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Multidimensional Synthetic Aperture Radar for Arctic Surveillance

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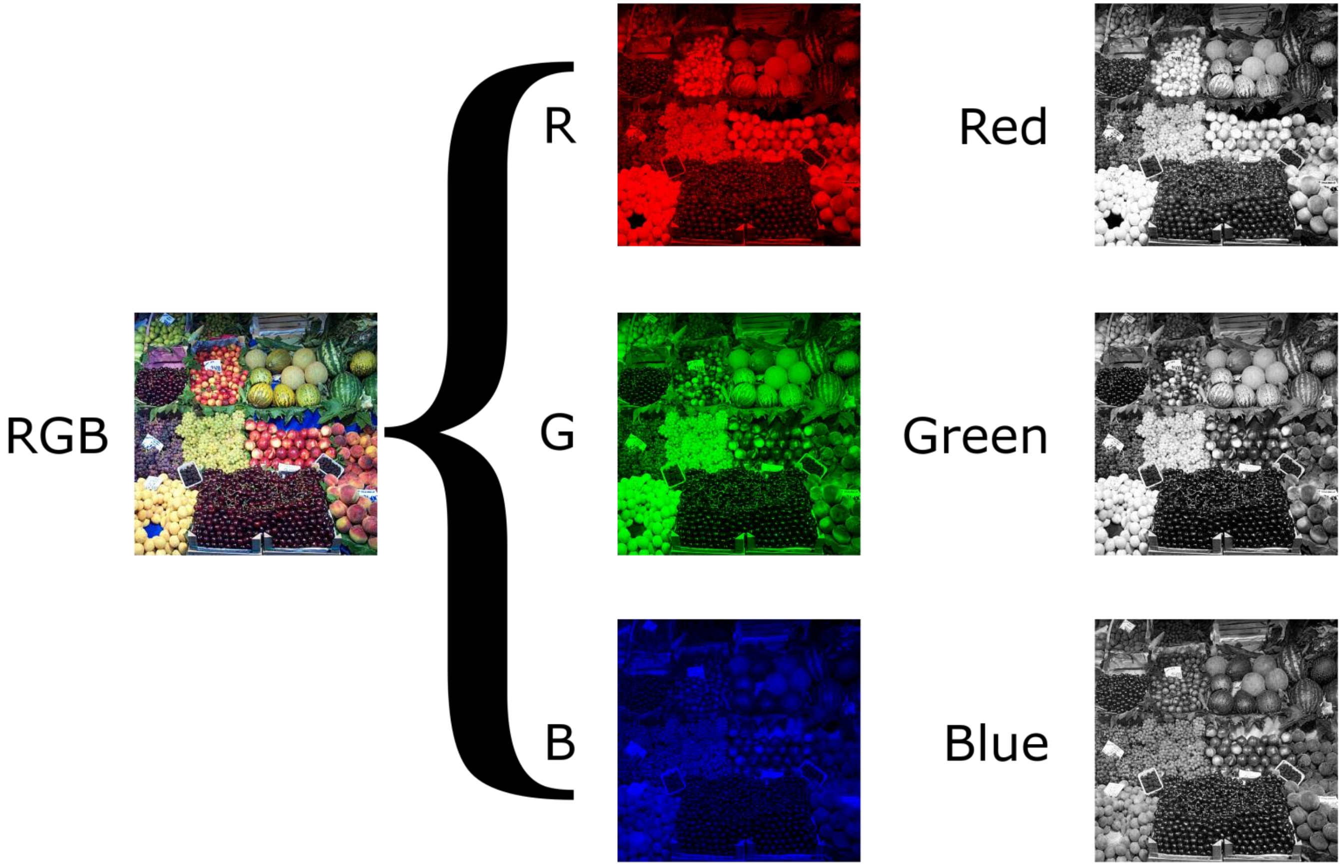
Overview of Contents

- Dimensionality in radar imaging
- Use of polarisation for increasing number of dimensions
- Basic radar polarimetry
- Synthetic aperture radar (SAR)
- DALOEX test campaigns with DLR F-SAR
- Test sites
- Ground truth collection
- Data processing
- Selected examples
- Summary and conclusion

Colour Image in Terms of RGB



Radar Dimensionality

Classical systems

- Monostatic
- Single channel
- Single frequency
- Single polarisation

$$P_r = \frac{P_t G_T}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times A_e$$

For each resolution cell

- One real number
- **Grayscale** signatures

Multidimensional systems

- Multiple frequencies
- Spatial diversity
  - Bi-/multistatic
- Use of orthogonal polarisations

$$V_r = A\, e^{j\varphi}\, \vec{p}_R^{\,*} [S]^* \vec{p}_T^{\,*} \frac{e^{-j2kr_0}}{4\pi r_0^2}$$

For each resolution cell

- Many parameters
- **Colour** signatures and advanced representations

Polarimetric Radar - Basics

- Any polarization state can be resolved into two orthogonal polarizations, e.g.
  - Horizontal-Vertical Linear
  - Right-Left Circular

- Transmit H, receive H and V
- Transmit V, receive H and V

	H	V
H	HH	HV
V	VH	VV

Scattering Matrix

$$[S] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}$$

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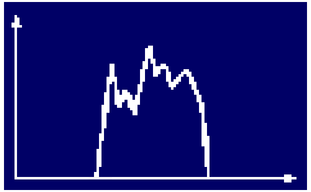
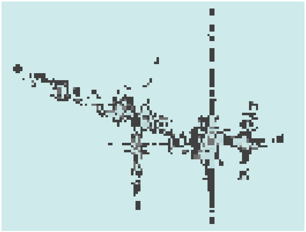
Scalar vs. Polarimetric (Colour) Radar Imaging

- **Scalar techniques – same polarization for T/R**
  - One-dimensional amplitude signatures (high range resolution or high cross-range resolution)

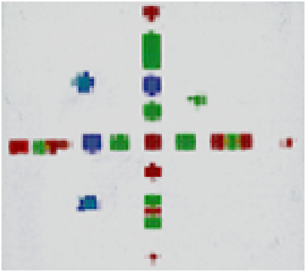


  - Two-dimensional amplitude signatures (high range resolution and high cross-range resolution combined)



One-, two-, multidimensional …

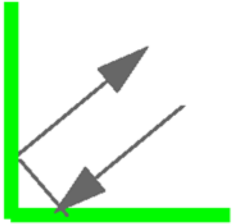
- **Polarimetric techniques – four combinations of T/R pol.**
  - Separation of scattering mechanisms
  - Invariant target descriptors
  - One image (in colour!) can represent true RCS (intensity) as well as scattering **mechanisms** for each resolution cell



Polarimetric Characteristics of Elementary Scatterers

$$[S]_{sphere} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

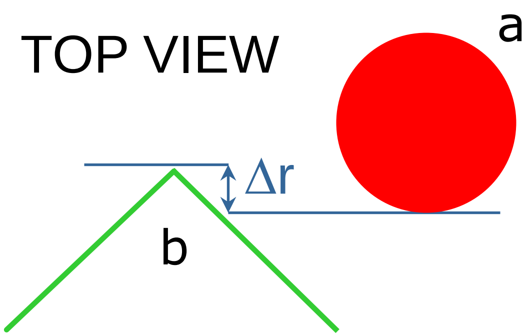
$$[S]_{wire} = \begin{bmatrix} \cos^2\theta & \frac{1}{2}\sin 2\theta \\ \frac{1}{2}\sin 2\theta & \sin^2\theta \end{bmatrix}$$

