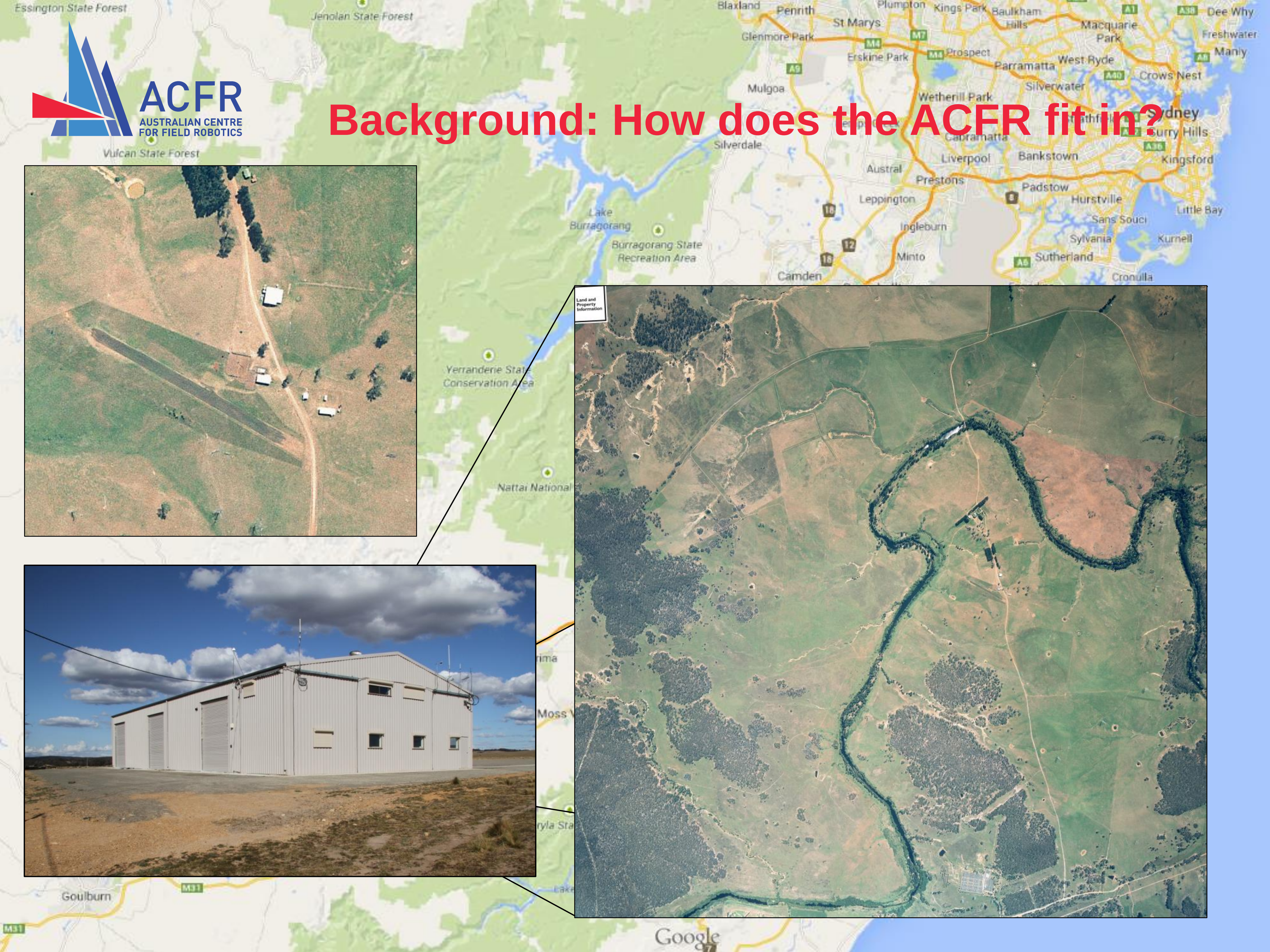
Robust Situation Awareness: From Active Sensing to Coherent Active Perception

Dr David Johnson

Acknowledgements: Robert Fitch, James Underwood, Thierry Peynot, Trevor Anderson, James Spedding and many others


E300 Viewer
Span 4.8m
Weight 15kg
Duration 2.5Hrs
PATRICK
SHRIMP

Background: How does the ACFR fit in?



Overview

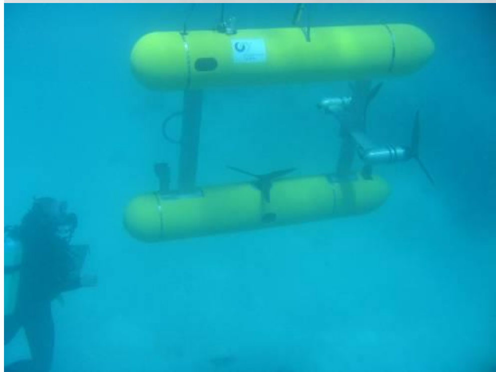
- Motivation
- Background
- Some Definitions
- Sensing Technology
  - Radar / Lidar
  - Machine Vision
  - Coherent Sensor Fusion
- Application Examples
  - Mining
  - Agriculture / Asset Monitoring
  - Security / Defense
- Future Directions
- Shameless Plug

Motivation: Field Robotics in Australia

- Australia leads the world in *civilian* field-robotic applications
  - Dirty, Dull and Dangerous is a way-of-life
  - Big country
  - Small population
  - Low subsidies

→ Innovate or perish

- **Mining**: Rio Tinto's 'Mine of the Future' program
  - World's largest non-military robotics programme
- **Agriculture**: 1st IEEE Agricultural Robotics Summer School held in Sydney, Feb 2015
- **Logistics**: Port of Brisbane (and now Port Botany)
  - World's 1st fully-automated container-handling terminal



Some Definitions

- ***Autonomy*** is the automation of *<u>independent</u>* perception, learning, control and action.

- Humans are very good at controlling remote vehicles using low-quality visual data, as seen by FPV-racing.

- Much of this is instinctual, using *<u>context</u>* and *<u>experience</u>* to 'fill in the gaps' and guess what will happen next.
- It is not surprising that these tasks are difficult to automate, but we can make the sensors better, the processing faster, etc.

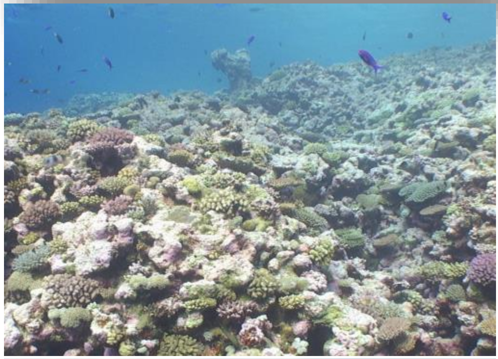
Perception Challenges

Scale *(complexity)*

Variability *(novelty)*

Interaction *(not a black box)*





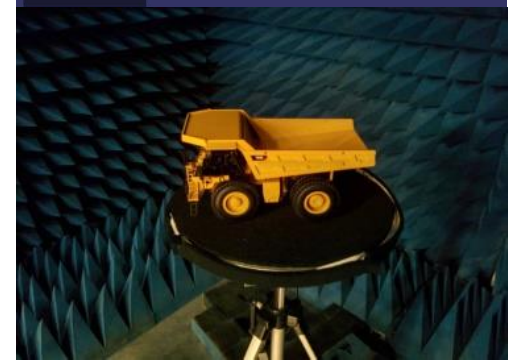

Perception Challenge #1: Scale

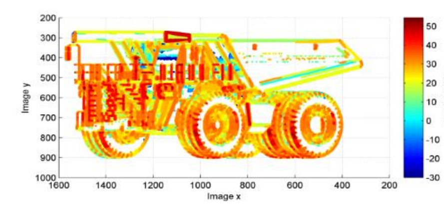
Space - Localisation at the mm scale across km-wide maps.

Time - Online processing with real-time requirements for high speed ground, air and water-based vehicles with revisit-times ranging from ms to years.

Frequency - Coherent sensing and communications from kHz to THz, optical and beyond

Number – Dimensionality of many different variables

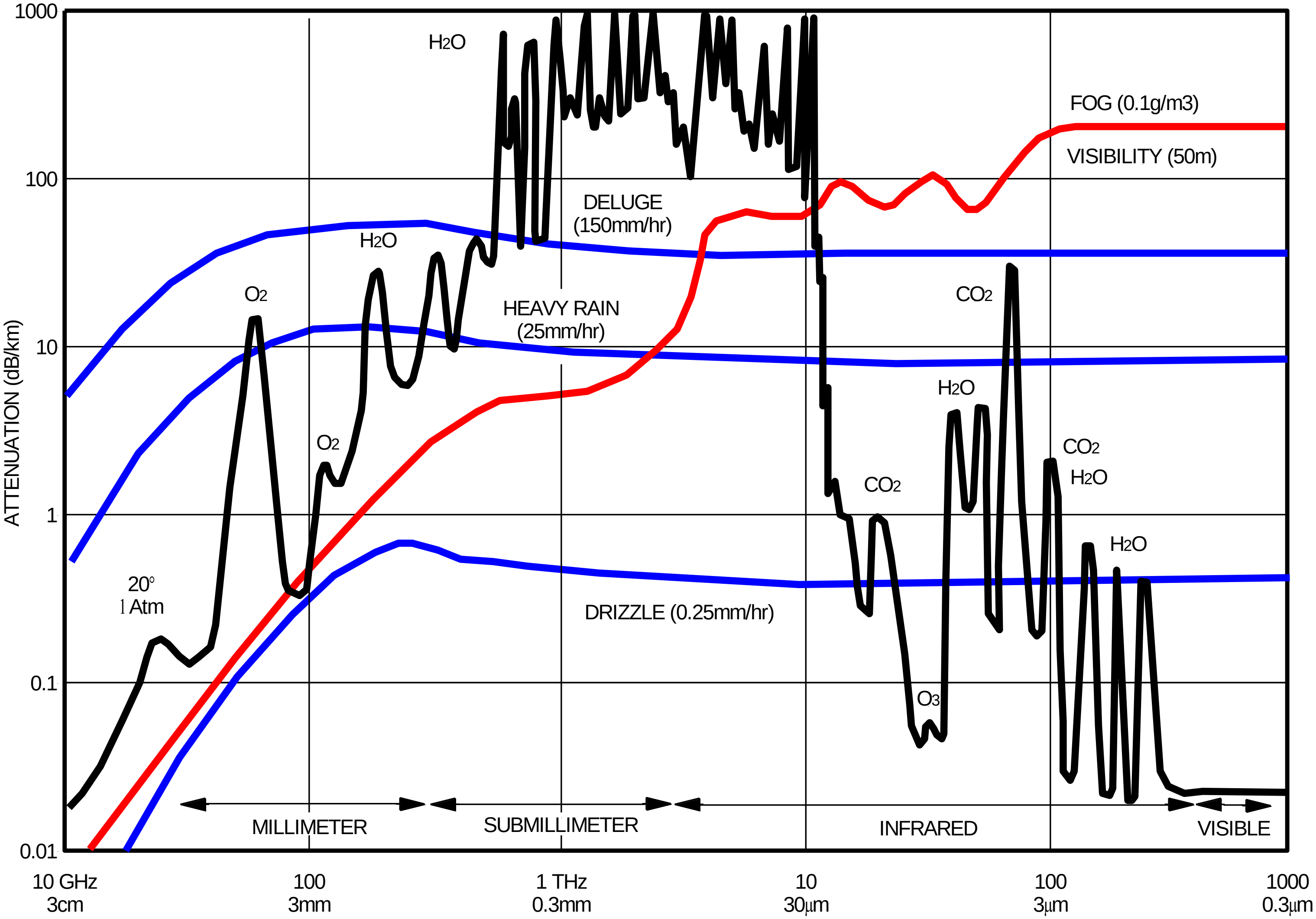




Perception Challenge #2: Variability

- Challenges for computer-vision:
  - Illumination
  - Object pose
  - Clutter
  - Occlusions
- Challenges for active sensors
  - Attenuation
  - Multipath
  - Interference
  - Sample-aliasing

Atmospheric attenuation



Preissner, J. (1978, The Influence of the Atmosphere on Passive Radiometric Measurements. AGARD Conference Reprint No. 245: Millimeter and Submillimeter Wave Propagation and Circuits.

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AUSTRALIAN CENTRE
FOR FIELD ROBOTICS

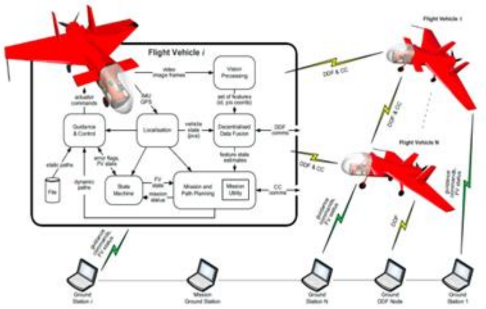
Perception Challenge #3: Interaction

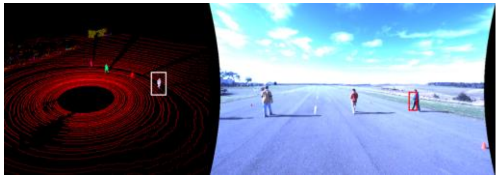
- Human Control Interface – User interaction, levels of autonomy

- Human Environment – Co-habitation vs. isolation

- Natural Environment – Manipulation *of* and attenuation *by*

- Machine Interaction – Systems of Systems, collaboration, communication





Some Definitions

- ***Robustness***
- *Situational Awareness*
- *Active Sensing*
- *Coherence*
- *Active Perception*

- Robust to purpose (*reliability*)
  - Minimal false-negatives / false-positives
- Robust to the environment (*persistence*)
  - Minimal unknown failure modes
  - Onboard diagnostics
- Robust to the (less-skilled) operator (*trust*)
  - Functional safety
  - Intuitive operation
- Robust to scale (*cost*)
  - Designed for mass-production
  - Full product life-cycle considerations
  - Spectrum congestion
  - Standards compliance
  - ‘Big-Data’ processing

