Applications and challenges for MMW and THz sensors
John N. Sanders-Reed

ABSTRACT

MMW and THz sensors offer unique imaging capabilities and challenges. This paper will provide a brief discussion of illumination, propagation, and resolution in these and adjacent bands, followed by a discussion of some application areas for these sensors, in particular imaging in Degraded Visual Environments (DVE), stand-off screening and chemical detection, and surveillance and monitoring. Comparisons with other sensing modalities will be provided discussing some of the relative strengths and weaknesses of MMW & THz sensing compared to these other modalities.

Keywords: Vision, sensing, MMW, THz, imaging, obscurants, Degraded Visual Environments, Stand-Off detection, pilotage, atmospheric propagation.

1. INTRODUCTION

Selecting a sensing band in the electromagnetic spectrum involves trade-offs in resolution and aperture size, penetration of various materials and obscurants, interaction with various materials, active versus passive sensing, technology maturity, and compatibility with existing systems. Selecting an appropriate wavelength regime, sensor type, and the various sensor parameters requires an understanding of the application. In many situations, there is a desire to utilize a single sensor for multiple purposes. This in turn brings a need to balance performance across these multiple applications.

As one moves from visible through infra-red (IR) to tera-hertz (THz), millimeter wave (MMW), and beyond, one passes from a regime in which purely passive sensing using reflected solar radiation is possible (visible) through the IR bands in which it is possible to sense using black body self emission, to the radar bands (X band and longer) in which active illumination is required. The MMW and THz bands fall at the long wavelength limit for current technology to sense using thermal self emission which means these wavebands can be treated as either radar bands (active illumination) or extremely long wavelength IR bands (passive sensing using self emission). The relatively long wavelengths of the MMW and THz regions are longer than the characteristic particle size of many small particle obscurants such as dust, smoke, and fog, which means that these wavelengths have an inherent penetration capability advantage compared to even Long Wave Infra-Red (LWIR, 8-12 um) in which the wavelength is comparable to or shorter than the characteristic particle sizes, resulting in strong multiple scattering. Of course resolution is inversely proportional to wavelength, so the MMW and THz regions provide much lower resolution for a given aperture than the IR and visible bands, but much better resolution than other (longer wavelength) radar bands. As in the IR wavebands, in the MMW and THz regions there are observable spectral resonances for compounds of interest including explosives and various drugs. The penetrating power of MMW and THz radiation means that these spectral characteristics may be observed even when concealed by some masking materials.

An understanding of the requirements for various applications is also important in order to determine if a particular waveband offers inherent advantages or limitations compared with other potential wavebands. In this paper we will look at some of these applications such as pilotage in Degraded Visual Environments (DVE), targeting, stand-off chemical detection, stand-off screening, communications, and hostile fire indication. Each of these has resolution, range, and phenomenology aspects which must be understood and matched to sensing capabilities.

2. PHENOMENOLOGY

In order to evaluate the potential of MMW and THz sensing, it is important to understand how it compares to adjacent wavebands. In this section we discuss scene/target illumination in the various bands, atmospheric propagation, resolution and aperture, and chemical absorption spectra.

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It is useful to begin by summarizing the frequencies and wavelengths of the MMW and THz bands and the adjacent spectral bands. The MMW bands are generally considered to comprise the Ku, Ka, and W bands. For most of the discussion (except stand-off chemical detection) we will use THz to refer to the shorter frequency THz (1) band.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>8-12 GHz</td>
<td>25.0-37.5 mm</td>
</tr>
<tr>
<td>Ku</td>
<td>12-18 GHz</td>
<td>16.7-25.0 mm</td>
</tr>
<tr>
<td>Ka</td>
<td>24-40 GHz</td>
<td>7.5-12.5 mm</td>
</tr>
<tr>
<td>W</td>
<td>70-110 GHz</td>
<td>2.7-4.3 mm</td>
</tr>
<tr>
<td>THz (1)</td>
<td>205-215 GHz</td>
<td>1.40-1.46 mm</td>
</tr>
<tr>
<td>THz (2)</td>
<td>300 GHz - 10 THz</td>
<td>30-1000 um</td>
</tr>
<tr>
<td>LWIR</td>
<td>25.0-37.5 THz</td>
<td>8-12 um</td>
</tr>
<tr>
<td>MWIR</td>
<td>60-100 THz</td>
<td>3-5 um</td>
</tr>
</tbody>
</table>

