SAR Pointing Calibration for Ocean Surface Radial Velocity Estimation: Challenges and Alternatives

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Background & Motivation
Radial Velocity Estimation: Doppler Centroid Anomaly

- Demonstration of feasibility using Doppler Centroid Anomaly (DCA) to estimate ocean surface radial velocity

$$\omega_D = 2\pi f_D = \frac{d\varphi}{dt} = \frac{4\pi}{\lambda}\frac{dR}{dt} = \frac{4\pi}{\lambda} v_{rad}$$

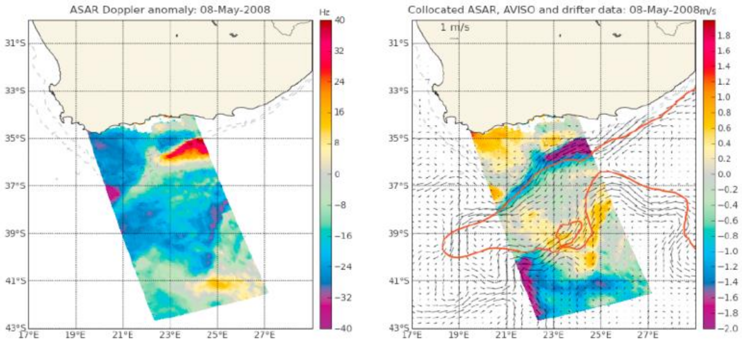
$$f_D = \frac{2\, v_{rad}}{\lambda}$$

$$f_{DCA} = \underbrace{f_{DC_{SAR}}}_{\text{measured}} - f_{DC_{point}}$$

$$f_{DC_{point}} = \underbrace{f_{DC_{ATT}} + f_{DC_{mech}}}_{\text{pointing knowledge}} + f_{DC_{elec}}$$

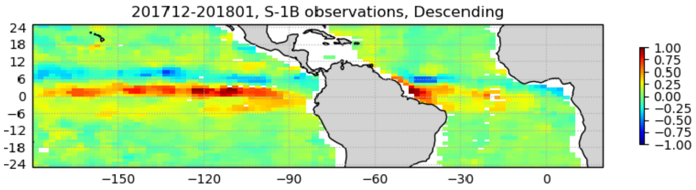
- Estimation of $f_{DC_{ATT}}$ using AOCS quaternions
- Calibration over land (homogeneous areas) for estimation of $f_{DC_{point}}$

ENVISAT/ASAR



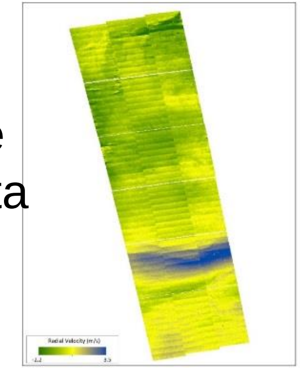
M. J. Rouault, A. Mouche, F. Collard, J. A. Johannessen, and B. Chapron, "Mapping the Agulhas Current from space: An assessment of ASAR surface current velocities," *J. Geophys. Res. Ocean.*, vol. 115, no. 10, pp. 1–14, 2010.

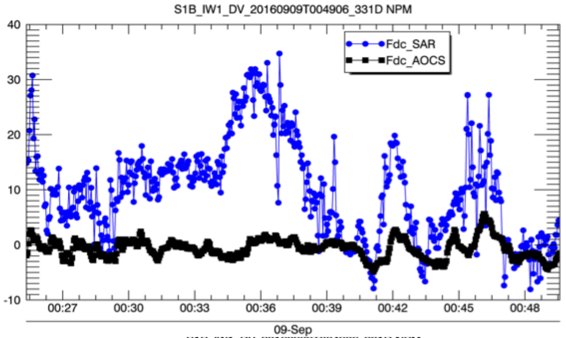
Sentinel-1

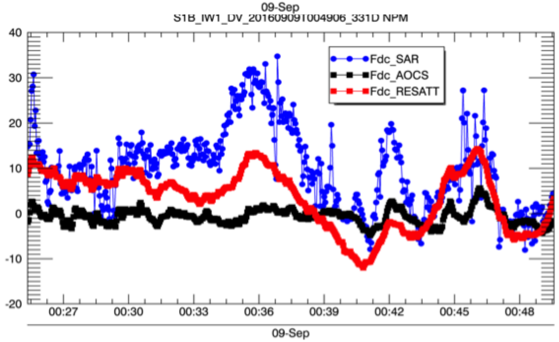


Sentinel-1 Radial Velocity Estimation

Sentinel-1 Radial Velocity (RVL) product relates Doppler Centroid Anomaly (DCA), i.e. geophysical Doppler, to ocean surface radial velocity using IW and WV mode data



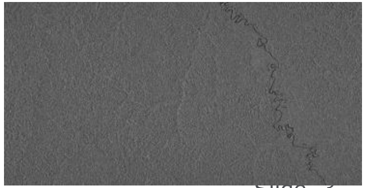




DCA estimation:

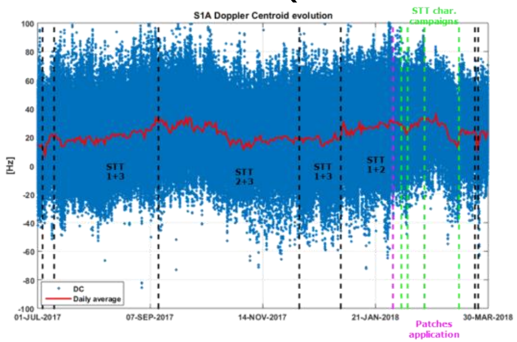
- $f_{DC_{SAR}}$ (blue): estimated in SAR image
- $f_{DC_{ATT}}$ (black): based upon knowledge of on-board platform attitude (quaternions)
- $f_{DC_{RESATT}}$ (red): Restituted attitude, estimated on-ground to improve platform attitude knowledge
- $f_{DC_{elec}}$: based upon Antenna Model

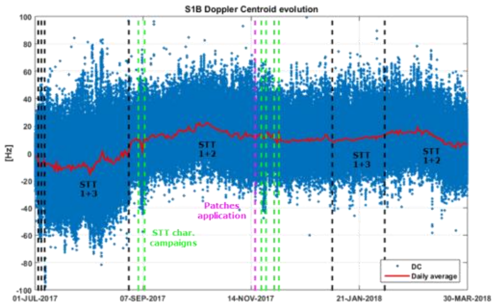
$\Rightarrow$ Major focus on estimation of $f_{DC_{ATT}}$ and $f_{DC_{RESATT}}$ e.g. using area with stable and homogeneous backscatter (Amazon)

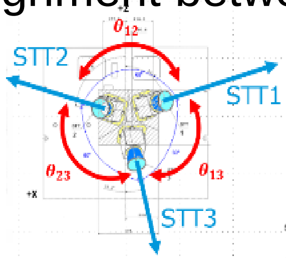


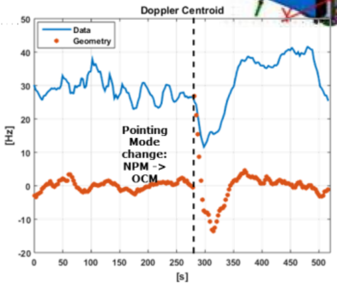
Sentinel-1 Attitude Knowledge vs Doppler

- Doppler Centroid bias variation (jumps) due to mis-alignment between Star Trackers (3 different combinations)



