R3-A.2: Computational Models & Algorithms for Millimeter Wave Whole Body Scanning for Advanced Imaging Technology (AIT)

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II. PROJECT DESCRIPTION

A. Project Overview

Two main projects are described in the following description: the general ray-based inversion algorithm for the Smiths eqo CW (single frequency, 24 GHz) raster scanned mm-wave AIT scanner system; and a novel accelerated electromagnetic computational modeling method which for the first time allows for arbitrary wave excitation of any axisymmetric structure. The former extends the focused ray analysis undertaken last year to accurately predict the range displacement of the focal peak relative to the position of bare skin, along with the differential phase, and while establishing a unique dielectric constant and thickness determination for infinitely wide slabs. The second project couples to the first by providing a means of analyzing, with extreme accuracy, the scattering variations present for finite slabs as the focal point approaches an edge. It extends the axi-symmetric Finite Difference Frequency Domain (FDFD) to a more general Quasi Axisymmetric FDFD method (QAFDFD), which is applicable to off-axis point source or inclined plane wave excitations.
B. State of the Art, Technical Approach, and Major Contributions in the Year 5

B.1. Inversion Algorithm

Faster and more efficient security checkpoints are required to effectively prevent airplane terrorist attacks while minimizing the inconvenience of long security lines. This research project develops an algorithm for the characterization of weak dielectric slabs that might be explosive threats, using a focused continuous wave (CW) radar system, like the Smiths Detection Inc. eqo [1]. The eqo focuses mm-waves on a raster-scanned set of pixels in 3D space and measures scattered signal at each point by adjusting the phase (0 or π) of each array element. We consider the responses received from focal points along the axis perpendicular to the array as a function of distance from the array. It is assumed that dielectric slab is smooth with small variation in thickness and perfectly attached to the body, with no gaps, and that the highly conductive skin surface is reasonably approximated as being a planar metal ground plane.

The Virtual Source model was previously developed by Sadeghi [2] to predict the expected return signal from weak dielectric slabs on the surface of the human body. This paper presents an inverse model. By comparing the measured return signal for focal points along the range axis for a bare metal plane (or skin) versus for a dielectric slab on a metal background, two observable parameters related to the signals’ shapes are identified and used to determine the basic characteristics of the dielectric slab: its thickness and permittivity.

Figure 1 is the schematic of the simulation geometry, with Figure 1(a) showing rays focused on a bare metal ground plane parallel to the transmitter/receiver array, and Figure 1(b) showing rays focused inside a dielectric slab with thickness of \( d \), lying on the metal ground plane at a distance \( H \) from the array. The transmitted continuous wave is iteratively focused on a set of focal points along the range axis \( (z \text{ axis}) \), and the receiver coherently combines the returning rays from each focal point to give the magnitude and phase of the reflected response. The response will have a distinct peak at the range corresponding to the focal point of maximum reflection.

Based on the VS model [2], the magnitude and the phase of the reflected continuous wave responses over the \( z \) axis can be modeled as a function of \( H, d \), and dielectric permittivity. Two defined observables are: (i) the range displacement of the dielectric covered response peak from the bare metal peak, and (ii) the mean of the differential phase between the covered peak and the bare peak.

Ideally, for lossless dielectric objects, we expect the magnitude peak height ratio between the bare metal and metal covered with dielectric to be close to one (energy conservation). Any decrease in peak height with the dielectric response is most likely due to be the dissipated power inside the dielectric.
For this simulation setup, the 1.0m by 1.0m array is located at a nominal distance of $H = 80$cm from the ground plane. Figure 2 is the illustration of the two observables (Fig. 2(a) is the displacement and Fig. 2(b) is the phase difference) as a function of dielectric slab thicknesses and permittivity derived from three-dimensional version of the VS model. The ripples in the displacement are due to the constructive and destructive interference of reflections from dielectric front and back interfaces, and the rapidly changing phase difference is due to the natural wrapping behavior of the phase.