Table 1. Waveband frequency & wavelength

2.1. Illumination

The MMW and THz regions of the spectrum represent a transition region from thermal emission (self-illumination) to active illumination. In the visible domain, illumination is dominated by reflectance of solar illumination. The Mid-Wave Infra-Red (MWIR) region of the spectrum represents a transition from solar reflectance to thermal (black-body) self emission. By the time we reach the Long Wave Infra-Red (LWIR) region, solar illumination is 2-3 orders of magnitude lower than self-emission. Moving from the LWIR band to the W band, black body radiance drops by more than 7 orders of magnitude. The graph in Figure 1 [1] illustrates these effects. The “solar illuminated” curve in Figure 1 represents the approximate radiance of an object with 50% Lambertian reflectance [2].

![Figure 1. Black body emission versus wavelength](image)

While passive imaging MWIR and LWIR sensors capable of detecting thermal black body radiation are commonly available, detection of black body radiation in the MMW regime (Passive MMW or PMMW) pushes the state of the art due to the extremely low signal levels. However, as wavelength increases, the emissivity of many metals drops significantly. The result is that contrast in scenes increases at these longer wavelengths. A typical phenomenon is a metal object seen against a terrain background. While the terrain background may have an emissivity close to 1 and radiates according to the black body curve for its temperature (for example 300K), the metal object, with an emissivity of 0.1 or lower may be reflecting a cold sky (which may be as cold as 50K). Table 2 shows the relative radiance for different
temperature objects at both the THz 1.5 mm and the W band 3 mm wavelengths. We can see almost an order of magnitude difference between a 50K cold sky and a hot 400K object.

<table>
<thead>
<tr>
<th>Temp (K)</th>
<th>THz (1.4 mm)</th>
<th>W-band (3 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>9.71e-8</td>
<td>4.87e-9</td>
</tr>
<tr>
<td>200</td>
<td>6.35e-7</td>
<td>3.04e-8</td>
</tr>
<tr>
<td>300</td>
<td>4.20e-7</td>
<td>2.02e-8</td>
</tr>
<tr>
<td>400</td>
<td>8.51e-7</td>
<td>4.06e-8</td>
</tr>
</tbody>
</table>

Table 2. Radiance of different temperature objects in THz and W bands (W/m²/sr/μm)

For imaging types of applications, the method of illumination determines the type of data collected. For passive imaging systems relying on solar reflection or black body thermal emission, imagery is inherently 2-dimensional (2D), producing an azimuth/elevation map (no range). For active illumination systems such as radar or lidar, 3-dimensional (3D) data consisting of azimuth, elevation, and range can be obtained. This will be discussed further in the Resolution section. The fact that both passive and active imaging are possibilities in the MMW and THz regimes means that the system designer can choose to use an active system, producing 3D data, or he can choose to use a passive system, giving only 2D data.

2.2. Propagation

The selection of wavebands to use for various applications is influenced by the ability of the radiation to propagate through the atmosphere from an object of interest to the sensor. Figure 2 [3-6] shows atmospheric attenuation as well as attenuation by various obscurants such as fog and rain. The atmospheric conditions corresponding to the atmospheric attenuation curve are Temperature = 20°C, Pressure = 1 atm, and water vapor content off 7.5 g/m³. In the graph “Heavy Rain” corresponds to 150 mm/hr, “Medium Rain” to 25 mm/hr, “Light Rain” to a drizzle of 0.25 mm/hr, and the fog to a density of 0.1 g/m³.

![Figure 2. Atmospheric Absorption & Obscurant Penetration versus wavelength](image_url)
Penetration through many obscurants is limited by multiple scattering from suspended obscurant particles. In the graph, the particle sizes are shown near the bottom in frequency equivalent to that of electro-magnetic radiation whose wavelength is equal to the particle diameter. Actual particle sizes [7-10] are tabulated in Table 3.

