

# R3-A.3: Multi-Transmitter/Multi-Receiver Blade Beam Torus Reflector for Efficient Advanced Imaging Technology (AIT)

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## II. PROJECT DESCRIPTION

### A. Overview and Significance

We are developing a custom-designed elliptical toroid reflector which allows multiple overlapping beams for focused wide-angle illumination to speed data acquisition and accurately image strongly inclined body surfaces. Building on the concepts and analysis of project R3-A.1, we are extending the Blade Beam Reflector from a single illuminating antenna into a multi-beam Toroidal Reflector, with multiple feeds. Each feed gen-

erates a different incident beam with different viewing angles, while still maintaining the blade beam configuration of narrow slit illumination in the vertical direction. Having multiple transmitters provides horizontal resolution and imaging of full 120 deg. of body. Furthermore, the reflector can simultaneously be used for receiving the scattered field, with high gain, overlapping, high vertical resolution beams for each transmitting or receiving array element. The multistatic transmitting and receiving array configuration sensing avoids dihedral artifacts from body crevices and reduces non-specular drop-outs.

### B. *State-of-the-Art and Technical Approach*

Concealed threat whole-body scanning systems are becoming increasingly prevalent at airports, secure building entrances, and meeting venues. The preferred scanning modality which effectively penetrates clothing but does not produce ionizing radiation is millimeter-wave radar. Portals employ translating transmitters and receivers which illuminate and observe scattered waves from multiple positions to image body surface and any unusual attached objects. Currently employed systems in airports are multi-monostatic, with multiple mm-wave radar transceivers, each using the same antenna for transmission and reception [1, 2]. Well-established Fourier optics theory is used to quickly and effectively process the observed field data and reconstruct body surface profiles. Monostatic imaging is physically limited in imaging, with dihedral artifacts from oppositely-inclined body surfaces, such as the between the legs, between an arm and torso, or between folds of skin which cannot be removed by processing.

Alternatively, multistatic radar sensing avoids the dihedral artifacts because scattered rays are received from many directions simultaneously, rather than only from the spectral direction defined by the surface normal. Multistatic radar is more complicated than monostatic because the receiver electronics is physically displaced from the transmitter, although no transceiver circulators are needed [3-5]. In addition, balancing the compromise between coverage aperture and great numbers of radar antenna elements is challenging. It is important to provide both sufficient element density and array size to yield a high resolution point spread function (PSF), but avoid the financial and computational expenses of dense arrays. One cost-savings approach to a large 2-dimensional array is a reflector that produces a small focal PSF spot at the target position [6]. This prolate spheroidal reflector must be mechanically rotated in two directions to scan across the entire target. If instead the reflector is doubly curved: elliptical in the vertical direction but parabolic in the horizontal direction, it will produce a horizontal focal line on the target [7]. The reflector would only be translated vertically to scan a 2D target, and all processing would be performed on separate 2D slices of data, and stacked to form the reconstructed target surface [8-10]. Reflectors are wideband, inexpensive and lightweight, but to illuminate different regions around the target, multiple reflectors must be used, which presents a problem of careful spacing to avoid overlapping.

### C. *Major Contributions*

A solution to the multiple reflector problem is to smoothly blend several adjacent reflectors into an elliptical toroidal reflecting surface. This surface is generated by rotating a vertical ellipse about a vertical axis. For limited illumination, the circular variation in the horizontal direction approximates parabolic curvature. The feed positions pass through the primary ellipse focus on an arc, also centered on the reflector axis of rotation. The radius of this arc is about half of the reflector radius, but must be numerically optimized for the offset geometry. Multiple feeds on the feed arc can generate non-interacting overlapping illumination patterns on the reflector which in turn generate separate transmit beams. In addition, the same reflector can be used for received signals with receiving elements placed along the feed arc in-between transmitting elements. The reflector is a sufficiently offset ellipse section, to prevent any feed blockage of the aperture.

The equation for an ellipse with major axis ( $2a$ ) tilted at an angle  $\alpha$  relative to the horizontal ( $y$ -axis) with a fixed target focal point at  $(y, z) = (r_s, 0)$  and with minor axis  $2b$  is:

$$Az^2 + By^2 + Czy + Dz + Ey + F = 0$$

where:

$$\begin{aligned}
 A &= -b^2 - c^2 \cos^2 \alpha \\
 B &= -a^2 + c^2 \cos^2 \alpha \\
 C &= -2c^2 \cos \alpha \sin \alpha \\
 D &= 2c(b^2 + c r_s \cos \alpha) \sin \alpha \\
 E &= 2(a^2 r_s - c \cos \alpha (b^2 + c r_s \cos \alpha)) \\
 F &= -a^2 r_s^2 + (b^2 + c r_s \cos \alpha)^2
 \end{aligned}$$

An example of this offset ellipse with primary feed focus at  $(-55, -17.78)$ , a secondary target focus at  $(r_s, 0)$ ,  $r_s = -15$ ,  $\alpha = 0.418$  rad,  $a = 72.8$ ,  $b = 71.97$ , and  $c = 10.94$  is shown in Figure 1. The selected section of the ellipse provides  $\pm 0.40$  rad of view angle at the target focal point. Note that no reflected rays are blocked by the feed.