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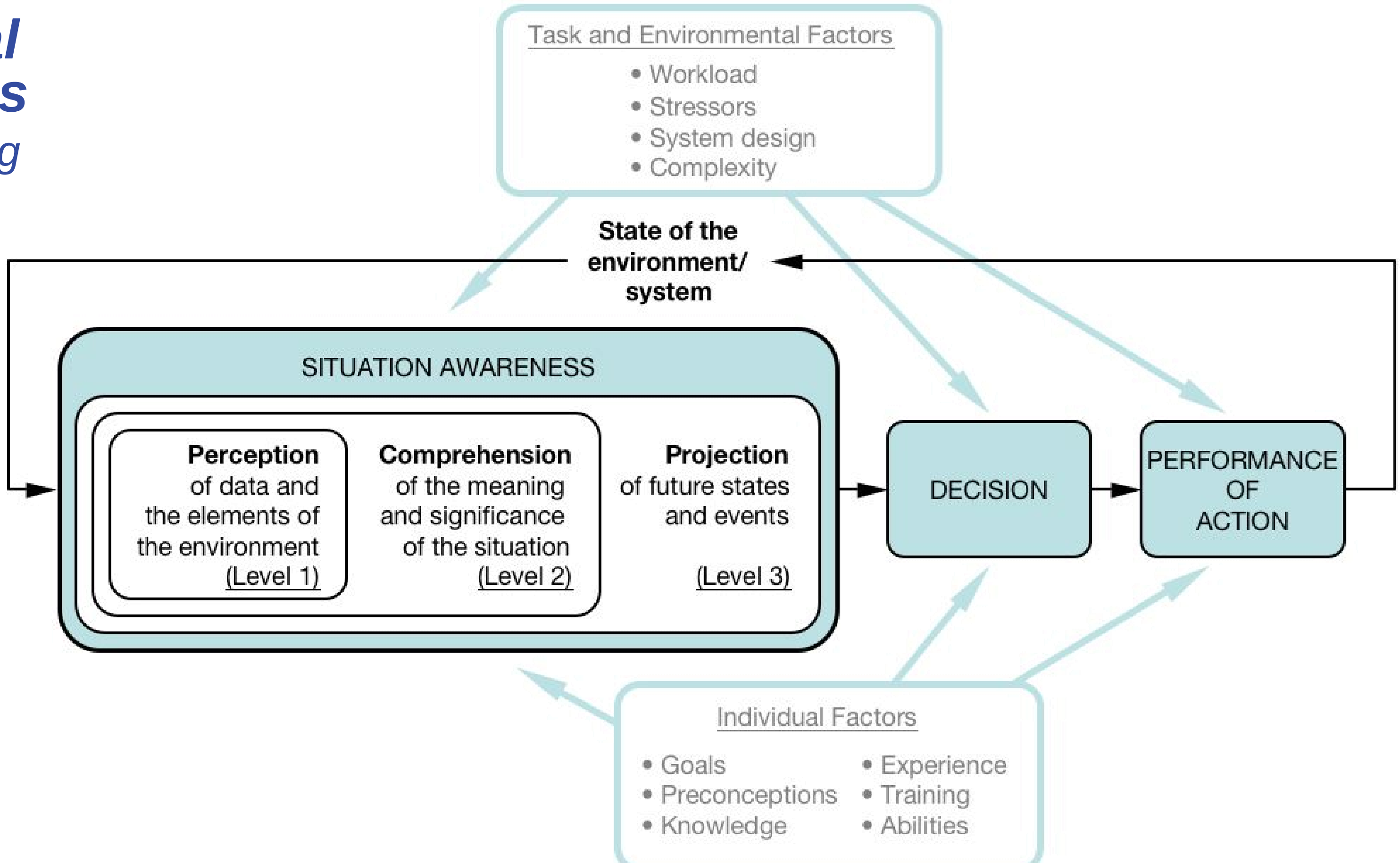

Some Definitions

- *Robustness*
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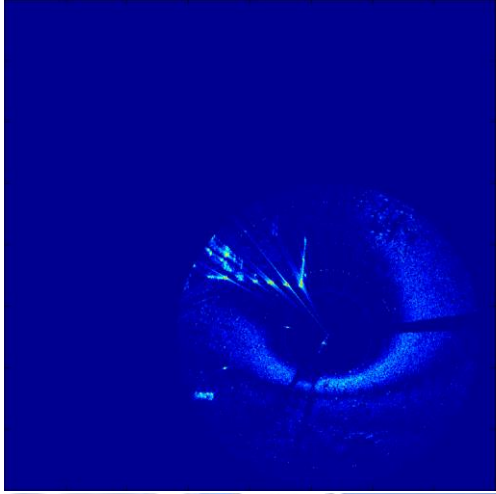
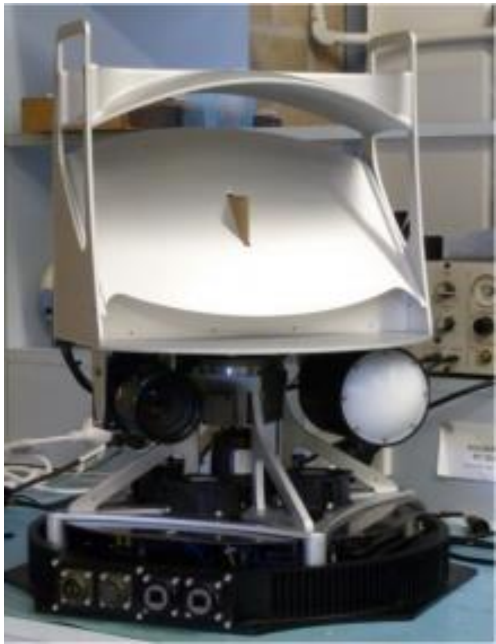
Active sensors put a ***controlled*** signal into the environment, and measure the interactions between that signal and the environment to infer information.

Examples:

- RADAR, LIDAR, X-ray Imaging
  … use the EM field
- SONAR, Seismic
  … use pressure waves





Active Sensing Primer

- A portion of the EM spectrum is transmitted, reflects from a ‘scatterer’, and gets picked up by a receiver.

- 2 ways of forming high-range-resolution:
  - A very short pulse in time (TOF)

$$\text{Range Resolution} = \frac{\text{Speed of Light x Pulse Width}}{2}$$

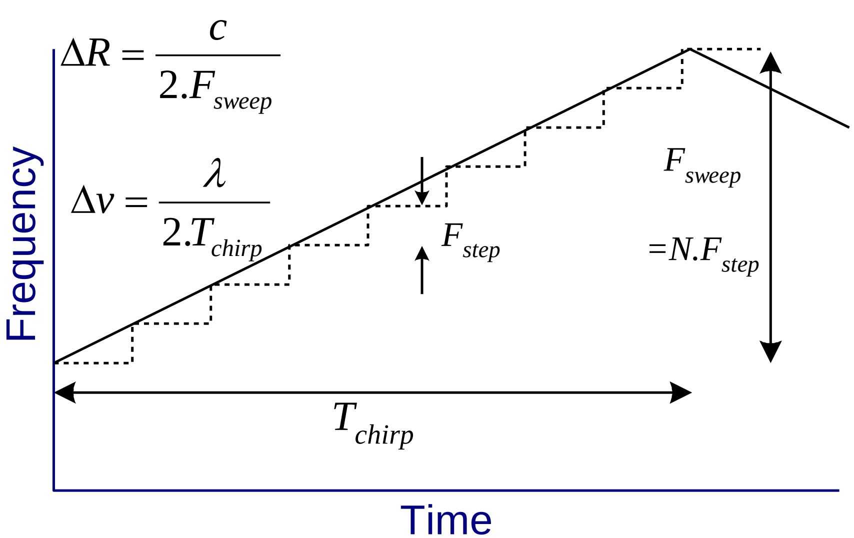
  - A very wide swept-frequency-bandwidth (FMCW)

$$\text{Range Resolution} = \frac{\text{Speed of Light}}{\text{2 x Bandwidth}}$$

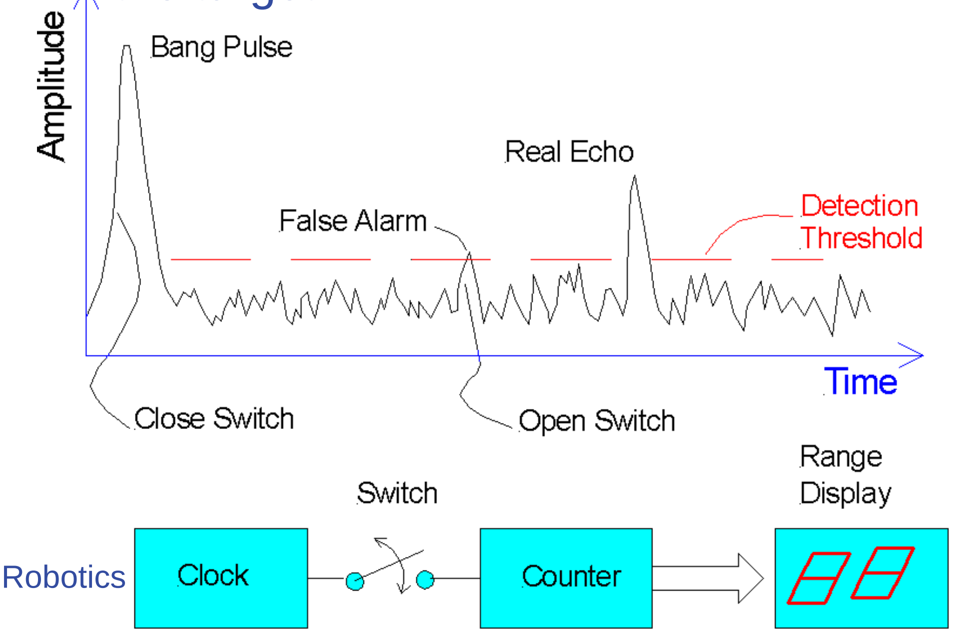
- Hence to achieve 10mm resolution requires either a pulse width of <0.1ns, or a swept bandwidth of 15GHz

(Linear) FM or ToF Waveforms

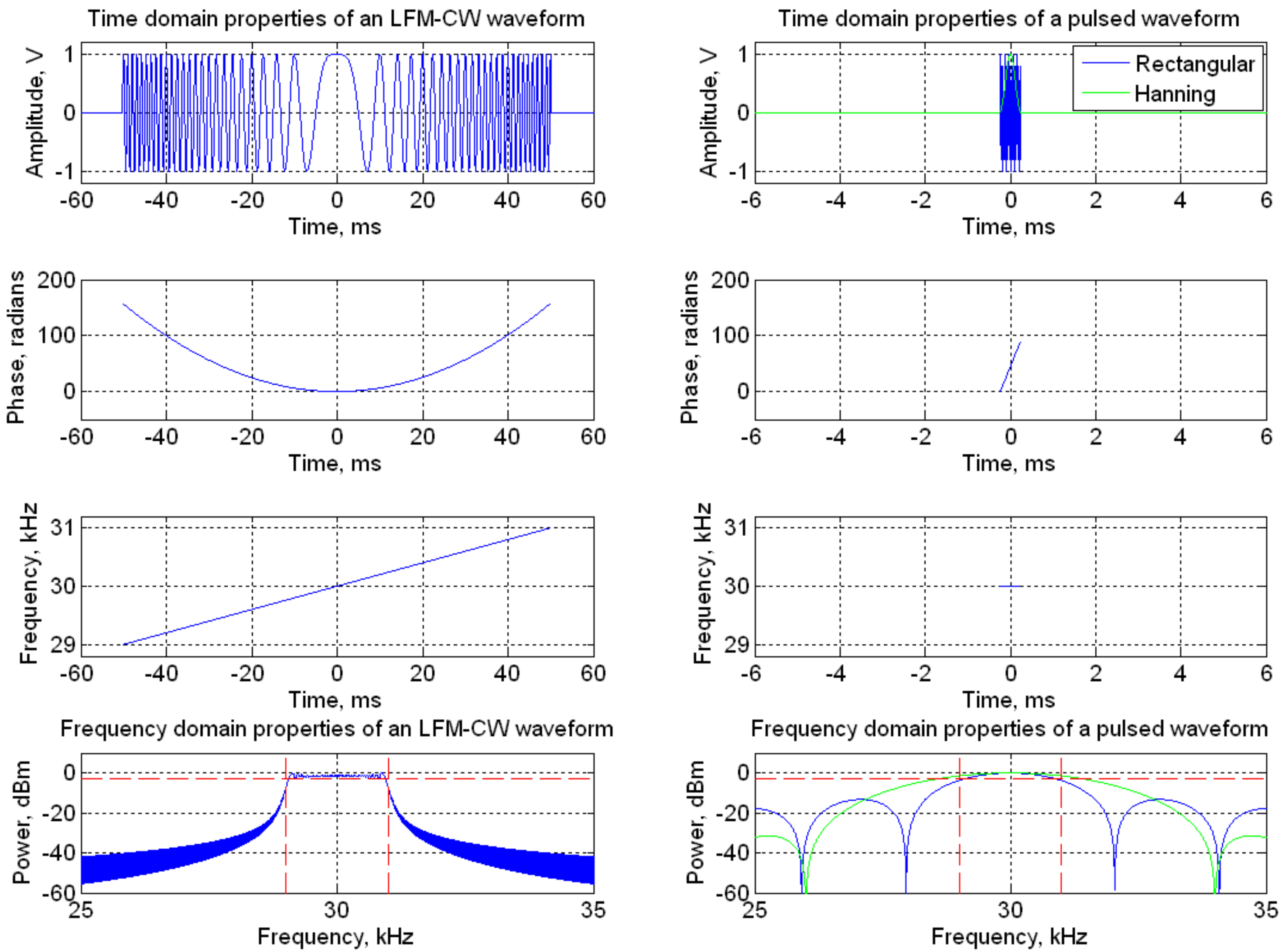
- Range resolution improves with swept bandwidth
- Velocity resolution improves with sweep time



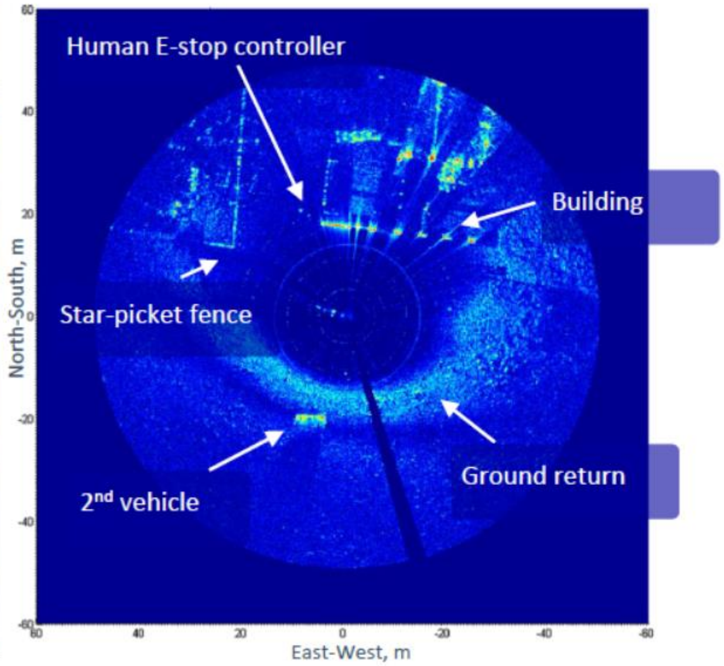
- Range to a target is measured by running a counter from the time a pulse is transmitted until the echo is received.
- The echo is detected when the received signal envelope exceeds a predetermined threshold
- Knowing the signal propagation velocity it is possible to calculate the range to the target