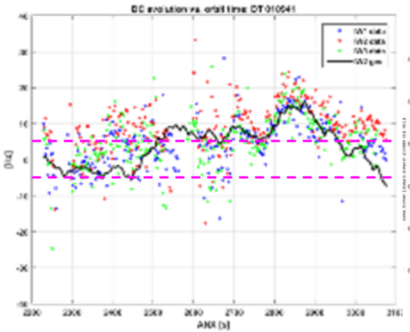


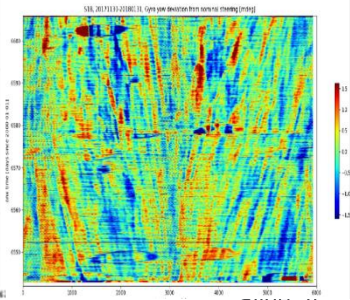




Improvements:

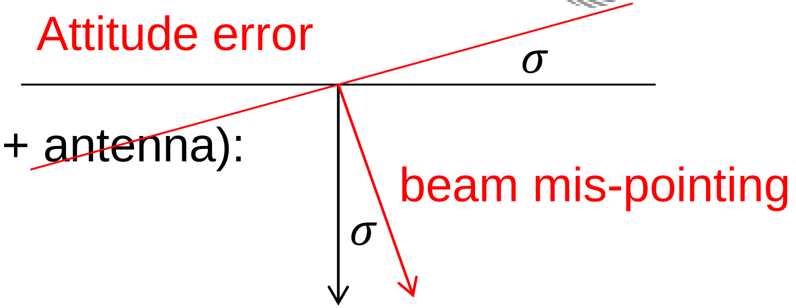
- STT re-alignment campaign and relativistic *light aberration correction*
- Optimization of AOCS gain (Kalman filter) settings
- Improvements in estimation of Restituted Attitude
- Gyro-based (no STT) Restituted Attitude





Attitude Knowledge Requirements

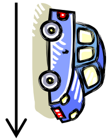
$$f_{DCA} = f_{DC_{SAR}} - f_{DC_{point}}$$



Doppler offset due to pointing (spacecraft attitude + antenna):

$$\underbrace{f_{DC_{point}} = f_{DC_{ATT}}}_{\textit{pointing knowledge}} + \underbrace{f_{DC_{mech}} + f_{DC_{elec}}}_{\textit{calibration}}$$

$$f_{DC_{ATT}} = \frac{2}{\lambda} v_{Sat} \sin\sigma \quad \Rightarrow \quad \sin\sigma = P\cos\vartheta_{elev} - Y\sin\vartheta_{elev}$$

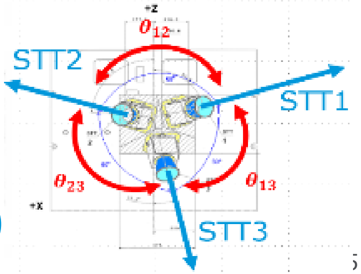
v_{rad}  Line-of-sight velocity

σ: $1 mdeg \;\cong\; f_{DC_{ATT}}: 4.6\ Hz$ (C-band)

$$f_D = \frac{2\, v_{rad}}{\lambda} \quad \Rightarrow \quad v_{rad} = v_{sat} \sin\sigma$$

Requirement: $\delta v_{rad} \cong 0.1\ \mathrm{m/s} \quad \Rightarrow \sigma \cong 0.76\, mdeg$

Ideally: $f_{DC_{ATT}} \cong 2Hz \quad \Rightarrow \sigma \cong 0.43\, mdeg$ (knowledge)

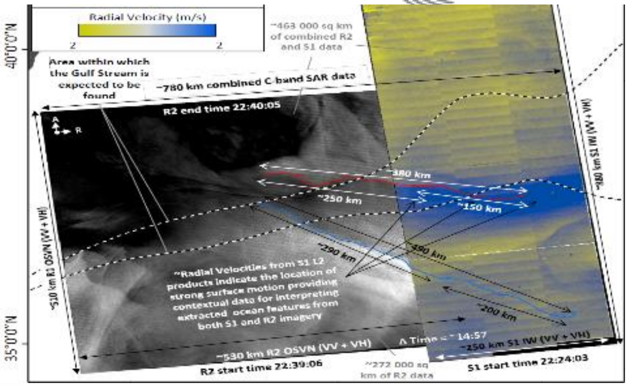


$\Rightarrow$ Challenge to achieve with state-of-the AOCS (star tracker, gyro, etc)

Sentinel-1 L2 RVL Product

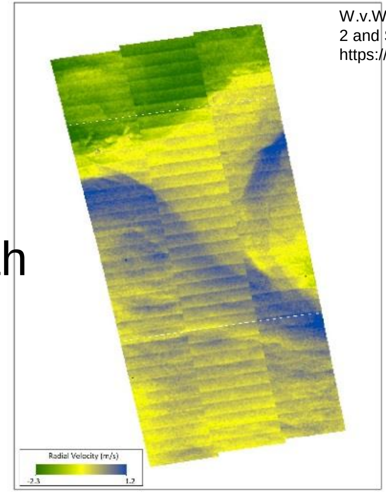
- Studies on ocean signature analysis, e.g. estimation of gradient wall location of the Gulf stream current
- Synergistic acquisitions of RADARSAT-2 and Sentinel-1 data (S-1 RVL product)

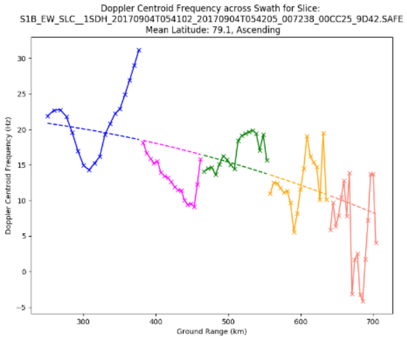
⇒ using ***relative*** radial velocity (only)



W.v.Wychen, P.W. Vachon, J. Wolfe, K. Biron, “Synergistic RADARSAT-2 and Sentinel-1 SAR images for Ocean Feature Analysis”, CJRS 2019, https://doi.org/10.1080/07038992.2019.1662284

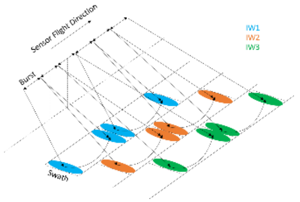
- current RVL product shows non-geophysical artifacts, not related to attitude knowledge
  - residual ramps in azimuth
  - varying Doppler biases from swath to swath (discontinuities),
  - different Doppler trends across range





TOPS De-ramping Function

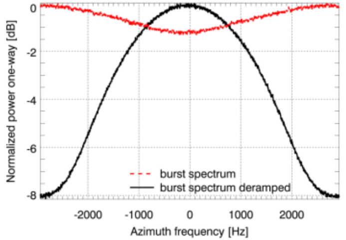
- Large Doppler variation (5 kHz) due to TOPS azimuth beam steering
- De-ramping operation results in the demodulated signal



$$s_d(t) \approx \beta \cdot exp\left(j\pi k_{eff}(t - t_0)^2\right) \cdot \left(j\pi k_s({t_0}^2 - {t_{mid}}^2)\right) \cdot exp(-j2\pi k_s(t_0 - t_{mid}) \cdot t)$$

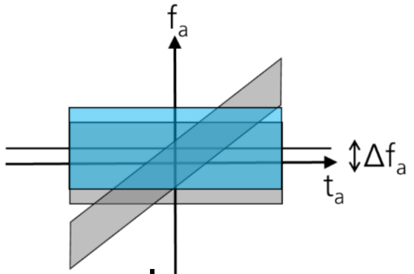
β contains the azimuth weighting and range phase terms
$k_{eff} = k_a - k_s$: effective chirp rate; k_a Fm rate, k_s : Doppler rate due to azimuth antenna steering
center exponential term: residual phase term (no impact)

$\Rightarrow$ last term is responsible for the demodulation: t_{mid} : burst center time

