Concealed explosive detection on personnel using a wideband holographic millimeter-wave imaging system

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ABSTRACT

A novel wideband millimeter-wave imaging system is presently being developed at Pacific Northwest National Laboratory (PNNL) that will allow rapid inspection of personnel for concealed explosives, handguns, or other threats. Millimeter-wavelength electromagnetic waves are effective for this application since they readily penetrate common clothing materials, while being partially reflected from the person under surveillance as well as any concealed items. To form an image rapidly, a linear array of 128 antennas is used to electronically scan over a horizontal aperture of 0.75 meters, while the linear array is mechanically swept over a vertical aperture of 2 meters. At each point over this 2-D aperture, coherent wideband data reflected from the target is gathered using wide-beamwidth antennas. The data is recorded coherently, and reconstructed (focused) using an efficient image reconstruction algorithm developed at PNNL. This algorithm works in the near-field of both the target and the scanned aperture and preserves the diffraction limited resolution of less than one-wavelength. The wide frequency bandwidth is used to provide depth resolution, which allows the image to be fully focused over a wide range of depths, resulting in a full 3-D image. This is not possible in a normal optical (or quasi-optical) imaging system.

This system has been extensively tested using concealed metal and plastic weapons, and has recently been tested using real plastic explosives (C-4 and RDX) and simulated liquid explosives concealed on personnel. Millimeter-waves do not penetrate the human body, so it is necessary to view the subject from several angles in order to fully inspect for concealed weapons. Full animations containing 36 - 72 frames recorded from subjects rotated by 5-10°, have been found to be extremely useful for rapid, effective inspection of personnel.

Keywords: Explosive detection, weapon detection, millimeter-wave imaging, surveillance

1. INTRODUCTION

Improved weapon detection technologies are critically needed to counter the threat of modern weapons at high-security locations. At this time, personnel screening security systems rely heavily on metal detectors and X-ray imaging systems (for carried items). Metal detectors are insufficient for screening modern threats, which may include plastic and liquid explosives, plastic or ceramic guns and knives, as well as traditional metal guns and knives. X-ray imaging is effective for screening carried items. Technology that allows low-power X-ray imaging of personnel is being developed, however, it may not be allowed due to real or perceived health threats of ionizing X-ray radiation[1,2].

Millimeter-wave imaging provides an alternative to X-ray imaging for personnel screening. Millimeter-waves are electromagnetic waves generally between 30 and 300 GHz with wavelengths ranging from 1 to 10 mm. This wavelength is quite long compared to optical wavelengths, which allows the waves to penetrate many optically opaque materials, such as common clothing materials. Millimeter-waves are typically reflected by the human body and by metals. Dielectric materials such as plastics, ceramics, and organic materials will cause some reflection of the waves, and some transmission, so they will

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be seen as partially transparent. Millimeter-waves are non-ionizing, and effective imaging systems can be operated at extremely low power levels. The IEEE standard for power density levels in this frequency range is less than 10 mW/cm^2. Our imaging system operates at power levels 2-3 orders of magnitude lower than this standard.

In this paper, results obtained using a wideband, millimeter-wave, holographic imaging system are presented. This system uses active millimeter-wave illumination to form high resolution fully-focused three-dimensional images of the person being screened. The imaging system uses coherent illumination and detection (magnitude and phase) of the scattered wavefront. This wavefront is then mathematically focused (or reconstructed) to form a full 3-D image[3-6]. Three-dimensionality is required in this application because a high-resolution millimeter-wave imaging system will have a very short depth of field due to the low F-number of the system (less than F-1). The human body is not flat, therefore, without wideband (3-D) operation, it is impossible to obtain an image in which all of the body is in focus at the same time. Wideband imaging allows for three dimensional imaging through the range resolution of the wideband system, which allows each depth to be in complete focus.

There are alternative imaging systems which have been proposed for this application. Low-power X-ray backscatter imaging systems have been developed and are effective systems[1,2]. These systems are relatively large and expensive (as is the millimeter-wave technology) and make use of ionizing radiation which may hamper their acceptance. An alternative millimeter-wave imaging technology has also been proposed[7,8]. This system uses a millimeter-wave imaging array placed at the focal-plane of a lens, and operates in a manner analogous to optical video cameras. This system has been proposed in both active and passive implementations. This configuration is conceptually appealing, but may not possess the high-resolution of a full-body aperture system such as described in this paper.

