A 600 GHz Imaging Radar for Contraband Detection

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Abstract **— We have developed and demonstrated 3D imaging for contraband detection using a submillimeter-wave frequency modulated continuous wave (FMCW) radar with a fast microwave chirp and phase coherent detection. The technique provides an important advantage over more traditional CW RF imaging because of the ability to time-gate the return signals. This can be used to discern specific objects by greatly reducing clutter from unwanted targets or specular reflections. The prototype system uses a 600 GHz RF signal with a 28.8 GHz chirp producing a 2.3 MHz/µsec sweep yielding a range resolution of approximately 0.6 cm or less. Lateral resolution on the scene is set by a 40 cm diameter reflector producing approximately 0.5 cm at 4 m distance.**

I. INTRODUCTION

Detection and imaging of contrabands carried by potential subjects hidden under garments at stand-off distances is a major thrust area for security agencies. There is an ongoing debate as to what frequency band and techniques are best suited for these applications. Since small size and portability is a major requirement for these instruments, aperture size is limited to tens of centimeter to a meter at most. Microwave frequencies are capable of penetrating clothes, however, they lack in required resolution (for a given aperture size). On the other hand, visible and infrared frequencies can provide very high resolution but can not penetrate garments to unveil concealed explosives and other contrabands. That leaves us with submillimeter-wave frequencies, which is capable of achieving both these objectives – high resolution and penetration. However, at frequencies above 300 GHz the background (sky temperature) is relatively warm and does not provide enough contrast for an object against the background. With room temperature detectors, passive imagers at these frequencies do not provide enough sensitivity for detecting contraband at standoff distances of 25 meters or more.

One technique that shows great promise for achieving through-garment imaging at standoff ranges from 5 to 100 m is active submillimeter-wave imaging using coherent heterodyne detection. Between 100 GHz and 1 THz most clothing is reasonably transmissive [1], while at the same time high image resolution can be achieved with a compact aperture. For example, with a standoff range R = 25 m, an antenna diameter D = 50 cm, and an operating wavelength λ = 0.5 mm (600 GHz), the two-way diffraction-limited image resolution is about 2 cm, sufficient for many of the applications. With available output power at 600 GHz from solid-state sources reaching milliwatts [2], [3], and the double sideband (DSB) noise temperature of room temperature Schottky diode based mixers reaching 2000 K and lower [4], signal to noise for active submillimeter-wave imager can reach 70-80 dB, which includes 20 dB of atmospheric loss, 20 dB of backscatter coefficient from the object, and 25 ms of integration time. Therefore, with the ability to penetrate clothing, the potential for centimeter-scale spatial resolution and signal-to-noise ratios in excess of 10^7, it is not surprising that active submillimeter imaging has attracted great interest for standoff contraband detection. But the question everyone asking is whether this high signal to noise and good resolution sufficient to reliably detect concealed objects.

In this paper we argue that it is not sufficient to have high signal to noise and resolution, because when outside the laboratory set-up an active coherent imager will typically exhibit very poor contrast between a concealed object and the surrounding clothing and skin – even for metallic objects such as guns. The challenge of active coherent submillimeter-wave detection of concealed objects involves extracting signals from scene clutter rather than from noise. We believe that this problem can be addressed by a broadband submillimeter-wave radar which is capable of three-dimensional imaging with centimeter-scale resolution in all three dimensions. Using this technique, we demonstrate in this paper our ability to generate high-resolution images and remove the clutter signals to reveal hidden objects at standoff ranges of 4 m. We show that we can readily scale the existing system to 25 m standoff, but that increasing its speed to near-real-time frame rates will require a substantial effort to develop a multi-pixel imaging radar array.

