Research Thrust R1
Subsurface Sensing and Modeling

A. Overview
B. Fundamental Sensor Research
C. Computational Modeling
D. Anticipated Results and Impact

Bahaa Saleh
Carey Rappaport

Diverse Problems – Similar Solutions
A. Overview
Subsurface Sensing and Modeling

Bio-Medical Applications

Environmental-Civil Applications

Validation Testbeds

Physics-Based Signal Processing and Image Understanding

Image and Data Information Management

Fundamental physics of SSI
Sensor design and testing
Mathematical and computer modeling
R1 Goals

L3 Engineered System
- Incorporate new sensors in Engineered System
- Incorporate new modeling algorithms in Software Resource Center

L2 Enabling Technologies
- Test and validate new sensors
- Incorporate modeling in testBEDs

L1 Fundamental Science
- Develop better understanding of physics of SSI
- Develop new SSI concepts (nonlinear, dual wave)
- Develop new comput. modeling algorithms
- Integrate phys & math modeling with inversion
- Develop a unified phys/math framework for SSI

E Education
- Enhance engineering curriculum in photonics, acoustics, electromagnetics
Need for a Unified Framework

Diverse problems...

**Probe**
- Electromagnetic
- Optical/IR
- Acoustic
- X-ray
- CW
- Pulsed
- Modulated
- Coherent
- Partially Coherent
- Multi-Spectral
- Classical
- Quantum
- Outside
- Inside
- Auxiliary

**Medium**
- Absorption
- Dispersion
- Scattering
- Diffusion
- Clutter
- Inhomogeneous/Layered
- Rough Surface

**Object**
- Absorption
- Fluorescence
- Nonlinear Absorption
- Scattering
- Nonlinear Scattering
- Diffusive
- Phase Object
- Depolarizing
- Stationary
- Moving
Broad Scale of Target Detail and Wavelength

Subcellular Biology
- 1 nm - 10 μm
- 1 cm - 100 m

Tissues & Organs
- 10 μm - 1 cm
- 10 cm - 1 km

Underground Diagnosis

Optics
Ultrasound

Radar
Sonar

Underwater Exploration
Three Subsurface Imaging Modalities

Localized Probing & Mosaicing (LPM)

Confocal Imaging
- Focused Illumination
- Focused Detection
- Pinhole

Time-Resolved Imaging
- Pulsed probe
- Time
- Detector
- Target
- Focused or Pulsed Probe
- Focused or Gated Detector

Optical Coherence Tomography (sectioning)
- Mirror
- Detector
- Target
- x
- Time
- Detectors
- Diffusive
- Ballistic
- Snake
Multiview Tomography (MVT)

X-ray CAT Scanning & Diffraction Tomography

Sources

Detectors

Crosswell Radar Tomography

Transmitter Array

Plume

Receiver Array

Interwell Region

Diffusive Wave Optical Tomography

Source Array

Detector Array

Target

Similar mathematical models
Multispectral Discrimination (MSD)

Fluorescence Microscopy
- Multi-wavelength Source(s)
- Filters
- Detector

Satellite Hyperspectral Imaging

Ultra-Wideband GPR Resonance

$|E_x|$ (non-specular)

Power Spectral Density

TNT Target Scattering in Smooth & Rough Sand
Need for Better Understanding of Physics

- Physical properties (e.g., density, porosity, stiffness, ..)
- Chemical composition
- Metabolic information
- Extrinsic markers (dyes, chemical tags)

Acoustic
- Density
- Compressibility
  - Linear/nonlinear

Optical
- Susceptibility
- Refractive index
- Absorption,
- Birefringence
- Fluorescence
  - Linear/nonlinear

Electromagnetic
- Dielectric constant
- Conductivity
- Nuclear spin

X-Ray
- Absorption
- Geometry

Electrical
- Conductivity
- Impedance
R1 Barriers

**Barrier 1**
Inadequate understanding of physics of SSI

**Barrier 3**
Lack of robust, physics-based recognition & sensor fusion techniques

**Barrier 4**
Lack of computationally efficient, realistic physical models

**Barrier 5**
Lack of Optimal End to End Sensor Design Methods

**Barrier 8**
Lack of a unified framework for diverse sensing & imaging modalities
B. Fundamental Sensor Research

- Nonlinear Wave Imaging (R1a)
- Dual-Wave Imaging (R1b)
Research Directions

- Greater contrast
- Greater SNR
- Finer axial resolution
- Finer transverse resolution
- Deeper penetration
- Avoidance of obstructions & occlusions

Improvement based on conventional state-of-the-art SSI techniques will only be incremental

Nonlinear-Wave Imaging

Dual-Wave Imaging
Nonlinear-Wave Imaging (Optical)

Two-Photon Fluorescence Microscopy
- Intense Laser
- Detector

Entangled-Photon Fluorescence Microscopy
- Laser
- Nonlinear Crystal
- Weak Entangled-Photon Beams
- Photon Pairs
- Fluorescence Photons
- Time

- Reduced phototoxicity
- Enhanced resolution

Barrier 1: Inadequate understanding of physics of SSI
- Understand the process of two-photon absorption for entangled light, including the effect of entanglement time and entanglement area
- Determine axial and lateral resolutions for various configurations
Nonlinear-Wave Imaging (Acoustic)

- Nonlinear beam propagation & scattering from interfaces
- Nonlinear bubble dynamics in Newtonian & viscoelastic media
- Bioeffects (Cavitation, Heating)

Barrier 1: Inadequate understanding of physics of SSI

- Nonlinear beam propagation & scattering from interfaces
- Nonlinear bubble dynamics in Newtonian & viscoelastic media
- Bioeffects (Cavitation, Heating)