<table>
<thead>
<tr>
<th>Obscurant</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoke</td>
<td>0.05-1 um</td>
</tr>
<tr>
<td>Dust</td>
<td>0.05-250 um</td>
</tr>
<tr>
<td>Fog/Haze</td>
<td>0.1-20 um</td>
</tr>
<tr>
<td>Mist</td>
<td>5 um – 1 mm</td>
</tr>
<tr>
<td>Rain</td>
<td>1-5 mm</td>
</tr>
<tr>
<td>Snow</td>
<td>1-10 mm</td>
</tr>
</tbody>
</table>

Table 3. Obscurant particle sizes

The obscurants listed above cause multiple scattering with the result that at shorter wavelengths, most of the detected photons have been scattered many times off the obscurant particles resulting in essentially zero contrast signals. For particles larger than the wavelength of the radiation, scattering is approximately constant with wavelength. As the wavelength approaches the diameter of the scattering particles, Mie scattering [11] causes an increase in scattering and then as the wavelength becomes longer than the particle size and we enter the Rayleigh scattering regime [11], where scattering drops sharply with increasing wavelength. This is clearly visible in the curves for attenuation due to rain: Looking at the “Light Rain” attenuation curve we see a constant attenuation with wavelength until we approach 1000 GHz (300 um) at which point the attenuation increases until it peaks at about 210 GHz (1.4 mm) and then rapidly declines. As the rate of rainfall increases, the average size of the raindrops increases, so we observe the Mie scattering peak move to longer wavelengths as the rate increases.

The attenuation curve for fog shows significantly more structure which can be interpreted as different size water droplets, but as with the rain curves, the fog attenuation curve can be easily correlated with the particle size distribution: attenuation is relatively constant until we approach 5 THz (60 um) at which point the attenuation begins to drop rapidly. While we do not have explicit attenuation versus wavelength curves for dust, based on the particle sizes we anticipate a curve similar to that of the fog curve. In a similar vein, while we do not have an explicit curve for snow, we anticipate that it would have a shape similar to the Heavy Rain curve, but shifted even more to the left (longer wavelengths).

If one examines the plot of atmospheric absorption versus wavelength, it is apparent that there is a band of strong atmospheric absorption between about 150 GHz and 10 THz in which absorption is 10-1000 times larger than in adjacent regions. This forms a “forbidden” region, especially for passive sensors. For sensing through fog and dust this has important implications. As we shall discuss in the next section, for a given diameter aperture, resolution decreases with wavelength (or for a given resolution, aperture diameter increases). The attenuation due to scattering for dust and fog is approximately constant from visible through the LWIR region and then drops about 2 orders of magnitude in the forbidden region. Without the forbidden region, one could select an operational wavelength to optimize resolution or aperture size versus penetration. However, due to the forbidden region we have a step function from short wavelength, high attenuation in the LWIR to much longer wavelengths and increased penetration in the THz and MMW bands.

While scattering from “small particle” obscurants such as smoke, dust, fog, and mist, drops dramatically by the time one reaches the W band (94 GHz), there is little benefit from these wavelengths, compared to the LWIR and shorter wavelength bands, for large particle obscurants such as rain and snow. In order to begin to see through heavy rain and snow, it is necessary to move to the longer Ka and even Ku bands, but as we will see in the next section, this can impose an unacceptable aperture or resolution penalty on many applications in which aperture size is constrained.

While the preceding clearly indicates that longer wavelengths provide a natural benefit for obscurant penetration, this comes at the expense of resolution or aperture diameter such that a system designer looking at different sensors will naturally seek to determine if there are ways in which shorter wavelength sensors can overcome the multiple scattering limitation and penetrate obscurants while retaining the resolution or aperture benefits of these shorter wavelengths. Obscurant penetrating lidar operating at 1.55 um provides an example. These devices typically emit a short pulse of light (on the order of 1 ns) and then digitize and analyze the returns. While the vast majority of the returns are scattered
photons, a very few will have traveled through the obscurant, reflected off a solid object, and returned. Details of the algorithms are proprietary and beyond the scope of this review. However, the end result is that obscurant penetrating lidar systems provide significant penetration improvement over either the unaided eye or simple lidar systems, while still falling far short of the penetration capability of longer wavelength systems such as MMW, for small particle obscurants. On the other hand, while THz and W-band MMW do not obtain a penetration benefit from their wavelength when sensing through rain or snow, the same pulse return processing can significantly enhance lidar penetration of these large particle obscurants. Thus without considering resolution, one might select a MMW system for small particle obscurants but a lidar system for large particle obscurants.