The inversion algorithms work based on Figure 2, using observable pairs: peak displacement and phase difference, to solve for the dielectric slab thickness and permittivity.

![Figure 2: Observables from simulation of bare metal and metal covered with dielectric for different dielectric thicknesses and permittivities: (a) displacement of the magnitude of the response peaks and (b) mean phase difference of responses between the peaks of the magnitude responses.](image)

The first step is to find the overlap of the observed displacement with the observed phase difference. This pair of observables will have multiple solutions, due to the multi-valued nature of the phase plot and the oscillations of the displacement values.

To avoid the multiple solutions, we considered that the thickness of the dielectric is likely to be changing slightly over its surface. Therefore, there are multiple thicknesses with the same dielectric permittivity that result in multiple observable pairs and different solution regions. Using the fact that each of the solutions for different pairs should result in the same dielectric permittivity but similar thickness, the non-realistic solutions can be discarded.

This method is implemented for example, when the correspondence test with three pairs of observables for
the dielectric with \( \epsilon_r = 2.9 \) and thicknesses say of \( d = 3.6, 3.7 \) and 3.8cm. The displacements and wrapped phase differences for these three thicknesses are: (0.9, -2.1), (1.8, -3), and (2.2, 2.9). Figure 3(a) shows all the possible combinations of thickness and relative permittivity that generate the same pair of response observables in blue, red and green respectively.

To find the unique solution of each observable pair e.g. \( (1.8, -3) \), corresponding to \( d = 3.7 \)cm and \( \epsilon_r = 2.9 \) two more binary masks based on other two observables are formed (without knowing \textit{a priori} the true values of the different \( d \)). Each mask is built by extending the solution dots for the two different \( d \) values in Figure 3(a) \( \pm 2 \)mm in thickness. If the original observable lies within both binary masks, all three solutions are declared to be physical. Figure 3(b) shows the results of the inversion algorithm by multiplying each individual observable pair solutions to the masks derived from other two observable pairs.

The improvement due to using multiple pairs of observables over a single pair for a dielectric slab with thickness \( d = 3.7 \)cm and relative permittivity \( \epsilon_r = 2.9 \) for our proposed inversion algorithm is illustrated in Figure 3(b). Note that all the non-physical solutions have vanished, with reconstruction accuracy of about 3%.

Using observable values for a high explosive as a nominal case for a low loss dielectric slab, we were able to isolate its exact and unique relevant parameters: thickness and relative permittivity through exhaustive search. The same procedure can be used for various objects like silicone sealant, different kinds of plasticine, bees wax, powder soap, candle wax, and explosives like Semtex with different thicknesses. The variation of the inversion parameters over different thicknesses of the same object plays a key role.

This research has direct relevance to the Smiths Detection eqo system and could be applied to many other scanning systems to characterize detected anomalies and rule out innocent objects that currently generate false alarms. This can lead to more informed decisions about potential threat objects, which means shorter lines and heightened security for all parties involved.
B.2. *Quasi Axisymmetric Finite Difference Frequency Domain Method*

Modeling the scattered fields created by a single frequency dipole scanning array intended to image a TNT layer on top of skin is a challenging problem. The Year 4 project description considered approximating the field using geometric optics ray-based algorithms. In this project, we are interested in computing the full 3D fields for this difficult geometry which in general requires a 3D FDFD algorithm that is computationally expensive and storage prohibitive. For the special case where the underlying problem geometry is axisymmetric, the 3D FDFD algorithm may be replaced with an equivalent 2½D FDFD code which can accommodate any distribution of sources with any polarizations, which we have named the Quasi Axisymmetric Finite Difference Field Domain (QAFDFD) algorithm. A geometry is defined as axisymmetric with respect to an axis, which we designate to be the $z$ axis, such that $\partial / \partial \phi = 0$ for all material parameters within the problem under consideration. The QAFDFD algorithm differs from the “strict” 2D axisymmetric FDFD code which not only requires that the material geometry be axisymmetric, but also requires that all sources be composed of $\phi$-polarized axisymmetric electric or magnetic current loops (which by duality can also describe $z$ polarized on-axis dipoles). These strict 2D sources are very limited and unable to model most of the interesting real-world problems; plane waves, for example, are automatically excluded under strict axisymmetric conditions.

