STEREOID: an Earth Explorer 10 mission candidate to observe land, ice, and ocean dynamics

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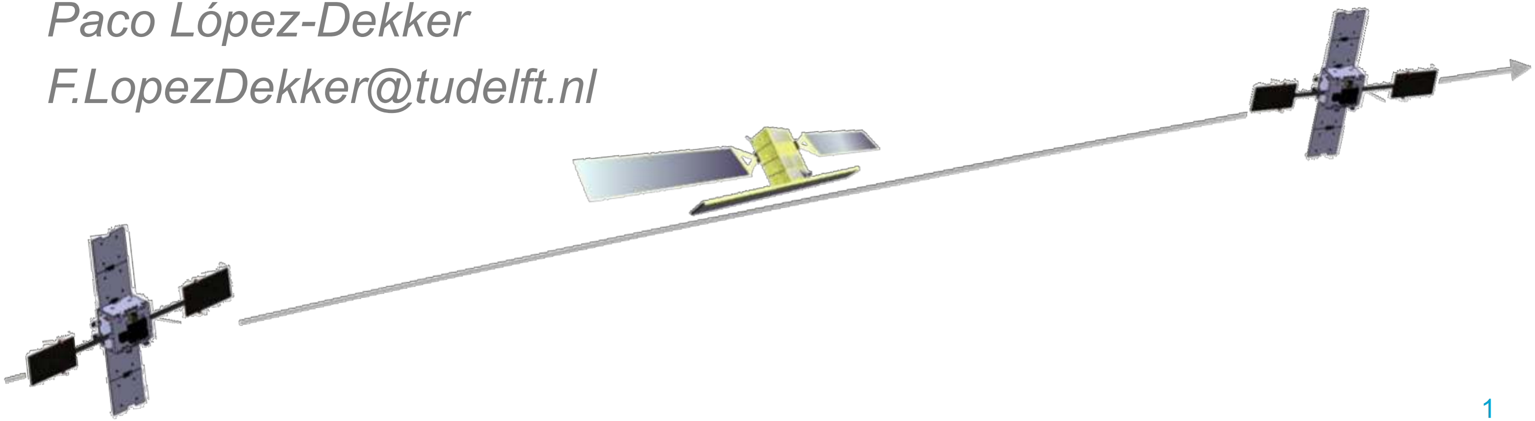

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STEREOID for Earth Explorer 10

Lead Investigator			
	Lopez-Dekker, Paco, Associate Professor	Delft University of Technology Department of Geoscience and Remote Sensing	
Proposing Team			
	Name	Affiliation	Country
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2	Gommenginger, Christine, Dr.	National Oceanography Center	GB
3	Johnsen, Harald, Dr.	NORUT	NO
4	Collard, Fabrice, Dr.	Oceandatalab	FR
5	Hansen, Morten, Dr.	Nansen Environmental and Remote Sensing Center (NERSC)	NO
6	Korosov, Anton, Dr.	Nansen Environmental and Remote Sensing Center (NERSC)	NO
7	Rott, Helmut, Dr.	ENVEO IT	AT
8	Nagler, Thomas, Dr.	ENVEO IT	AT
9	De Zeeuw – van Dalfsen, Elske, Dr.	KNMI	NL
10	Hooper, Andy, Professor	University of Leeds	GB
11	Hanssen, Ramon, Professor	Delft University of Technology	NL
12	Poland, Mike, Dr.	US Geological Survey	US
13	Menenti, Massimo, Professor	Delft University of Technology	NL
14	Su, Zu (Bob) Prof.	University of Twente	NL
15	Tebaldini, Stefano, Assistant Professor	Politecnico di Milano	IT
16	Larsen, Yngvar, Dr.	NORUT	NO
17	Prats-Iraola, Pau, Dr.	DLR	DE
18	Zurita, Albert, Ing	Airbus Defence and Space, Spain	ES
19	Esposito, Marco	Cosine	NL

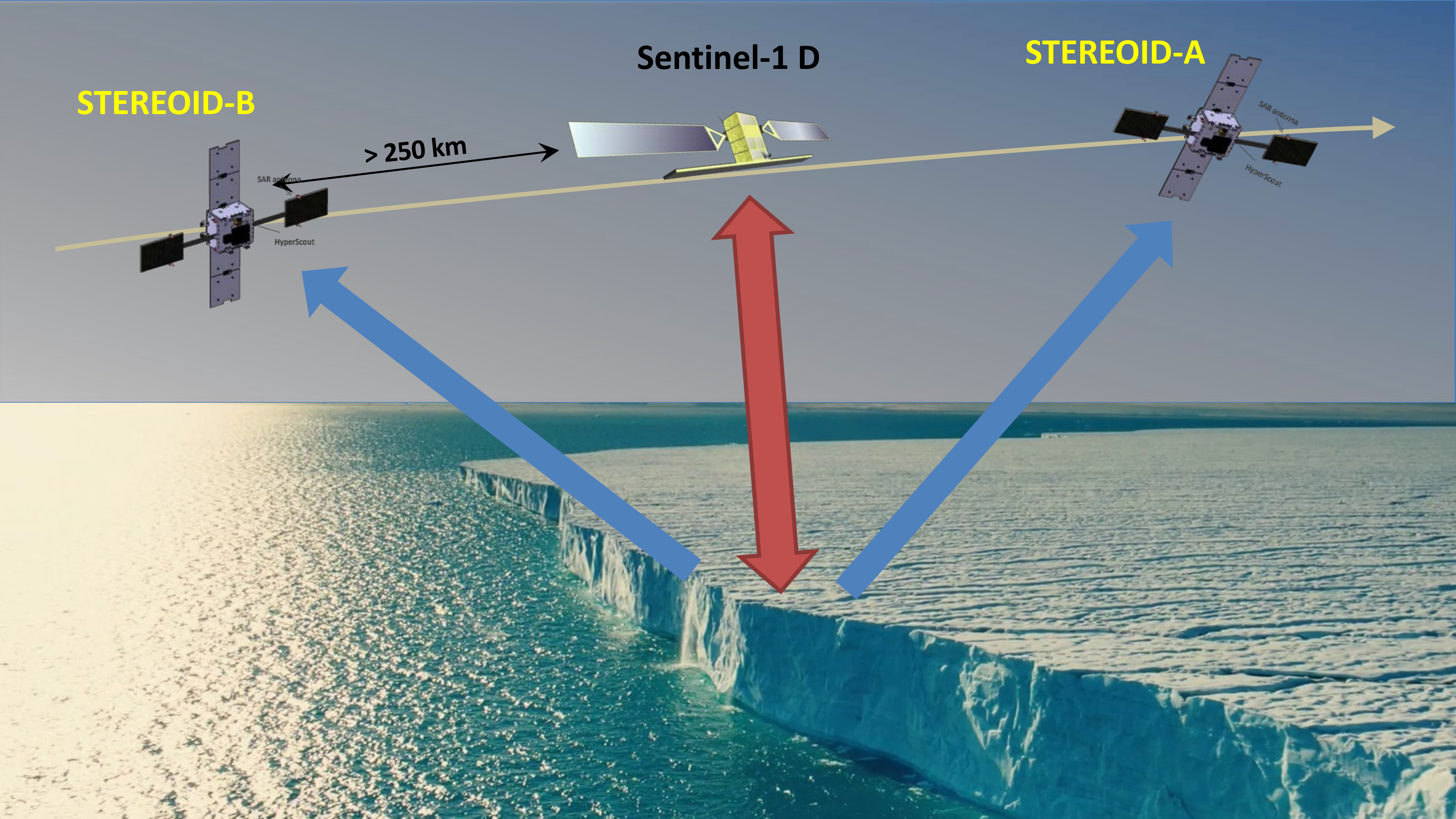
arth Observation (ACEO),
Proposals submitted in the
he procedures followed by

tember 2017 (cf. ESA/PB-

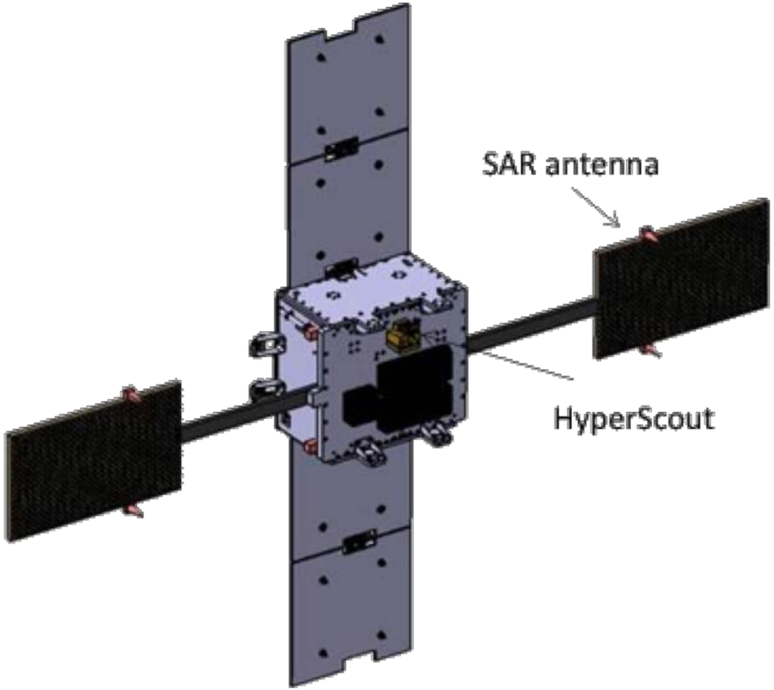
id down in the Call, been

port of two scientific panels.
total of 32 external experts.
technical and programmatic
rvation Programmes and the
s carried out using the seven

ACEO recommends three Mission Ideas for further assessment studies at pre-feasibility level, i.e. phase 0 study (without order of priority), namely STEREOID, Daedalus and G-CLASS:H2O.


STEREOID-B
> 250 km
Sentinel-1 D
STEREOID-A
SAR antenna
HyperScout
SAR antenna
HyperScout

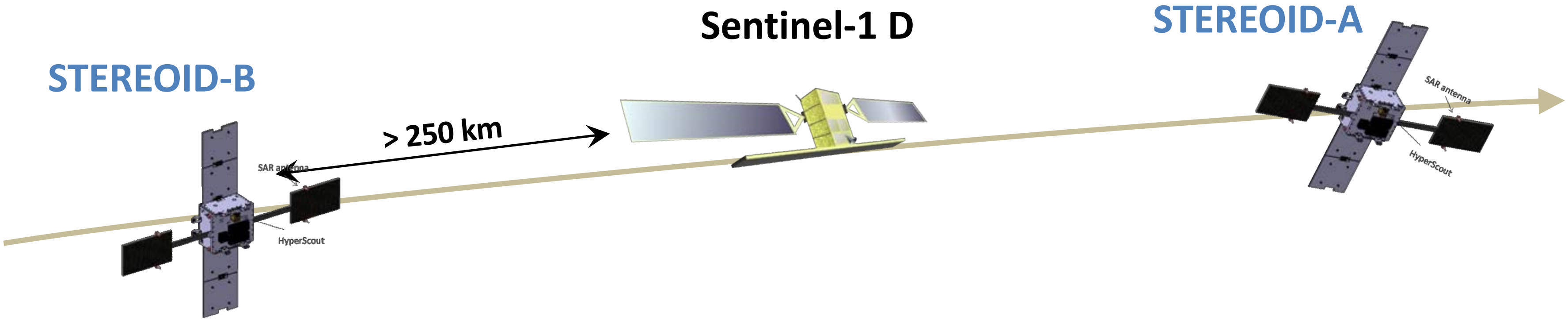
Space-segment (in proposal)



Platform

- < 500 kg
- Which is small for an Earth Explorer

Mission phases: variable formation



- **Stereo formation**
  - Maximum line-of-sight diversity
  - Best for surface current vectors and 3-D surface deformation

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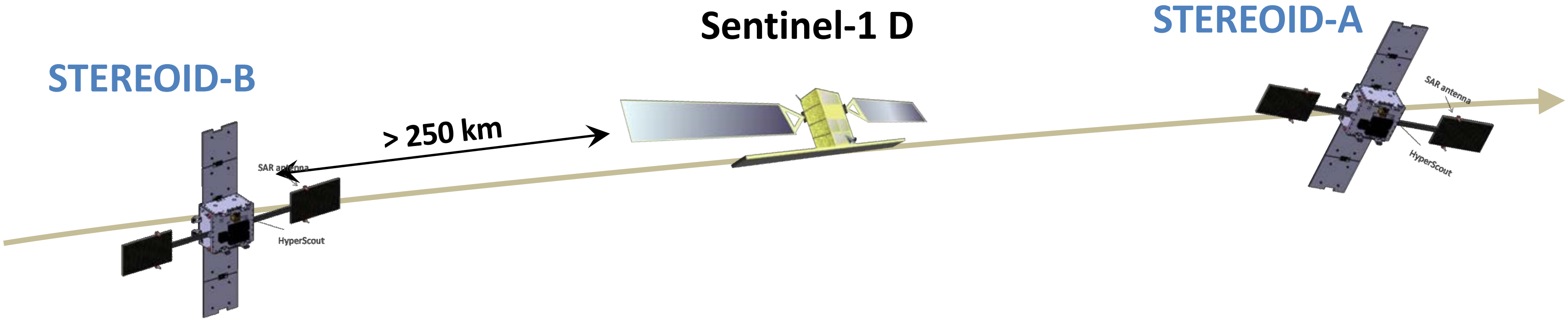
Mission phases: variable formation