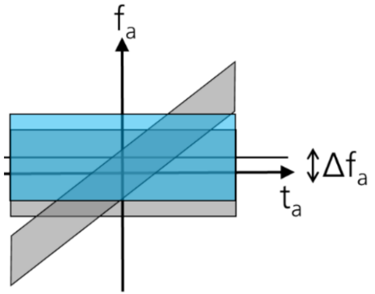


from Theory:

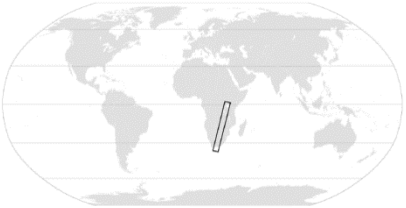
- Error in t_{mid} causes asymmetries of antenna patterns $\Rightarrow$ bias in Doppler $\Rightarrow$ discontinuities between sub-swaths



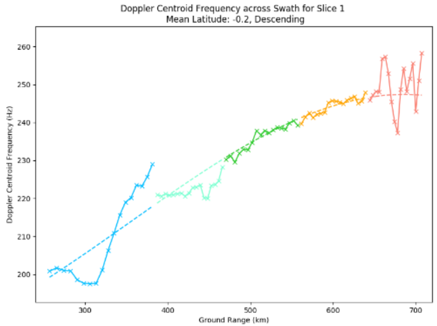
- Error in steering rate $\Rightarrow$ Pointing error w.r.t. steering angle causes (residual) Doppler variations along azimuth (ramps)

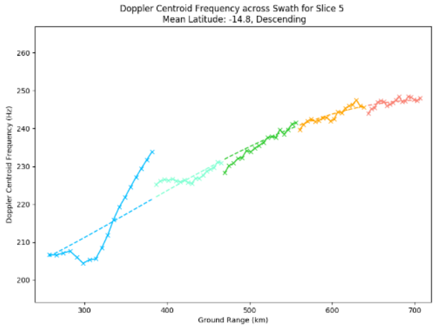


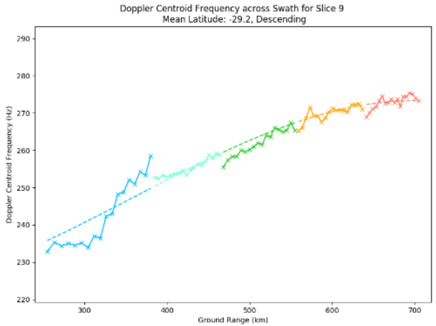
EW Mode: Doppler Centroid across Swath

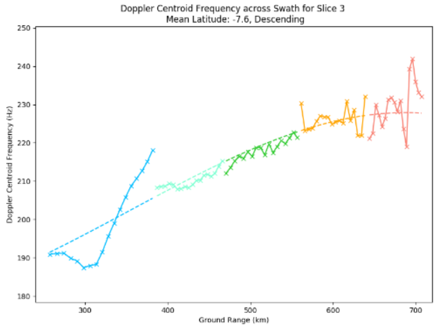


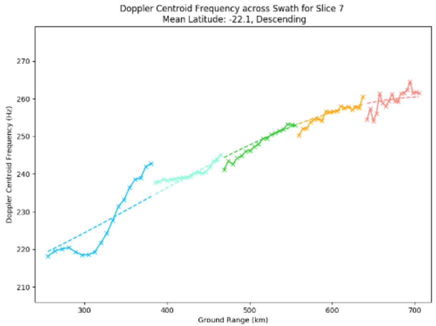
S-1B EW Acquisition over Africa, 2016 06 11