The QAFDFD code makes the ansatz that all fields can be expressed as superpositions of modes such that

$$F(\rho, \phi, z) = \sum_m \tilde{F}(\rho, z; m) \exp(i m \phi)$$

where the sum over $m$ is infinite and each mode $m$ requires an inversion of a 2D FDFD matrix of size $3N_{\rho} \times 3N_{\rho}$. (The factor of 3 in each dimension of the FDFD matrix results from the need to solve for $E_\rho$ and $E_z$ simultaneously with $E_\phi$. By contrast, TE and TM results are obtained in the strict 2D algorithm from $E_\phi$ or $H_\phi$ alone, and the other components are found secondarily from these azimuthally-directed fields.) In practice, the modal expansions converge because the computational area is finite. The QAFDFD code does not require large amounts of computational storage because the linear matrix equations to be solved remain two-dimensional and can be solved sequentially. However, the code can be somewhat slow, because each one of a (possibly large) number of modes requires its own 2D FDFD computation. The QAFDFD analysis is meant to probe the limits of simpler, quicker methods such as geometrical optics and ray-based algorithms and help develop intuition for the underlying scattering problem.

The canonical sources for the QAFDFD code are single-mode right hand circularly polarized (RCP), left hand circularly polarized (LCP), and $z$ directed dipole rings located at specific radii $\rho$ and height $z$. In last year’s R3-A.2 Project Report (Year 4), we described on-axis (axisymmetric) focusing from a $\gamma$-polarized dipole array, completely specified by two-mode QAFDFD using only sources with $m = \pm 1$. In this year’s project report, we relax the focusing condition on the array and allow it to focus anywhere along the $x$ axis, which we will show requires the full multimodal QAFDFD computation. This problem is important because it is valuable to know how the focused response changes as it is scanned away from the center and approaches the edge of a finite slab.
This problem seeks to model scattering from a 37 mm thick and 50 mm radius cylindrical slab of TNT of dielectric \( \varepsilon = \varepsilon_0 (2.9 + 0.001i) \) placed on the skin, where the skin layer is modeled as a perfect electrical conductor. A 24 GHz \( y \)-polarized circular dipole current sheet array, with radius 125 mm sits 200 mm above the skin surface and focuses along the \( x \) axis from 0 mm to 40 mm (not getting too close to the edge of the TNT). We choose the smallest geometry possible that preserves the essential information to be extracted from the scattered fields in order to minimize the computational time, particularly critical in the off-axis focusing case. The circular array source is a \( \frac{1}{4} \) scaled version of the 1000 mm X 1000 mm eqo reflect-array. It is positioned \( \frac{1}{4} \) as far from the target as the nominal eqo scanner. Table 1 lists the parameters that are used in the test problem. Although the experimental array is 800 mm from the skin and the TNT layer is actually a 200 mm radius slab, we see in Figure 4 that reducing the dimensions by a factor of four in both \( \rho \) and \( z \) preserves the general appearance of the background and scattered fields for the case of focusing at \( z_F = 37 \) mm (on the front of the TNT layer) and \( x_F = 0 \) mm (axisymmetric focusing). Although there are slight differences between the two simulations, visible particularly in the magnitude plots, they are not expected to be significant and the savings (by over a factor of 25) in computational speed in reducing the computational grid make the tradeoff worthwhile.

