Defence Research and Development Canada
Recherche et développement pour la défense Canada

Through-Wall Synthetic Aperture Radar (TWSAR)

Overview of Canadian R&D

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Radar Sensing & Exploitation
DRDC - Ottawa Research Center

NATO SET-247 Specialists’ Meeting
Remote Intelligence of Building Interiors
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DRDC | RDDC

Canada

Acknowledgements

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- The DRDC Valcartier LIDAR team:
  - Jonathan Fournier, Stéphane Messier, Gilbert Tardif (retired)

Photos by J. Lang, DRDC Ottawa

Acknowledgements

- NATO SET-155: Advancing Sensing Through the Walls Technologies
  - Oct 2009 – December 2014
  - Participating nations: US, CA, IT, NO, SWE, FR
  - Joint trials in October 2013
- NATO SET-100: Sensing-Through-The-Wall Technologies

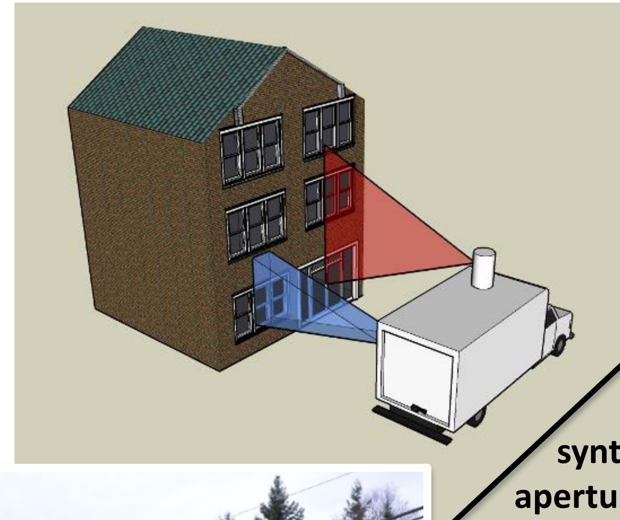
Outline

- The TWSAR system
- Overview of capabilities
- Data exploitation

The TWSAR system

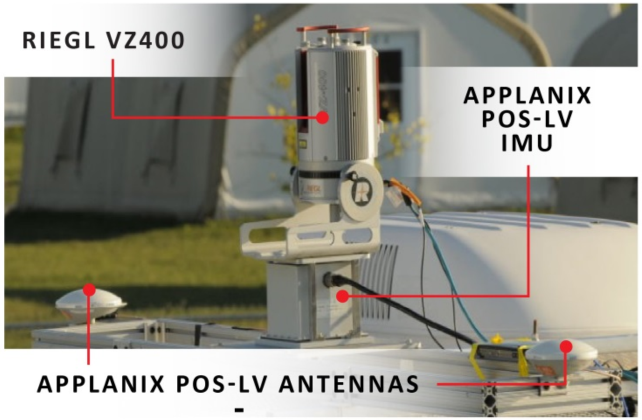
The objectives and concept of operation

- To develop novel through-wall radar and LIDAR technologies to generate 3-D images of building interiors and exteriors, including targets of interest within buildings
- The vehicle-mounted system is driven in front of a building of interest
- Standoff distance: typically a few meters to 20 meters

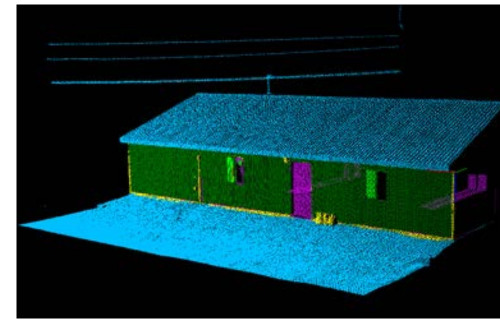


synthetic aperture radar (SAR) processing

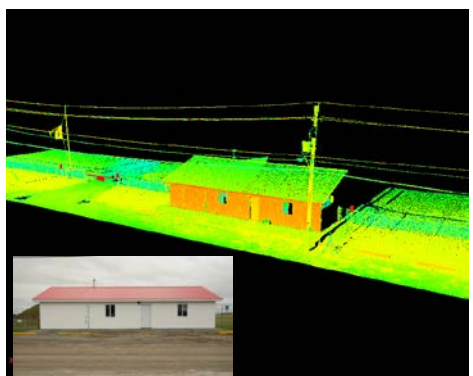
The DRDC vehicle-mounted imaging system includes a LIDAR and geo-positionning system

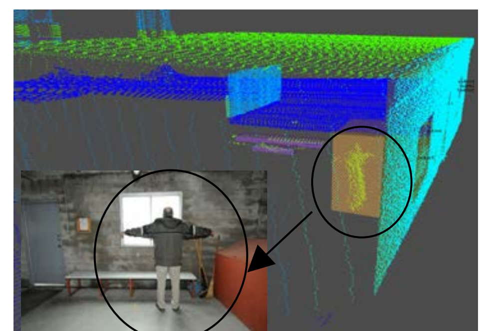


Detects wall features using automatic point cloud processing



Provides context information

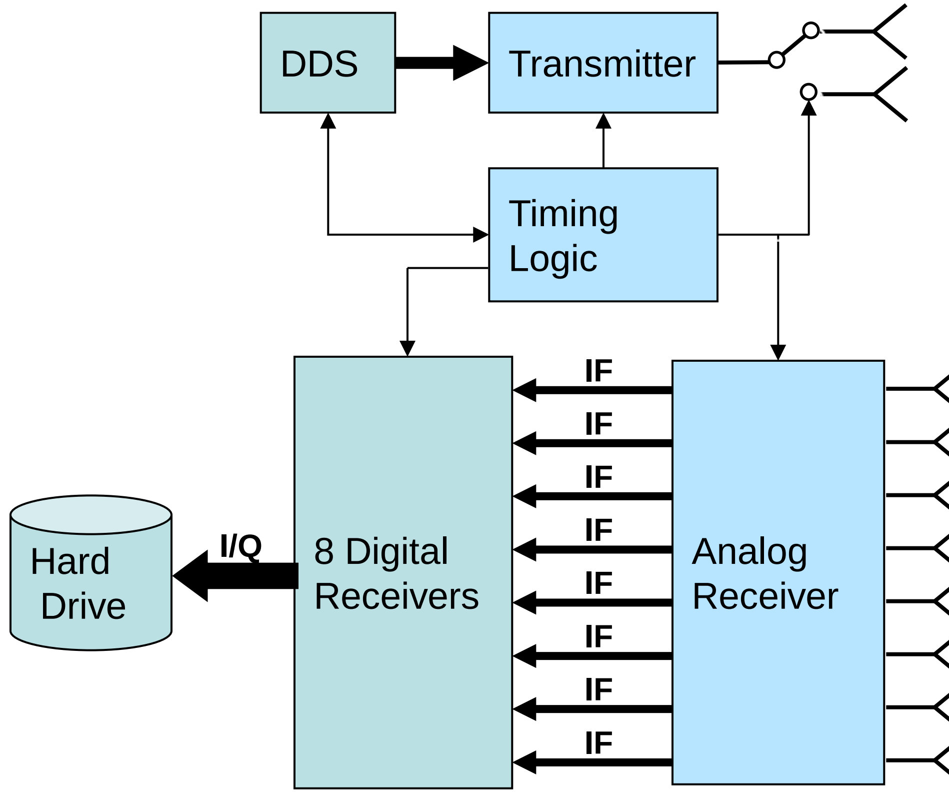




Acquires points on targets located behind uncovered windows

The TWSAR radar

- L-band FMCW radar (0.8 to 2.7 GHz)
- Both COTS and custom components
- Constant pulse repetition frequency (PRF)

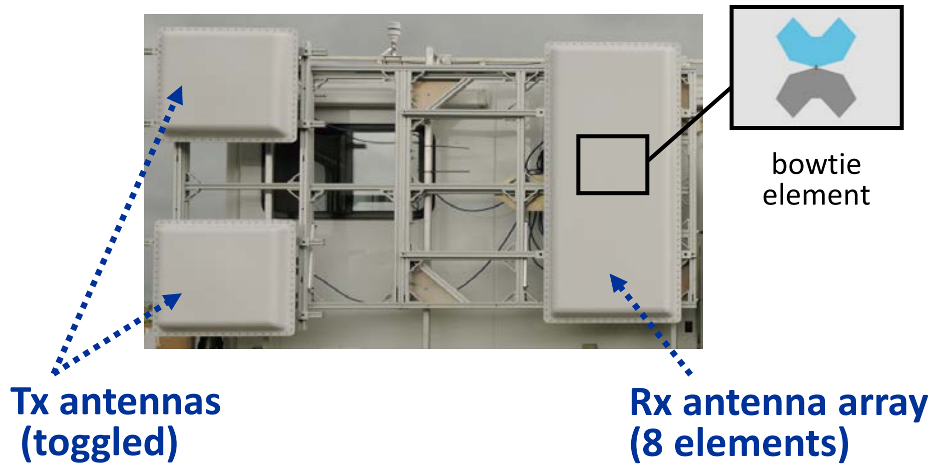


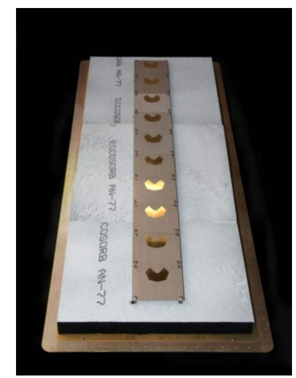
COTS

In-house development

The TWSAR antennas

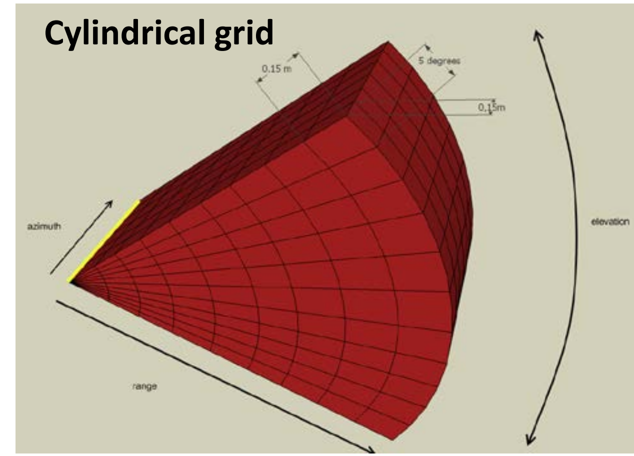
- Compact Y-shaped printed bowtie elements
- Element antenna pattern:
  - quasi-omnidirectional for H-plane (azimuth)
  - ≥60 degrees for E-plane (elevation)
- V polarization
- Slow-time MIMO operation for doubled resolution in elevation