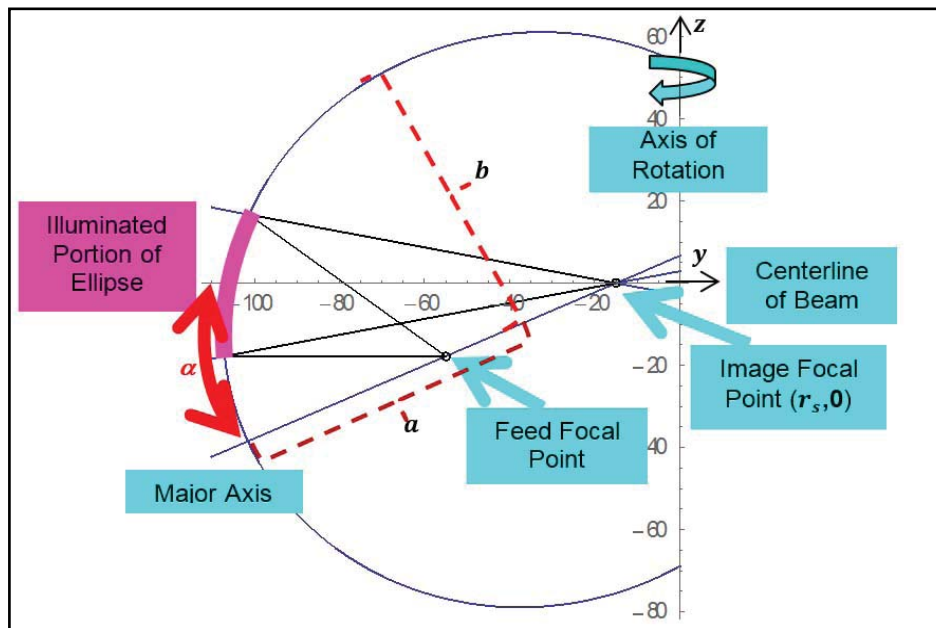


Figure 1: Ellipse section with major axis tilted by  $\alpha$ , with foci and top and bottom ray paths. Units in cm.

The ellipse is rotated about the vertical  $z$ -axis from  $-\pi/3$  to  $\pi/3$ , which can be stated mathematically by merely replacing  $-y$  with the cylindrical radius  $\rho$ , as displayed in Figure 2 on the next page. Figure 3 on the next page shows a top view, indicating the focal arc and simplified target contour with incident field intensity due to illumination from an open ended waveguide feed at 60 GHz.

The reflector surface illumination and projected elliptical cylinder target PSF, computed using Physical Optics are shown in Figure 4 on the following page. Note that for all feed cases: 0, 15, 30, and 45 deg., the target PSF is a short, wide slit, which both concentrates the power on the particular region of interest, and allows for 2D reconstruction of one short slit at a time. Although the target has varying depth and width, the PSF is uniform and consistent for all angles. The received signal scattered from the target back to the reflector and then to receiving elements on the focal arc behaves analogously to the transmitted signal.

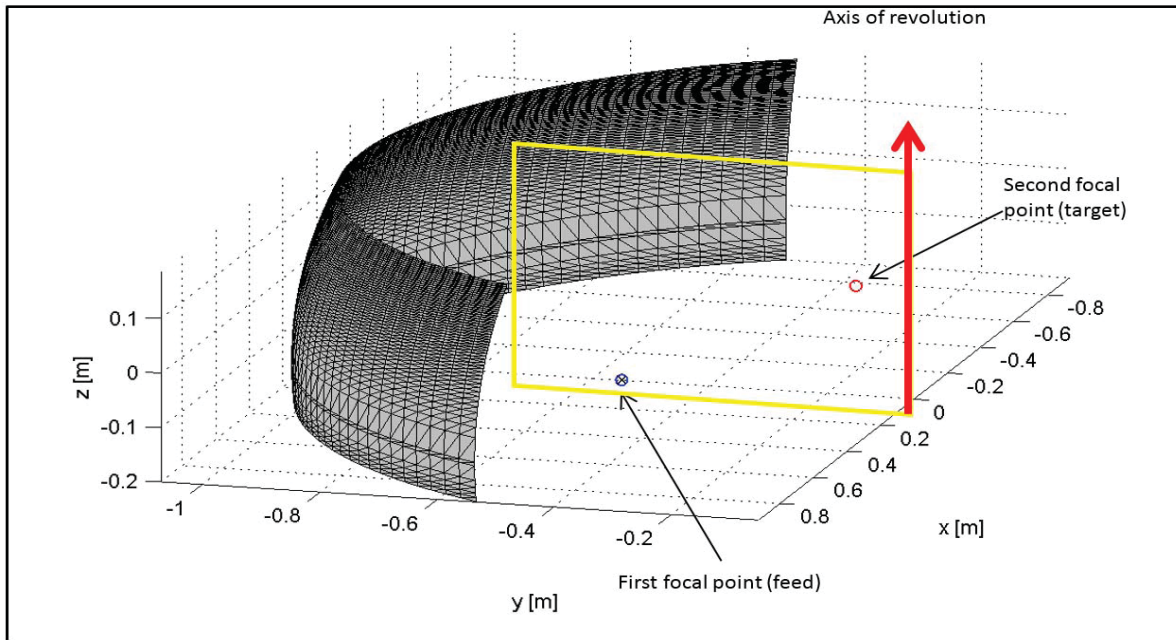


Figure 2: View of offset elliptical torus blade beam reflector surface with focal points and axis of rotation.