Short burst of high-intensity diffraction-limited ultrasonic beam at high frequency $f_0$

Backscattered wave received at $2f_0$

Nonlinear medium (tissue) or medium with nonlinear "agents," e.g., bubbles

Image of in situ vein graft patch
Note improved contrast & resolution
Dual-Wave Imaging (Acousto-Photonic)

**Conventional Diffusive Optical Tomography**

- Optical Probes
- Detectors
- Object

**Sound-assisted Diffusive Optical Tomography**

- Optical Probe
- Acoustic Beam
- Detector
- Doppler-shifted Virtual probe
- Object

**Applications:** Soft-tissue imaging
- Breast tumor detection
- Pre-natal monitoring
- Stroke differentiation

** Addresses limited-view problem**

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**Barrier 1**

Inadequate understanding of physics of SSI

**Barrier 3**

Lack of robust, physics-based recognition & sensor fusion techniques
Dual-Wave Imaging (Photo-Acoustic)

- No ground contact is required
- Non-metallic objects & objects with no dielectric contrast can be detected

Field-test of laser-induced mine detection by NU & Laser Science, Inc, at Univ. of Mississippi, Aug. 99

Barrier 1: Inadequate understanding of physics of SSI
<table>
<thead>
<tr>
<th><strong>R1a Nonlinear Imaging</strong></th>
<th><strong>R1b Dual Wave Imaging</strong></th>
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<tbody>
<tr>
<td>Bahaa Saleh, BU</td>
<td>Ron Roy, BU</td>
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<tr>
<td>Leader</td>
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<td>Robin Cleveland, BU</td>
<td>Bahaa Saleh, BU</td>
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<td>Alex Sergienko, BU</td>
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C. Computational Modeling
Why Is Computational Modeling Essential?

Lack of computationally efficient, realistic physical models
SoilBED experiments show need for modeling the distorting effects of realistic ground roughness on Ground Penetrating Radar.
The scattering signature of the buried target is highly distorted by the complex underground environment.

FDTD Simulation of short-pulse GPR interaction with rough, dispersive ground and a buried plastic pipe.

The scattering signature of the buried target is highly distorted by the complex underground environment.
By characterizing rough surface clutter, we establish strategies for best sensor placement.
Although we cannot observe clutter-only signal, we can use it to guide sensor placement.
Priorities:
- ABCs for lossy media (1.5 yr)
- Auto. multiple time scales (2.5 yr)
- Geometry-specific gridding (3 yr)
- Non-linear field modeling (4 yr)
- Hybrid methods (5 yr)
- Statistical param. variation (5 yr)
- Real-time, 3D computation (10 yr)

Computational Modeling (Goals)

Total Field, 2 GHz Mod. Gaussian Pulse

PML Absorbing Boundary Conditions (ABC)

Dispersive Media Modeling in Time

Gaussian rough surface specification
### R1c Computational Modeling

<table>
<thead>
<tr>
<th>Role</th>
<th>Name</th>
<th>Institution</th>
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<tr>
<td>Leader</td>
<td>Carey Rappaport</td>
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<td>Ann Morgenthaler</td>
<td>NU</td>
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D. Anticipated Results & Impact
The strong coupling between R1 and R2 is a unique aspect of CenSSIS, which is expected to revolutionize SSI.
L1 research will result in new imaging techniques which will be validated in L2 testbeds. L1 research will address difficulties encountered in L2 testbeds and L3 applications.
**What Will Be Our Initial Program?**

<table>
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<tr>
<th>New System Concepts</th>
<th>New Sensing Concepts</th>
<th>New projects</th>
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<td>Multi-Layer Hyperspectral Imaging</td>
<td>Entangled-photon microscopy</td>
<td>SeaBED</td>
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<td>Electrical Impedance Tomographs</td>
<td>Nonlinear ultrasonic imaging</td>
<td>MedBED</td>
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<td>Hi-Res Undersea Visualization</td>
<td>Acousto-photonic imaging</td>
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<td>Civil-Underground Sensor Fusion</td>
<td>Photo-acoustic</td>
<td>SoilBED</td>
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<td>Subcellular Tracking</td>
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**Yr 1** | **Yr 2** | **Yr 3** | **Yr 4** | **Yr 5**
Impact on Education

New courses in subsurface imaging & sensing

- Graduate course, Diagnostic Ultrasound Medical Imaging, Barbone & Szabo (Agilent), BU-AM503
- Graduate course, Microscopy (planned)
- Freshman course, Subsurface Sensing & Imaging, Saleh, BU-EK130

Modules added to existing engineering courses
(Photonics, EM, Acoustics)

- Graduate course, Signals & Images (on Subretinal Imaging), Roysam, RPI-BMED4470
- Graduate course, EM Computational Modeling, Rappaport, NU-ECE3347
- Freshman course, Engineering Design/Subsurface Applications, Rappaport, NU-GE1103

Experiments added to existing labs courses
(Photonics, EM, Acoustics)

Student participation in relevant, applied, multi-disciplinary, theoretical & experimental research in sensing & imaging
## Summary of Anticipated Results

**L3: Engineered System**
- Incorporation of new sensors in I-PLUS
- New modeling algorithms in Software Resource Center

**L2: Enabling Technologies**
- Testing of nonlinear & dual-wave sensors
- Incorporation of modeling in testBEDs

**L1: Fundamental Science**
- A unified phys/math framework for SSI
- Better understanding of physics of SSI
- New SSI concepts (nonlinear, dual wave)
- New & improved comput. modeling algorithms
- Integration of phys/math modeling & inversion

**E: Education**
- An impact on engineering curriculum