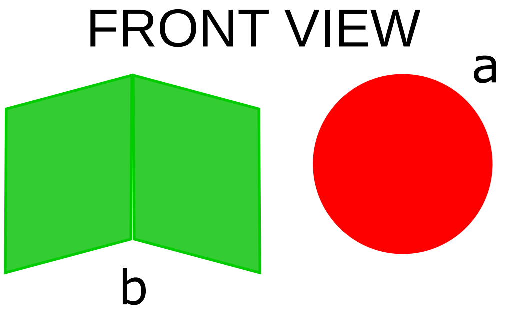


$$[S]_{diplane} = \begin{bmatrix} cos\,2\theta & sin\,2\theta \\ sin\,2\theta & -cos\,2\theta \end{bmatrix}$$

$$[S]_{helix} = \frac{1}{2}\begin{bmatrix} 1 & \pm j \\ \pm j & -1 \end{bmatrix}$$

Polarimetric Decomposition - Basics





TOTAL SCATTERING MATRIX:

$$[S] = \frac{1}{2}\begin{bmatrix} a + b\ e^{-j2k\Delta r} & 0 \\ 0 & a - b\ e^{-j2k\Delta r} \end{bmatrix}$$

NOTE: FREQUENCY DEPENDENT!

Polarimetric decomposition: $|HH + VV| = a\ ;\ |HH - VV| = b$

Complex quantities a (sphere) and b (dihedral) can be completely and coherently separated by a polarimetric radar, but not by a traditional single polarization radar, i.e., scattering mechanisms can be separated using polarimetric information

Pauli Decomposition

$$[S] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} = k_1 [S]_{sphere} + k_2 [S]_{dihedral(0°)} + k_3 [S]_{dihedral(45°)}$$

$$[S]_{sphere} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad [S]_{dihedral(\theta)} = \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix}$$

$$\underline{k} = [k_1 \quad k_2 \quad k_3] = \frac{1}{\sqrt{2}} [S_{HH} + S_{VV} \quad S_{HH} - S_{VV} \quad 2S_{HV}]^T$$

HH-VV (k_2)	HV (k_3)	HH+VV (k_1)

Sphere, Diplane, Helix Decomposition

$$[S] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} = e^{j\phi}\{e^{j\phi_s} k_s [S]_{sphere} + k_d [S]_{diplane(\theta)} + k_h [S]_{helix(\theta)}\}$$

$$[S]_{sphere} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad [S]_{diplane(\theta)} = \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix} \qquad [S]_{helix(\theta)} = \frac{1}{2} e^{\mp j 2\theta} \begin{bmatrix} 1 & \pm j \\ \pm j & -1 \end{bmatrix}$$

In circular (right, left) polarization basis:

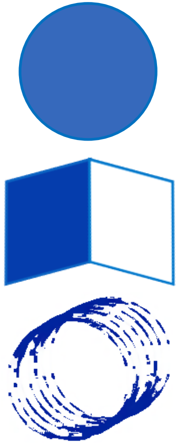
$$k_s = |S_{RL}| \qquad k_d = \min(|S_{RR}|, |S_{LL}|) \qquad k_h = \big|\, |S_{RR}| - |S_{LL}| \,\big|$$

$$\varphi = \tfrac{1}{2}(\varphi_{RR} + \varphi_{LL} - \pi) \qquad \theta = \tfrac{1}{4}(\varphi_{RR} - \varphi_{LL} + \pi) \qquad \varphi_s = \varphi_{RL} - \tfrac{1}{2}(\varphi_{RR} + \varphi_{LL})$$

k_s	k_d	k_h

NATO has it ...

HH	HV
VH	VV



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What's in a Resolution Cell?





Generic Scene for Synthetic Aperture Radar (SAR) Imaging

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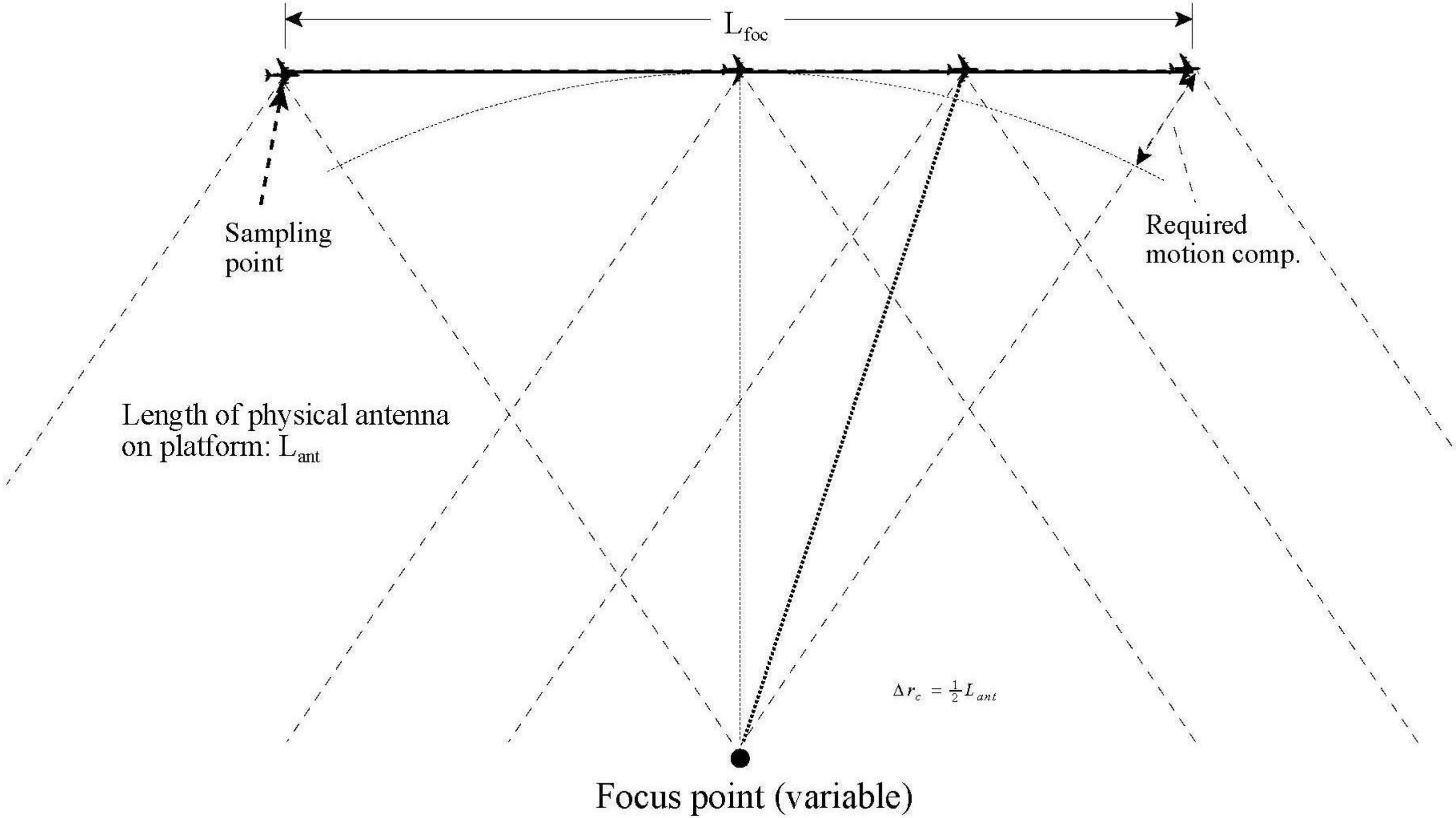
Synthetic Aperture Radar (SAR)



DALOEX 2014 and 2015

Exploration of Possibilities With Advanced SAR Systems in the Arctic Region

- In relation to a working group on future capabilities for solving tasks in the Arctic region, DALO wanted to test and demonstrate an advanced SAR system with full polarimetric and interferometric capability and as many frequency bands as possible.