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<th>Value</th>
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<td>frequency</td>
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</tr>
<tr>
<td>( d_{\text{TNT}} )</td>
<td>thickness of TNT layer</td>
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</tr>
<tr>
<td>( R_{\text{TNT}} )</td>
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<td>( \varepsilon_{\text{TNT}} )</td>
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<tr>
<td>( \text{ppw (air)} )</td>
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<td>( n_{\text{PML}}, n_z \text{PML} )</td>
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<tr>
<td>( h )</td>
<td>height of dipole from skin surface</td>
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<td>(-20 ) mm</td>
</tr>
<tr>
<td>( z_{\text{max}} )</td>
<td>Maximum value of ( z ) in computational grid</td>
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<td>( z_F )</td>
<td>Focusing depths in ( z )</td>
<td>( d_{\text{TNT}} + [-110:5:52] ) mm</td>
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<tr>
<td>( x_F )</td>
<td>Focusing widths in ( x )</td>
<td>([0.5 0.8] R_{\text{TNT}} )</td>
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Table 1: TNT + skin computational parameters at a glance
The source has a non-axisymmetric current distribution given by

\[ \mathbf{J}(\rho, \phi, z) = j K_S(\rho, \phi) \delta(z - h) \]

where \( K_S \) is a surface current with units of A/m and \( h = 200 \text{ mm} \). The array is designed to focus at the Cartesian point \((x, y, z) = (x_F, 0, z_F)\) so the current distribution is given in Cartesian coordinates by

\[ \mathbf{J}(x, y, z) = j K_{S0} \delta(z - h) \exp \left( -i k_0 \sqrt{(x - x_F)^2 + y^2 + (h - z_F)^2} \right) \]

where the path length phase is chosen to vanish at \((x, y) = (0, 0)\) and \( k_0 \) is the wavenumber in free space, equal to 503 m\(^{-1}\) at 24 GHz. Switching to cylindrical coordinates, we find
where the constant $R_F = \sqrt{x_F^2 + (h - z_F)^2}$ and the mode coefficients $c_{mR}$ and $c_{mL}$ precede expressions for the RCP and LCP dipole ring sources, respectively. There are no z-polarized dipole sources included in (1) as these are orthogonal to the y-polarized current sheet. The mode coefficients may be found taking the dot product of both sides of (1) with the unit vectors $\hat{z}$, and then performing the usual Fourier inversion process of multiplying both sides by $\exp(-im' \phi)$ and integrating over $\phi$:

$$
\begin{align*}
J(\rho, \phi, z) &= \left(\hat{\rho} \sin \phi + \hat{\phi} \cos \phi\right) K_S \delta(z-h) e^{-ik_0 \sqrt{\rho^2 - 2x_F \rho \cos \phi + R_F^2}} \\
&= \sum_m c_{mR} \left(\frac{\hat{\rho} + i\hat{\phi}}{2\pi \rho \sqrt{2}}\right) e^{im\phi} \delta(z-h) + \sum_m c_{mL} \left(\frac{\hat{\rho} - i\hat{\phi}}{2\pi \rho \sqrt{2}}\right) e^{im\phi} \delta(z-h)
\end{align*}
$$

(1)

For on-axis focusing, $x_F = 0$ and the term in the square root in (2) is independent of $\phi$ so only the $m = 1$ and $m = -1$ modes survive the $c_{mR}$ and $c_{mL}$ integrals, respectively; this two-mode QAFDFD algorithm was the basis of last year’s work, as previously mentioned. For off-axis focusing, all mode coefficients are nonzero and sufficient numbers of modes must be kept to ensure convergence of the scattered electric fields.

The QAFDFD algorithm starts by computing the 2D FDFD results for the $m = 0$ mode and then adds the results for the $m = 1$, $m = -1$, $m = 2$, $m = -2$ modes and so forth, checking for convergence at each step. Because the modal expansion is essentially a superposition of spherical Hankel functions, the underlying modes in spherical geometry, the scattered fields essentially go as $m^{3/2} \left(\frac{ek_0 R^2}{2 r_0 m}\right)^m$ for large values of $m$. Figure 5 shows how the scattered field magnitude converges as a function of $m$ and demonstrates excellent agreement with the simple asymptotic model. For the example described above, it takes about 50 modes ($|m| \leq 26$) to reach a truncation error of 0.001% with convergence coming quickly after a relatively long plateau as shown in the figure. From the asymptotic expansion, we expect that the mode truncation limit $m_{max}$ to be approximately $m_{max} \approx \frac{ek_0 R^2}{2 r_0}$, which is 17 in this case where $r_0 \approx \frac{R_F}{2}$.