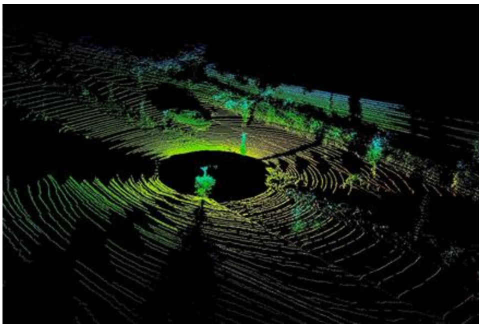
Equivalent resolution using AM or FM



ACFR Radar Sensors



Examples of Lidar Sensors



	HDL-64E	HDL-32E	VLP-16
# Lasers	64	32	16
Max Range (10% refl)	50m	50m	50m
Field of View (H / V)	360° / -24.8° to +2°	360° / -30° to +10°	360° / -15° to +15°
Scan Rate	5 - 15 Hz	5 – 20 Hz	10 Hz
Points per Scan	~140k	~70k	~30k (x2)
~ Cost (AUD)	~$60k	~$30k	~$10k
Communications Standard	Ethernet (UDP)	Ethernet (UDP)	Ethernet (UDP)

More Examples of Lidar Sensors

	UTM-30LX	VZ-1000	LMS-Z620
# Lasers	1	1	1
Max Range (10% refl)	30m (cal board)	700m	750m
Field of View (H / V)	270° / N.A.	360° / 100°	360° / 80°
Scan Rate	40 Hz	120 V-lines / sec	20 V-lines / sec
Points per Scan	~1k	122000 pts / sec	11000 pts / sec
~ Cost (AUD)	~$5k	~$250k	~$150k
Communications Standard	USB 2.0	GbE	100Mbps Ethernet

Some Definitions

- *Robustness*
- *Situational Awareness*
- *Active Sensing*
- *Coherence*
- ***Active Perception***

Bajcsy (1998) - Active Perception

"Intelligent data acquisition"

[Closing the perception-action loop]

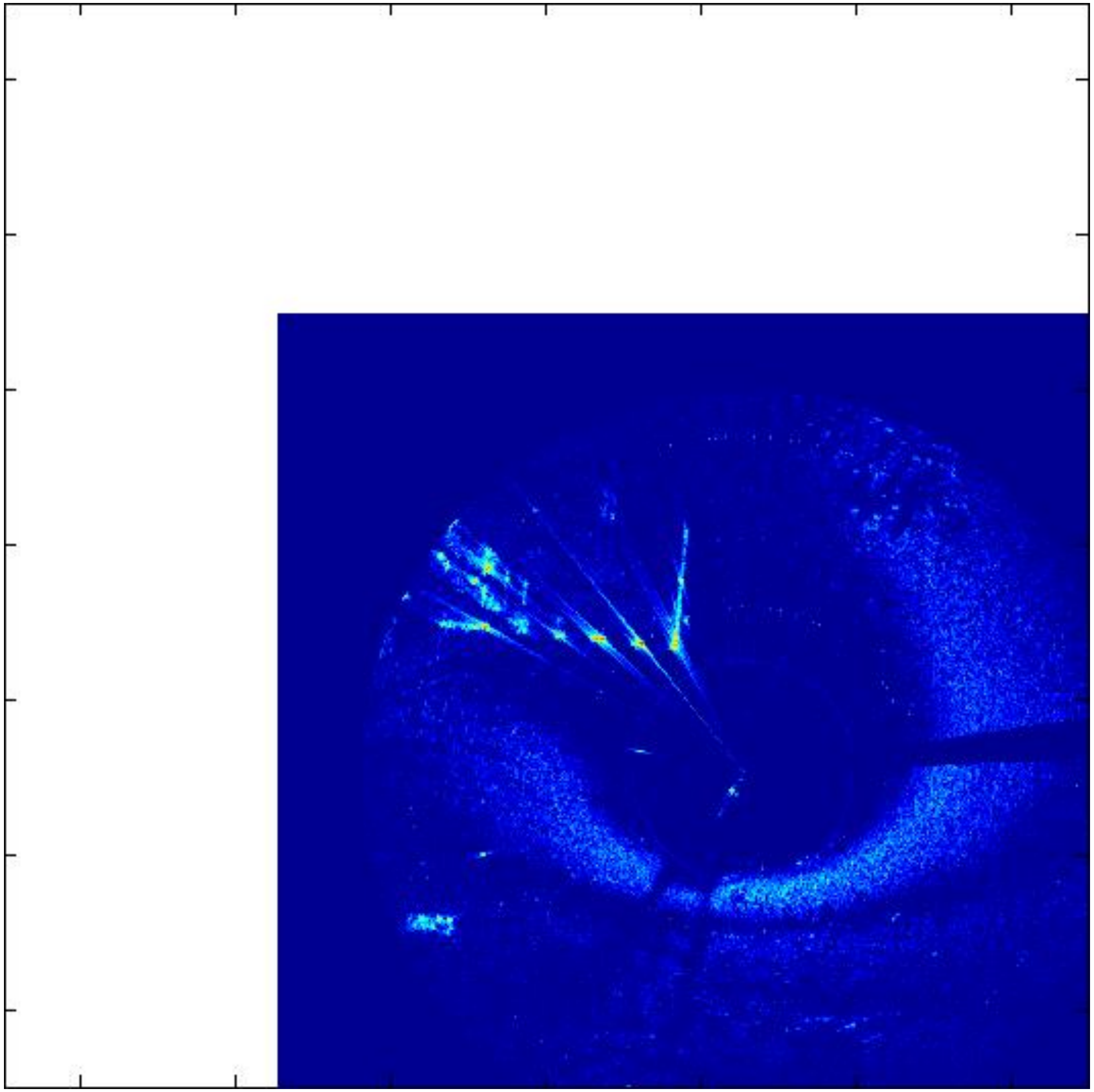
Bottom-up: Data driven

Top-down: Goal driven

Haykin (2006) - Cognitive Radar Networks

Cognitive Radar is an intelligent system that is aware of its surrounding environment (i.e., outside world), uses prior knowledge as well as learning through continuing interactions with the environment, and thereby adapts both its receiver and transmitter in response to statistical variations in the environment in real-time so as to meet specific remote-sensing objectives in an efficient, reliable, and robust manner.

Additional Information in the data



Some Definitions

- *Robustness*
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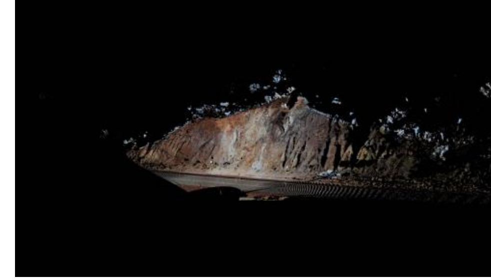
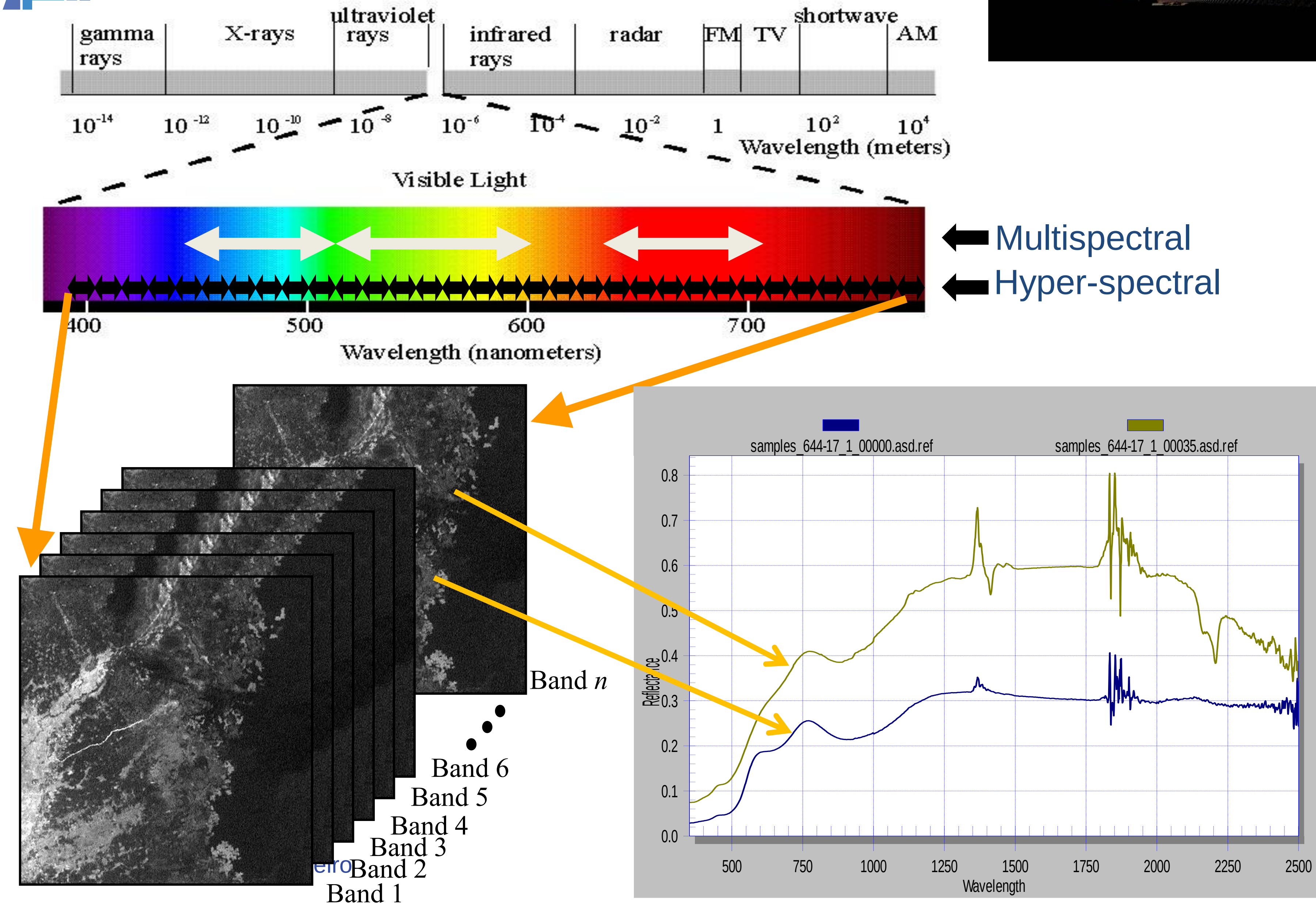
- ***Coherence***
- ***Active Perception***

- ***Coherent*** (multi-modal) sensing
  - Correlation of pre-processed data to associate data across multiple spectral bands.
- ***Coherent Active Perception*** used to adapt sensor parameters to the environment. Based on:
  - Context
  - Experience (prior information)
  - External cues
- For example: Vision-guided RF tomography
  - UWB radar prone to boundary-layer disturbance
  - Structured-light or Stereo Vision provides highly accurate geometric surface model
  - Combined solution allows this disturbance to be removed from the raw radar signal

Multi-Modal Sensor Fusion: Lidar & Hyper-Spectral

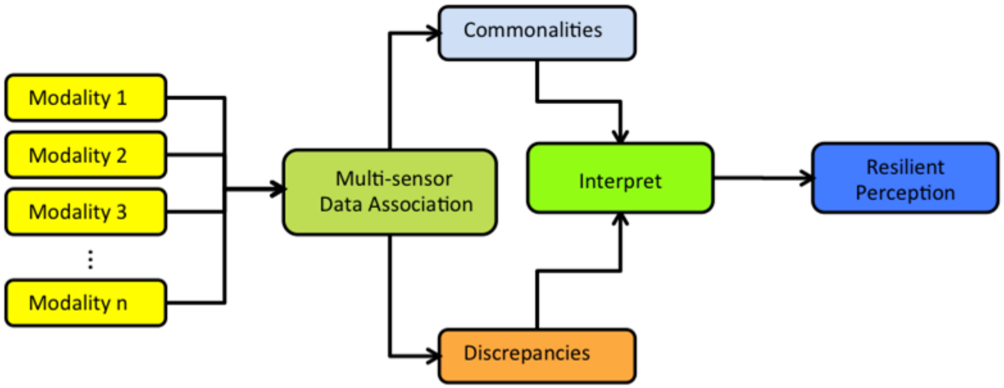


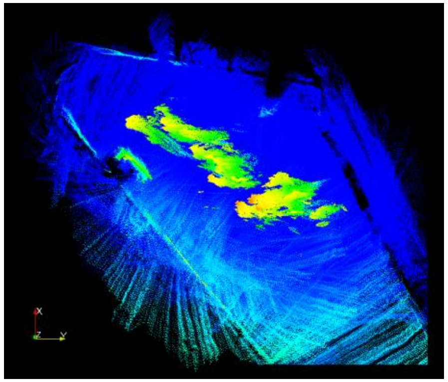
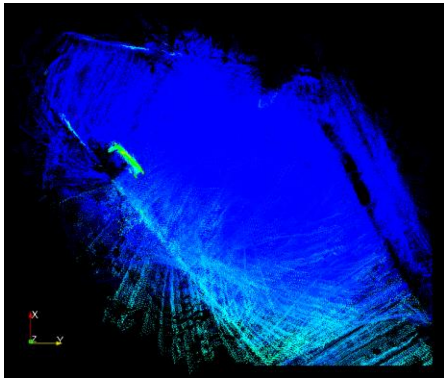


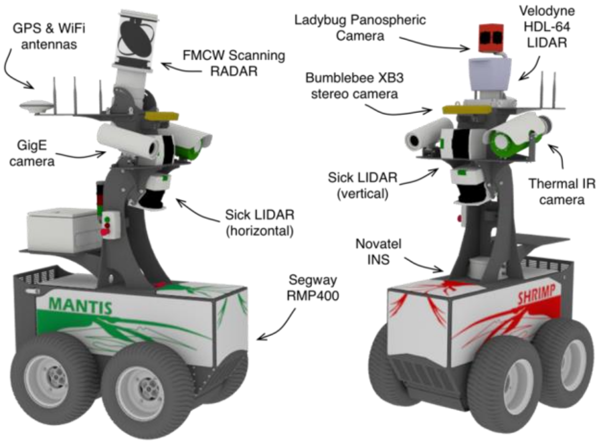
Multi Modal Sensor Fusion: Lidar & Radar



- Multi-modal resilient perception
- Simultaneous data association and classification