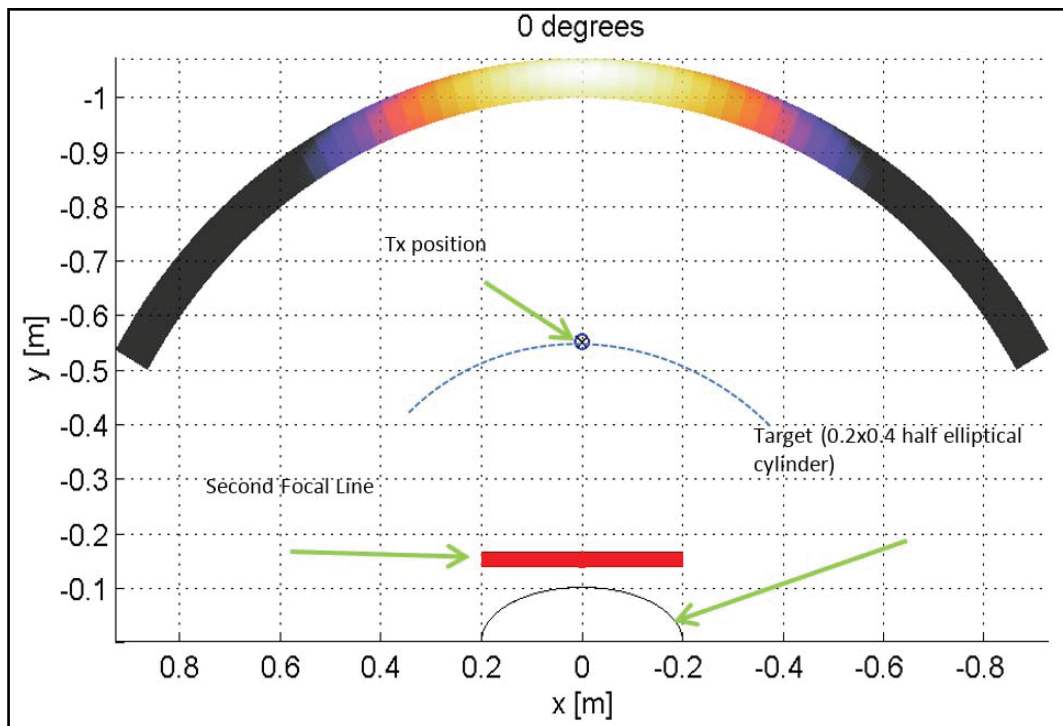


Figure 3: Top view of illuminated reflector, showing feed arc, torso target shape, and secondary focal line for central beam.