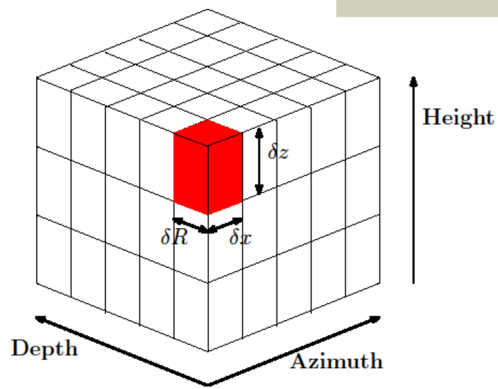


3-D synthetic aperture radar

- Large radar bandwidth
  - Range or across-track resolution (~12 cm)
- Synthetic aperture radar processing
  - Azimuth or along-track resolution
  - Fixed synthetic aperture angle for equal resolution at all ranges (typically 50° to obtain ~12cm resolution)
- Physical vertical array
  - Elevation resolution (3.4°)
- Time-domain backprojection algorithm (delay-and-sum)
  - Post-processing
  - No wall compensation or mitigation
  - No multipath exploitation



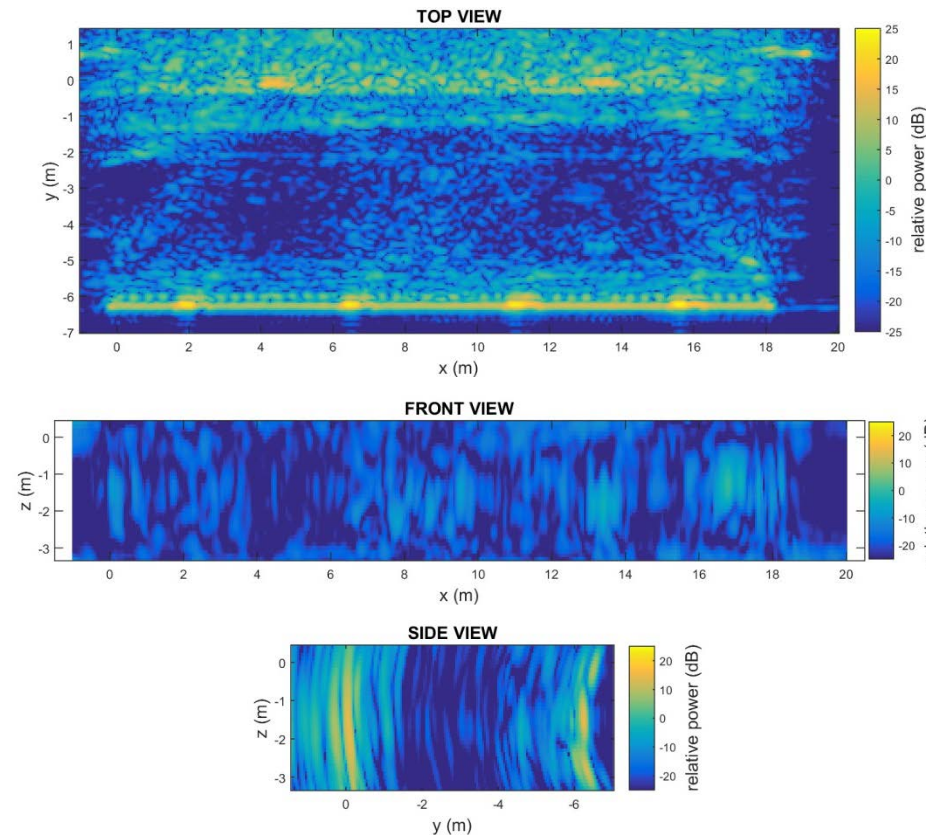
Cartesian grid



TWSAR capabilities
or
“It’s there.” Really?

The basic 3-D SAR image

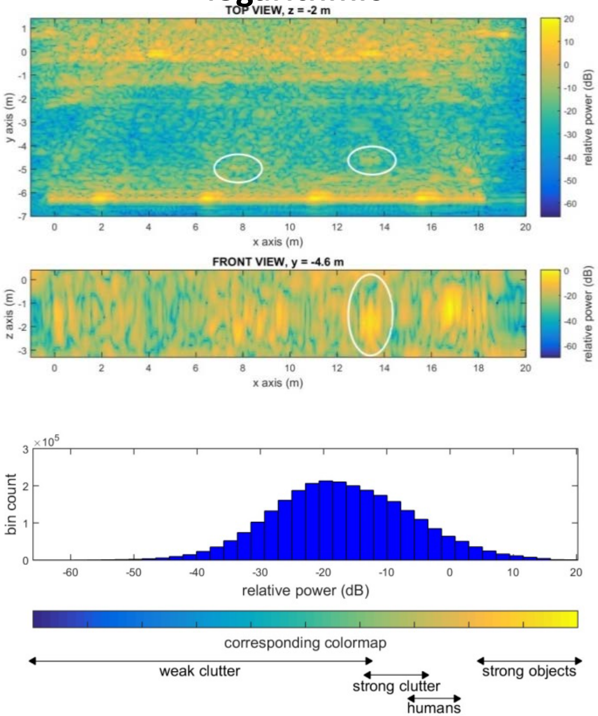
- 3-D matrix or data cube
- Coordinate axis are aligned with the building, origin at one corner
- Data displayed as three orthogonal slices:
  - Top view
  - Front view
  - Side view



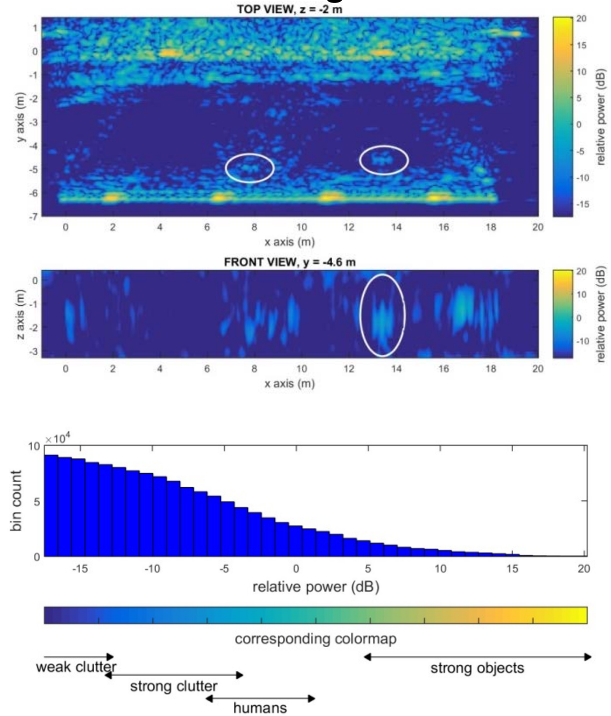
But is it truly there?