Optically Derived Simulation Environment

- Complex target signatures remain poorly understood
  - Polarisation
  - Prevalence of Diffraction
  - Electrically large scenes
- MMW Radar and Side-scan Sonar operate in the optical regime within their respective domains
- Optical ray-tracing renderers therefore provide the capability for developing radar/sonar simulation engines to assist:
  - Characterisation of existing sensors
  - Understanding of complex scatterer behaviour
  - A means to potentially identify and classify targets

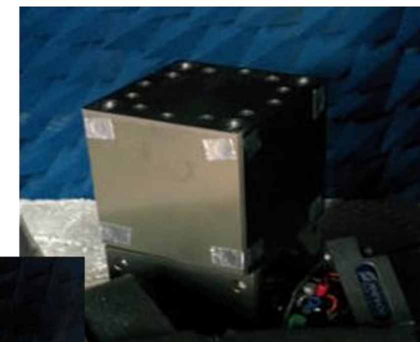
Our Approach

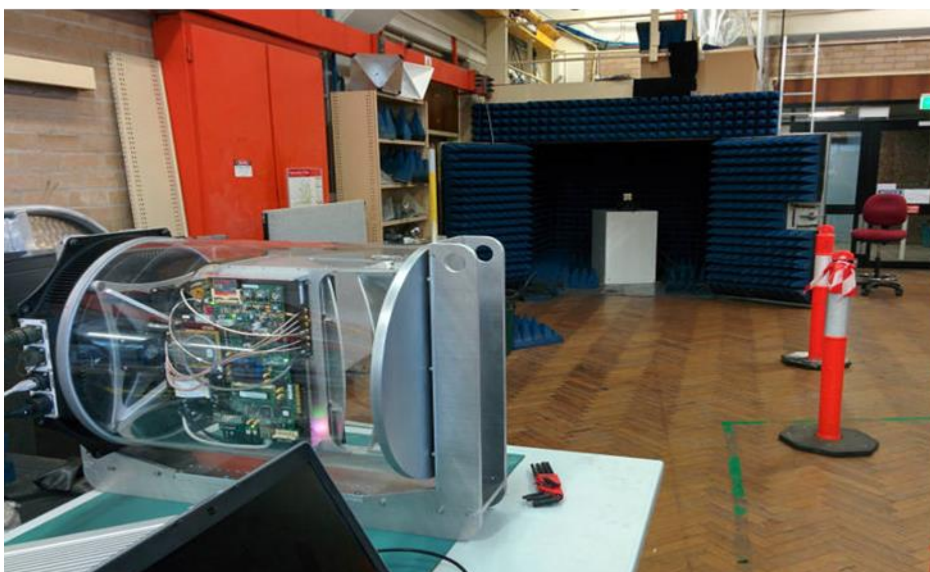
- Within an existing ray-tracing renderer ‘pbrt’ we implemented both *physical* and *geometric* optics modifications to provide:
  - Frequency Dependence
  - Polarisation Dependence
  - Phase Dependence and Interference
  - Geometric Edge Diffraction

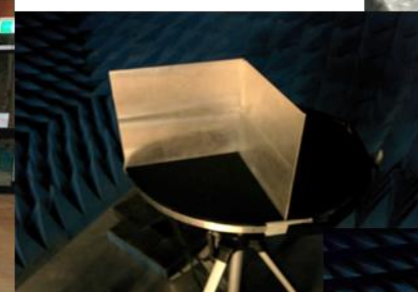
  - Of these, diffraction is the main stumbling block, requiring quite sophisticated edge detection.
  - The Uniform Theory of Diffraction [Kouyoumjian and Pathak] is then applied, however finding a smooth transition between specular and diffractive behaviour proved elusive.

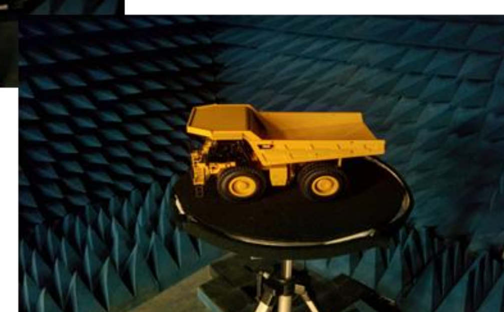
Experimental Validation

- 94GHz FMCW radar (on its side)
  - 5 deg elevation (now azimuth) beam-width
  - 0.5 deg azimuth (now elevation) beam-width
  - 7cm range-resolution
- 90mm (Power-) Cube
- 150mm dihedral reflector
- 1:40 Scale model haul-truck