Figure 6 shows the magnitude of the electric field $|E_y|$ plotted on a dB scale and taken on a slice in the x-z

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Figure 5: Convergence of the maximum magnitude of the scattered electric field as a function of mode index $m$ plotted on a dB scale. The dashed blue line is the asymptotic formula applied for $m > m_{max}$. From the asymptotic expansion, we expect that the mode truncation limit $m_{max}$ to be approximately $m_{max} \approx \frac{ek_0 R^2}{2 r_0}$, which is 17 in this case where $r_0 \approx \frac{R_F}{2}$. Figure 6 shows the magnitude of the electric field $|E_y|$ plotted on a dB scale and taken on a slice in the x-z
plane through the $y$ axis for two different focuses: $x_F = 0$ mm and $x_F = 40$ mm; in both cases $z_F = 22$ mm so the array focuses at the range of maximum reflection from the ground plane at the back of the TNT slab. The axisymmetric focusing simulation is quick – taking less than a minute – because the dipole sheet can be described with only two modes ($m = \pm 1$). The second simulation takes about 12 minutes (about 50 times longer) because 2D simulations of the fields from all sources with mode index $|m| \leq 26$ must be summed. The displacement of the range peak when the antenna focus shifts from 0 to 40 mm is quite clear in Figure 6. Additionally, strong standing waves from the PEC reflection are observed within the TNT layer (but not in the air region, as this is scattered field).

Figure 6: Electric field $E_y$ taken on an $x$-$z$ slice at $y = 0$. The array antenna is located 200 mm above the ground plane and the focusing in the $z$ direction is at 22 mm, in the middle of the TNT slab at the virtual focal point corresponding to the point with maximum reflection from the PEC ground plane. The figure on the left focuses on axis at $x_F = 0$ mm while the figure on the right focuses off axis at $x_F = 40$ mm. Note the asymmetry in the fields on the right (off-axis focusing) while the fields in the on-axis focusing case are symmetric as expected.

We would typically like to model the output of the observed scattered field at the array antenna. For the eqo system, the received field is captured by the reflect-array with the same phase weighting used when it acts as a transmitter. This is accomplished by integrating the scattered fields received over the entire surface of the array, being careful to weight the scattered fields by the transmitter pattern, including its polarization:

$$E_{\text{rec}}(z = h) = \int_{\rho = 0}^{R_F} \rho \, d\rho \sum_{m} \int_{\phi = 0}^{2\pi} d\phi \left( E_{\rho z} \cos \phi - E_{\phi z} \sin \phi \right) \exp \left( i m \phi + ik_0 R_F - ik_0 \sqrt{\rho^2 - 2\rho x_F \cos \phi + x_F^2} \right)$$

Here, the $\rho$ integral is just a summation over all the dipoles in the array. This received signal is now a complex number which can be plotted as a function of the focusing parameters. Figure 7 shows how the received
signal varies with focusing distance \( x_F \) and focusing depth \( z_F \) for both the TNT-skin case described above and also the “bare skin” case where the TNT target is replaced with air. The range focusing depth \( z_F \) ranging from \(-73 \text{ mm} \) to \( 87 \text{ mm} \) where the back of the TNT is located at \( 0 \text{ mm} \) and the front at \( 37 \text{ mm} \). Three transverse focusing offsets are shown in solid (\( x_F = 0 \text{ mm} \)), dotted (\( x_F = 25 \text{ mm} \)) and dashed (\( x_F = 40 \text{ mm} \)) linetypes. In all cases, the TNT + skin case is shown in blue and the bare skin case in red. The “bare skin” axisymmetric curve (\( x_F = 0 \)) has a maximum at \( z = 0 \) and adding the TNT layer shifts the curve to the right by approximately \( 22 \text{ mm} \), which is essentially identical to experimental results provided by Smiths Detection. The differential between the skin only and skin + TNT curves is approximately the same for the two choices of \( x_F \). All curves have roughly a point spread function (sinc function) shape. Note that a 3 dB amplitude taper has been added to the transmitter array (and hence the receiving array as well) for the results in Figures 7 and 8 which replaces \( K_{S0} \) by \( K_{S0} \cos(\pi \rho / 3R_A) \) where \( R_A \) is the antenna radius so that the amplitude drops from 1 at the array center to \( 1 / \sqrt{2} \) at its edge (\( \rho = R_A \)); this taper is expected to model the physical radar system more exactly than an array with no taper.