- Sometimes it's a matter of scaling the SAR images

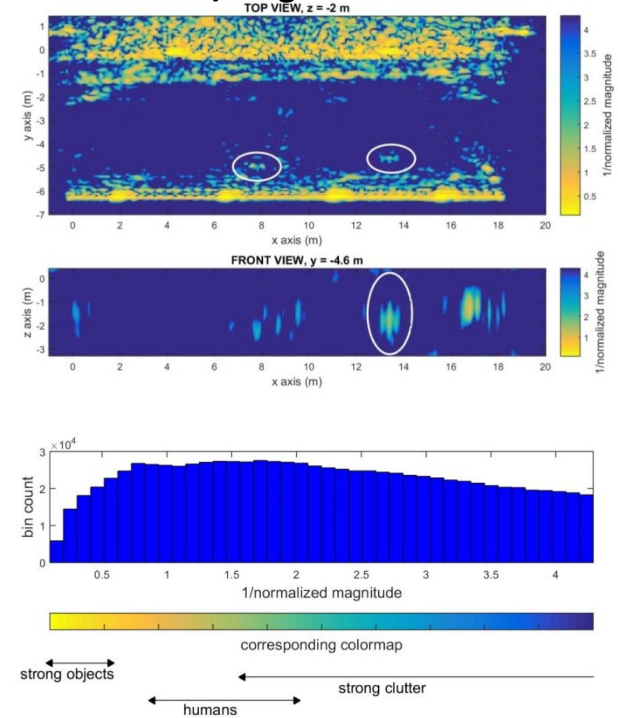
logarithmic



thresholded logarithmic

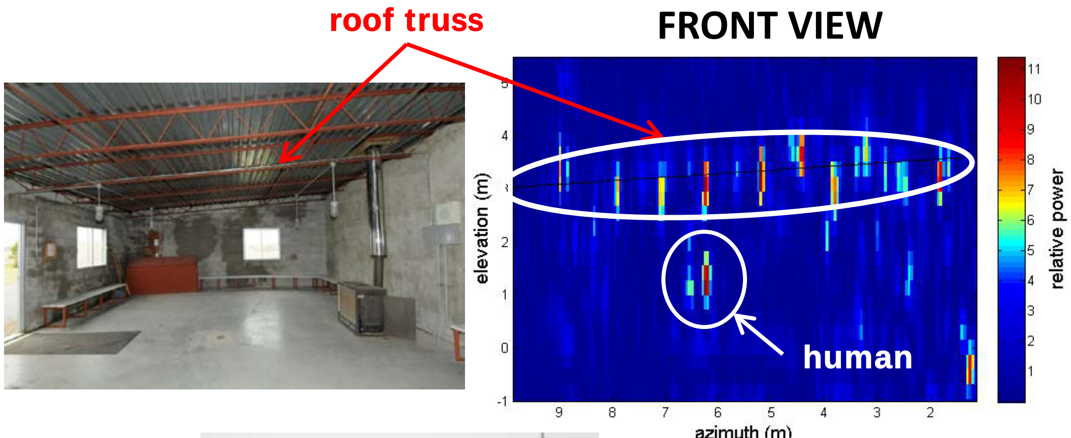


1/magnitude

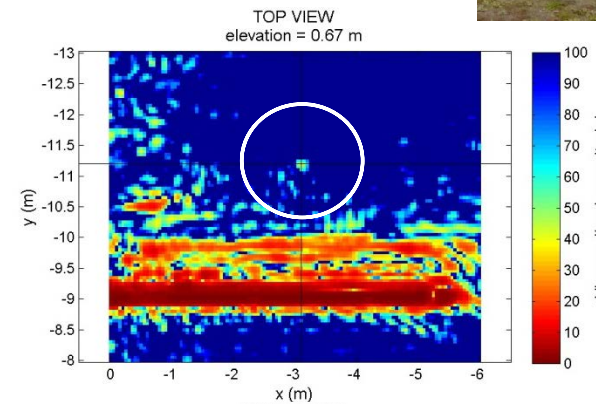


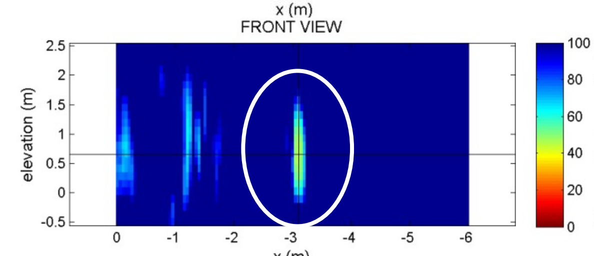
The through-wall radar can detect targets behind challenging walls

- Cinder block wall



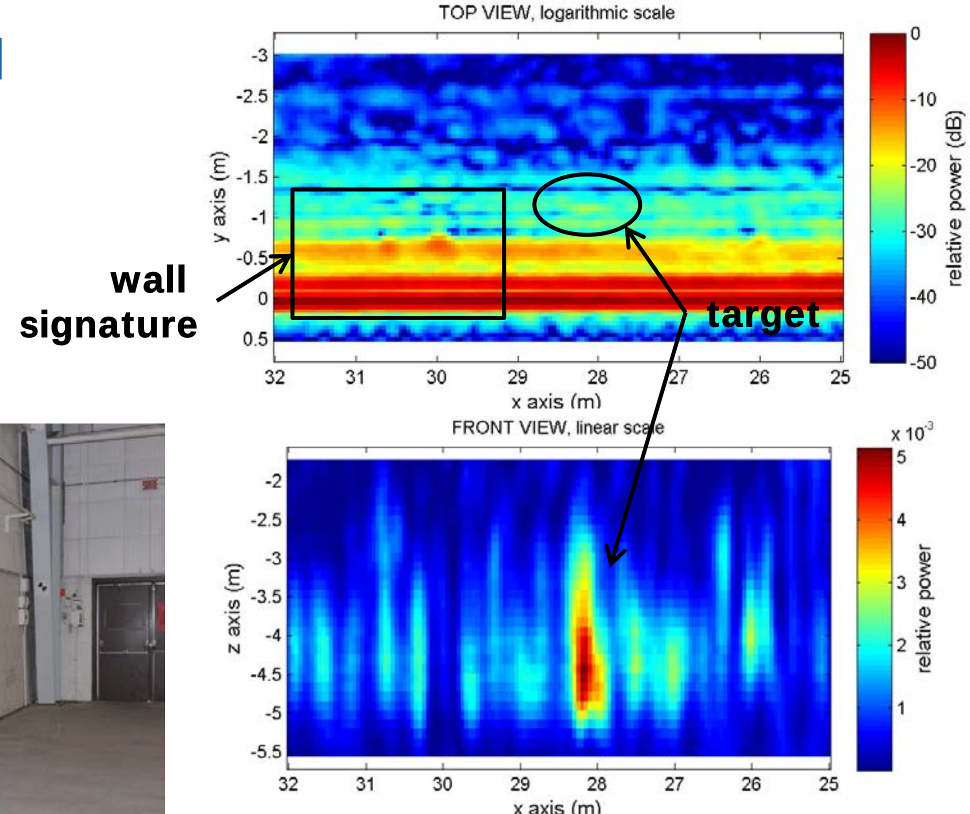
- 10 inches reinforced poured concrete wall



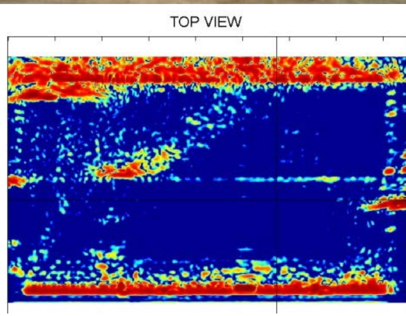


The through-wall radar can detect targets behind challenging walls

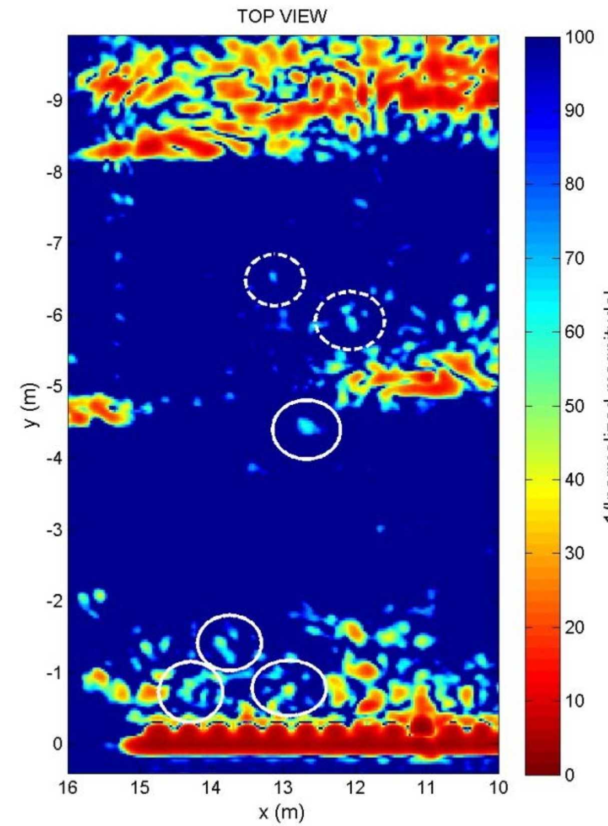
- 8 inches cinder block and 4 inches brick
- Human target 40 cm behind wall



The through-wall radar can detect multiple human targets in a small room

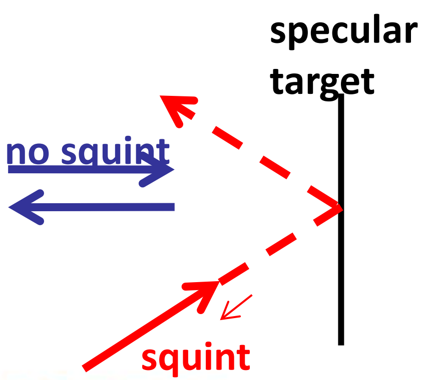


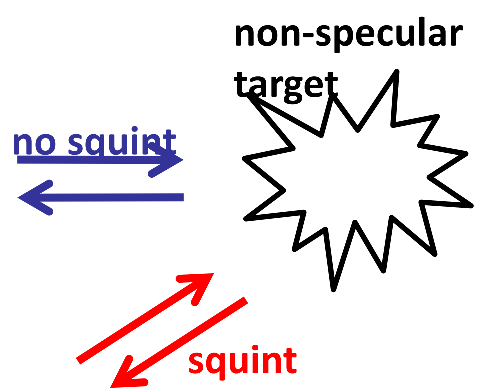
Inside the small room are positioned 6 human targets

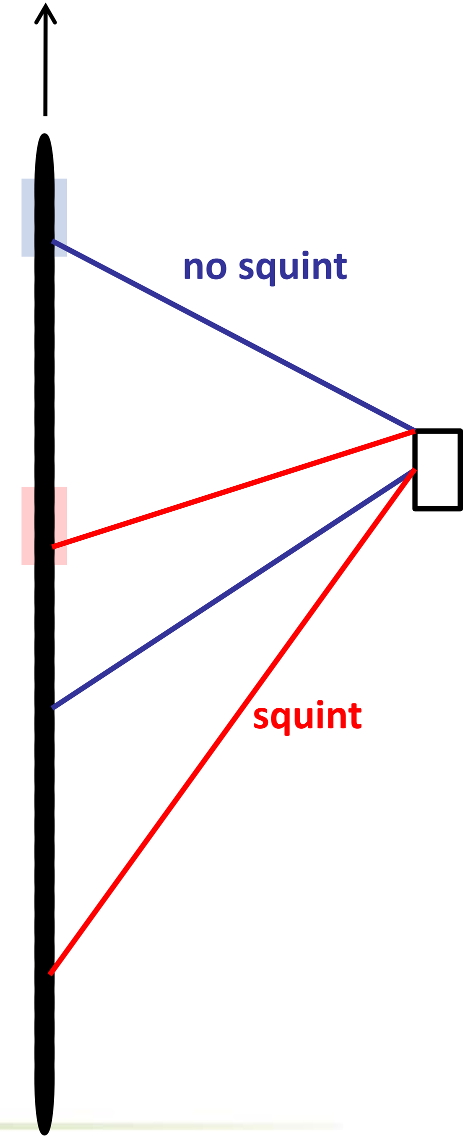


Squinted SAR geometry

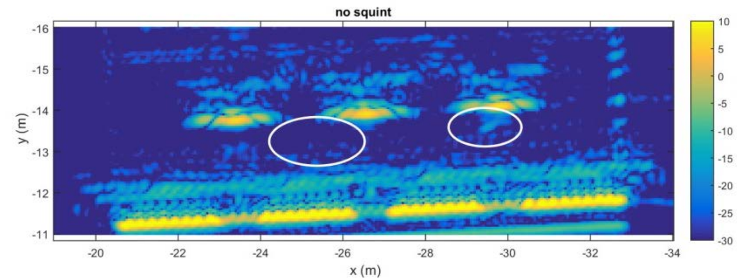
- The antennas have very large beamwidth in azimuth: it allows to process the *same* raw data using various squinted geometries
- Using a squinted SAR geometry:
  - The return from specular targets is minimized
  - The return from non-specular targets remains the same
- Also useful when the non-squint line-of-sight is blocked