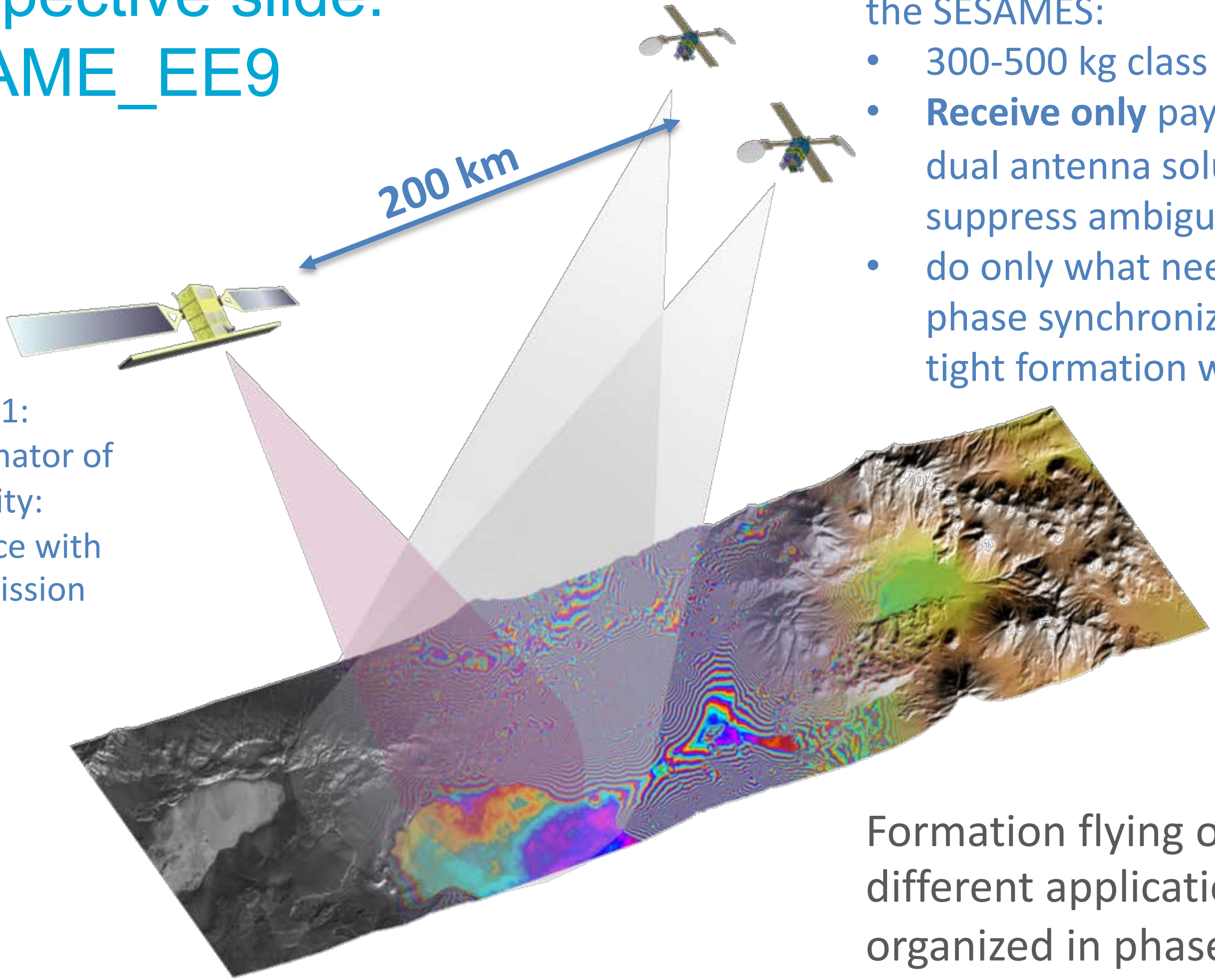
- **XTI formation**
  - Close-formation (TanDEM-X style)
  - Intended for DEM time-series
  - 400 m to 1 km baselines
- **ATI formation**
  - 100 m to 200 m along-track separation

One slide of history

Retrospective slide: #SESAME_EE9

the SESAMES:

- 300-500 kg class satellites
- **Receive only** payload with dual antenna solution to suppress ambiguities
- do only what needed: no phase synchronization nor tight formation with S1



Sentinel-1:
Used as illuminator of opportunity:
no interference with Sentinel-1 mission

Formation flying optimizes to different applications/ROIs: mission organized in phases.

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Science objectives

Mission objectives (1 min overview)

Solid Earth

- 3D surface deformation (volcanic, seismic, landslides)
- Sudden topographic changes

Cryosphere

- Glacier and ice sheets topography/volume/mass change
- High resolution ice flows/deformation
- Sea ice drift and topography
- Marginal Ice Zone variability

Oceans

- High resolution surface currents and wave data for coastal processes
- Small-scale (100 m to 10 km) ocean dynamics
- Surface deformation field ($\nabla \cdot$ TSCV) Divergence/strain, vorticity, shear
- Extreme weather events

Common theme

Surface deformation

- Ocean surfaces
- Sea ice
- Ice sheets & glaciers
- Solid earth

Dynamic processes

Climate change

- Sea-level
- Ice-atmosphere interactions
- Ocean-atmosphere interactions
- …

Natural Hazards

- Unstable land (landslides)
- Volcanoes
- Seismic events
- …

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Science objectives: cryosphere

1. Topography change of glaciers, ice caps and outlet glaciers of ice sheets → volume change → contribution to sea level rise

2. 3-D deformation and flow dynamics of ice sheets and glaciers

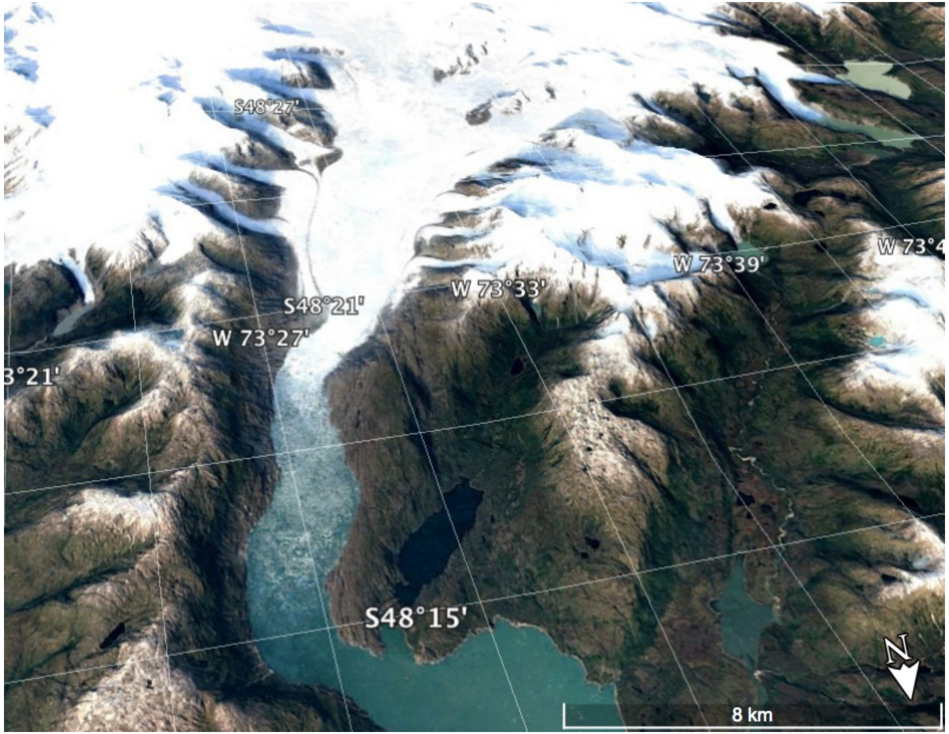
3. Sea ice
   - Instantaneous drift
   - Thickness and roughness

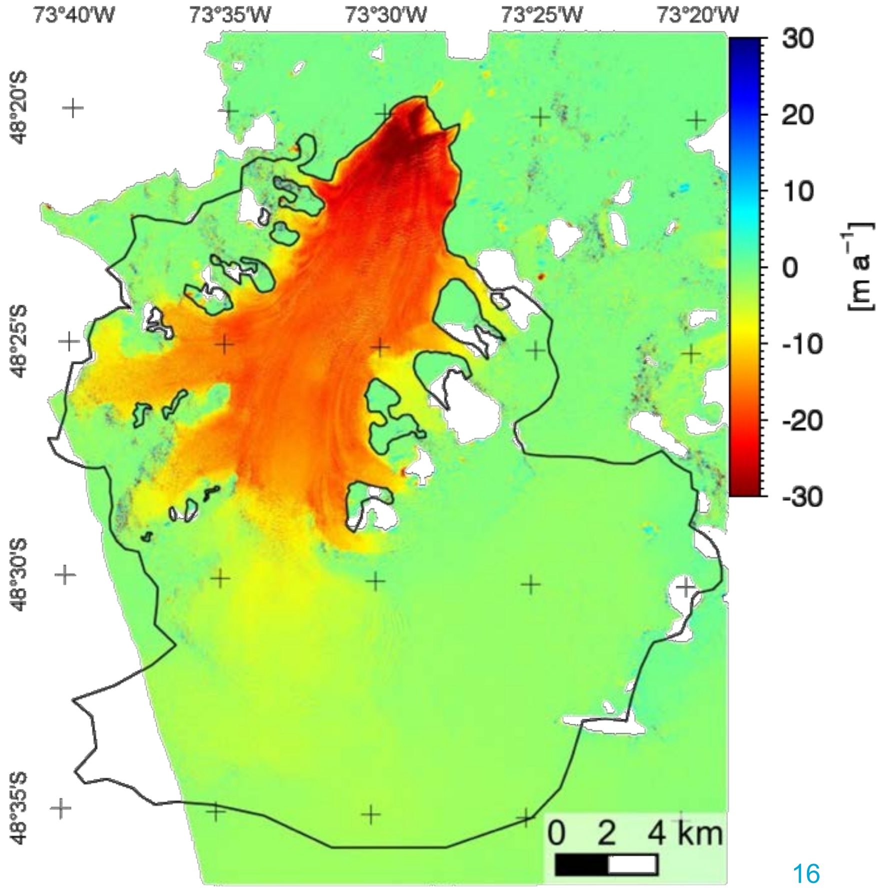
4. Marginal Ice Zone (MIZ) mesoscale variability

Science objectives: cryosphere (proposal version)

	Short description	ESA challenge
SC-1	Quantify the temporal change of volume and mass of glaciers, ice caps and outlet glaciers of ice sheets and their contribution to sea level change	C2
SC-2	Study the 3-D deformation and flow dynamics of ice sheets and glaciers to better understand their stability and dynamic response to climate change	C1
SC-3	Measure instantaneous sea ice drift velocity and deformation, improve estimations of sea ice roughness and thickness in support of sea ice model development, to improve operational forecast and mass balance studies.	C3
SC-4	Quantify sea ice and Marginal Ice Zone (MIZ) mesoscale variability	C3

Ice loss in mountain glaciers





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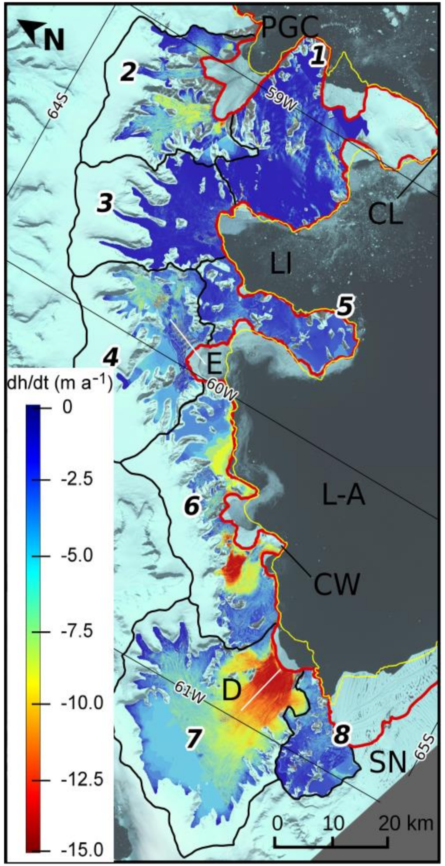
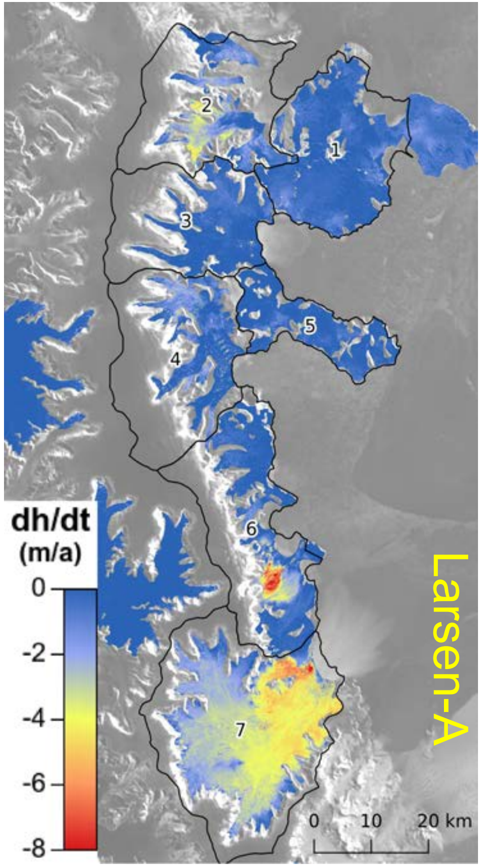
ΔDEMs for mass balance

Annual change in surface elevation (dh/dt) for Antarctic Peninsula outlet glaciers by means of TanDEM-X DEM Differencing

