Document Title:	**Raytheon's Approach to a Passive mmW High-Throughput Concealed Weapons Detection Portal**
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Raytheon's Approach to a Passive mmW High-Throughput Concealed Weapons Detection Portal

Technical Report – Phase I

September 2007 - November 2008

ABSTRACT

Raytheon addresses law enforcement's concealed weapons detection (CWD) problem in the enclosed two-phased approach. Previous RVS efforts in millimeter wave (mmW) detector development afford us a strategic position for the development of a low-cost passive mmW high-throughput CWD imaging portal for venue security.

Using internal funding, Raytheon developed unique COTS mmW detectors with a Noise Equivalent Temperature of sub-20K using COTS technology in the 75 to 140 GHz band. The goal of Phase I is to the existing detectors to demonstrate imaging of concealed weapons/objects such as razor blades, knives, and guns from an 8 element linear array using our high-performance, high frame rate, and highly sensitive commercial-off-the-shelf (COTS) mmW detectors. Raytheon's detector technology is based upon the combination of individual micro-antennas monolithically integrated into each pixel with a high-speed COTS direct detector fabricated by our small business partner Microwave Device Technologies (MDT). This combination of technologies provides a direct path to low-cost production, using both of our existing facilities. Advantages of our approach include:

- Based on Established Low-Cost, COTS Sensors
- Small Size, High Speed, and Sensitivity
- Entirely Passive
- No Radiation Emitted
- Covert: No Signal to be Detected by Suspects
- Monolithic Chip (similar to a mega-pixel digital camera)
- Real-time High Frame Rate Imaging - Automated or Operator Recognition
- Operational from 75 to 400 GHz providing >10× improved resolution
    - Comparable technologies operate from 27 to 38 GHz

PROGRAM PURPOSE

The overall purpose of this program is to provide to law enforcement personnel an affordable, high-throughput covert passive imaging system with sufficient sensitivity, resolution, and scan speed to rapidly and accurately detect concealed weapons including knives, razor blades, guns, bullets, and explosives.

STATEMENT OF RESEARCH PROBLEM

Our low-cost, light weight, and uncooled mmW detectors demonstrated using internal funding, provides excellent propagation through clothing and the atmosphere, and excellent sensitivity for the detection of concealed weapons using a low-cost COTS solution. The only remaining challenge is the development of a high-speed imaging system for use in a real-time high-throughput CWD imaging portal.

RESEARCH GOALS AND PROGRAM OBJECTIVES

Our objective is to demonstrate the feasibility of our detectors for the potential use in a high-throughput CWD imaging system which meets the requirements set forth in the NIJ SL 000757 document. The end-result of the Raytheon CWD imaging system will meet or exceed the primary requirements including providing law enforcement officials with a walk-through portal with the following attributes: capable of screening 4000 individuals within 1 hour while minimizing the amount of second scans required; operational within 24 inches of the subject; posing no health hazard to the operator or the subject; real-time concealed weapons detection; detection of small concealed objects (3/4 inch) such as razor blades or bullets; and costing less than $10,000.

This program is a two-phase 24 month program. RVS is currently under contract to perform a laboratory demonstration of our passive mmW detector technology. The program initiated on September 3, 2008. The Phase I schedule is shown in Figure 1.

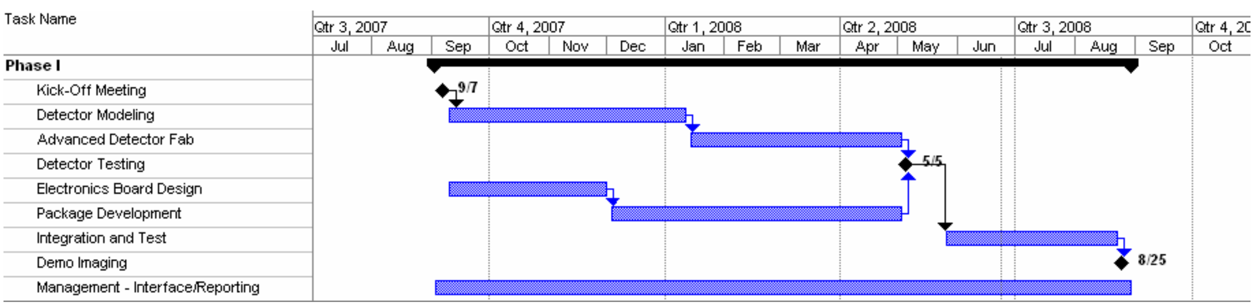

Figure 1. Phase I Schedule.