2. PROTOTYPE IMAGING SYSTEM

A millimeter-wave imaging system has been developed for the FAA as a prototype for personnel screening at airport checkpoints. This system is fully-functional, but is not yet intended to handle full passenger throughput. A block diagram of the imaging system is shown in Figure 1. A 128 element linear switched antenna array is supported within a 2 meter vertical high-speed scanner. A transceiver creates the wideband illumination and measures the magnitude and phase of the scattered wavefront. An interface board controls the timing and the synchronization of the system with the computer. Data from the transceiver is digitized using an A/D converter and transferred to the computer. After a full aperture of data is collected, the computer reconstruction algorithm (developed at PNNL) is used to focus the data into a 3-D image. The 3-D data set is then collapsed into a single 2-D fully-focused image which is displayed on the computer. Table 1 shows many of the relevant specifications of the millimeter-wave imaging system.

A photograph of the prototype imaging system is shown in Figure 2. A close-up of the 128 element (27 - 33 GHz) millimeter-wave array with transceiver and interface electronics is shown in Figure 3. The transceiver uses two voltage controlled oscillators (VCO's) offset from each other by an intermediate frequency (IF). One oscillators' output is frequency doubled (to 27 - 33 GHz) for transmission, while the other oscillator is frequency doubled and used to provide the local-oscillator (LO) signal. This LO is used to down-convert the receive millimeter-wave signal to the IF frequency, which is subsequently down converted to baseband to yield the in-phase signal (I). This signal contains the amplitude and phase of the scattered wavefront, which is the desired measurement.

The 128 element millimeter-wave array is composed of two sequentially switched 64 element arrays placed back-to-back. One 64 element array is dedicated to transmission of the millimeter-wave signal and is composed of 9 single-pole eight-throw (SP8T) switch modules. The 64 element receive array is identical. The SP8T switch module is fabricated using a fin-line pin-diode configuration in a split-block waveguide structure. An interleaving scheme is used to obtain 127 independent samples of the scattered wavefront across the 0.75m horizontal aperture.

The image reconstruction algorithm has been developed from holographic reconstruction techniques modified from optical holographic, or wavefront reconstruction, techniques[9]. The original implementation of the system shown in Figure 2 utilized a coherent single frequency transceiver. Image reconstruction of this data is completely analogous to the optical reconstruction process used in optical holography, which is why we refer to our imaging system as ‘holographic.’ The single frequency system suffered from a number of shortcomings. The signal from the transceiver was subject to DC drift of the in-phase and quadrature components of the signal, which limited the overall sensitivity of the system. Also, calibration was difficult, particularly with the front cover in place. The primary limitation of the single-frequency imaging system was the limited depth of field. The image could be electronically focused to any specified depth away from the array, however, the image information from other depths would be significantly out of focus. The solution to all of these problems was modifying the system to operate over a relatively wide frequency bandwidth. The in-phase (I) and quadrature (Q) signals are then AC in nature and not subject to DC drift. The front cover is range-resolved from calibration or other targets, and can therefore be algorithmically filtered from the remainder of the image. Also, the range-resolution overcomes the limited depth of field limitation by essentially range-gating around each plane to yield a number of focused, range-resolved planes. The 3-D reconstruction algorithm is based almost entirely on Fourier Transforms which are implemented using the FFT algorithm for very high efficiency. Two-dimensional Fourier Transforms are used to decompose scattered wavefronts at each frequency into plane wave components which can be ‘back-propagated’ to form focused images[9-11]. The reconstruction algorithm makes no assumptions about being in the far-field of the target or scanned aperture and makes no Fresnel or Fraunhofer approximations. Therefore, the resolution obtained is essentially diffraction limited. The lateral and range resolutions are approximately

$$\delta_{\text{lateral}} = \frac{\lambda}{2}\left(\frac{R}{L}\right) \tag{1}$$

$$\delta_{\text{range}} = \frac{c}{2B} \tag{2}$$

where λ is the wavelength (center frequency), R is the distance to the target, L is the aperture length, c is the speed of light, and B is the bandwidth. For the 27 - 33 GHz imaging system, this corresponds to resolution of approximately 0.5 cm lateral and 2.5 cm depth. The depth resolution is not shown in typical imagery, however, it must be comparable to the depth of field for the image to be completely focused.