Before leaving this section, it is worth noting that THz and MMW systems also have an ability to penetrate certain “solid” materials such as clothing, paper, and other dry dielectric materials and as such provide useful screening tools to detect objects concealed under clothing and inside packaging.

2.3. Resolution

Two characteristics drive the selection of a waveband for imaging: The ability to detect radiation from the target (illumination and propagation) and the ability to detect sufficient information to perform a useful task. In most imaging type applications, this second criteria comes down to resolution. Spot size is given by the Rayleigh criterion for the first minimum in the Airy disk (equation 1) indicating that the angular divergence ($\theta$) is proportional to the wavelength ($\lambda$) and inversely proportional to the diameter (d) of the aperture [12]. In active systems, the spot size refers to the beam diameter while in passive imaging systems the spot size is the observed diameter of a point source at infinity. In well designed systems this should correspond to about 1 pixel.

$$\theta = \frac{1.22\lambda}{d}$$  \hspace{1cm} (1)

Thus as we increase the wavelength moving from visible to IR to THz and MMW, we either lose resolution for a fixed diameter aperture, or we must increase the aperture diameter to maintain resolution. The wavelength change going from the LWIR band to the THz or W-band is a 140 to 300 times increase, with a corresponding loss in resolution or increase in aperture diameter (Figure 3).

While beam or spot size are given by the Rayleigh formula, resolution is the ability to distinguish two closely spaced objects. The commonly used metric for detection, classification, recognition, and identification in 2D imagery is the Johnson Criteria [13,14]. According to Johnson, the minimum criteria for 50% probability of detection (This can be extended to other performance probabilities [15]) of an object is 0.75 cycles or 1.5 pixels across an object. Figure 3 shows the aperture diameter scaling required to maintain a fixed Rayleigh criterion spot size and the Johnson criteria detection range for a 1 m object as a function of wavelength, for various diameter apertures. For reference, the 0.14 mrad spot size corresponds to 20/20 vision.

![Figure 3](image_url)

Figure 3. Aperture Diameter versus wavelength at various resolutions (left) and Johnson criteria detection range for a 1 m object versus wavelength for various diameter apertures (right)
Systems operating in the THz and MMW bands can be either passive imaging or active radar type systems. While passive systems provide only cross range information (Azimuth and Elevation), active systems add range, resulting in 3-dimensional (3D) data sets. Because cross range resolution has a fixed angular value independent of range, the actual physical cross range resolution increases linearly with range as shown above. However, range resolution is determined by timing accuracy (out-going pulse width and return signal sampling) and tends to be more constant with range. Typical values for currently available lidar systems are on the order of 1 cm while those for MMW radar systems are on the order of 21 cm.

In some cases, detection, recognition, and identification in 3D data can be very different than with 2D data. When objects are in contact with their background, the process in both cases is similar. However, if an object is offset from the background (e.g. an aircraft of a suspended power line), it can be much more easily separated from any background when using 3D data. For localized objects, such as aircraft, 3D data also allows the use of techniques such as monopulse [16] to refine target location beyond the classical limits. Depending on the Signal to Noise Ratio (SNR) of the return to the background, an angular improvement of 5X is not unreasonable. Of course this approach is equally applicable to lidar systems as to MMW radar so the same wavelength considerations already discussed, apply for both resolution and propagation.

