

Passive and Active Imaging of Humans for Contraband Detection at 640 GHz

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Abstract — Submillimeter wave images of a human subject have been obtained at 640 GHz using a scanned single pixel Schottky diode mixer operating at room temperature. The experimental results are in rough agreement with the radiometer equation, and show that thermal emission from body heat can be detected with integration times as low as 10 milliseconds. It was demonstrated that a metal object hidden under cotton fabric could be detected passively due to the contrast between the body temperature and the reflections of the environment. In a separate experiment, it was demonstrated that the high receiver sensitivity allows a commercially available ceramic heat lamp to be used as a modulated illumination source, so that reflective materials such as metal can be actively detected. This means that it should be possible to construct an imaging instrument that combines a passive detection mode with an active mode using a thermal emitter in a single instrument. If a large number of channels (pixels) could be included in such an instrument, it could even operate at or near video speed frame rates (30 Hz), which would make it extremely useful for contraband detection.

Index Terms — Imaging, object detection, submillimeter wave imaging, submillimeter wave mixers, submillimeter wave measurements, submillimeter wave receivers, submillimeter wave technology.

I. INTRODUCTION

Events in recent years have led to increased concerns about the dangers from objects that can be hidden by clothing and transported on or near a person's body - primarily different types of weapons, but also other types of harmful or illicit contraband. In applications like airport, border and military checkpoints, an imaging system that could detect such contraband and alert monitoring staff could potentially provide extra levels of security. One concept is to use the ability of microwaves to penetrate most fabrics and many other materials to reveal such contraband. Unfortunately, this approach has the disadvantage that the long wavelengths result in considerably larger diffraction effects than in for example an infrared camera, especially if the object or person that is being imaged is not in immediate proximity to the instrument. The instrument may need to be very large to achieve high resolution - even at 100 GHz, an imager with a 2.5 cm spot (pixel) size at a range of 30 m would need a focusing element with a diameter of 4.5 m. A tradeoff

clearly needs to be made between penetration and resolution, which in the checkpoint applications referred to above would likely result in a choice of frequency somewhere between 100 GHz and 1 THz for a passive system, but possibly higher in a system where an external illumination source can be used to boost the penetration.

Passive imaging without artificial sources would be advantageous for many potential applications. "Passive imaging" means either that the thermal far-infrared emissions from the person or object is being detected, or that contrast is achieved by varying amounts of reflected radiation from natural sources, for example the sun (hot), the sky (cold) or the surrounding terrain. The advantages are that an irradiating source does not have to be included in the system, that the risk of detection (in a military application) is lower, and that personnel and materiel are not exposed to radiation that may be, or at least may be perceived as being, dangerous. Active sources such as lasers, backward-wave oscillators, or solid-state multipliers, could be employed in applications where irradiation is not an issue, which would improve the ability to see reflective objects hidden under thick fabric, and which would also allow higher image frame rates in systems that are limited by detector noise. One issue that can complicate this use of sources is the speckle effect, which is a result of diffraction between reflections off different details of an observed object within a single pixel. A common optical example is the mottled speckle pattern that can be seen when an optical laser is projected onto a wall and scattered. The average solid angle of these optical speckles is determined by the pixel solid angle set by the wavelength, the diameter of the eye pupil, and by the RMS roughness of the surface (as measured in wavelengths). Due to the wavelength, the speckles are bigger for microwave instruments than for comparable optical systems, so that objects much larger than a pixel could easily be masked and even so that the entire image would become impossible to interpret. The most effective way of defeating this speckle effect is to use several spatially separated and mutually incoherent sources for the illumination.

A variety of cryogenic detectors have the sensitivity needed for producing 30 Hz frame rate images in a passive mode, for example bolometers made from InSb, HgCdTe as well as superconducting bolometers and tunnel junctions. When cooling to very low temperatures (<80 K) is not an option, these detectors do not work, or work with impaired performance. For applications that require high sensitivity (<1 K resolution), and where the instrument needs to operate at a temperature between 80 K and room temperature, heterodyne detectors (mixers) therefore are an option. The temperature resolution ΔT that can be achieved by a heterodyne instrument observing a source at temperature T is given by the Radiometer Equation :

$$\frac{\Delta T}{T + T_R} \approx \frac{1}{\sqrt{\Delta f \cdot \Delta t}} \quad (1)$$

where T_R is the receiver noise temperature, Δf is the intermediate frequency bandwidth, and Δt is the integration time. With realistic numbers for all parameters, the equation shows that a temperature resolution of about 0.25 K should be achievable at video sampling rates. This temperature resolution is definitely sufficient to detect body heat against a room temperature background, but it does come at the price of increased system complexity and the heat dissipation that is caused by the local oscillator (LO) source and the intermediate frequency (IF) amplifier. In a practical imager a large number of channels will need to be incorporated into a compact focal plane array, so these issues of LO power distribution and IF processing will require serious attention.