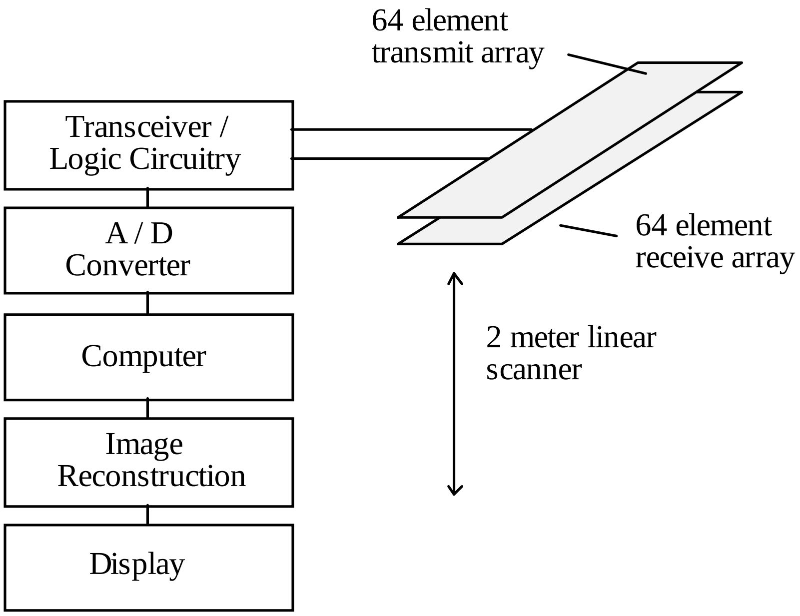

Figure 1 Block-diagram of the wideband millimeter-wave imaging system.

Table 1: Millimeter-wave imaging system specifications	
Frequency range	27 - 33 GHz
Wavelength (30 GHz)	1.0 cm
Number of elements	128
Resolution	0.5 - 1.0 cm
Lateral aperture	0.75 m
Vertical aperture	2.0 m
Scan speed	1.0 second

Figure 2 Prototype wideband millimeter-wave imaging system.

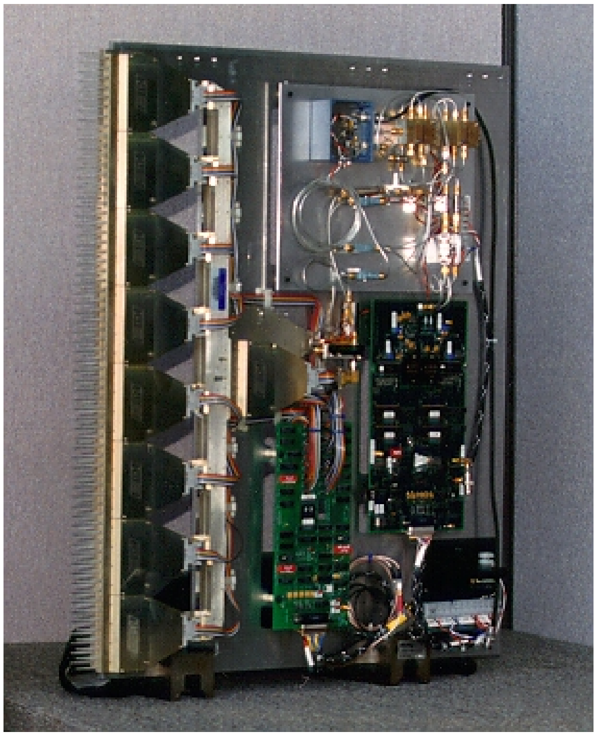

Figure 3 128 element, 27 - 33 GHz millimeter-wave linear array.