It should be noted that there are scan time and coverage issues associated with the choice between passive 2D and active 3D imaging. Most passive imaging systems today (visible, IR, PMMW) generate image frames at a rate of 30 Hz or higher (depending on the application). These systems generally have a fixed number of pixels which can be enlarged to give a larger Field Of View (FOV) image and lower resolution, or a higher FOV image at higher resolution. They also provide simultaneous full coverage of the FOV. In comparison, most 3D systems (with the exception of 2D flash lidar), rely on scanning a beam over the area of interest. This typically takes significantly longer (on the order of 0.5-2 seconds in many implementations). With these systems, one can trade off FOV, resolution, and scan time. A large FOV with a large beam size can be scanned quickly, while a smaller beam size will increase the time to scan the same FOV. Further, different portions of the FOV are typically scanned at different times using a raster scan. However, other scan patterns are possible, such as a non-overlapping rosette pattern [17] which gives full FOV coverage at coarse resolution and then fills in details. Flash lidar systems provide simultaneous full coverage of the FOV and like passive imaging systems, FOV and resolution are tightly coupled by the fixed focal plane pixel count. While this can be attractive, these systems spread the beam energy over the entire FOV rather than concentrating it in a beam, which results in shorter range for a given emitter power. Finally we note that 3D systems (lidar or radar), do not have to continuously scan an area but can instead be cued to a small region, scan it for objects, and then sample only those objects at a much higher sample rate. Details are beyond the scope of this paper but the important concept is that in the MMW and THz region, one can choose either active 3D scanning or passive 2D imaging and each has strengths and weaknesses in terms of how one trades off resolution, FOV, scan time, and requirements for simultaneous full area coverage versus sequential sampling.

2.4. Chemical Absorption Spectra

While many applications involve 2D or 3D imaging, stand-off chemical detection involves detection of chemical spectra from the species of interest. The current spectral region of interest is the THz (2) region (300 GHz – 10 THz). This region has been shown to contain detectable, unique spectra for a range of explosives and illegal drugs [6,18,19]. In particular, both intra-molecular and inter-molecular vibrational modes can be excited revealing both chemical and structural information such that different, chemically similar compounds can be differentiated.

However, as discussed earlier, this region also falls within the atmospheric absorption “forbidden band” between IR and MMW, meaning that there is little ambient radiation to detect. As a result, most THz spectroscopy assumes an active illumination source, usually coherent. In fact, for laboratory applications, samples are often placed in reduced atmosphere containers to limit atmospheric absorption of the illuminating radiation.

Many compounds of interest have a very low vapor pressure meaning that they do not outgas and hence can be very difficult to detect when concealed under clothing or in packaging. While this is not a problem for laboratory analysis of prepared samples, it clearly poses a problem for screening of personnel or packages. For screening applications, sensing in the IR portion of the spectrum requires detection of trace amounts of residual material, for example left on door handles, clothing, or the outside of packaging when the material was being handled. In contrast, THz radiation can...
penetrate many dry dielectric materials such as paper, clothing, and cardboard to provide detection of concealed material.

3. APPLICATIONS

In this section, we examine some of the applications for MMW and THz sensing and discuss why these sensing modalities are of interest. As with any application, one begins by defining the mission (e.g. pilotage in DVE conditions or detection of concealed explosives) and then the operational requirements (object size, range, FOV, obscurant density). These are then flowed down to engineering requirements (resolution, range, etc.), and finally comparisons between competing technologies can be performed to select the most appropriate solution. This process is shown in Figure 4.

![Figure 4. Requirements Flow Down.](image)

3.1. Pilotage in Degraded Visual Environments

An application of strong interest for MMW and THz sensing is pilotage in Degraded Visual Environments (DVE). During operations in Iraq and Afghanistan, there was a particular emphasis on operations in self-induced dust, so called “brown-out” conditions (Figure 5, from [20]). However, as operations in those regions wind-down DVE operations in a wider range of obscurants are of interest. These include snow, rain, fog, smoke, and dust.

![Figure 5. Helicopter induced Brown-out.](image)

Sensor requirements for DVE operations include specification of obscurant density based on operational requirements, as well as required object size and range at which the objects must be detected, and the required FOV coverage. Detection range is set by airspeed and reaction time of the pilot and airframe. DVE operations can be divided into 2 broad classes: 1) Approach, Landing, and Take-Off, and 2) En-route (low level) flight. The former is characterized by slower speeds and the need to detect smaller obstacles such as rocks, ditches, and terrain slope which might pose a roll-over hazard, while the latter is characterized by higher speeds (implying longer range detection), and generally larger objects such as poles, buildings, trees, and terrain (hills).
We note that while power lines have a very small physical cross section (1/4 – 1") they are long objects spanning many pixels and tend to have high contrast (due to low emissivity) when seen as cold sky reflectors against warmer terrain. As a result, very small pixel fill factors are detectable. These pixel fill factors can be smaller than 5% for 2D imagery [21] and significantly less than 1% for 3D imagery [22].