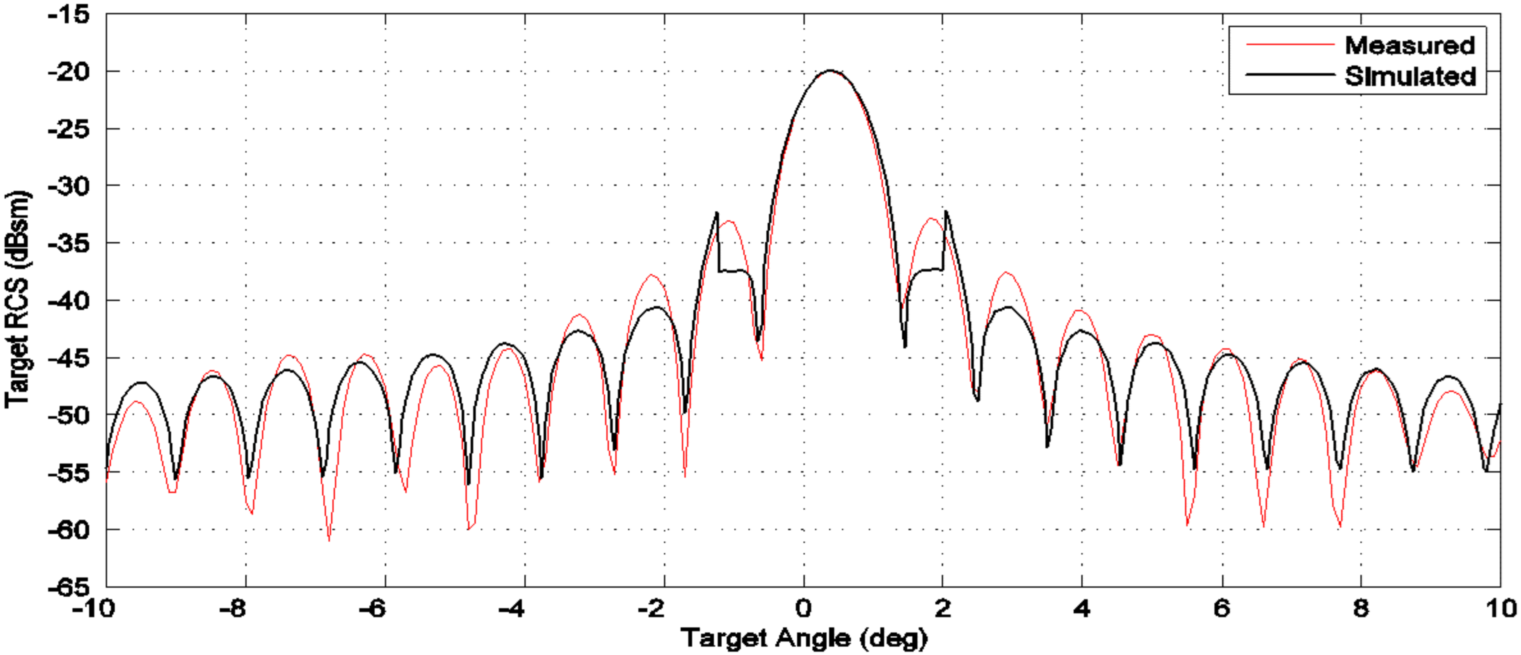




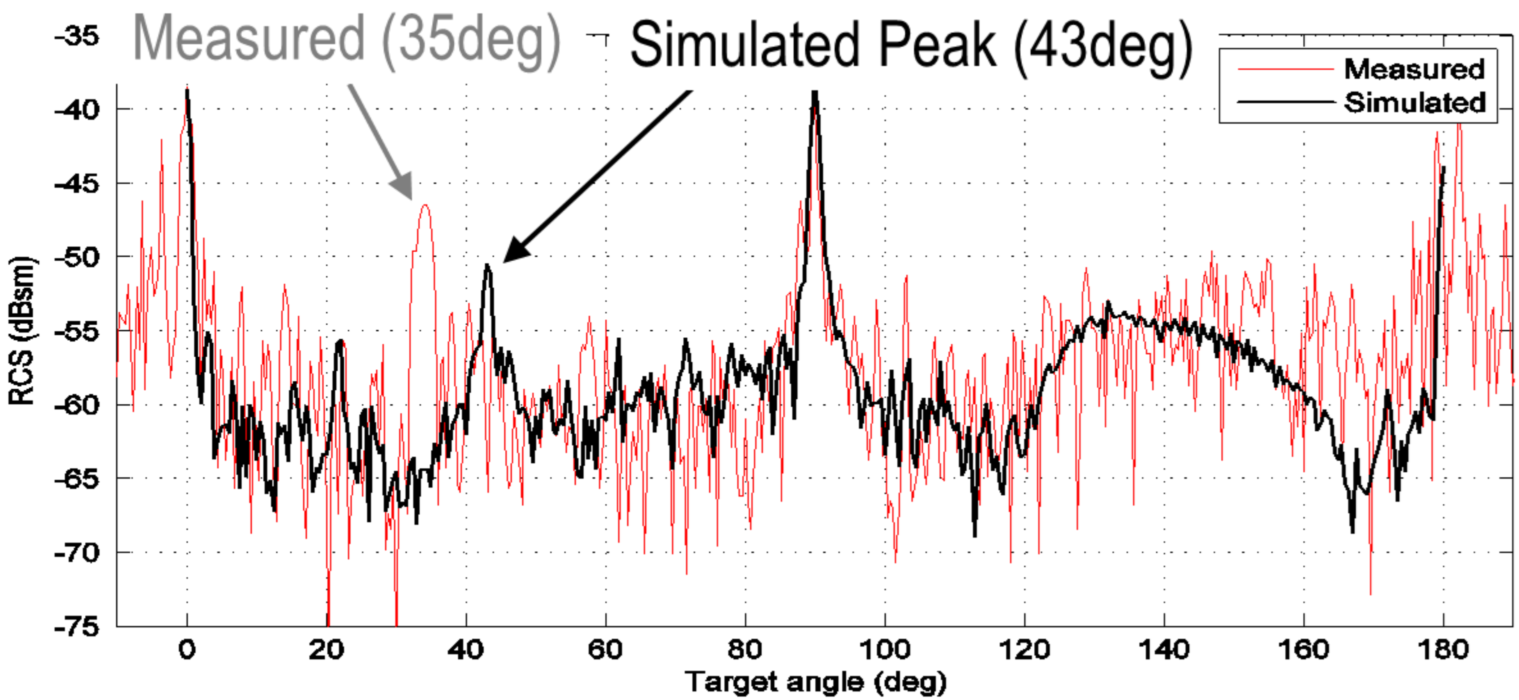


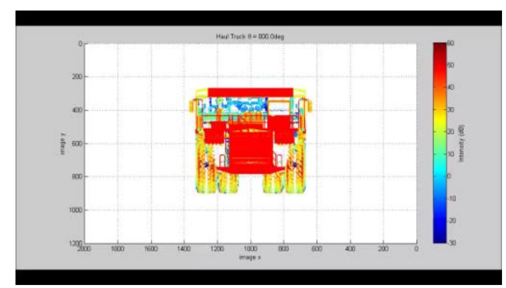
Rotating Cube

- PowerCube Actuator, rotational accuracy of 0.01 deg



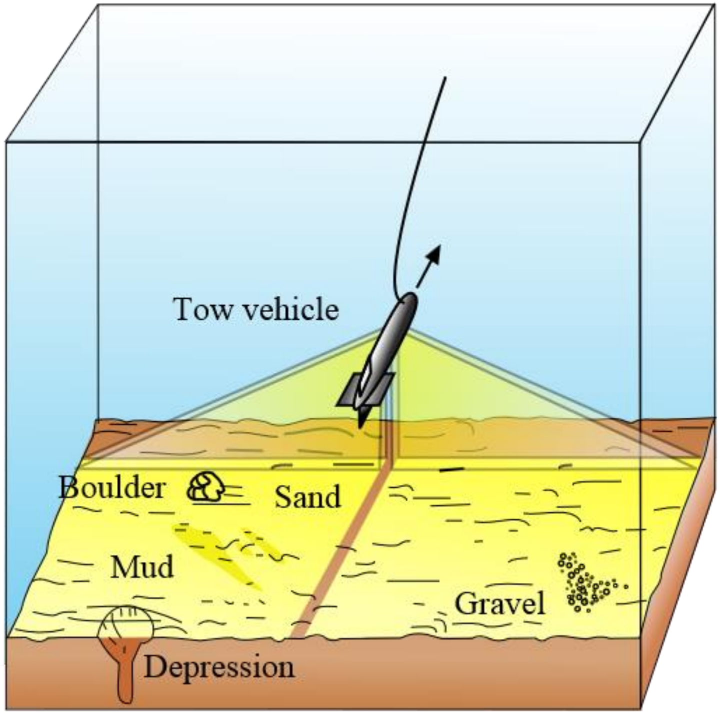
Scale Model Haul Truck

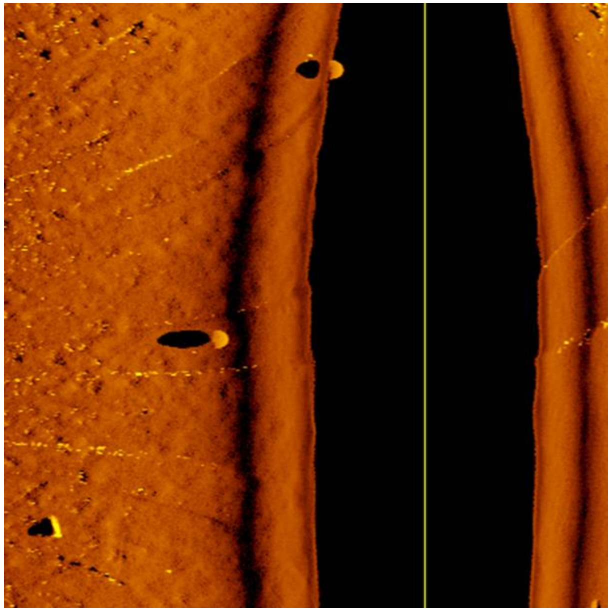




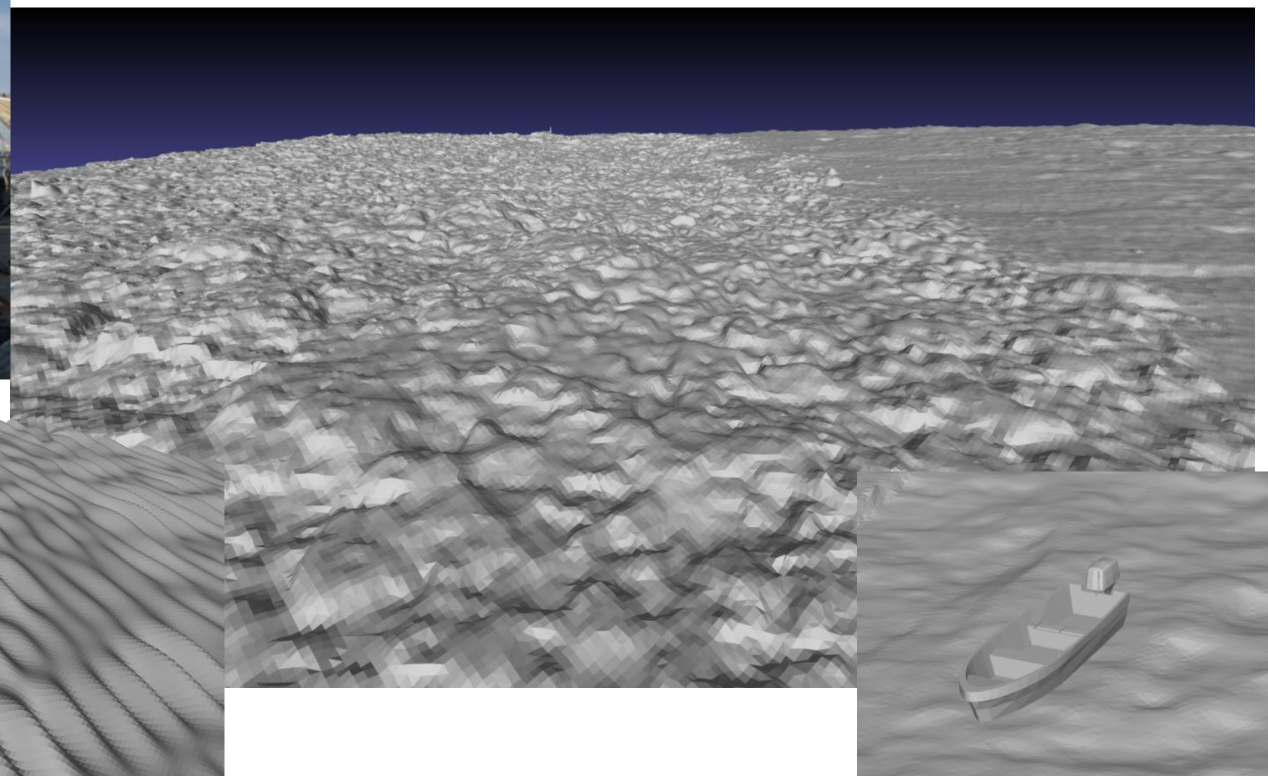
From Radar to Sonar

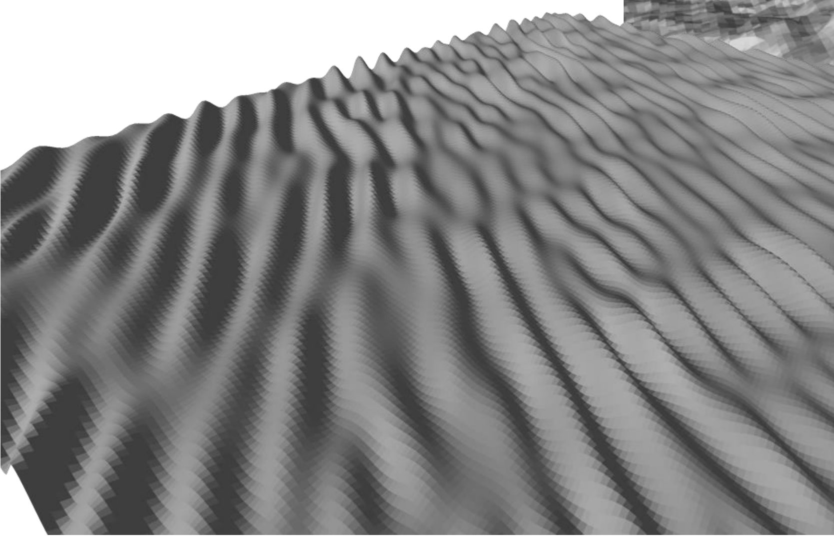
- DST Group DSP project: Real-time Sonar Simulation
- Based on Nvidia Optix GPU





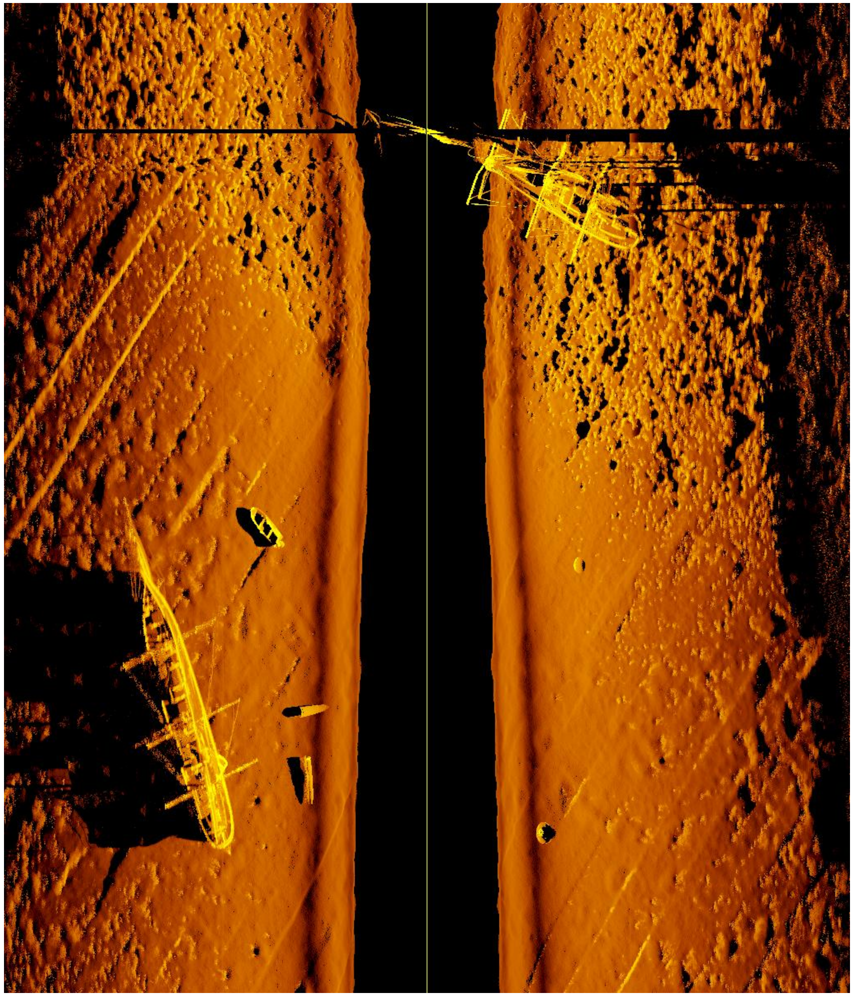
Ground-Truthed Virtual Environment



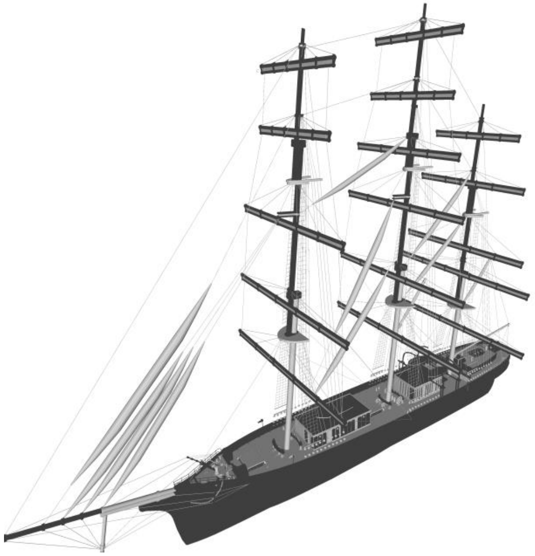


Beall, Chris, et al. "Bundle adjustment in large-scale 3D reconstructions based on underwater robotic surveys." *OCEANS, 2011 IEEE-Spain*. IEEE, 2011.