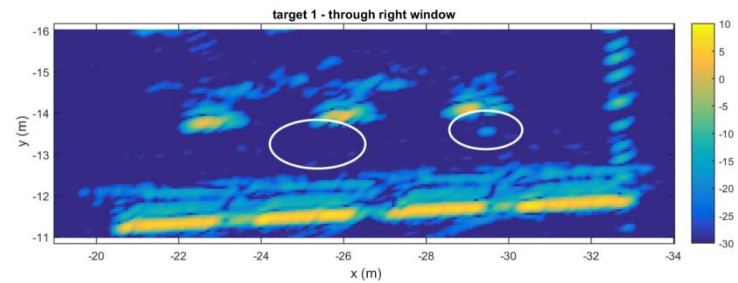


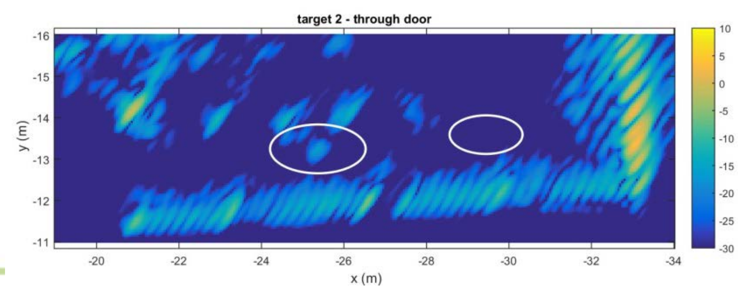


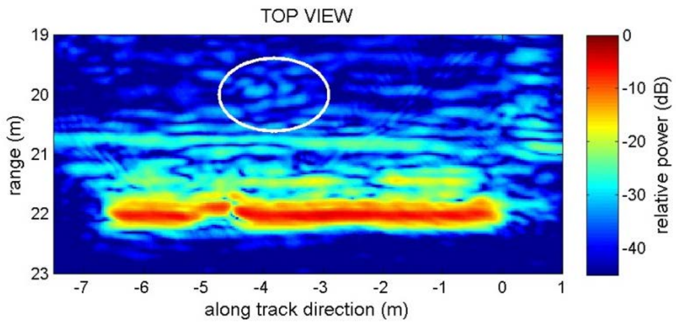


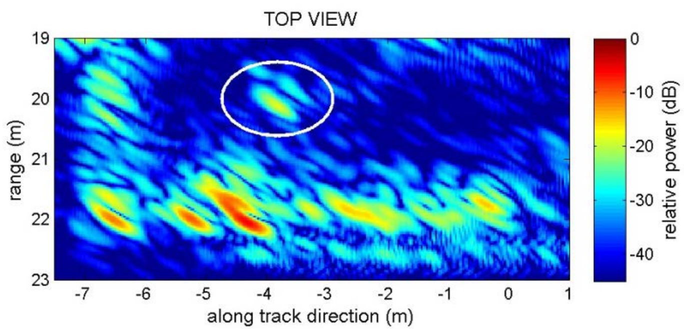
Squinted SAR detections





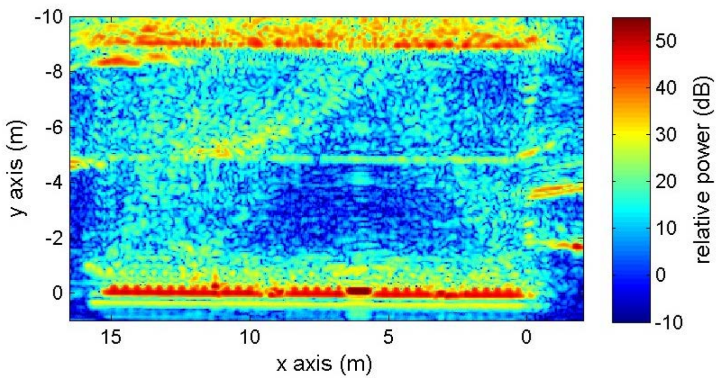




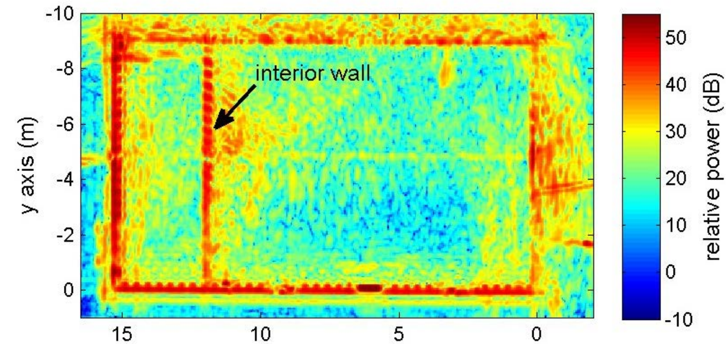


The through-wall radar can provide information on interior room layouts

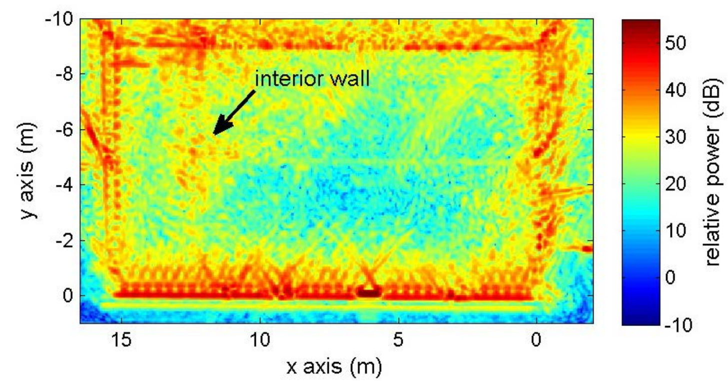
- Vinyl/gypsum/wood studs building
  - Top view
  - Reference front path image



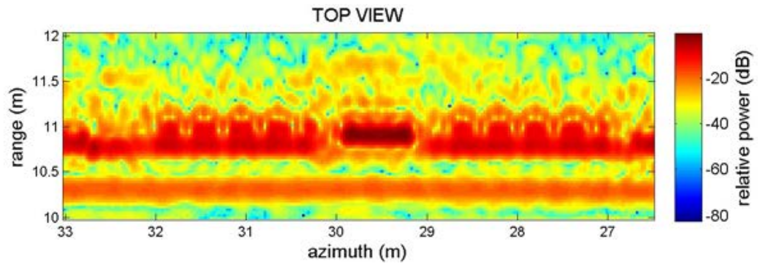
- With access to two sides of a building
  - Sum of front and side path intensity images

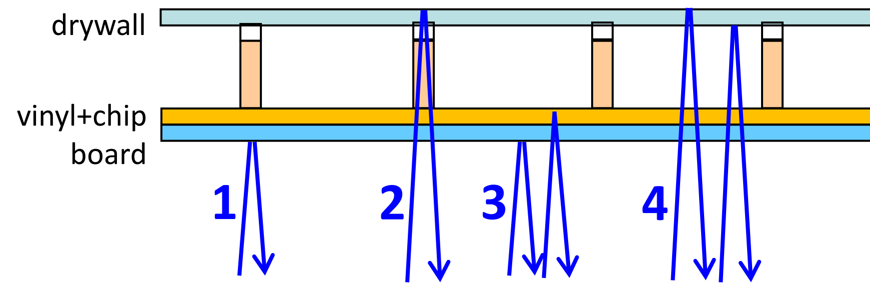


- Using front path only and multiple look angles
  - Sum of three squinted geometry intensity images

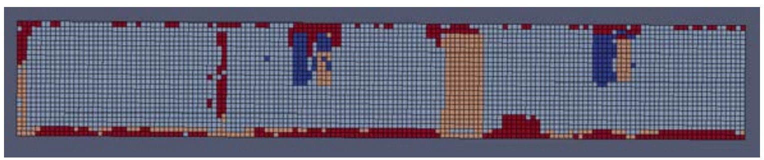


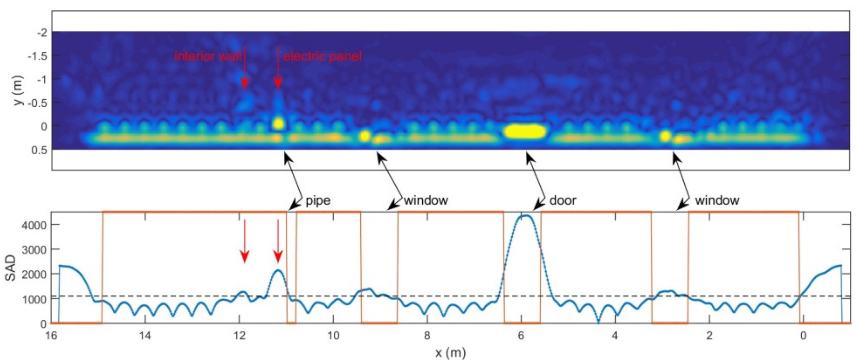
The through-wall radar can provide information on the internal wall structure and on anomalies behind the wall