In order to meet the program goals, RVS performed an imaging demonstration using an 8-channel step-scan system. The target was scanned across the field-of-view using a set of motorized stages. RVS modeled three different antenna designs to ensure the program objectives were met.

PHASE I ACCOMPLISHMENTS

Modeling and Simulation of the mmW Antennas

In Phase I, an advanced electro-magnetic (EM) simulator was used to model the following different antenna designs to optimize the collection of radiation from 75 to 140 GHz:

- Square spiral
- Log-periodic
- Folded dipole

Each antenna was chosen to be modeled because of its unique ability to meet the program goals. For instance, the square spiral and log-periodic antennas are broadband antennas designed to collect radiation from 75 to 400 GHz, but require a diode impedance of ~100 Ohms. Remember that our diode dynamic resistance (R_d) is approximately 300 Ohms, so a 100 Ohm load represents a 25% power loss in reflection. Therefore the square spiral and log-periodic designs enable better resolution because of the higher frequency response, but are not ideally matched, which could result in a loss of sensitivity. The folded dipole was chosen because it can increase the load impedance requirement to greater than 300 Ohms, which results in a perfect match/no-loss situation. Since the folded dipole antenna is traditional dipole antenna modified to increase the load impedance enabling more effective collection of the mmW radiation, the antenna is a narrowband and can only operate between 100 to 140 GHz limited the resolution of the system.

The EM simulator was used to determine the antenna patterns, the input impedance, and frequency response of each of the antenna designs. For each antenna design we desired to have a collection angle of 40° to maximize the collection efficiency. The results from the modeling, which are shown in Figure 2, were sent to MDT for fabrication of the parts using there standard process.

Our goal on this program is to achieve passive mmW imaging requiring an extremely sensitive detector. Illuminating thru the substrate enhances the responsivity of the detector by at least 10×[1]. A ball lens or a micro-lens with a precise radius of curvature further enhances the responsivity by improving the collection efficiency of the antenna[2]. Realizing this requirement RVS designed a micro-lens, which could be integrated directly on to the back-side of the substrate using photo-resist. This is accomplished by using a gray-scale mask to form a pattern of the micro-lens. Once the pattern is formed the micro-lens is etched into to the substrate using a reactive-ion-etcher (RIE). This promising technology enables the micro-lens to be fabricated in one easy lithographic step. RVS used a a gray-scale mask procured from Canyon Materials to begin experimenting with this technology. A Veeco optical profiler was used to precisely measure the radius of curvature of the micro-lens pattern formed in the photo-resist. Since the radius of curvature of the micro-lens shown in Figure 3 is not ideal, RVS is currently optimizing the process by varying the exposure time and thickness of the photo-resist.

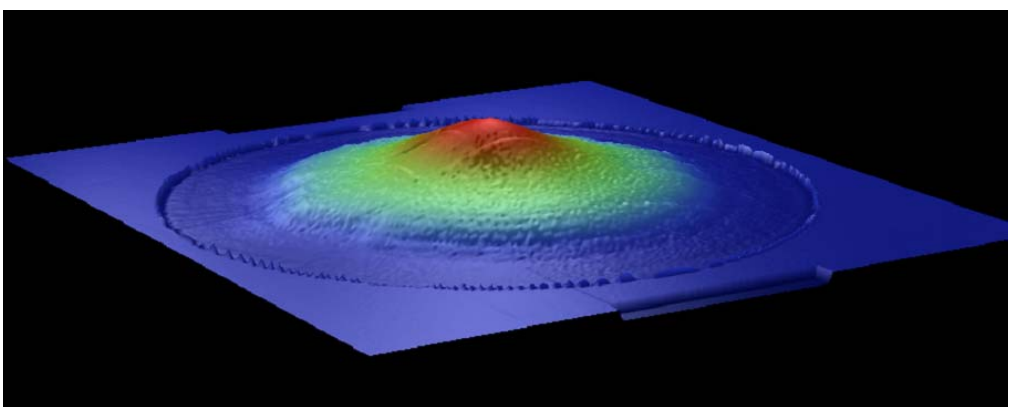

Figure 3. Micro-lens Development. *Resist profile measured with a Veeco optical profiler showing the potential for development of a micro-lens using a gray-scale mask.*