3. IMAGING RESULTS

The wideband millimeter-wave imaging system described in the previous section has been extensively tested for personnel screening using a wide variety of concealed weapons and innocuous items. All of the following imaging results were obtained in near real-time (1-2 second scans) using the system described in the previous section.

Figure 4 shows six wideband (27 - 33 GHz) images of a man carrying two concealed handguns as well as several innocuous items. The first image shows a Glock-17 handgun tucked at the belt line under the man's shirt. The second image shows a small handgun in the man's left pants pocket. The third image shows a vinyl/paper checkbook in the left back pocket. The fifth image shows a leather wallet in the man's right back pocket.

Explosive detection is of critical importance for personnel screening applications, since relatively small amounts of explosives can be used to cause considerable loss of life. In this section, the millimeter-wave system was used to image personnel with a number of real and simulated explosives. In Figure 5, a bag of simulated liquid explosive (liquid dish washing soap) was concealed near the small of the man's back. An optical image and an image of the man without the concealed explosive are also shown in the figure for reference. Figure 6 shows similar imagery, this time a thin sheet of simulated 'plastic' explosive (duct putty) was concealed between the man's shoulder blades.

To determine the effectiveness of using duct putty as a simulated 'plastic' explosive, a comparison test was performed by imaging samples of duct putty placed beside samples of actual explosives RDX and C-4. These images are shown in Figure 7. The overall reflectivity of the duct putty is comparable to that of both real explosives. The primary difference in the images is that the duct putty images show coarser texture than the real explosive images. This is because the duct putty was not formed into smooth rectangular blocks as were the RDX and C-4.

Figures 8 and 9 show millimeter-wave images of concealed blocks of C-4 and RDX along with optical pictures which depict the location of the concealed explosives. In both of these images the explosive is readily visible near the center of the man's back.