II. FREQUENCY MODULATED CONTINUOUS WAVE RADAR

Frequency-modulated continuous-wave (FMCW) radar techniques are ideal when available transmitter power is limited, as in the case of submillimeter-wave radars. The block diagram of our 600 GHz FMCW radar is shown in

Fig. 1. The transmitter uses a chirped signal from about 576 to 605 GHz which is generated by upconverting a fixed frequency signal with a chip signal generated by a hybrid direct digital synthesis/phase-lock loop (DSS/PLL) synthesizer, and then frequency multiplying the signal by x36. The DSS/PLL is typically ramped between 2.5 and 3.3 GHz in 12.5 ms which results in a transmitted 576-604.8

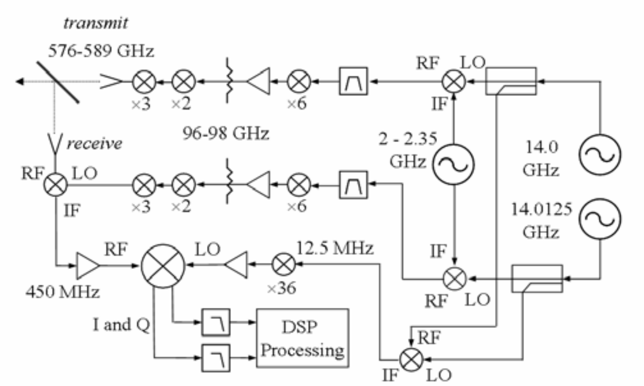

Fig. 1: Schematic block diagram of the 600 GHz radar imager. The transmit signal and receiver local oscillator are achieved by multiplying microwave sources by a factor of 36. A 2.5-3.3 GHz chirp generated by a DDS/PLL synthesizer results in a final FMCW signal with a 28.8 GHz bandwidth. The submillimeter-wave multipliers and mixer designed and build at the Jet Propulsion Laboratory are

GHz chirp with a rate K = 2.3 MHz/μs. Linearity of the chirp signal is an important factor for FMCW radars. We use a digital compensation algorithm as discussed in [5] and [6] to have a linear stable waveform for the transmitted signal. The transmitter signal goes through a silicon beamsplitter to a secondary mirror which deflects the beam to a 40 cm diameter ellipsoidal reflector, which focuses the beam at 4 meters standoff (fixed by the mirror focal length) with a half-power width of approximately 0.6 cm. The radar return signal is mixed using a JPL developed double sideband balanced mixer. The IF output is mixed again in an I-Q mixer, and is fed to the digital backend which uses FFT-based range compression to yield both the magnitude of the target's reflected power and its range. Images are acquired by scanning the focused beam over a target, typically requiring several minutes to capture a torso-sized field of view.

Fig. 2 shows a photograph of the 600 GHz imaging radar stage with a 40 cm diameter mirror installed. Upon leaving

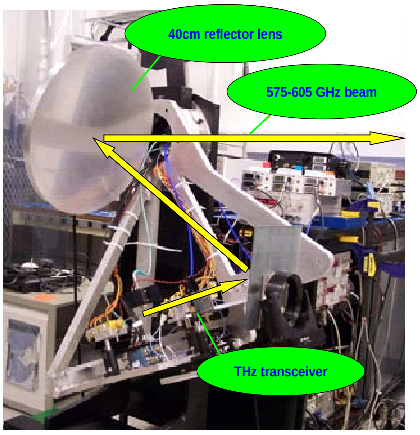

Fig. 2: Photograph of the imaging radar hardware showing different components of the imaging system.

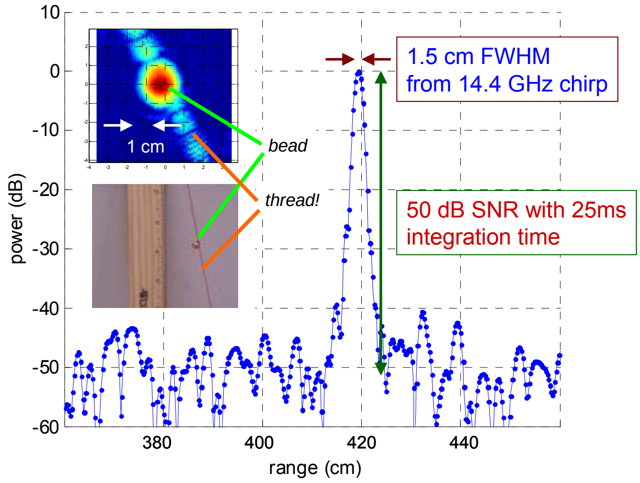

Fig. 3: 600 GHz scanned radar image of a 3 mm gold bead at 4 m standoff range and suspended by a thread and the radar return signal. The photograph of the bead is also shown. Even the single cotton thread is detected by the radar.

