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SDRD SITE-DIRECTED RESEARCH & DEVELOPMENT

Millimeter-wave imaging diagnostic for high-explosive fireball characterization STL-011-19, Year 3 of 3

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AFRL, Eglin AFB: Dr. Greg Meyer, Adam Rutkowski

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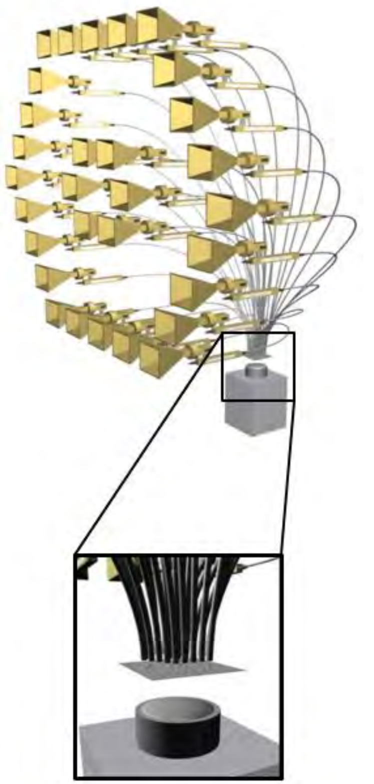
Challenge

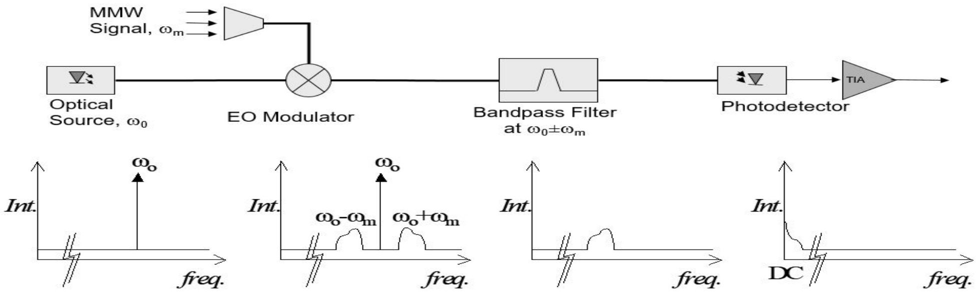
- Large-scale high explosives test events conducted at facilities like BEEF can generate significant optical obscurants at early times, preventing accurate characterization of important test parameters such as case fracture pattern and mean particle size
- Our challenge is to address the need for early-time estimates of particle size distribution, density, temperature, and emissivity of the cloud
- Quantify important test parameters for HE test performance and model verification and prediction

A recent high explosive test event at the Air Force Research Laboratory's (AFRL) High Explosives Research & Development facility, Eglin AFB, Florida

Innovation

- Apply a distributed aperture array of mm-wave antennas to form an imager capable of seeing through obscurants
- This work will provide the first measurements of an active/passive mm-wave RF imaging capability in a high explosive test environment
- Unlike optical sensing modalities, millimeter-wave (mmW, 60–100 GHz) imaging can see through the soot, smoke obscurants, and metal fragments
- Phased array RF antenna architecture designed by Phase Sensitive Innovations under AFRL contract
  - Up-conversion of RF signals onto optical carriers
  - EO modulators enable spatially ‘coherent’ RF Tx and Rx over octaves of BW
  - Phase preservation allows for spatial correlation (beam forming)





Phased array imager developed by AFRL & PSI (top)

RF signal capture schematic (left)

Photodetector is a commercial LWIR camera (inset top)

Technical Approach Summary

- Team with AFRL to leverage their work on mm-wave imaging
  - AFRL has interest in fragment tracking
  - Developed common requirement at AFRL meeting
- Develop models:
  - Particle cloud model based on Mie theory
  - mm-wave sensor model
- Verify models with laboratory data
- Hand off to AFRL via MIPR in place
- Sponsor MIPR for FY22 in process

Requirement	**Objective**
Mass	+/-5%
Velocity	
Determine shape	Morphology
Number of initiations	10
Velocity range	0.5 to 2.5 km/s
Minimum mass	0.4 grams
Minimum resolution	
Track object location	+/-10 m
Form tracks	with other sensors
Tie to other sensors	Other such as x-ray

