Interference Mitigation for Synthetic Aperture Radar Data using Tensor Representation and Low-Rank Approximation

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URSI GASS 2020

Outline

01 **Background and Motivation**

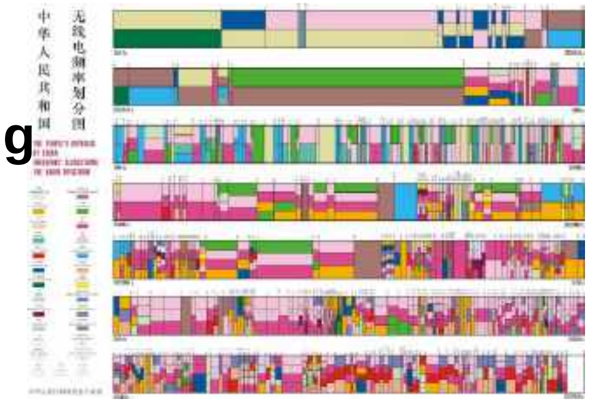
02 **RFI Characterization**

03 **RFI Mitigation Strategy**

04 **Conclusion Remarks**

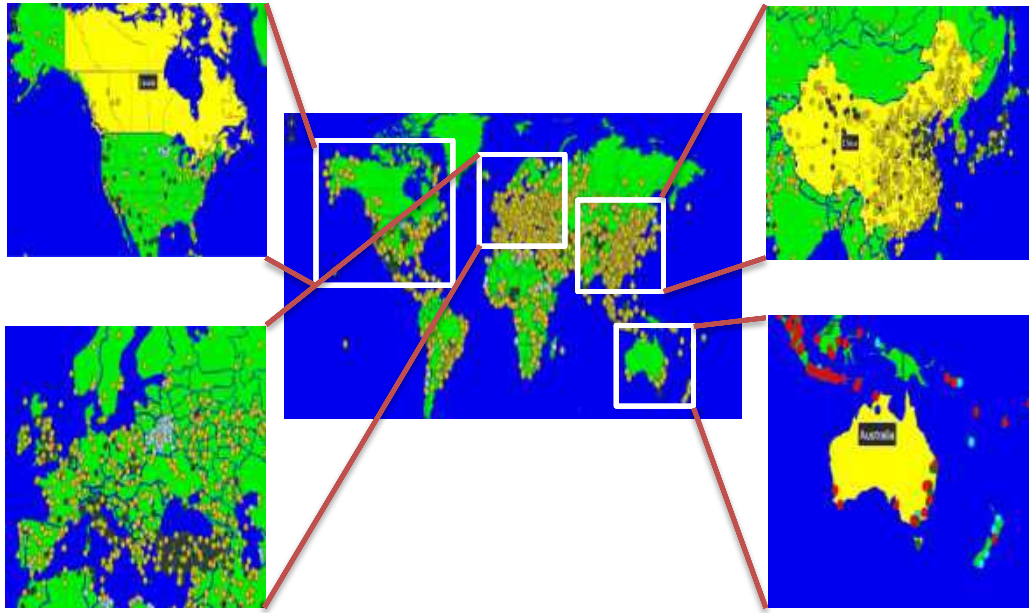
1. Motivation – Congested and Contested Electromagnetic Environment

Synthetic Aperture Radar (SAR) -- an important active microwave remote sensing instrument, critical for earth monitoring and understanding



Radio Frequency Interference (RFI) -- Unavoidable spectrum sharing for high-resolution SAR systems with large bandwidth

- ***Frequency Distribution* --** RFI at low bands (P/L) is abundant and spread worldwide
- ***Spatial Distribution*** -- Significant geographical differences (severe in densely populated area)
- ***Time Variation*** -- Steadily increased and varying over time (RFI issue growing worse)
- Detrimental to global and regional scientific research (especially for space-borne system)