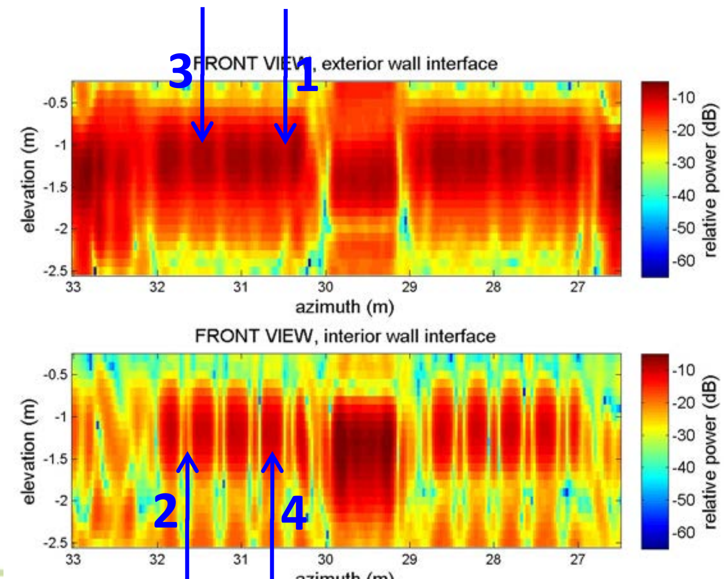


LIDAR occupancy grid





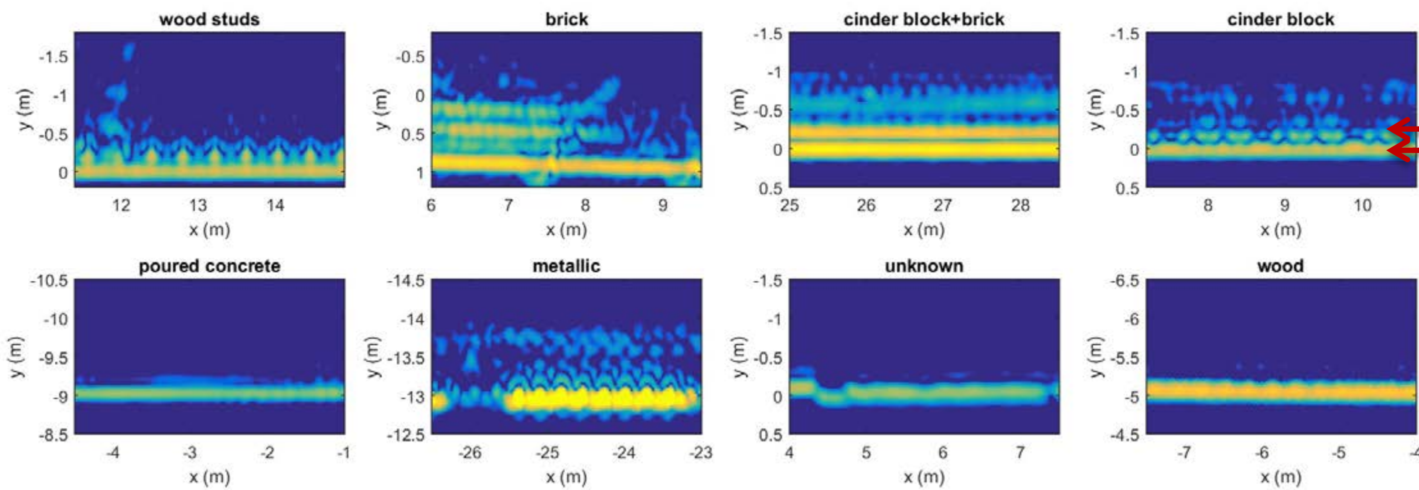
Sum of Absolute Differences (SAD) template matching



Determining the wall category

- 17 different walls, 5 different categories:
  - 1-vinyl/gypsum/wood studs, 2-cinder blocks, 3-brick+cinder blocks, 4-poured concrete, 5-others
- Using LIDAR occupancy grid of the front wall to determine valid azimuth samples
- TWSAR wall signature features

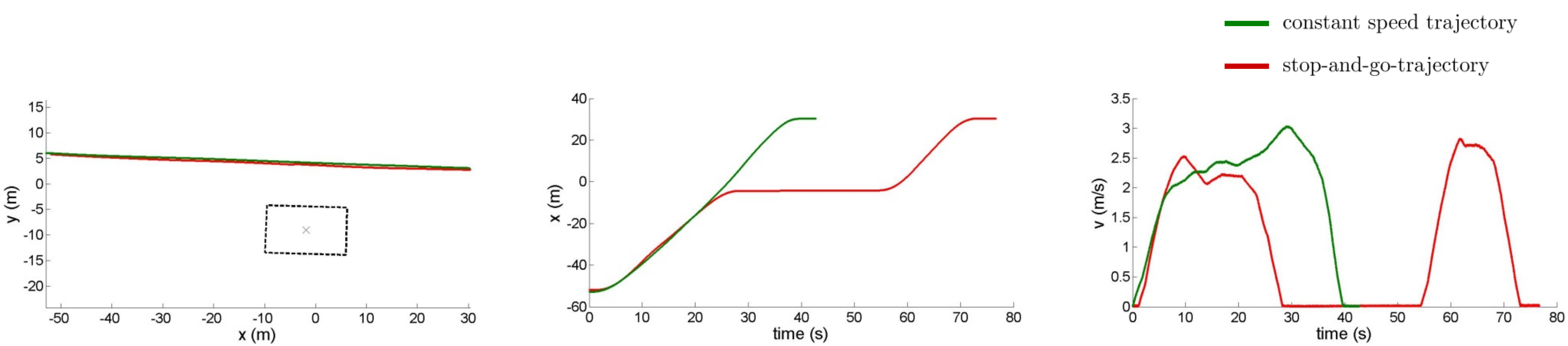
2-D top view slices of different wall materials



Features are related to the first and second peaks in the range profile

The stop-and-go SAR trajectory for joint imaging and motion detection

- The vehicle approaches a building of interest on a straight path, at constant speed
- It stops in front of the building for approximately 30 seconds
- It then continues on its original path
- Constant Pulse Repetition Frequency (PRF)
- 1-D range information only while stationary



Weighting of samples before azimuth compression

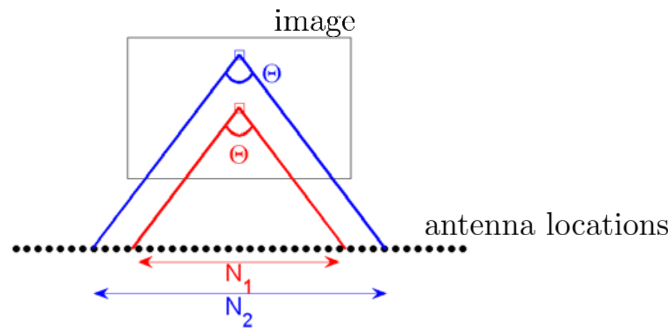
- We use constant integration angle to obtain constant azimuth resolution across the image

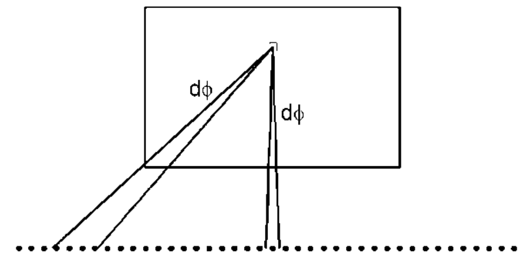
- Per unit angle $\mathrm{d}\phi$, there are more pulses at large azimuth angles, which causes undesired weighting of the high frequency component of the imagery

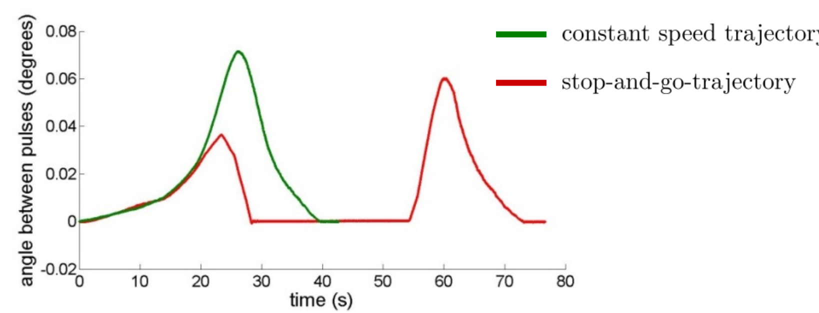
- We use the angle between consecutive pulses as a weighting function:

$$\sum_{\phi_i \geq -\Theta/2}^{\phi_i \leq +\Theta/2} (\phi_{i+1} - \phi_i) s_i = \Theta s_o$$