2011 to 2013



2013 to 2016



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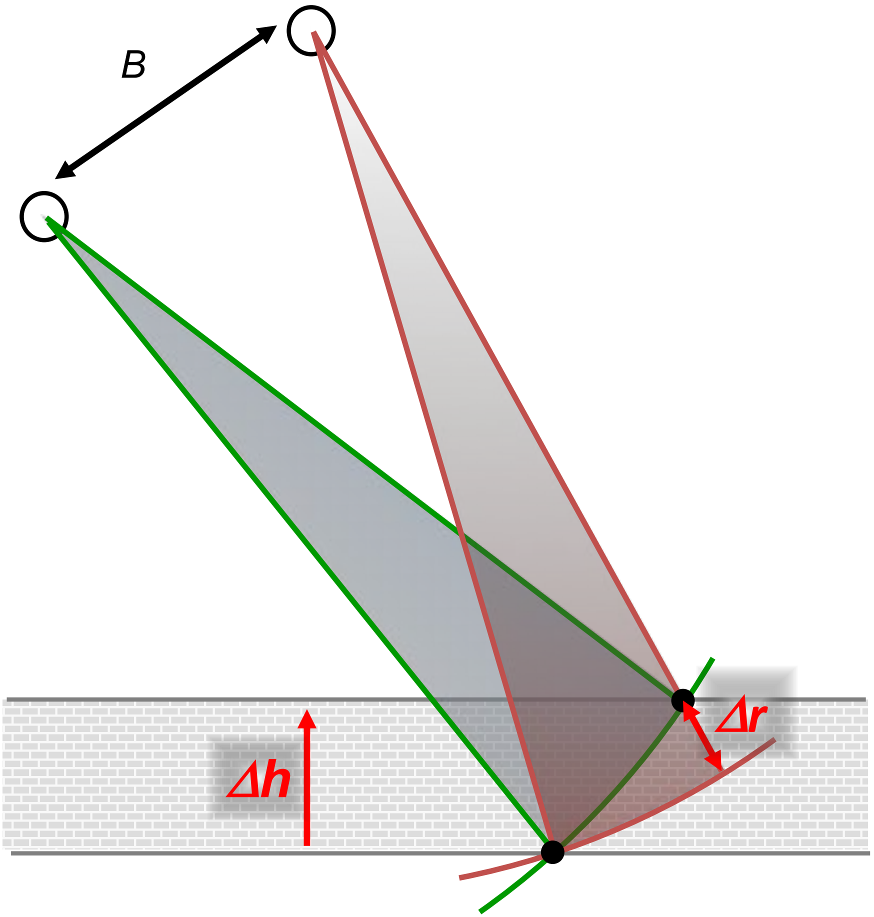
Measurement principle

- Single-pass cross-track interferometry
  - No temporal decorrelation
  - Virtually no atmospheric errors
  - Large and reconfigurable baselines

- Challenges/limits
  - Baseline changes along orbit
  - Precise baseline knowledge
  - System-level phase errors: synchronization
  - Penetration depth



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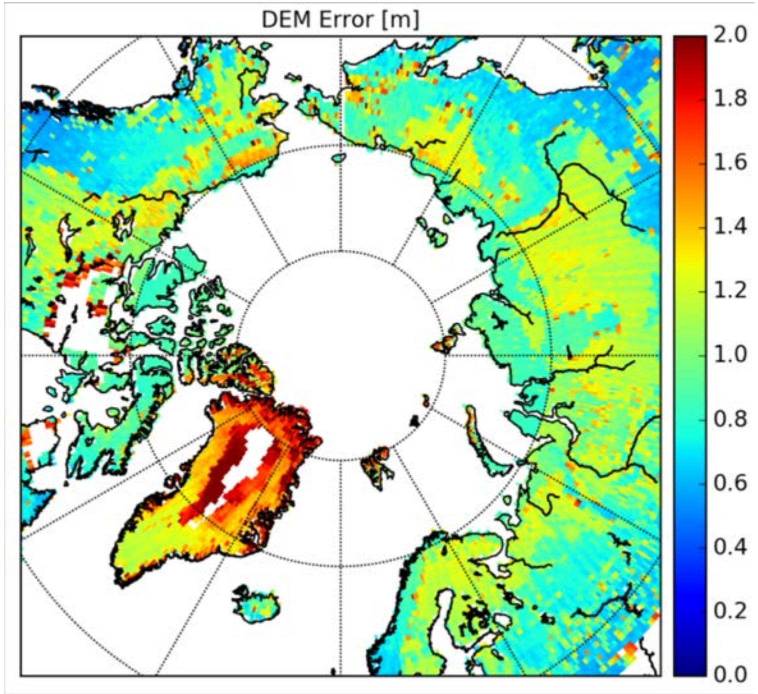
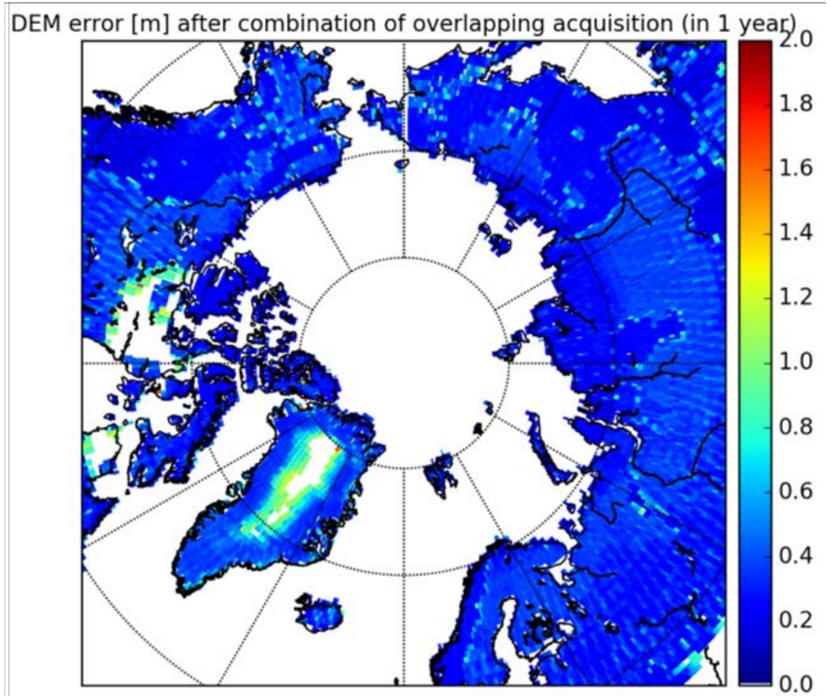
DEM performance example: SESAME, 100m resolution

Single Acquisition



Yearly average



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Main open issue (remote sensing wise): penetration depth