PSI SOW – Reflector Design for Standoff

- Task 1: Finalize Reflector Design (from previous subcontract)
  - High spatial resolution imagery (<2 cm spatial resolution) at standoff ranges (~10 m)
  - In configurations that offer maximal protection for the imager
  - Including trade-offs in imaging frame rate vs. passive sensitivity
- Task 2: Lens Fabrication & Test (AFRL MIPR)
  - Fabricate lens finalized in Task 1
  - Characterize assembly
  - To be completed in FY22 with pass-through MIPR from AFRL
- Task 3: Kinetic test (AFRL MIPR)
  - Three-day test at AFRL
  - Final report & test data
  - To be completed in FY22 with pass-through MIPR from AFRL
- STL analysis of kinetic test data (AFRL MIPR)
  - Continued model and fragment prediction

STL Mie Scattering Modeling Capabilities

- Modified and enhanced from Matler's implementation of Bohren & Huffman's Mie model
  - Predict Measured Attenuation - completed
  - Reverse process - Predict radius from measurements based on Beer-Lambert
    - Separate extinction into absorption (emissivity, ε) and scattering (ρ)

$$T = \left(e^{-R\cdot\sum_{r_{min}}^{r_{max}} C_{abs}\cdot N(r)\cdot dr}\right)\left(e^{-R\cdot\sum_{r_{min}}^{r_{max}} C_{sca}\cdot N(r)\cdot dr}\right) = (1-\varepsilon)(1-\rho)$$

$T = 1 - \varepsilon - \rho + \rho\varepsilon$ – not this includes absorption of scattered light

    - Develop method to extract intensity from imagery
    - **Convert absorption, transmission & scattering into particle size – to be completed in follow on work**