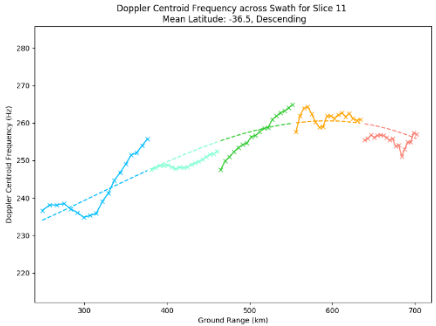




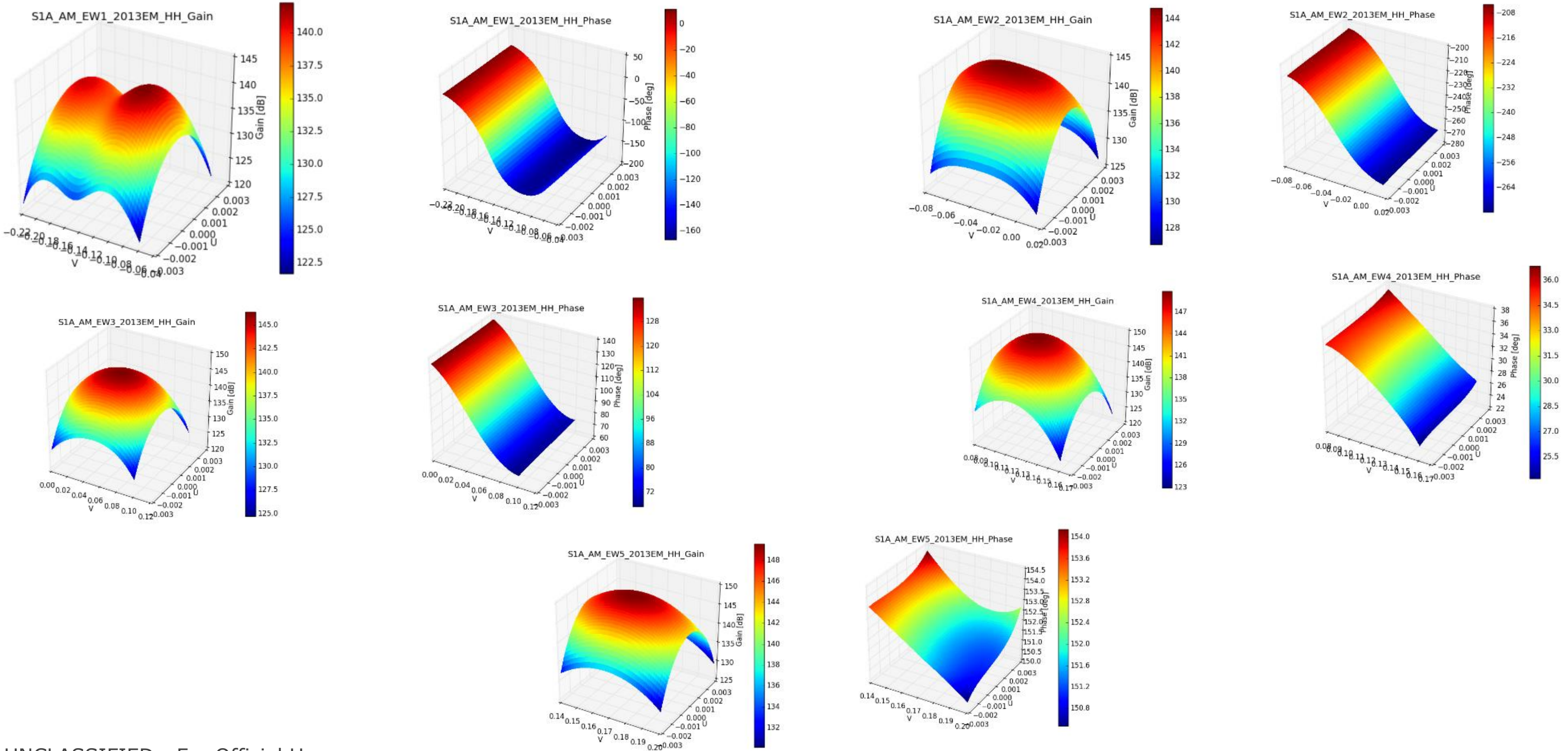




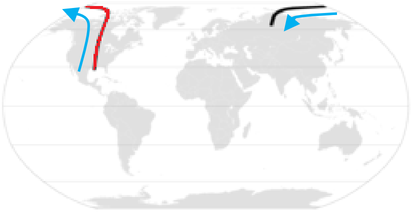




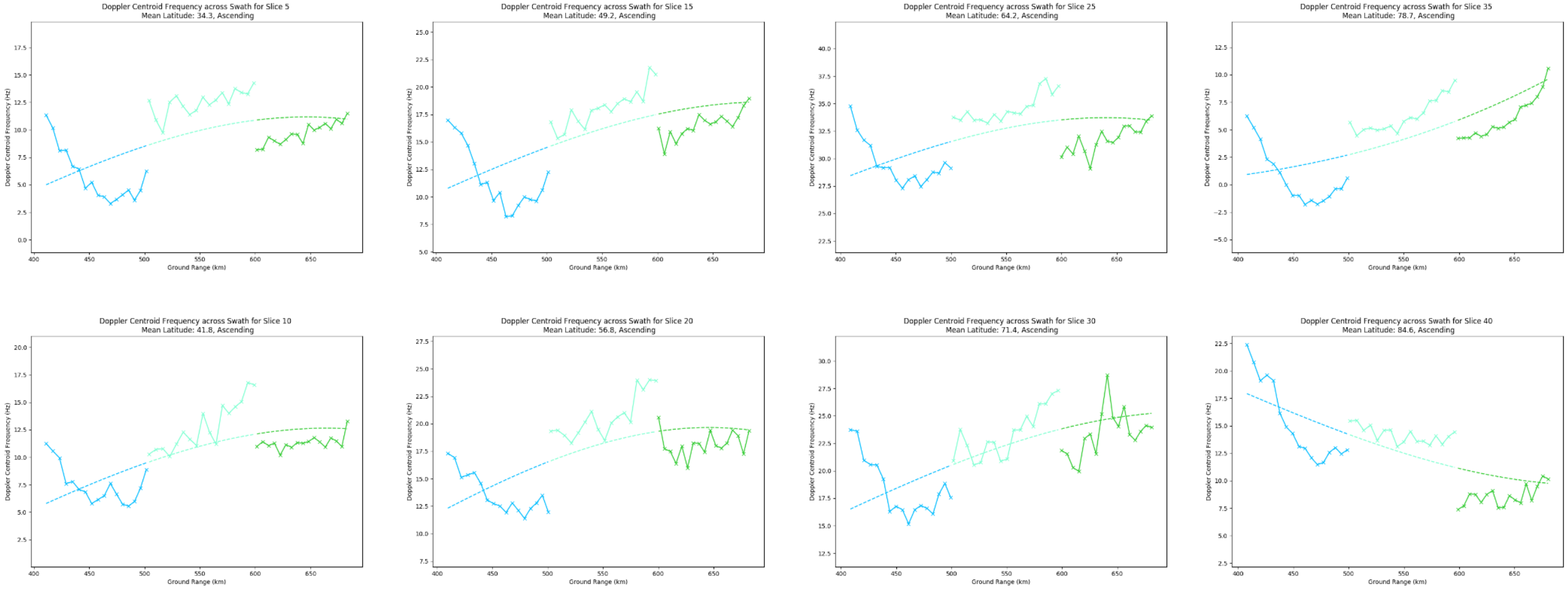
EW Antenna Model Output: Gain and Phase



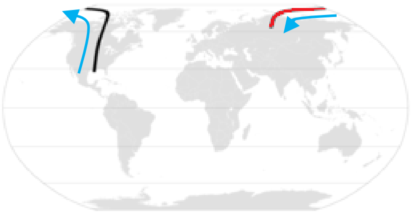
IW Mode: Doppler Centroid across Swath (ascending orbit)



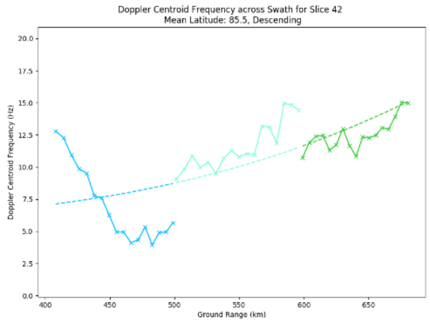
S-1B IW Acquisition over North America, 2016 09 09

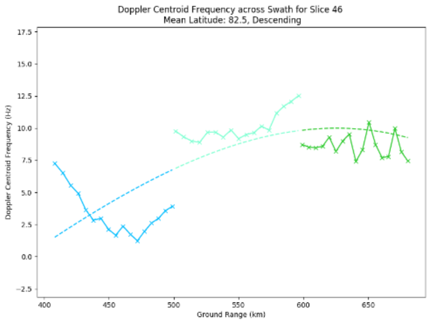


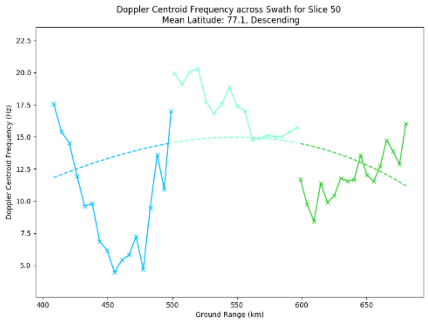
IW Mode: Doppler Centroid across Swath: (descending orbit)

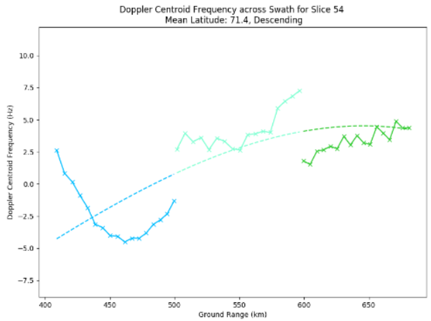


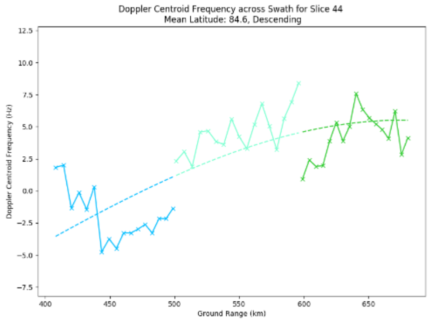
S-1B IW Acquisition over North America, 2016 09 09