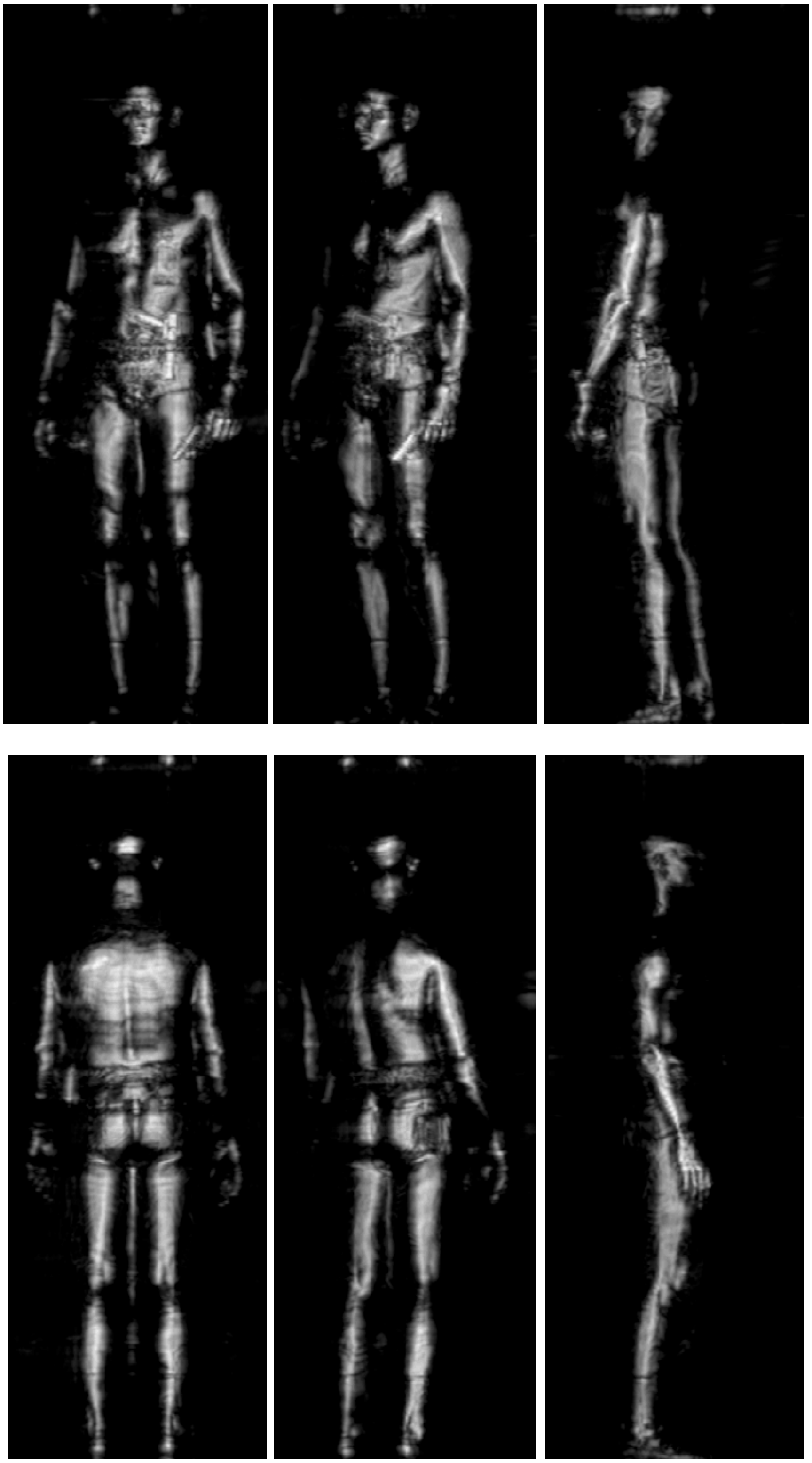

Figure 4 Wideband (27 - 33 GHz) images of a man carrying two concealed handguns along with several innocuous items.

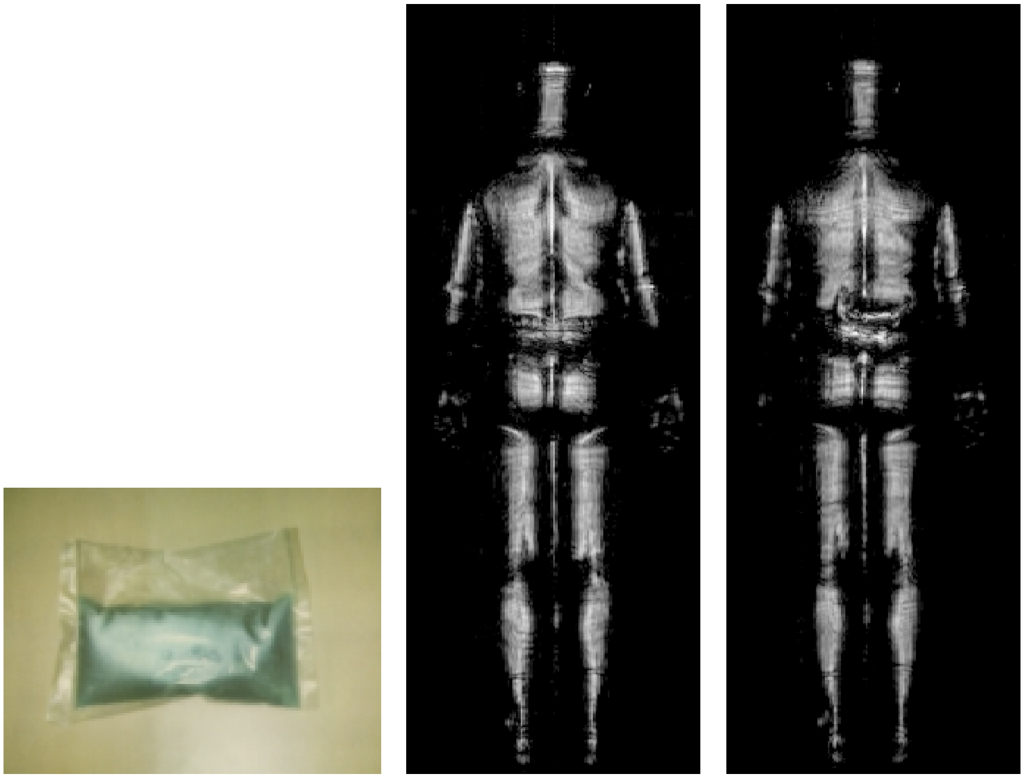

Figure 5 Wideband images of a man with a concealed liquid explosive near the small of the back. (a) Explosive simulant (dish washing soap) (b) Millimeter-wave image with no explosive (c) Millimeter-wave image with explosive.