- DALO chose to conduct tests with the fully polarimetric and interferometric F-SAR system of DLR (German Aerospace Center) with five frequency bands in the range 300 MHz to 10 GHz.

- Initial tests in Denmark in October 2014 (DALOEX 2014) before the main campaign DALOEX 2015 in Greenland in April/May 2015.

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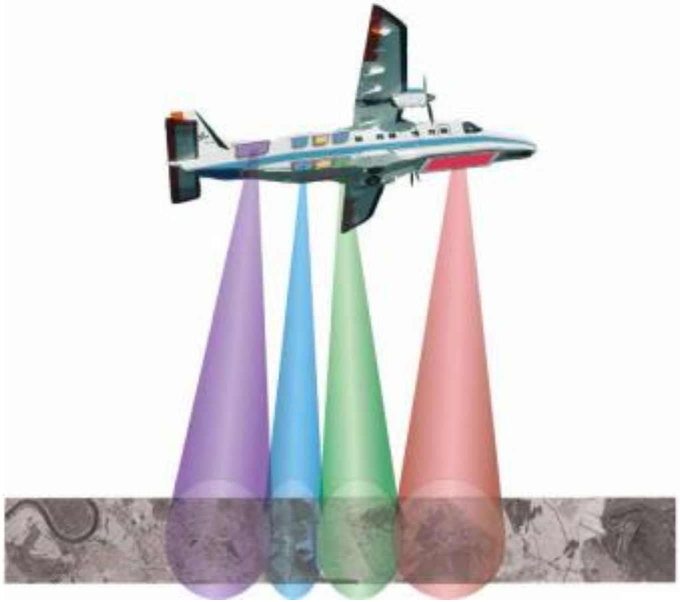
DLR F-SAR (Flugzeug-SAR)

Fully polarimetric and interferometric system on Dornier 228

	X	C	S	L	P
Frequency [MHz]	9600	5300	3250	1325	435
Polarisation	all bands are fully polarimetric				
Bandwidth [MHz]	760	384	300	150	50
Resolution [m]	0.25	0.5	0.6	1.0	4
Off-nadir angle range	25° (near range) to 57° (far range)				



German Aerospace Center

DLR

DALOEX 2014 F-SAR Test Sites

Great Belt East Bridge (Denmark)

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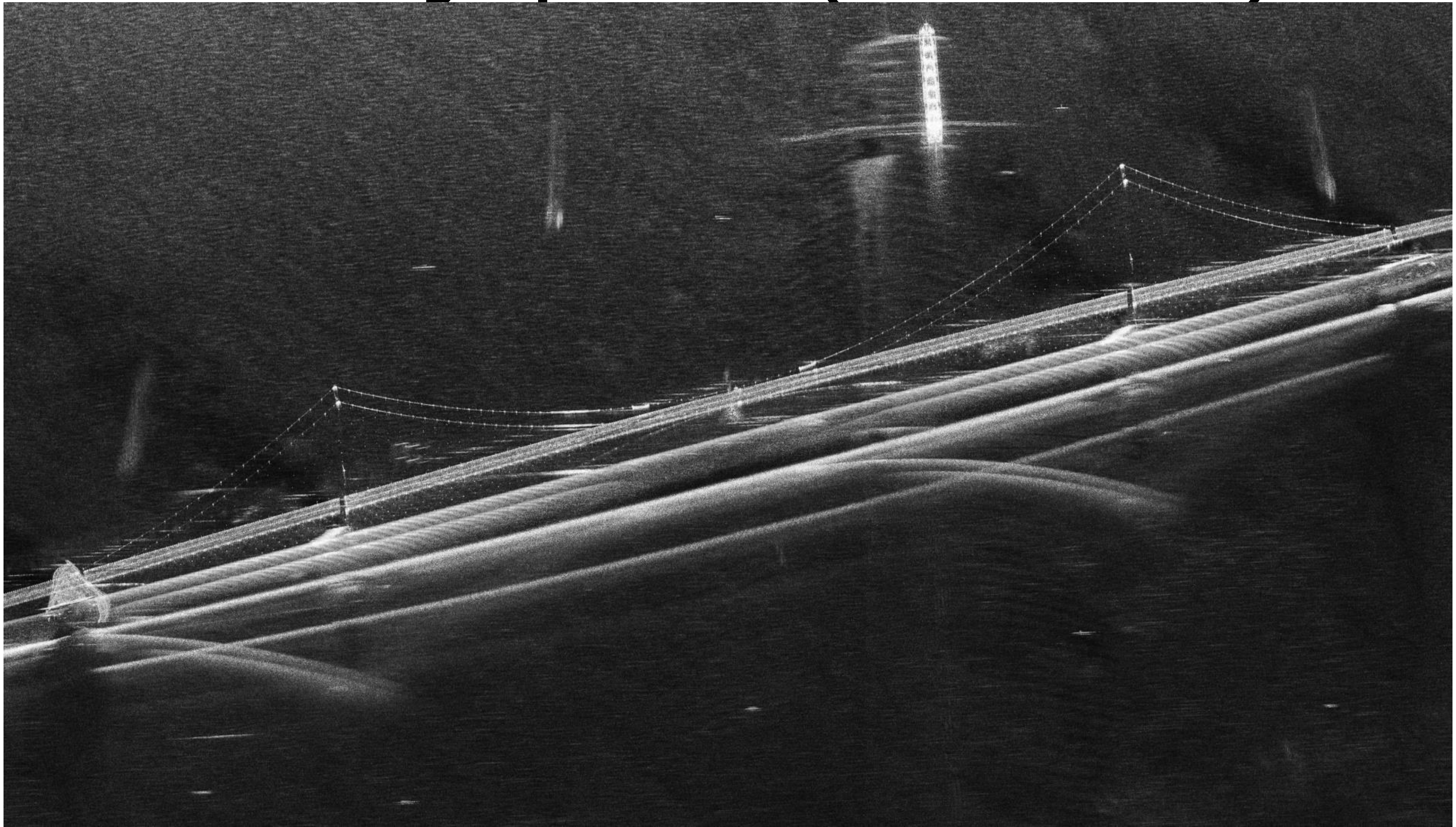
Great Belt East Bridge – X-band Flight path W-E (DALOEX 2014)