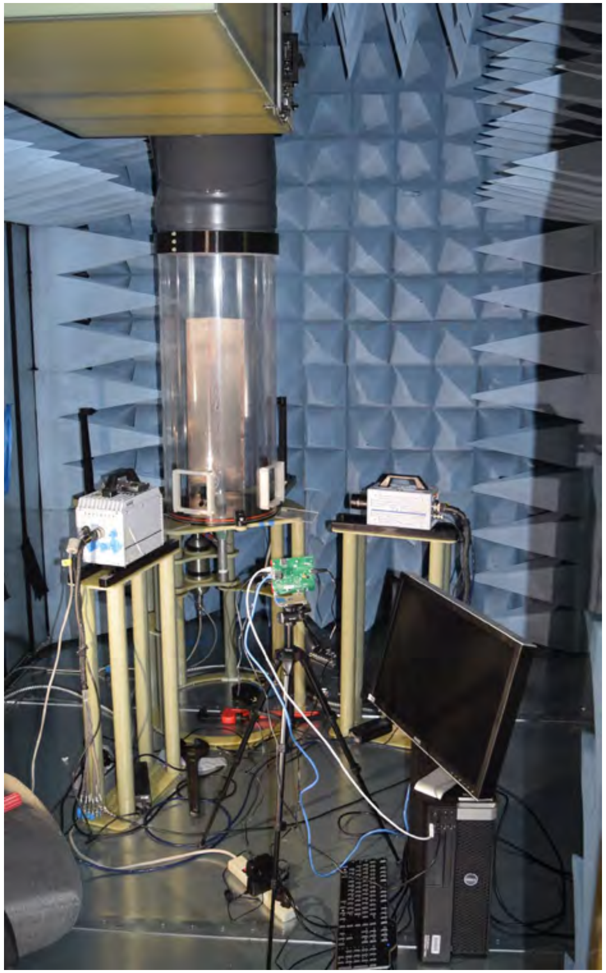
Predict measured attenuation

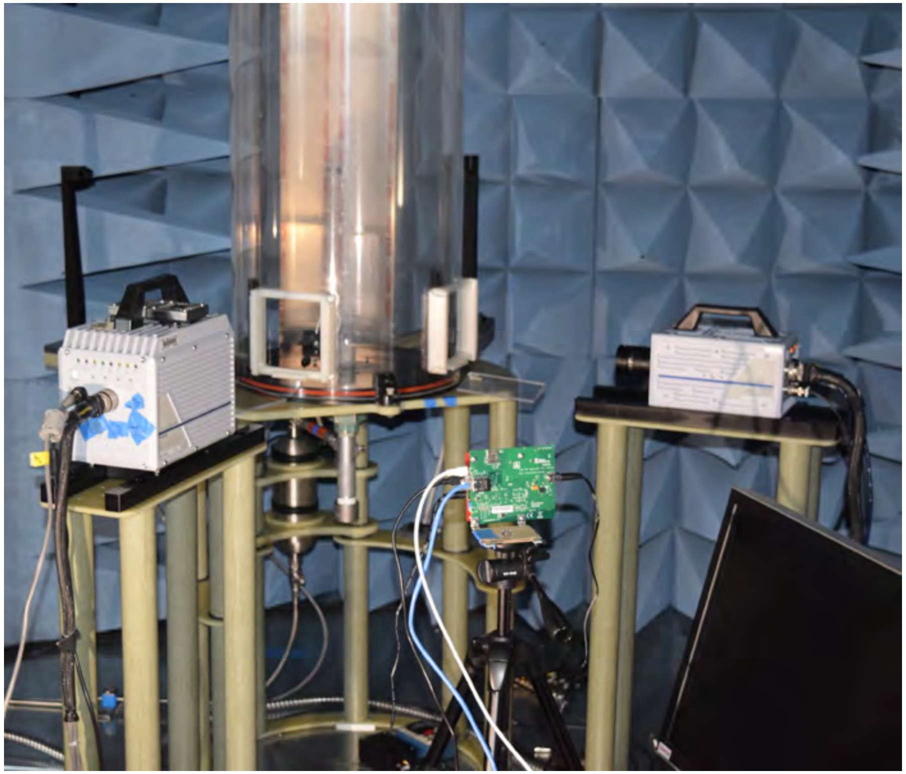
Inputs	Outputs
• λ • Material Dielectric constant, bulk density & weight • Volume of cloud material • $\langle radius \rangle$±σ • Temperature	• Mie Coefficients • Scattering • Absorption • Cloud attenuation

Predict radius from measurements

Inputs	Outputs
• λ • Material Dielectric constant & bulk density • ***Background imagery*** • ***Cloud imagery*** • Approx. range & weight of material • Temperature	• Aerosol cloud emission • Scattering • Volume of cloud • $\langle radius \rangle$±σ

STOA for Model Verification





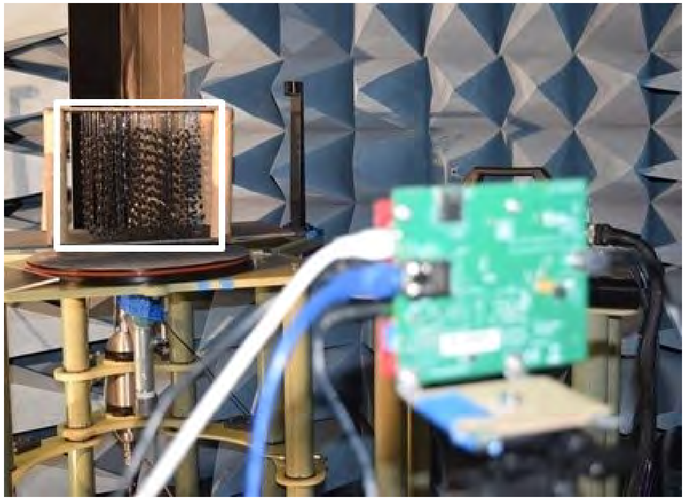
SHOCK TUBE OVERPRESSURE APPARATUS (STOA) IN DYNAMIC VERIFICATION CONFIGURATION

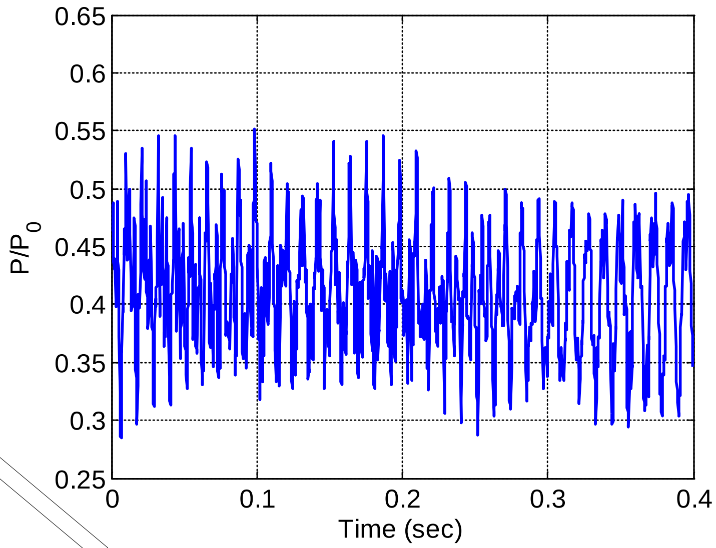
Static Verification Data – 77 GHz TI Radar

