VH-Roda and CEOS SAR Workshop 2019

Towards Operational SAR Imaging Geodesy: An Extended Time Annotation Dataset for Sentinel-1 Image Products

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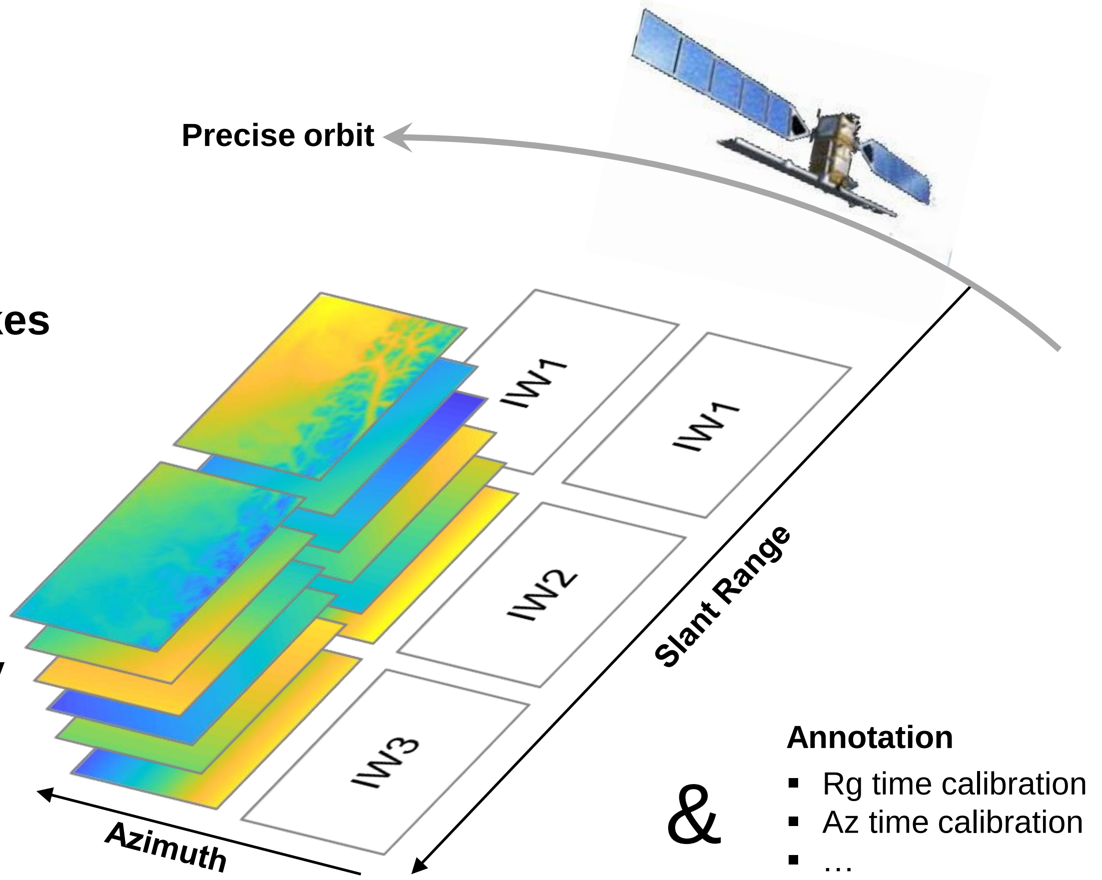
Motivation for ETAD: Extended Time Annotation Dataset for Sentinel-1

- SAR achieves very high geolocation accuracy at the centimetre level when applying geodetic corrections
- ESA has commissioned DLR to develop a geodetic SAR product for S-1 to make this accessible to users
- **ETAD product key features**
  - Support for **all Sentinel-1 SM & IW data takes** (EW desirable)
  - Fully **applicable to** SM & IW **SLC products**
  - Includes the Sentinel-1 **precise orbit solution**
  - User-friendly products with full **coverage of Sentinel-1 data takes**
  - **Burst-wise** grouping of **gridded corrections** for direct usage
  - Regularly sampled **grids in slant range and azimuth** (~200m)
  - **NetCDF4/HDF5 data format** distributed as SAFE containers
- **Demand for a highly efficient processor at S-1 PDGS**
  - Robust and accurate **methods supporting global applicability**
  - Reliable **background data with timely availability**
  - **High throughput** to keep up with Sentinel-1 data acquisition

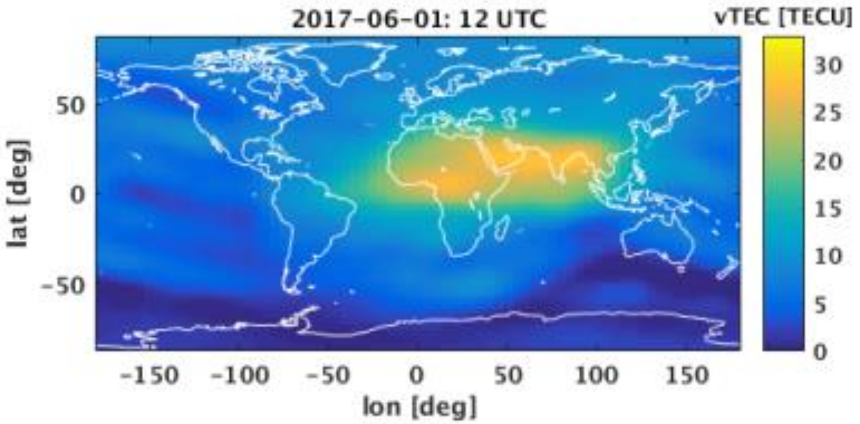


Ionospheric Delay and Solid Earth Tides Corrections

- Implementation of geodetic techniques to model the ionospheric delay and the solid Earth tidal deformations

