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Millimeter-wave imaging of thermal and chemical signatures

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ABSTRACT

Development of a passive millimeter-wave (mm-wave) system is described for remotely mapping thermal and chemical signatures of process effluents with application to arms control and nonproliferation. Because a large amount of heat is usually dissipated in the air or waterway as a by-product of most weapons of mass destruction facilities, remote thermal mapping may be used to detect concealed or open facilities of weapons of mass destruction. We have developed a focal-plane mm-wave imaging system to investigate the potential of thermal mapping. Results of mm-wave images obtained with a 160-GHz radiometer system are presented for different target scenes simulated in the laboratory. Chemical and nuclear facilities may be identified by remotely measuring molecular signatures of airborne molecules emitted from these facilities. We have developed a filterbank radiometer to investigate the potential of passive spectral measurements. Proof of principle is presented by measuring the HDO spectral line at 80.6 GHz with a 4-channel 77-83 GHz radiometer.

Keywords: Millimeter-Wave Imaging, Radiometer, Spectroscopy, Remote Sensing.

1. INTRODUCTION

This paper investigates the potential of millimeter-wave radiometer technology for remote detection of thermal and chemical signatures related to weapons of mass destruction facilities. Most proliferant facilities release heat in abundance as a byproduct and is usually dissipated in the air or waterway. Thus an indication of a clandestine activity may be revealed from sensing the temperature rise of effluents released to the ambient. Although thermal information alone is not specific enough to identify a process, it can be used as a cueing device to bring to bear other remote or on-site verification technologies.

Radiometry in the mm wave lengths has been used for remote sensing of the earth and atmosphere.¹ Earth resources such as vegetation, soil moisture, and snow cover, as well as weather pattern and military targets have been imaged with this technology. Unlike the visible or infrared (IR) techniques, mm-wave radiometer has the advantage of all weather capability. Because the thermal contrasts of objects are different in the mm and IR bands, mm wave radiometer can complement the IR imaging systems. In this work, we will investigate the potential of mm-wave focal-plane imaging for remote mapping of thermal signatures.

Another potential application of mm-wave radiometer technology is detection of airborne molecules associated with chemical and nuclear proliferation facilities. Passive mm-wave spectroscopy measures rotational emission spectra of molecules. Using heterodyne radiometric technique, mm and sub-mm spectral lines of upper atmospheric molecules have been measured from mountain tops and satellites.² Terrestrial measurement of molecular spectra, however, is more difficult because of: (a) the spectral lines are broader due to the pressure-broadening phenomenon and (b) the earth surface does not offer uniform "cold space" background as the sky. In this work, we will also investigate the potential of passive mm-wave measurements for airborne chemical detection.

2. FOCAL-PLANE IMAGING

Figure 1 gives a 160-GHz focal-plane imaging radiometer designed and built for mapping thermal signatures of objects. It is a total power heterodyne radiometer with its local oscillator power derived from a frequency-doubled Gunn diode oscillator at 75.2 GHz. The front end is a 6-mm aperture conical horn matched to a 15-cm lens. The radiometer is mechanically scanned at the focal plane of the lens to create an image. Figure 2 shows, for example, a scanned image of a hammer placed on the floor of the laboratory at a distance of 36 inch from the lens plane. The metallic head and wooden handle of the hammer are

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clearly seen in the image. The image contrast is mainly due to differences in emissivity of the materials. In another example, an image (Fig. 3) is obtained of scene in which sand and hot water are held in plastic cups. Due to higher temperature, the hot water cup looks brighter than the sand cup. Thus, a comparison of time-lapsed mm wave radiometric images can identify the appearance of hot effluents.

(a) (b)
Fig. 1. Focal-plane imaging radiometer at 160-GHz (a) Block diagram and (b) Picture.

Fig. 2. Millimeter wave image of a hammer with wooden handle and metallic head.

Fig. 3. Millimeter wave image of sand (upper) and hot water (lower) held in plastic cups.

3. PASSIVE MILLIMETER WAVE SPECTROSCOPY

The radiometric temperature of a molecular cloud is a function of line strength of the molecule, temperature of the molecular cloud in relation to the background, emissivity of the background, and atmospheric attenuation.

3.1. Radiometric emission model

Consider a down-looking sensor pointed at the plume such as from an aircraft. Assume that the molecular cloud is at temperature T_c with thickness D and that the background is at temperature T_g . The spectral radiance or brightness observed by the sensor looking down the molecular cloud will have contributions from (i) brightness of the cloud, (ii) brightness of the ground, and (iii) brightness of the atmosphere.³

$$B_t = B_c (1 - e^{-\tau_c}) e^{-\tau_a} + B_g e^{-(\tau_a + \tau_c)} + B_a, \quad (1)$$

where B_t = total brightness, B_c = brightness of the cloud, B_g = brightness of the ground, B_a = brightness of the atmosphere, τ_c = optical thickness of the cloud, and τ_a = optical thickness of the atmosphere between the sensor and the cloud. The optical thickness of a molecular cloud of thickness D is