In this paper we provide a demonstration of thermal

imaging at 640 GHz, using a single-channel waveguide Schottky diode mixer that was originally built as part of a prototype spectrometer for a microwave limb sounder in NASA's Earth Observing System (EOS-MLS) [2]. The first purpose is to show that a submillimeter-wavelength room-temperature Schottky mixer can indeed detect the thermal emission of a person in front of a colder (room temperature) background, and that an object hidden under a layer of clothing can be detected by the contrast it creates between the emission from the person and reflections from the ambient. The second purpose is to show that a radiating heater, in this case a small and inexpensive ceramic heat lamp [ref to Iguana], can be used as an active source to emphasize hidden objects through reflection. A future dual-function imaging instrument could incorporate both these mechanisms by applying a distinct modulation to the heater, allowing the instrument to simultaneously separate materials and tissue both by temperature and reflectivity. In order to provide a more uniform illumination and to avoid any speckle-related issues, as well as reducing the overall power requirements, the heat source in such an instrument should have a much larger area than the one used here, and operate at a lower temperature. One advantage with using an emission source that relies only on thermal emission is that it seems more likely to receive widespread public acceptance in applications such as airport screening than some active illumination sources, which may be perceived to be hazardous.

II. MEASUREMENT SYSTEM

The measurement system shown in fig. 1 consists of an off-axis parabolic focusing mirror, submillimeter wave

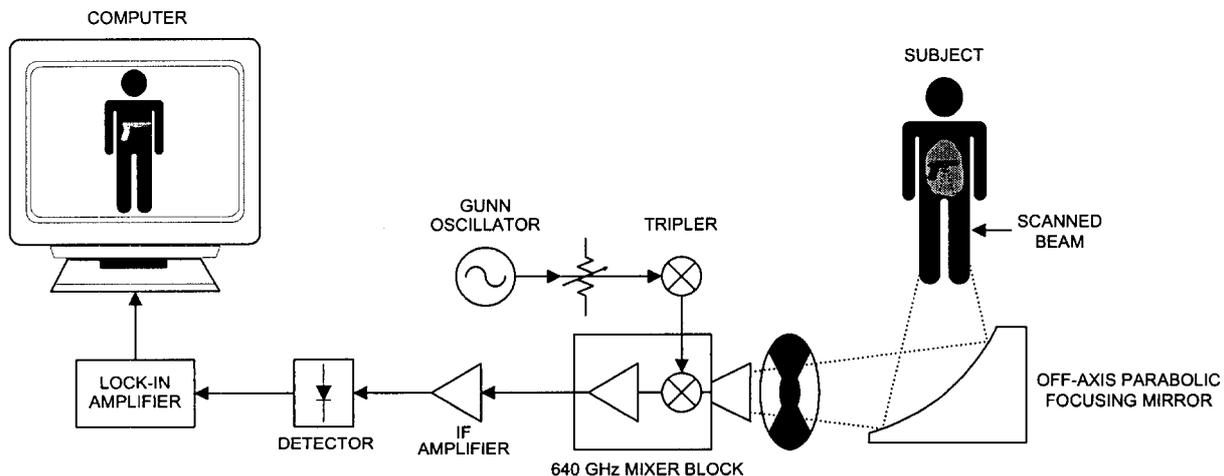


Fig. 1. Block diagram of measurement system

mixer [1]-[2], local oscillator chain [3]-[5], IF amplifier and detector all mounted to a 2-axis rotation stage. The focusing mirror is mounted so as to provide a beam waist slightly in front of the mixer's Pickett-Potter horn instead of at the beam waist of the horn. This results in the beam being slightly focused down at the subject instead of remaining parallel.

The mixer block is a subharmonically pumped double sideband planar design developed for the Microwave Limb Sounder instrument onboard the Earth Observing System Aura satellite, scheduled for launch in March 2004. The block was designed for a center frequency of 642 GHz and has an integrated 6-18 GHz IF amplifier, yielding conversion bands of 624-636 and 648-660 GHz. Since the 2 converted bands are folded onto each other in the mixing process, the pre-detection bandwidth is one-half of the converted spectrum, or 12 GHz.

This 6-18 GHz IF signal is fed to a second high-gain IF amplifier and crystal detector, which in turn is read by a lock-in amplifier. By chopping the input signal to the mixer, only the difference in received power between the subject and a fixed RF load is measured. As a result, all drift in the mixer, LO, IF amplifiers and detector is cancelled.

The system was calibrated by recording the lock-in amplifier output voltage (corresponding to detected power) with the receiver beam terminated in an Eccosorb® load at 295 and 78 K. Radiometric noise temperature was then calculated using

$$T_R = \frac{T_H - T_C}{P_H - P_C} * (P_{IN} - P_C) + T_C \quad (2)$$

where T_R is the noise temperature to be calculated, T_H and T_C are the temperatures of the calibration hot and cold loads with corresponding measured powers P_H and P_C , and P_{IN} is the power measured from the subject.

The rotation stage scans the receiver beam in a raster pattern, alternating the horizontal scan direction on each vertical increment. Any significant latency in data acquisition could be seen as an alternating shift in image data between adjacent horizontal scans. A lock-in amplifier integration time of 10 milliseconds was used, yielding a theoretical acquisition speed of 100 points per second. However, some shifting of the data between adjacent scans was noticed at this speed, so the scan speed was set lower by a factor of 20 to completely assure good registration of the data.