Ice is semi-transparent

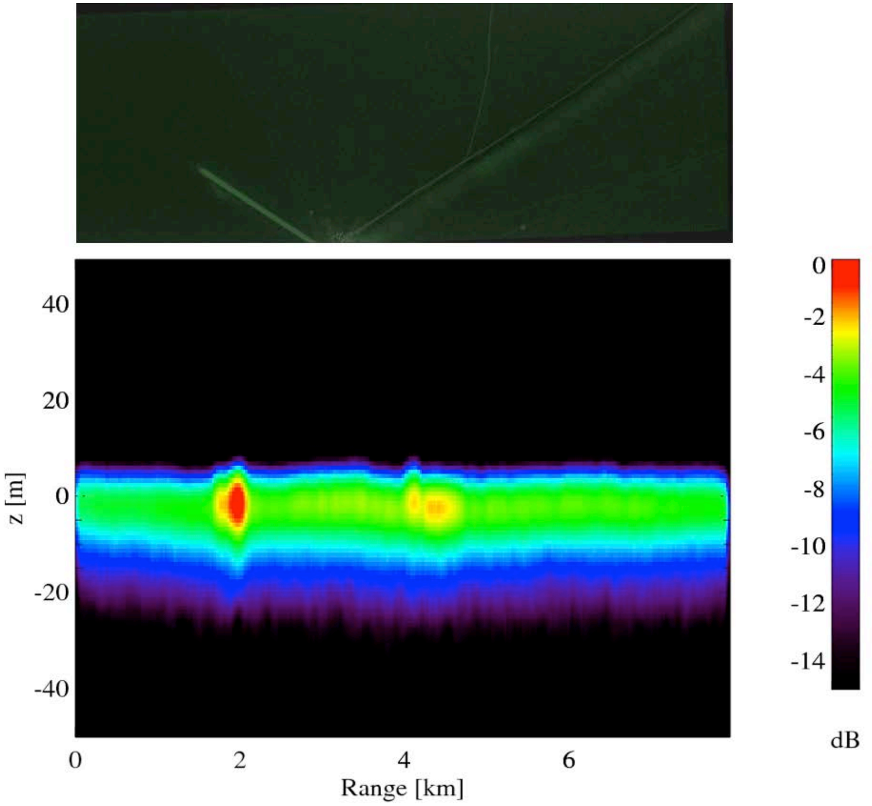
↓

InSAR phase-center height below ice surface

↓

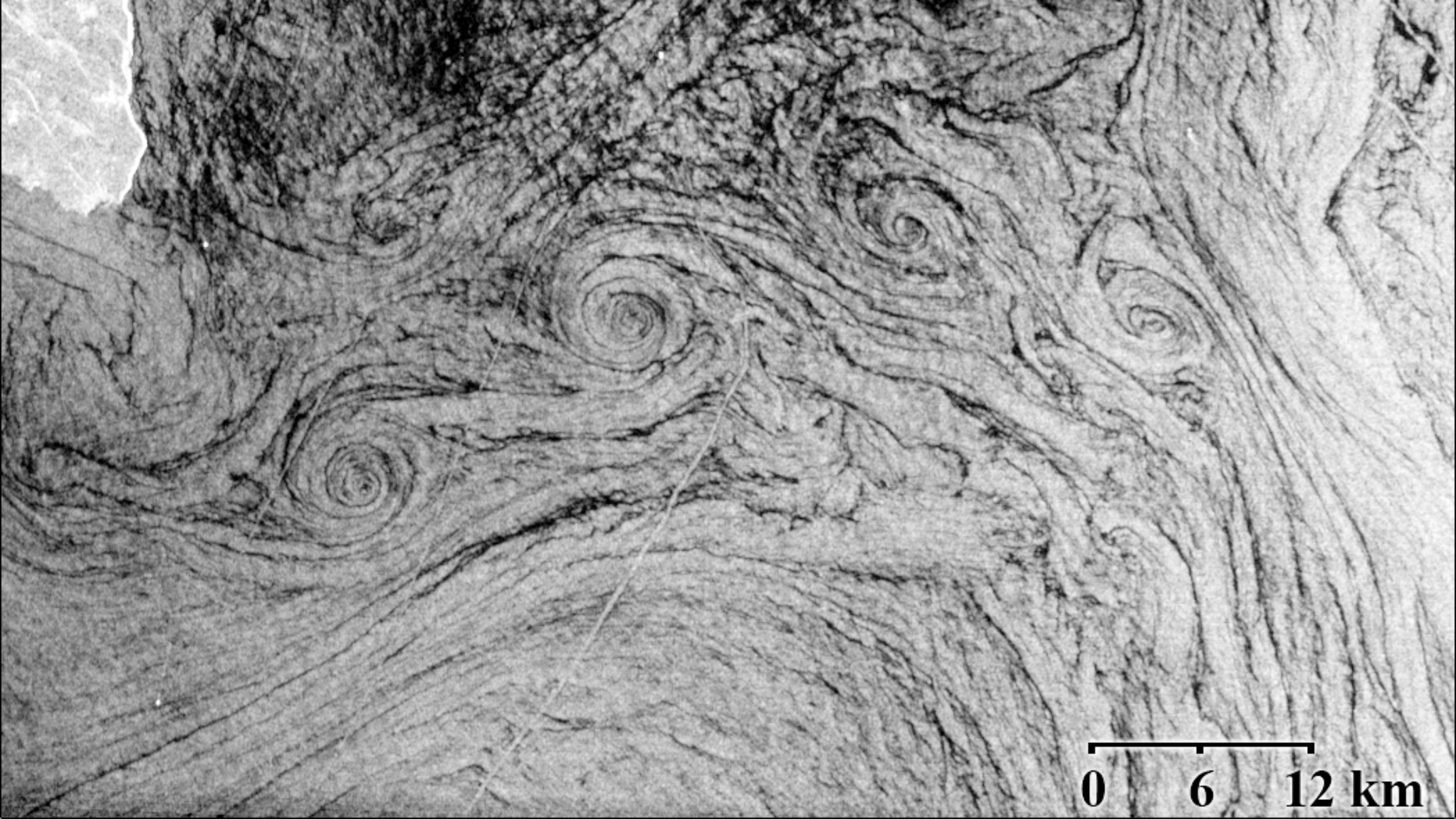
Problem if penetration depth varies

TSX tomographic image over lake Vostok

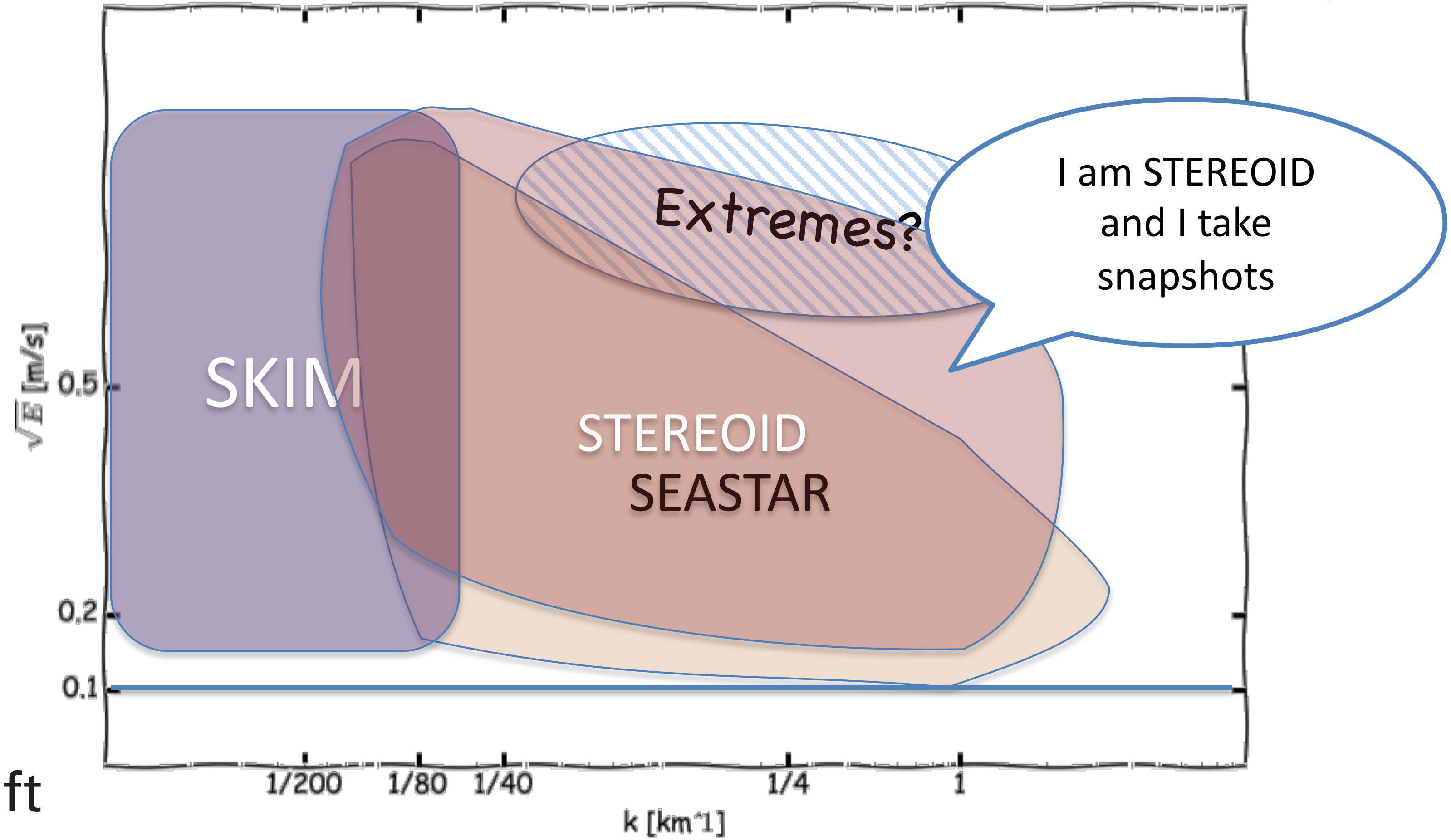


Science objectives: oceans

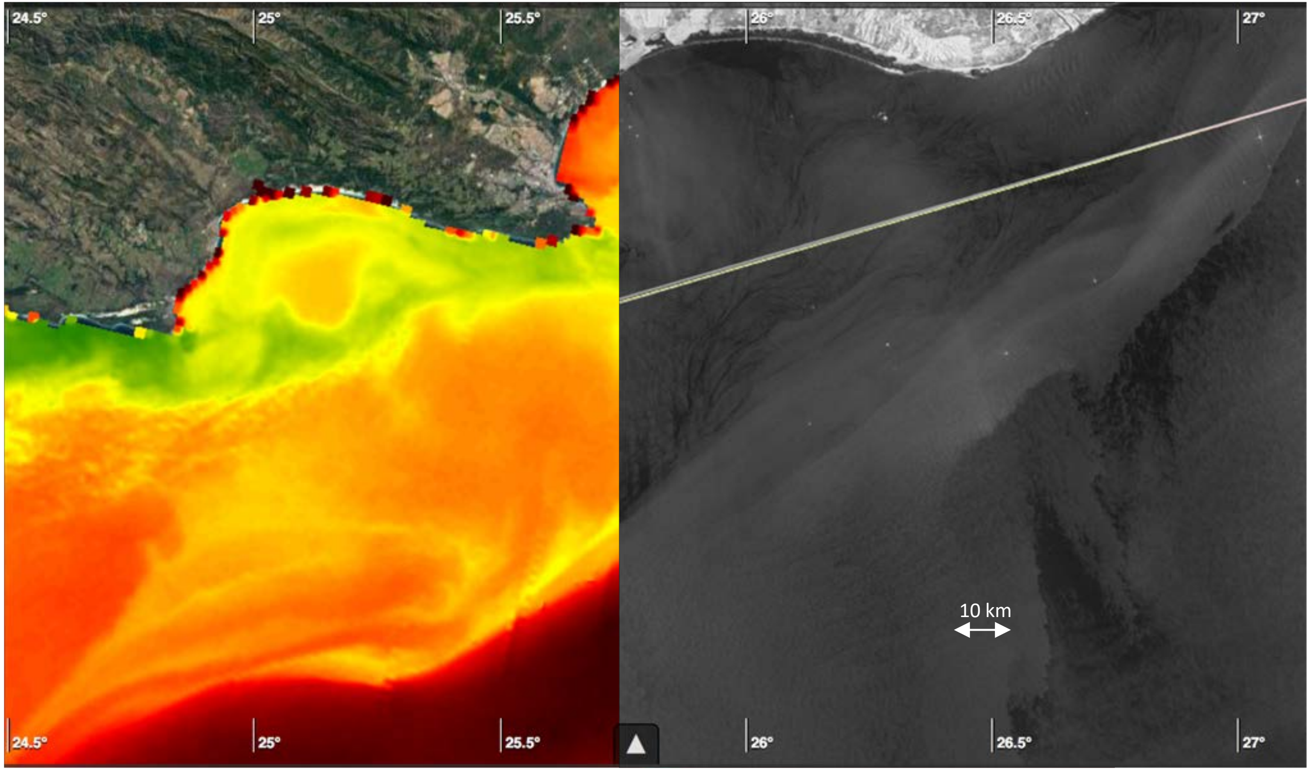
1. High resolution surface currents and wave data to validate and develop models for coastal processes
2. Characterize and quantify small-scale (100 m to 10 km) ocean dynamics
3. Measure the surface deformation field (gradients TSCV)
   - Divergence/strain
   - Vorticity
   - Shear
4. Improve our understanding of air-sea interactions
5. Extreme weather events


0
6
12 km

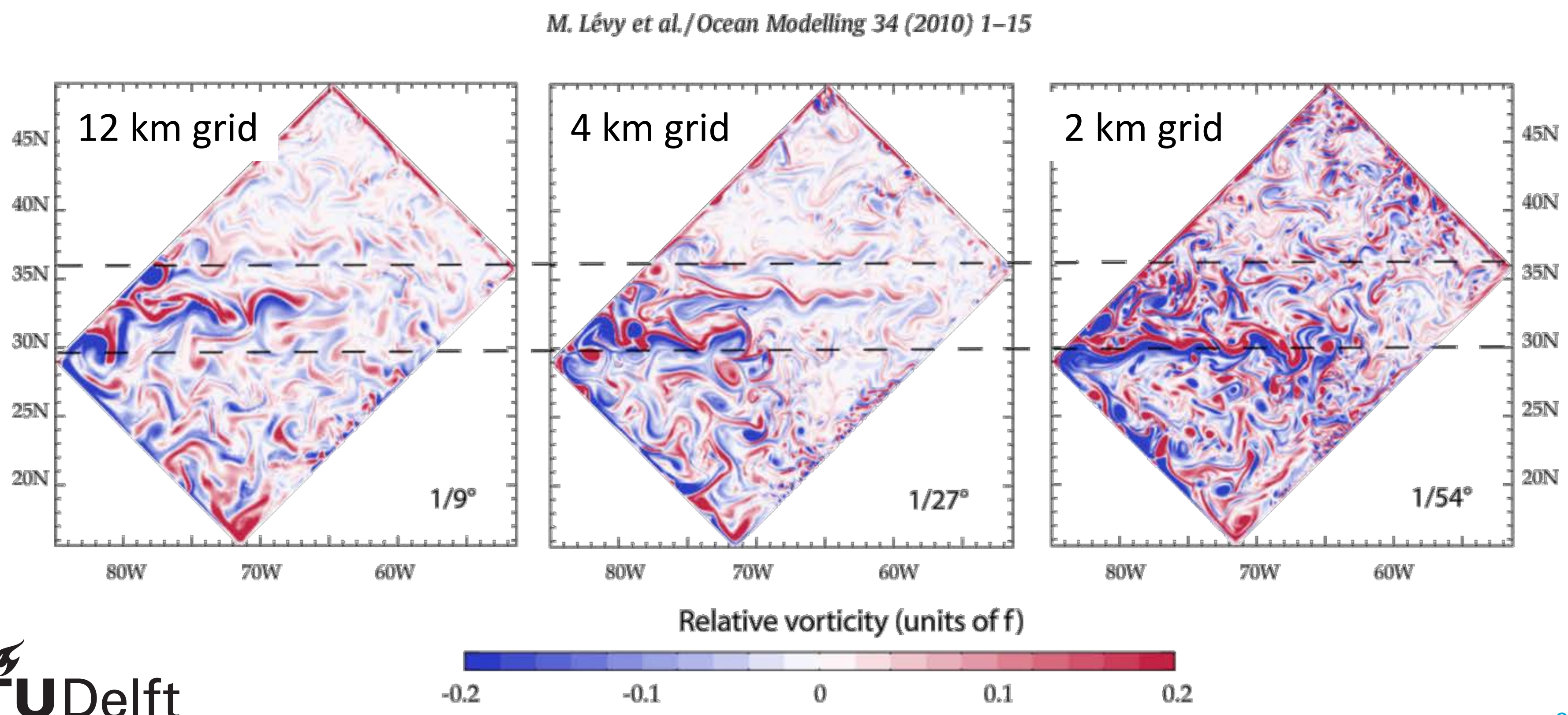
And attempt to contextualize STEREOID (TSCV)



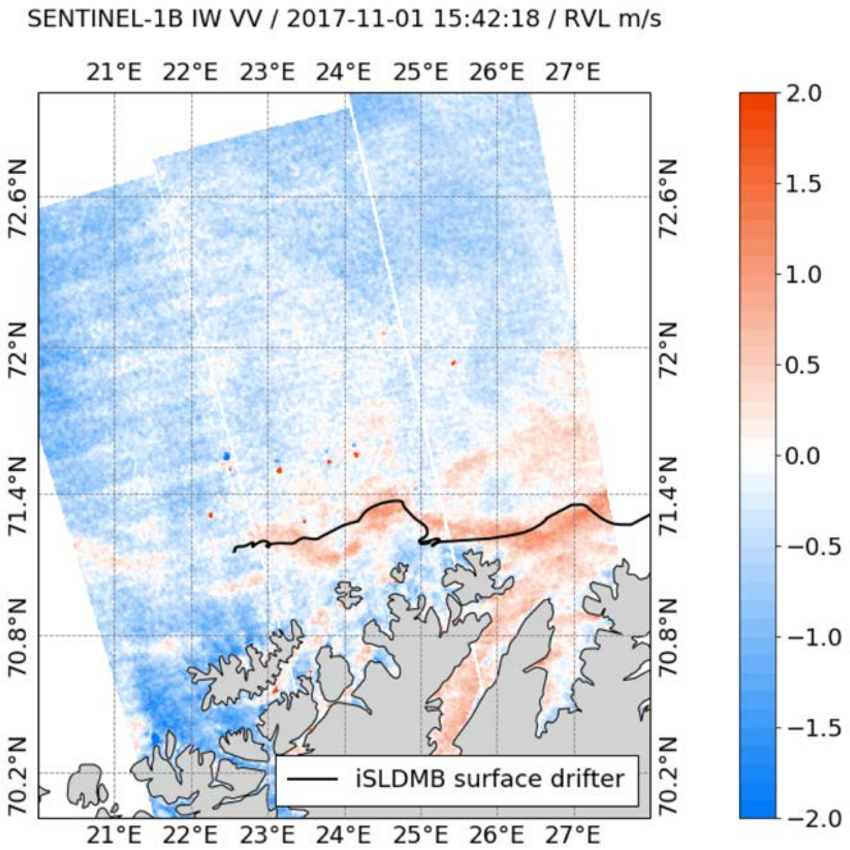
TIR + radar rationale



The value of resolution (for example, vorticity)



Radial velocities measured by Sentinel-1



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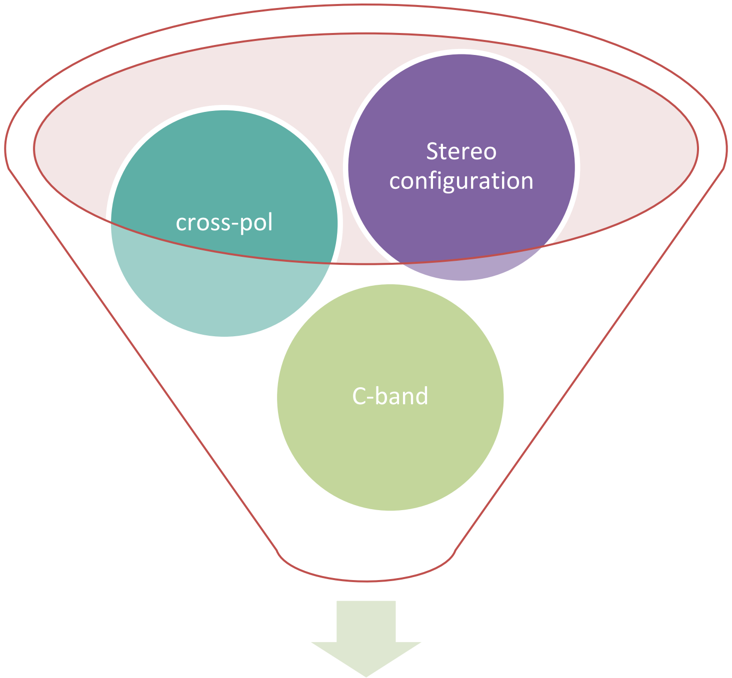
Main open issue: (wind) wave bias

- Problem:

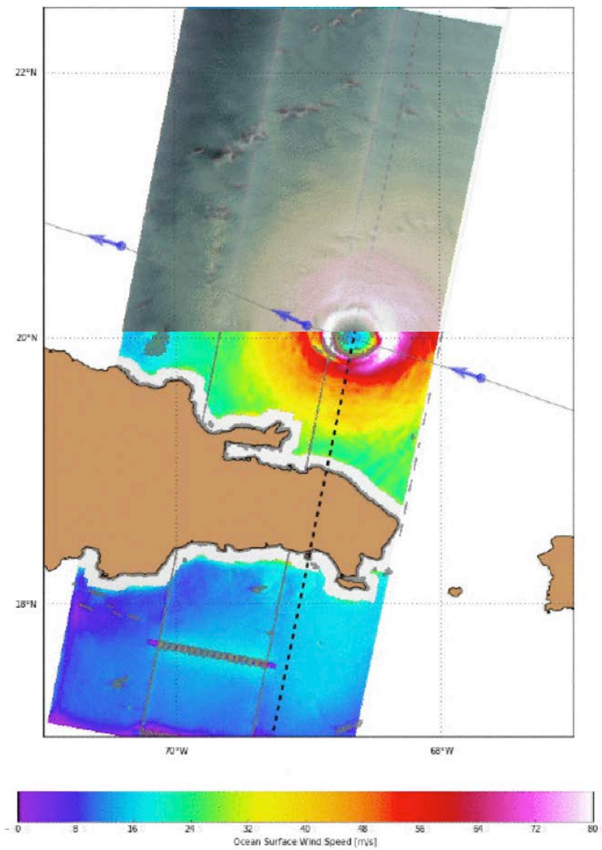
$$v_{\text{Doppler}} = v_{\text{Wave-Bias}} + v_{\text{TSC}}$$