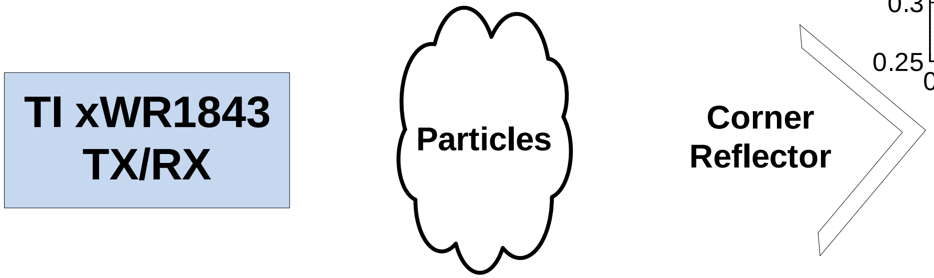
- Verification method still in the works
  - Absorption (emissivity, ε) could not be checked due to sensor phase noise
  - Working on expressions for measured data using setup to get ρ and T.

$$\frac{P}{P_0} = \frac{\rho}{\rho_0} + \frac{T^2}{\rho_0}$$

- Due to corner reflector being further from xWR1843, we added a correction factor for steradian subtense of reflector and beads
- First estimate of ρ ignores T^2, multiplies by π
  - Moving beads changed return
  - Model scattering into π steradians = 86.51%
  - From this, we compute ~85±5%
- Need to improve setup to get estimate to verify 'new' equation







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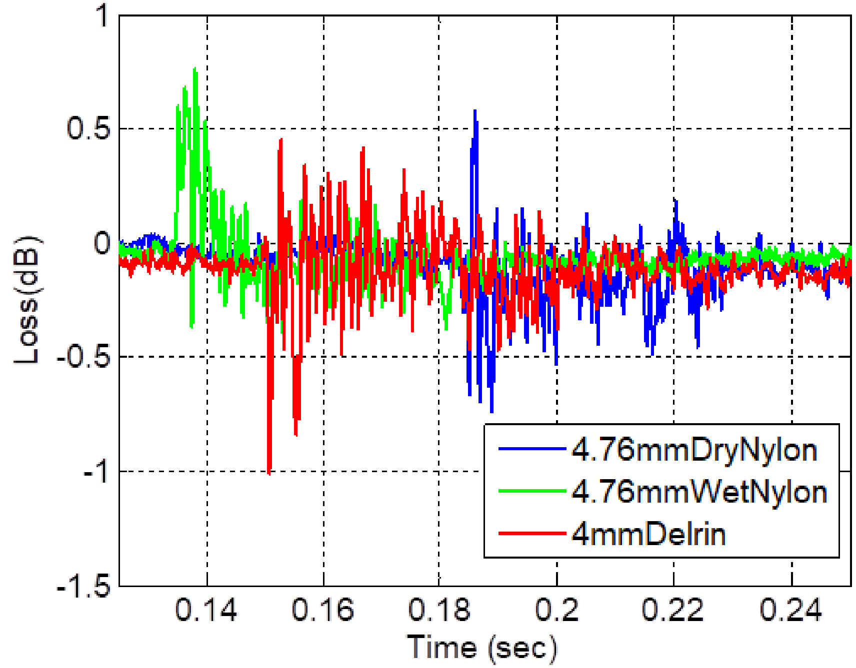
SDRD SITE-DIRECTED RESEARCH & DEVELOPMENT

