Australian Government
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Augmentation of the Slow-Time k-Space for Narrowband High-Resolution Radar Imaging

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Outline

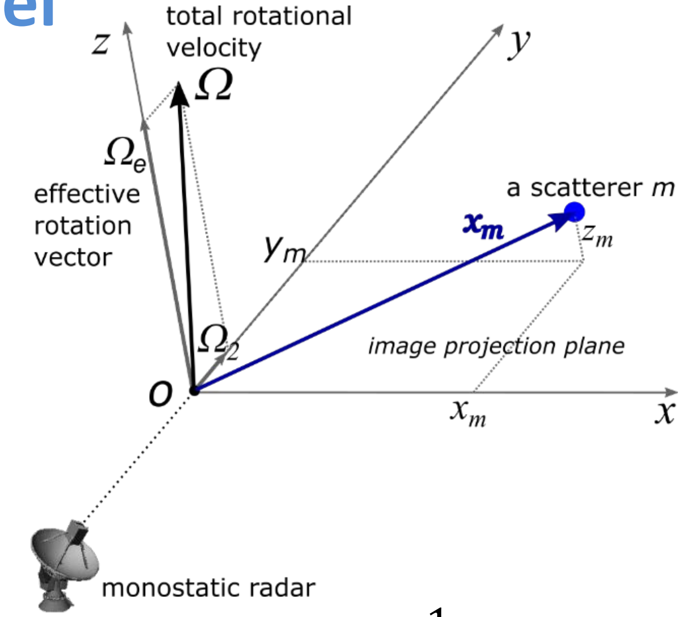
- Problem formulation
  - Signal model
  - Standard Doppler Radar Tomography (DRT) – theory
- The slow-time *k*-space
  - Brief theory
  - Augmented DRT
- Application of Compressive Sensing - OMP
- Demonstration with Experimental Data

Problem Formulation – Signal Model

- Current treatment restricted to 2D Imaging & monostatic configurations.
  - Readily extended to multistatics & 3D
- Uses the far-field approximation
- Requires ultra-narrowband radar
  - Doppler processing only
  - Low sampling rates (lower system cost)
  - Motion compensation involves only relative target *velocity*.
- Imaging aperture defined by relative target rotation (or variation of aspect)
- Cross-range bandwidth:

$$B_\perp = f\,\Omega_e T_{CPI} = f\,\Delta\theta$$

- Non-linear effects compensation



$$r_m(t_k) = y_m + x_m \Omega_e t_k - \frac{1}{2}\, y_m \Omega_e^2 t_k^2 + \cdots,$$

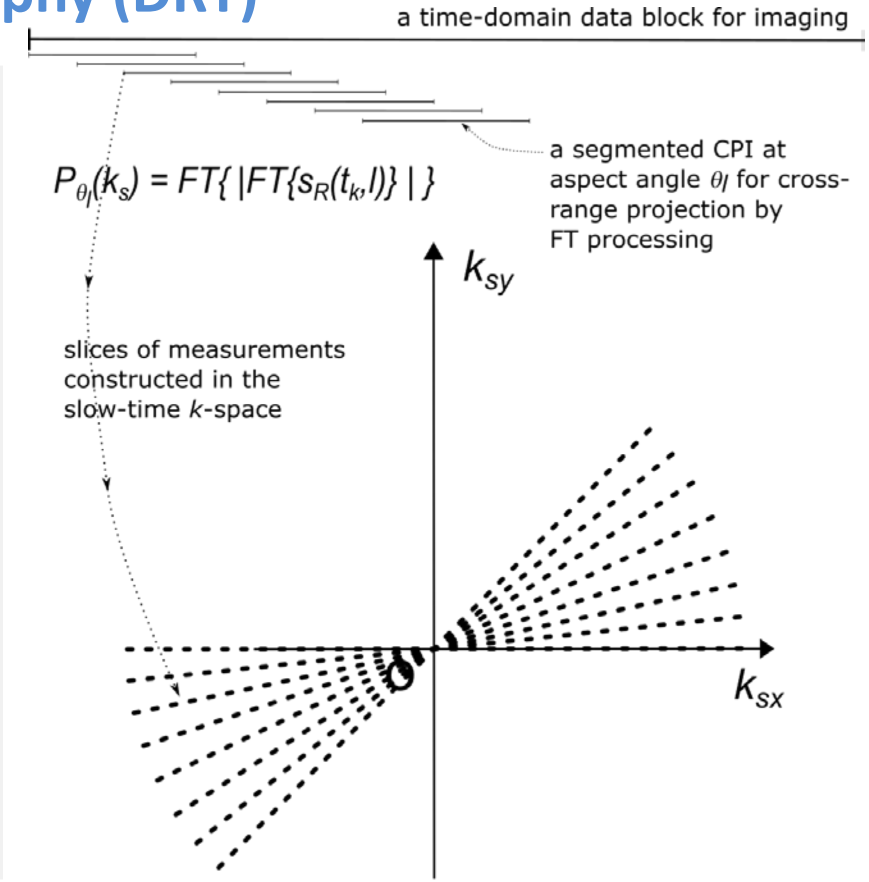
$$s_R(t_k, f) \propto \exp\left\{-j4\pi f \frac{R_0(t_k)}{c}\right\} \sum_{m=1}^{M} \sigma_m \exp\left\{-j\frac{4\pi f}{c} r_m(t_k)\right\}$$