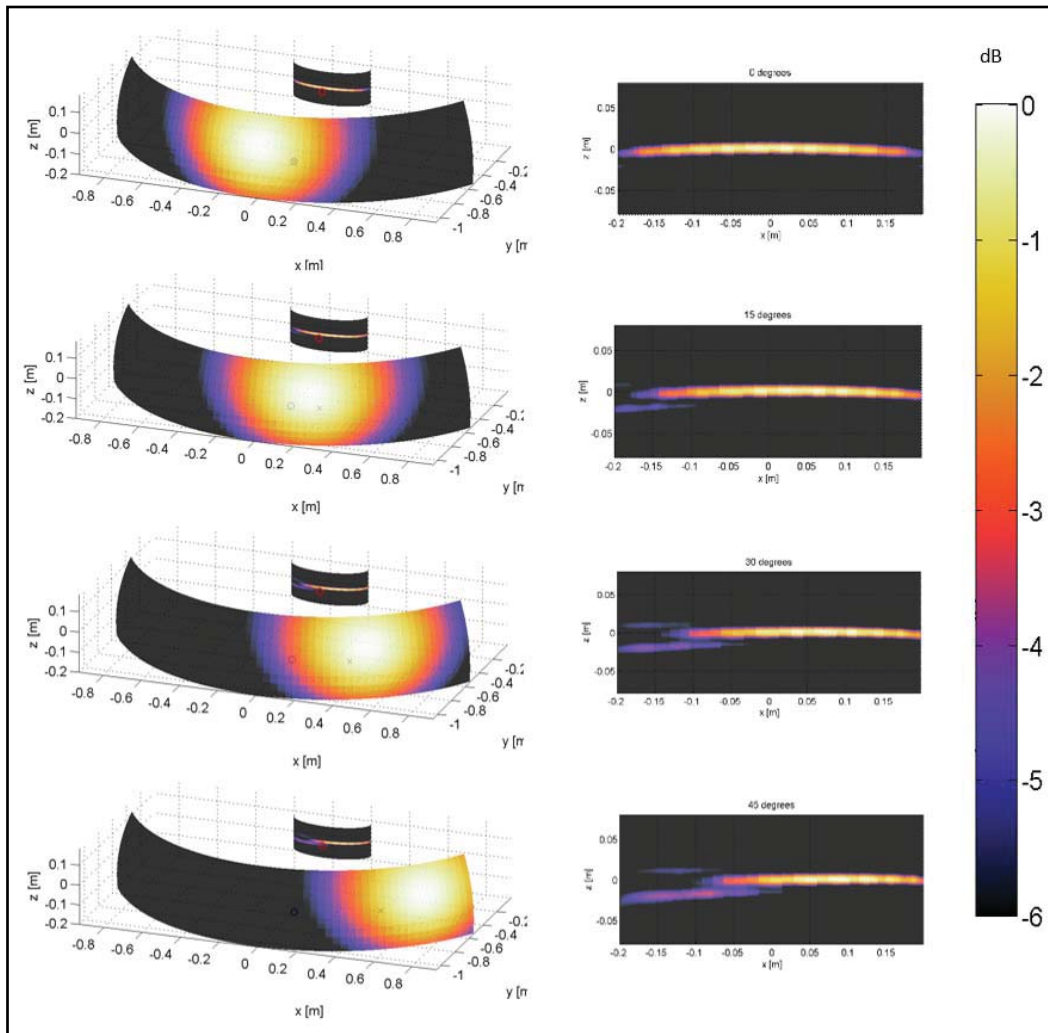
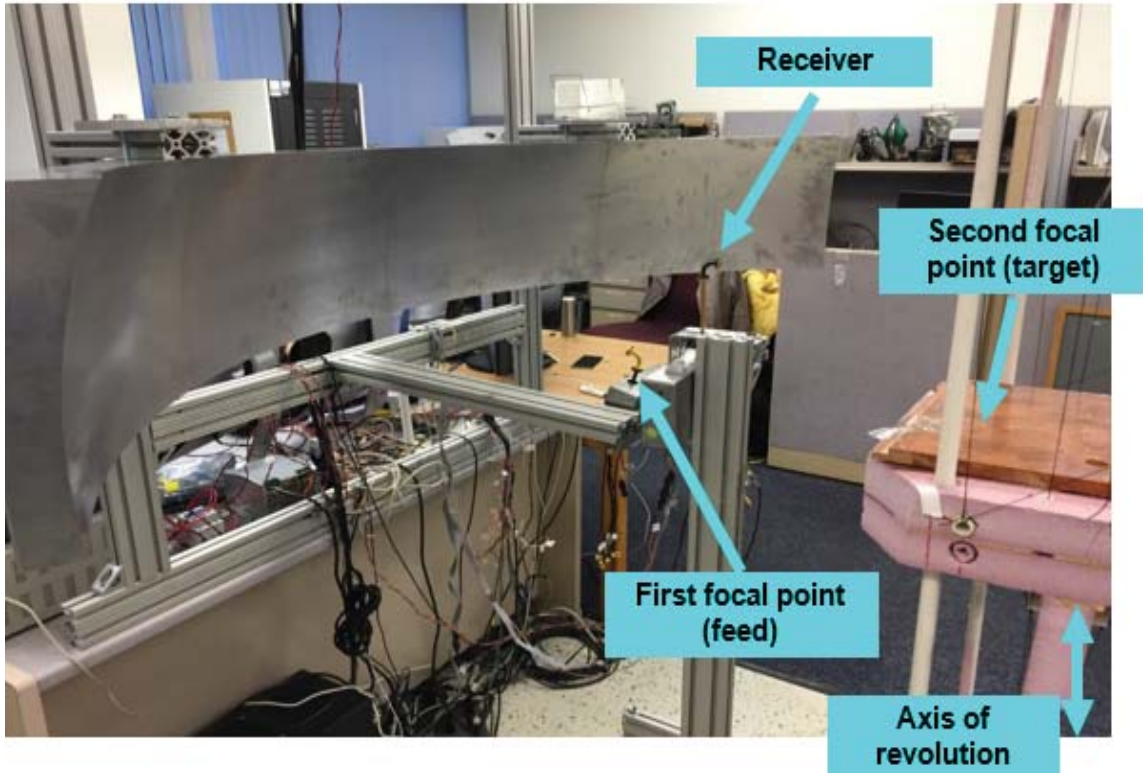


Figure 4: Reflector illumination (right) and torso target PSF (left) for 0, 15, 30, and 45 deg. beams.

Figure 5 on the next page shows the reflector as built with a waveguide feed on the primary focal point arc, facing the reflector, and the vertically-translating target platform at the second (image) focal point. The receiver waveguide is also on the focal arc, but in this instance is pointing towards the target region. Normally the receiver would also point toward the reflector. The reflector was fabricated using a computer numerically controlled mill, in four identical sections, each encompassing 30 deg. of circular arc. The sections are carefully aligned and bolted together, with seam error (as well as overall surface roughness) less than 0.2 mm. The entire reflector weighs roughly 35 kg. Additional reflector surfaces with 0.2 surface accuracy can now be cast from this aluminum form. Resin layups can be formed to be both thin and strong, and would weigh a fraction of the aluminum reflector. Thus the eventual implementation would be lightweight and easy to mount and move.

One important aspect of this reflector configuration is the alignment of the feeds. Although high quality reflected beams are formed when the reflector is illuminated by feeds positioned at any point along the focal arc, the accuracy of the feed position is critical. The feed must be positioned at the correct height (exactly on the plane of the bottom of the reflector, at the precise distance from the reflector, and be pointing perpendicularly to the reflector). This alignment need only be done once, but must be accurate to  $1/20^{\text{th}}$  of a wavelength, or 0.25mm. We do this alignment electronically, scanning a receiver across the target region to map the reflected beam intensity, and adjusting the feed position to optimize.

