COMPLEX DIELECTRIC MATERIAL CHARACTERIZATION BY MM WAVES FOR 3-D PASSENGER SCREENING AND IMAGING Steven A. Johnson
TeleSecurity Sciences Las Vegas, NV
Department of Home Land Security (DHS) Conference/Workshop

## ALERT

(Awareness and Localization of Explosives-Related Threats)
Northeastern University (NEU)
A DHS CENTER OF EXCELLENCE
Boston, MA
November 8-9, 2011
(Stayed at Holiday Inn, 69 Boson Street, Boston, MA)

## SUMMARY OF PRESENTATION

- 1. A new method for using millimeter ( mm ) wave scanning of human subjects and objects is proposed which reconstructs a 3-D image of dielectric constant and electrical conductivity.
- 2. It is an extension of a working clinical method for making 3-D images of breast cancer using ultrasound INVERSE SCATTERING TOMLGRAPHY.
- 3. A tentative specification and architecture is show to construct such a passenger scanner.
- 4. Using this architecture, images of two respective simulated passengers, with objects of different conductivities attached to their skin, were computed using the Born approximation from simulated data.
- 5. Color scale rendition of these computed images clearly show the same body but different objects.


## Simulated, EM (IST) Image of Cylinder with Attached Objects



SIMULATED RECONSTRUCTION OF FIRST OBJECT
SINGLE-FREQUENCY SIMULATED HOLOGRAPHIC BACK-PROPAGATION TOMOGRAPHIC (HBT) RECONSTRUCTION OF A HORIZONTAL SLICE THROUGH A LOSS DIELECTRIC CYLINDER ("TORSO") WITH NEARBY RECTANGULAR EXTERNAL OBJECT. THE INVERSE SCATTERING ALGORITHM IS ABLE TO RESOLVE THE GAP BETWEEN THE OBJECT AND TORSO, INDICATING A TRUE REENTRANT 3-D IMAGE RECONSTRUCTION. IN THIS IMAGE, THE ELECTRICAL CONDUCTIVITY OF THE BODY AND THE EXTERNAL OBJECT IS $1 \mathrm{~S} / \mathrm{M}$ (SIEMENS/METER).


SIMULATED RECONSTRUCTION OF SECOND OBJECT A COLORIZED IMAGE THAT SHOWS THE CONTRAST BETWEEN THE EXTERNAL MATERIAL OBJECT (METALLIC) AND THE CYLINDRICAL BODY (LOSS DIELECTRIC). IN THIS IMAGE, THE ELECTRICAL CONDUCTIVITY OF THE BODY IS THE SAME AS IN THE IMAGE TO THE LEFT, BUT THE EXTERNAL OBJECT CONDUCTIVITY IS $100 \mathrm{~S} / \mathrm{M}$. THE DIFFERENCE IN COLOR OF THE OBJECT BETWEEN THE RIGHT AND LEFT IMAGES IS DUE TO A RESCALED COLOR PALETTE. NOTE THE APPARENT CHANGE IN SHAPE AND COLOR OF THE EXTERNAL OBJECT DUE TO ITS GREATER CONDUCTIVITY THAN IN THE LEFT SIMULATION.

MATERIAL CHARACTRIZATION ABLE
Millimeter Wave Passenger canner


## Combined mono-static and bi-static antenna geometry and ray paths



Simple formula for product $c(x) \sigma($ x)
$\square$ On solving these four equations for $c(\mathbf{x})$ and $\sigma(\mathbf{x})$, we derive a quantitative material measure:
$\square c(x) \sigma(x)=\left[\ln \left(I_{1} / I_{2}\right) V\left(t_{1}-t_{2}\right) . \quad\right.$ Equ.(1)

## Fresnel Reflection Coefficients:

## $E v=s \& E H=p$



Figure 3 - Refraction plane defined by incident, reflected \& refracted rays.


## Reflection Coefficients: <br> V \& H



Figure 4- Reflection coefficients
$\mathrm{R}_{\mathrm{S}}\left(=\mathrm{R}_{\mathrm{V}}\right)$ and $\mathrm{R}_{\mathrm{P}}\left(=\mathrm{R}_{\mathrm{H}}\right)$, for $\mathrm{n}_{2}>\mathrm{n}_{1}$.