Standard Doppler Radar Tomography (DRT)

- Dates back to the 1980s (Mensa et al)
- Algorithm - 4 main steps:
  - Time-domain data segmentation
  - Translational motion compensation
  - Populating the (slow-time) *k*-space
  - Image inversion
- Image inversion:
  - Traditionally can be via “filtered back projection” technique
  - More modern/powerful technique: the <u>non-uniform FFT</u>

Notes:

- Limited to small angles of rotation for each segmented CPI
- Require extensive total angular coverage



a time-domain data block for imaging

$$P_{\theta_l}(k_s) = FT\{\,|FT\{s_R(t_k, l)\}|\,\}$$

a segmented CPI at aspect angle θ_l for cross-range projection by FT processing

slices of measurements constructed in the slow-time *k*-space

Augmented *k*-space & Augmented DRT

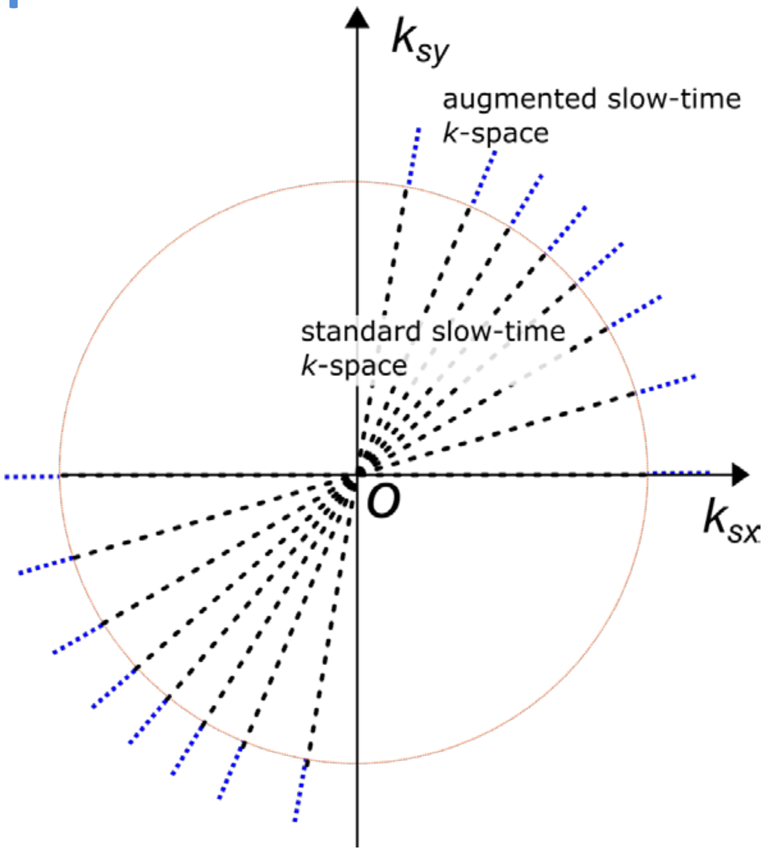
- ❑ Extent of *k*-space

$$k_s \in \left(-\frac{2\pi f}{c}\Delta\theta, \frac{2\pi f}{c}\Delta\theta\right)$$