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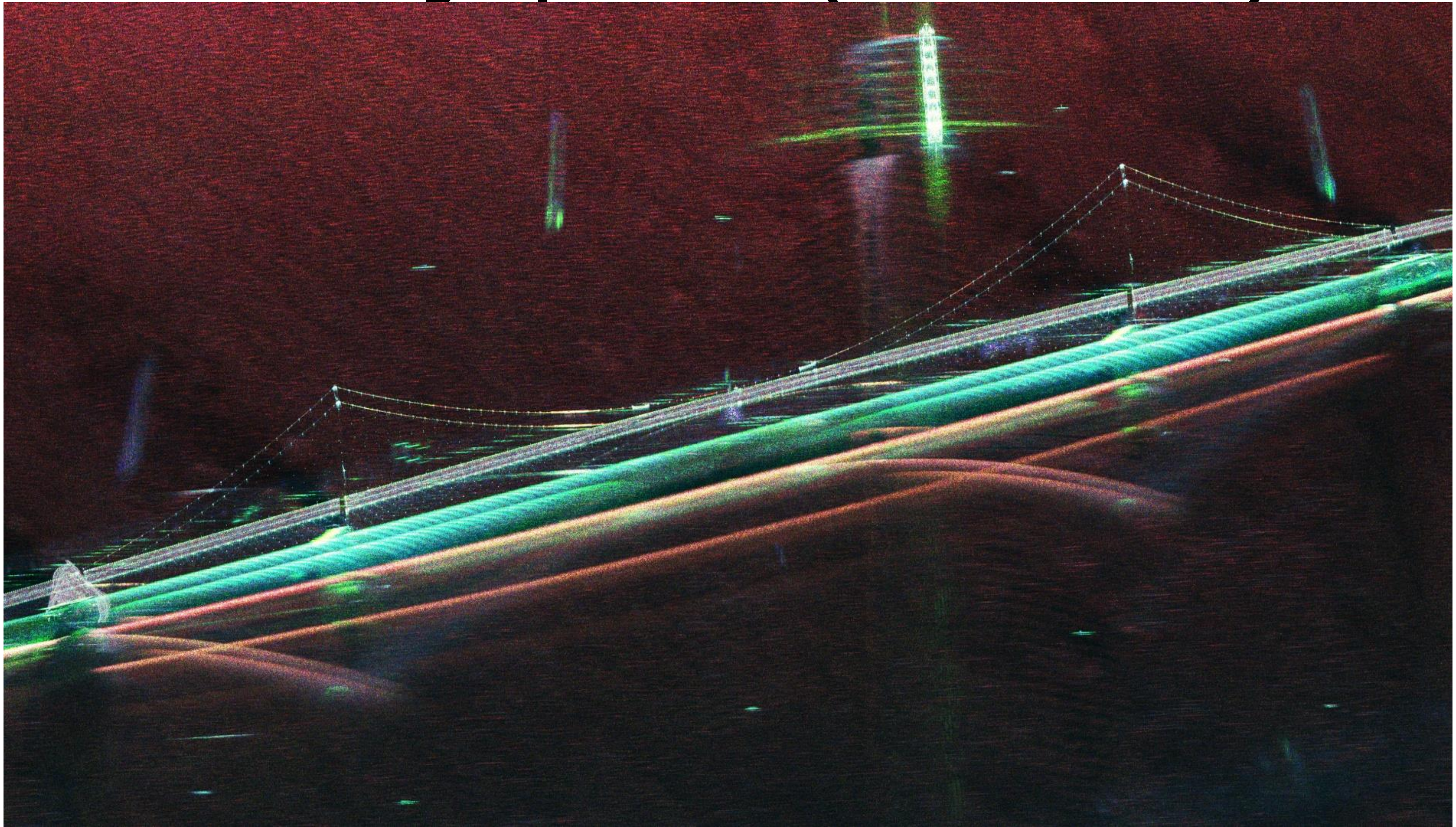
Great Belt East Bridge – X-band, SDH Flight path W-E (DALOEX 2014)



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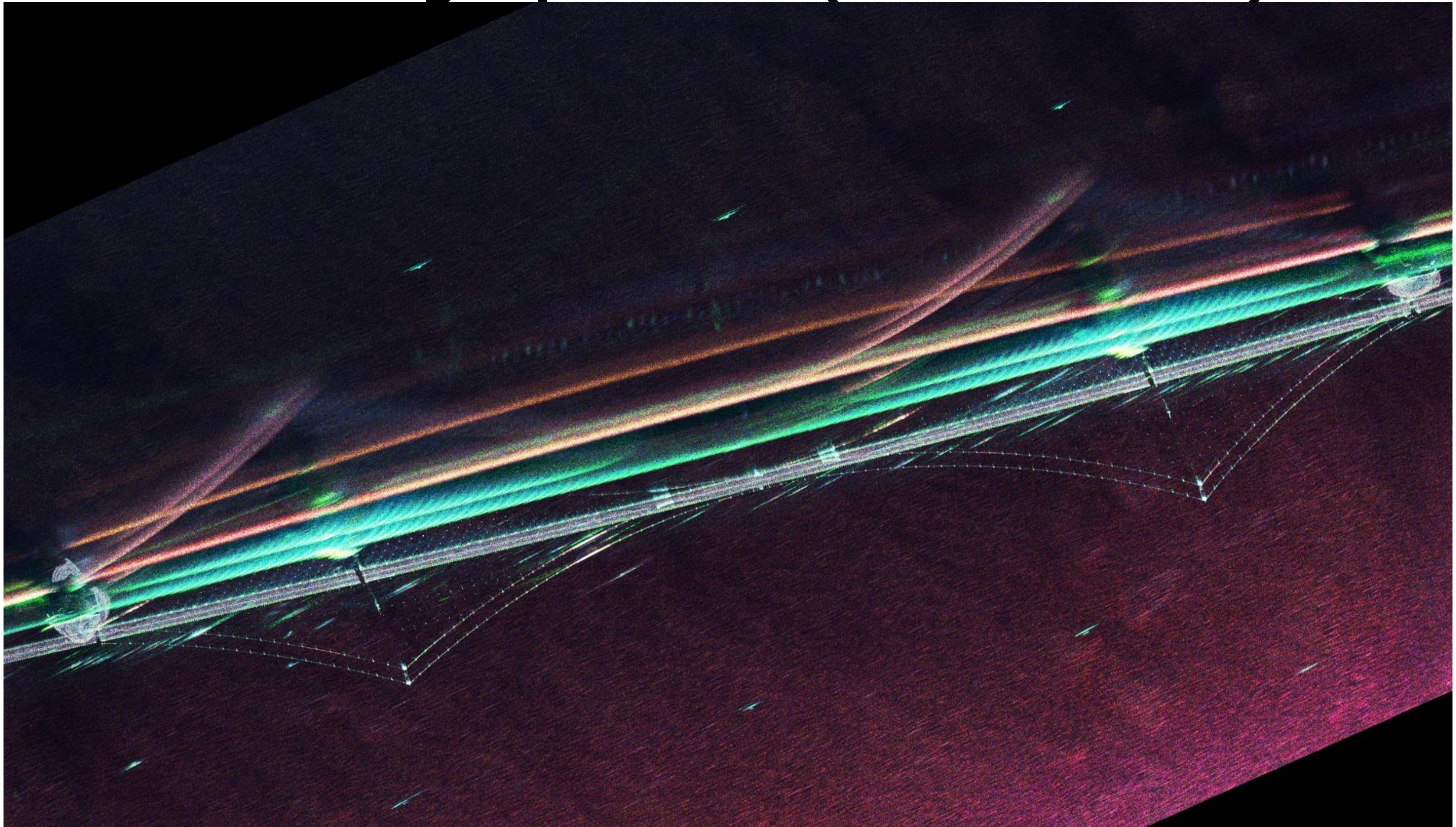
Great Belt East Bridge – X-band, SDH Flight path E-W (DALOEX 2014)



