Terahertz-Frequency Remote-Sensing of Biological Warfare Agents

D.L. Woolard[1], E. R. Brown[2], A. C. Samuels[3], J. O. Jensen[3], T. Globus[4], B. Gelmont[4] and M. Wolski[5]

[1] Army Research Laboratory, Army Research Office, Research Triangle Park, NC
[2] University of California at Los Angeles, Los Angeles, CA
[3] Edgewood Chemical and Biological Center, Aberdeen Proving Ground, MD
[4] University of Virginia, Charlottesville, VA
[5] Naval Surface Warfare Center, Dahlgren, VA

Abstract — **This paper presents a detailed assessment of terahertz-frequency spectroscopy as a technique for the remote detection of biological warfare agents. Design studies are presented for a differential-absorption-radar (DAR) approach that utilizes the spectral signatures of *Bacillus (B.) subtillus* spores within the terahertz (THz) regime as the detection mechanism. The signature data used in these studies is taken from laboratory measurements performed on uniform thin films of *B. Subtillus* spores and the system performance is assessed for both incoherent and coherent detector modalities. These studies consider DAR remote sensing of biological (bio) clouds at significant ranges (i.e., 1 km) and include the effects of realistic atmospheric conditions. A high-level remote-sensor design is used to estimate the probabilities of detection (p_d) and false-alarm (p_{fa}) associated with this general technique. These studies suggest useful remote-detection performance can be achieved (i.e., $p_d > 0.9$ & $p_{fa} << 10^{-4}$ for bio-cloud densities < 10^3 cm^{-3}) at 1 km ranges if the THz signature information remains predictably stable under varying atmospheric conditions (e.g., changes in humidity, spore activity state, etc). Furthermore, a realistic bio-agent airframe attack scenario is utilized to demonstrate standoff detection of bio-clouds with ~100% confidence while outside the threat-level concentrations. All together, these results demonstrate that standoff detection of bio-agents is feasible for threat-level concentrations in practical battlefield environments at sufficient ranges to provide for early warning.**

I. Introduction

The past and ongoing proliferation of chemical and biological (CB) agents as instruments of warfare and terrorism has elevated the task of developing an adequate civilian and military defense to CB threats to a very high priority. The particular seriousness of this type of threat was emphatically underscored when the leaders of our nation (i.e., both the President and Congress) just recently endorsed a military intervention into Iraq to, if necessary, forcibly neutralize all nuclear and CB warfare capabilities. In the event that our military forces or civilian population faced such threats in the future, an adequate defense would necessitate the ability to rapidly detect and identify both known and unknown threat-agents. Clearly, the most serious threat of CB agents is the potential harm they present to the short and long-term health of the victim(s). However, the actual or perceived threat of CB warfare agents can impact the operational capability of a military force in the field and the productivity of the private sector even when conventional counter-measures (i.e., protective equipment and clothing) are successfully employed. This is true because protective equipment can interfere with vision, speech intelligibility, personal recognition and dexterity. For these reasons, the development of reliable approaches for the detection and identification of CB agents in the field of operation, and within our homeland, is imperative. While much work remains to improve overall sensing capabilities for both chemical and biological agents (Woolard et al., 2000), the present standoff detection (and therefore also identification) techniques for biological (bio) warfare agents are very limited. In fact, the development of a bio early-warning capability is of the *highest priority* to the Joint Future Operation Capability, as well as to the Joint Service Leader for Contamination Avoidance and most importantly to the Department of Defense. Fortunately, recent scientific work in biological spectroscopy at very high frequencies has suggested a novel avenue for a terahertz (THz) electronic approach to bio-warfare agent detection and identification (Woolard et al., 2001) and the extension of this work to practical sensing methodologies is the subject of this paper.

This paper discusses general issues and reports important results related to the practical application of terahertz-frequency absorption spectroscopy as a novel technique for achieving standoff detection of bio-warfare agents. Transmission spectroscopy at THz frequencies (i.e., ~ 0.01-10 THz) has previously demonstrated applicability as a potential new technique for the detection and identification of biological agents. Indeed previous research results generated by our group have shown that due to a large number of unique resonance features that arise from phonon modes, the THz regime can be extremely useful for the study, analysis and identification of biological macromolecules under controlled laboratory conditions (Woolard et al., 2002). Here, detailed studies on DNA and complete cellular biological samples revealed detailed and high-level numerical structures possibly due to vibrational lattice and local phonon modes and other physical mechanisms of interactions between radiation and biological materials (Globus, Bykhovskaia et al., 2002, Globus, Woolard, et al., 2002). These investigations were subsequently extended to other relevant materials (e.g., RNA) and to bio-agents (e.g., bio-spores). Measurements demonstrated that spore materials (i.e., *Bacillus (B.) subtillus*) also contained similar spectral signature, which are most probably attributable to the protein molecules that make up most of the spore's protective shell. While the spectral resonance characteristics are quite weak (i.e., 5-15 % variations between local minimum and maximum), these results motivated a system design study to determine the sensitivity limits of various sensor architectures that utilized a differential-absorption-radar (DAR) remote-detection approach. This paper presents system performance estimates of incoherent (i.e., direct detection) and coherent DAR sensors applied towards the detection of aerosol bio-clouds. As these performance estimates utilize spectral signature data obtained from laboratory measurements on thin spore films, the issue of signature stability is also addressed. Finally, a realistic air-frame release scenario is used demonstrate the high levels of detection confidence (~100%) that can be achieved by monitoring a very small field-of-view (~ 0.5 degrees). These results demonstrate that standoff detection of bio-agents is extremely feasible for threat-level concentrations in practical battlefield environments at sufficient ranges to provide for early warning.