[1] C. Fumeaux, M. Gritz, I. Codreanu, W. Schaich, F.J. Gonzalez, and G. Boreman, "Measurements of the resonant lengths of infrared dipole antennas," *Infrared Physics and Technology*, **41**, 271-281 (2000).

[2] M. Gritz; R. Hernandez; E. Gordon; A. Larussi; G. Zummo; G. Boreman, and L. Chen "Direct detection antenna-coupled mmW sensors for the detection of explosive vapors," SPIE Proceedings – Passive mmW Imaging, **6548**.

Integration and Testing of the mmW Detectors

For Phase I, we proposed two different methodologies to develop and demonstrate mmW imaging. The first possible approach for image generation was to rotate the linear array of detectors at a constant speed in only a single direction [See Figure 4].

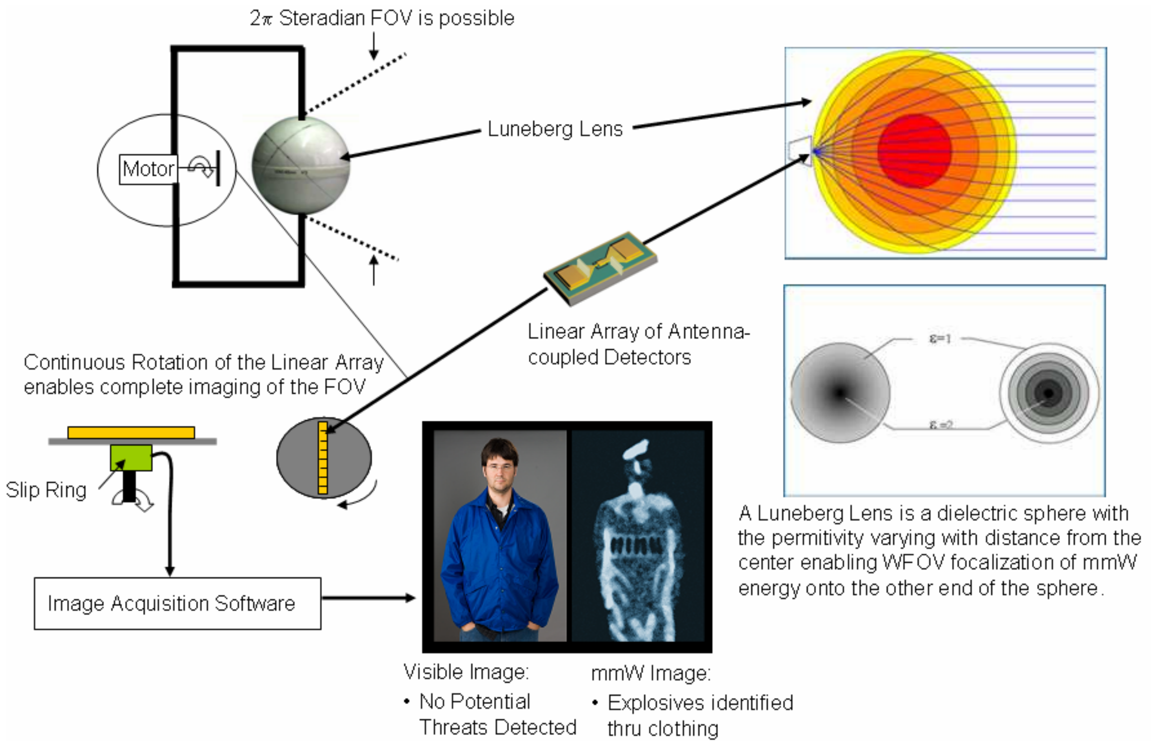

Figure 4. mmW Imaging. *A linear detector continuously rotated enables complete imaging of the FOV captured by the luneberg lens.*

The second approach for a high-throughput CWD imaging system is for the entire detector assembly, which includes a lens and a stationary linear detector array, to step and scan across the suspect standing in the high-throughput CWD imaging portal. Figure 5 depicts this concept.