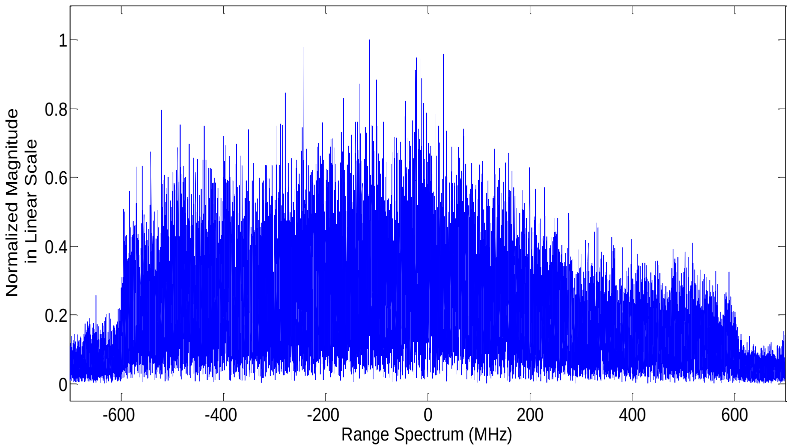


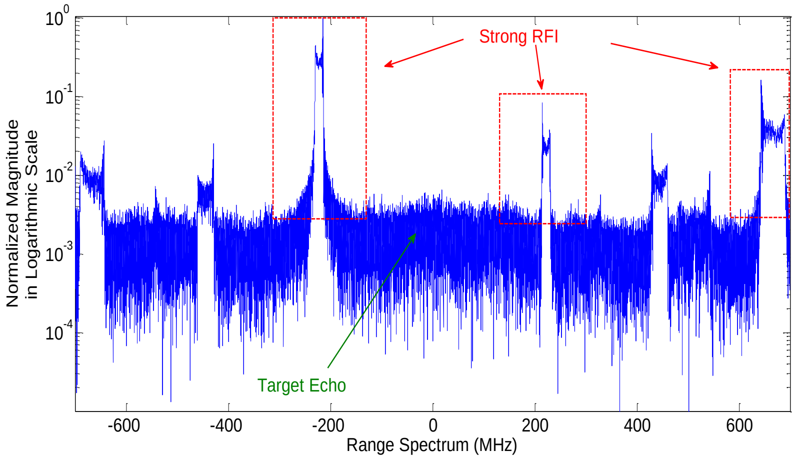
* Database of Frequency Allocations for Microwave Remote Sensing and Observed Radio Frequency Interference (RFI)

1. Motivation – Adverse Impacts of RFI

Data Collection

- Reduce raw echo SINR, bury target response, distort the dynamic range of the raw echoes
- High-power in-band emissions may even lead to receiver saturation, especially when aimed towards the interfering sources in main-lobe
- Requires specific receiver design, e.g., wide dynamic range for low probability of saturation





A particular example: the range spectrum of the SAR echoes (a) without RFI and (b) with RFI. The dashed rectangle marks the first three largest interference components.