II. DAR System Study

Design studies were performed on differential-absorption radar (DAR) architectures that utilize active detection for sensing *B. subtillus* spore clouds. While passive schemes were consider in earlier studies (Brown et al., 2002), they were found to be too insensitive at the ranges (i.e., up to 1 km) and bioparticle concentrations (~ 10^3 cm^{-3}) due to the small absorption cross section of the typical spectral signature and the strong absorption by water vapor in the THz region. Alternatively, active sensors are potentially more sensitive than passive ones since they provide their own source of coherent radiation at a spectral density far above the background levels. The active DAR sensor considered here consists of a coherent transmitter operating minimally at two frequencies – one at the center of the absorption signature and one at the edge. By subtracting the received power alternately at the two frequencies, the absorption signature can be detected even in the presence of fluctuations in the atmosphere caused by wind and variable humidity. The technique is similar in principle to differential absorption lidar (DIAL) commonly used at IR wavelengths. An illustration of the type of absorption signature obtained from the DAR system is given in Fig. 1. Here, the system is measuring the power transmitted through a cloud of bioparticles at two hopping frequencies.

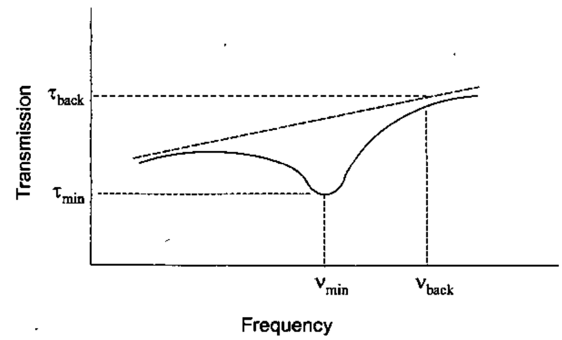

Fig. 1. Notional bioparticle absorption signature.

For the signature of Fig. 1 and assuming that the background transmission at each ν is constant one obtains

$$\Delta\tau \equiv \tau_{back}\{1-\exp[-\alpha_0(\nu_{min})L\rho/\rho_0]\} \qquad (1)$$

where Table I lists the values of ν_{min}, $\alpha_0(\nu_{min})$, ν_{back} and $\Delta\nu$ derived from laboratory transmission measurements through dry films of *B. subtillus* containing $\rho_0 \approx 1\text{x}10^{12}$ cm^{-3} – a density that is necessary to get an accurate measure of $\Delta\alpha$, but is much larger than expected in airborne bio-warfare agents. The results listed in Table I describe five different absorption features having center frequencies between 327 and 1075 GHz. In the THz region, the remote detection of these signatures depends critically on the atmospheric transmission $\tau(\nu_{back})$.

Table I. THz absorption signatures of *B. Subtillus*

Freq, ν_{min}	α_0 (ν_{min}) (cm^{-1})	ν_{back} , $\Delta\nu$ (GHz)	τ (ν_{back})
327 GHz	1.3	334.5, 7.5	0.008
421.5 GHz	0.7	430.5, 10.0	0.25
619.5 GHz	1.3	600.0, 19.5	~10^{-11}
940.05 GHz	1.7	930.0, 10.05	~$5\text{x}10^{-4}$
1075.5 GHz	1.2	1057.5, 18.0	<10^{-30}

A commercial radiative transport code, PCLnWin was applied to determine the level of atmospheric attenuation introduced by indigenous molecules. This code is based on the Fascode engine originally developed by the U.S. Air Force. The code solves for the radiation transmission as a function of slant angle and range for different model atmospheres in the presence of the common molecular species. Table I also lists the atmospheric transmission computed by PcLnWin for the 5 signatures of *B. Subtillus* at the line-center frequencies. Because of the high relative transmission ($\tau \approx 0.25$), the signature centered at 421 GHz has the best chance of being detected by an active remote sensor having practical levels of transmit power and is the center-frequency considered in this study. This analysis adopted the sensor-target scenario shown in Fig. 2 consisting of a ground- or air-based active sensor looking into the sky at a target consisting of a cloud of dry bioparticles at temperature T_M and pressure P. Note here