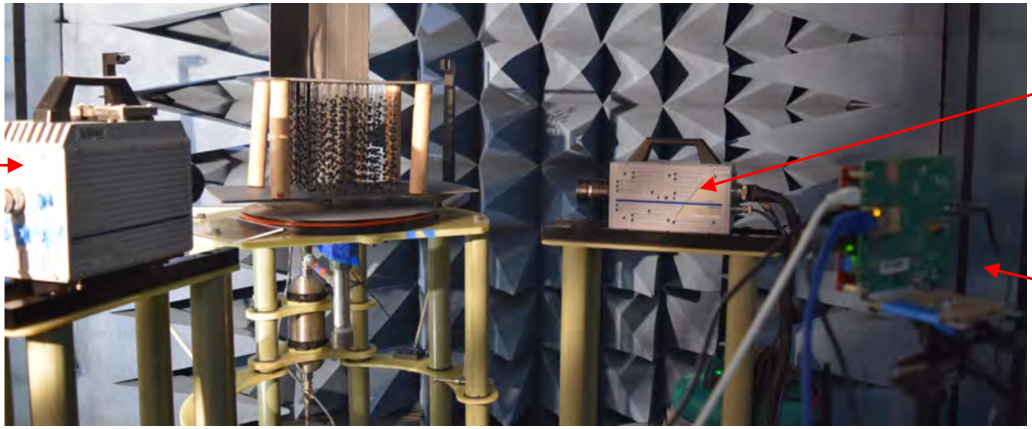
Dynamic Verification Data – 77 GHz TI Radar

- Dynamic experiments in Shock Tube Overpressure Apparatus (STOA)
  - Selected 4–5 mm diameter beads with different absorption coefficients
  - Total mass load calculated to verify model
  - Approximate particle velocity was 200 m/s