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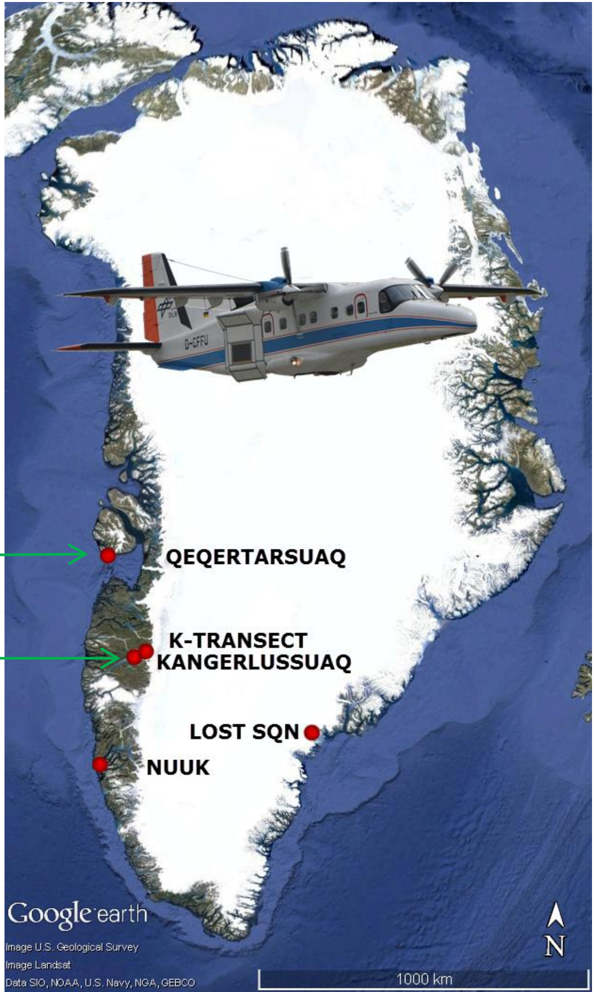
DALOEX 2015 F-SAR Test Sites

GREENLAND

Qeqertarsuaq – Disko Island

Kangerlussuaq – airport area



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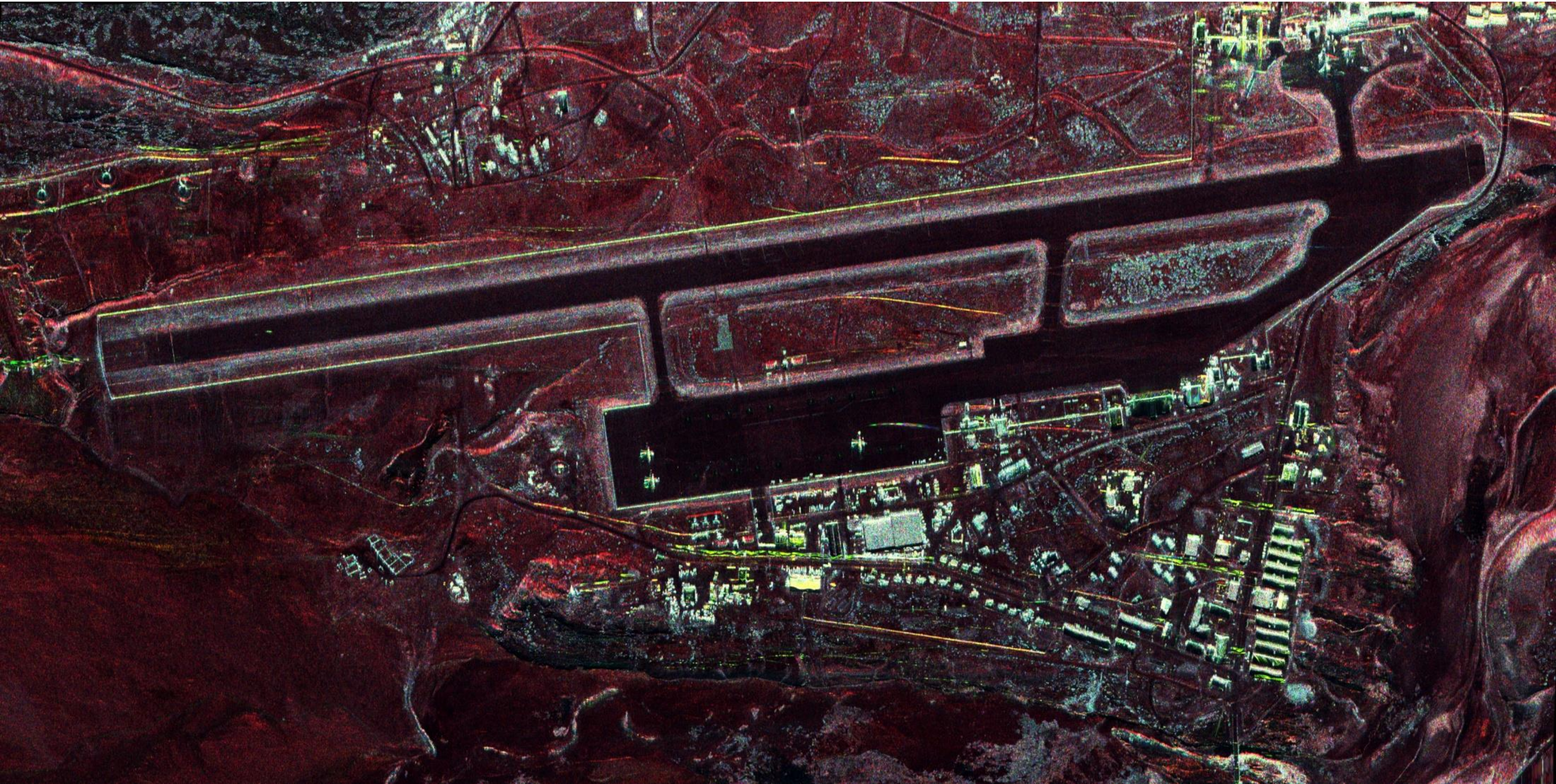
Kangerlussuaq - L-band - SDH