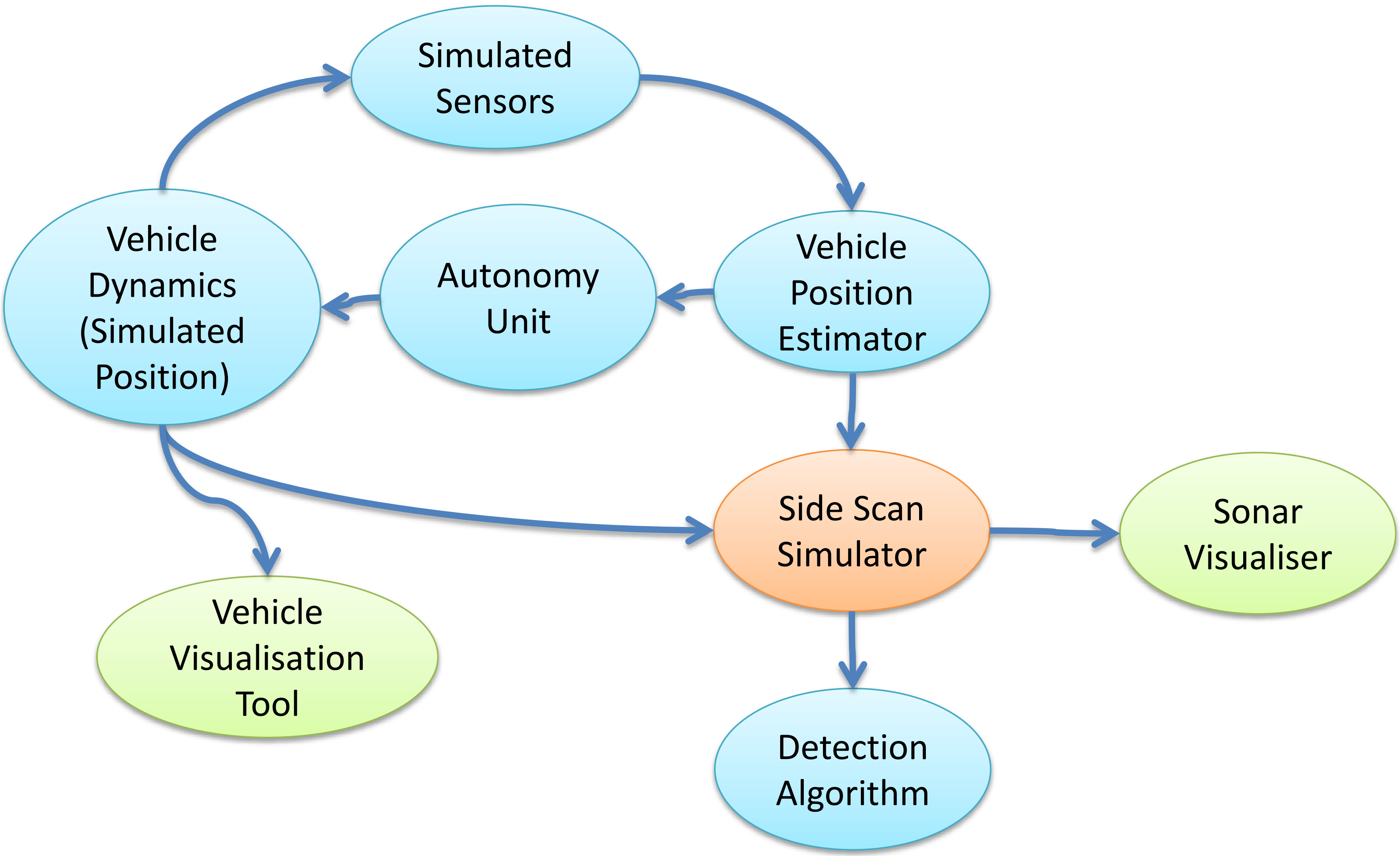
Complex Object Simulation



- Vertices: 206113
- Faces: 389552
- File size: 36.5 MB



Integration with MOOS



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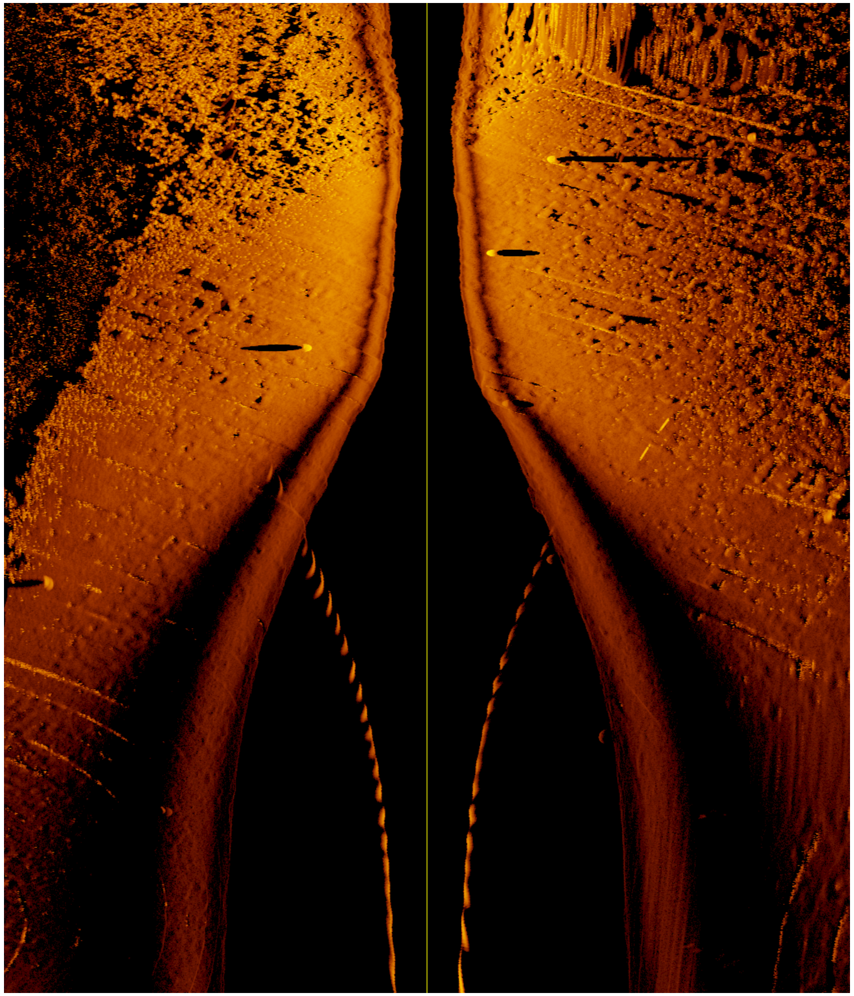
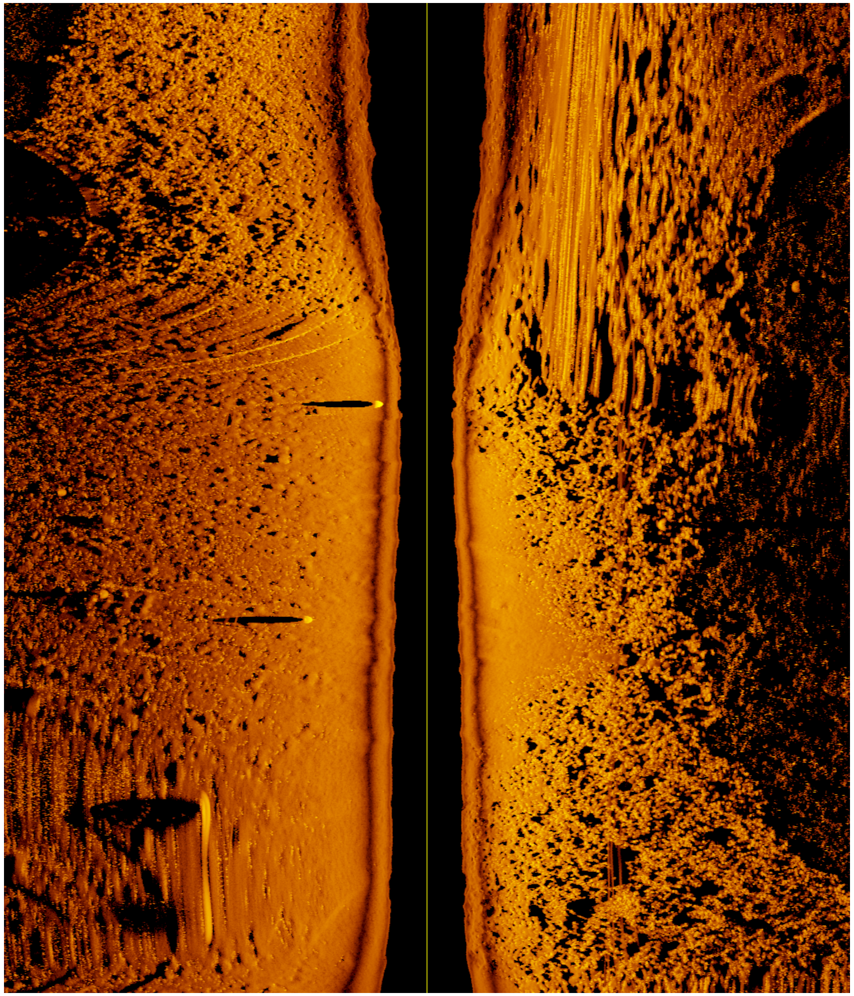
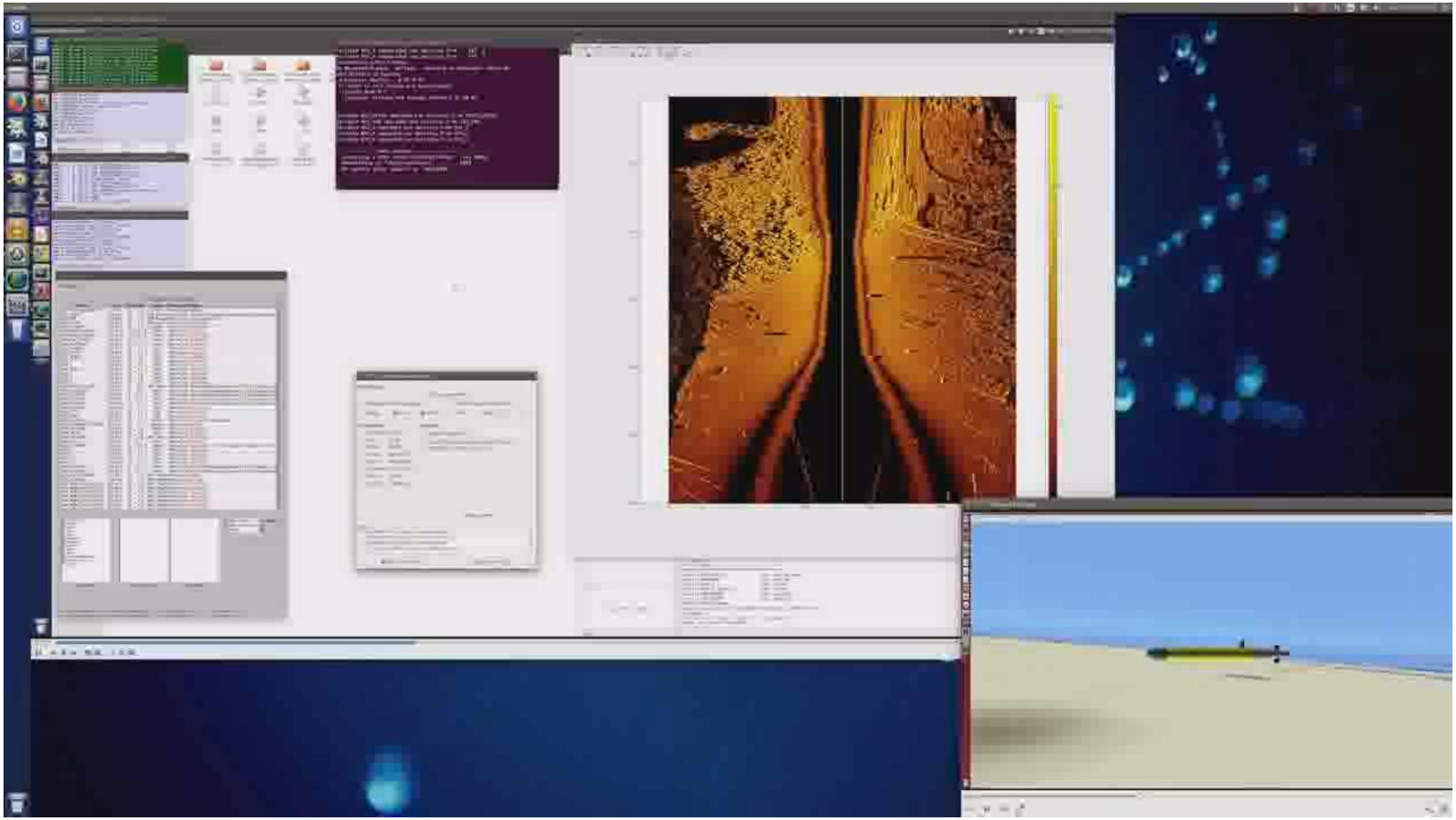


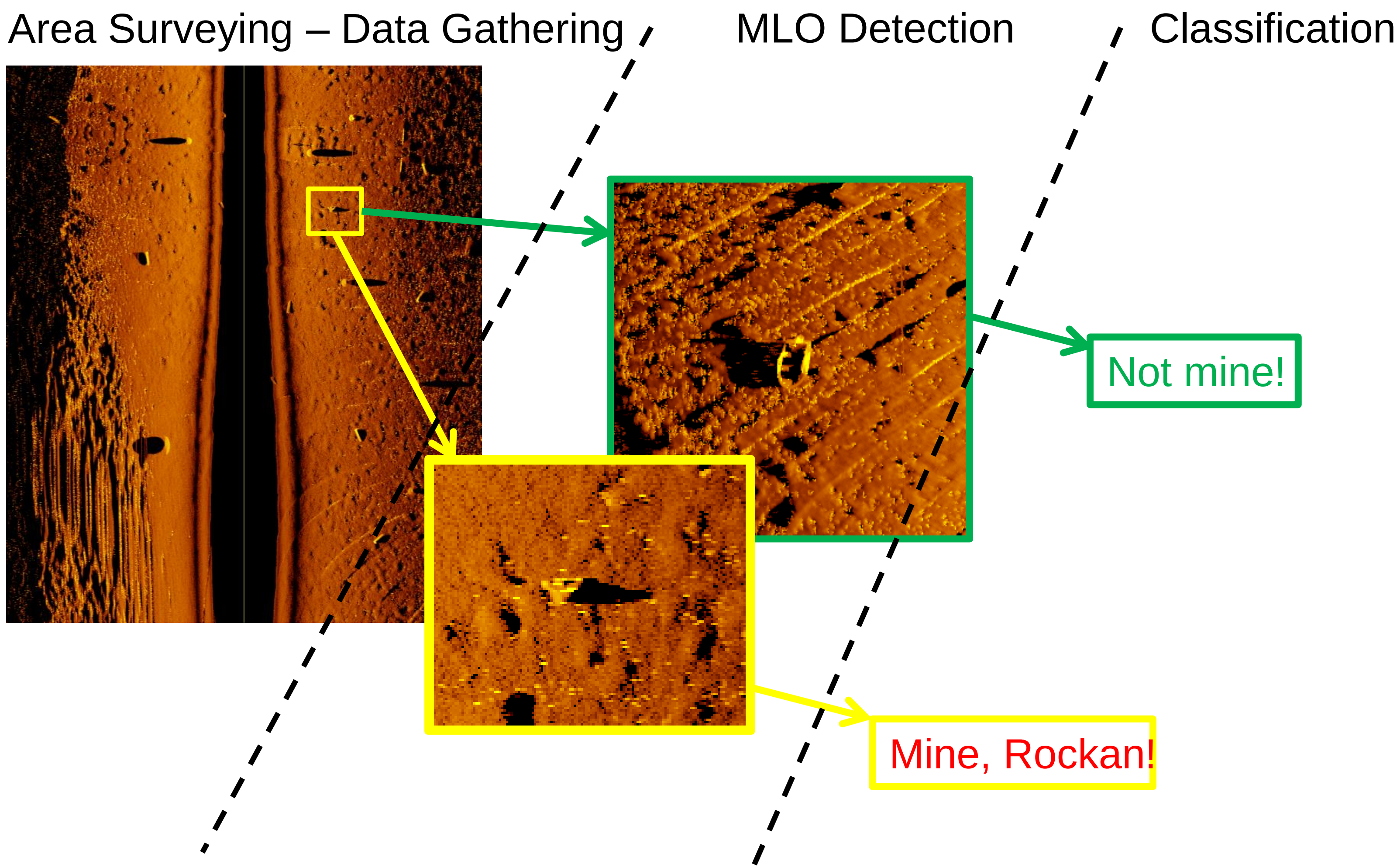


Result - Video



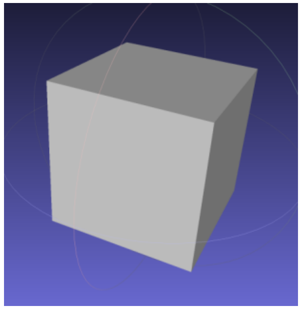
Using a Ray Traced simulator to perform model based classification.

- 2nd DSP Project: Model-based closed-loop sonar perception

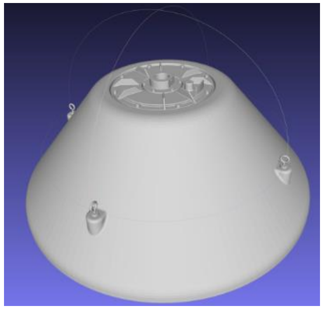


Mugshot Simulator

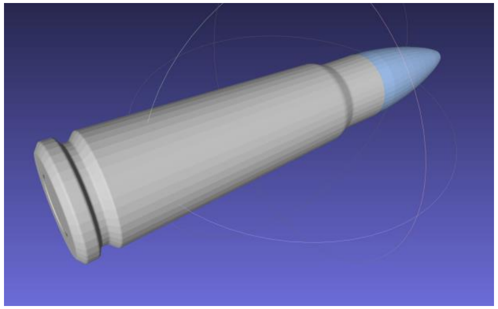
- Only interested in mugshots → Only simulate mugshots
- Effectively assumes detection is a solved problem
  - Most likely as a result of 1st pass detection by existing ATR algorithm
- Research Question: Can we determine a path that best discriminates between one type and another?



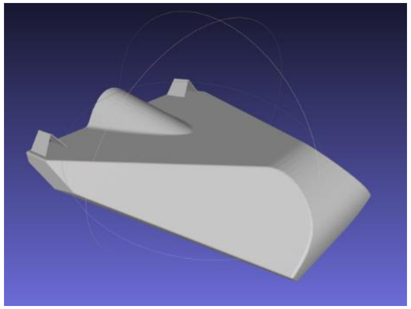
Cube



Manta



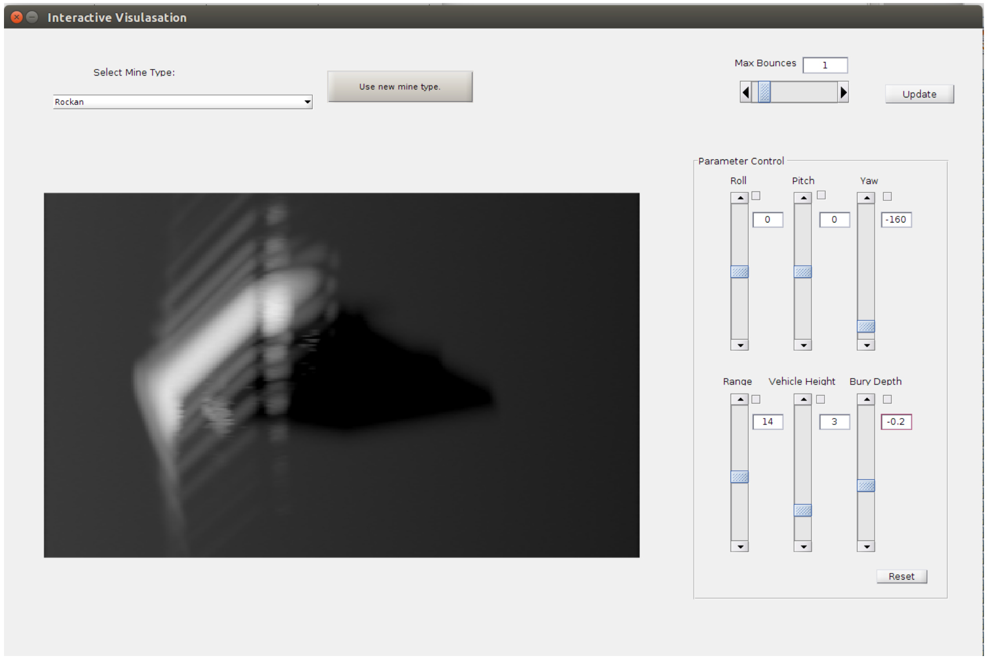
’Cylinder’