REFLECTOR

PHOTRON SA4 HIGH SPEED CAMERA



PHOTRON SA3 HIGH SPEED CAMERA

TI MM-WAVE TRANSMIT AND RECEIVE 77GHZ

STOA

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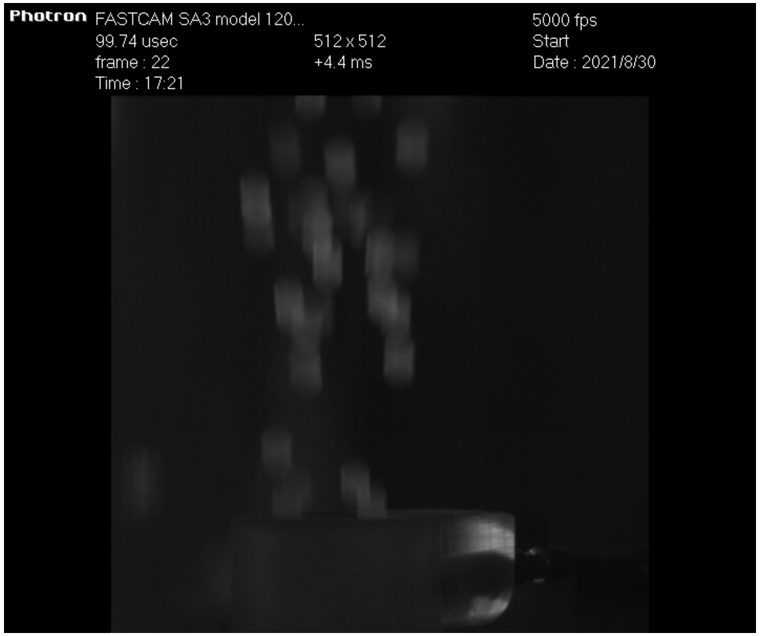
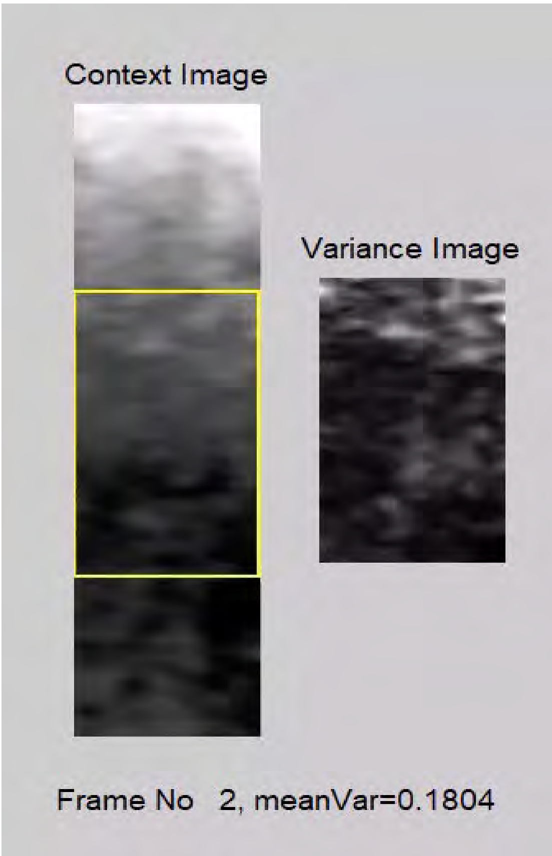
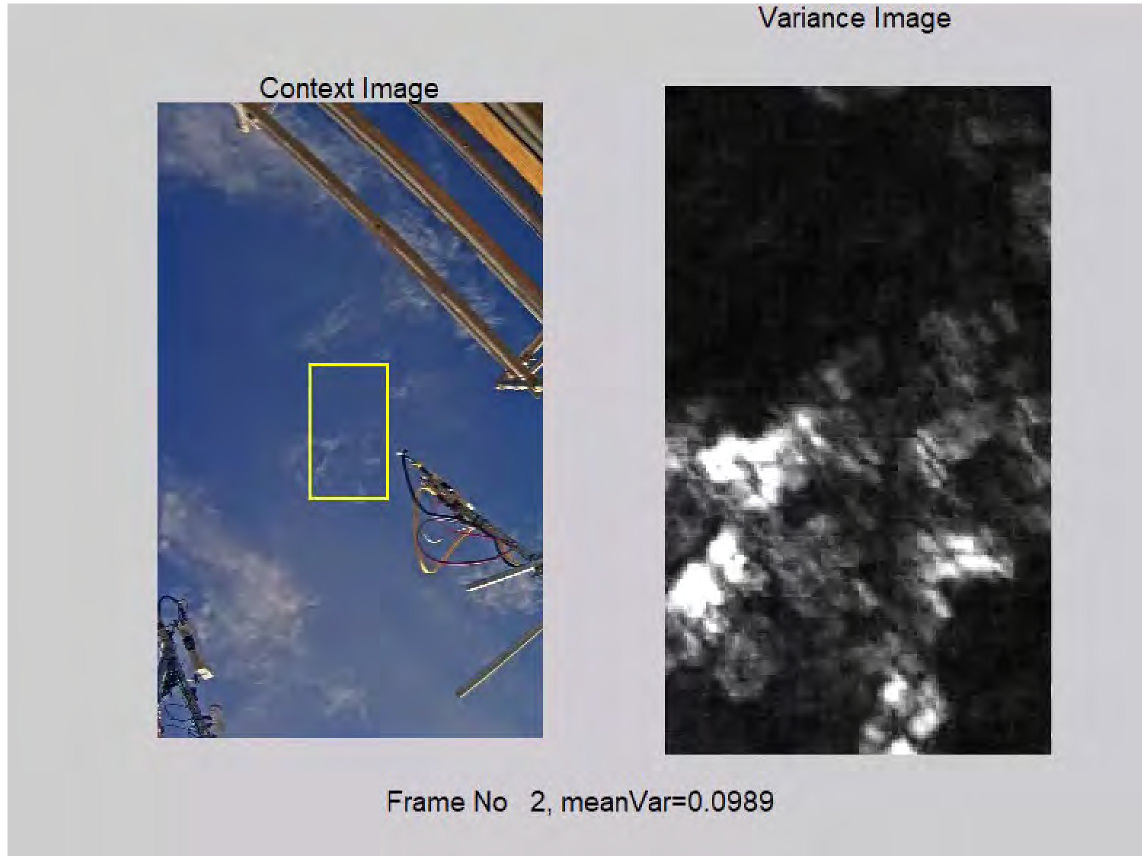


Sponsor data for model verification

Thruvision 250 GHz, TAC-16



Thruvision Context Visible



- **143 datasets of known aerosol particle size and quantity**
- **Visible and mm-wave data**