the transceiver the first null beamwidth is 28°. Owing to the two-way nature of the transceiver, the effective 3 dB cross-range resolution is about 0.4 cm, as indicated by the scan shown in Fig. 3, and in agreement with physical optics simulations. Fig. 3 also shows the actual radar return signal in terms of range versus power. In this image, the range-gated received power is plotted on a logarithmic scale for a target consisting of a 3 mm gold-plated bead suspended by a single cotton thread at a standoff range of 4 meters. Fig. 3 inset shows a photograph of the suspended bead along with a ruler (not present during the actual scan) to better indicate the target dimensions. Each of the approximately 10,000 pixels in the image of Fig. 3 was obtained using a 25 ms chirp (and integration time), and the maximum bead signal is about 60 dB above the background noise floor. In the range-compression spectrum, however, the bead SNR is apparently phase-noise-limited to 50 dB. Even a single thread can be detected with an SNR exceeding 20 dB in some places, as can be seen from Fig. 3.

III. Detection of Contrabands using Imaging Radar

Fig. 4 shows a THz image of a person with a concealed metallic gun replica at 4 m standoff. Although this image was acquired with the JPL FMCW radar working at 600 GHz, only the total power received for each pixel is shown – no range information is utilized in the image generation. The gun is not recognizable without prior knowledge of its location because there is very little contrast of the gun's backscattering strength compared to its surroundings. In fact, at certain locations on the target (the eyes, shoulder, and shirt sleeve), the received signal intensity is much brighter than that from most of the gun. Moreover, clutter from the laboratory wall also compromises the image quality.

Depending on an object's roughness and material properties, the THz reflectivity measured by a single-pixel

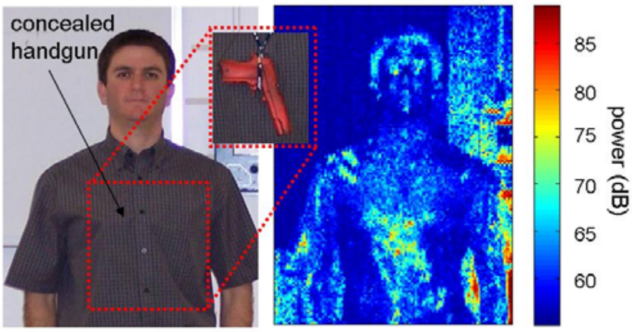

Fig. 4: Power-only active THz image of a person with a concealed metallic gun replica.

transceiver can be extremely sensitive to the beam's angle of incidence with the object. The reflectivity values at 600 GHz cited in [1] were obtained at normal incidence, and to assess the importance of specular effects, we used the 600 GHz radar to quantify the relative reflectivity of some common materials as a function of the angle of incidence. Three materials we measured were a block of unpolished aluminum, a crumpled sheet of aluminum foil, and a leather jacket (to mimic skin). Each of these items exhibits large variations in reflectivity as a function of incidence angle. For example, the signal from aluminum block drops by more than six orders of magnitude within only a few degrees of rotation, reaching levels more than 20 dB below the strongest reflection of the leather surface. The crumpled foil does not have the same sharp dependence at normal incidence, but with a reflectivity variation exceeding 30 dB over of rotation, it can appear either brighter or darker than the leather surface (which itself varies by 20 dB over ±10 degrees) depending on the angle of incidence. The results of this experiment are shown in Fig. 5.