- ❑ Larger *Δθ* requires compensation of nonlinear phase terms

$$r_m(t_k) = \ y_m + x_m\Omega_e t_k - \frac{1}{2}\ y_m\Omega_e^2 t_k^2 + \cdots$$

- ❑ Except for the longer CPIs (and associated compensation processing) the *Augmented DRT* algorithm consists of the same steps as *Standard DRT*.
  - ➢ Application of Compressive Sensing (sparse signal reconstruction)



Application of Compressive Sensing - OMP

- Use longer segmented CPIs – valid for chirp signal approximation – higher cross-range BW

$$B_\perp = f\,\Delta\theta, \Delta x = \mathrm{c}/2B_\perp$$

- In each CPI, solve for a sparse representation with chirp atoms
- Set up a chirp dictionary $\boldsymbol{\Psi}$ – a 2D parameter space
- Solve the sparse reconstruction problem with OMP
- Focusing action: replace all chirp atoms in the sparse solution with single-tone sinusoid functions with Doppler frequency at the mid-point of the segmented CPI;
- Compute the focused cross-range profiles

$$p_{\theta_l}(x) = |\mathcal{F}\{\tilde{s}_R(t_k)\}|$$

- Apply the usual steps of Standard DRT Algorithm

$$s_R(t_k,f) \propto \exp\left\{-j4\pi f \frac{R_0(t_k)}{c}\right\} \sum_{m=1}^{M} \sigma_m \exp\left\{-j\frac{4\pi f}{c} r_m(t_k)\right\}$$

$$r_m(t_k) = y_m + x_m\Omega_e t_k - \frac{1}{2} y_m \Omega_e^2 t_k^2 + \cdots,$$

$$\boldsymbol{s}_R = \boldsymbol{\Psi}\boldsymbol{\sigma} + \boldsymbol{\epsilon},$$

$$g(k) = \exp\left\{-j2\pi\left(f_g t_k + \frac{1}{2} c_g\, t_k^2\right)\right\}$$

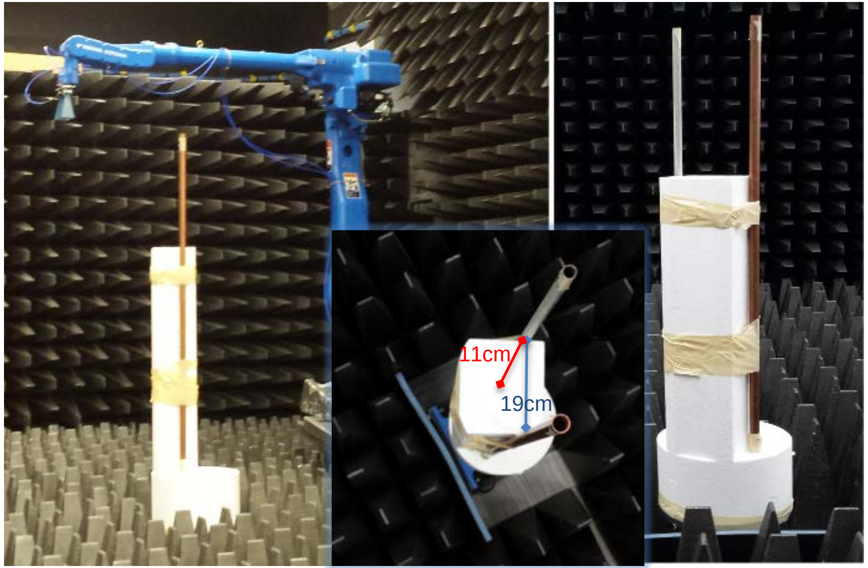
$$f_g = \frac{2\,x\,\Omega_e}{\lambda}, \qquad c_g = \frac{2\,y\,\Omega_e^2}{\lambda}$$