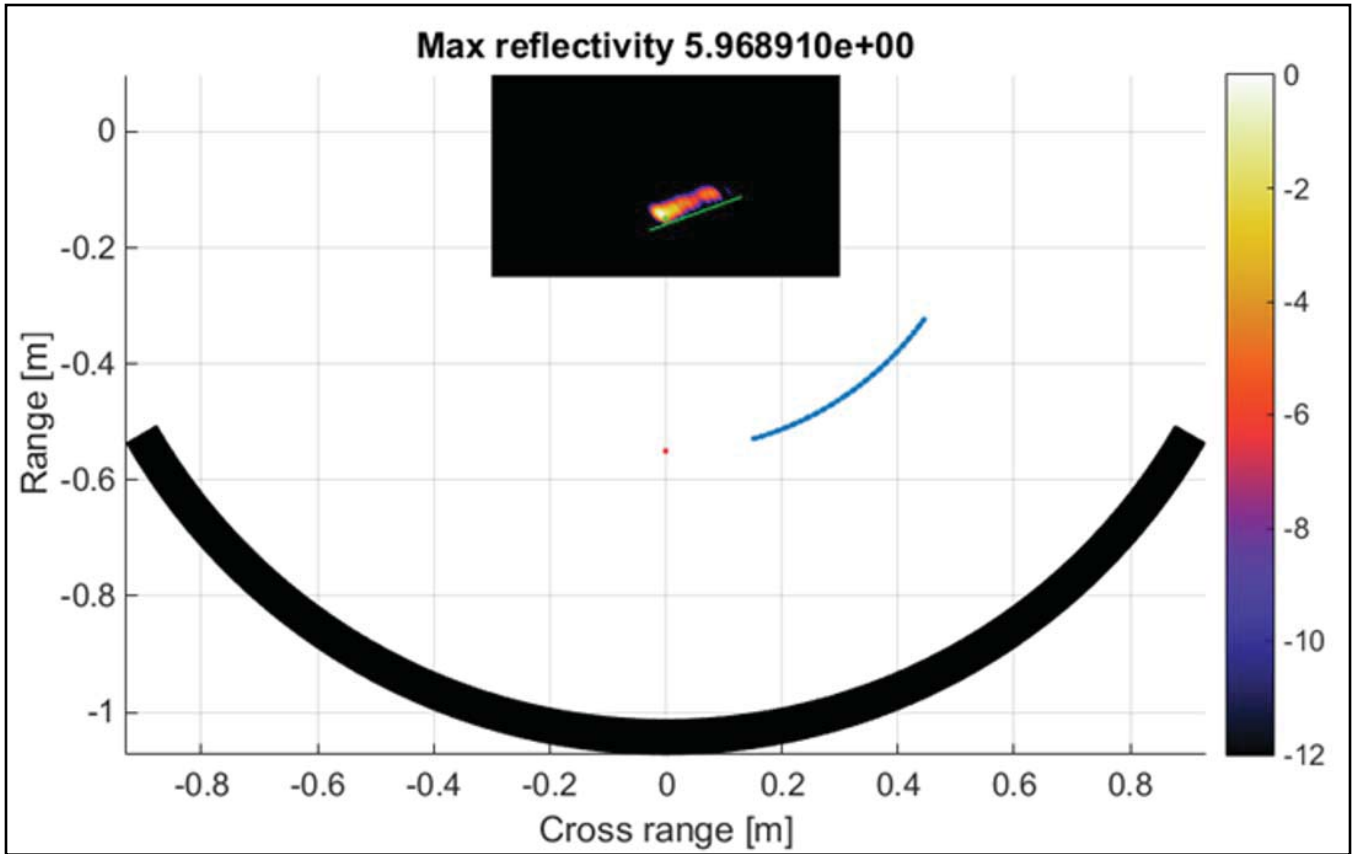




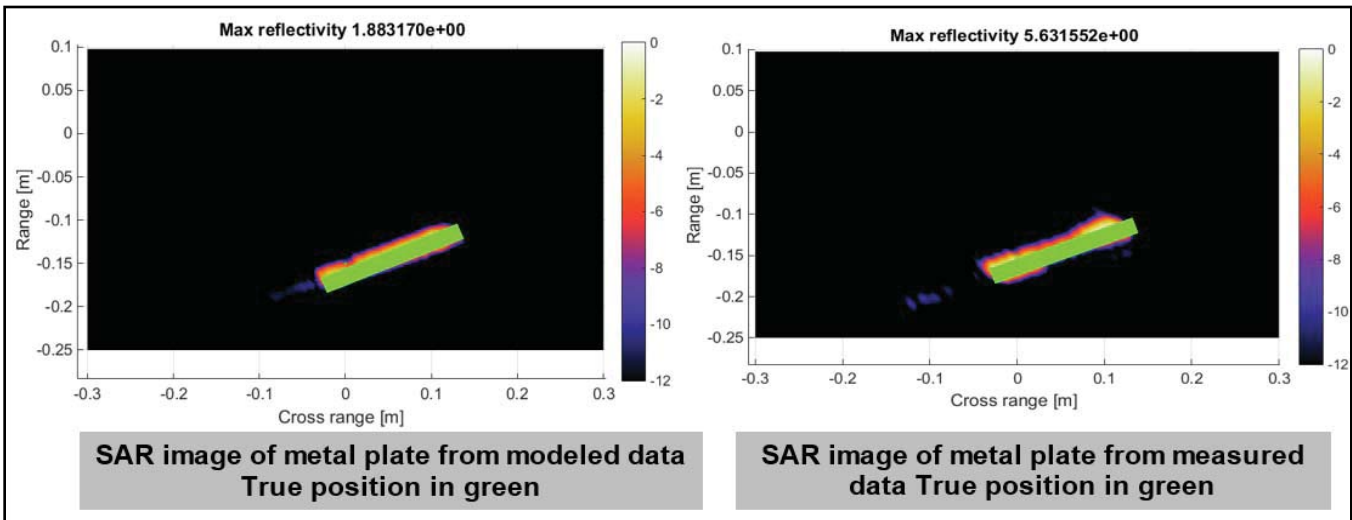
**Figure 5: Aluminum elliptical torus reflector, fabricated with a CNC mill in four sections, with transmit element feed and receiver mounted on a rotation arm.**