Figure 7: The scattered electric field magnitude (linear intensity scale) accumulated at the receiving antenna as a function of focusing depth (range) \( z_F \), where \( z_F \) ranges from \(-73 \text{ to } 87 \text{ mm} \); \( z_F = 0 \) at the ground plane. The on-axis focusing case (\( x_F = 0 \)) is shown in solid linetype while the two off-axis cases (\( x_F = 25 \text{ mm} \) and \( x_F = 40 \text{ mm} \)) are shown in dotted and dashed linetypes, respectively. TNT + ground plane results are shown in blue while ground plane only (“bare”) results are given in red. The QAFDFD results are given for 24 ppw (rather than 12 ppw, previously used for other figures) to ensure accuracy at the receiving antenna; the bare results are essentially indistinguishable from analytically-generated results using image theory at this grid fineness.

Figure 8 shows the phase difference for the same received electric field simulated in Figure 7. Here, the phase from the skin alone case is subtracted from the skin + TNT case and unwrapped.

Because the \( y \) dipole array is created by superposing RCP and LCP arrays, the same simulations can be trivi-
ally used to construct an \(x\)-polarized array instead. Since the focusing has been defined to be along the \(x\) axis, we can then consider the two distinct cases: (1) the focusing and the array polarization are the same; and (2) the focusing and array polarizations are orthogonal. The received fields are of course identical for the axisymmetric case where \(x_\text{F} = 0\). Interestingly, the received fields are only subtly different in the two off-axis focusing cases. The minor differences are sufficiently uninteresting that the equivalent plots to those in Figures 7 and 8 are omitted. Therefore, there appears to be no particular advantage or additional discrimination ability possible by considering \(x\)-axis focusing from both \(x\)-dipole and \(y\)-dipole arrays; on the positive side, however, alignment of the dipole array with respect to the focusing direction is not particularly critical.

### C. Milestones

We have optimized the transmitter and receiver positions along the torus feed arc to avoid overlapping of circuit boards, while maximizing the coverage for multistatic sensing.

We have tuned and validated the dielectric characterization algorithm for focused spot imaging radar. Our approach is well suited to the Smiths Detection eqo system, and we have used their experimentally generated measurements to confirm our inversion results. The performance of the algorithm indicates that the dielectric constant of a slab can be accurately predicted to within 5%.

Also in Year 5, we tested the QA-FDFD on useful representative target bodies of revolution. This high accuracy computational model supports the dielectric characterization algorithm by generating scattered fields due to focusing at off center points, thereby predicting the effects of edge scattering.
In Year 5, we successfully extended the ultra-fast time of flight body surface reconstruction algorithm to 3D surfaces. The work was published at the EuCAP conference in April 2018.

D. Future Plans (Year 6)

- In Year 6, we will explore the application of the Total Variation Method to the torus-based mm-wave radar sensor to accelerate reconstruction. As this algorithm works well with large datasets and sparse target objects, it is well-suited to the general multistatic inversion problem, and may be applicable to other fielded monostatic systems.

- Our toroidal reflector antenna scanning system modeling will be extended from stacked 2D modeling to out-of-plane scattering for more accurate 3D imaging.