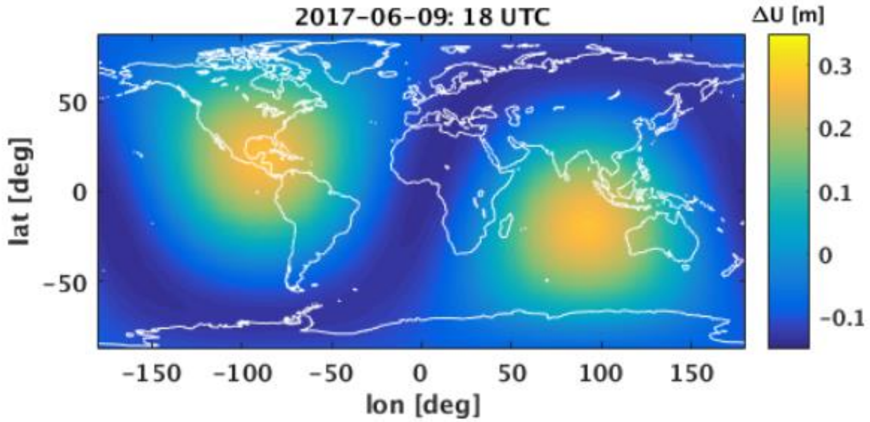
Ionosphere: products by IGS Analysis Centers[1]

- Vertical Total Electron Content (TEC) maps
- Based on global geodetic GNSS network
- Daily solutions: 5° x 2.5° x 1h → stack of 25 maps
- 1 TECU = 10^{16} electrons per m^2
- About 2 cm per TECU in C-Band slant range



Solid Earth tides: conventional model of IERS[2]

- Deformation of Earth's crust by gravitational force of Sun & Moon
- Vertical and horizontal displacements: ± 25 cm / ± 6 cm
- Full IERS model implementation sensitive to 1mm signals
- Mapping to SAR slant range & azimuth



[1] Hernández-Pajares et al. 2009, *The IGS VTEC maps: a reliable source of ionospheric information since 1998,* J. Geod.
[2] Petit and Luzum (eds.) 2010, IERS Conventions 2010, Online: www.iers.org

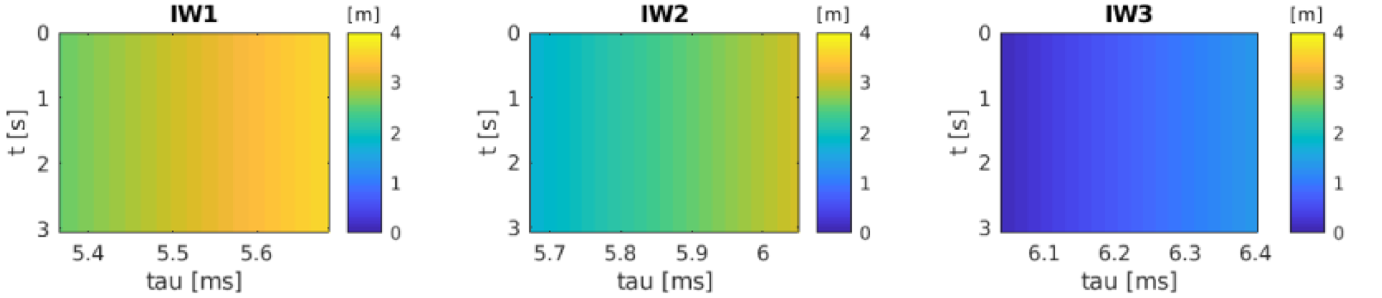
Sentinel-1 SAR System Corrections[1,2]

- Systematic effects due to the Sentinel-1 SAR IPF that cause deviations from the zero Doppler convention

  - **Bistatic Az Correction**

    $$t_{IPF} + \boxed{\frac{\tau_{mid,IW2}}{2} + \frac{\tau}{2} - \tau_0}$$

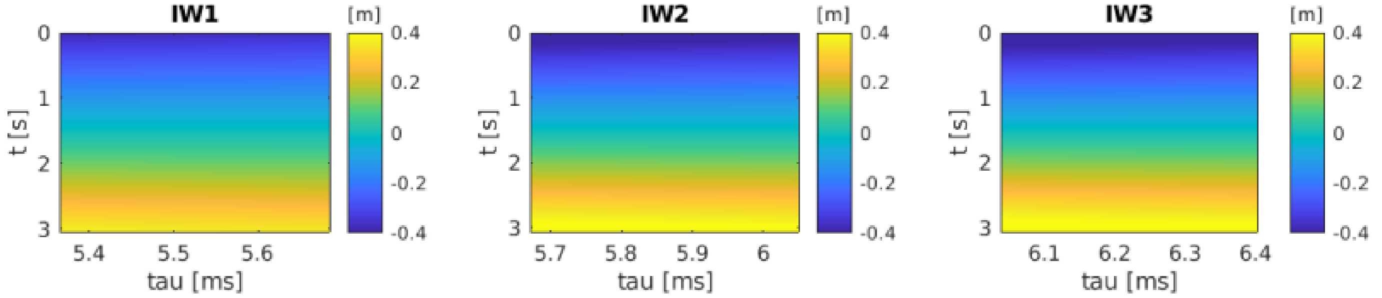
    τ_0 ... rank · PRI



  - **Doppler Shift Rg Correction**

    $$\tau_{IPF} + \boxed{\frac{f_{DC}(\tau, t)}{K_r}}$$

    f_{DC} ... Doppler Centroid with TOPS beam steering
    K_r ... FM-rate of range chirp



  - **FM-rate Mismatch Az Correction**

    $$t_{IPF} - \boxed{f_{DC} \cdot \left(\frac{1}{-k_{a_{geo}}} - \frac{1}{-k_{a_{IPF}}}\right)}$$

    k_a ... Doppler azimuth FM-rate

    ⇨ Depends on f_{DC} and **true terrain height vs. IPF modelled height** → **up to 1m at burst border**

