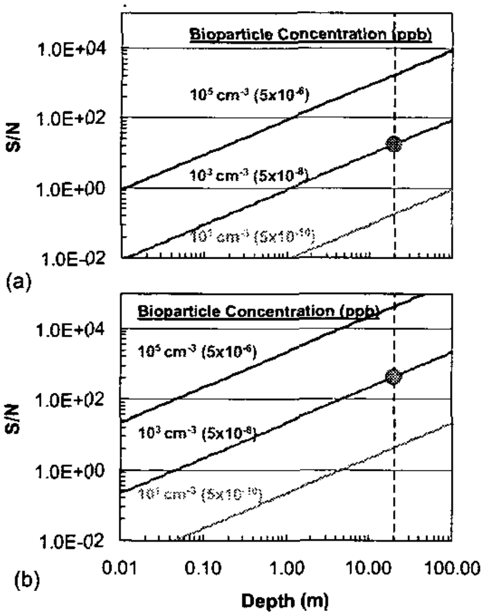

Fig. 2. (a) Difference-frequency SNR after LNA. (b) SNR after synchronous demodulation. The bullet defines the point compared to the incoherent-DAR performance.

to be B_{DF} = 0.6 MHz. The bioparticle absorption characteristics and atmospheric transmission (~0.25) are the same as in Ref. [1]. To compare on equal footing to the incoherent DAR, we need to calculate the SNR after demodulation and integration ($t_i \equiv$ integration time). Such processing will, in the worst case, increase the SNR as the square-root of the number of received samples, so that the post-demodulation value $SNR_{PD} \approx SNR_{DF} \cdot (B_{DF}\ t_i\ )^{1/2}$. Assuming t_i = 1 ms we obtain the curves of SNR_{PD} shown in Fig. 2(b). This SNR_{PD} is approximately 300 times larger than the analogous post-detection SNR of the incoherent Rx, which is approximately 1.0 under the conditions of the bullet in Fig. 2(b).

The bioparticle-detection process is inherently a statistical issue that depends strongly on how the Rx combines the signal and noise samples from the demodulator and integrator. In this first-pass study we assume that the only source of noise is the Rx physical noise described above, and that only one sample is processed, which for the given B_{DF} of 1 MHz means the measurement interval is 1 μs. In this case the demodulator output (current) amplitude for noise-alone has Rayleigh statistics,

$$P_n(i) = (i / < i_n^2 >)\exp(-i^2 / 2 < i_n^2 >),$$

and for signal-plus-noise has Rician statistics [2],

$$P_{s+n}(i) = (i / < i_n^2 >)\exp[-(i^2 + i_s^2)/2 < i_n^2 >]I_0(i \cdot i_s / < i_n^2 >)$$

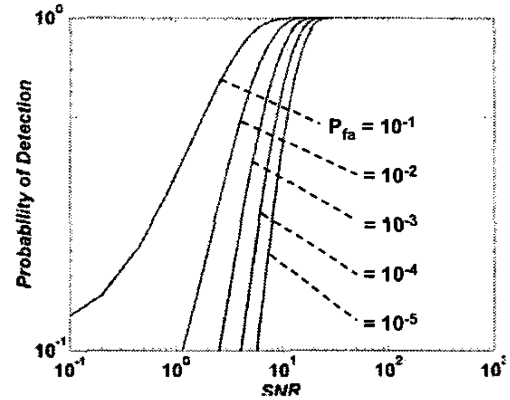

Fig. 3. Probability of detection vs signal-to-noise ratio parametrized by false-alarm probability.

where i is the post-detection current, i_n is the DF noise current, i_s is the DF signal current , < > denotes time average, and I_0 is the modified Bessel function of order zero [2]. We then assume a post-detection threshold i_t to calculate the probability of false alarm,

$$P_{fa} = \int_{i_t}^{\infty} P_n(i)di = \exp(-i_t^2 / 2 < i_n^2 >)$$

and the probability of detection

$$P_d = \int_{i_t}^{\infty} P_{s+n}(i)di ,$$

where the latter is integrated numerically. The results of this analysis are plotted in Fig. 3. For example, under the conditions bulletized in Fig. 2(a) for which the SNR_{DF} is 18, we find from Fig. 3 that $P_d \approx 0.99$ for $P_{fa} = 10^{-3}$, $P_d \approx 0.95$ for $P_{fa} = 10^{-4}$, and $P_d \approx 0.90$ for $P_{fa} = 10^{-5}$. These are, of course, just three points on a continuous P_d vs P_{fa} receiver operating characteristic (ROC) curve.

III. Conclusion and Acknowledgement

This first-pass study suggests that stand-off sensing of airborne biological particles is possible with a coherent radar designed for differential-mode detection of the bioparticle absorption signature. To facilitate the analysis several simplifications have been made, such as the use of a retro-reflector and the neglect of fading effects along the atmospheric path. These be examined in the next stage of analysis. This work was supported by the U.S. Army Research Office Scientific Services Program.

References

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