- Approaches being studied
  - Measure waves → estimate bias
  - Estimate wind from backscatter → model waves → estimate bias
  - Exploit polarimetric dependency of wave-bias

Extreme weather [Stereo]



Surface winds + TSCV



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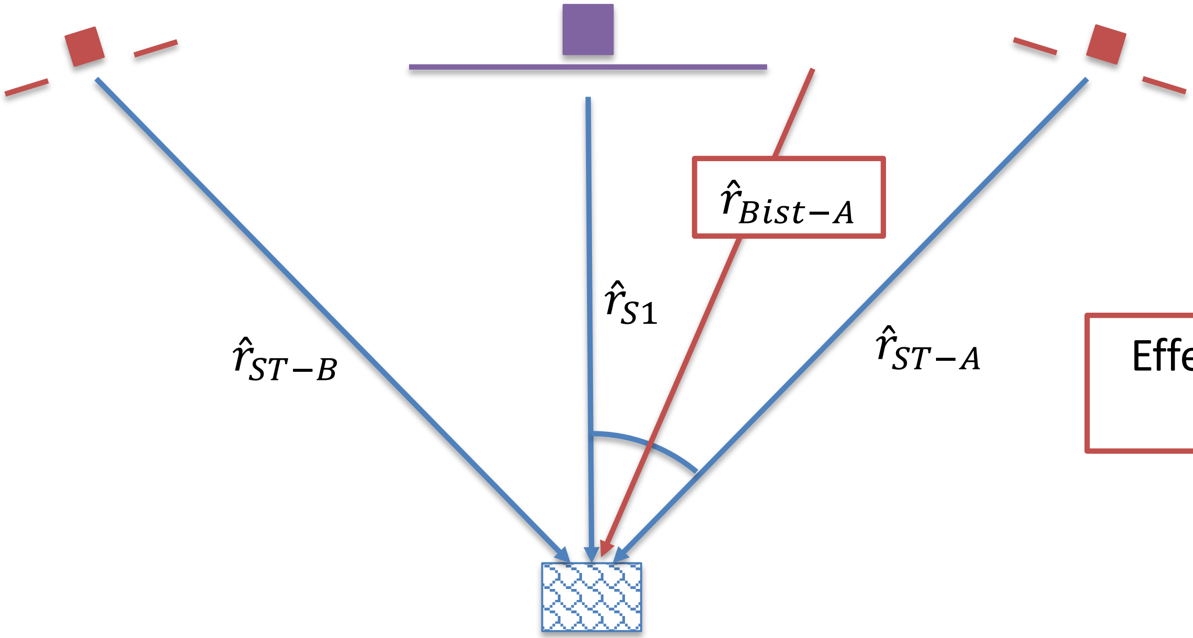
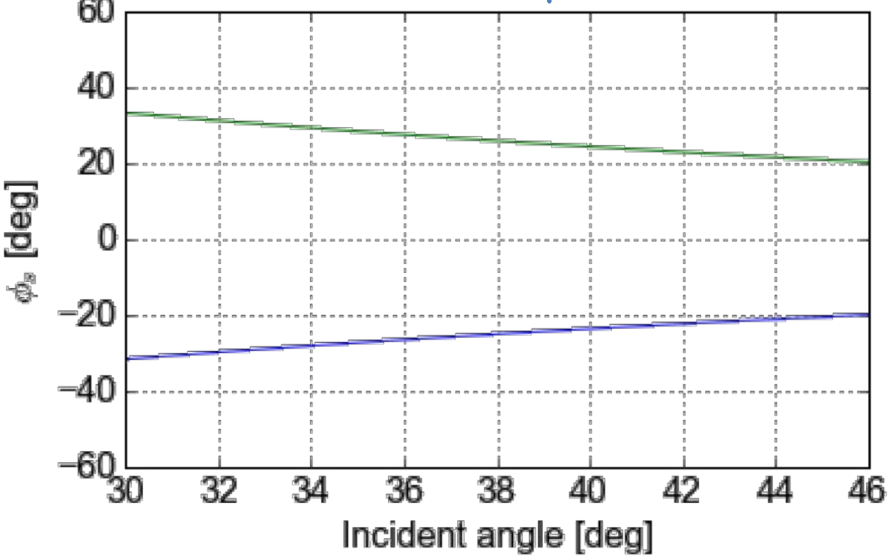
Squint angles (top view)



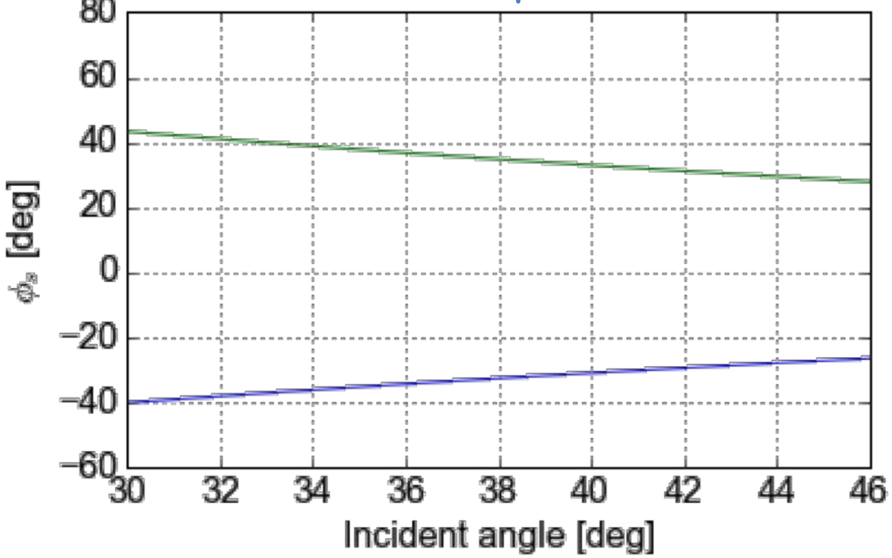
Effective squint angle limited by bistatic geometry

Squint angles

250 km separation



350 km separation



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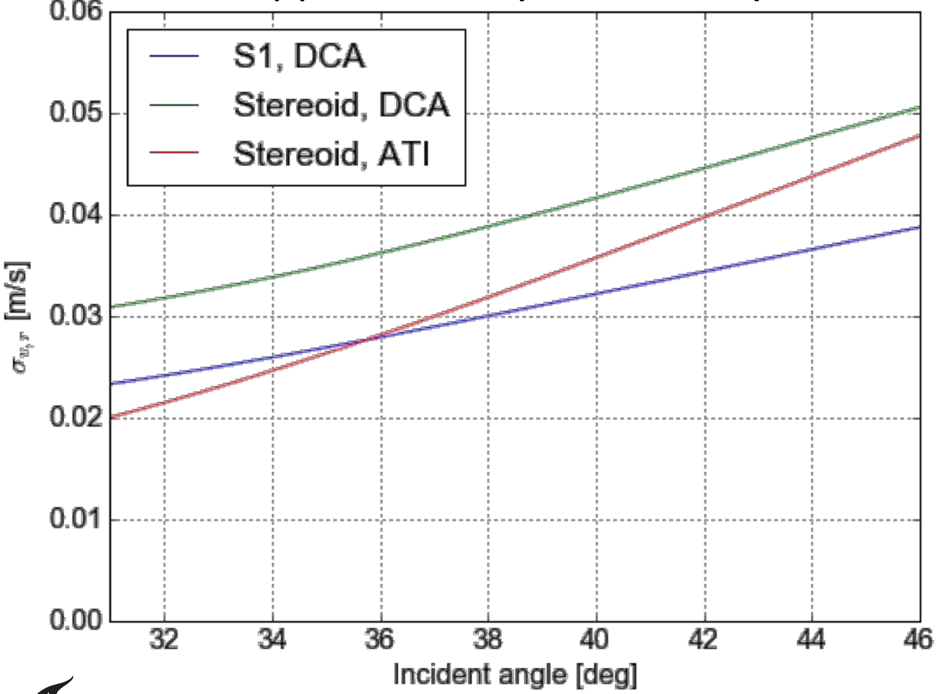
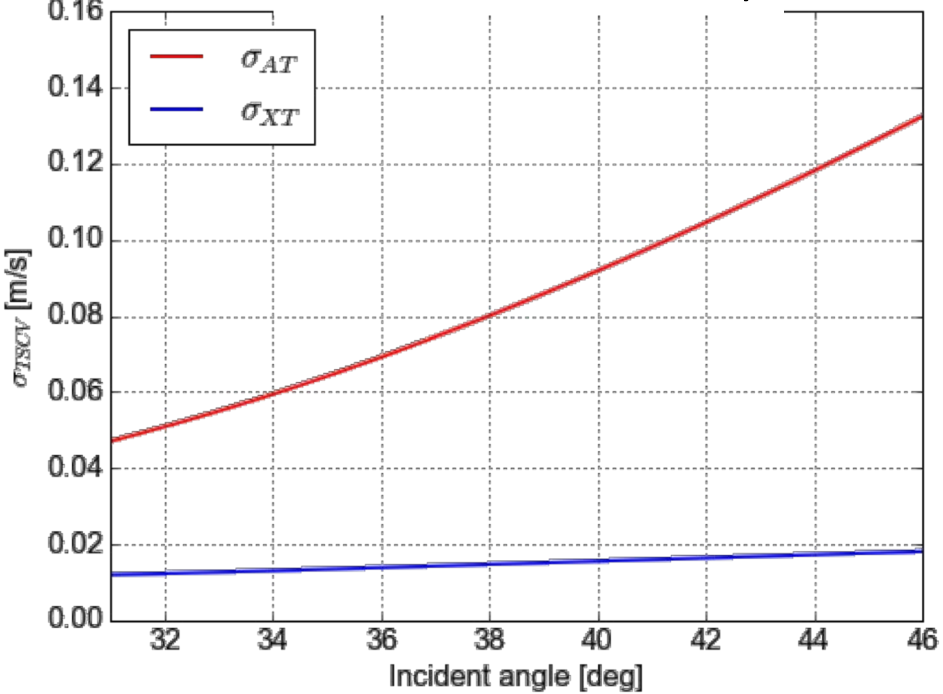
System Sensitivity (ideal retrieval)

- 3 km resolution
- 6 m/s wind
- 250 km separation

Doppler velocity uncertainty



TSCV vector uncertainty



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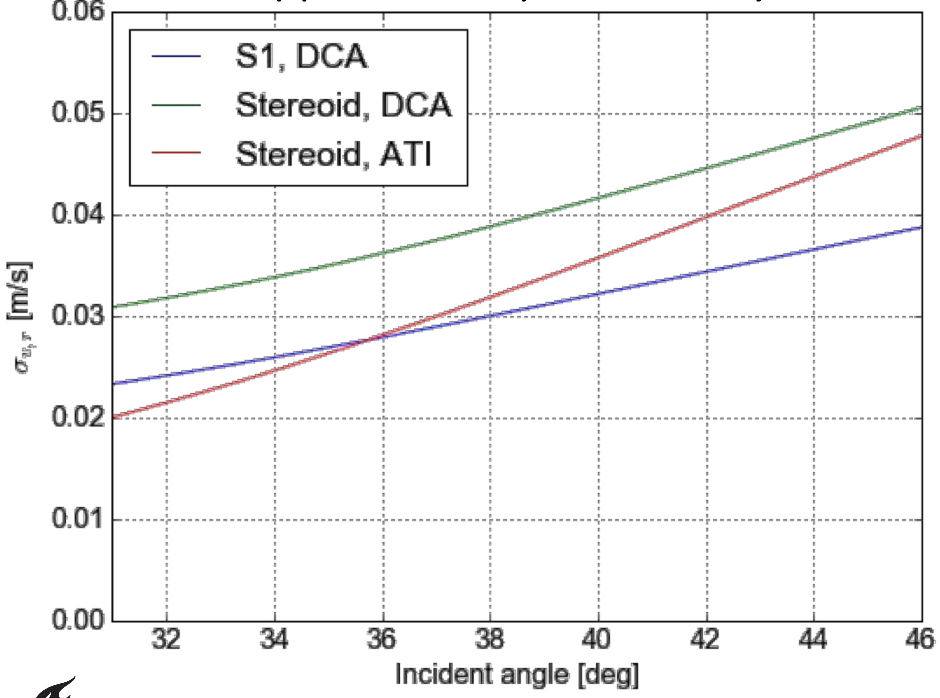
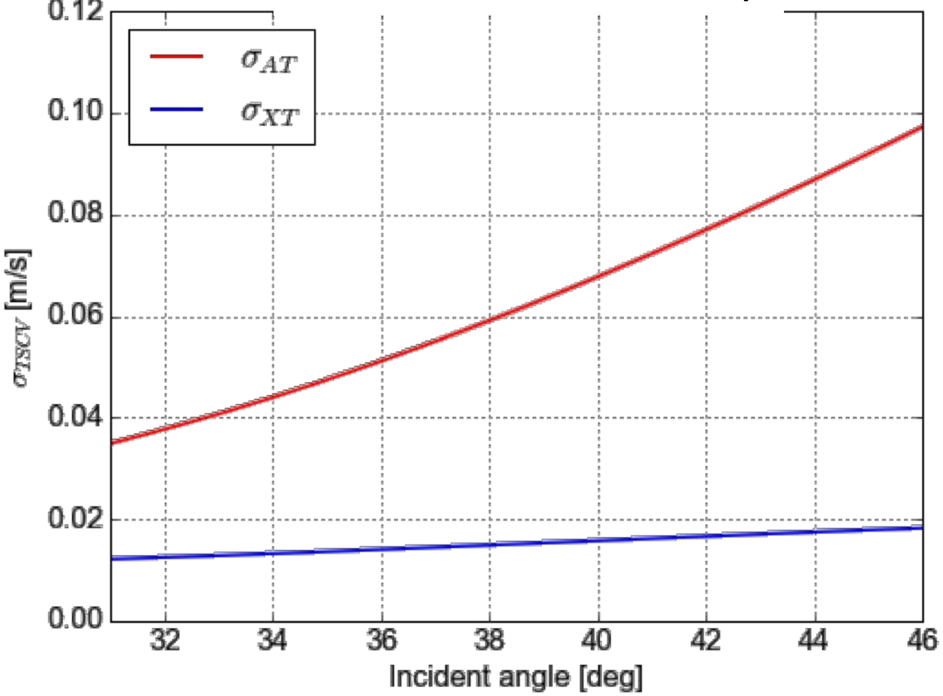
System Sensitivity (ideal retrieval)