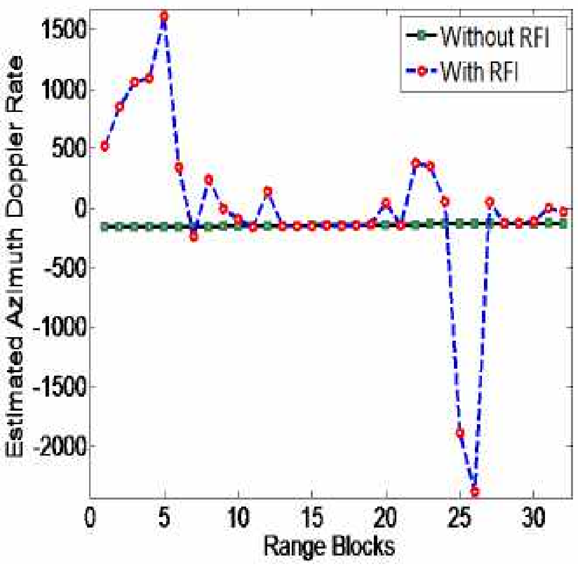
1. Motivation – Adverse Impacts of RFI

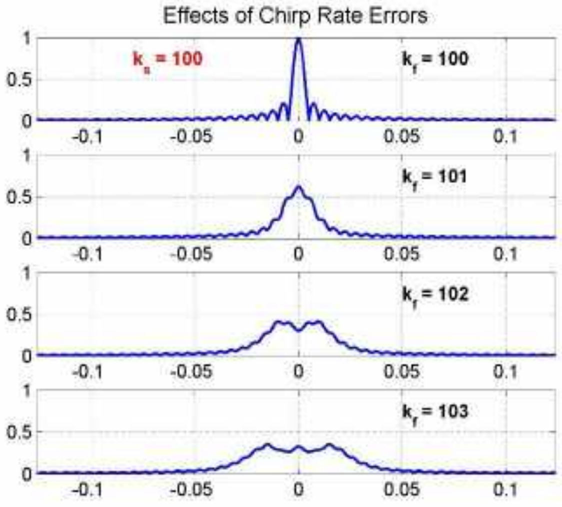
Data Collection

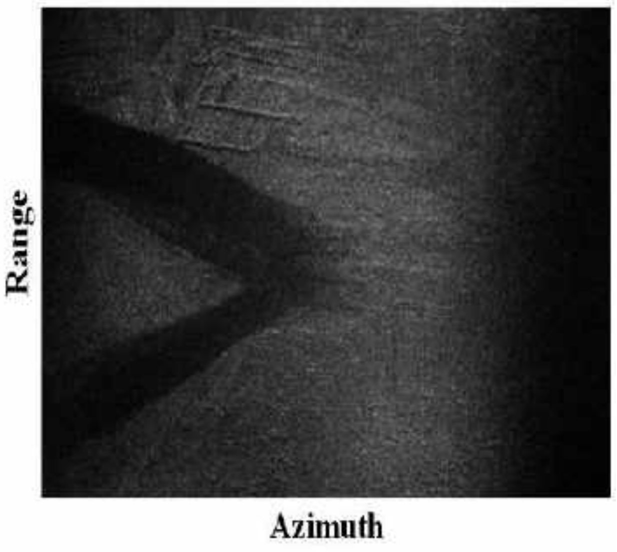
Image Formation

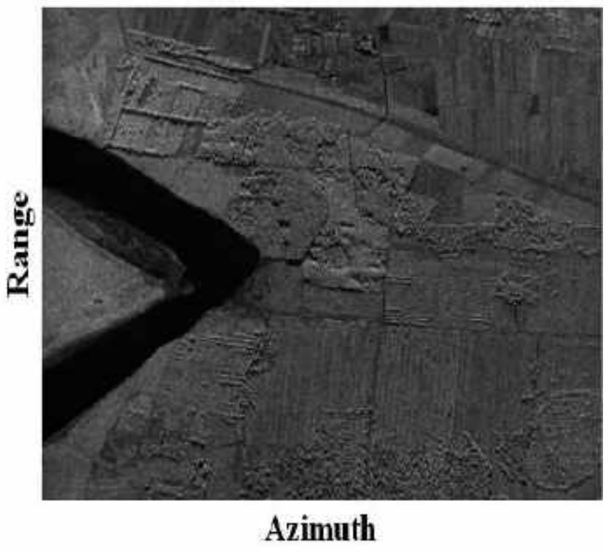
Image Defocusing after Match Filtering

- Biased estimate of matched filter parameters, (e.g., Doppler centroid, modulation rate)
- Imperfect energy accumulation due to incoherent contributions, distorting the target response