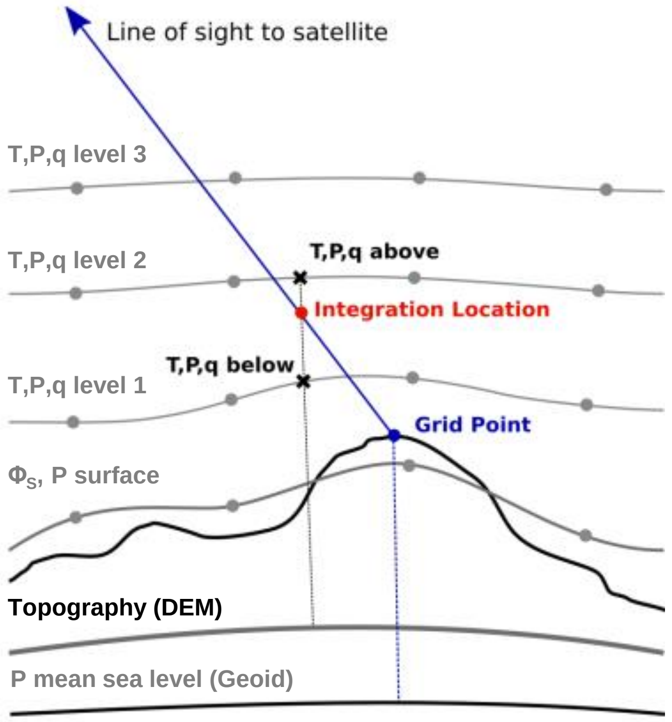
[1] Gisinger et al. 2018, *Recent Findings on the Sentinel-1 Geolocation Accuracy using the Australian CR Array,* Proc. IGARSS18
[2] Piantanida et al. 2018, *Accurate Geometric Calibration of Sentinel-1 Data*, Proc. EUSAR 2018

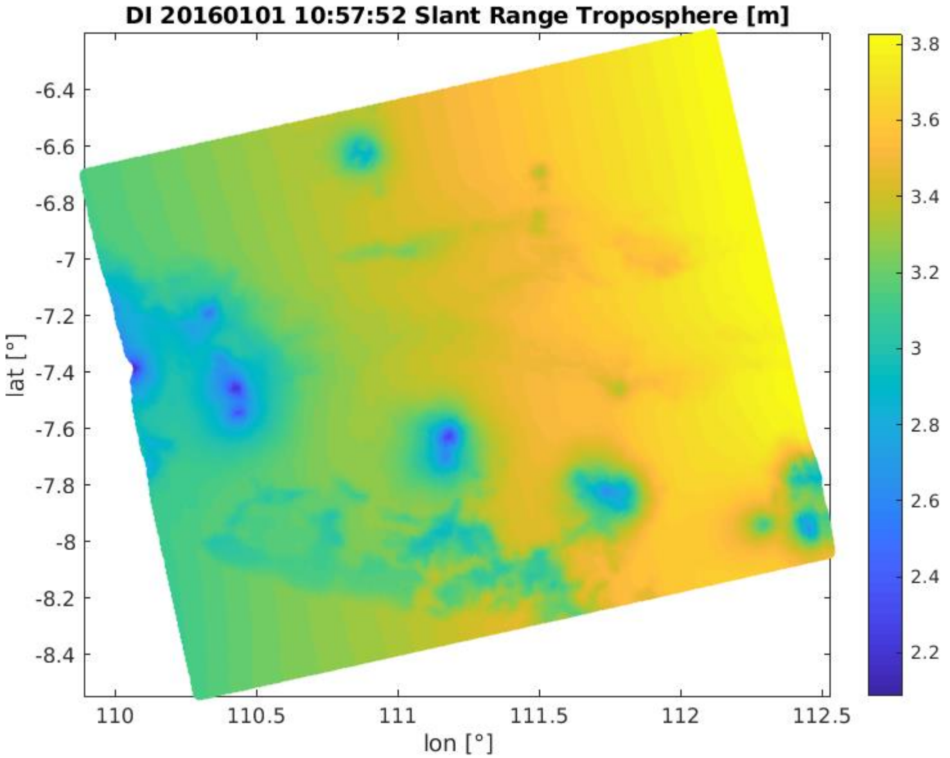
Tropospheric Delay: Direct Integration of ECMWF NWP Data[1]

- Numerical approximation of the LOS-integration of the refractive index derived from Operational ECMWF model

$$SPD = 10^{-6} \sum_n \underbrace{\left(k_1 \frac{p_n}{T_n} + k_2' \frac{e_n}{T_n} + k_3 \frac{e_n}{T_n^2} \right)}_{\text{Refractivity N (lat,lon,h,t)}} \Delta R \quad \text{for} \quad n \mid z_{obj} \leq z_n \leq z_{ML_{highest}}$$

- Challenge is 4D interpolation of *N* from ECMWF along the slant path:
  - Physical linkage of temperature, pressure, and specific humidity
  - Non linearity with height
  - Potential based heights levels → Geoid
- Computationally expensive





Island of Java: S1 IW Slice sampled at 200m (1 Mio. points)

→ computation time of 20 minutes

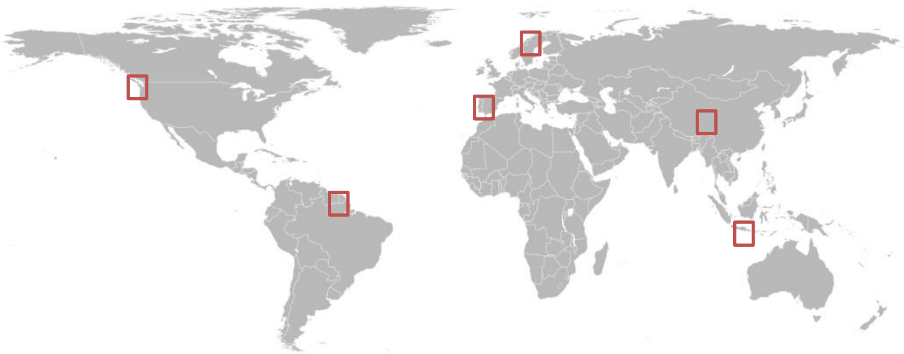
[1] Cong et al. 2018, *Mitigation of Tropospheric Delay in SAR and InSAR Using NWP Data*, Remote Sensing