In order to generate some order of magnitude numbers, we can take 140 kts as a representative “fast” speed for low level flight, combined with a 15 s pilot and airframe reaction time, to give a detection range requirement of about 1 km. Objects to be detected at this range might include wires, poles, buildings, smokestacks, radio towers, trees, and terrain. If resolution and obscurant penetration do not provide this range, slower speeds must be used for safe flight. Ranges for landing will tend to be less, but the objects are smaller as well: rocks, holes, ditches, stumps, personnel, and other vehicles.

Update rates for presentation to the pilot generally need to be 30 or 60 Hz. While a passive 2D sensor (LWIR or PMMW) can provide this type of image frame rate, active scanning sensors (lidar and MMW radar) are typically slower, on the order of 1 sec per scan. Because the active sensors provide 3D data which can be geo-registered, the resulting data can then be presented to the pilot as synthetic vision at the higher 30 or 60 Hz rate. The key here is that the terrain and obstacles do not change rapidly, but the platform position and orientation does. So as long as the 3D data exists, it can be rendered to show the pilot his position and orientation relative to the terrain.

3.2. Detection, Tracking, & Targeting

The requirements for detection, tracking, and targeting are to first detect a target and build time history trajectories of the target, leading ultimately to identification and a determination that the target is a threat. In order to prosecute it, relative or absolute coordinates are required. From a sensor perspective, targets can be divided into three categories:

1) Fixed, stationary targets with an a priori known position, in which case either a position only sensor (GPS or equivalent) is needed, or a position sensor and a short range end-game precision aim-point sensor is needed.
2) Actively designated target (e.g. laser designator).
3) Unknown, moving or stationary target.

The category of most interest for MMW & THz sensors is the last. In this case, the system (including host platform if applicable, plus weapon), must detect, track, and positively identify the target at the maximum range of the weapon. Typical ranges are 8 km to greater than 40 nm (74 km). Targets are typically aircraft or ground vehicles, resulting in target sizes on the order of 3-20+ m. The requirement for both much longer ranges and also greater resolution (identification as opposed to simply detection), makes this a much more stressing application than the DVE pilotage problem. Further, aperture sizes on missiles are even more constrained than those on rotorcraft. However, once a target has been acquired it is necessary for the weapon to accurately close with the (possibly moving) target and select an aim-point. It is desirable to be able to execute all of the above functions in all weather conditions.

While initial detection and identification at or beyond the range of the weapon is challenging for MMW technology, because of its all-weather capability, W-band has nevertheless proven popular in seekers for weapons such as Hellfire and Brimstone, among others. In this case, the weapon may be directed to the vicinity of the target (e.g. by GPS) where it then searches for candidate targets. Most vehicles have a large metal content which stands out from natural backgrounds. This can be used alone for stationary targets, or coupled with motion and other features, to help identify the target. In the end game, MMW can also provide target imaging for aim-point selection in all weather conditions. However, since the closing speeds can be supersonic, imaging and reaction time are limited.

In an air to air engagement, depending on the rules of engagement, if a target does not positively identify itself as friendly, it may be considered a threat, reducing the need for imaging type identification (Beyond Visual Range engagement). Further, in an air to air engagement in which a target is isolated from its background, monopulse techniques can be used to improve angular position estimates of unresolved targets [16].
The above discussion focuses on long range, moderate size targets. Another type of targeting application involving much shorter ranges and smaller targets is defense against swarming UAVs.

3.3. Stand-off Detection & Screening

The challenge for stand-off detection is to provide a screening capability, primarily to detect concealed explosives. Applications range from screening cars entering a facility to screening packages and screening personnel. A secondary application is screening for the presence of illegal drugs at control points such as border crossings. The challenge is that the substance of interest is usually concealed under clothing, in a vehicle, or in packaging. Many of the substances of interest have low vapor pressure so detection of outgassed material is not viable. The result is a need to either detect minute trace amounts left on externally visible material during previous handling of the material, or to be able to detect the hidden material in situ. Further requirements include rapid throughput of large numbers of personnel, vehicles, or packages without time consuming external swabs followed by analysis, or invasive searches.