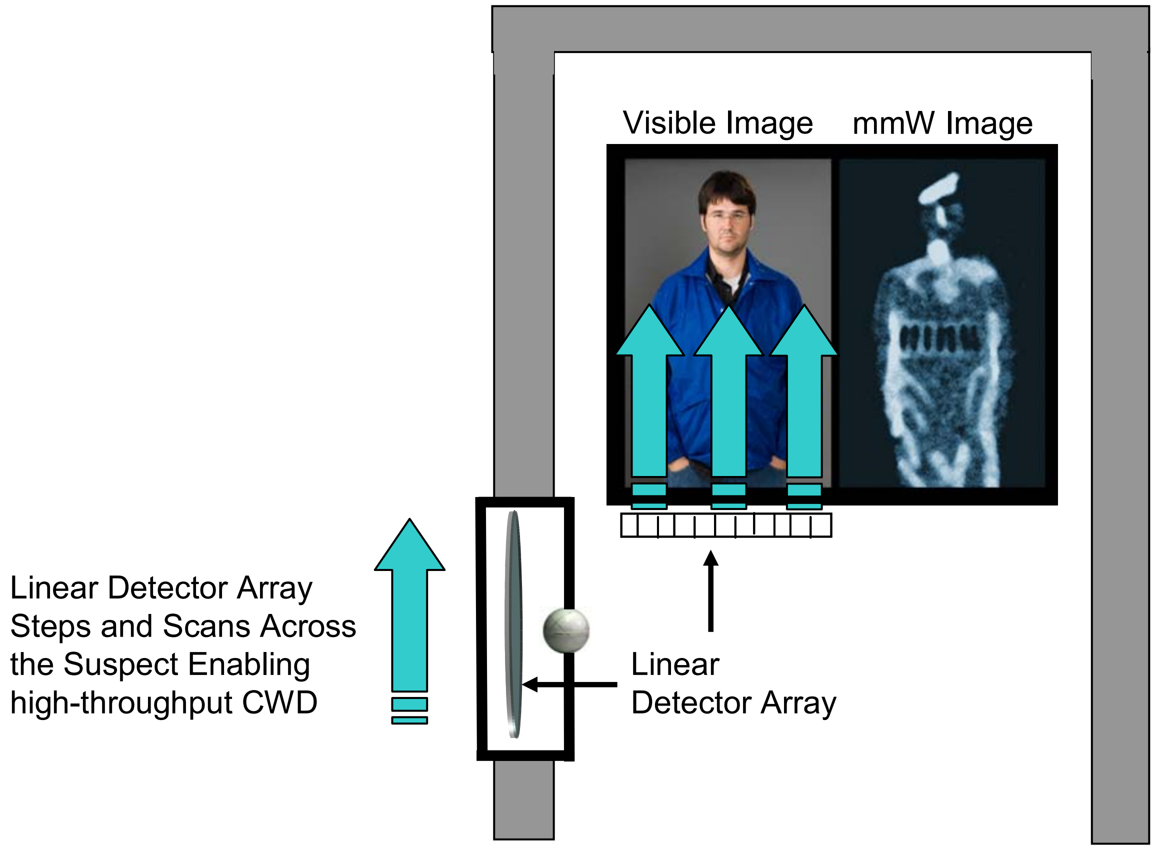

Figure 5. Alternate Approach for a High-throughput CWD Imaging Portal by Stepping and Scanning the Linear Detector Array Across the Suspect.

One significant advantage of the step and scan is that the scan speed and direction can be adjusted, as the scenario requires. For example, the scan speed could adjust, by increasing the scan aspect ratio, to avoid impacting people who are waiting in line for the venue. This scalability increases the utility of the CWD device. Another advantage is there are no rotating parts eliminating the extra complexity associated with a slip-ring. Due to these reasons the second approach was chosen as the method to generate images in the laboratory.