Rockan

Interactive Mugshot Visualisation

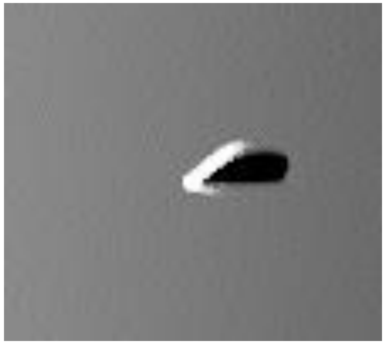
- Often the effect of a parameter on the sonar image isn't intuitive
- Human intuition is developed around interacting with things – making a change and seeing the response



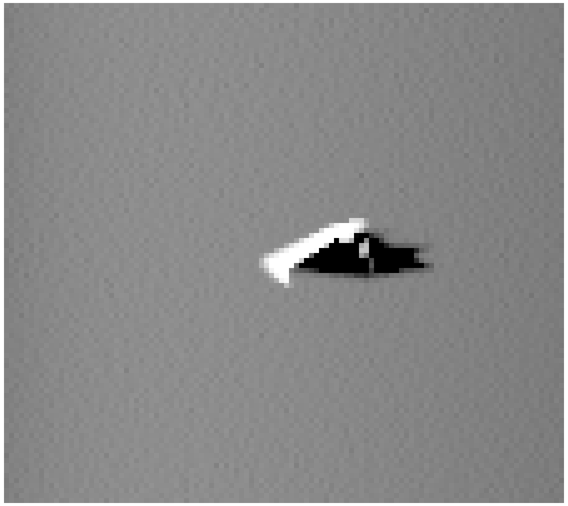
The Classification Problem

- Require parameter independent classification…
- Sonar imaging process is not determinate
  - Require probabilistic method
- Has many parallels to image identification

Cylinder:



Rockan:



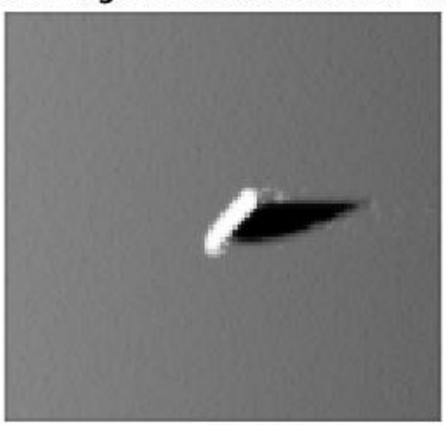
??

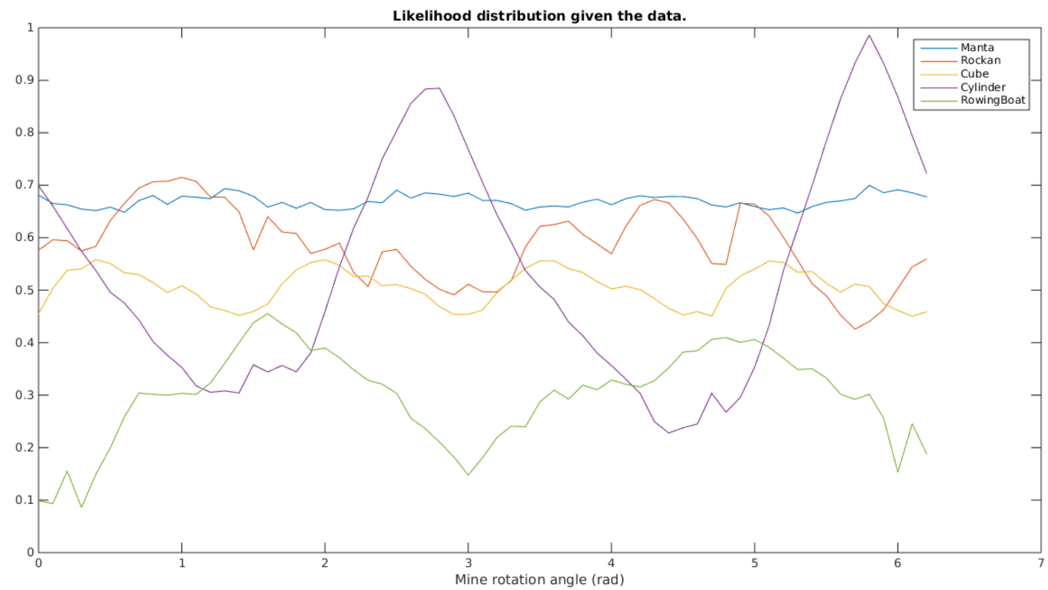
Image Comparison

- 2D Cross Correlation

$$r = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \bar{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \bar{B})^2\right)}}$$

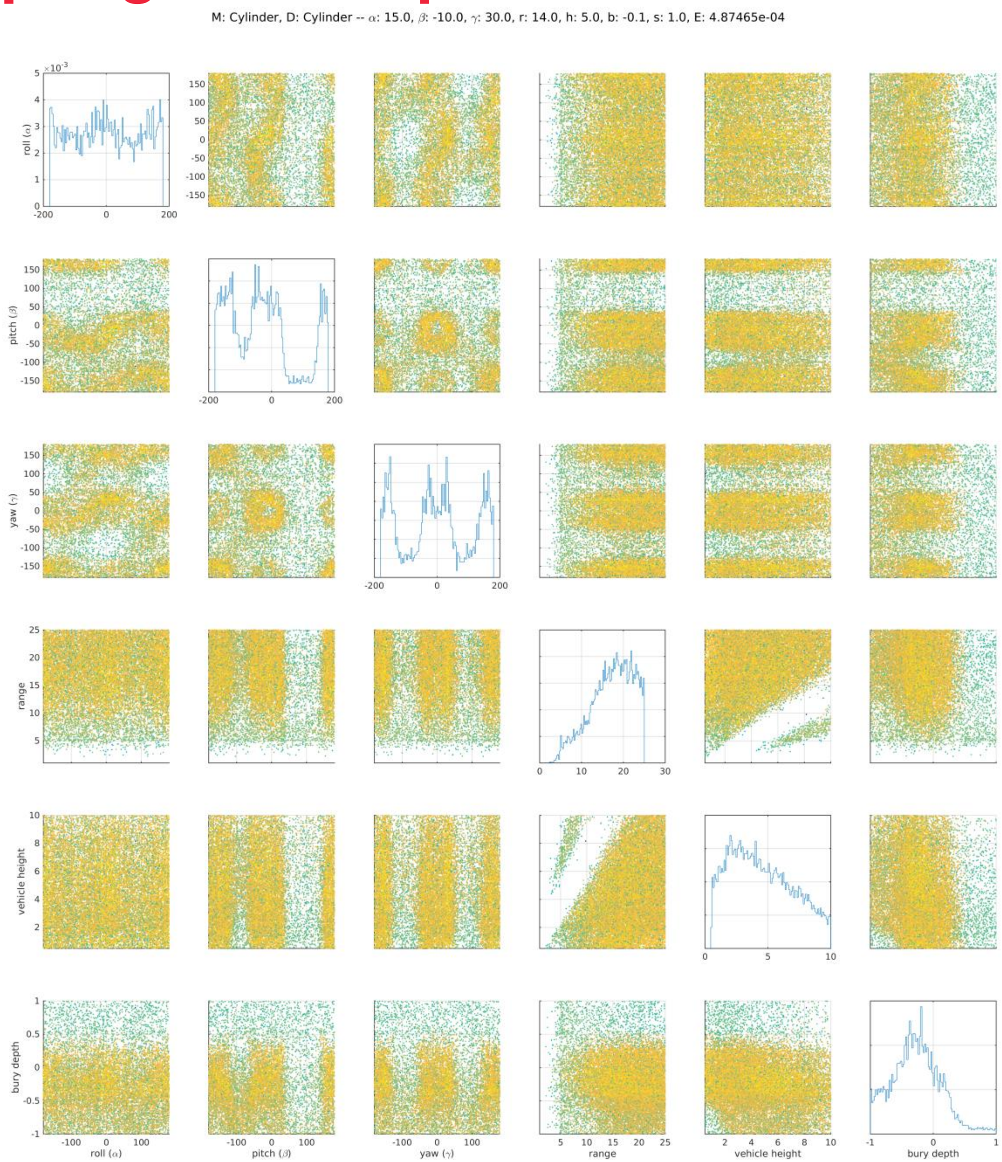
Selected image to use as Data for this trial





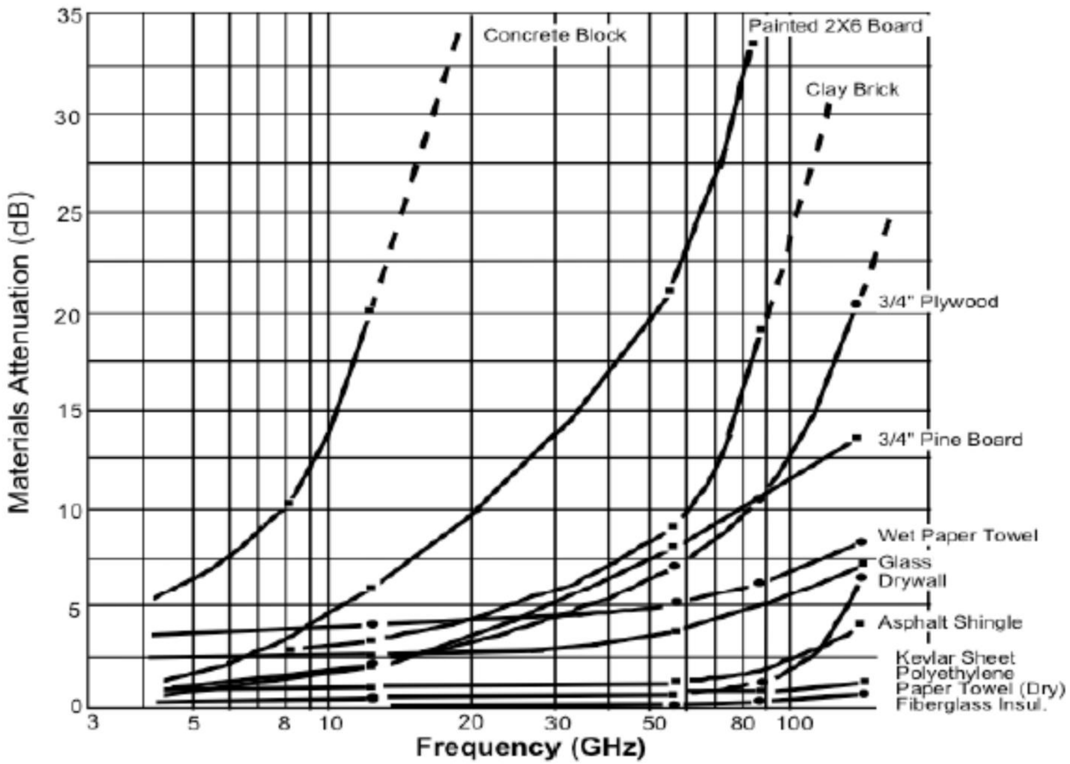
Gibbs Sampling the full parameter space.

- Randomly samples the parameter space
- Samples are rejected according to the correlation value
- Final sample distribution reflects probability density



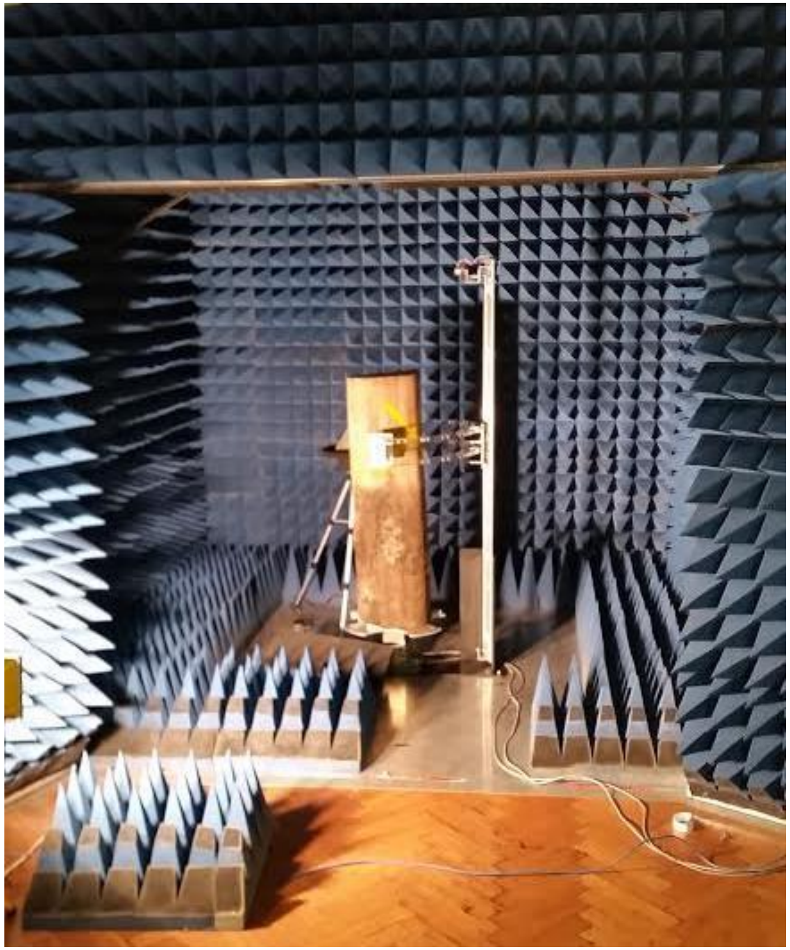
Non-Destructive Evaluation of Power Poles using RF Tomography