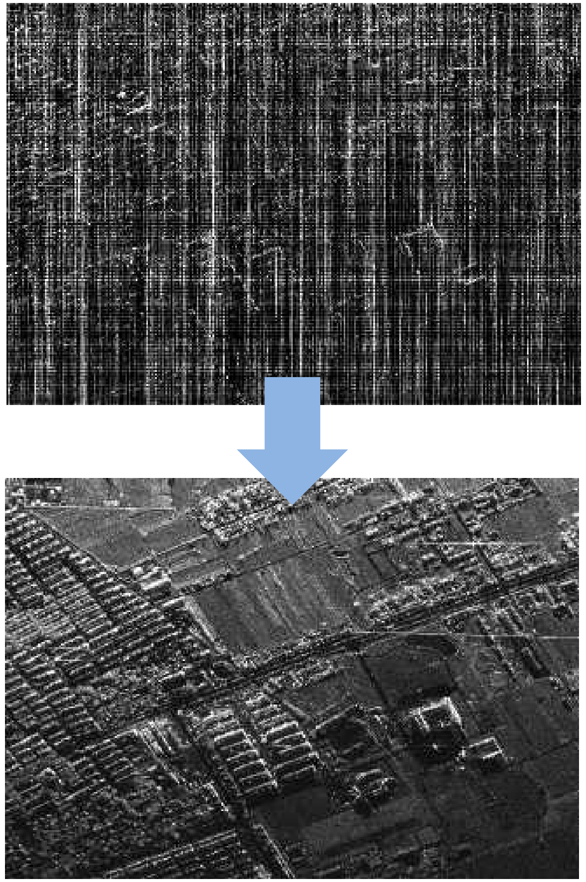




1. Motivation – Adverse Impacts of RFI

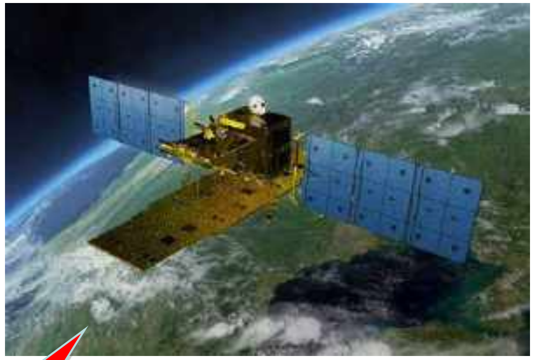
Data Collection → Image Formation → **Image Interpretation**

- **Amplitude & Phase Distortion**
  - Haze-like image artifacts or bright lines -- lead to inaccurate spatial and radiometric measurements
- **Hindrance to image interpretation and post-products analysis**
  - Phase distortion would de-correlate the data, producing inaccurate post-products such as polarimetric descriptor, coherence, and retrieved biological or physical parameters
  - Affect end applications like target detection, classification…



2. RFI Characterization – RFI Sources

② Space RFI Sources



- <u>RFI Source Types</u>
  - Mostly associated with human activity over land and widely reported
  - Rarely with mutual interference from satellites

① Terrestrial RFI Sources

2. RFI Characterization – ① Terrestrial Radiation Sources

- **Major Terrestrial RFI Sources for SAR -- *Wide variety of signals & modulations***

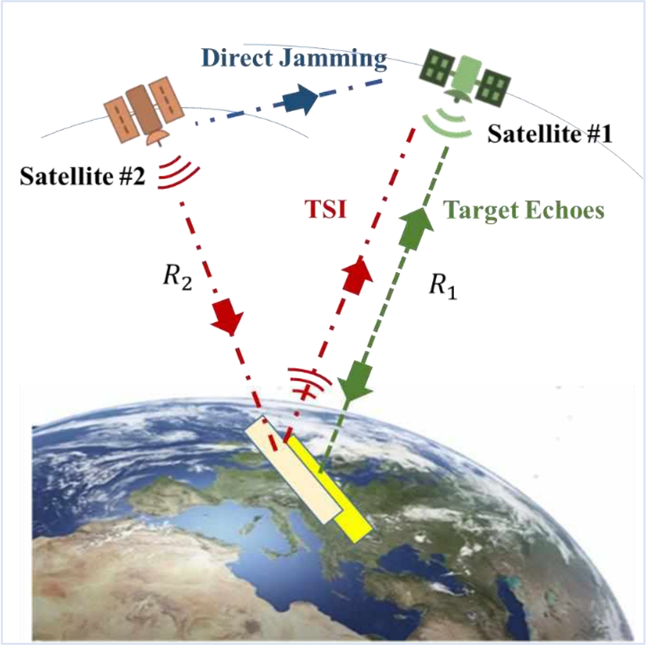
- **Long-range Radiolocation Radars -- Pulsed**
- **Telecommunication Devices -- Spread spectrum CW**
- **Television Networks -- Narrow-band CW**
- **Strong beacons**
- **Amateur -- weak & strong CW, SSB, NBFM, data, video**
- **…**

- **RFI has power advantage due to less antennation with distance (e.g single way propagation)**

2. RFI Characterization – ② Spaceborne RFI Sources

- **Spaceborne Satellite**
  - **Radio navigation signals from multiple satellite constellations**

    -- GPS/GLONASS/COMPASS/GALILEO (Broadcasting Continuously)
  - **Communication Satellite -- Broadband CW**
  - **Microwave Remote Sensing Satellite -- Incoherent Wideband**