- 3 km resolution
- 6 m/s wind
- **350 km separation**

Doppler velocity uncertainty



TSCV vector uncertainty



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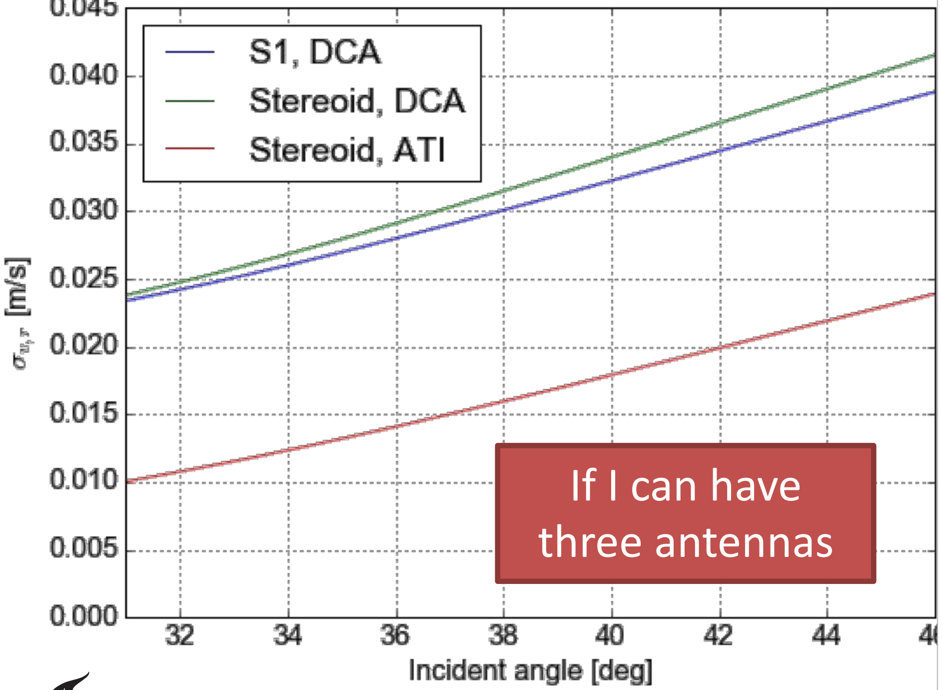
System Sensitivity (ideal retrieval)

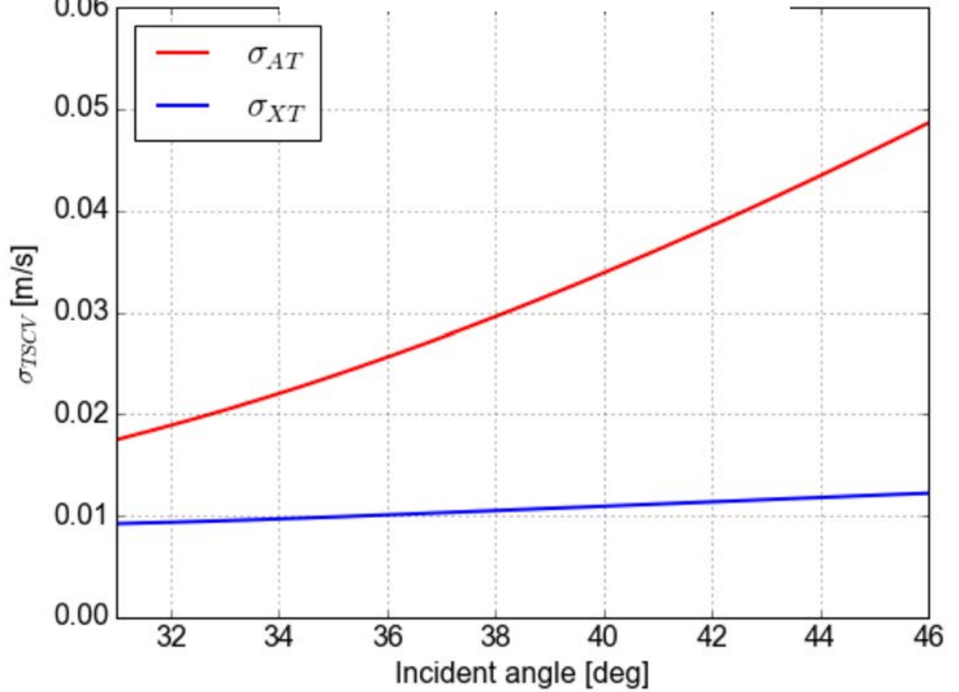
- 3 km resolution
- 6 m/s wind
- **350 km separation**

Doppler velocity uncertainty



If I can have three antennas

TSCV vector uncertainty



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Main sources of systematic (non-geophysical) errors

	DCA	Short-ATI	Long-ATI
Sentinel-1 pointing	Mispointings weighted by 1/beamwidths		
Companion mispointing			
Formation knowledge			Leads to ATI phase offset
Oscillator frequency offsets	Is a point of concern, but seems technically solved		

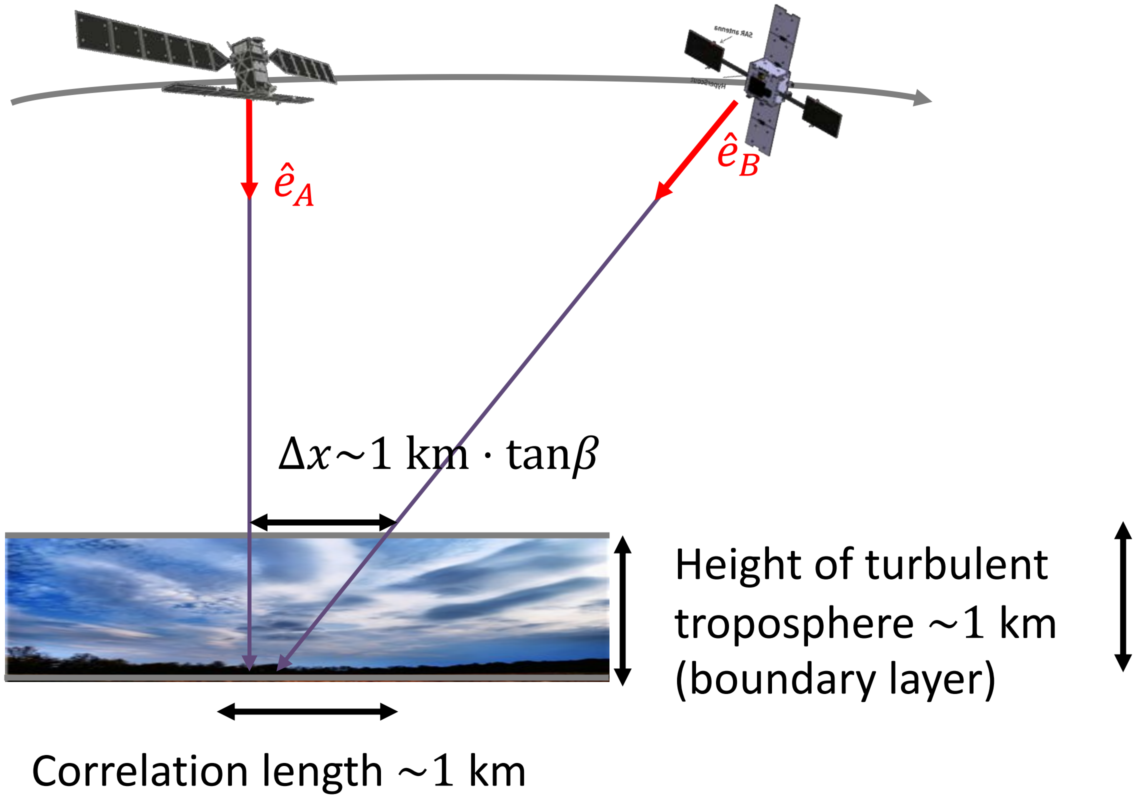
But emphasis on gradients

We can mostly live with low-pass systematic errors

Science objectives: solid Earth

1. Monitor 3D surface
   - co-seismic, inter-seismic, and post-seismic deformation;
   - tectonic rifting;
   - volcanism;
   - landslides.
2. Topographic changes (volume!) due to volcanic and landslide activity

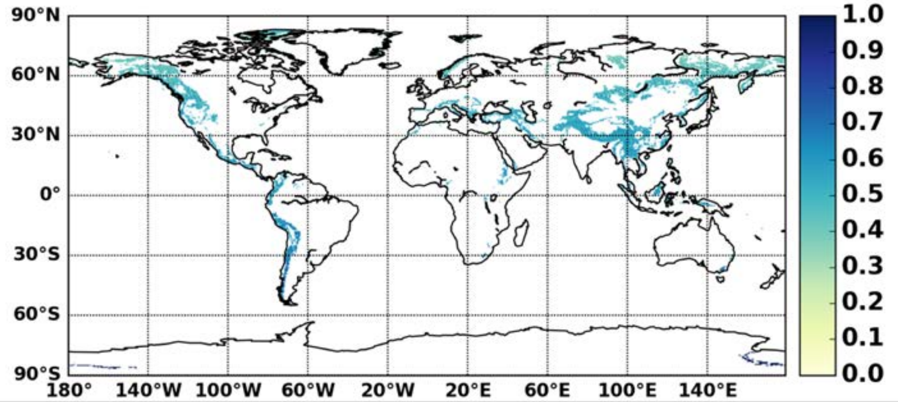
Geometry-diverse DInSAR



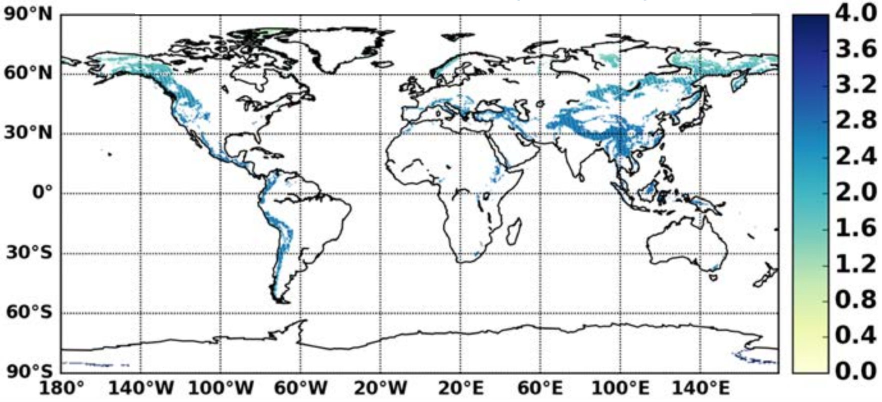
3D deformation

- Along track separation of 250 km
- Performance over 5 years
- Product resolution 100m x 100m
- $\tau = 40\text{days}, \gamma_0 = 1, \gamma_\infty = 0.15$
- Troposphere power 1 cm^2
- Only Sentinel-1 A (12 days repeat)

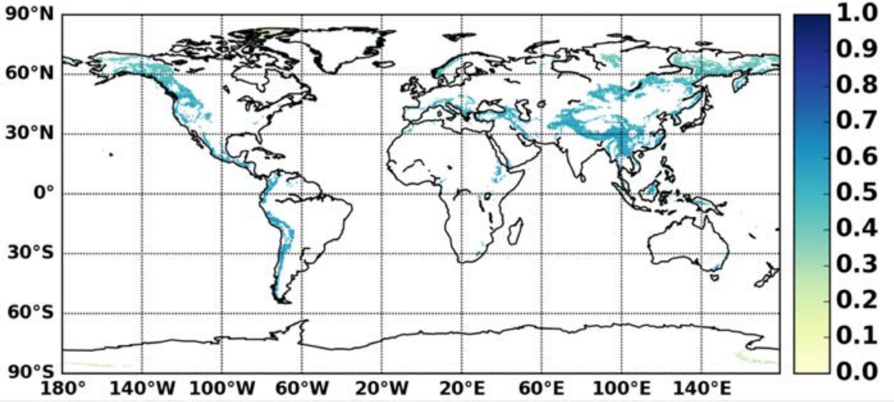
Up-Down accuracy (mm/year)



North-South accuracy (mm/year)



East-West accuracy (mm/year)



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From polarimetry to… multistatimetry?