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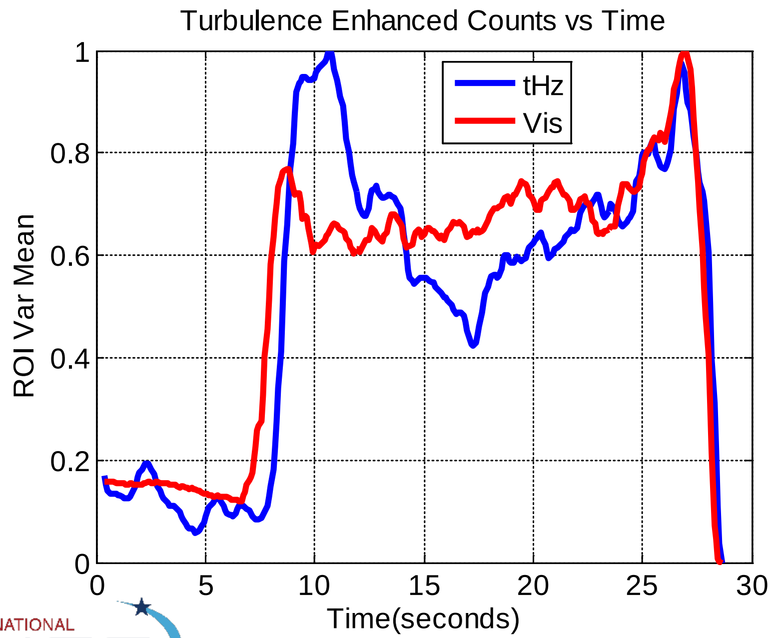
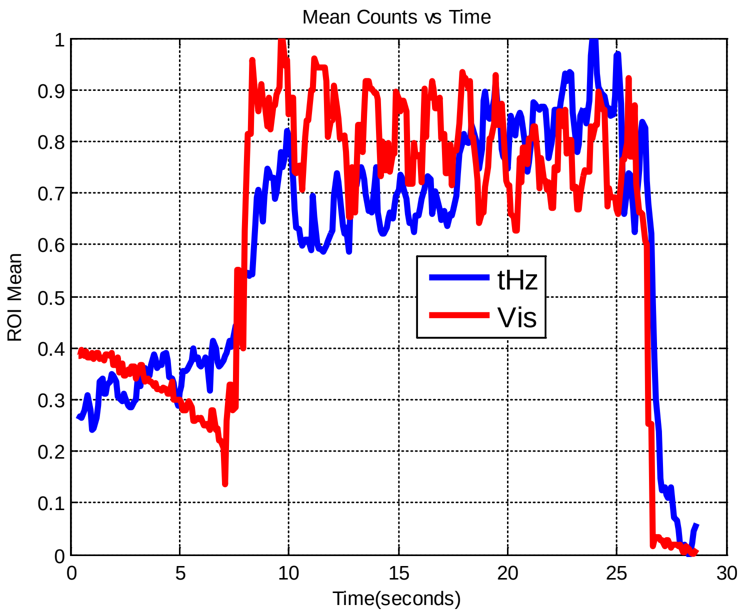
Example Intensity plots

- Using turbulence enhanced counts, ROIs for average counts – baseline gives background levels
- Conversion of counts to absorption, transmission, and scattering into particle size – to be completed in follow-on work for AFRL and DTRA





Summary

- Sensor model predicts AFRL mm-wave imager performance in a variety of conditions – updates based on PSI standoff design progressing
- Planned AFRL high explosives testing delayed due to Covid-19 and costs related to necessary mm-wave imager modifications
  - Contract with PSI is in place; last two tasks will be paid for by AFRL
- Model updates for estimating particle size from imagery progressing
  - DTRA mm-wave aerosol data complementary to this task
  - Developed new method based on Beer-Lambert's law
  - FY22 MIPR will continue the particle size work
- Dynamic model verification data collected
  - Completion of particle size model will be split between DTRA and AFRL funding

Impact

- Final tools address the need for
  - Early-time estimates of particle size distribution, density, temperature, and emissivity of the cloud
  - Intermediate time fragment tracking when cloud obscures the fragments
- Developed sponsor relationships based on common goals resulting in follow-on work
  - AFRL has pledged a significant contribution towards further testing in FY22
- Mie scattering model applicable to many projects