In order to prepare for the imaging demonstration, several key pieces of hardware were procured immediately in order to stay on schedule. First a precision motorized stage with 150mm of travel and micro-controller was purchased from Zaber Technologies (see Figure 6). An 8-channel digital image acquisition system from Pulse Instruments (PI) was purchased (see Figure 7). An 8-channel proto-typing board was modeled and built using COTS operational electronics (see Figure 8). The proto-typing board works by:

1. Using the square wave to electronically modulate the mmW radiation on/off to drive the detectors
2. The modulated signal is used as A clock to synchronize the image acquistion system
3. Mmw radiation is detected by the mmw antenna and converted to DC
4. Signal is amplified by the two-stage pre-amplifier

5. Analog switch synchronizes the amplifiers with the modulated signal and generates on/off signals
6. Differential amplifier takes the difference between the on/off signal and filters the signal in preparation for imaging
7. The PI image acquisition system acquires image based on the period of the modulated signal

Figure 6. Motorized Linear Stage. *A linear stage with a 150 mm of travel procured from Zaber enables the generation of mmW images in the PMMWI laboratory.*

The PI was programmed to generate the clock to both drive the mmW transmitter and the proto-typing board.

Figure 7. Image Acquisition System.

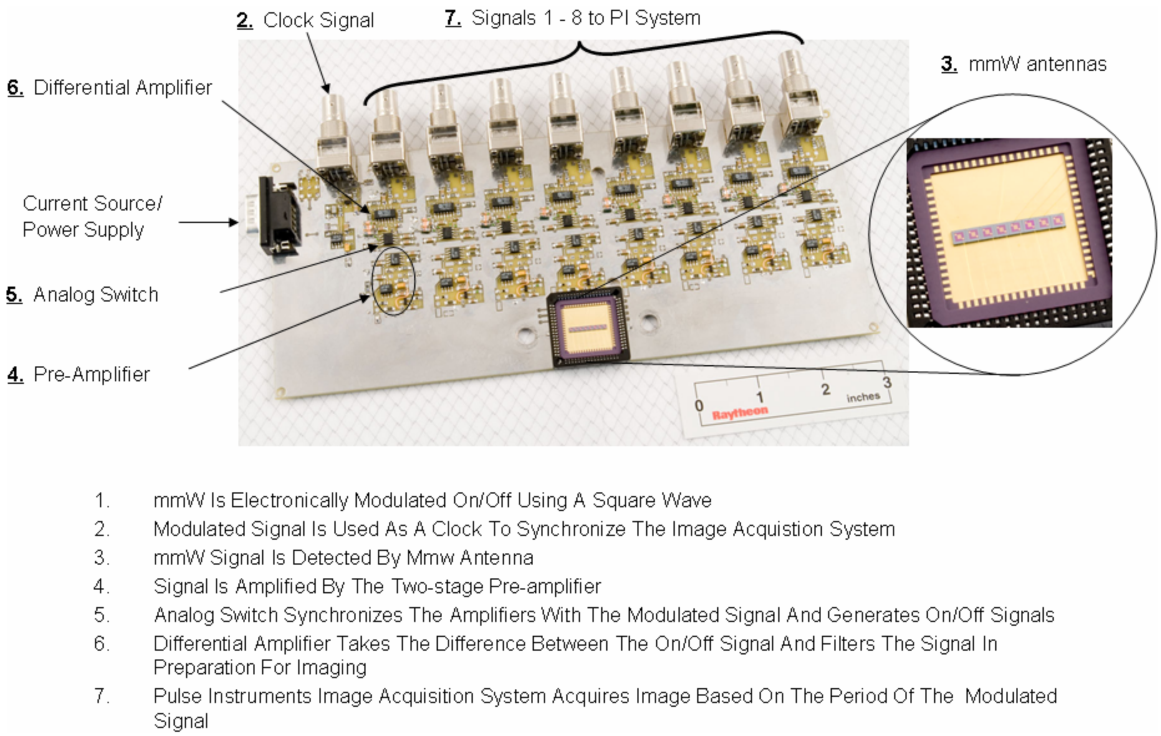

Figure 8. Proto-type Board. *8-channel proto-type built COTS parts to acquire and amplify detector signals.*