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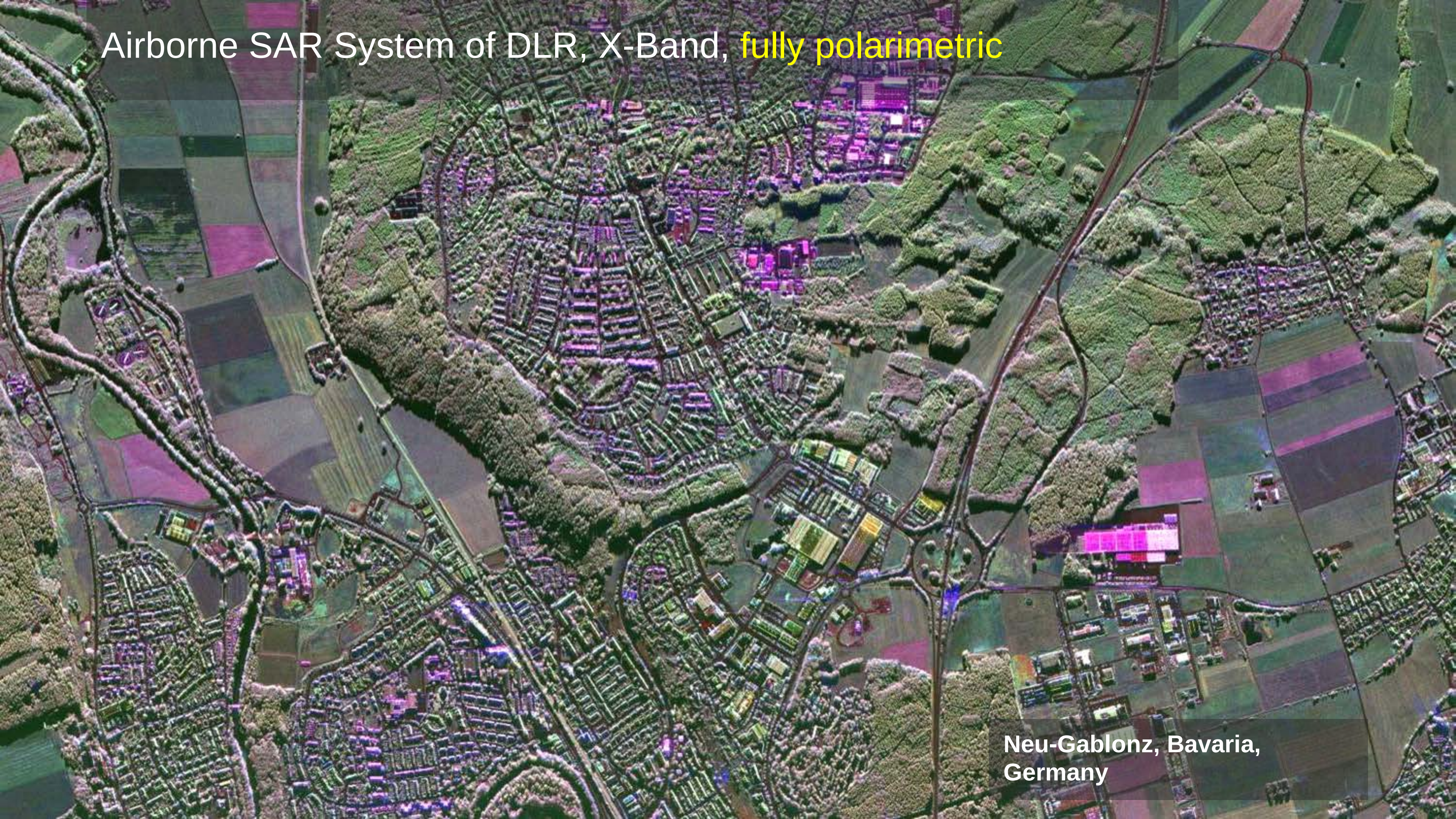
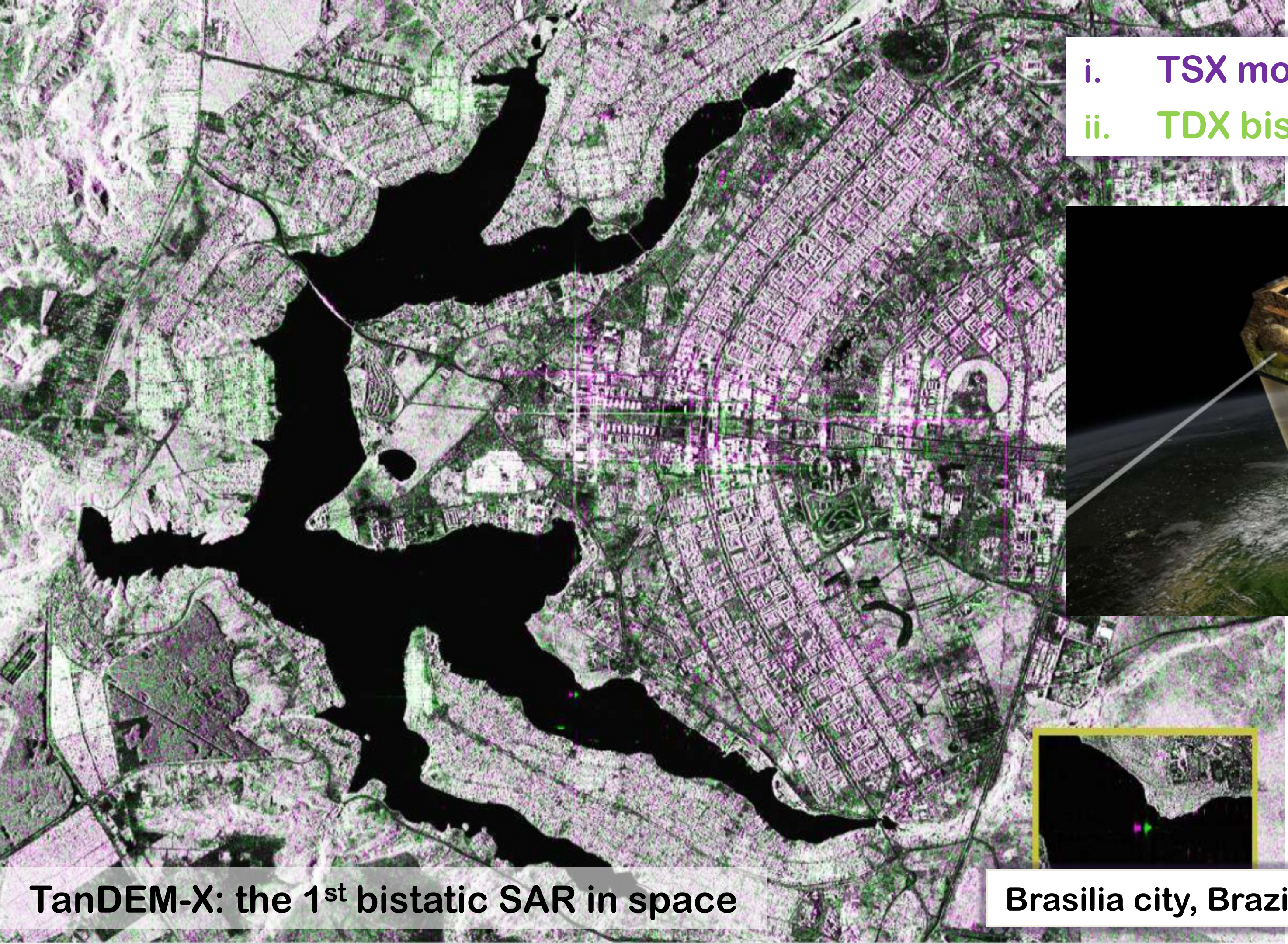
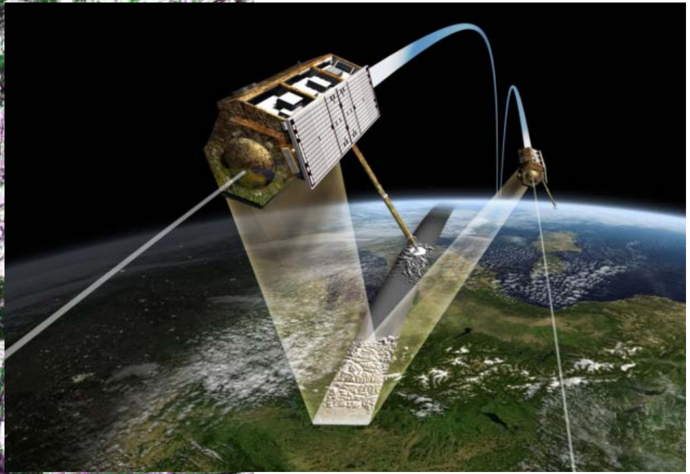
Airborne SAR System of DLR, X-Band, fully polarimetric



Very limited empirical experience with multistatic data



i. TSX monostatic image
ii. TDX bistatic image (20 km)



TanDEM-X: the 1st bistatic SAR in space

Brasilia city, Brazil, August 8th 2010

Space-segment side challenges

Formation flying

- Formation safety
- Cross-track baseline knowledge
- Common Doppler and along-track baseline control

Synchronization

- Phase
- Echo window

SAR performance

- Sensitivity
- Ambiguities

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Formation flying: cross-track baseline knowledge

- LOS baseline error translates directly into phase error:

$$\Delta\phi = 2\pi \cdot \frac{\Delta B_{\parallel}}{\lambda_0}$$

$$\epsilon_h = R \cdot \sin\theta_{inc} \cdot \frac{\Delta B_{\parallel}}{B_{\perp}}$$

Baseline rotation

- R $\sim$ 800 km
- $B_{\perp} \sim$ 200 m to 400 m
- Target $\epsilon_h \sim$ 10 cm

Baseline knowledge requirement from O(0.1 mm)

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Common Doppler loss

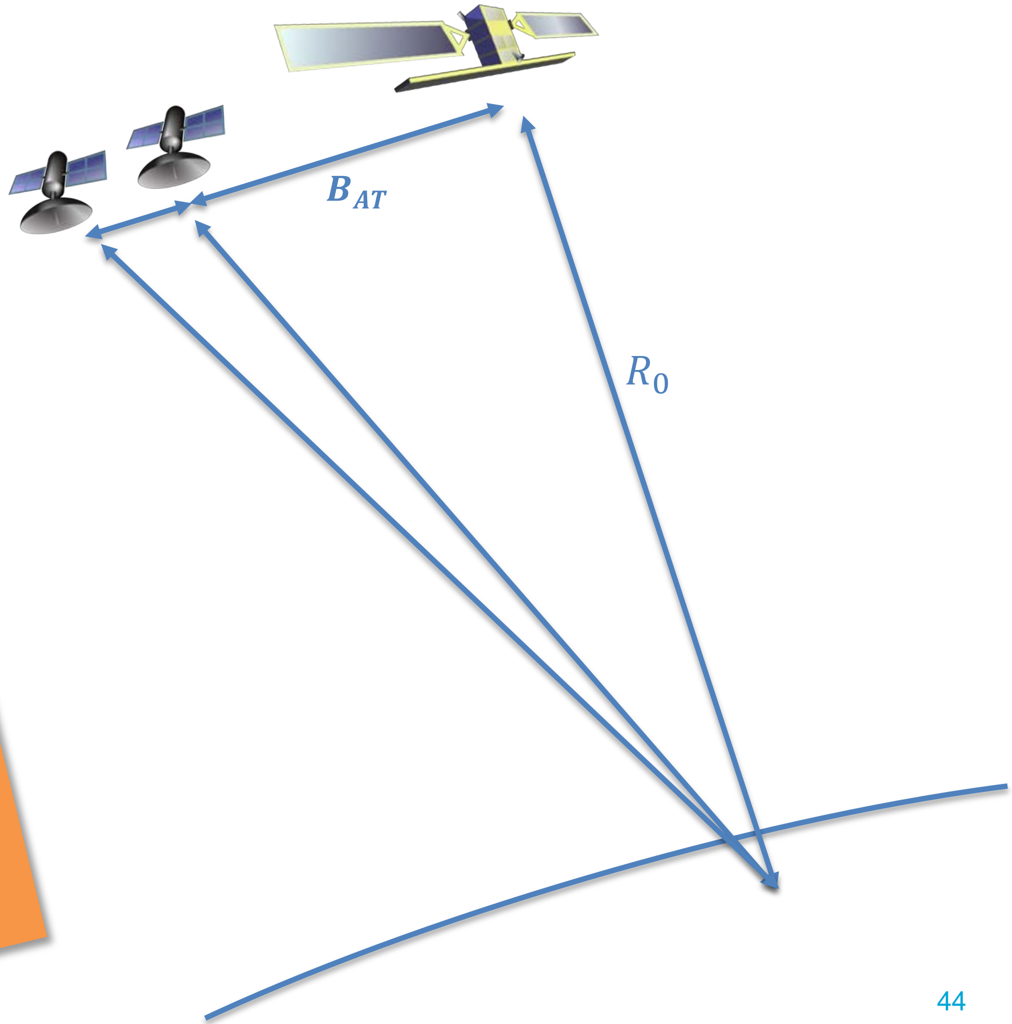
$$\Delta f_{\text{Dop}} = \frac{v_{orb}}{\lambda} \cdot \frac{B_{AT}}{R_0}$$

Should be small compared to processed Doppler bandwidth.