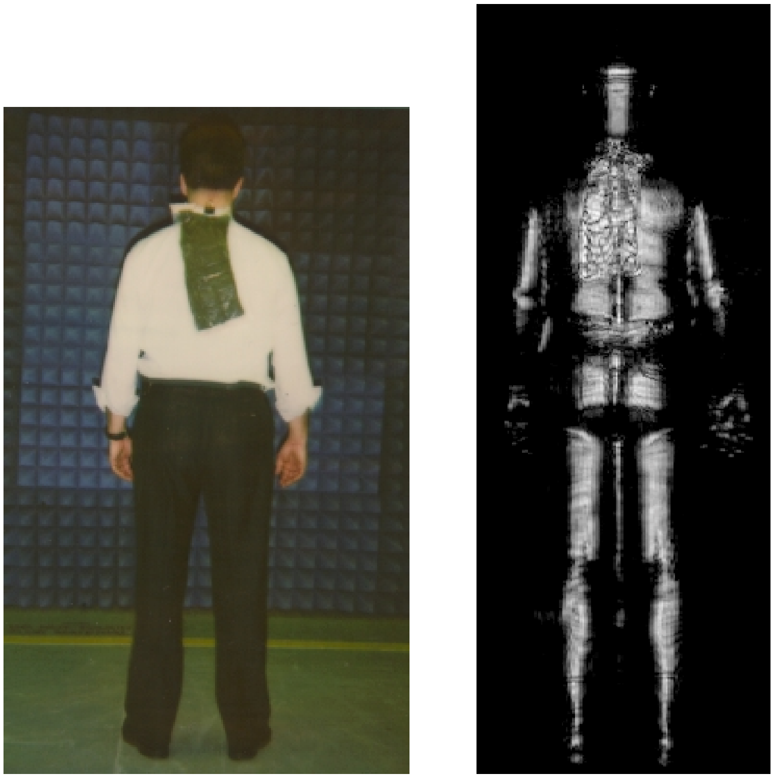

Figure 6 Wideband (27 - 33 GHz) image of a man with a thin sheet of simulated plastic explosive between his shoulder blades. (a) Optical picture (b) Millimeter-wave image.

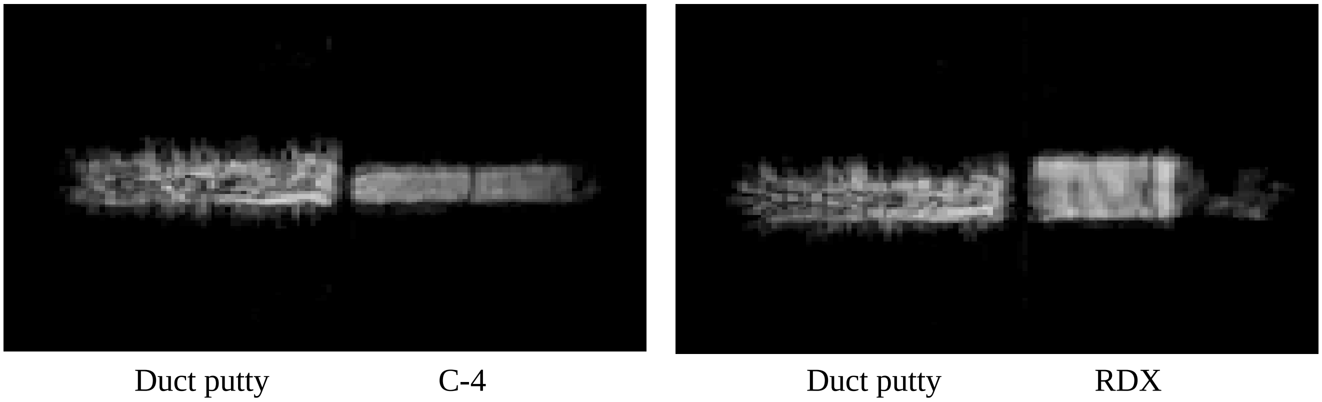

Figure 7 Comparison of wideband images of C-4, RDX, and ordinary duct putty.