where s_o is the signal from an isotropic point target

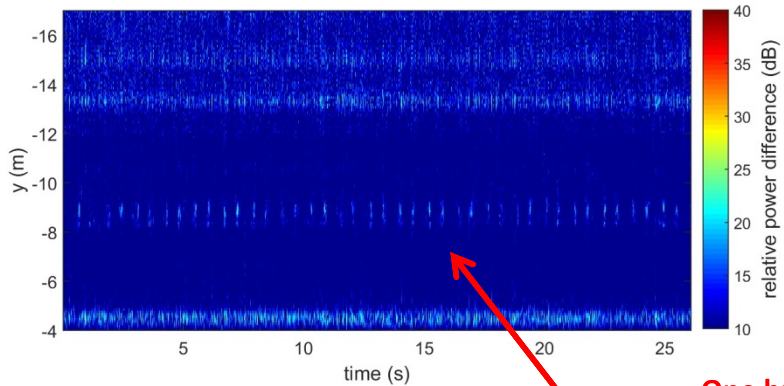


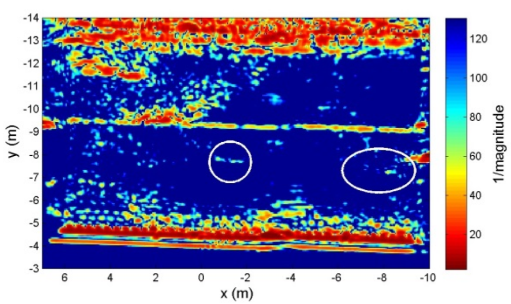




Motion detection – scenario A

- Difference image:
  - Consecutive pairs of pulses are subtracted

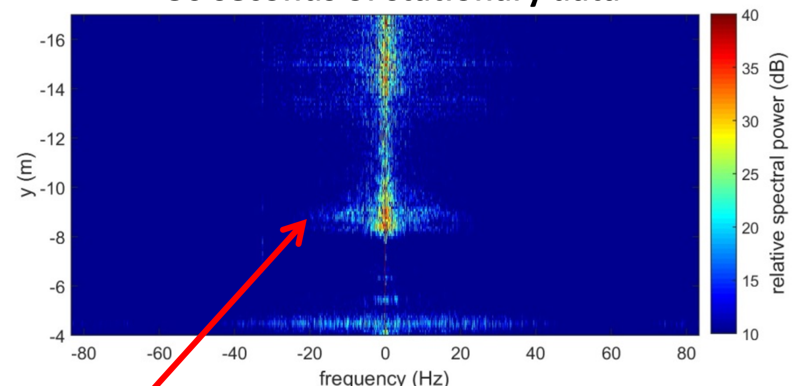




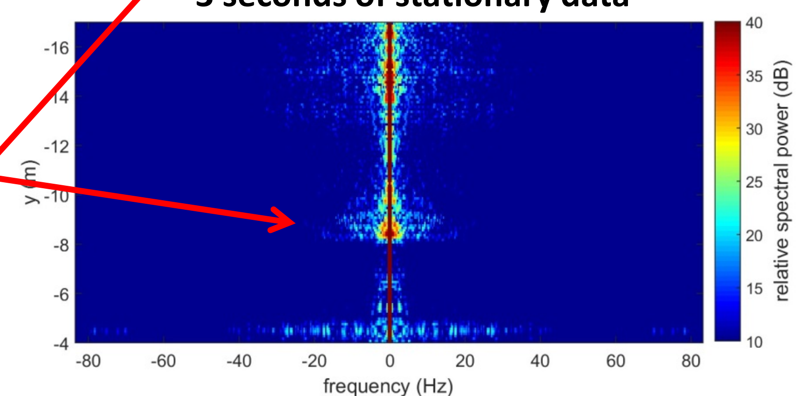
One human target stationary and still and one human target stationary but moving arms and legs

- Spectral images:
  - FFT across N pulses (in the slow-time direction)

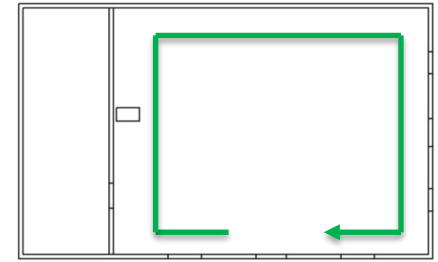
30 seconds of stationary data



3 seconds of stationary data

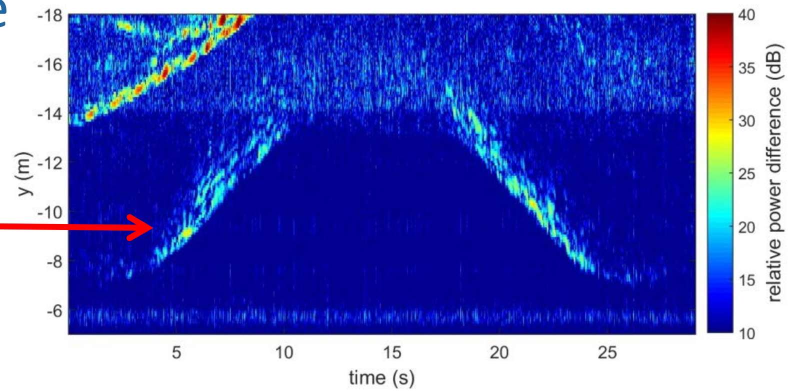


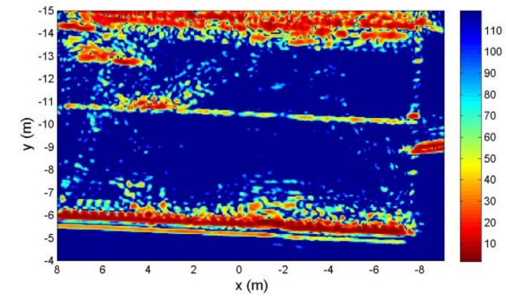
Motion detection – scenario B



- Difference image

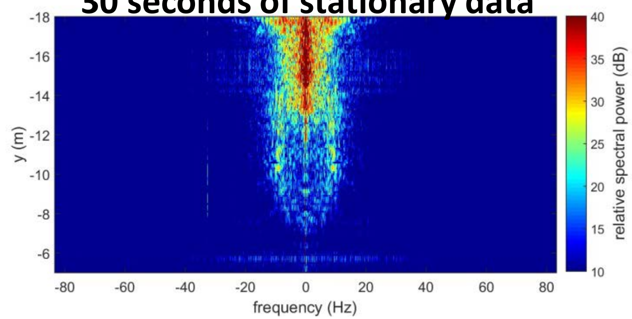
One human target walking on rectangular pattern inside the building



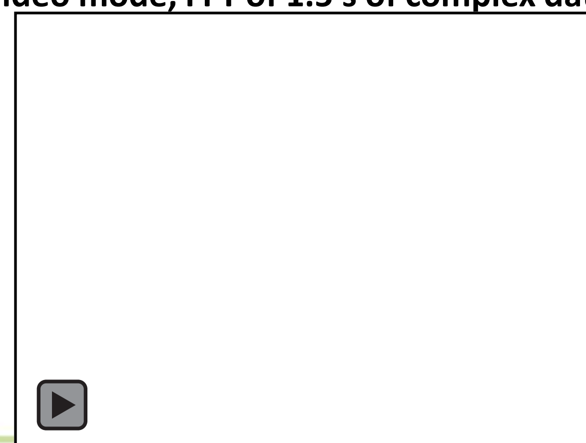


- Spectral images

30 seconds of stationary data



video mode, FFT of 1.5 s of complex data



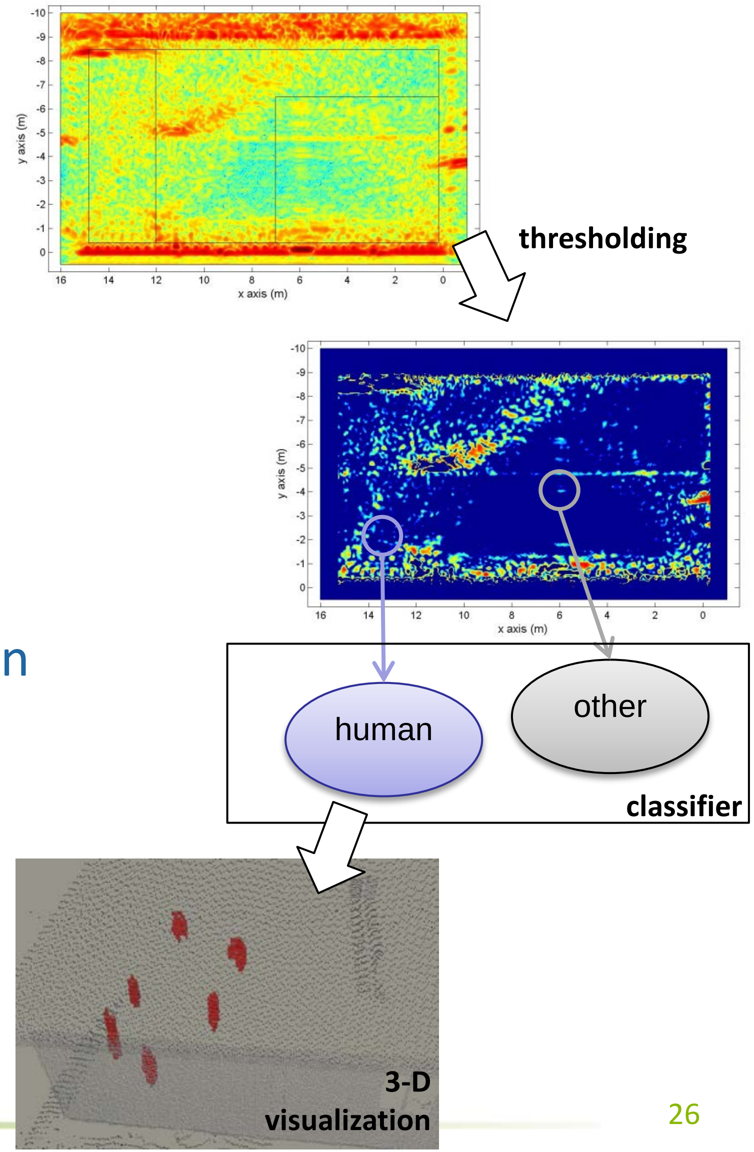
Data exploitation

or

“Could you please automate this process…”

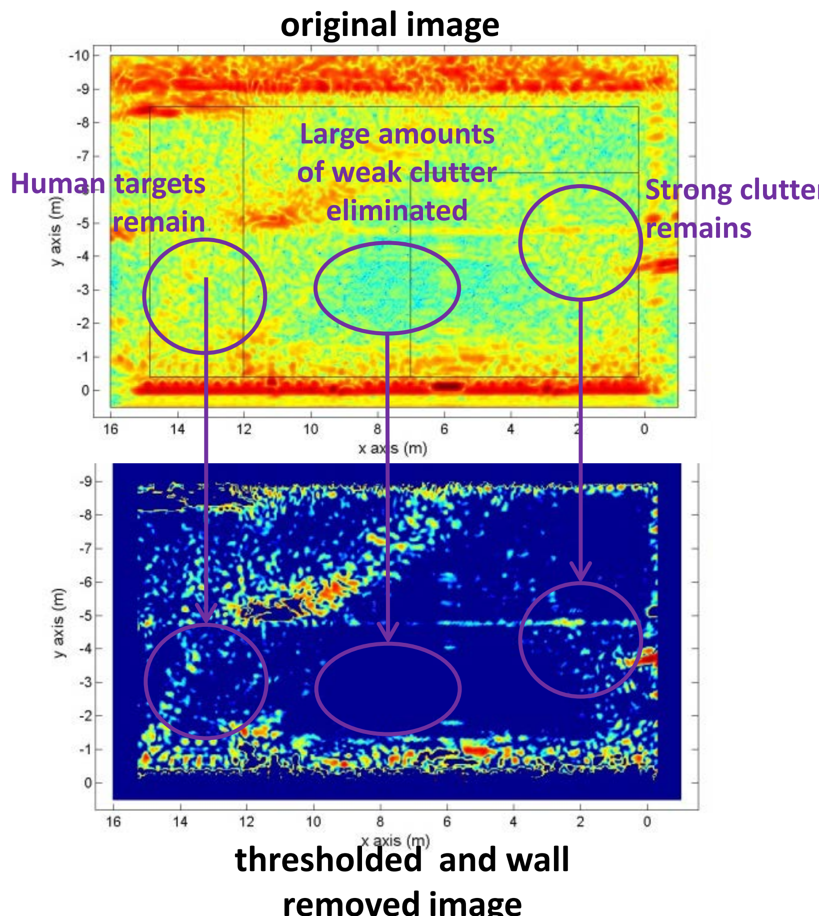
Automating the stationary human target detection task