The reflector has undergone preliminary testing for imaging simple scattering objects. Figure 6 on the next page shows the configuration and imaging results for a small metal box target, with face parallel to the floor and rotated roughly 25 deg. relative to the reflector axis of symmetry. The transmitter position is indicated by the red dot on the line of symmetry, and the receiver in this case points towards the reflector and is scanned along the blue 50 deg. circular arc. This simple case is actually quite important, because the front surface rotation exceeds the ( $\pm 22.5$ ) imaging capability of the previous Blade Beam reflector configuration (reported in R3-A.1). The reconstructed image of the box face is well-formed with at least 12 dB of signal above any noise or clutter, with the bright band being at the correct position and orientation, and having the correct width. A blown-up detail of the reconstruction based on measured data (see Fig. 6c) compares well with the entirely numerical model-based reconstruction (see Fig. 6b).

The most expensive components of the nearfield imaging radar system are the transmitter and receiver modules. Recent advances in RF electronics integration has led to a significant price reduction in these components. We have designed new RF circuit boards to take advantage of this new hardware. The new modules are 2 orders of magnitude less expensive. This will allow for receiving arrays with a multitude of inexpensive elements, rather than a rotating single element. With electronic switching rather than mechanical movement, the signal acquisition time will be 1000 times faster, and the system will then be able to scan an entire body at 200 different heights at high speed in practical scanning times. Figure 7 on the following page shows a specification drawing of a receiver module circuit board with four receiver chips, each with an integrated broad beam antenna. With the quad-receiver configuration, the receiving antennas can be positioned as closely as possible to each other for the best spatial sampling to fit the most elements into the receiving array.



a)



b)

c)

Figure 6: a) Measured imaging results for the elliptical torus reflector: 12 cm side metal box target, tilted at 25 deg. relative to axis of symmetry. Transmitter at nominal position on symmetry axis (red dot), receiver facing reflector on arm rotating 10 – 60 deg. along blue arc. Imaging detail showing results based on b) modeled, and c) measured data.

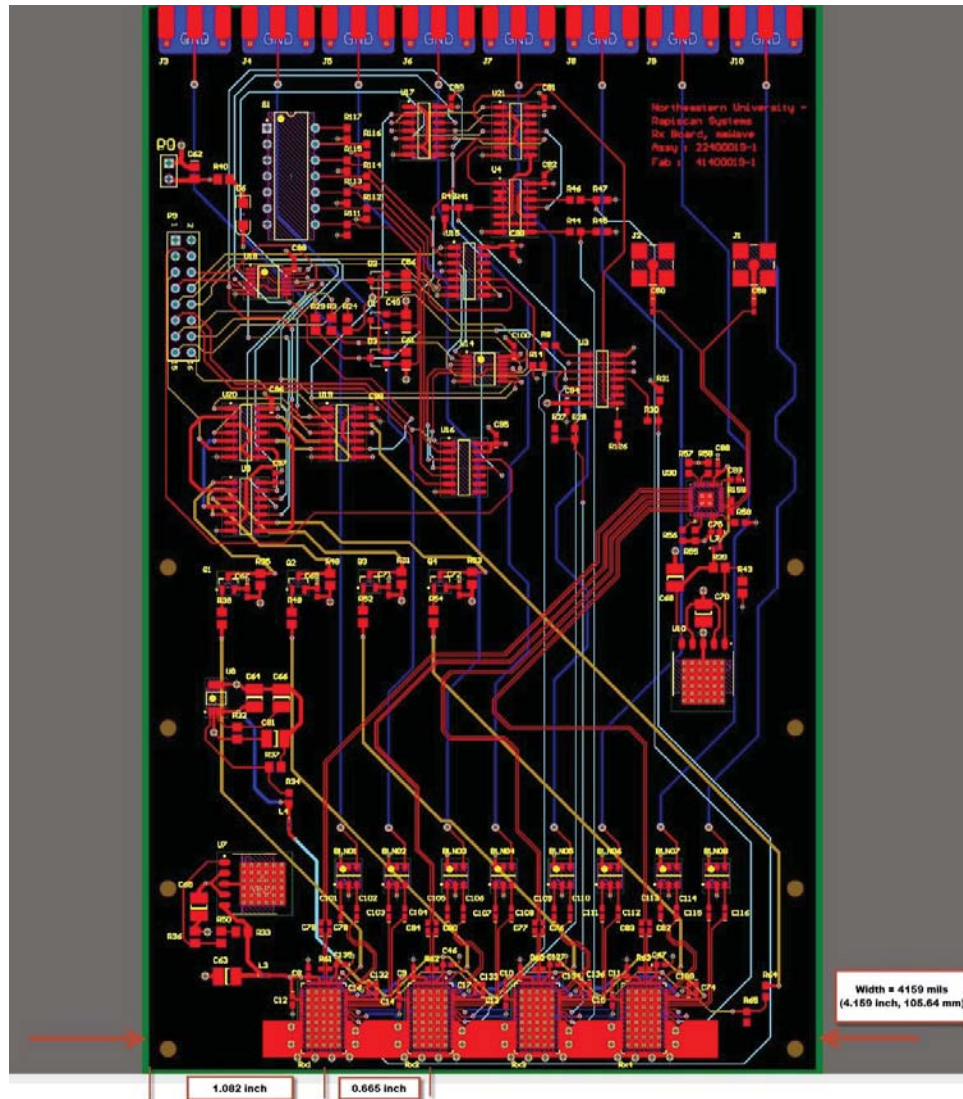


Figure 7: Novel receiver module circuit board with four independent receivers, each with integrated antenna (at bottom).