Figure 5 - Reflection coefficients
$\mathrm{R}_{\mathrm{S}}\left(=\mathrm{R}_{\mathrm{V}}\right)$ and $\mathrm{R}_{\mathrm{P}}\left(=\mathrm{R}_{\mathrm{H}}\right)$,
for $\mathrm{n}_{2}<\mathrm{n}_{1}$.

## Fresnel's Conservation of Energy Laws for Polarized Transmission and <br> Reflection

However the laws of power (not amplitude) distribution among incident (I), reflected $(\mathbb{R})$ and transmitted ( T ) rays is given by a third set of laws deduced by Fresnel, using conservation of energy, and are given for $S$ polarization by

$$
\mathrm{R}_{\mathrm{S}}=\mathrm{R}_{\mathrm{V}}=\left(\mathrm{n}_{1} \cos \theta_{\mathrm{I}}-\mathrm{n}_{2} \cos \theta_{\mathrm{T}}\right)^{2} /\left(\mathrm{n}_{1} \cos \theta_{\mathrm{I}}+\mathrm{n}_{2} \cos \theta_{\mathrm{T}}\right)^{2} .
$$

For S-polarized (also called V or vertical polarization, since the electric vector is perpendicular to the 2-D reflection-refraction plane) and by

$$
R_{P}=R_{H}=\left(n_{1} \cos \theta_{T}-n_{2} \cos \theta_{\mathrm{I}}\right)^{2} /\left(n_{1} \cos \theta_{\mathrm{T}}+n_{2} \cos \theta_{\mathrm{I}}\right)^{2},
$$

for P polarization (also called H or horizontal, since the electric field vector is in the plane of reflection- refraction). Conservation of energy gives $T_{V}=1-R_{V}$ and $T_{H}=1$ $\mathrm{R}_{\mathrm{H}}$. From the figures below we note that the $\mathrm{S}=\mathrm{V}$ and $\mathrm{P}=\mathrm{H}$ polarizations behave very differently (they only take common values at 0 degree incident angles and at 90 degrees for non- internally reflection case.

## Extension of above methods

$$
c(x) \sigma(x)=\left[\ln \left(I_{1} / I_{2}\right) V /\left(t_{1}-t_{2}\right) . \quad\right. \text { Equ.(1) }
$$

- Extension of above methods in a later version to use Fresnel reflection coefficients. As a refinement, we note that if the transmission ( $\mathrm{T}_{1}$ and $\mathrm{T}_{2}$ for respective paths 1 and 2) and reflection coefficients $R_{1}$ and $R_{2}$ for respective paths

$$
c(x) \sigma(x)=\left[\ln \left(I_{1} / I_{2}\right)-2 \ln \left(T_{1} / T_{2}\right)-\ln \left(R_{1} / R_{2}\right)\right] /\left(t_{1}-t_{2}\right)
$$

Equ.(2)

## Finding Absorption Coefficient $\sigma(x)$

- From the Fresnel formulas and measurements of $\theta_{\mathrm{V}}, \theta_{\mathrm{T}}, R_{\mathrm{S}}=R_{\mathrm{V}}$, and $\mathrm{R}_{\mathrm{P}}=\mathrm{R}_{\mathrm{H}}$, it is possible to solve for $n_{1}$ and $n_{2}$. Once $n_{1}$ and $n_{2}$ are known it is possible to use the bi-static data to find the absorption coefficient from the product $\mathrm{c}(\mathbf{x}) \sigma$ ( $\mathbf{x}$. Then, $\mathrm{c}_{2}(\mathrm{x})=\mathrm{n}_{2}(\mathbf{x}) \mathrm{c}_{\mathrm{o}}(\mathbf{x})$, and the absorption coefficient
- $\sigma_{2}(\mathbf{x})=[c(\mathbf{x}) \sigma(\mathbf{x})]_{2} / c_{2}(\mathbf{x})$.