- Typical through-wall SAR image contains lots of clutter
- The image texture is blob-like
- Human target signatures are present but buried in clutter
- We are developing automated tools for human target detection:
  - Data processing on the blobs
  - Image processing and supervised learning approaches
  - All the steps are now automated but optimization still required



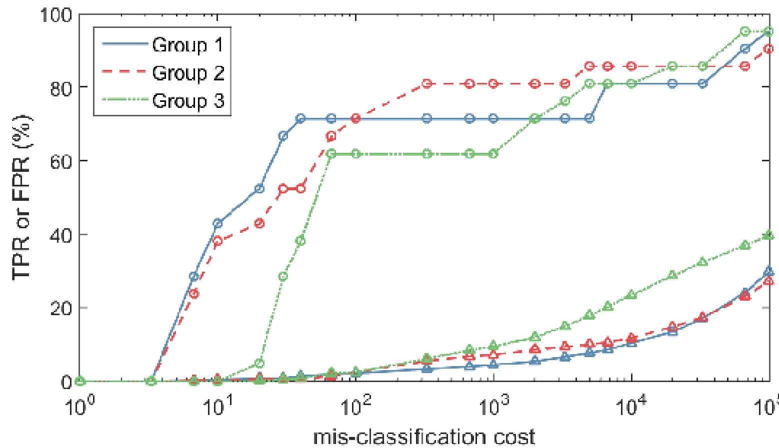
Thresholding for clutter reduction and identification of candidate targets

- Every voxel is assigned to only one blob using the watershed algorithm
  - one blob per local maximum in the 3-D matrix
- Threshold based on median of blob intensities
  - 50% of the blobs are eliminated
- Wall and strong features are removed using seeded region growing algorithm



Feature extraction and classification

- Features
  - Related to shape, intensity, neighbourhood, elevation
- Support Vector Machine (SVM) classifier



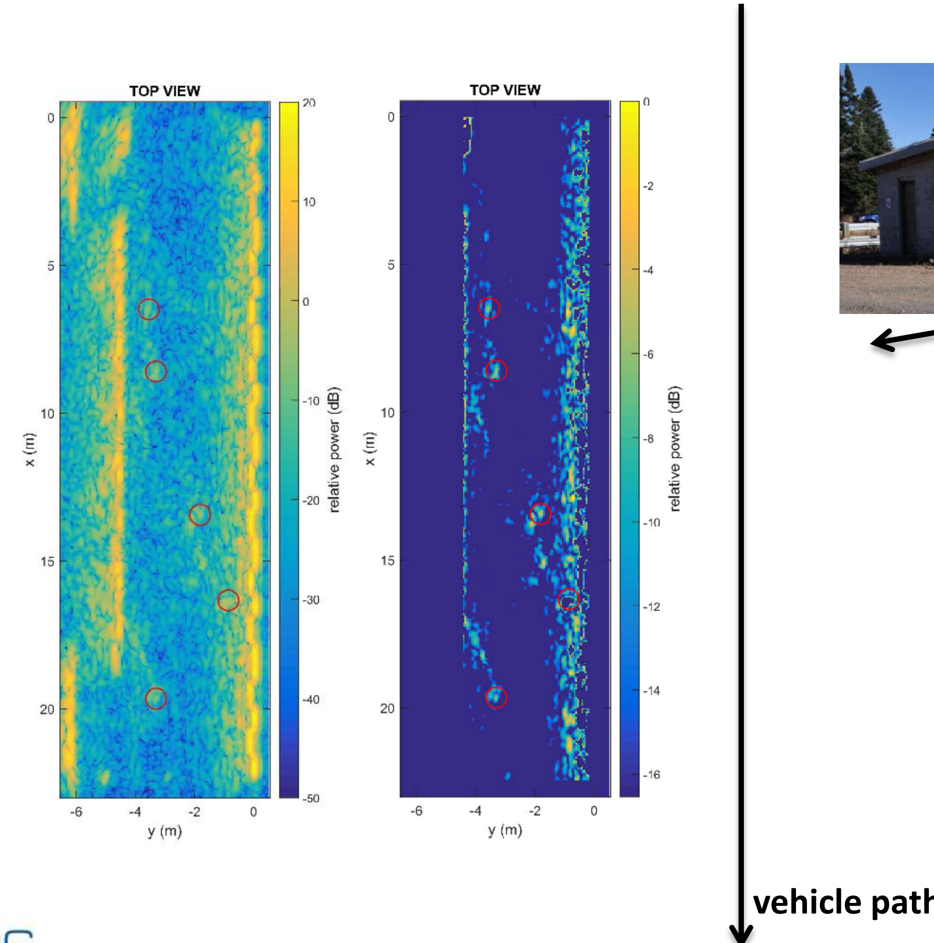
- Training data sets:
  - 12 different buildings, 74 data acquisitions, approx. 150 human target signatures
  - Various human positions (standing, sitting, holding rifle, etc.)
  - Various environments (empty space, nearby furniture, etc.)
  - Human target detections by the radar analyst are the “truth” for the classifier
    - Confidence levels were recorded

3-D visualization

- Classifier outcomes: a label as 1 (human) or 0 (other) for each candidate target or blob
- Classifier metrics:
  - Accuracy not useful for large class imbalance problems
  - True Positive Rate (TPR) and False Positive Rate (FPR)
- What is an acceptable FPR? Depends on where the false positives are located in 3-D
- 3-D visualization:
  - Region growing algorithm with seeds at the location of the classifier positives
  - ParaView as the 3-D visualization platform

Automated stationary human target detector

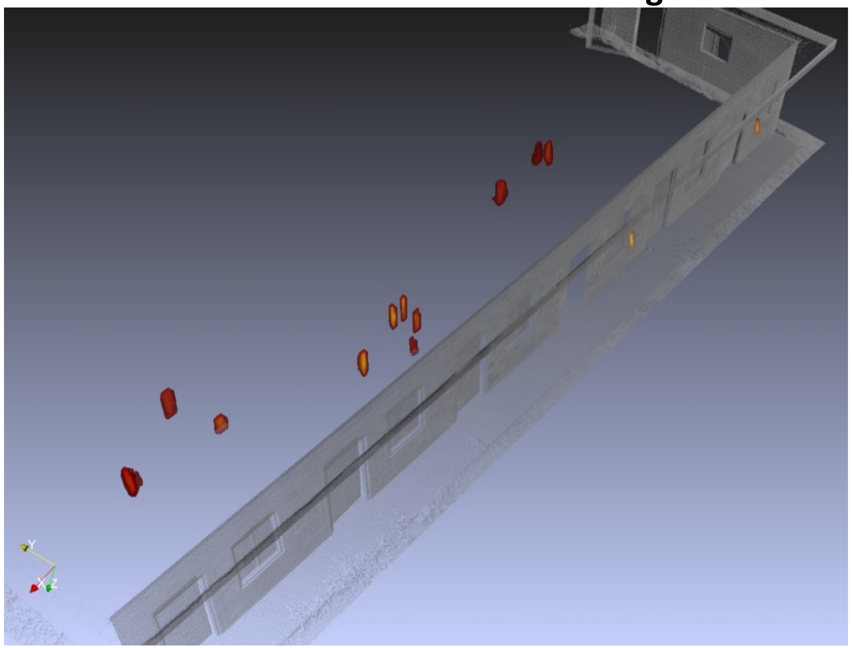
- Motel



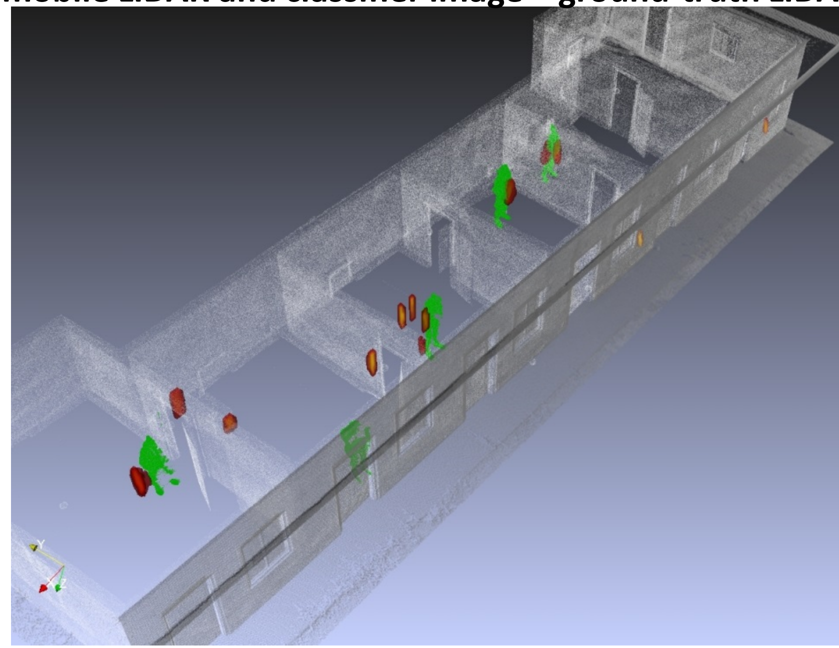
Automated stationary human target detector