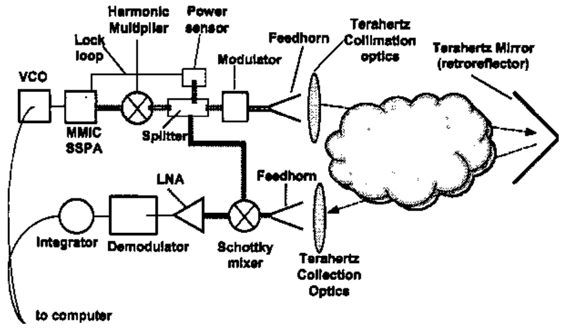

Fig. 2. Block diagram of sensor (coherent) and target scenario.

that the block diagram depicts an coherent detection system. The cloud is assumed to have physical thickness L and to be located at a range R from the sensor. Behind the cloud is a retrodirective mirror that allows the transmitter and receiver to be co-located. The mirror is oriented relative to the sensor along a line-of-sight that cuts through a trajectory of length L through the cloud. The transmitter is assumed to radiate a constant power sequentially at the two frequencies ν_{min} or ν_{back}. This particular system conceptualization is amenable to either a perimeter-defense type system (i.e., with a stationary mirror) or a remote detection scheme where a small mirror could be mounted onto an unmanned airborne vehicle. Studies performed considered both incoherent and coherent DAR sensing systems and the signal-to-noise ratio (SNR) performance and relative probabilities of detection and false alarm were assessed for each. Of course, the distinguishing element between the two is that the incoherent DAR utilizes a direct-detection receiver (Rx) and the coherent system employs a Rx that operates by homodyne down-conversion. The analysis performed was based upon standard radar techniques and employed very conservative sensor parameters – i.e., see (Woolard, Brown et al., 2002). As documented earlier, the results for a incoherent DAR that utilizes a state-of-the-art cryogenic (4.2 K) bolometer detector yields reasonably good results. For example, for a cloud depth of 20 m and a concentration of 10^4 cm^{-3} one can obtain a SNR of 10 and associated P_d and P_{fa} values of 0.75 and 0.006. However, the coherent DAR directly provides for significantly better overall performance. Indeed, the inherent homodyne down-conversion process provides for two important advantages. 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}, after the low-noise amplifier (LNA) leads to the curves shown in Fig. 3 (a). Furthermore, to compare on equal footing to the incoherent DAR, we need to calculate the SNR after

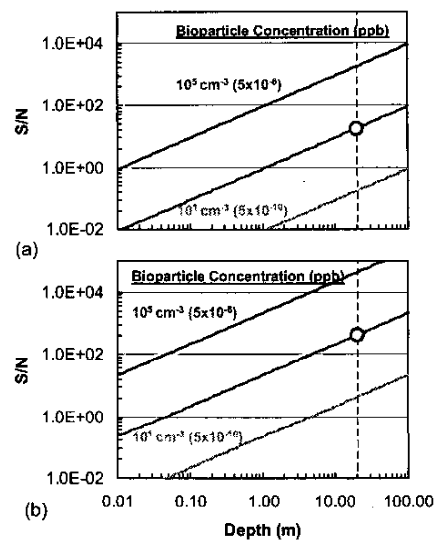

Fig. 3. (a) SNR_{DF} after LNA. (b) SNR_{PD} - Bullet defines point corresponding to incoherent DAR at SNR = 1.

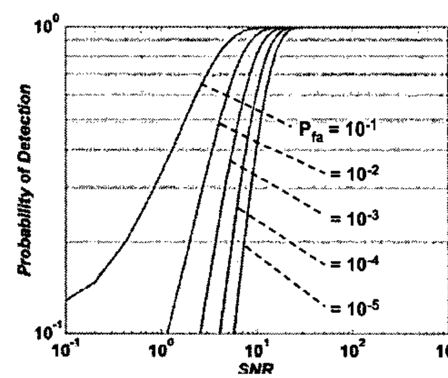

Fig. 4. Probability statistics for coherent DAR.

demodulation and integration ($t_i \equiv$ integration time). Assuming $t_i = 1$ ms the curves of SNR_{PD} shown in Fig. 3 (b) result. 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. 3 (b). Application of the appropriate statistics (i.e., Rayleigh for noise-alone and Rician for signal-plus-noise (Barton, 1998)) yields the probability results given in Fig. 4. For the conditions bulletized in Fig. 3 one can achieve the outstanding results 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.