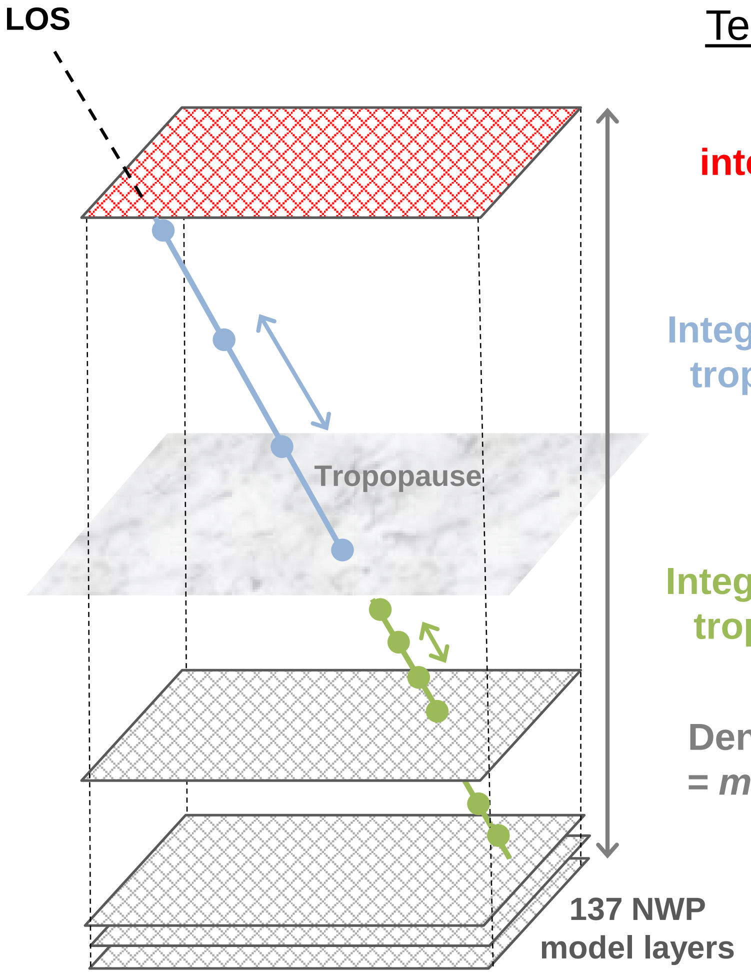
Sensitivity Analysis of Path Delay Integration

- Impact of configurable parameters on tropospheric path delay integration results

Test conditions:

- 28 S-1 datasets (Java, French Guiana, Spain, China, Norway, Canada)
- 1 Slice = 1 Mio grid points each test case
- H/W: 32 cores a 3.3 GHz & CentOS Linux
- Statistics of path delay differences: **custom. configuration vs. default**





Tested parameters:

Horizontal pre-interpolation of NWP layers *i = 50x*

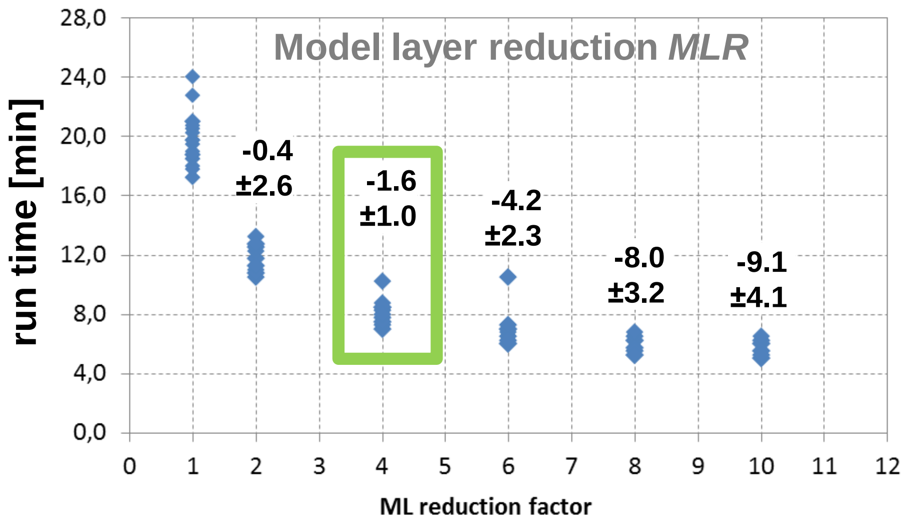
Integration interval above tropopause *int2 =100m*

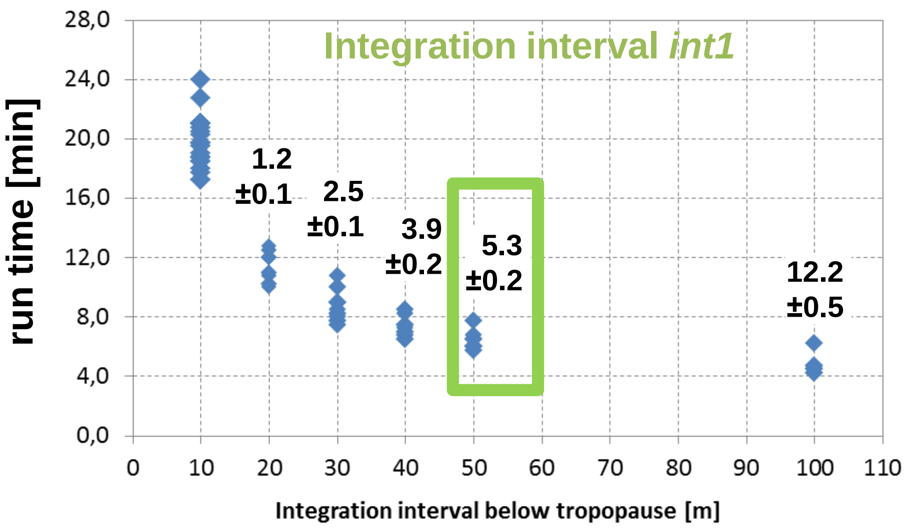
Integration interval below tropopause *int1 = 10m*