- **Two Possible Interfering Way**
  - **Direct jamming signal to the antenna side-lobe or back-lobe**
    - **Interference power due to direct reception by backlobes is non-negligible but tolerable**
  - **Terrain scattered interference reflected off of the earth**
    - **Reflections off of the Earth are potentially large due to Quasi-specular scattering, but with rare occurrence**

3. RFI Mitigation Techniques

- ***Goal & Mitigation Definition:***
  - **Reduce the adverse impacts of RFI to a large extent without introducing too much signal loss**
  - **Restore the amplitude while preserve the phase information**
  - ***Note:*** **It is nearly impossible to reconstruct the original signal completely**
- ***Challenges***
  - **Heterogeneous RFI environment is dynamic varying, rather difficult to characterize and model**

- **1-D Azimuth Echo**

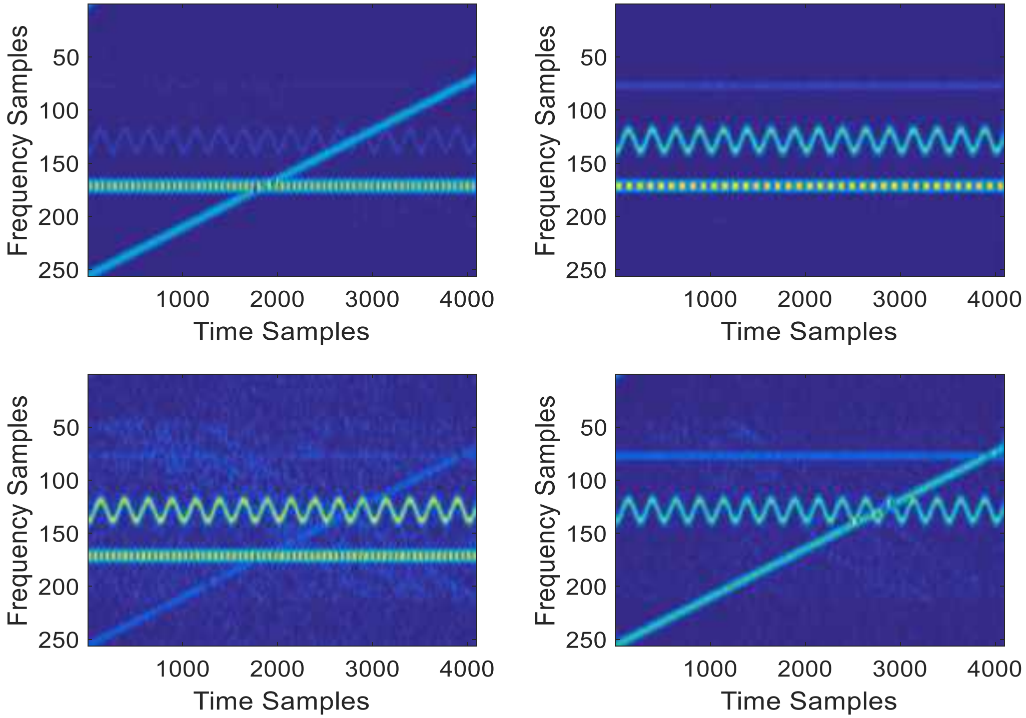
"single channel separation problem"

$$x(n)=s(n)+w(n)+I(n),\quad 1\le n\le N$$

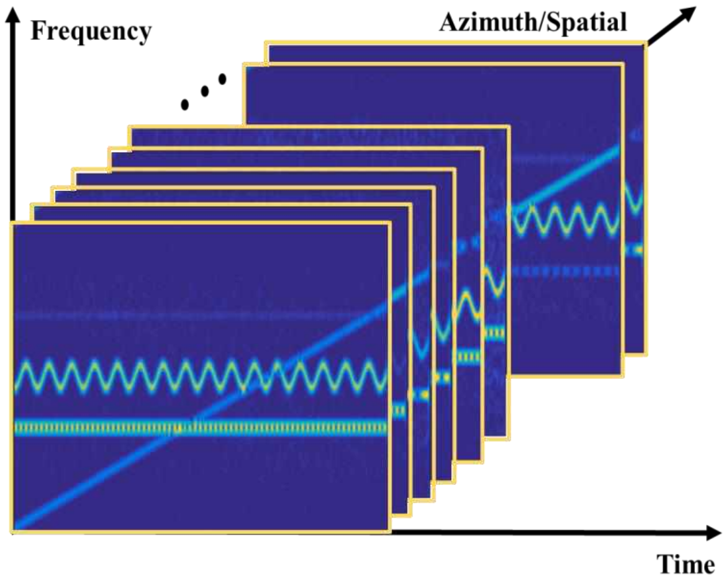
- **Target Return --** $s(n)$ **Thermal Noise --** $w(n)$ **WBI --** $I(n)$