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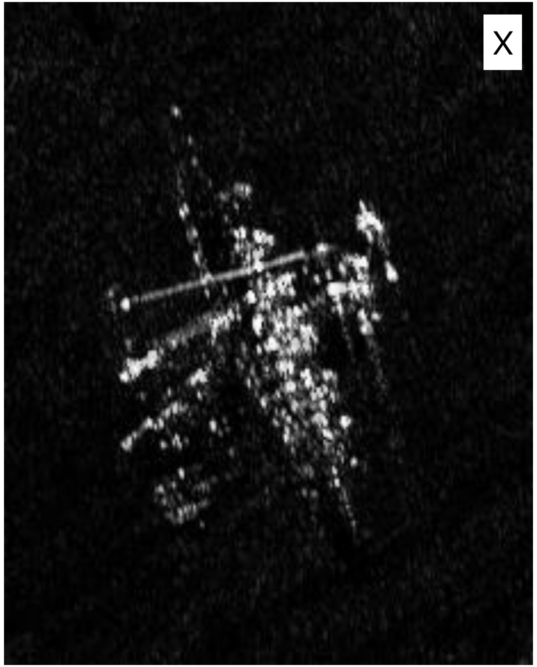
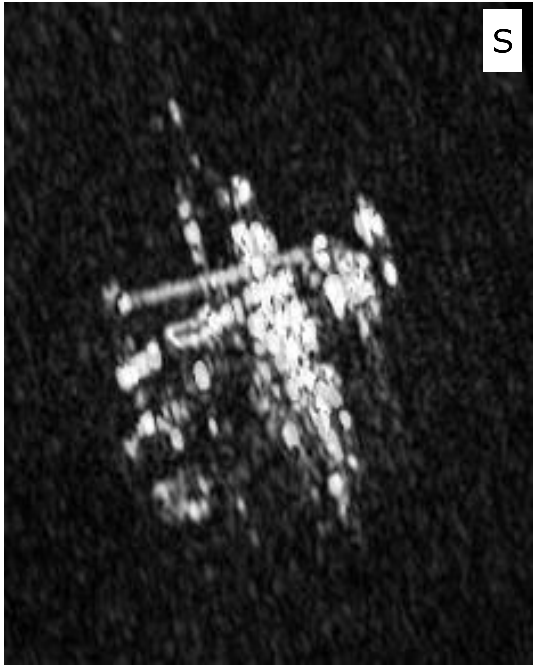
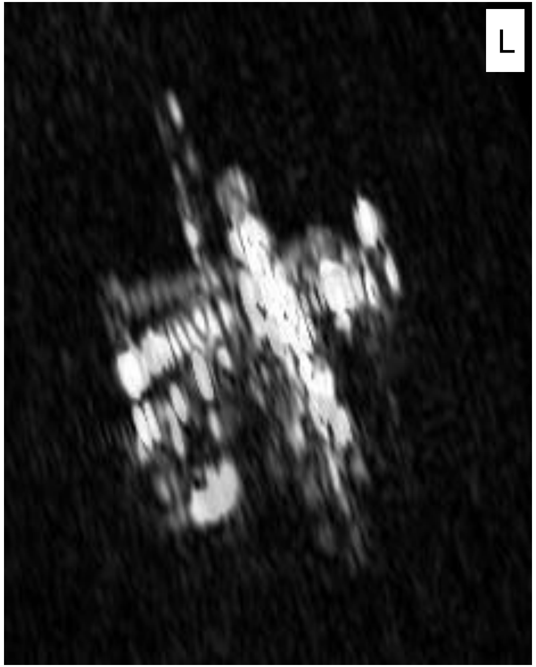
Kangerlussuaq – Parked Aircraft



X-band, 590 MHz BW



S-band, 300 MHz BW

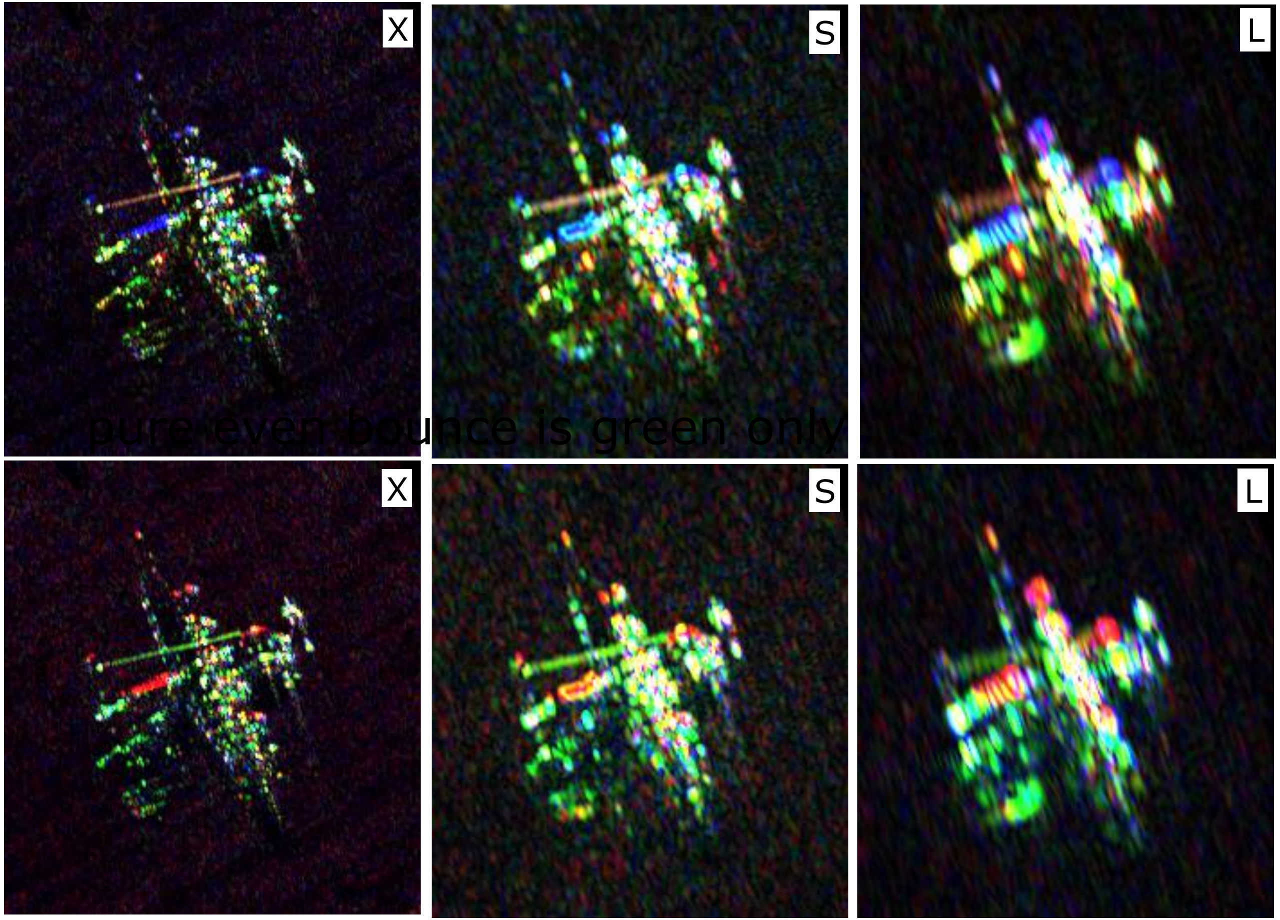


L-band, 150 MHz BW

Kangerlussuaq – Parked Aircraft

Pauli decomp.
Pure even-bounce contributions are green and/or red, depending on the orientation angle.

SDH decomp.
Pure even-bounce contributions are always green, independent of the orientation angle.