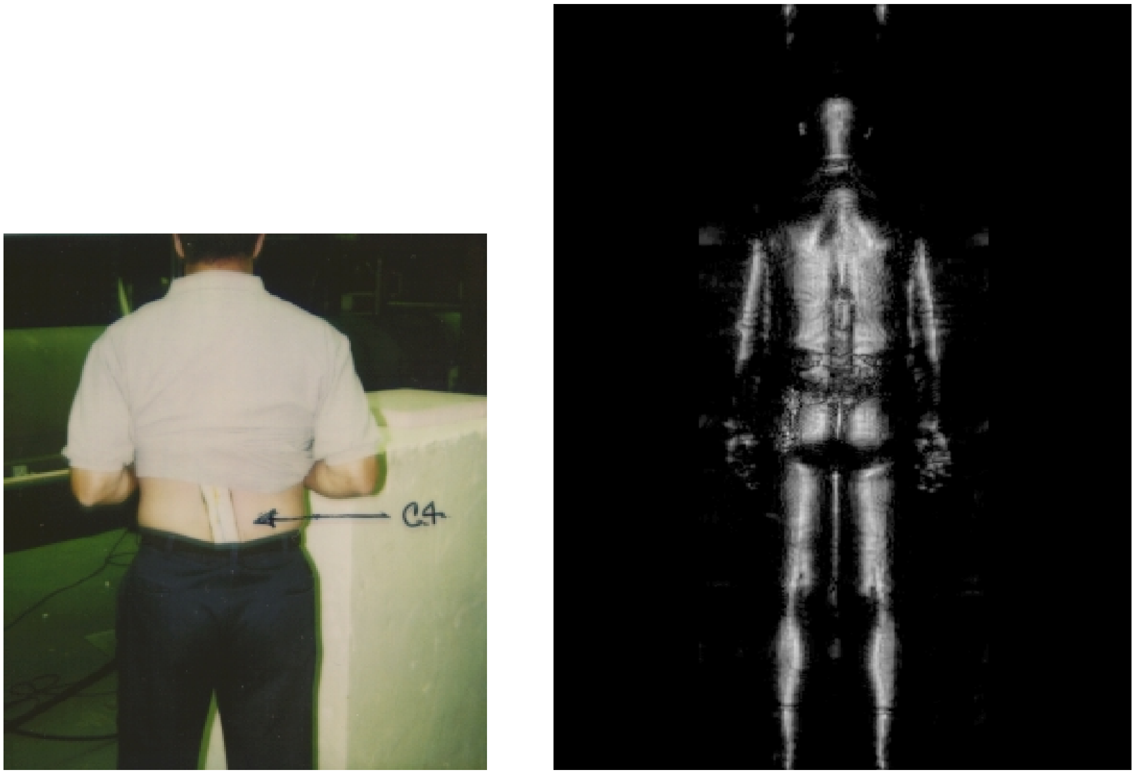

Figure 8 Wideband (27 - 33 GHz) images of a man carrying a concealed block of C-4 ‘plastic’ explosive near the center of his back. (a) Optical picture (b) Millimeter-wave image.

Figure 9 Wideband (27 - 33 GHz) images of a man carrying a concealed block of RDX ‘plastic’ explosive near the center of his back. (a) Optical picture (b) Millimeter-wave image.

4. CONCLUSIONS

High-resolution millimeter-wave images of personnel with concealed explosives have been shown. The millimeter-wave imaging system is very effective for finding concealed contraband of all types. However, the system cannot identify the chemical composition of the material, therefore the operator will not be able to determine specifically that an object is an explosive. The information that is presented is simply an image of the object. The operator must rely on this information to distinguish if this object is suspicious and should be removed for further examination. The millimeter-wave imaging system is also effective for detecting and identifying concealed conventional weapons, such as handguns and knives. These weapons may be metal, plastic, or ceramic. The system is also capable of allowing the operator to distinguish innocuous items, such as eyeglasses, watches, pens, etc., from actual threats.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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