Multistatic Nearfield Imaging Radar for Portal Security Systems Using a High Gain Toroidal Reflector Antenna

Carey M. Rappaport and Borja Gonzalez-Valdes
ALERT Center of Excellence, Northeastern University, Boston (MA), USA, rappaport@neu.edu

***Abstract*—A Toroidal reflector, consisting of a tilted ellipse rotated about the vertical axis, provides for multiple, overlapping high-resolution nearfield beams that form multi-view, true multistatic mm-wave imaging for security applications. Modeled results indicate the PSF on a torso target is wide and short, allowing for quickly computed 2D images which can be stacked to reconstruct detailed 3D surfaces.**

***Index Terms*— Imaging Systems, Multistatic radar system, Security scanning.**

I. Introduction

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]. 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. 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 [2]. 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 [3]. 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 [4]. 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.

This work is supported by Northeastern University's ALERT Center; funded by the Science and Technology Directorate, U.S. Department of Homeland Security under the Award Number "2008-ST-061-ED0001"

II. Elliptical Torus Reflector

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 α 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:

$$A = -b^2 - c^2 \cos^2 \alpha$$
$$B = -a^2 + c^2 \cos^2 \alpha$$
$$C = -2c^2 \cos \alpha \sin \alpha$$
$$\mathrm{D} = 2c(b^2 + c\, r_s \cos \alpha) \sin \alpha$$
$$\mathrm{E} = 2\left(a^2 r_s - c \cos \alpha \left(b^2 + c\, r_s \cos \alpha\right)\right)$$
$$F = -a^2 {r_s}^2 + (b^2 + c\, r_s \cos \alpha)^2$$

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 ± 0.40 rad of view angle at the target focal point. Note that no reflected rays are blocked by the feed.

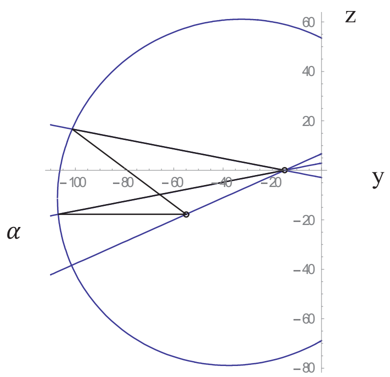

Fig. 1. Ellipse with major axis tilted by α, with foci and top and botttom ray paths. Units in cm.

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 ρ, as displayed in Figure 2. Figure 3 show 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.

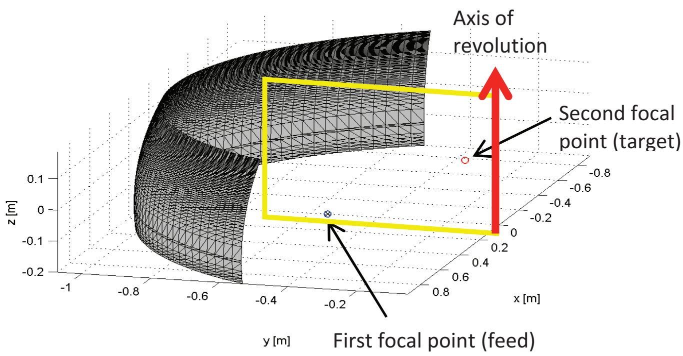

Fig. 2. Rotated offset elliptical section with foci for central beam.

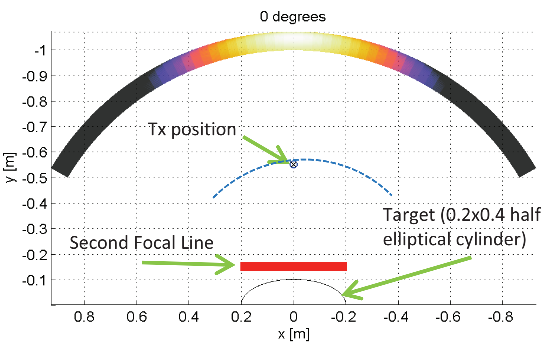

Fig. 3. Top view of illuminated reflector, showing feed arc, torso target shape, and secondary focal line for central beam.

III. Results and Conclusions

The reflector surface illumination and projected elliptical cylinder target PSF, computed using Physical Optics are shown in Figure 4. 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 reconstuction 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.

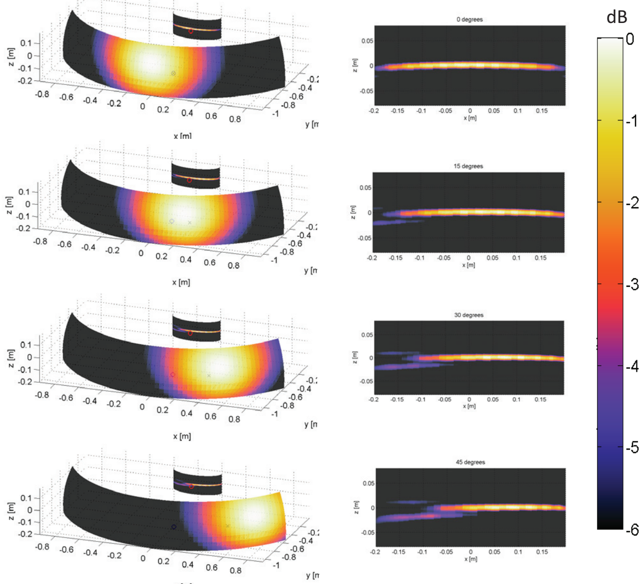

Fig. 4. Reflector illumination (right) and torso target PSF (left) for 0, 15, 30, and 45 deg. beams.

Acknowledgment

The authors are grateful to Jose A. Martinez –Lorenzo for many helpful discussions.

References

[1] D. Sheen, D. McMakin, and T. Hall, “Three-Dimensional Millimeter-Wave Imaging for Concealed Weapon Detection,” *IEEE T. Microwave Theory and Techniques*, vol. 49, no. 9, pp. 1581-1592, Sept. 2001.

[2] Cooper, K.B.; Dengler, R.J.; Llombart, N.; Thomas, B.; Chattopadhyay, G.; Siegel, P.H., "THz Imaging Radar for Standoff Personnel Screening," *IEEE T. Terahertz Science and Technology,* , vol.1, no.1, pp.169-182, Sept. 2011.

[3] Rappaport, C.M.; Gonzalez-Valdes, B., "The blade beam reflector antenna for stacked nearfield millimeter-wave imaging," *IEEE Antennas and Propagation Society Int'l Symp.* , vol., no., pp.1-2, 8-14 July 2012

[4] Alvarez, Y.; Gonzalez-Valdes, B.; Ángel Martinez, J.; Las-Heras, F.; Rappaport, C.M., "3D Whole Body Imaging for Detecting Explosive-Related Threats," *IEEE T. Antennas and Propagation,* vol.60, no.9, pp. 4453,4458, Sept. 2012.

[5] Martinez-Lorenzo, J.A; Gonzalez-Valdes, B.; Rappaport, C.; Gutierrez Meana, J.; Garcia Pino, A, "Reconstructing Distortions on Reflector Antennas With the Iterative-Field-Matrix Method Using Near-Field Observation Data," *IEEE T. Antennas and Propagation*, vol.59, no.6, pp. 2434-2437, June 2011.