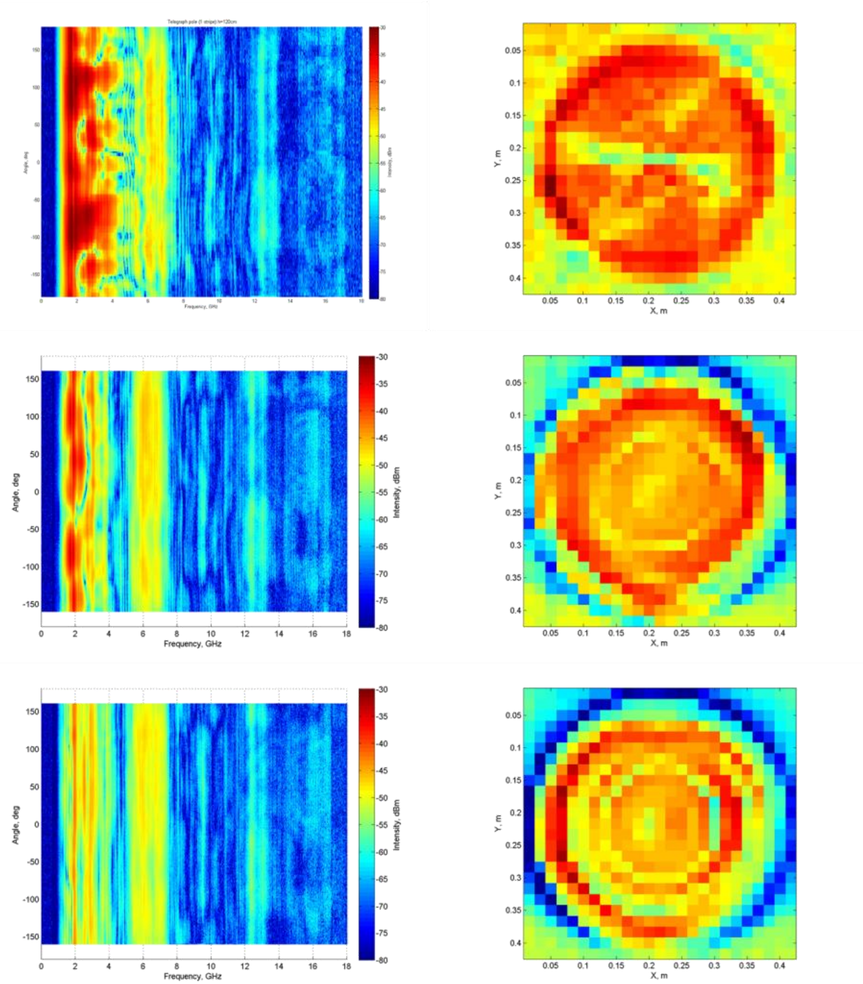
This technology is portable, non-ionising, potentially license-free and capable of high-resolution penetrative imaging over short distances



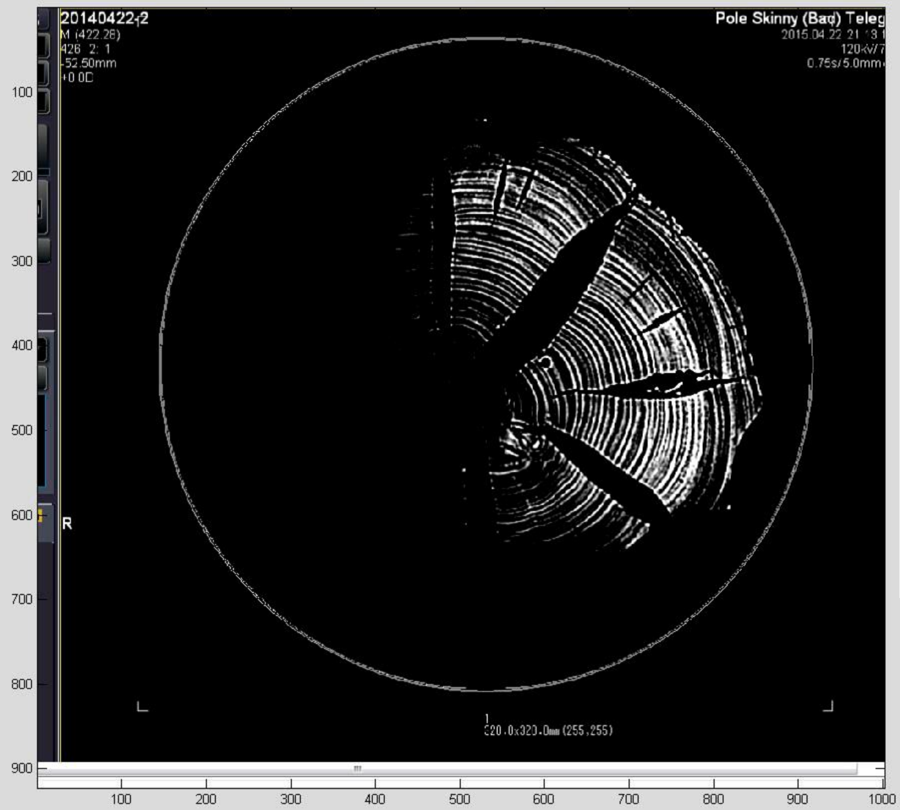
5 million wooden power poles in Australia
~1 billion worldwide

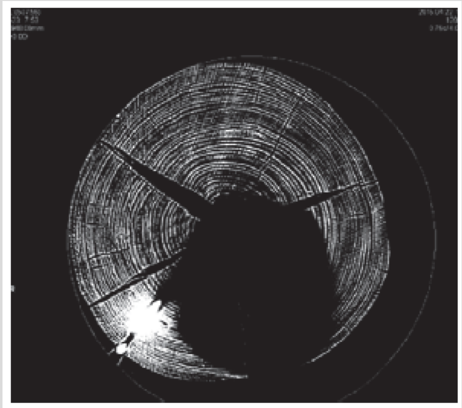
Transmissive results



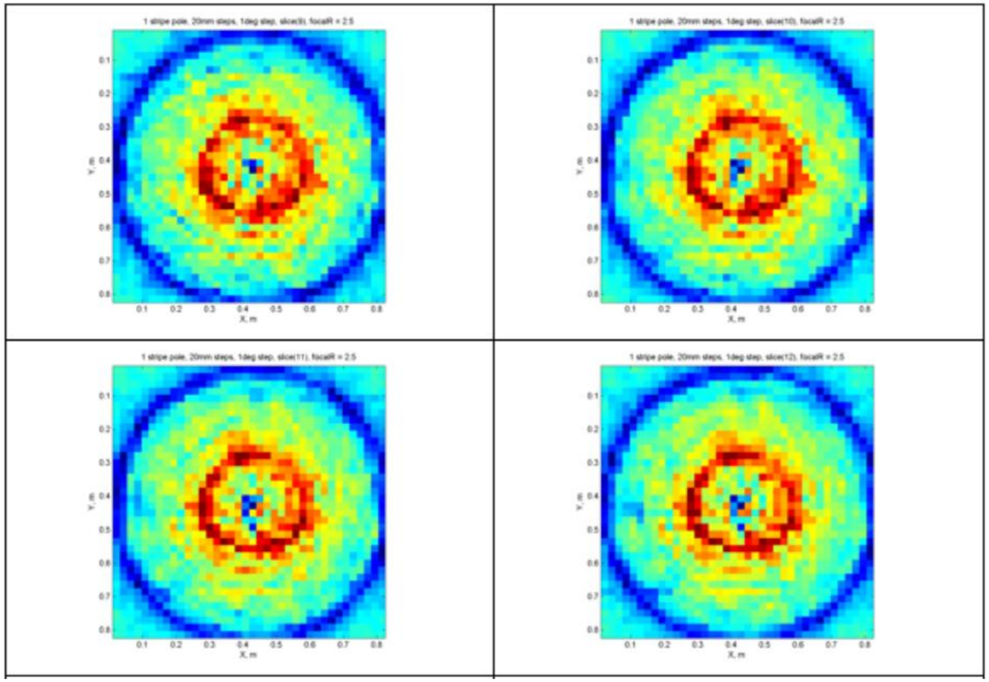


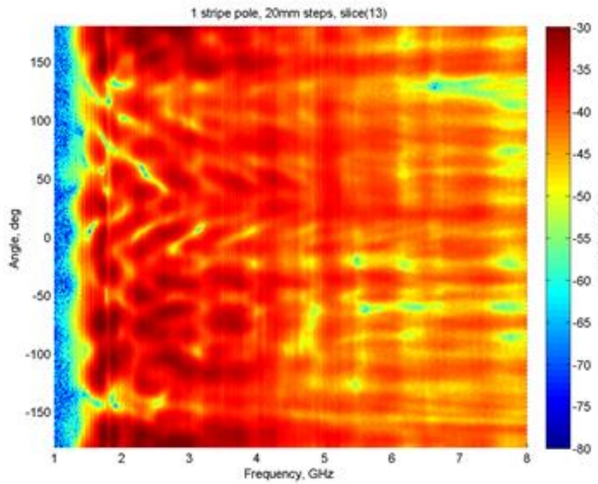
More Ground Truth Required: Faculty of Health Sciences owed us a favour

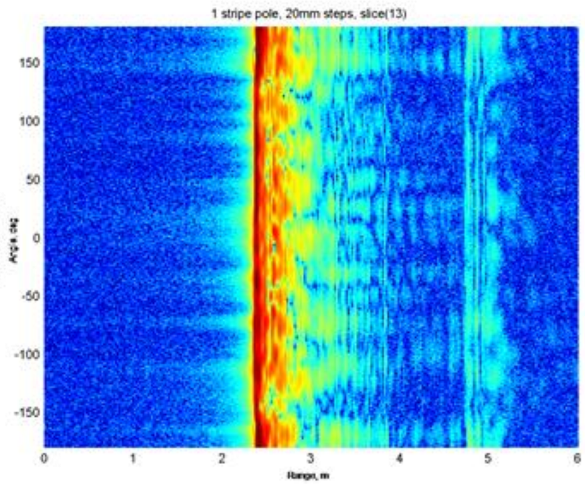


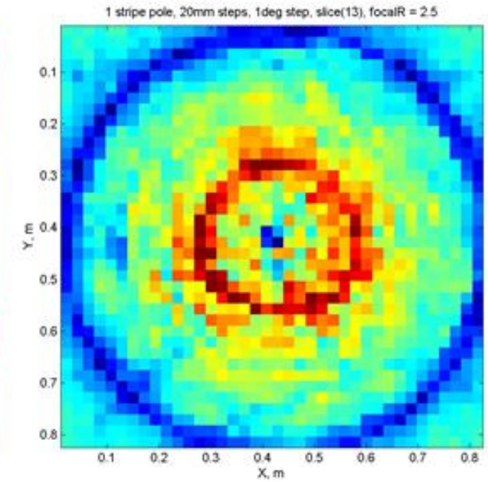


Reflection-mode scanning



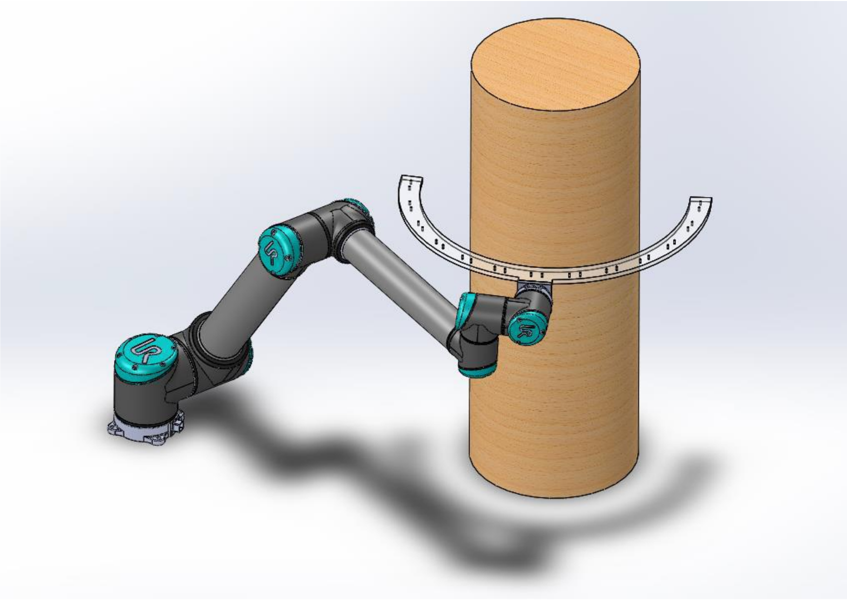






Next generation system: Multi-modal

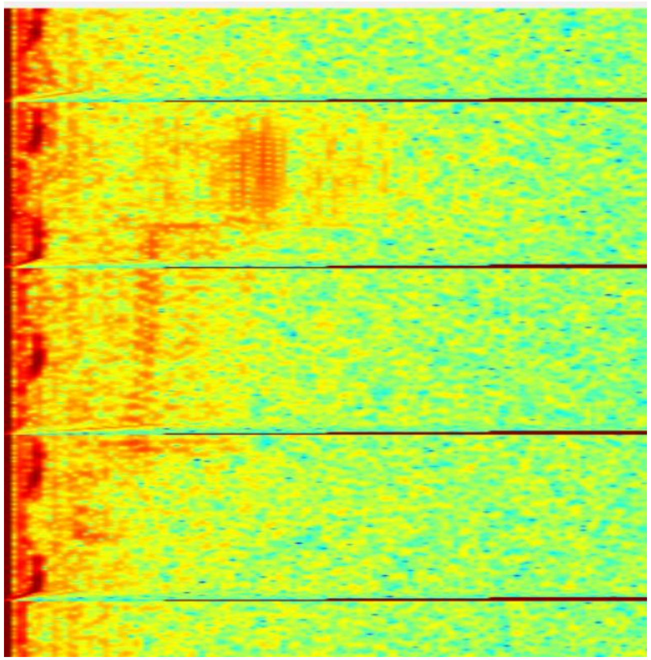
- Rotate around pole rather than vice versa.
- Arm kinematics don't allow in-plane rotation – hence require actuated carriages.
- Each carriage equipped with stereo-vision sensor to reconstruct external geometry and detect deformations.



- Bistatic reflection-mode images use geometry to allow phase/amplitude correction of waveform – true coherent active perception system!

Perimeter Surveillance

- Detection of low RCS targets (<-40dBm^2) at 2 - 50m, in clutter.
- Low-cost Doppler-radar mesh network
  - Currently 2, building 20 more



Summary

- Perception is *not* a solved problem – particularly when robust operation is essential.
- Active sensing is often complementary to passive (vision-based sensing), but more effort
- Active/Cognitive/Agile Sensing/Perception/Radar is a mean to close the action-perception loop
  - Adapting the system to seek refuting evidence of a hypothesis
- Various examples of how these ideas are being actively researched in the defence, mining, asset-monitoring and security domains have been shown.
  - I'm interested in solving your real-world problems (with radar)

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Future Directions

- System-level rather than platform-level sensor coherence.
- Dealing with those robustness issues identified at the start, particularly decentralised processing and communications
- Dealing with levels of autonomy – balancing coupled action/perception/learning with high-level tasks
- Dealing with complex dynamic environments
- Dealing with adversity
  - (Didn't mention my student projects on semi-autonomous FPV racing!)

- LIVE-ACTION ~~(WAR)~~ ROBOT GAMES.

IROS 2016 Workshop:
State Estimation and Terrain Perception

Topics of interest (including…)

- Onboard sensing for 3D mapping of unstructured environments
- Modelling and handling of uncertainties, drift, and outliers
- Terrain representation and estimation
- Integration of dynamical models and kinematic constraints
- Integration of prior knowledge (terrain type, maps, beacons)
- Dealing with dynamic environments
- Sensor failures, reliability and redundancy
- Tackling difficulties in outdoor perception (sunlight, low light, smoke, rain)
- Experimental results and full system integration in real world applications

Questions?