As previously discussed, chemical spectra appropriate for uniquely identifying specific compounds of interest are present in the THz and IR portion of the spectrum. While good sensors exist in the IR with high sensitivity for stand-off trace sample detection, these sensors do not provide significant penetration capability. Screening in the THz regime necessarily implies short ranges due to the strong atmospheric attenuation at these wavelengths.

The key requirements for this application are a sufficiently powerful, tunable source and detector such that one can scan the wavelength range of interest and have enough power to propagate from the source to the target, penetrate, and the emissions propagate back to the detector.

Stand-off screening is similar to stand-off chemical detection in that it is used to rapidly scan personnel, packages, and some vehicles to find concealed materials. However, in this version, detection is done via imagery and object recognition based on shape, rather than on spectra. Typical applications are airport scanners to see through clothing to detect weapons, or imaging through soft-sided trucks to detect concealed personnel. Compared to spectral detection working in the THz regime, this application tends to be implemented more in the MMW (W-band) regime and can use either active or passive imaging. However, even in active imaging, there tends to be less emphasis on the generation of 3D data than of 2D data. The key requirements are penetration of outer materials (clothing, paper, rubberized canvas), FOV, and sufficient resolution to alert the screening personnel of a potential threat.

For both types of screening, sample rates have some flexibility. While the ideal is a sample rate which does not impede traffic flow (e.g. people can walk past in single file without slowing down, vehicle traffic can drive by at normal speeds), we are used to the delays associated with airport screening. Traffic entering a parking garage typically has to stop to obtain a parking ticket. Thus screening times on the order of a few seconds are generally acceptable with the understanding that shorter times are preferred.

3.4. Surveillance & Other Applications

Surveillance can take many forms, from a fixed sensor monitoring a given area, to an airborne sensor covering large swathes of ground. Applications can vary from military to environmental monitoring, and traffic control, among others. A thorough discussion of the applications and requirements is beyond the scope of the current paper. Instead, we will highlight a few specific applications and requirements.

Detection of Foreign Object Debris (FOD) on runways and taxiways in all weather is a monitoring application of interest. The sensing requirements include sufficient resolution to detect an object of sufficient size to pose a threat, at the maximum range from the sensor to all portions of the runways or taxiways under surveillance. Runway lengths can exceed 10,000 ft (3000 m). While a single surveillance sensor will probably not need to view the entire length of a runway, because it will not be positioned at one end looking down the length, it will probably be offset some distance from the runway. The most likely geometry is a look down using an elevated sensor. In this case, the sensor tower will need to be sufficiently far from the runway so as not to pose a hazard. One can use the 2000 Concorde accident to set a size for FOD on runways. The Concorde was brought down by a titanium strip 43.5 cm long 3 cm wide and 1.4 mm thick. Further, FOD will be in contact with the solid runway as background meaning that 3D techniques are not likely to
be overly useful. While this implies a large aperture, this application benefits from the fact that the aperture is ground based and we are looking for change detection in a well controlled scene. Updates rates or revisit times are set by the arrival and departure intervals of aircraft. The maximum revisit rate is once per arrival or departure such that if an aircraft sheds a part on the runway it can be detected and traffic flow halted before the next aircraft transits the area. Of course, FOD detection should be functional in all weather, whenever the airport is operational.

Another type of surveillance is represented by harbor surveillance, either from shore installations or from ships in the harbor. There are various applications ranging from basic traffic control to smuggling or terrorism prevention. The latter two represent the more stressing applications in this context. Threats may be small boats (12 ft / 4 m) operating under cover of fog and other obscurants. If the boat is a smuggler it will presumably do its best to maximize the range between itself and potential sensors, so range will be dependent on the harbor geometry. For terrorism threats, against ships in harbor, one must estimate the maximum lethal range of the threat: Are we protecting against a Rocket Propelled Grenade (RPG) or against an explosive threat such as the attack on the USS Cole? In either case, an effective sensor must detect the threat at sufficient range to allow time for protective measures to be taken. Passive sensing may be preferred over active in order to conceal the presence and location of sensors.