Density of model layers = *model layer reduction factor MLR = 1*

Results of Path Delay Sensitivity Analysis

- Average mean and standard deviation **in millimeters** across the 28 cases: optimized – default configuration





Horizontal pre-interpolation *i*

50x default vs. 10x:

19:79 min vs. 18:50 min

with impact of

-0.1 ± 0.6 mm

Integration interval *int2*

No significant speed-up of execution

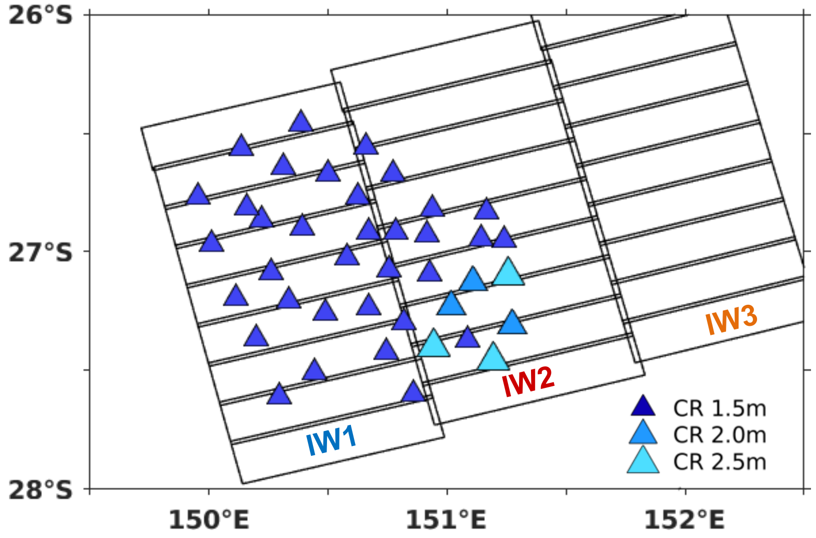
- Combination of all tunable parameters: changes with respect to default

MLR = 4, int1 = 50 m, int2 = 100 m			
Horizontal interpolation i	**Average mean**	**Average STD**	**Avg. execution time**
10 x	3.4 mm	±3.9 mm	**2.69 min**

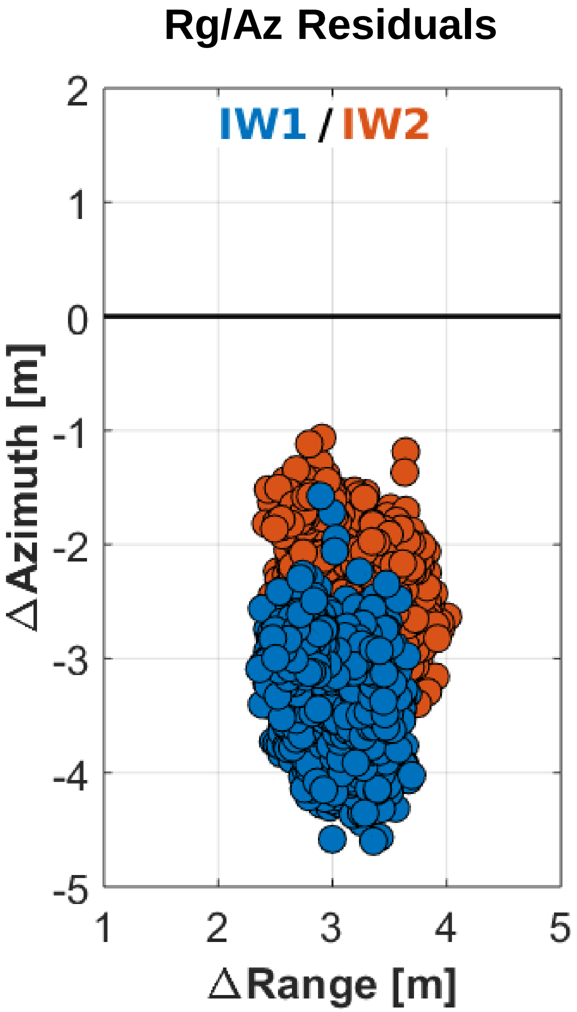
⇨ ***Our basis for further code optimizations***

Data Quality Preview: S1B Geolocation at Australian CR Array

- Australian CR array with 40 CRs
  - 79 S1B IW datatakes from orbit 111
  - Period: 10/2016 – 10/2019
  - S-1 precise orbit product
  - Accurate ITRF CR coordinates
- Geolocation quality of Rg & Az
  - **Default product**



	Rg [m]	**Az** [m]
Default	**3.118 ± 0.305**	**-2.916 ± 0.652**



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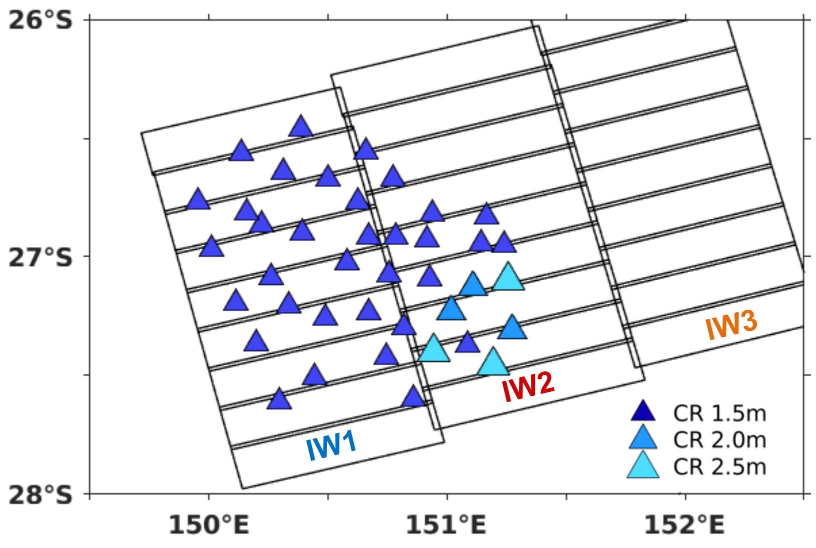
  - **Tropospheric delays (VMF3)[1]**