$$\tilde{s}_{\boldsymbol{R}}(t_k) = \sum_{m=1}^{M} \sigma_m\, g_m(t_k) \Rightarrow \sum_{m=1}^{M} \sigma_m\, \tilde{g}_m(t_k)\,.$$

$$\tilde{g}_m(t_k) = \exp\left\{-j2\pi f_g^{(mid)} t_k\right\}$$

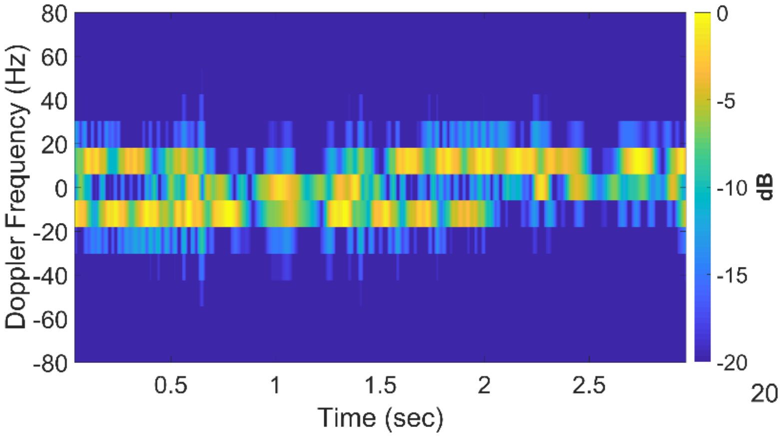
An Experiment

- ☐ Used a wideband stepped-frequency waveform, X-band, 8 - 12 GHz, over 101 steps.
- ☐ Transmit and receive horns on robotic arms
- ☐ Target is two metallic rods, on a rotating pedestal, approx. 19 cm apart and 11 cm from rotation centre,
- ☐ Signal sampled at every 0.1 deg angular steps
- ☐ Fast rotating targets can be emulated from this start-stop data collection.
- ☐ Also included bistatic configurations
  - Only monostatic channel, and single frequencies, are used in this work.



With sincerely thanks to Lorenzo Lo Monte & Nihad Alfaisali, and the Mumma Laboratory at University of Dayton, Ohio, USA, for collecting and providing the experimental radar data in May 2016.