X-band, 590 MHz BW | **S-band, 300 MHz BW** | **L-band, 150 MHz BW**

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US Hercules at Kangerlussuaq

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Disko Island Test Site May 2015






Disko Island Test Site May 2015

Situational photos from drone

Person in cave

Ladder in cave

Aluboxes in cave

Person in cave

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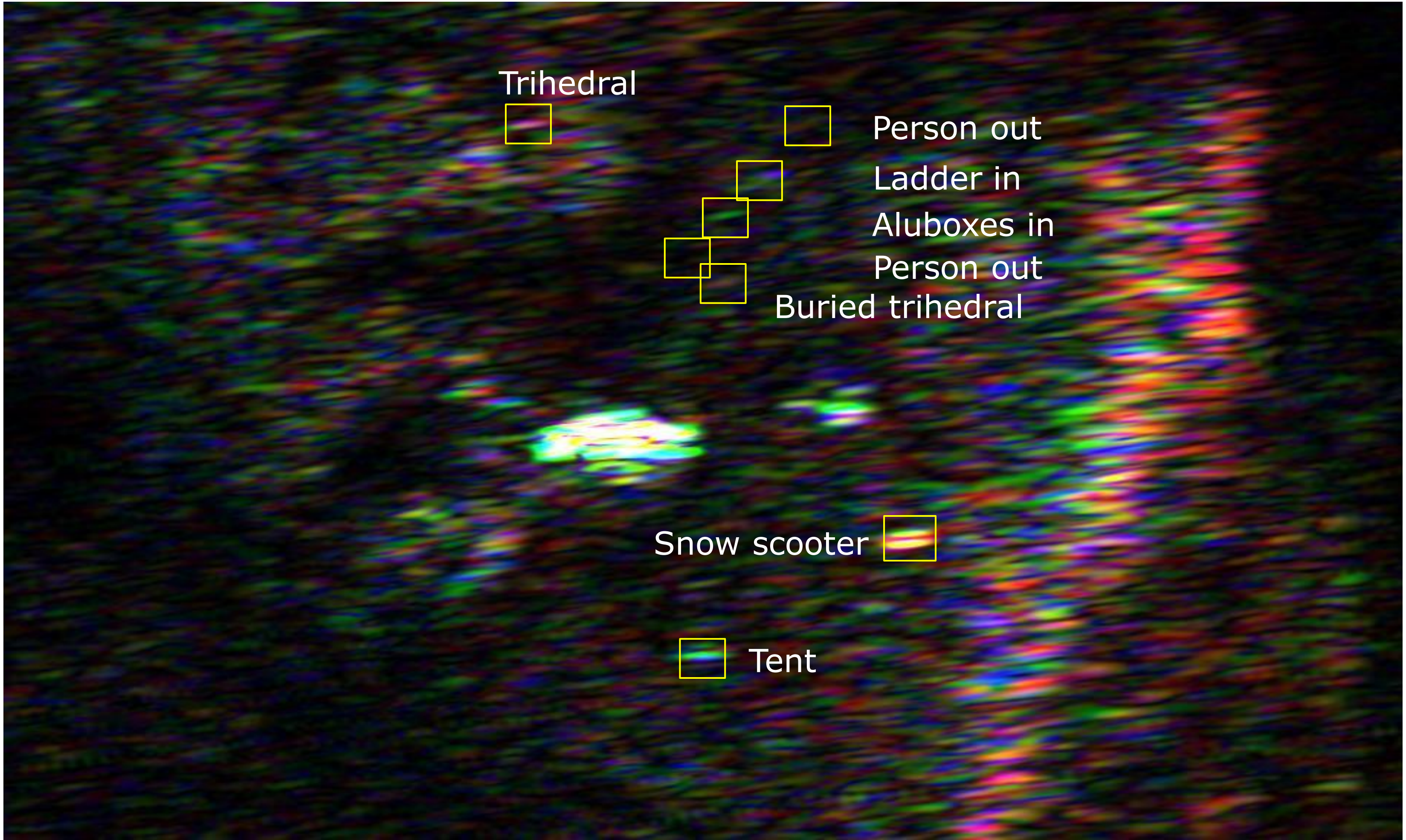
P-Band – Pass 1605