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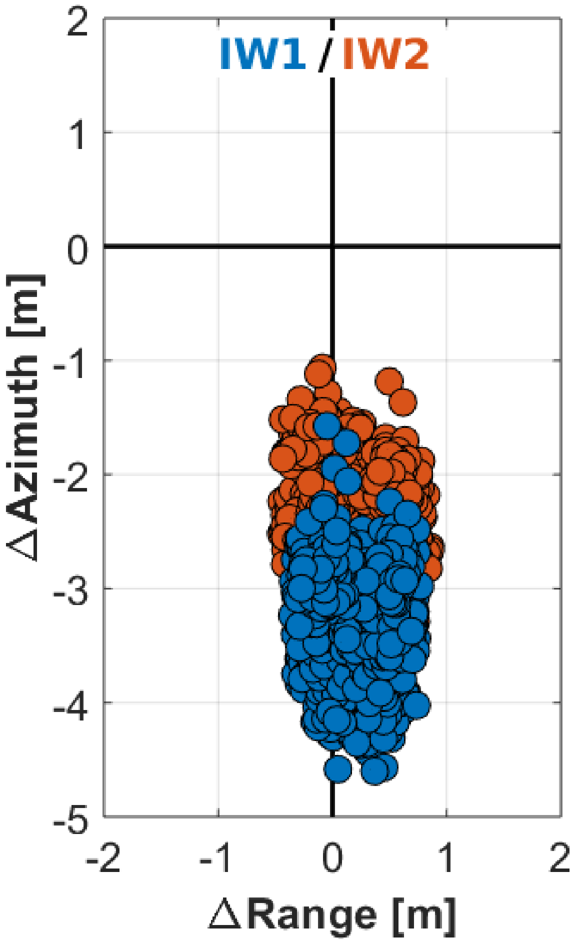
Rg/Az Residuals



[1] Landskron and Böhm 2017, *VMF3/GPT3: refined discrete and empirical troposphere mapping functions*, J. Geod.

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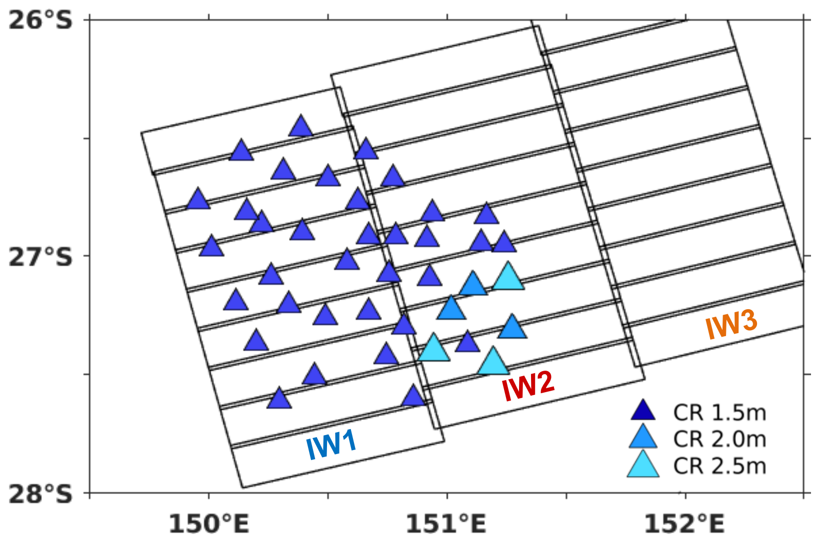

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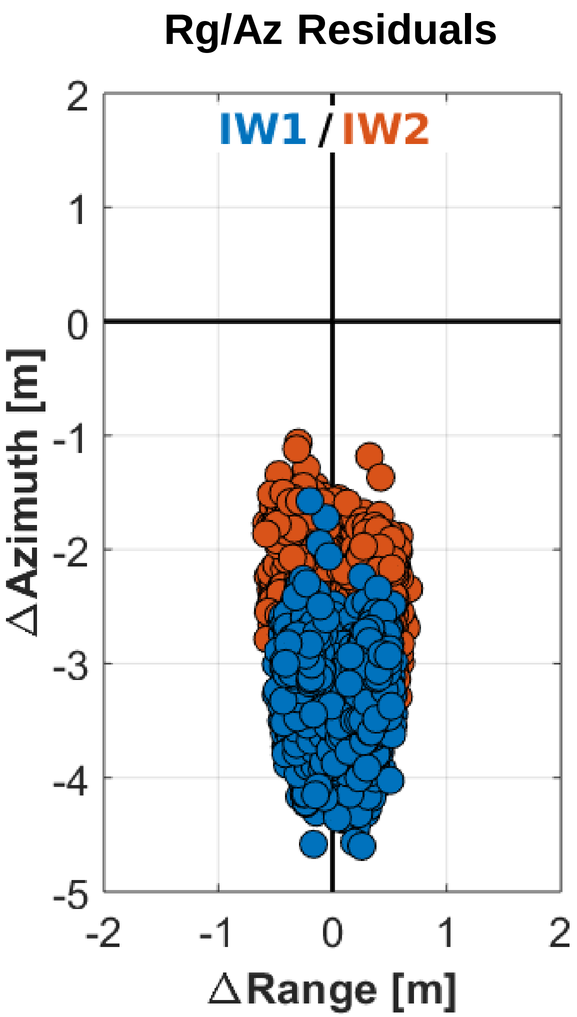