$$\tau_c = \alpha(f) D, \quad (2)$$

where $\alpha(f)$ is the absorption coefficient of the cloud as a function of frequency f . The Plank's law for brightness power can be approximated in the mm-wave region as

$$B = \frac{2kT}{\lambda^2}, \quad (3)$$

where λ is the wavelength. Eq. (1) can be rewritten in terms of brightness temperature as

$$T_t = T_c(1 - e^{-\tau_c})e^{-\tau_a} + T_g e^{-(\tau_a + \tau_c)} + T_a, \quad (4)$$

where T_t is the total brightness temperature as seen by the sensor, T_c and T_g are the actual temperatures of the cloud and ground, respectively, ϵ is the emissivity of the ground, and T_a is the brightness temperature of the atmosphere as seen by the sensor. If the wavelength range of observation is chosen to lie in one of the atmospheric windows, the atmospheric attenuation τ_a may be neglected. Then

$$T_t = T_c(1 - e^{-\tau_c}) + \epsilon T_g e^{-\tau_c}. \quad (5)$$

Let ΔT_{ob} be the observable signal of the cloud, defined as the difference in antenna signals with and without the cloud. Then,

$$\Delta T_{ob} = T_t - \epsilon T_g \cong \tau_c (T_c - \epsilon T_g). \quad (6)$$

The emissivity dependence:

From Eq. (6), the observable signal is a linear function of ϵ . One obtains maximum observable signal from the cloud when $\epsilon = 0$, and no observable signal for the case of $\epsilon = 1$ and $T_c = T_g$. Because the ground materials seldom behave like a blackbody, one would obtain reasonable signal even for the situation $T_c = T_g$. Typically the emissivity of the ground elements varies between 0.5 (concrete buildings) to 0.95 (grass land under wet conditions).

The temperature dependence:

Let $(\Delta T)_c = T_c - T_g$ be the actual temperature difference between the cloud and the background. Then the observable signal in Eq. (6) becomes

$$\Delta T_{ob} = \tau_c (\Delta T)_c + (1 - \epsilon) \tau_c T_g. \quad (7)$$

Thus the observable signal varies linearly with the difference between the cloud and background temperatures.

Computer simulation of emission temperature

Figure 4 shows a 1-km cloud at 300K with 10 ppm of HCN added to the atmosphere with $T_c = 300$ K, $T_g = 0$, and $\epsilon = 0.0$. The absorption coefficient α (f) of HCN was simulated from the JPL molecular database⁴ and fitted with Lorentzian line shape function for pressure broadening.⁵ This scenario may mimic the situation where a ground-based radiometer looks up the molecular cloud against a cold sky background. The HCN absorption causes the features near 87, 177, and 266 GHz. Note that at the peaks of the strong lines, the emission saturates near 300 K, but between them it is quite cold. The lower line in the figure is the atmospheric emission without the added HCN. Since modern radiometers are capable of 1 mK detection sensitivity, detection of HCN appears possible in the measurement windows, 75-110 GHz and 220-300 GHz where the atmosphere is nearly transparent and less interfering to mm waves.

If the background emissivity corresponds to $\epsilon = 0.5$ and the temperatures of the cloud and background are equal to 300 K, Figure 5 results. Again, the strong features saturate near 300 K, but the peaks of the weak lines appear relatively smaller than the cold background case. However, the detectability of HCN is essentially unchanged because of measurable spectral features relative to the continuum. Even though both the cloud and background are at the same temperature, the background is not black at the frequencies of the molecular absorption; as a result the total scene is blacker and therefore a stronger emitter.

Fig. 4. Emission temperature of 1 km cloud with 10 ppm of HCN in the atmosphere $T_c=300$ K, $T_g=0$, and $\mathcal{E}=0$.

Fig. 5. Emission temperature of 1 km cloud with 10 ppm of HCN in the atmosphere $T_c=T_g=300$ K and $\mathcal{E}=0.5$.

3.2. Proof of principle tests

A four-channel radiometer (Fig. 6) was built for proof-of-principle testing. An antenna receives millimeter wave radiation in the 75-110 GHz range. A 3-way waveguide switch allows the radiometer to be switched between the scene of interest and a

calibration source which is a noise tube of known power in the range of 75-110 GHz. A mixer (double balanced, Schottky barrier diode) with a local oscillator at 85.3 GHz down-converts the received radiation into 2-8 GHz IF (intermediate frequencies) frequencies. A low-pass waveguide filter is used in front of the mixer for rejecting image frequencies in the upper sideband. The IF signal is amplified up to 80 dB with low-noise IF amplifiers. A power divider splits the signal into four narrow-band (500 MHz) channels with center frequencies at: 3.2, 3.7, 4.2, and 4.7 GHz. These correspond to RF bandwidths of 80.35-80.85 GHz, 80.85-81.35 GHz, 81.35-81.85 GHz, and 81.85-82.35 GHz, respectively. A diode detector (square-law type) converts the RF power in each channel into a voltage signal, which is further amplified and filtered by a video amplifier. The output signal of each channel is proportional to the radiation power in the corresponding RF channel, which in turn is proportional to the brightness temperature (equivalent temperature with reference to a blackbody) of the scene in the field of view of the antenna.