#### D. Milestones

Although the RF electronics hardware has been tested for individual operation, it must be incorporated into the torus reflector geometry. Getting the electronics to work as part of the overall system is critical and of highest priority.

Following the full RF electronic circuit configuration, there will be numerous tests of 2D imaging to determine capabilities and limitations of the full radar system. This will naturally extend to multiple height 2D imaging and stacking for 3D imaging.

We will apply improved computational models and algorithms on the data generated with the working system to accelerate the imaging process, and determine practical bottlenecks which slow the process. This information will provide feedback for spiral development and improvement of reconstruction algorithms to be addressed by R3-A.2.



### *E. Future Plans*

Going forward, we will use the results of computational studies conducted in R3-A.2 to build an optimal sparse, fixed receiver feed array with interspersed transmitters along the focal arc. This will avoid the use of a rotating receiver arm and speed the measurement process. One important aspect of this major re-configuration is the coupling between adjacent elements. Initial computational studies have indicated that the coupling is low, but steps may have to be taken to further isolate elements with absorbing material.

There will be several months needed to tune the elements in the feeding array for best position and performance, as well as to enable the various elements to fire and record at the intended times.

The measurement campaign that follows this re-configuration will be as extensive as the first two years of project R3-A.1, with many cases to consider: flat tilted targets, horizontally varying targets, metal and dielectric targets on metallic backgrounds, curved targets, targets with rapid surface variation, 3D targets, and finally human targets. We have obtained IRB approval for human subjects, but we will not use humans until the radar acquisition time is fast enough to avoid motion artifacts.

## **III. EDUCATION AND WORKFORCE DEVELOPMENT ACTIVITY**

### *A. Student Internships, Jobs or Research Opportunities*

Research Experience for Undergraduates (REU) students: 2014: Abeco Jean Claude Rwakabuba (minority student) from Middlesex Community College; Thurston Brevett (minority student) Northeastern University; 2015: Kurt Jaisle, Jacob Messner, Northeastern University

Undergraduate students currently participating in this project: Michael Woulfe, Andrew Mello, Zamir Johl, and Sara Davila.

### *B. Interactions and Outreach to K-12, Community College, Minority Serving Institution Students or Faculty*

NSF Young Scholars (high school students): Shiva Nathan and Lingrui Zhong.

## **IV. RELEVANCE AND TRANSITION**

### *A. Relevance of Research to the DHS Enterprise*

1. The custom developed AIT hardware developed in the R3-A3 project provides faster, more accurate imaging, increasing resolution, improving detection and reducing false alarms. The concept and implementation of stacking 2D imaging (stacked image slices) reduces hardware requirement by a factor of 100 (for 1 cm resolution), computation by a factor of 10,000, and providing near real time processing.
2. Commercial Off-The-Shelf (COTS) communication modules repurposed used in the R3-A3 project, as AIT screening radar saves money (radar module cost savings from \$12,000 to \$150), allows for general security use and makes the R3-A3 project results more likely to transition to our commercialization partners.
3. The multistatic radar configuration practiced in R3-A3 project extends imaging performance by giving multiple views of each body surface pixel and helps eliminate dihedral artifacts.

### B. *Potential for Transition*

We have established a collaborative relationship with Rapiscan Laboratories, Inc. using funding from the John Adams Innovation Institute to work with the radar system developed in R3-A.3 to test the feasibility of the On-The-Move sensing system discussed in R3-B.1. As a first step for full 360 deg. whole body imaging with a fixed set of multistatic 60 GHz arrays, we are considering a 2D cross section geometry. Unlike the Blade Beam reflector system which produces 2D illumination of a 3D object, this transition project is considering only a 2D human body cross section, contained within a pair of parallel plates. The received signals will be reconstructed to form a slice image of the object placed between the transmitters and receivers. This work forms a 2D experimental proof-of-concept study which will be expanded following the project's conclusion into fully 3D image reconstruction for full size personnel screening.

The project began on January 1, 2015, with effort focused on designing the sensor, simulating the RF mm-wave reflections for various geometries of the transmitters (Tx) and receivers (Rx) and determining the layout of the transmitters and receivers for the sensor, as shown in Figure 8. From this layout, we developed a block diagram of the hardware components that will comprise the sensor, ordered parts, fabricated 12 transmitter boards and 12 quad-receiver boards, fabricated the parallel plate guide with slots and slides for the boards, and began testing components. Once the hardware is debugged and the radar signals are generated and recorded as intended, we will conduct imaging experiments using algorithms developed as part of R3-A.2 to quickly reconstruct 2D target objects.

The same hardware will be applicable to the elliptical torus Blade Beam, so there is an effective dual-use strategy for this experiment.