Imaging Demonstration

The imaging demonstration of the 8-channel linear array was performed in the PMMWI laboratory at the Raytheon facility in Goleta, California. The 8-channel prototype board was integrated onto an optics bench as shown in Figure 9. A 75 to 140 GHz tunable source was integrated with a 3” collimator to focus the mmW radiation onto the target. The spot size at 130 GHz is approximately 5.6mm, which encompasses 3 of the 2 mm sensors, leaving only 2 pixels of resolution. In order to recognize a target at range at least 6 pixels is usually required. In order to overcome this issue RVS purchased another stage to perform a raster scan. A cut-out of a metal gun was chosen to be imaged first. The Zaber stage is scanned across the field-of-view (FOV) of the 8-channel linear array. An F/1 3” polyethylene focusing lens was placed in front of the detectors to maximize the signal collected by the detectors. The PI image acquisition system computer is used to collect the signals from the detector and convert them to digital information. This first image shown in Figure 10 was generated using an active source. Passive mmW imaging can be accomplished by illuminating thru the GaAs substrate integrated with a micro-lens and an mmW ARC.

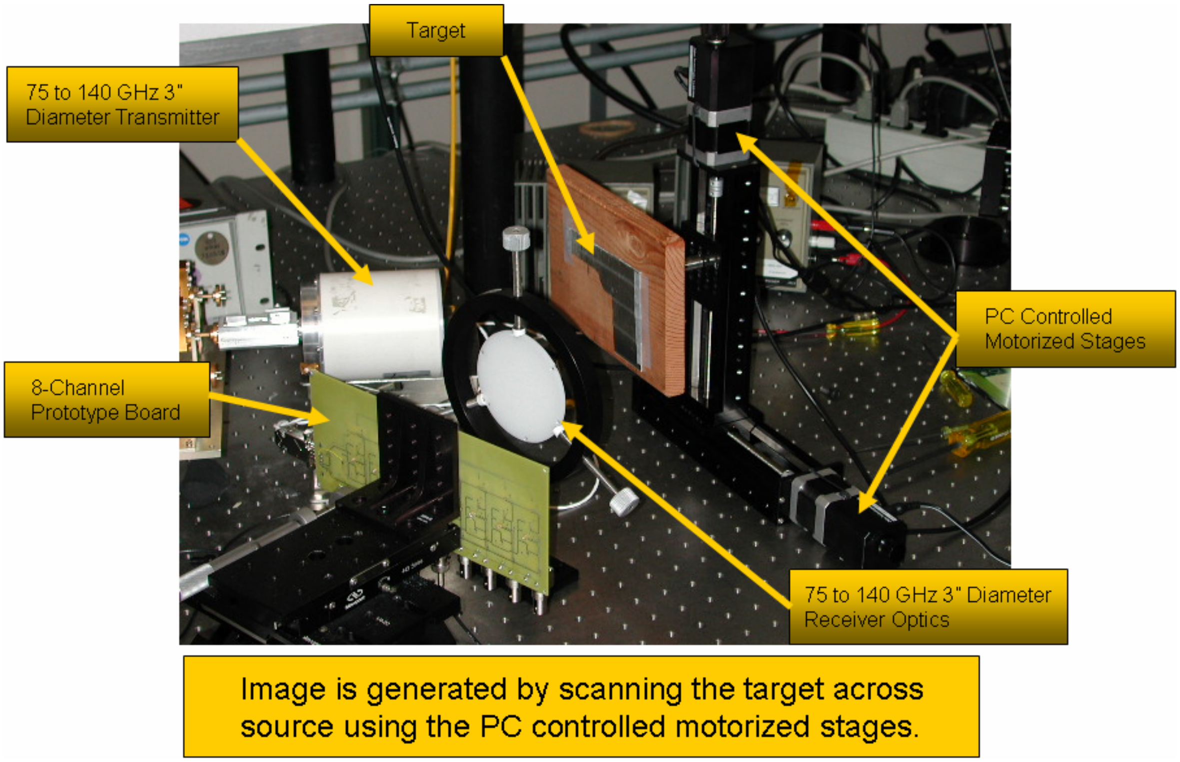

Figure 9. mmW Test Set-up. *8-channel mmW proto-type board integrated onto the Zaber stages in preparation for image generation.*