Fig. 6. Block diagram of 4-channel radiometer in the 77.3-83.3 GHz range.

Passive spectroscopy test against cold background

Figure 7 shows the experimental setup used for emission line detection. HDO was used as a test gas for proof of principle testing. It was fed into a 1.4-m long gas cell fitted with (mm-wave transparent) quartz windows. A lens antenna (7.6 cm size) collected the radiation from the gas against an absorber (blackbody) at liquid N₂ temperature. The radiation pattern of the antenna was designed such that it collected the radiation close to the axis of the cell (away from the cell wall). The outputs of the four channels were acquired with a Personal computer.

Fig. 7. Radiometer test setup for emission line detection.

The radiometer output for a given channel consists of the radiation signal from the gas in the cell and from the blackbody at liquid N₂ temperature

$$V_g = C \left\{ T_g (1 - e^{-\alpha(f)L}) + T_N e^{-\alpha(f)L} \right\} + V_{\text{offset}}, \quad (8)$$

where V_g is the radiometer output with the gas in the cell, C is a constant relating the temperature of the scene to voltage, T_g is the temperature of the gas in the cell (290K), T_N is the temperature of the liquid N₂ (77K), $\alpha(f)$ is the absorption coefficient of the gas at frequency f of the channel, V_{offset} is the radiometer dc offset, and L is the length of the gas cell (1.4 m). The radiometer output without the gas (vacuum) in the cell is given by

$$V_0 = C T_N + V_{\text{offset}}. \quad (9)$$

The difference in voltages with and without the gas, from (8) and (9), is

$$\Delta V_g = V_g - V_0 = C (1 - e^{-\alpha(f)L}) (T_g - T_N). \quad (10)$$

The constant C was determined from (9) by measuring the voltage outputs in an empty cell corresponding to two known temperatures, ambient and liquid N₂. Knowing C , ΔV_g may be converted to brightness temperature difference.

Figure 8 gives the measured changes in brightness temperature for 2.5 and 5 torr of HDO. The expected brightness temperature change ΔT_g due to HDO in the gas cell can be calculated theoretically from

$$\Delta T_g = (1 - e^{-\alpha(f)L}) (T_g - T_N), \quad (11)$$

where $\alpha(f)$ was determined for HDO at 2.5 and 5 torr using the JPL catalog of mm-wave spectral lines.⁴ The dashed line in Fig. 8 gives the theoretical brightness temperature differential. Good agreement is obtained between the theoretical and experimental results. Note that channel 2 of the radiometer appears to drift relatively more with time.

Fig. 8. Emission temperature of HDO at 2.5 torr and 5 torr in a gas cell against liquid N₂ background.

For pressure broadened measurements, the gas cell is first filled with HDO to the required partial pressure and the balance then filled with N₂ to simulate atmospheric pressure. Because the radiometer drifted badly by the time the experiment could be completed with and without HDO pumped into the gas cell to 1 atm of N₂ background, no pressure broadened data are reported here. The system must be modified to employ frequent calibrations to eliminate drift problems. For this, a chopper-based calibration system may be used in which the antenna beam is switched between the scene of interest and known temperature (hot and cold) loads.

4. CONCLUSIONS

The potential of passive mm-wave technology has been investigated for remote detection of thermal and chemical signatures. With a 160-GHz focal-plane imaging system, high resolution mm-wave images have been produced for different objects in the laboratory. The scanned radiometric images indicate the potential of the technique for remote mapping of hot effluents associated with WMD facilities. The mm-wave imaging technique has applicability to broad area search of clandestine nuclear, chemical, and biological activities of undeclared/underground WMD facilities. The findings of the system may cue other systems that are more sensitive to specific signature detection. It may also be used for location, tracking, and mapping of chemical plumes.

A radiometric emission model has been developed to calculate the brightness temperature of a molecular cloud against different backgrounds. The model indicates the feasibility of a multichannel radiometer for remote detection of polar molecules such as HCN. The proof of principle of molecular emission line measurements has been tested with a 4-channel radiometer in the frequency range of 77-83 GHz. The HDO line at 80.6 GHz was measured in a gas cell at low pressures against liquid N₂ background and the measured data agreed well with theoretical predictions. Further work is required to demonstrate molecular emission line measurements at atmospheric pressure. The spectral lines at atmospheric pressure are broadened (typically around 4 GHz half width at half height) due to molecular collisions. High frequency radiometers with wide bandwidths are required to detect such broad lines. Because the line strength generally increases with the square of the frequency, a high frequency system will also improve the sensitivity of detection. The highest possible mm-wave transparent atmospheric window exists in the 220-300 GHz range for remote sensing. A filterbank radiometer in this frequency range, which can be built with the current state of the art, holds promise for passive detection of airborne molecules deployed from a ground- or aircraft-based platform.

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