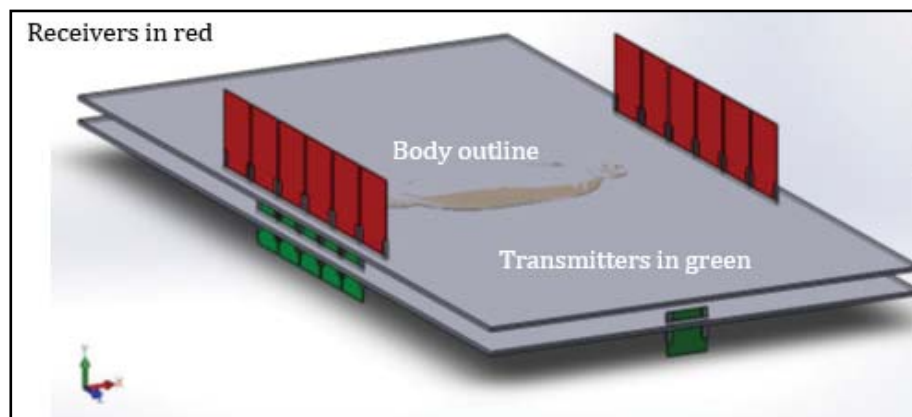


Figure 8: Parallel plate 2D cross section imaging system developed in conjunction with Rapiscan, showing transmitter circuit boards (in green), and quad-receiver boards, shown in Fig. 7 (in red). Radar chips with integrated antennas are positioned so that they radiated into the 3mm space between the plates. Waves are guided with electric field perpendicular to the plate surfaces, and scatter from flat 3mm thick metallic and dielectric objects positioned within the plates.

### C. *Data and/or IP Acquisition Strategy*

Disclosures of the patentable innovation have been submitted. Some of the innovation is being treated as a "trade secret."

### D. *Transition Pathway*

The collaboration with Rapiscan is ongoing and strong. As potential end-users of the R3-A.3 technology and partners in the development of these concepts, they are already in the process of transitioning for an end user. The next steps for Rapiscan are to decide on a commercialization strategy for further concept development and eventual implementation as a product.

*E. Customer Connections*

Rapiscan Laboratories Inc., Burlington, MA.: Shiva Kumar, Ed Morton, Dan Strellis

## **V. PROJECT DOCUMENTATION**

*A. Peer Reviewed Journal Articles*

**Pending -**

1. Borja Gonzalez-Valdes, Yuri Álvarez, Spiros Mantzavinos, José Ángel Martínez-Lorenzo, Fernando Las-Heras, Carey M. Rappaport, "Imaging Effectiveness of Various Multistatic Radar Configurations for Human Body Imaging," in review for publication in IEEE Transactions on Antennas and Propagation, 7 pages.

*B. Peer Reviewed Conference Proceedings*

1. Carey Rappaport, Borja González-Valdés, and José Ángel Martínez-Lorenzo, "Advanced Portal-Based Multistatic Millimeter-Wave Radar Imaging for Person Security Screening," IEEE Carnahan Conference on Security Technology, Rome Italy, October, 2014, 3 pages.
2. Rappaport, C. and González-Valdés, B., "Multistatic Nearfield Imaging Radar for Portal Security Systems Using a High Gain Toroidal Reflector Antenna," EuCAP 2015, Lisbon, Portugal, April, 2015, 2 pages.
3. Gonzalez-Valdes, B., Álvarez, Y., Gutierrez-Meana, J., Rappaport, C., Las-Heras, F., Garcia-Pino, A., and Martínez-Lorenzo, J. A., "On-the-Move Millimeter Wave Imaging System Using Multiple Transmitters and Receivers," EuCAP 2015, Lisbon, Portugal, April, 2015, 2 pages.

*C. Other Presentations*

1. Seminars
  - a. Carey Rappaport, "Whole Body Imaging with Multistatic Millimeter-Wave Radar for Security Screening", February 25, 2015, International Village Seminar Series.
  - b. Carey Rappaport, "Advanced Airport Security Scanners: How They Work, But Why Superman Wouldn't Be Satisfied with What They Reveal", March 23, 2015, Northeastern University Scholars Program, Master Class.
2. Poster Sessions
  - a. Thurston Brevett, Michael Woulfe, Alastair Abrahan, Scott Pitas, Borja Gonzalez-Valdes, Jose A. Martinez-Lorenzo, and Carey Rappaport, "Distinguishing Dielectric from Metal Anomalies Using Near Field Millimeter Wave Whole Body Radar," Northeastern University Scholars Program, March 4, 2015.
  - b. Thurston Brevett, Michael Woulfe, Scott Pitas, Borja Gonzalez-Valdes, Jose A. Martinez-Lorenzo, and Carey Rappaport, "Millimeter Wave Whole Body Scanning Radar," DHS Program Review, March 10, 2015.
  - c. Mohammad H. Nemati, Borja Gonzalez-Valdes, Thurston Brevett, Mike Woulfe, Alastair Abrahan, Jose A. Martinez-Lorenzo and Carey M. Rappaport, "Multistatic Nearfield Imaging Radar system using High Gain Reflector Antenna," DHS Program Review, March 10, 2015.

### 3. Briefings

- a. Carey Rappaport, "Advanced Portal-Based Multistatic Millimeter-Wave Radar Person Security Screening," 3/3/15, Northeastern University Gov't Outreach.

## VI. REFERENCES

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