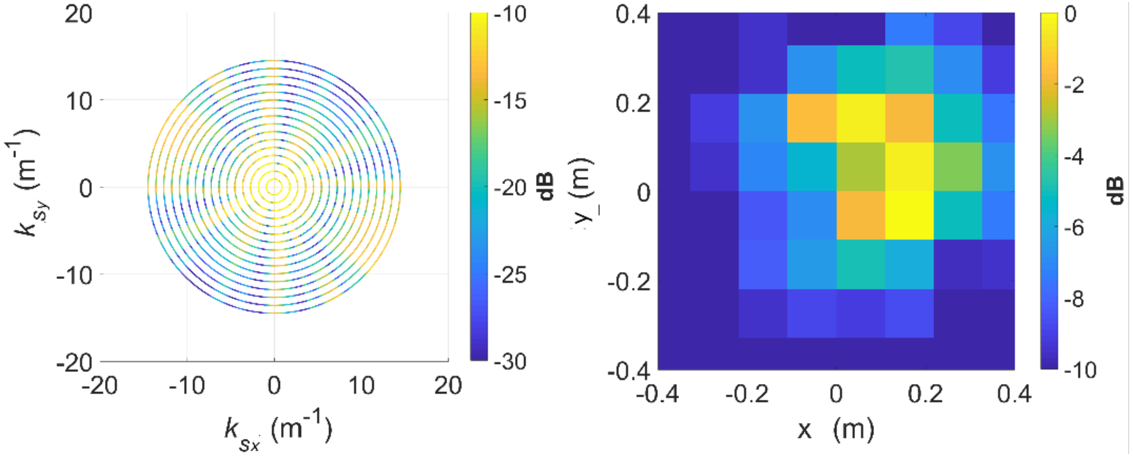
Imaging Results – Standard DRT



Signal spectrogram of original signal, at 8 GHz

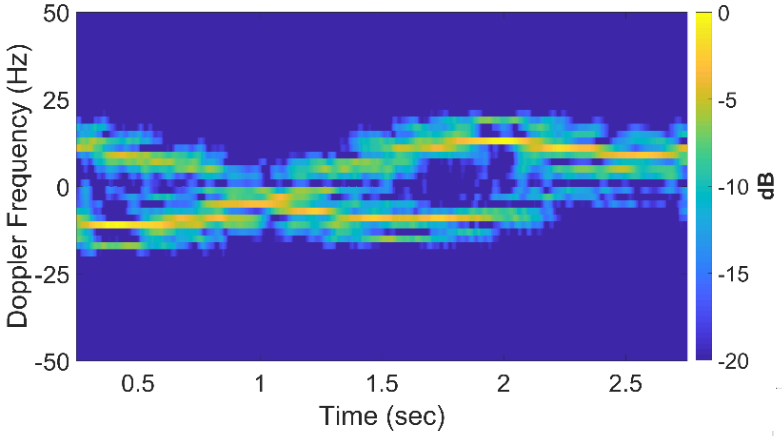
General characteristics:

- Small Doppler frequency extent and coarse resolution
- No migration through resolution cell
- Relatively low imaging resolution



Populated *k*-space & DRT image

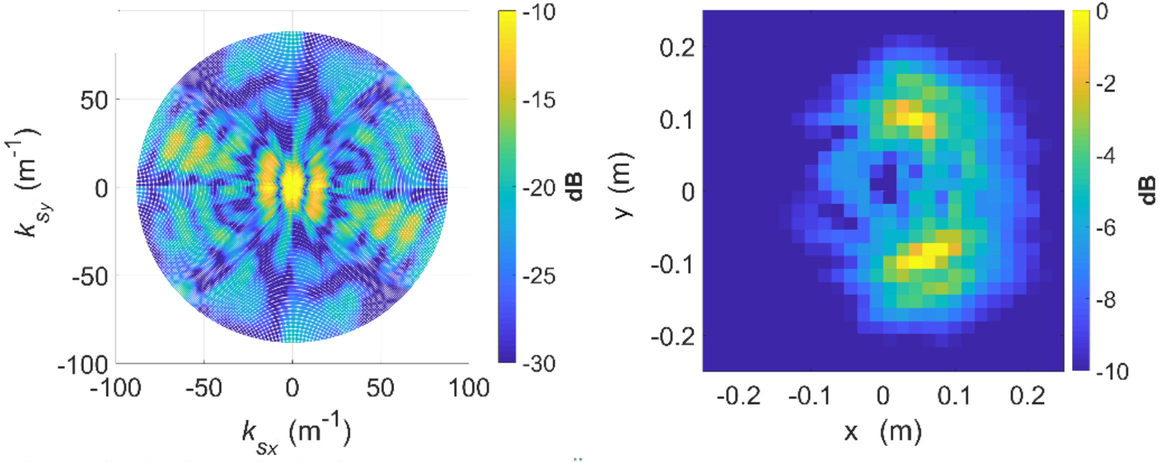
Imaging Results – Standard DRT (with longer CPIs)



Signal spectrogram of original signal, at 8 GHz, augmentation factor = 6.

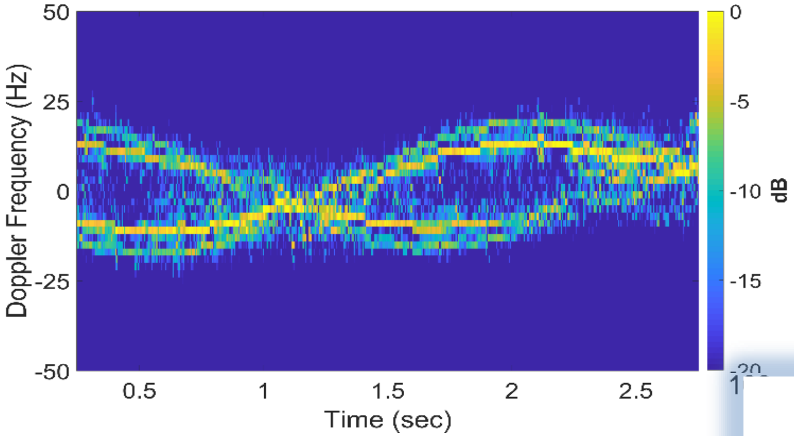
General characteristics:

- ☐ Same Doppler frequency extent, higher Doppler resolution
- ☐ Enhanced focusing in radial dimension only
- ☐ Blurred resolution in azimuth



Populated *k*-space & DRT image

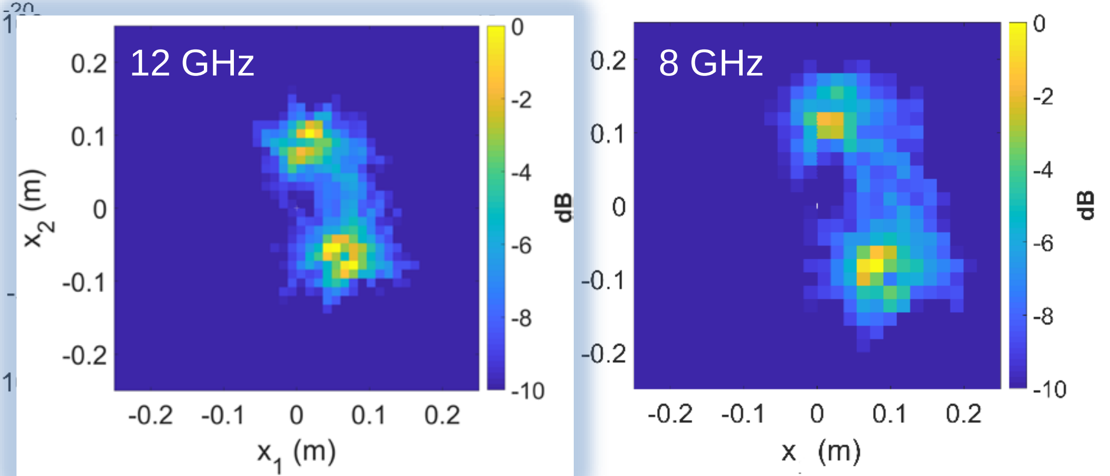
Imaging Results – Augmented DRT



Signal spectrogram of *OMP-reconstructed* signal, at 8 GHz, augmentation factor = 6

General characteristics:

- ☐ Best resolution performance
- ☐ Require control of what atoms, and how many of them, to include in the sparse solution
- ☐ Not specific to OMP



Populated *k*-space & augmented DRT image

Discussion Points

Advantages

- Compared to wideband imaging techniques, translational motion compensation for DRT imaging is simpler
    - Only velocity compensation
    - Extension to multistatics is less sensitive to phase errors
- Numerous other sparse reconstruction techniques can be used
- Atoms can be defined in polar formats
    - Prior knowledge about expected locations of atoms can be used to confine parameter space to small intervals – faster to process.

Challenges

- Real targets are often not ideal point scatterers
    - Artefacts may appear
    - Need more advanced theory
- Real targets consist mostly of off-grid scatterers
    - Need further special processing for refocusing
- Higher augmentation factors require compensation for higher-order terms (beyond the linear chirp approximation)

Concluding Remarks

- A novel theory for Augmented DRT and the slow-time *k*-space is presented
- Performance demonstrated with experimental radar
- A potentially robust solution for high-resolution narrowband imaging
  - And effective response to the increasingly congestive RF spectrum
- Other sparse reconstruction techniques of CS can be useful for Augmented DRT imaging
- Computational cost
  - For 2D imaging, the dimensionality of the parameter space for CS is 2 - computational cost should be manageable.
  - Atoms and CS dictionary can be defined in multiple forms – further cost reduction can be achieved.

Thank You

With the team at the Mumma Laboratory at University of Dayton, Ohio, May 2016.