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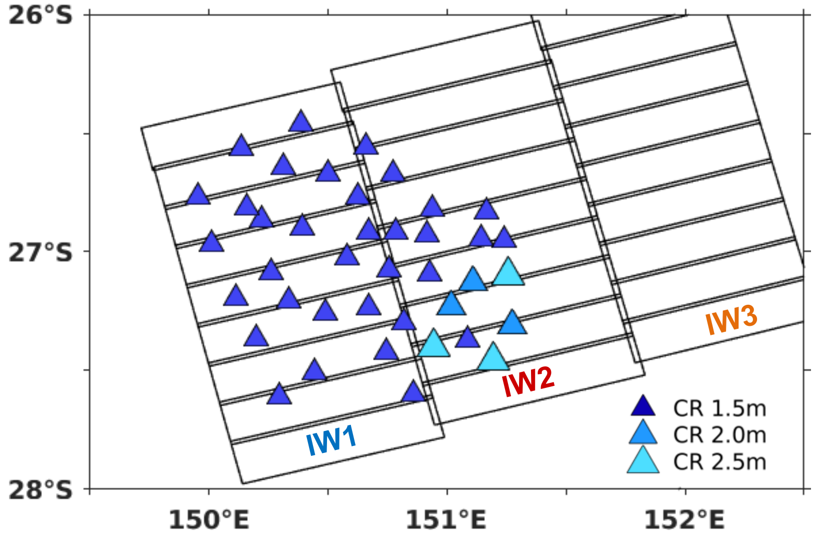

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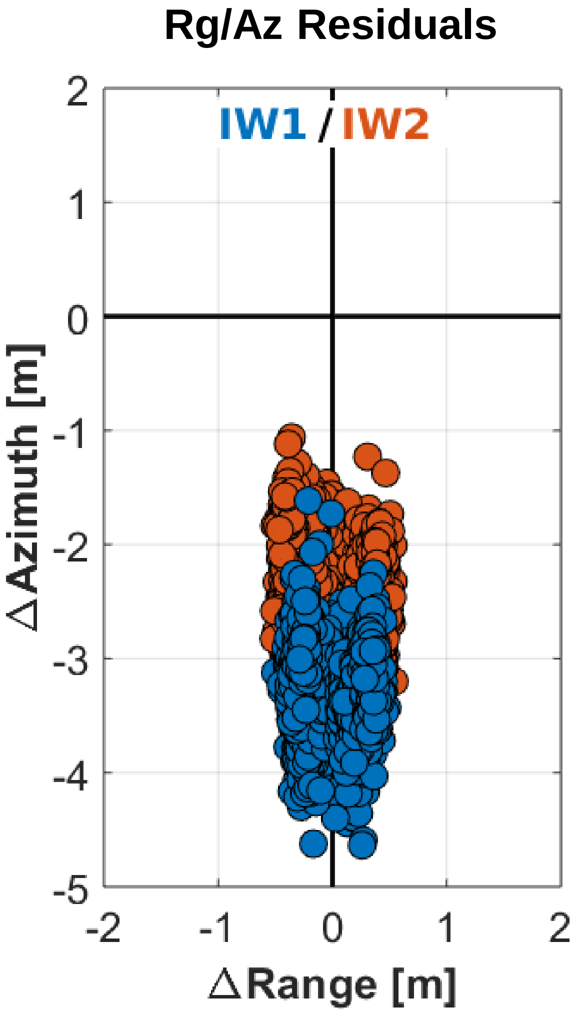

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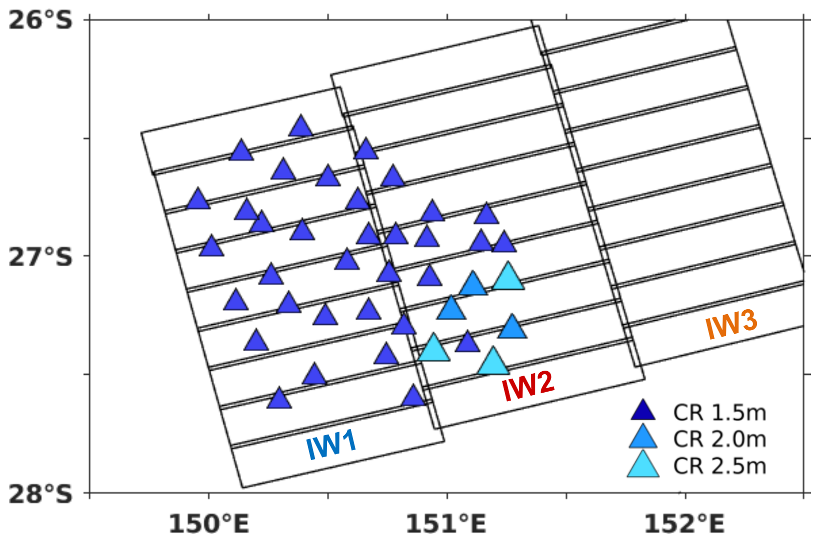