- Motel

mobile LIDAR and classifier image

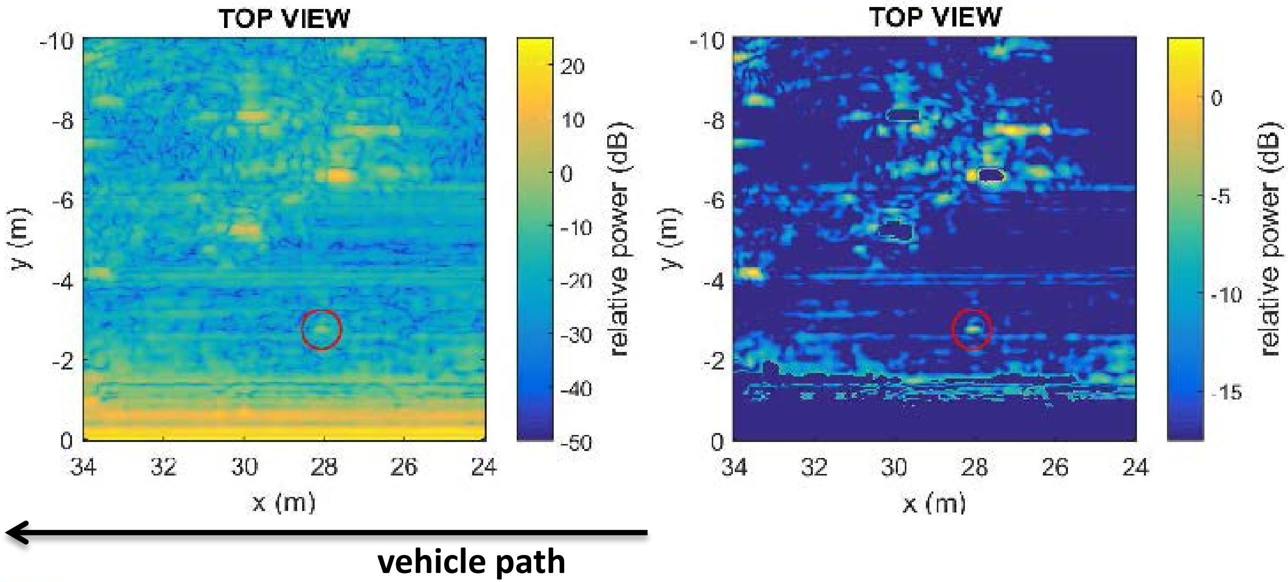


mobile LIDAR and classifier image + ground-truth LIDAR



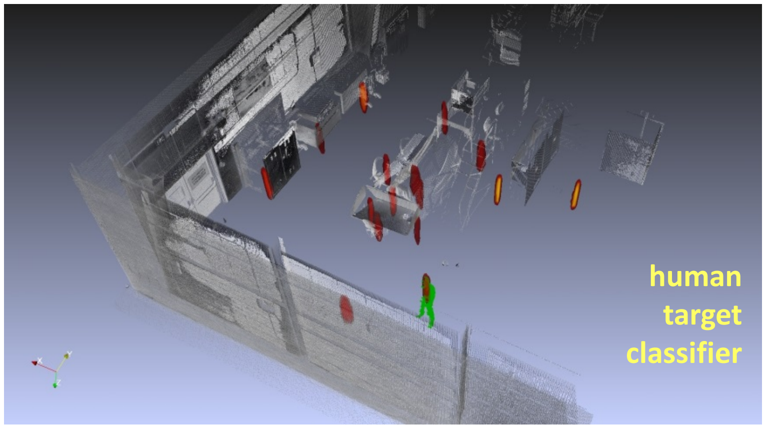
Automated stationary human target detector

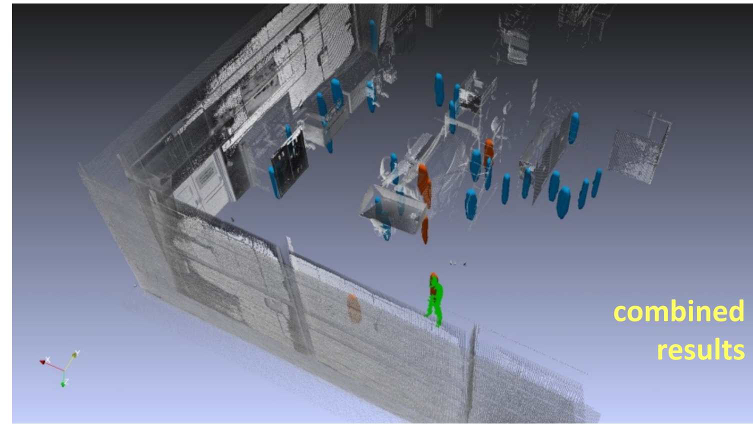
- B502, cluttered scene

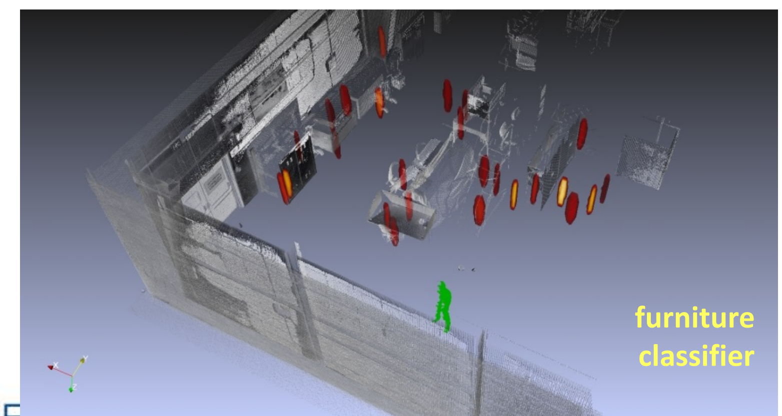


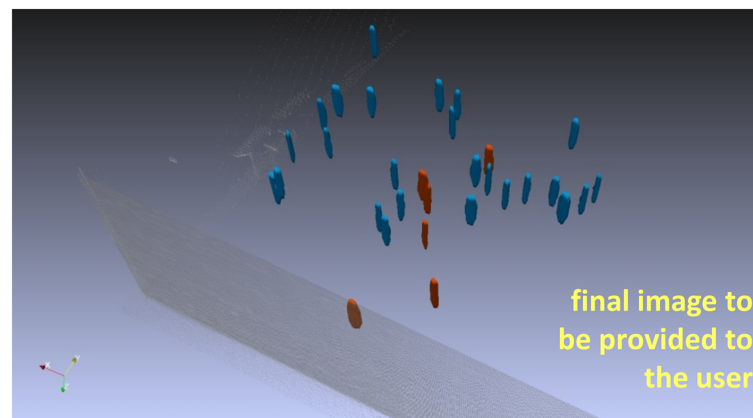
Automated stationary human target detector

- B502



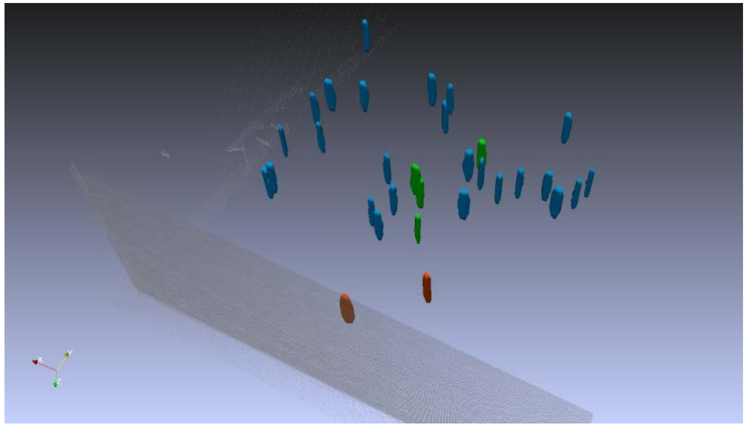






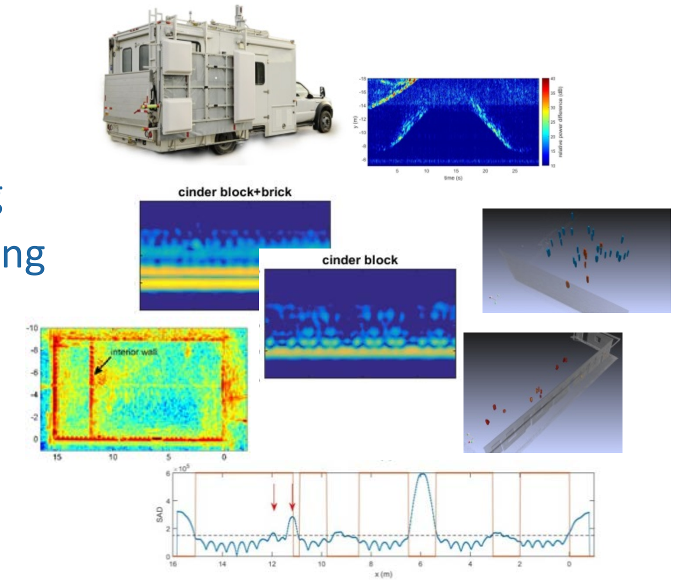
Automated stationary human target detector

- We need:
  - More human target and furniture samples
  - More and better features
  - Better overall understanding
- Behind the wall detector?
- Will there always be a false positive?
- Exploitation of motion information may be required
  - Stop-and-go not always possible
  - 2 (or more) phase centers strategies such as Displaced Phase Center Antenna (DPCA)



A few concluding remarks

- Shared a few successes
  - TW radar imaging is promising but remains challenging
  - We have focused on the stationary human target, aiming for robust approaches
- Other signal processing algorithms of interest
  - Compressed sensing
  - Wall clutter mitigation using e.g. singular value decomposition (SVD)
  - Etc, etc.
- Other hardware possibilities
  - Polarization
  - Effect of antenna beamwidth
- Trials data are important
  - There are no two buildings alike



TW radar imagery: a tool in the toolbox