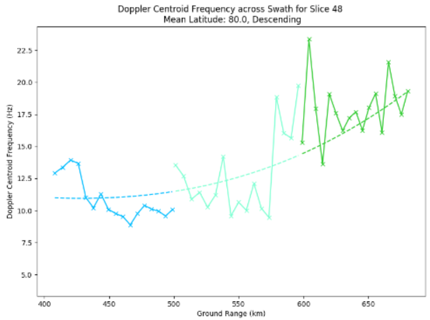


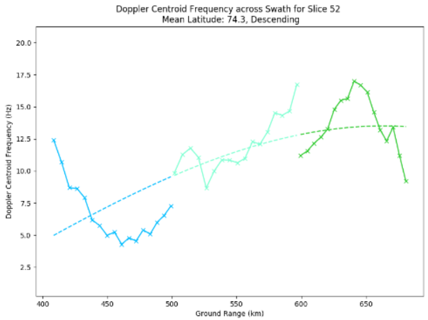


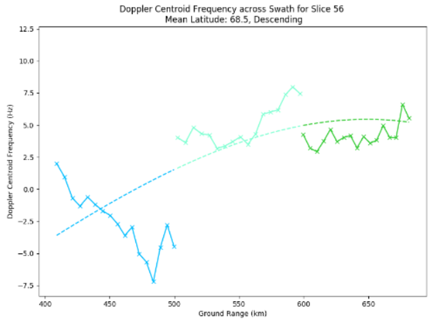




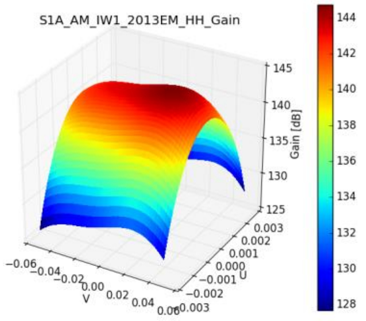


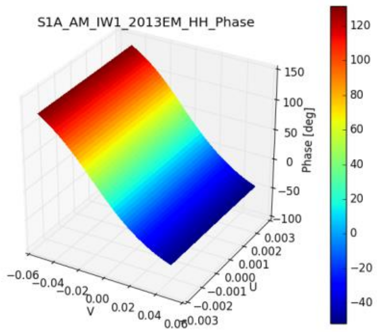


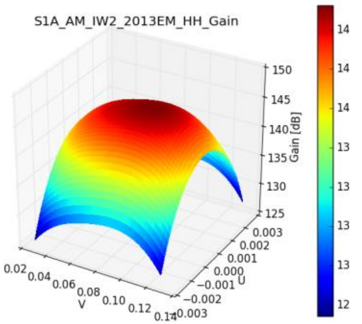


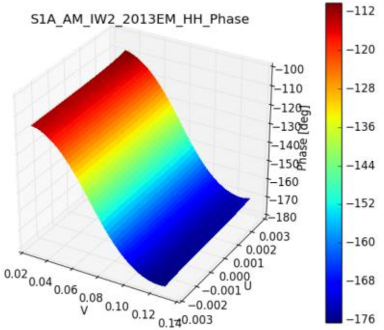


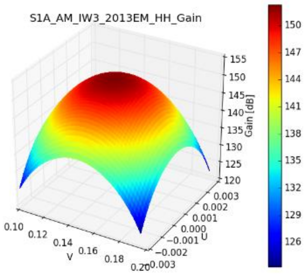
IW Antenna Model Output

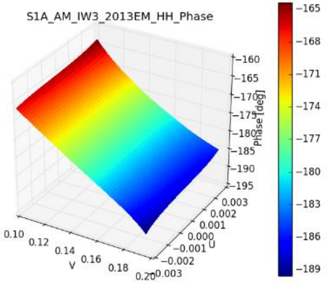




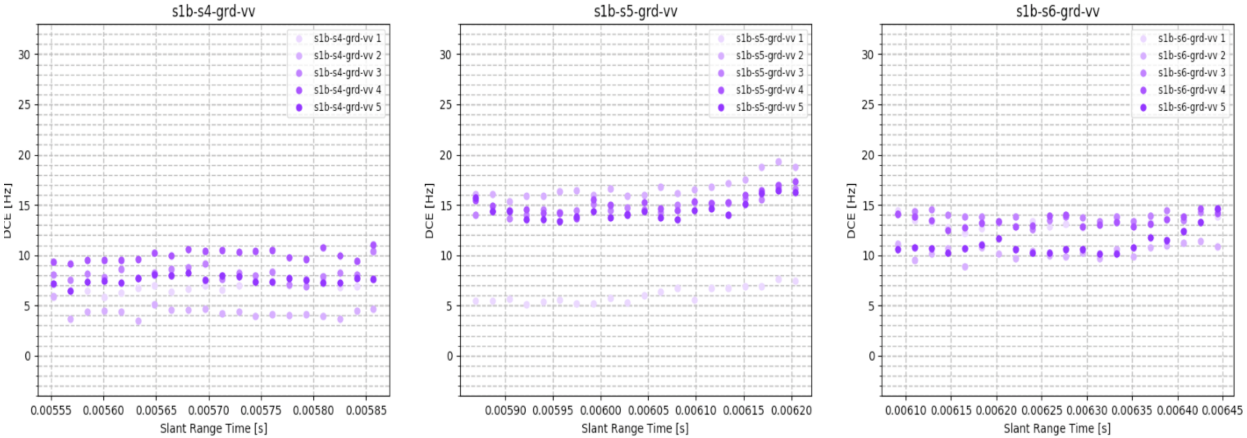


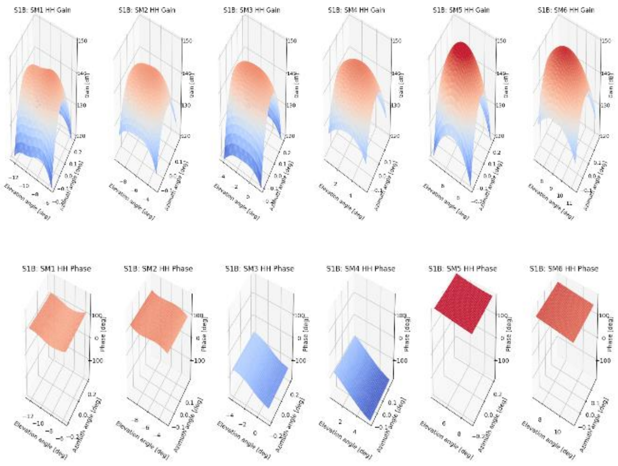






Sentinel-1B SM: Doppler Centroid Results





- DC bias and slope as expected from theory (pitch and yaw attitude)

⇒ Indicates that for IW and EW, the issues are related to TOPS and tapering of antenna pattern

S1B_S4_GRDH_1SDV_20170920T224504_20170920T224533_007481_00D352_3A12
S1B_S5_GRDH_1SDV_20170929T100405_20170929T100433_007605_00D6DC_5648
S1B_S6_GRDH_1SDV_20170922T101248_20170922T101309_007503_00D3F6_3EF1