The final application we look at is airborne ground surveillance. Resolution requirements depend on the application but for military applications a key metric is the ability to find vehicles and to perform change detection. This imposes a Ground Sample Distance (GSD) on the order of a meter, depending on the size of the object and whether detection, classification, or identification is required. Airborne platforms will most likely be operating from 10,000 ft (3000 m) altitude or higher with some offset leading to longer slant ranges. The result is a sample resolution smaller than 0.3 mrad which at a 3 mm wavelength implies a 12 m aperture but only a 4 cm aperture in the LWIR band. The motivation to use MMW imaging (active or passive) is to provide all weather surveillance and deny an adversary the cover of inclement weather. Synthetic Aperture Radar (SAR) at longer wavelengths is used for all weather surveillance, so in contrast to the longer wavelength bands, W-band can offer smaller apertures.

4. PERFORMANCE & TRADE-OFFS

When selecting a sensing modality for any of the above applications, a system designer must trade-off the basic physics described above (resolution/aperture and atmospheric/obscurant penetration) and the technical maturity of sensors, between different wavebands. As we look at longer wavelengths, radar systems are mature and transitioning from conventional to AESA type units. At shorter wavelengths we have high pixel count LWIR focal planes and mature lidar systems with adjustable optics and scan rates. In the MMW regime, conventional radars are mature, but AESA type radar is a new development in its infancy, Passive MMW imagers have been demonstrated (Figure 6) [22] but not fully matured, and THz sources and detectors are rapidly developing. Short range MMW imagers for airport screening are mature and have become a dominant screening tool in this application.

Figure 6. Imagery from an early Passive Millimeter Wave imager (500 mm diameter aperture, 7.8 mrad resolution).

It is instructive to understand why MMW sensing has been selected over other modalities for current applications. For missile seekers MMW radar has a clear resolution / aperture size advantage over longer wavelength radar systems. While the shorter wavelength of MMW degrades its performance in heavy rain and snow, compared to longer wavelength radars, the improved resolution coupled with the fact that it is difficult to fly in the worst weather conditions, favors the
MMW regime. On the other side, while imaging LWIR or lidar seekers provide significantly better resolution, they provide very limited capability in fog and smoke. Hence MMW provides a balance of obscurant penetration and resolution compared to the wavebands on either side. In fact, many seekers are multi-mode, using both imaging LWIR and MMW and sometimes lidar. As obscurant penetrating lidar capability improves (e.g. for pilotage applications), one might question whether the position of MMW seekers will remain secure.

Airport screeners provide another example in which MMW technology has dominated. Again, the key is the ability to penetrate obscurants (in this case clothing) and provide modest resolution. The short range, modest resolution strongly favors a MMW approach while LWIR and lidar systems have limited or no ability to penetrate clothing and packaging material. As a result, the place of MMW technology for screening would appear to be secure for now.

We now turn to emerging applications to examine how MMW & THz technology compares to competing wavebands. Sensing for pilotage in DVE conditions is a current priority in a number of countries. Significant efforts are being made to develop technologies to sense through all types of obscurants. In addition to mature MMW radar, there are efforts to develop AESA type MMW radar [23], Passive MMW imaging [24,25] and THz radar systems [26], as well as a number of efforts to develop 3D obscurant penetrating lidar systems [27-31]. As with many other applications, the challenge is to obtain sufficient resolution through obscurants. In order to select a sensor it becomes critical to specify both the obscurant density through which the sensor must image, and the required resolution, derived from object size and detection range. Lidar systems can meet the resolution requirements and have worked hard to improve obscurant penetration performance. While lidar systems offer penetration significantly better than the human eye, improvements appear to have plateaued using current techniques. MMW systems on the other hand offer good penetration but poor resolution. Efforts to improve resolution include operating at higher frequency [26] trading off some penetration capability and accepting increased atmospheric attenuation, to gain improved resolution. Other efforts include investigation of sparse aperture PMMW systems [25] allowing aperture on the order of the size of the platform to be used.

Stand-off chemical detection appears to be limited to the THz and IR bands, based on the chemical vibrational spectra to be detected. In this application, the ability to image through concealing materials such as clothing, paper, and other materials appears to give THz a long term advantage over IR imaging. However, suitable sources and sensors must be developed.

REFERENCES

1. Values in the graph computed using the Black body calculator at: http://www.spectralcalc.com/blackbody_calculator/blackbody.php. The author has previously validated the values obtained from this tool.