TOPS
SESAME

$$B_{AT} \ll \frac{\lambda \cdot R_0}{v_{orb}} \cdot B_{proc}$$

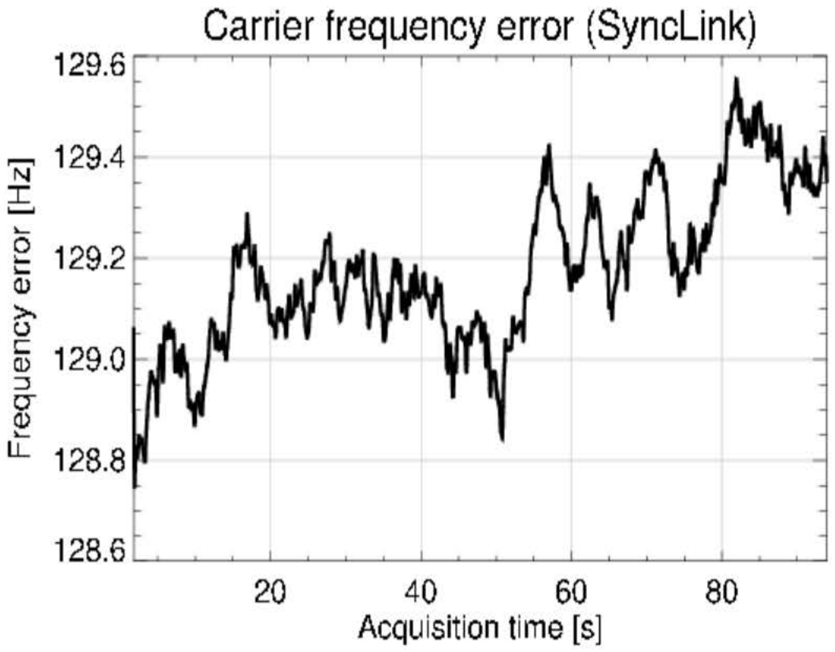
For STEREOID O(300 m) separation OK



Space-segment side challenges

Formation flying			Synchronization		SAR performance	
Formation safety	Cross-track baseline knowledge	Common Doppler and along-track baseline control	Phase	Echo window	Sensitivity	Ambiguities

Phase synchronization



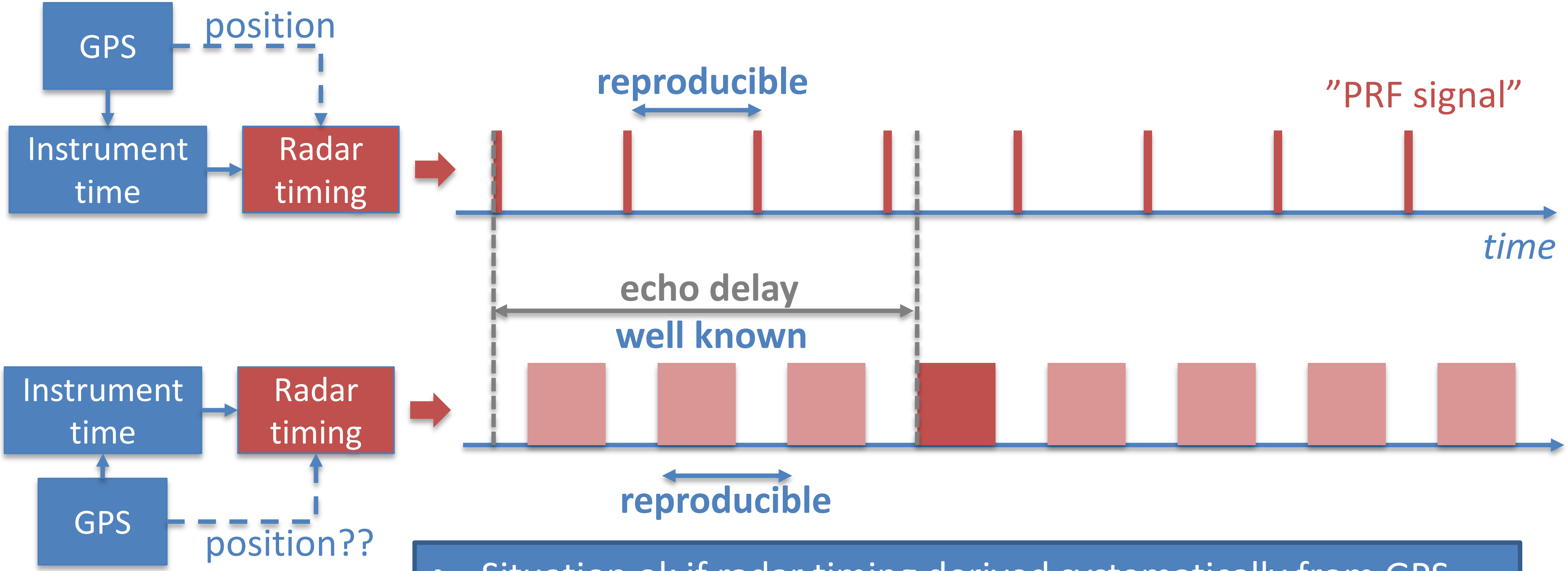
From TanDEM-X SyncLink

Frequency and phase synchronization always a critical issue.

Carrier frequency and phase synchronization: lessons we think we have learnt

- GPS tagging/disciplining ➡️ Frequency offsets
- Data driven (AutoSync, etc) ➡️ Relative phase errors
  - Often good enough
  - Issues for sure
- Explicit synchronization link
  - Two way synchronization between receivers needed

Echo window synchronization



- Situation ok if radar timing derived systematically from GPS-referenced instrument time
- Position derived timing potential trouble maker.

Technical challenges

Formation flying			Synchronization		SAR performance	
Formation safety	Cross-track baseline knowledge	Common Doppler and along-track baseline control	Phase	Echo window	Sensitivity	Ambiguities

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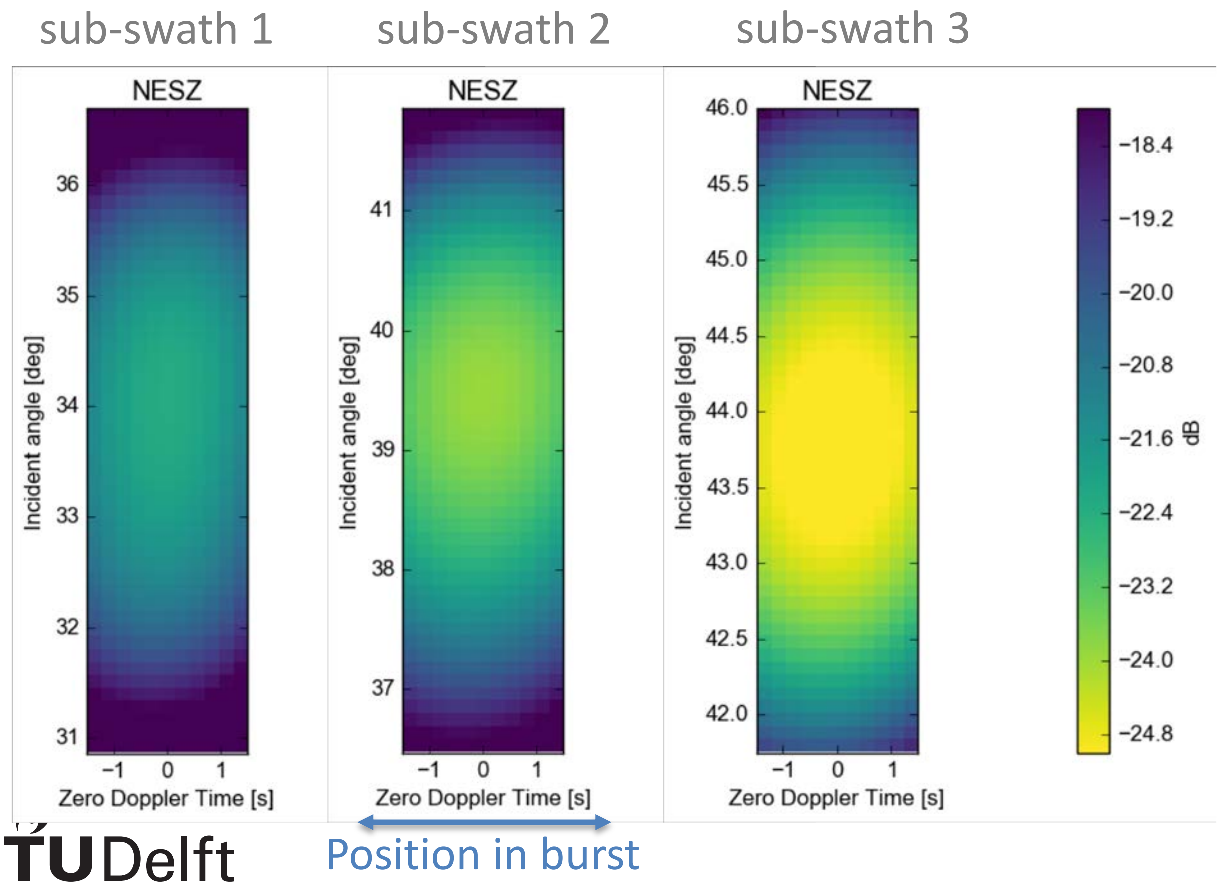
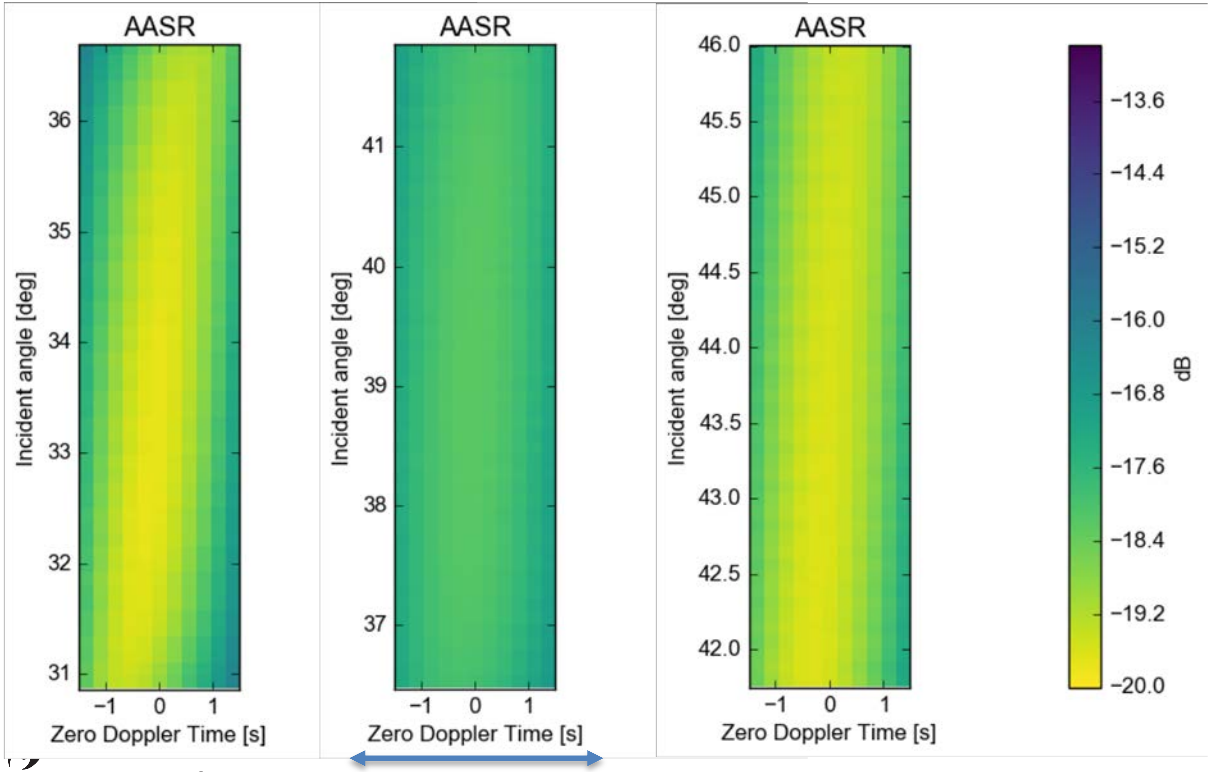
Imaging performance: NESZ (Imaging mode)



- NESZ generally adequate to good
- Probably a bit less gain in exchange of wider elevation beams would be better.
- Or SCORE
- + 3dB for ATI mode

Imaging performance: AASR (imaging mode)

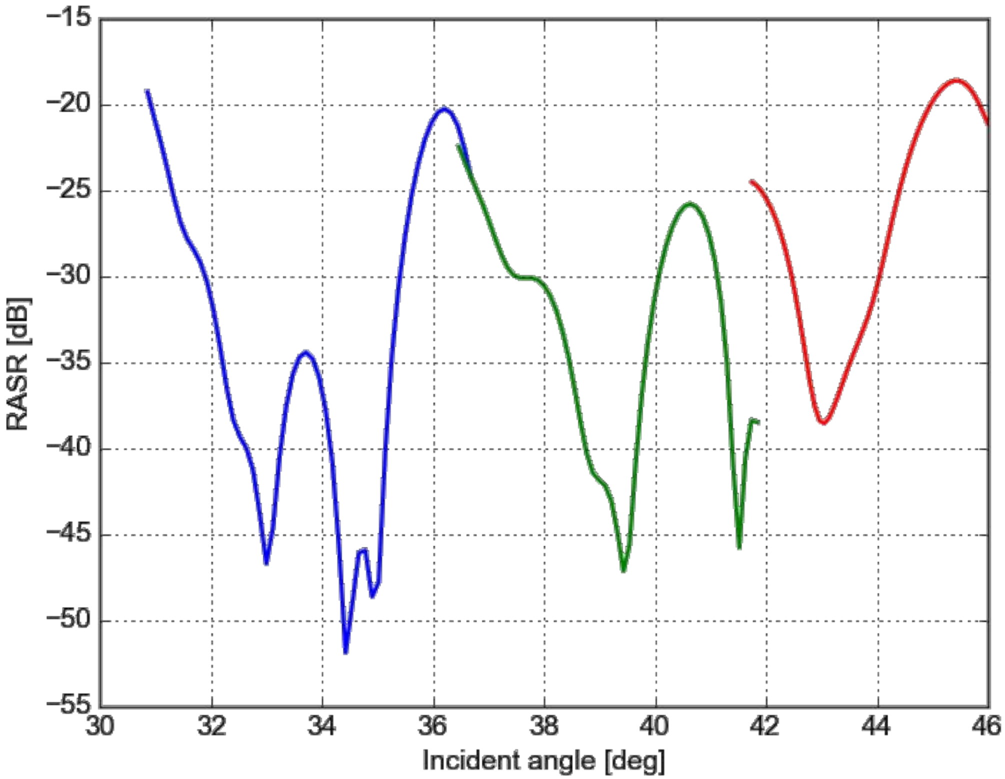
sub-swath 1 sub-swath 2 sub-swath 3



Position in burst

- AASR in -17 to -18 dB range.
- Quite good given small total antenna area
- Sub-swath variability due to Sentine-1 PRFs

Imaging performance: RASR



- RASR < -20 dB
- Good, but we need to accommodate large dynamic ranges (varying wind conditions)

- Misalignment between pattern footprint and iso-Doppler lines

Range ambiguities Doppler shifted (need to account for range-azimuth ambiguities)

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Outlook (1/2)

- We have a (very strong) MAG
  - "UK" members: Juliet Biggs (U. Bristol & COMET), Andy Hooper (U. Leeds & COMET), Julienne Stroeve (UCL).
  - First meeting in January

- ESA in process of preparing Phase-0/A ITTs
  - Preliminary MRD and SoW being discussed just now at ESA.

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Outlook (2/2)

- No technical show-stoppers up to know
- We are sure that we would produce good science
- Some level of scientific prioritization needs to happen
  - Multi-purpose nature both a strength and a weakness
  - For selection we need compelling but also simple story line.
- We need to formulate & justify mission requirements