ENVISAT ASAR ScanSAR Doppler across Swath

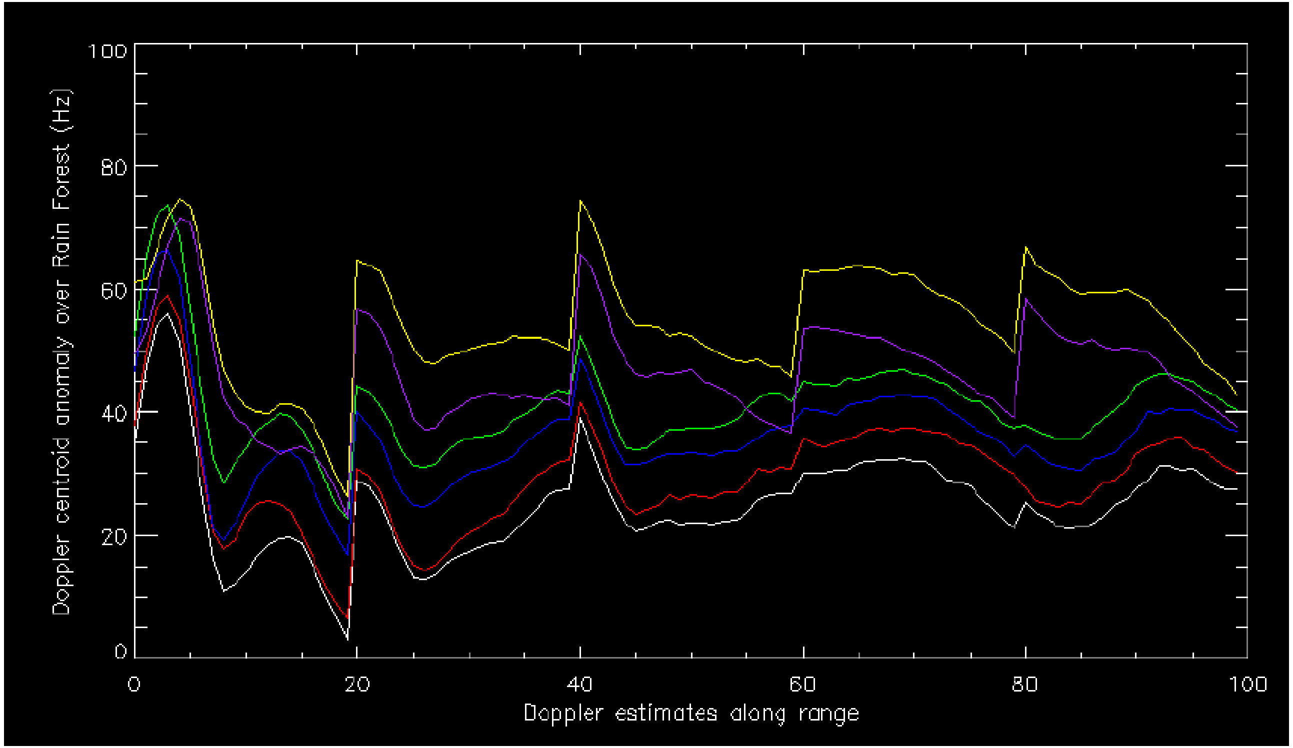
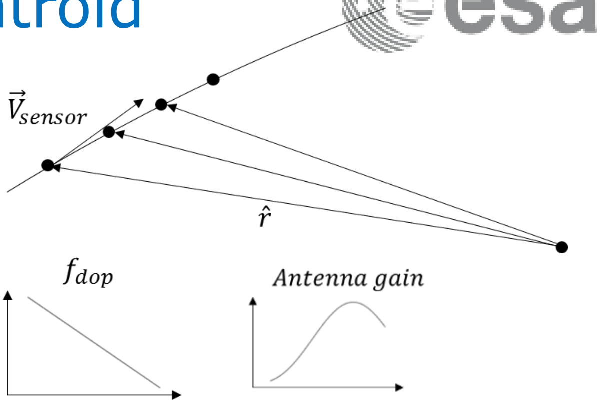
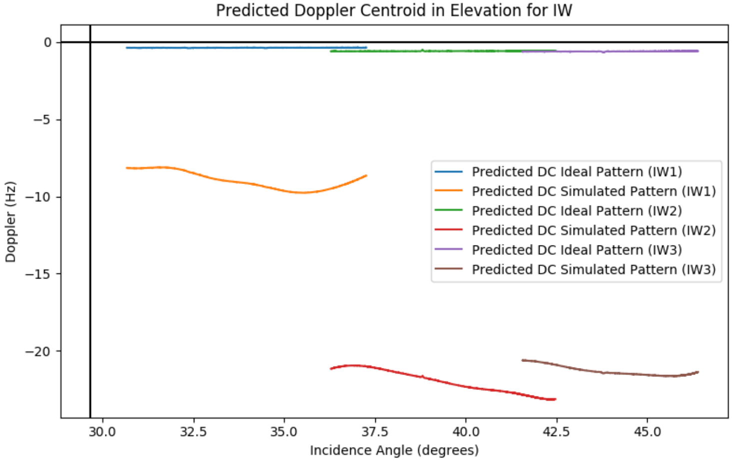


Figure courtesy of CLS

Effect of Antenna Patterns on Doppler Centroid

- Doppler prediction on a point by point basis
- Doppler bandwidth is simulated for each output grid point
- Predicted Doppler Centroid is the weighted average of Doppler bandwidth, where weighting is given by antenna patterns





- Simulation of DC assuming perfect zero-Doppler geometry (no squint)
- DC is predicted using ideal symmetric theoretical patterns and antenna patterns (simulated from AM)
- Tapering of antenna patterns causes variations across range, and biases varying between sub-swaths $\Rightarrow$ analysis on-going

Sentinel1-NG High-Level Mission Requirements 1/2

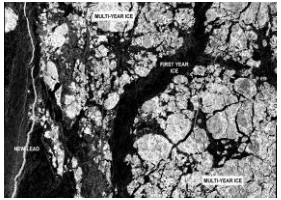
1. **Continuity of C-band data** beyond next decade (2030)

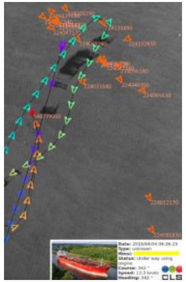
- *Ensure continuity of Copernicus services*

  ⇒ improve ***existing*** and support ***evolving*** operational applications
- *Sentinel-1NG data quality shall be equal or better than S-1/A-D*

CMEMS Copernicus Maritime Environment Monitoring
CEMS Copernicus Emergency Management Service
CLMS Copernicus Land Management Service
C3S Copernicus Climate Change Service

2. **Better spatial resolution + shorter revisit time + improved radar sensitivity + full polarisation** than currently achievable with Sentinel-1:

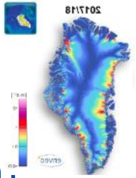




- ***Sea ice mapping*** (classification, drift monitoring, iceberg detection)

  ⇒ *twice daily coverage above 60 deg. North*
- ***Maritime surveillance*** (vessel detection) and ***Oil spill detection***

  ⇒ *once daily coverage north of + 45 deg.* (optionally +30 deg.) *and south of -45 deg.*
- ***Ice discharge*** monitoring in *Arctic/Greenland* + *Antarctic ice shelves* and glaciers

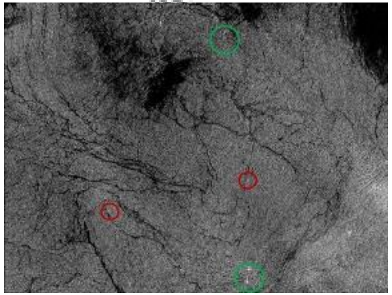


- ***Land deformation*** + ***Coherent Change Detection*** monitoring + precise *Geolocation*

  ⇒ min. *4-day repeat-pass interval for SAR Interferometry* + systematic global coverage

  ⇒ ground resolution of $25m^2$ ($150m^2$) at instantaneous coverage of 400 km (min. 600km)

Sentinel1-NG High-Level Mission Requirements 2/2



3. ***Novel*** and ***innovative*** measurement capabilities to support:

- ***Detection*** of (small) ***vessels*** under challenging sea state conditions, and accurate ***estimation*** of their ***velocity***

  ⇒ Vessel size of *min.15m length* with *90% probability* of detection and *false-alarm* of less than $2.5(10)^{-9}$

  ⇒ Vessel velocity (total) estimation accuracy of less than 2 knots (1m/s)

  using GMTI/ATI capability

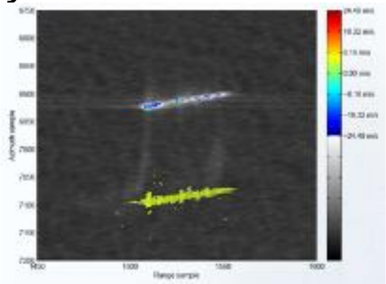


Image courtesy: Ch. Gierull, DRDC

- ***Ocean Surface Current Velocity*** estimation

  ⇒ Ocean surface current velocity at accuracy of 0.1 m/s for $500 m^2$ ground resolution cell size

using *Along-Track Interferometry (ATI)* vs. Doppler measurements

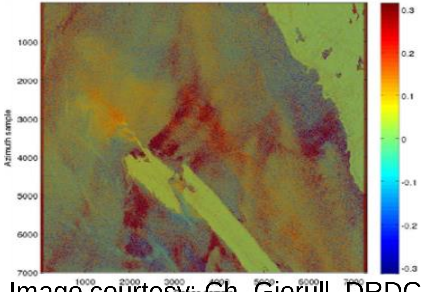
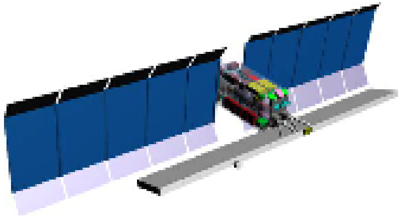