The impact of specular reflection can also be seen in Fig. 6, which shows two 600 GHz radar images of a mannequin

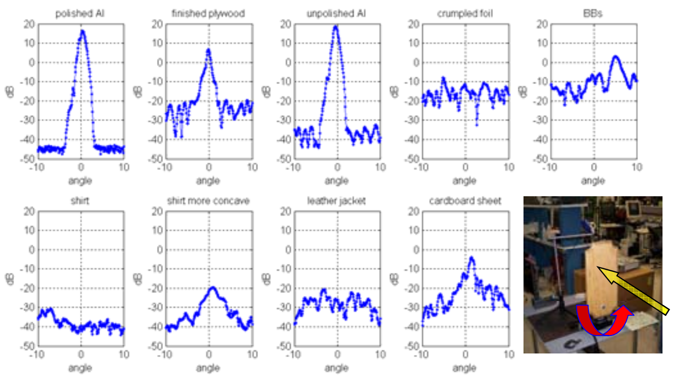

Fig. 5: Terahertz backscatter radar images of different materials with the radar transmit signal incident on the object at ± 10 degrees.

with a metallic gun replica concealed by a T-shirt. Like in Fig. 4, these images were obtained at 4 m standoff and represent power only, but for clarity the clutter signals from the laboratory wall and the near-range optics and leakage were filtered out by gating the power in a range swath encompassing the mannequin body. In Fig. 6a, the gun was carefully positioned for normal beam incidence, and it can be clearly identified in the THz image. However, Fig. 6b shows an image of the same target after it had been rotated by about 20 degrees. With the gun no longer at a normal angle of incidence, it essentially disappears. Any active, coherent THz imager that relies only on power detection must contend with this difficulty of identifying objects whose intrinsic reflectivity contrast may be overwhelmed by the effects of specular reflection.

We have addressed this problem by using the ultra-high range resolution of the THz imaging radar to enhance the

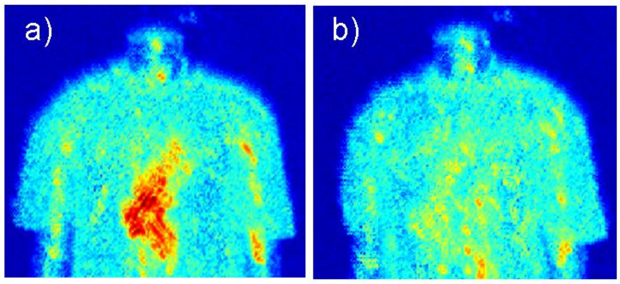

Fig. 6: Power-only terahertz image of a mannequin with a metallic gun replica concealed by a T-shirt. a) Near-normal beam-gun angle of incidence. b) Mannequin rotated ~20° away from normal incidence.

contrast of concealed objects on persons and obtaining three dimensional images. Fig. 7 shows three-dimensional scene reconstructions based on the identical raw data obtained in the scan of Fig. 4. These reconstructions were obtained by selecting, for each pixel of the image, the range-compressed signals corresponding to the "front" and the "back" target surface encountered by the beam. This was done using an adaptive algorithm based on the range returns meeting certain threshold and surface continuity criteria [7]. The result is that the "front" surface in Fig. 7a shows a faithful

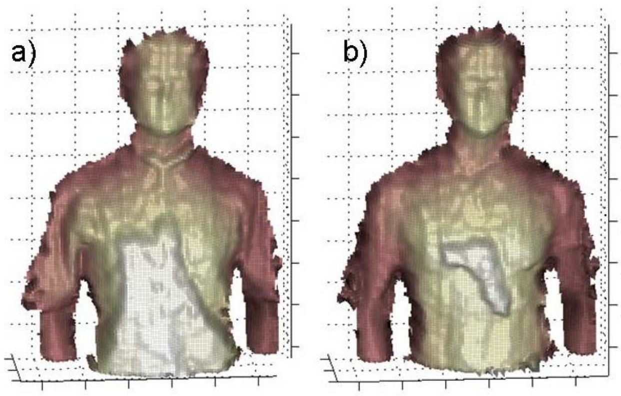

Fig. 7: (a) Front-surface – on the shirt and (b) back-surface – on the skin three-dimensional reconstructions of the scene shown in Fig. 4, obtained by utilizing the high range resolution terahertz FMCW radar.

reconstruction of the target's exposed skin and his shirt, while the "back" surface in Fig. 7b reveals an image of the body with a distinctive gun-shaped protrusion. A similar radar image is shown in Fig. 8 where range gating capability of the radar was used to electronically strip the shirt off the object revealing the concealed object.