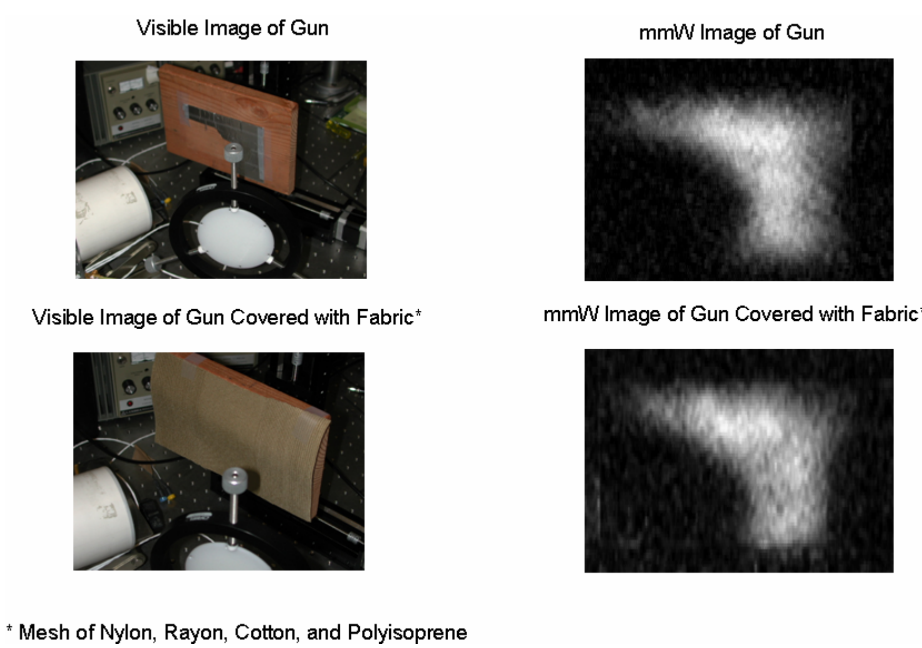

Figure 10. mmW Images. *Demonstration of imaging through clothing using Raytheon's mmW imaging technology.*

SUMMARY

The objective of this first Phase of the program is to demonstrate CWD imaging. Raytheon accomplished this task by building an 8-channel linear array of antenna-coupled mmW detectors. Imagery was generated by scanning the target across the detectors FOV. Table 1-1 compares Raytheon's antenna-coupled mmW camera to a traditional passive mmW camera.

Table 1-1. Comparison of mmW Technologies

	Raytheon's mmW Camera	Traditional mmW Imager
Array Type	2D Staring Array	Line or Single Element Scanner
Image Type	≤ 30 ms	2 to 10 seconds
Cost	$10K (Estimated Cost)	>$100K

In the next phase of this program (if funding is approved), RVS will improve the sensitivity of the devices using micro-lenses and mmW ARC to move towards achieving passive mmW imaging. Additionally a larger linear array with the proper center-to-center spacing will be fabricated eliminating the need for raster scanning. The larger array will also enable imaging of larger targets. Raytheon is currently on track to achieve the end goal of passive imaging at the end of the next Phase of this program. In Phase I, RVS has made the following accomplishments:

- Modeled and fabricated antenna-coupled detectors operating from 75 to 140 GHz
    - Test data indicates detector is operation from 75 to 400 GHz.
- Measured an 25× improvement in the responsivity of the detectors
- Designed, integrated, and tested an 8-channel proto-type board
- Purchased and programmed a PI image acquisition system for generation of images
- Developed calibration and image processing algorithms for final product demo
- Purchased a linear stage with 150mm of travel
- Purchased and designed a gray-scale mask for the fabrication of a back-side micro-lens to achieve the program goal of passive mmW imaging