3. RFI Mitigation Techniques

- **Remark I:**
  - **Since adjacent azimuth pulses constitutes the synthetic aperture, it ignores the correlation among the azimuth samples. The amplitude and frequency of interference may vary at each time instants, while the useful echoes are highly correlated.**



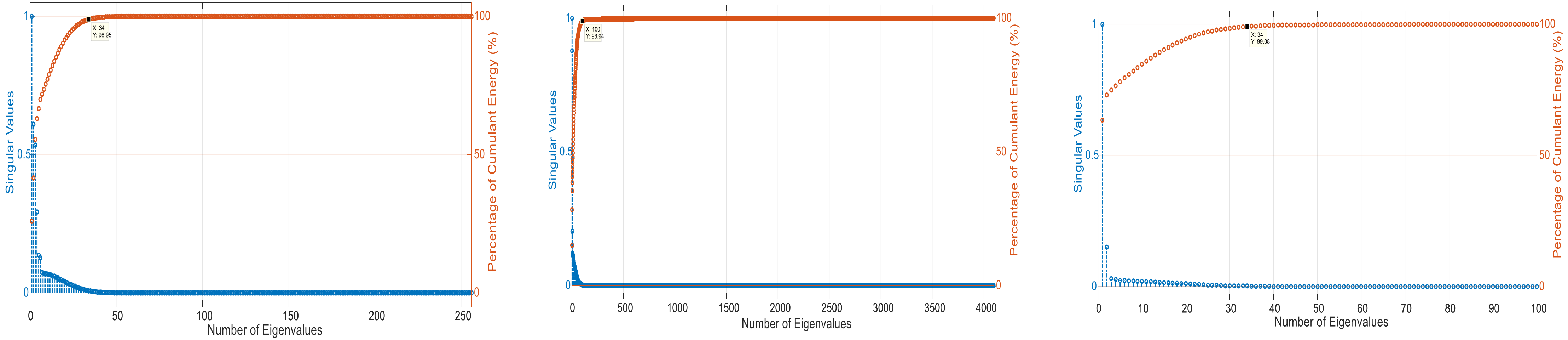
spectrogram of adjacent azimuth pulses at different slow time instants



3-D (range) time-frequency-azimuth tensor model

3. RFI Mitigation Techniques

- **Remark II:**
  - **In the first two modes, it is observed that the eigenvalues are dominated by a few large values, which indicates the low-rank property is satisfied.**
  - **The evolvement of the curve for the third mode is not as steep as the first two modes. This may result from the fact that the existence of spatial correlation among the azimuth samples.**