Compared to the power-only THz image of Fig. 4, the advantage of using ultra-high resolution radar is clear from Fig. 7. Significant enhancement of concealed objects can be achieved by measuring their three-dimensional shape rather than simply the reflected power. Also, because the radar resolution is inversely proportional to its bandwidth and independent of the standoff range, extending the system's capabilities to tens of meters standoff is feasible as long as the antenna size increases commensurately, and we have made successful through-clothes radar images at 25 m standoff [7]. Besides long range operation, a more serious challenge to the active THz radar for real-world security applications is its slow imaging time. To achieve near-video frame rates for this system, a more complex and costly multi-pixel active scanning array will likely be needed.

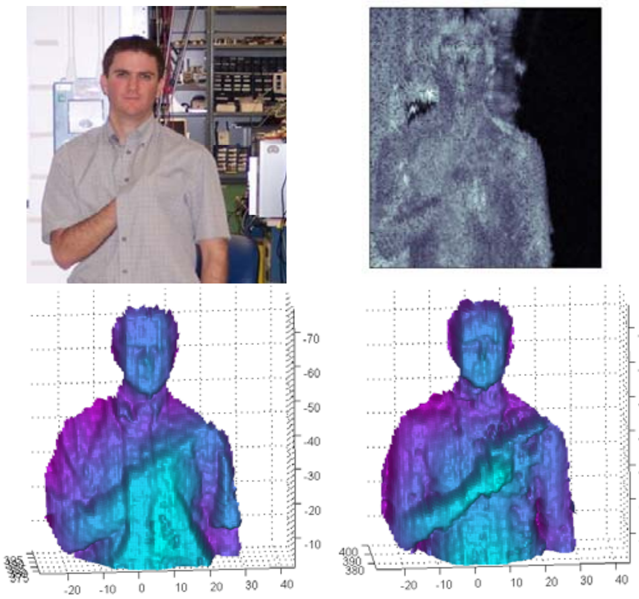

Fig. 8: 600 GHz FMCW radar image range gated to electronically strip off the shirt (bottom) showing the concealed gun. Intensity only image of the same scene is shown in top right.

CONCLUSIONS

We have shown that a 600 GHz FMCW radar system can be used to detect weapons or contraband under clothing at significant stand-off distances. We have also shown that simple active imaging using a CW source reflected off a target cannot distinguish between scene clutter or readily contrast hidden objects due to the variation in backscatter with angle and object reflectivity. By employing an FMCW radar with high range and spatial resolution and simple front- and rear-surface detection algorithms, we can actually peel away layers to reveal hidden objects with high accuracy and resolution. This added capability is believed to be critical for realizing an imaging system that can be used effectively in the field.

Although the enabling RF hardware is not readily available off the shelf at this time, we know from our own development efforts that adequate room temperature solid-state sources and heterodyne sensors can be produced to meet the requirements of such a system. Extending the effective range for a given lateral resolution is a practical issue driven mainly by aperture scale. Fortunately, there is an advantage in SNR and axial resolution when using the active radar imaging approach because the backscattered signals do not degrade with distance if the lateral resolution is maintained. Atmospheric attenuation is a concern, but working in an atmospheric window (such as 670 GHz) mitigates this problem. The biggest hurdle, we believe, is in bringing the imaging system up to video rate. However we believe this is possible by employing a linear transceiver array and we are currently pursuing this avenue of research.

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