Image courtesy: Ch. Gierull, DRDC

SAR Instrument Concepts and Launcher Compatibility

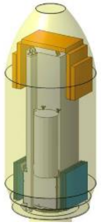
- Sentinel-1 NG multi-channel SAR system vs single-channel on Sentinel-1

Phased Array Antenna

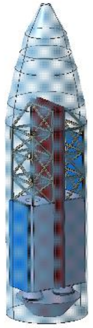


Antenna Length: 12.8m, Height: 1.2m

- Electronics design based on S-1 heritage
- Antenna technology available in Europe
- ATI for velocity estimation (vessels, ocean currents)
- High transmit power (900W) and mass (2100 – 2600) kg



Vega E



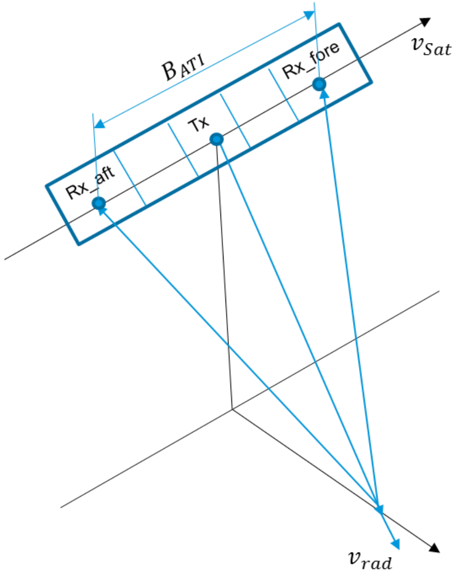
A6-2

Reflector Antenna + Hybrid Concept

Antenna: Diameter: 9m, Focal length: 9m

- Large and light antenna
- Low transmit power (300W) and mass (1500 – 2000 kg)
- Complex SAR instrument electronics
- Reflector antenna not available in Europe
- ATI capability only for Hybrid concept

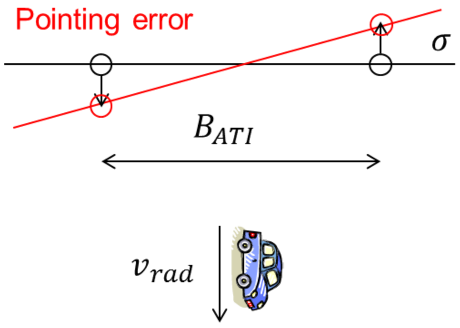
Along-Track Interferometry (ATI) Concept



$$\varphi_{ATI} = \frac{2\,\pi\,B_{ATI}}{\lambda\,v_{sat}}\frac{dR}{\tau_{ATI}} = \frac{2\,\pi\,B_{ATI}}{\lambda\,v_{sat}}\,v_{rad}$$

$$\tau_{ATI} = \frac{B_{ATI}}{2\,v_{sat}} \quad \text{for} \quad \begin{aligned} B_{ATI} &= 7.5\,m \\ \tau_{ATI} &= 0.5\,ms \end{aligned}$$

$$f_D = \frac{1}{2\pi}\frac{\varphi_{ATI}}{\tau_{ATI}} = \frac{2}{\lambda}\,v_{rad}$$



Phase offset due to pointing error resulting from additional slant range difference

- Canada's RADARSAT-2: C-band SAR system capable of collecting ATI ScanSAR data on a single space-borne platform

Conclusions

- DCA approach for estimation of *ocean surface radial velocity* requires very precise pointing knowledge of both spacecraft (attitude) and SAR beam pointing

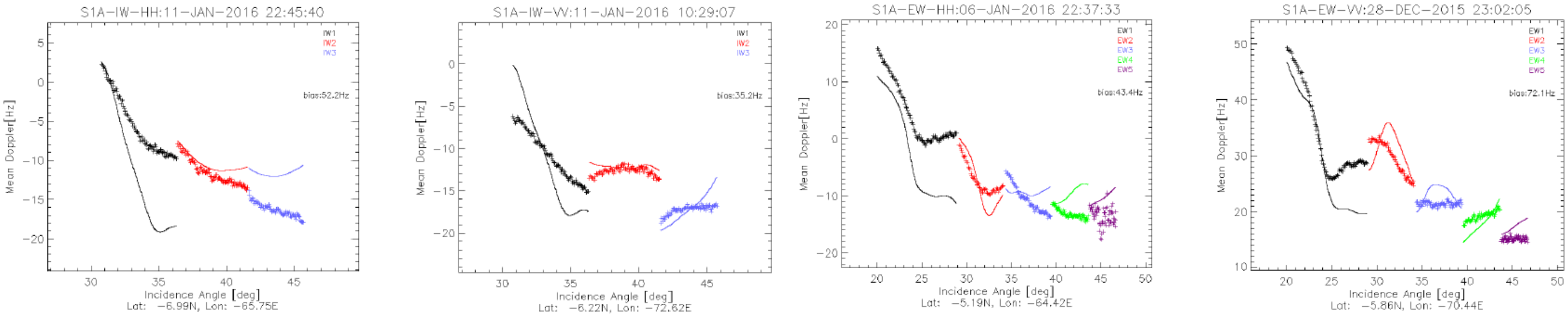
  ⇒ difficult to achieve with state-of-the-art AOCS systems (STTs)
- Estimation of DC in TOPS data requires perfect de-ramping taking into account the effective azimuth antenna steering rate (pointing) and knowledge of burst center time to avoid ramps
- Ramps in S-1 RVL products may be related to residual DC variation due to TOPS
- Tapering of antenna patterns, when projected onto the ground, seems to cause variations in DC offsets (discontinuities) and different slopes
- Simulations show that for symmetric antenna patterns there are no DC artifacts

⇒ Single platform ATI may provide alternative and/or complementary solution to DCA approach for estimation of *ocean surface radial velocity*

Backup Slides

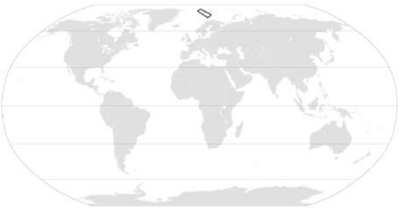
The issue with Sentinel-1 has been known and under investigation since its launch

An example of a residual effect that has been under analysis over the rainforest is the variation of Doppler as a function of range (or incidence angle)