## Comparison of Features

## TABLE B -- Comparison of Features

| Feature | L-3 <br> Provision | Proposed TSS System |
| :---: | :---: | :---: |
| Lateral Resolution on surface | 8.3 mm (air) | 4.7 mm (air) |
| Depth resolution | 7.5 mm (air) | 4.3 mm (air) |
| Material Characterization | none | (1) Fresnel Reflectivities: $R_{V}, R_{H}$ for respective V, H Polarizations. <br> (2) Product of attenuation coefficient and phase speed $=\left[\left(\mathrm{c}_{0} \mathrm{n}\right) \mathrm{s}\right]$. <br> (3) Attenuation $=\sigma_{2}=\left[\left(\mathrm{c}_{\mathrm{o}} \mathrm{n}\right) \sigma\right]_{2} /\left(\mathrm{c}_{\mathrm{o}} \mathrm{n}\right) 2$. <br> (4) Polarization: $R_{V} / R_{H}$ or $\left(R_{V}-R_{H}\right) /\left(R_{V}\right.$ $+R_{H}$ ). |

## Block Diagram of proposed Scanner



Inverse Scatter (Inversion) Tomography (IST) Ultrasound Breast Cancer Scanner


$\triangle$ Fibrogland $\diamond$ Fat $\quad$ Ca $\quad \triangle$ FA $\quad$ Comp Cyst $\quad$ Simp Cyst

## Ductal Carcinoma In Situ

## Coronal Axial Sagittal

Sound speed

## Attenuation

## Reflection

## Benign Tumors Axial <br> Sagittal

## Sound Speed


(100)

## Top View of "phone booth scanner"



## Transmitter switching circuits

transmitter antenna elements


## Alternate way with amplitude control



## Finding absorption coefficient $\sigma_{2}(x)$

- From the Fresnel formulas and measurements of $\theta_{\mathrm{V}}, \theta_{\mathrm{T}}, R_{\mathrm{S}}=R_{\mathrm{V}}$, and $\mathrm{R}_{\mathrm{P}}=\mathrm{R}_{\mathrm{H}}$, it is possible to solve for $n_{1}$ and $n_{2}$. Once $n_{1}$ and $n_{2}$ are known it is possible to use the bi-static data to find the absorption coefficient from the product $\mathrm{c}(\mathbf{x}) \sigma$ ( x ). Then, $\mathrm{c}_{2}(\mathrm{x})=\mathrm{n}_{2}(\mathbf{x}) \mathrm{c}_{\mathrm{o}}(\mathrm{x})$, and the absorption coefficient
- $\sigma_{2}(\mathbf{x})=[c(\mathbf{x}) s(\mathbf{x})]_{2} / c_{2}(\mathbf{x})$.


## Plots of Transmit vs. Receiver Plane

 Element Number (scattering not shown)

## More Plots of Transmit vs. Receiver Plane

## Element Number (scattering not shown)



# THE FINAL STEP: SIMULATION RESULTS 

The above ray-based mathematics indicates that the problem for quantitative imaging of layers of materials is well posed and not singular.

Therefore, we skip ray-based inversion and pass on to finely sampled wave equation methods using an inverse scattering approach.

Use the Born approximation, since the simulated sample on the skin is thin (a few wave lengths thick).


Fig.7.a Simulated reconstruction of first object
Single-frequency simulated holographic back-propagation tomographic (HBT) reconstruction of a horizontal slice through a lo̊ss dielectric cylinder ("torso") with nearby rectangular external object. The inverse scattering algorithm is able to resolve the gap between the object and torso, indicating a true reentrant 3-D image reconstruction. In this image, the electrical


FIG. B SIMULATED RECONSTRUCTION OF SECOND OBJECT
A COLORIZED IMAGE THAT SHOWS THE CONTRAST BETWEEN THE EXTERNAL MATERIAL OBJECT (METALLIC) AND THE CYLINDRICAL BODY (LOSS DIELECTRIC). IN THIS IMAGE, THE ELECTRICAL CONDUCTIVITY OF THE BODY IS THE SAME AS IN THE IMAGE TO THE LEFT, BUT THE EXTERNAL OBJECT CONDUCTIVITY IS 100 S/M. THE DIFFERENCE IN COLOR OF THE OBJECT BETWEEN THE RIGHT AND LEFT IMAGES IS DUE TO A RESCALED COLOR PALETTE. NOTE THE APPARENT CHANGE IN SHAPE AND COLOR OF THE EXTERNAL OBJECT DUE TO ITS GREATER CONDUCTIVITY THAN IN THE LEFT SIMULATION 26

## Normalizing for Antenna Response

- Remove the angular, polarization, frequency, Tx and Rx coupling and noise properties of antenna


## THE END

Thank you.