Eigenvalues of the time-frequency-azimuth tensor representation along each mode

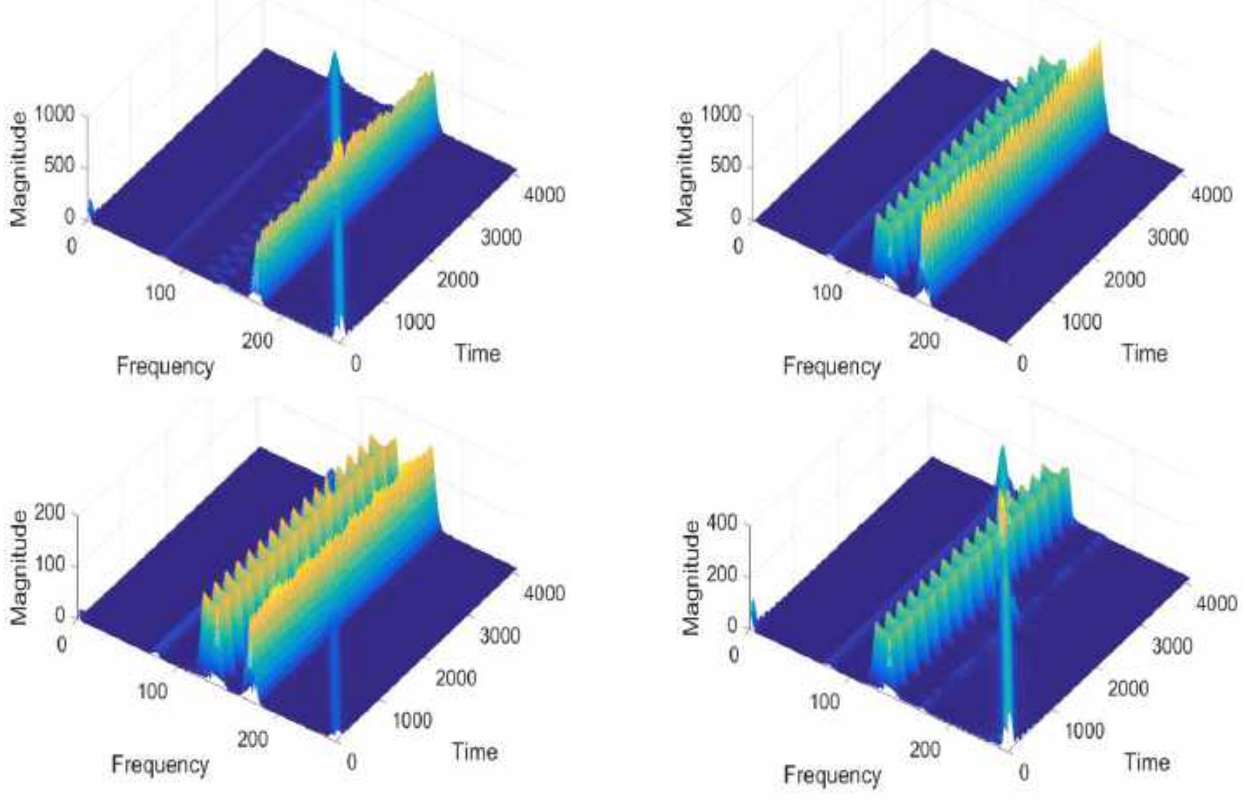
3. RFI Mitigation Techniques

Low Rank Tensor Estimation Problem

$$\begin{cases} \max \quad \left\| \mathcal{X} \times_1 \mathbf{U}_{(1)}^T \times_2 \mathbf{U}_{(2)}^T \times_3 \mathbf{U}_{(3)}^T \right\|^2 \\ s.t. \quad \mathbf{U}_{(n)}^T \mathbf{U}_{(n)} = \mathbf{I} \end{cases}$$

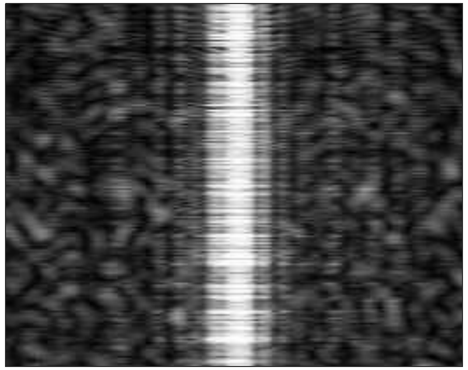
⇨

$$\begin{aligned} \hat{\mathcal{S}} &= \mathcal{X} - \hat{\mathcal{I}} \\ &= \mathcal{X} - \mathcal{X} \times_1 \mathbf{U}_{(1)}\mathbf{U}_{(1)}^T \times_2 \mathbf{U}_{(2)}\mathbf{U}_{(2)}^T \times_3 \mathbf{U}_{(3)}\mathbf{U}_{(3)}^T \end{aligned}$$



Estimated Interference Components at different specific time instants

⇨



Imaging results before interference separation

Imaging results after interference separation

4. Conclusion Remarks

- A novel 3-D time-frequency-azimuth tensorial representation is proposed
- the low-rank property of the interference is exploited for interference separation by applying the low-rank tensor approximation
- The experimental results show the potential of tensor algebra, and more advanced and efficient tensor-based techniques remain to be investigated.
- Worth Noting: Not all interference can be removed in post-processing
  - Current techniques work best for interfering signals that have sparse spectral or temporal or spectral-temporal occupancy with the target echoes
  - The data after RFI mitigation is not as good as RFI-free data

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Thank You for Your Attention !