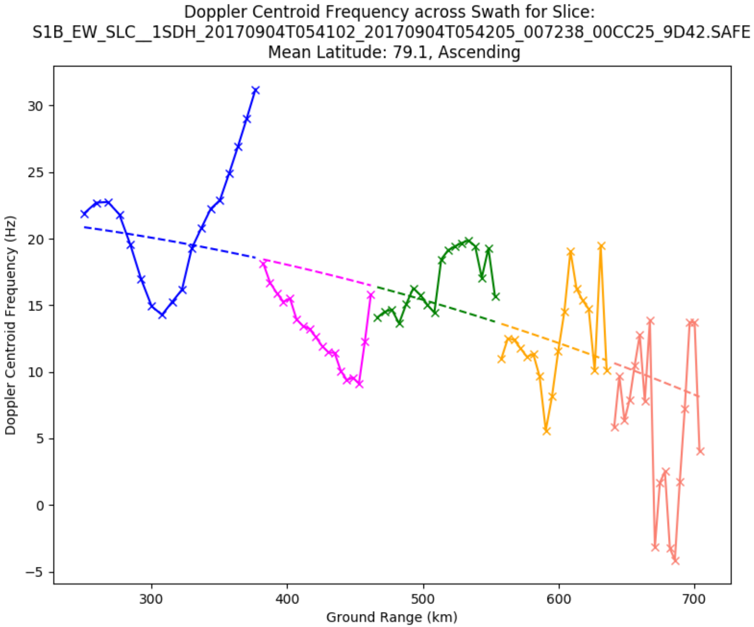


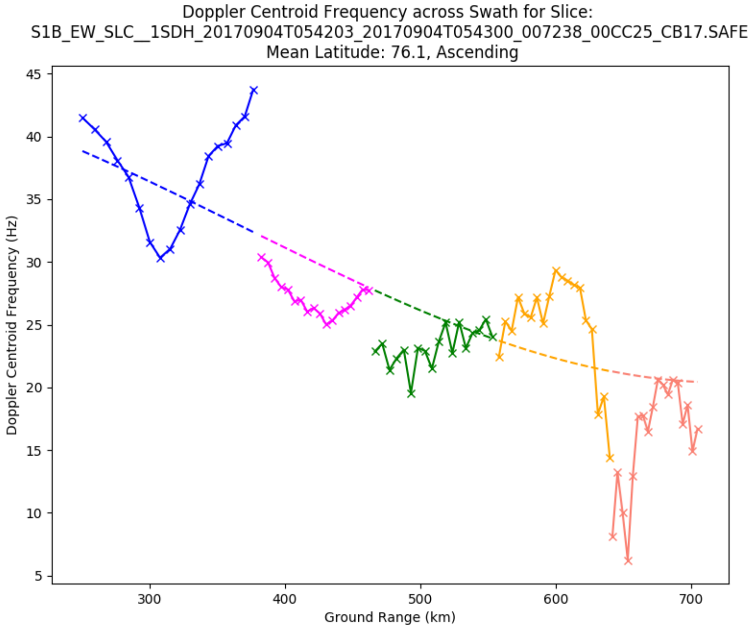
P. Meadows, "S1-A and S1-B Annual Performance Report for 2016," https://sentinels.copernicus.eu/documents/247904/2370914/Sentinel-1-Annual-Performance-Report-2016, Last Accessed December 2017.

Doppler Centroid across Swath



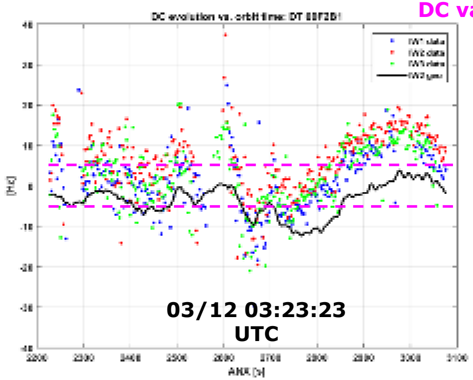
S-1B EW Acquisition over Svalbard, 2017 09 04

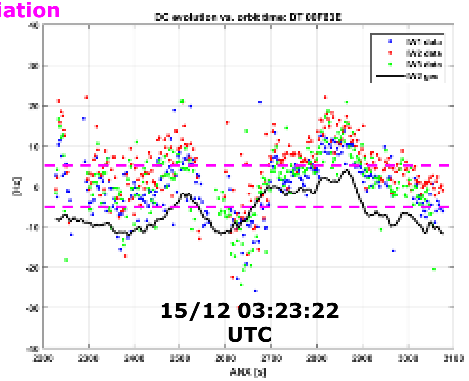


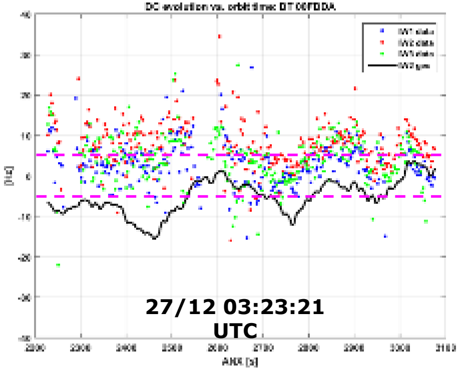


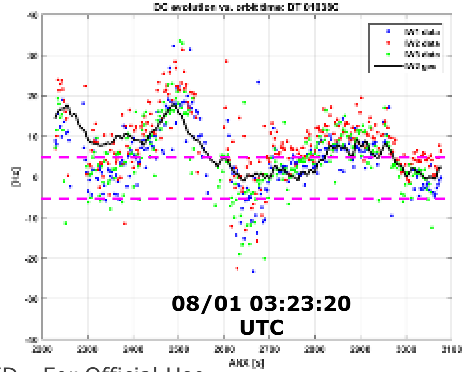
RESATT files example: Middle East/Africa

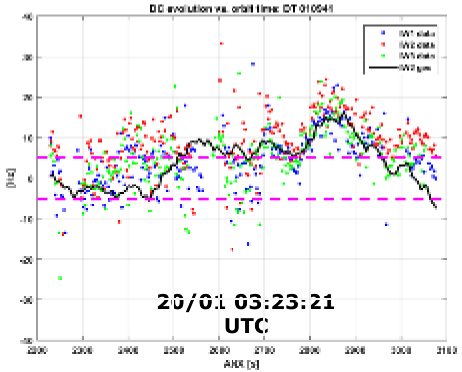
Typical GEO DC variation





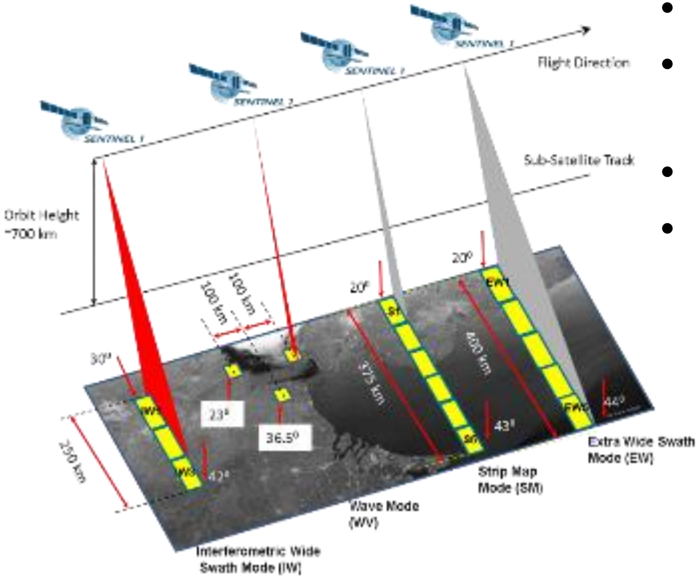






Sentine-1 SAR Imaging Modes

• SAR Instrument provides *4 exclusive SAR modes* with different resolution and coverage



- *Interferometric Wide Swath (IW) mode* for land & coastal area
- *Extra Wide Swath* (EW) mode for sea-ice monitoring and maritime surveillance
- *StripMap* (SM) for volcanic islands and emergency situations
- *Wave (WV)* mode is continuously operated over open ocean

Mode	Incidence Angle	Single Look Resolution	Swath Width	Polarisation
Interferometric Wide Swath (IW 1-3)	30-42 deg.	Range 5 m Azimuth 20 m	250 km	HH+HV or VV+VH
Wave mode WV1 WV2	23 deg. 36.5 deg.	Range 5 m Azimuth 5 m	20 x 20 km Vignettes at 100 km intervals	HH or VV
Strip Map S1-S6	20-43 deg.	Range 5 m Azimuth 5 m	80 km	HH+HV or VV+VH
Extra Wide Swath (EW 1-5)	20-44 deg.	Range 20 m Azimuth 40 m	400 km	HH+HV or VV+VH

- SAR duty cycle per orbit: up to *25 min* in any imaging mode + up to *74 min* in Wave mode