- We will implement surface reconstruction algorithms on GPU-based parallel processors to accelerate computation to approach real-time imaging.

- We will develop a general theory of signal response from arbitrarily shaped dielectric material volume on realistic curved body surfaces (rather than uniform thickness and planar slabs).

- We will attempt to test our wideband dielectric characterization algorithm using measured experimental data collected by the PNNL 30 GHz bandwidth AIT system. This data was used for the Kaggle AT Challenge, which ended in December 2017. Assuming we can obtain ground truth information on the foreign objects attached to human subjects, we will be able to test the accuracy of our predictions of their material composition.

- We will support the sub-project as part of Project R3-A.3’s “On-the-Move” hallway nearfield radar detection systems for scanning at speed implementation with modeling and reconstruction algorithms. This modeling would include performance analysis of the antenna; 3D scattering of the body and objects attached to it; and the most challenging aspect, stitching together reconstruction of various views of a moving, walking subject with changing pose.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

We have been working collaboratively with Smiths Detection PLC on the AIT dielectric “material-on-skin” characterization algorithm. Our effective partnership includes semi-monthly international telephone meetings with chief scientists at Smiths Detection, and free exchange of measured data and modeled responses. The algorithms developed in this project are specifically tuned to existing scanning focused beam mm-wave portals systems. They will provide greater characterization of concealed threats, thereby reducing the probability of false alarms. This concept, which was described in previous project reports, has been approved as a two-year DHS Task Order. The science and implementation of the algorithm will be transferred to Smiths Detection.

B. Potential for Transition

The modeling effort is of great interest to Smiths Detection. During our biweekly meetings, the company has benefited from our ray-based modeling and dielectric object characterization. Although it appears that the eqo system may no longer be supported, the computational modeling applies to Smiths Detection’s latest mm-wave scanning system, and we are in discussions for further collaboration.
C. **Data and/or IP Acquisition Strategy**

We have received a provisional patent for the CW raster scanned focal point (eqo-like) system.

D. **Transition Pathway**

Smiths Detection is in the process of generating a white paper that will suggest a path forward for collaboration with ALERT for modeling and target reconstruction for wideband mm-wave portal scanning. This collaboration is based on more than one year of discussions and brainstorming, facilitated with biweekly telephone meetings with groups in Edgewood, Maryland; Cork, Ireland; and Wiesbaden, Germany.

E. **Customer Connections**

Biweekly telephone meetings are held with Christopher Gregory, Claudius Volz, Christoph Weiskopf, Martin Hartik, and Michael Jenning of Smiths Detection (Edgewood, MD, USA and Wiesbaden, Germany).

IV. **PROJECT ACCOMPLISHMENTS AND DOCUMENTATION**

A. **Education and Workforce Development Activities**

1. **Student Internship, Job, and/or Research Opportunities**
   a. Three ALERT Research Experience for Undergraduates (REU) students conducted research as part of Project R3-A.2: Daniel Castle, Jacob Londa, and Nikhil Phatak.

B. **Peer Reviewed Conference Proceedings**


C. **Other Presentations**

1. Seminars:

b. Rappaport, C. “Advanced Millimeter-Wave Radar Concealed Threat Person Scanning System – or, How to Design an Airport Scanner that is so Accurate that We Won’t Need Humans to Look at Images.” Ronald E. Hatcher Science on Saturday Lecture Series, Princeton Plasma Physics Laboratory, February 10, 2018.


D. **Student Theses or Dissertations Produced from This Project**


E. **Technology Transfer/Patents**

1. Patent Applications Filed (Including Provisional Patents)

F. **Software Developed**

1. Models
   a. Virtual Source (VS) ray-based method for focused CW raster scanned characterization of dielectric slabs on the body (May 2018).
   b. Quasi Axisymmetric Finite Difference Frequency Domain computational method (June 2018).

2. Algorithms
   a. Inverse Virtual Source algorithm, based on VS model and exhaustive search using range peak displacement and differential phase observables (on-going).

V. **REFERENCES**