| TABLE C -- Comparison of Technical Specifications |  |  |
| :---: | :---: | :---: |
| Specification | L-3 Provision | Proposed TSS System |
| Band width = B <br> Number of frequencies $=\mathbf{N}_{\mathrm{f}}$ <br> Frequency sample interval $=\mathrm{Df}=\mathrm{B} / \mathrm{N}_{\mathrm{f}}$ | $\begin{aligned} & 14 \mathrm{GHz} \\ & 32 \\ & 14 \mathrm{GHz} / 32=0.44 \mathrm{GHz} \end{aligned}$ | $\begin{aligned} & 40-50 \mathrm{GHz} \\ & 90-100 \\ & 40 \mathrm{GHz} / 95=0.42 \mathrm{GHz} \end{aligned}$ |
| Lateral Resolution $=\lambda[(2 \sin (\mathrm{q} / 2)]=$ | $(26$ to 40 GHz$)=>8.3 \mathrm{~mm}$ | 50 to 90 GHz$)=>4.4 \mathrm{~mm}$ |
| Depth Resolution $=\mathrm{c} / 2 \mathrm{~B}=$ | $3 \times 10^{\wedge} 10 / 2 \times 14 \times 10^{\wedge} 9=>1.07 \mathrm{~mm}$ | $3 \times 10^{\wedge} 10 /\left(2 \times 25 \times 10^{\wedge} 9=>0.6 \mathrm{~mm}\right.$ |
| Accuracy of reflectivity $=\mathrm{D}(\mathrm{R}) /<\mathrm{R}>$ | Not quantattive | $10 \%$ |
| Accuracy of $\mathrm{D}(\mathrm{cs}) /<$ (cs) $>=$ | Not quantattive | $10 \%$ |
| Polar $\left[\left(\left\langle\mathrm{E}_{\mathrm{V}}\right\rangle-<\mathrm{E}_{\mathrm{H}}\right\rangle /\left(\left\langle\mathrm{E}_{\mathrm{V}}\right\rangle+\left\langle\mathrm{E}_{\mathrm{H}}\right\rangle\right](\mathrm{q})=\right.$ | none | $0 \%$ < polarization < $100 \%$ |
| Stand-off Range (outside clothing) | Circle of $\mathrm{Rcm}=40 \mathrm{~cm}$ | Circle of R cm less range gate $=10 \mathrm{~cm}$ |
| Image rendering | Holographic image rendered as a gray surface | Inverse scattering reconstruction with color scale calibrated to material properties |
| Scan time | 3 sec | 4 sec |
| Compute time | 6 sec | 4 seconds |
| Purchase price for customer | \$200,000 | \$300,000 |
| $\mathrm{B}=$ bandwidth, $\mathrm{q} / 2=$ half angle of aperture, $\mathrm{c}=$ speed of light in air $3 \times 10^{\wedge} 10 \mathrm{~cm} / \mathrm{sec}$. Finite skin thickness material parameter inversion. $\mathrm{S}=(0.61$ $\lambda) /(\mathrm{n} \sin (\mathrm{q} / 2))=$ Resolution, $\lambda=$ wavelength, $\mathrm{n}=$ Refractive index, $\sin (\mathrm{q})=$ maximum angle of light gathering. Both n and $\sin (\mathrm{q})$ are constants for a given objective lens, their product is referred to as N.A. or "Numerical Aperture". |  |  |


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| Depth resolution | 5 mm (air) | 0.6 mm (water) |
| Material Characterization | None | (1) Fresnel Reflectivities: $\mathrm{R}_{\mathrm{V}}, \mathrm{R}_{\mathrm{H}}$ for respective $\mathrm{V}, \mathrm{H}$ Polarizations. <br> (2) Product of attenuation coefficient and phase speed $=\left[\left(c_{0} n\right) s\right]$. <br> (3) Attenuation $=s=\left[\left(c_{0} n\right) s\right] /\left(c_{0} n\right)$. <br> (4) Polarization: $\mathrm{R}_{\mathrm{V}} / \mathrm{R}_{\mathrm{H}^{\prime}}\left(\mathrm{R}_{\mathrm{V}}-\mathrm{R}_{\mathrm{H}^{\prime}}\right) /\left(\mathrm{R}_{\mathrm{V}}+\mathrm{R}_{\mathrm{H}}\right)$. |
| Image Rendering | Gray surface | Color surface with material classification |
| Scan time | 2 seconds/scan | 2 seconds/scan |
| Throughput | 200 to 300 <br> passengers/hour  | 300 passengers/hour |
| Cost (large production) | \$120,000 | \$200,000 |


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