II. Sensing Science & Bio-Agent Attack Scenario

A complete assessment of DAR sensor performance can only be achieved by considering its implementation within a realistic bio-agent attack scenario. Here, the issues of signature stability and enhancement also play important roles. If the goal is the monitoring of bio-clouds at a distance (i.e., where a mirror must be deployed to a point opposite the cloud) then the issue of sensitivity over the field-of-view (FOV) for the cloud (i.e., how much of the cloud can you image) and how that varies as a function of time (i.e., how long can you see the cloud) become very important. This is important because it will define how many mirrors are required to provide the adequate levels for P_d and P_{fa} over the entire battle-space. This issue is being addressed through the incorporation of data generated for a biological attack scenario. Here, numerical maps of bio-agent density time-dependent evolution are simulated using the VLSTRACK computer model. This allows for mapping the system probability statistics over the user FOV and demonstrates the utility of the system on the battlefield. Figure 5 depicts one bio-agent scenario considered where 1 kilogram of material is released and drifts over a 30 km range. Imaging studies were

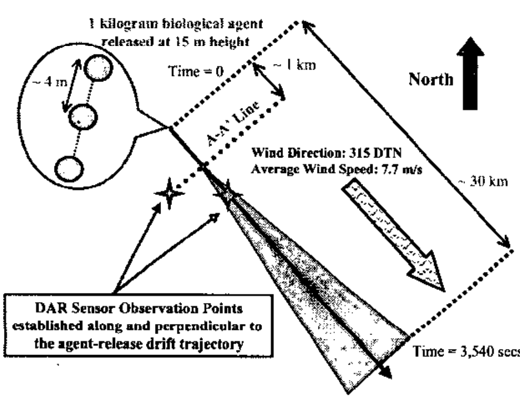

Fig. 5. Diagram of bio-agent release scenario.

performed from observer positions perpendicular (A'-A line) to and along the cloud drift region. Figure 6 (a) gives an image of the trajectory mass (i.e., the bio-particle mass within a cylinder of aperture 1 m^2 along the DAR sensing trajectory) of the cloud along the A'-A and 300 s after the release. Here, the observer point is 1 km downwind and 0.5 km from the release trajectory. Figure 6 (b) gives a mapping of the p_d from a position along the release trajectory. Here, the observer point is 1.5 km downwind and the ranging used is 1 km. These, and other images, have been used to determine that 100% confidence in remote detection can be achieved while the bio-concentration remains significantly below threat levels (i.e. < 0.6 cm-3).

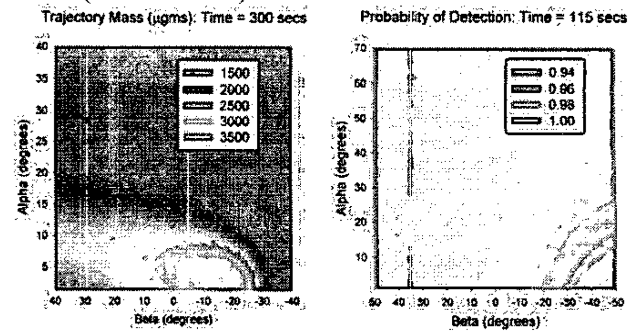

Fig. 6. (a) trajectory mass of cloud, and (b) p_d for cloud.

V. Conclusion

These results demonstrate that THz DAR standoff detection of bio-agents is feasible for threat-level concentrations in practical battlefield environments at sufficient ranges to provide for early warning.

References

E. R. Brown, D. L. Woolard, et al., "Remote Detection of Bioparticles in the THz Region," in proceedings to the IEEE 2002 IMS, Seattle, WA, June 2002.

T. Globus, D. Woolard, et al., "Submillimeter-Wave FTIR Spectroscopy of DNA Macromolecules and Related Material," *J. of Appl. Phys.* Vol. 91, pp. 6106-6113, 2002.

T. Globus, M. Bykhovskaia, et al., "Submillimeter-wave Spectral Signatures of Artificial RNA Molecules," invited to *J. of Appl. Phys.* D, 2002.

R. H. Kingston, *Detection of Optical and Infrared Radiation,* (Springer, New York, 1978).

D. Woolard, "Terahertz Electronics Research for Defense," in the proceedings to the 2000 Space THz, 2000.

D. Woolard, T. Globus, et al., "The Potential Use of Submillimeter-Wave Spectroscopy as a technique for Biological Warfare Agent Detection." in proceeding to 22nd Army Science Conf., 2000.

D. Woolard,, T. Globus, et al., "Submillimeter-Wave Phonon Modes in DNA Macromolecules," *Phys. Rev. E,* Vol. 65, 051903, May 2002.

D. L. Woolard, E. R. Brown, et al., "Terahertz-Frequency Spectroscopy as a Technique for the Remote Detection of Biological Warfare Agents," 23rd Army Science Conf.. 2002.