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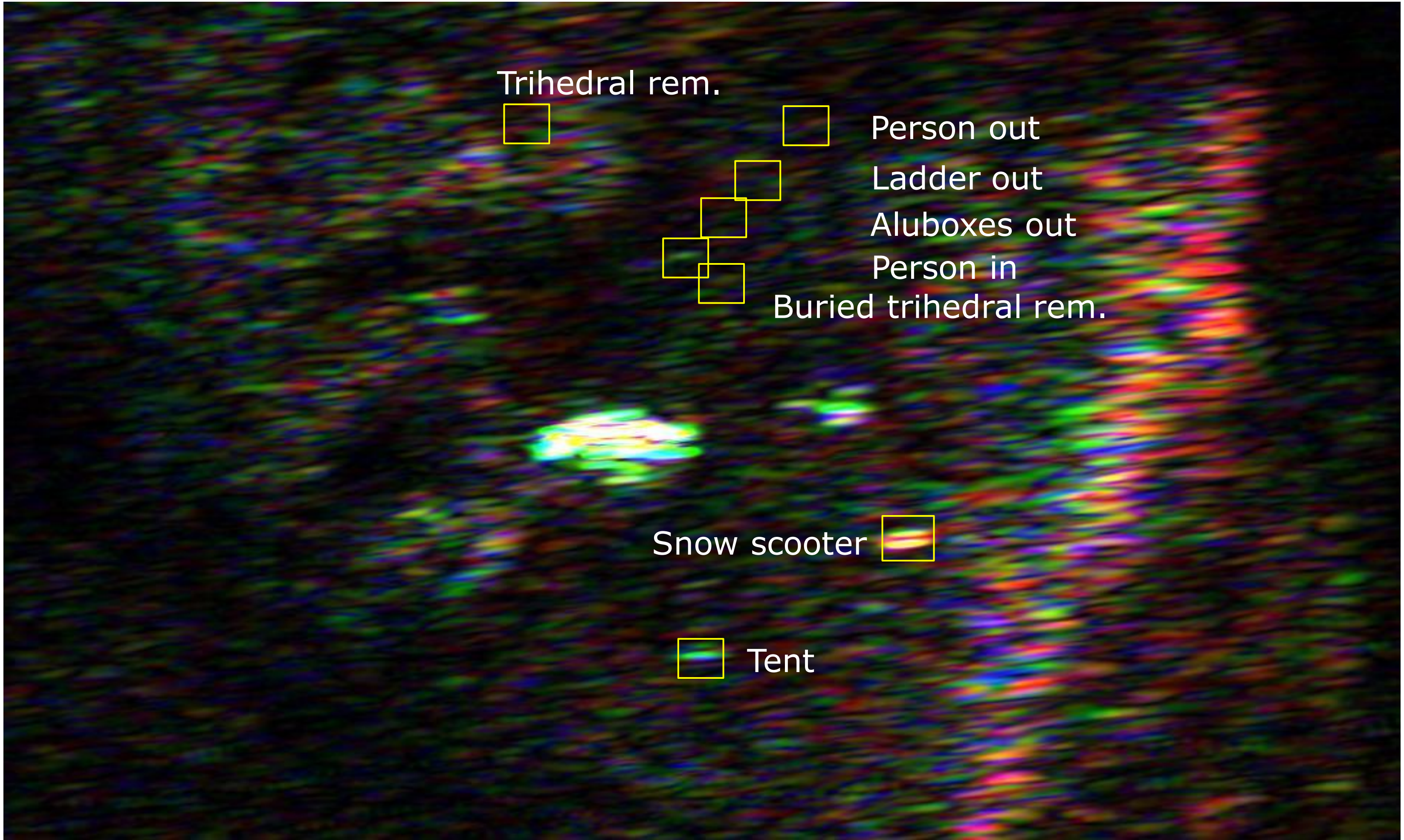
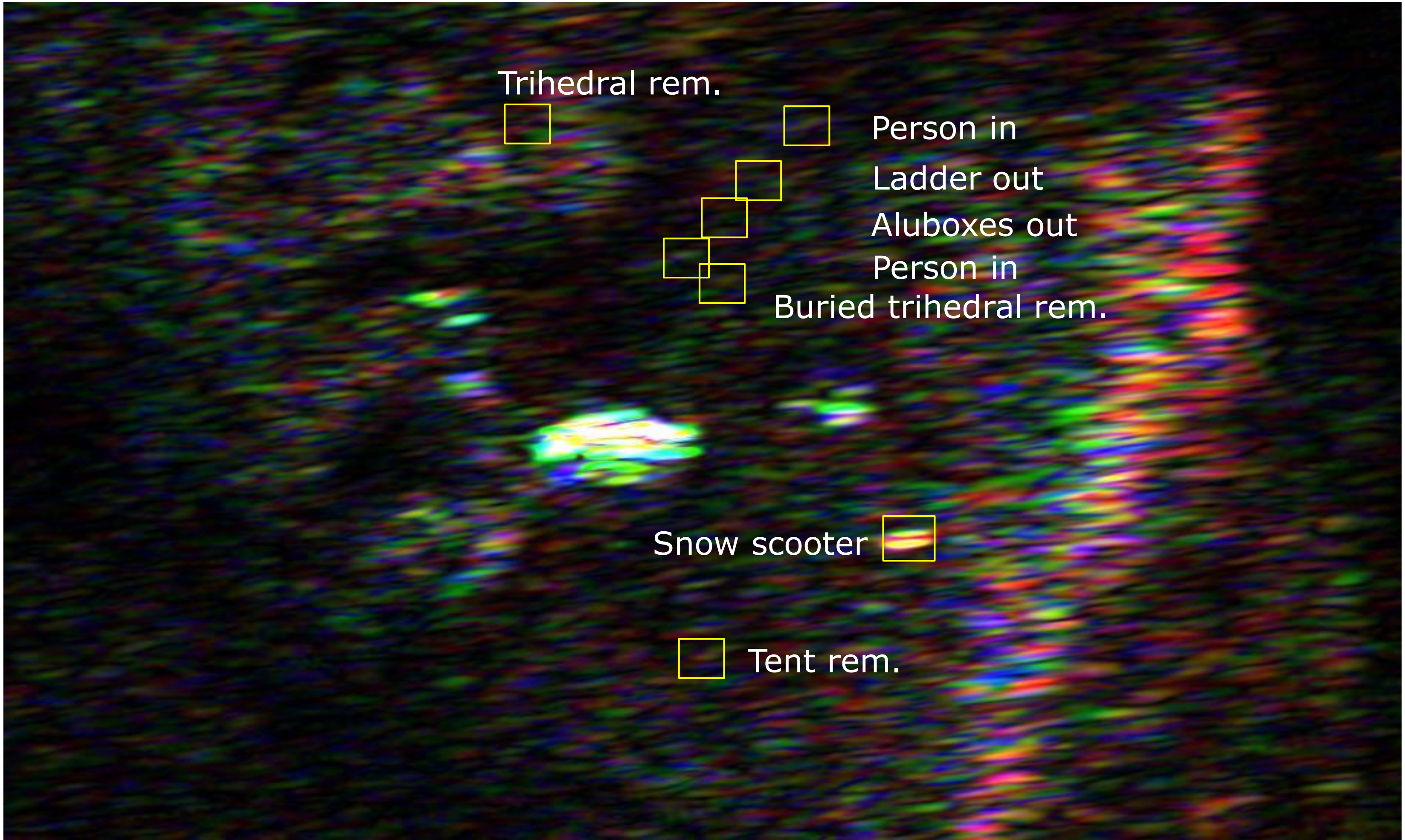
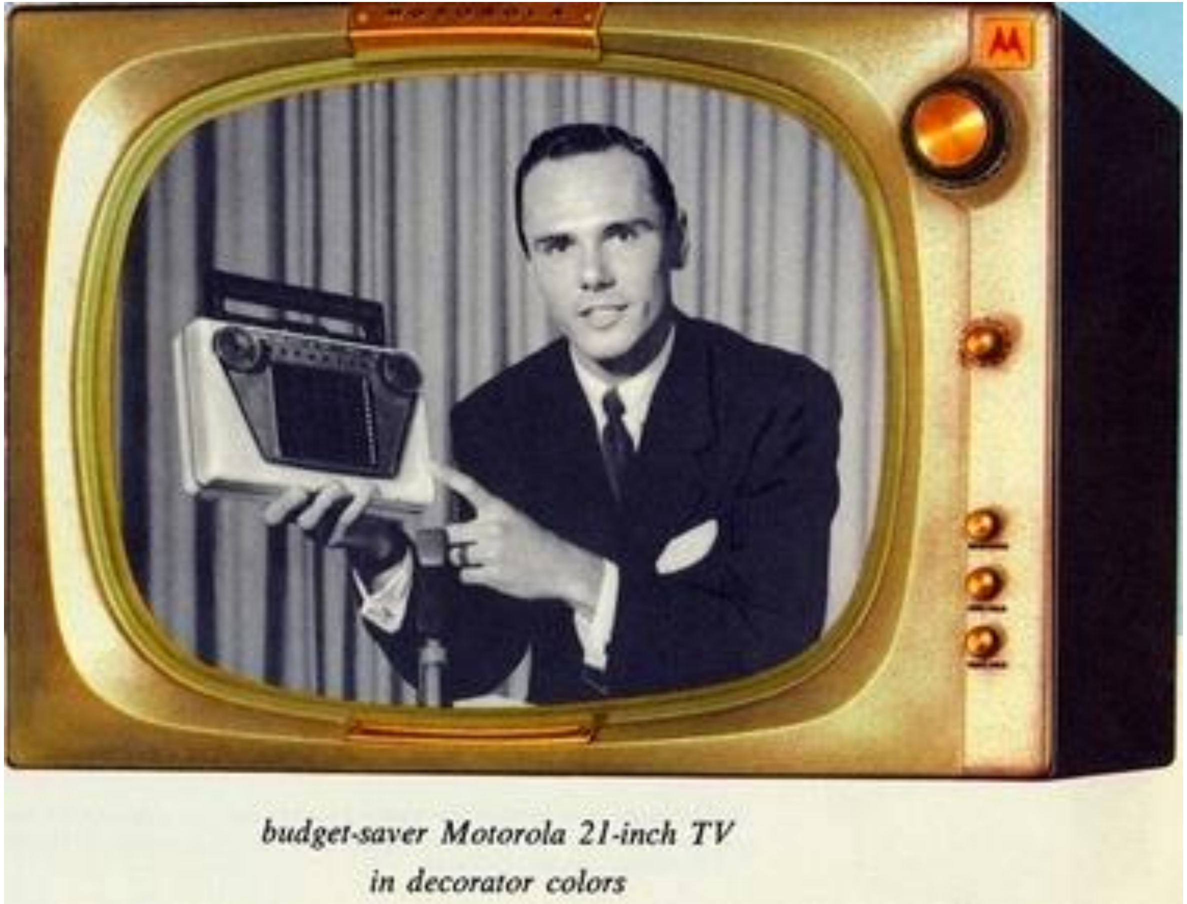
P-Band – Pass 1606



P-Band – Pass 1607



One-, two-, multidimensional …



Summary, conclusion and challenge

- Polarimetric radars yield multichannel output with a complex scattering matrix per pixel rather than a single scalar
- Polarimetric data processing reveals target scattering characteristics that cannot be determined by single-polarization systems, even by increasing resolution and/or number of frequency bands
- Multiple radar frequency bands reveal different target features and characteristics – need for multichannel processing and visualization
- The power of multiple channels – the power of colour and more
- Challenge: How do we get modern-day multidimensional solutions into requirements and procurement process?

Thank you for your attention!