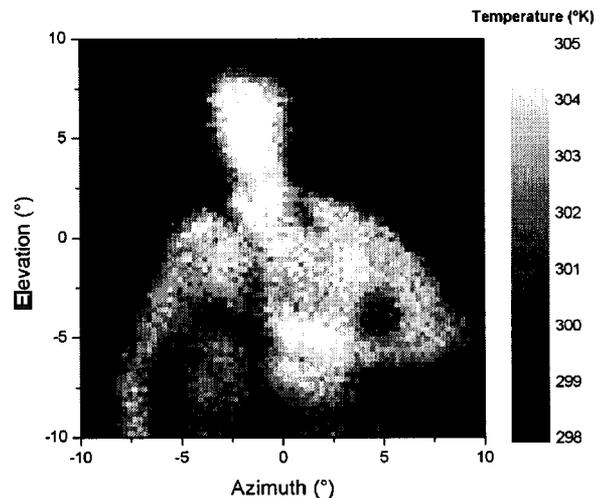


Fig. 2. 0.25° resolution image of body heat passively acquired at 640 GHz. A metal wrench held underneath the shirt can be seen as a dark shadow on the left side.

III. PASSIVE MEASUREMENT RESULTS

The measurement system was tested on an ordinary human subject with a crescent wrench hidden underneath the subject's shirt.

The acquired images were taken with the lock-in amplifier integration time set to 10 milliseconds. At this integration time, 6500 pixels could be acquired in 25 minutes, with an experimental RMS noise level of 0.69 K. This is within a factor of 2 of the prediction from the radiometer equation for a noise temperature of 3600 K double-sideband. The difference is partly explained by the chopping, which effectively halves the observation time in each reading. With the pixel size now less than the beam diameter, another scan was performed with the subject holding a crescent wrench underneath his shirt. Fig. 2 clearly reveals a "cold" object (around 299 K) in an area normally at 303-305 K. Fabric layers in the middle of the shirt (around -2 to -3° azimuth) can also be seen.

IV. ACTIVE MEASUREMENT SYSTEM

In order to enhance the ability to image hidden objects, particularly in outdoor areas where the ambient temperature is greater than body temperature, an active illumination source consisting of a 150-watt ceramic infrared heat emitter [7] was placed above and in front of the objects. This heat emitter has good emissivity in the submillimeter range, with a measured noise temperature very close to its physical temperature. The chopper wheel

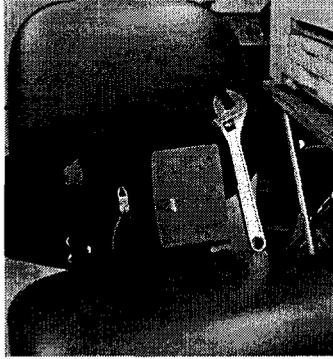


Fig. 3. Inanimate objects used for active imaging experiment.

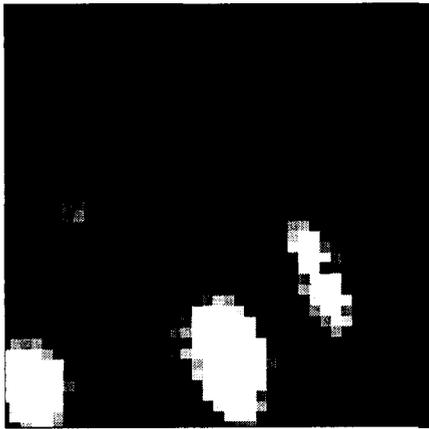


Fig. 4. Composite of 4 scans at different illumination/receiver beam incidence angles. Although not recognizable, 3 of the 4 objects are visible.

was also moved in front of the heat emitter so that only energy reflected from the scene would be detected by the receiver.

Initial measurements revealed that there was insufficient power reflected from the heat emitter off of the subject and into the receiver beam for adequate imaging. This was largely due to the use of a quasi-point source for illuminating the subject. Although a more distributed source was not available, one could be simulated by summing several images acquired at different angles of incidence, and by increasing the integration time. Because of the longer acquisition time, the human subject was replaced by a set of inanimate objects, which were placed in a chair rotated at different angles for each scan. At 1 second integration time, each scan took about 2 hours even with the number of pixels in the image reduced from 6500 to 1680.

VII. CONCLUSION

A single-pixel scanned 640 GHz receiver has been successfully used to passively image individuals. Objects hidden underneath clothing are clearly visible. Improvements to the focusing mirror should dramatically improve the image resolution. The time required to acquire an image could be drastically reduced if an array of receiver channels were to be built, and video frame rates could be achieved if the number of channels was high enough to allow an unscanned "staring" operating mode. Additionally, active imaging using a chopped noise source has been investigated for the purpose of detecting contraband in conditions of high ambient temperature. It is anticipated that the use of a more distributed blackbody noise source for illuminating the subject will yield results comparable in resolution and speed to the passive images.

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