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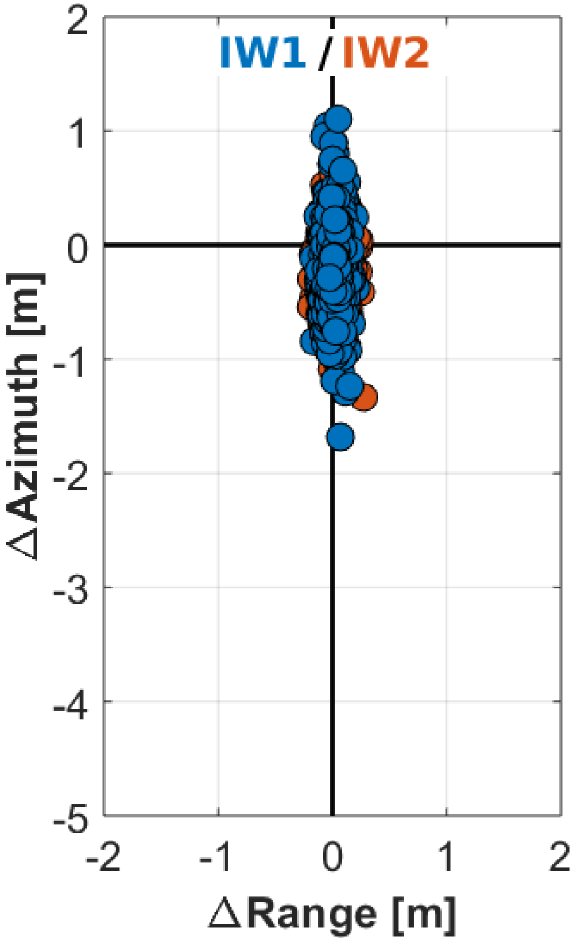

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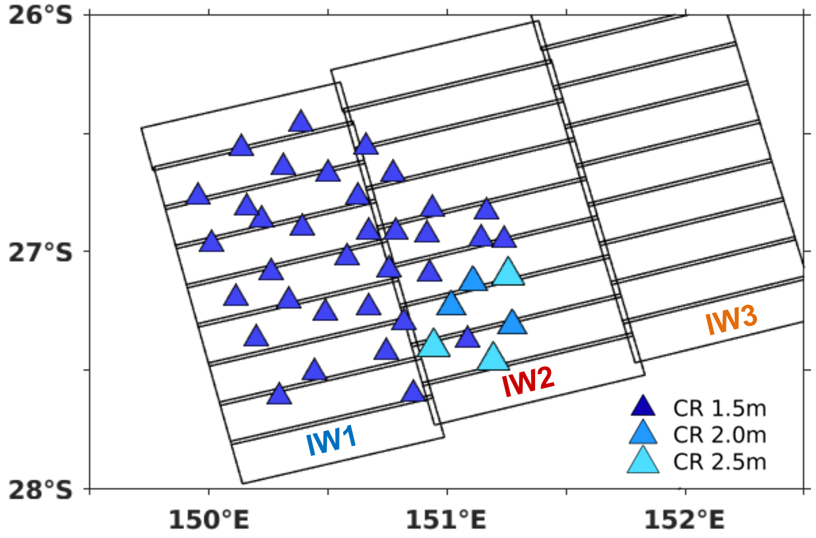

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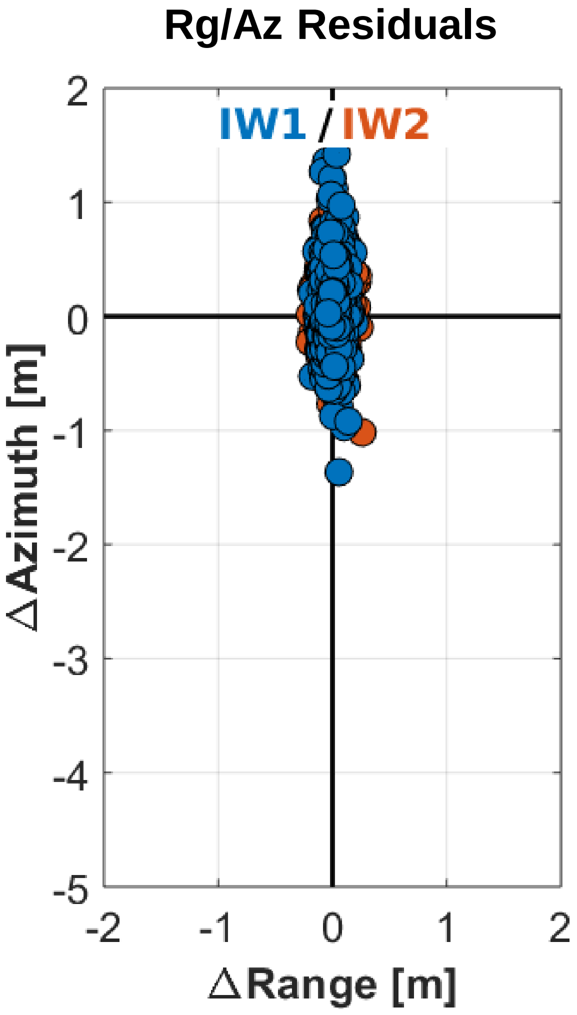

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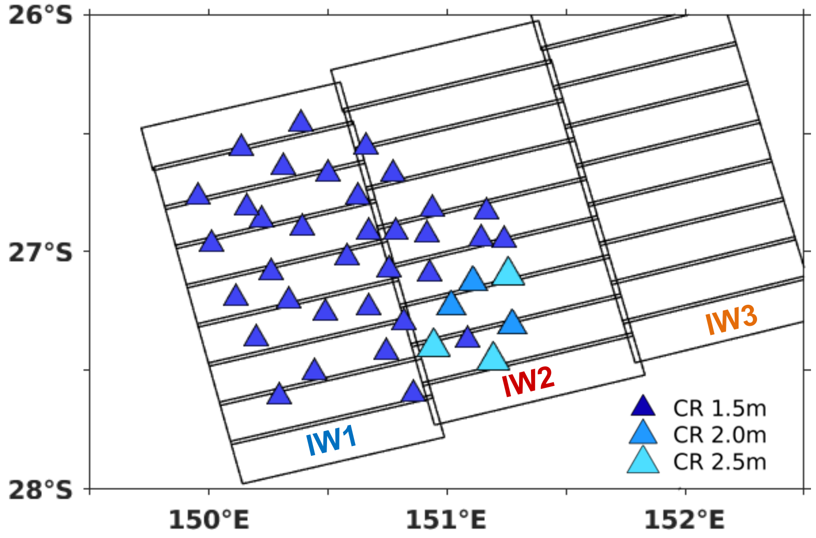

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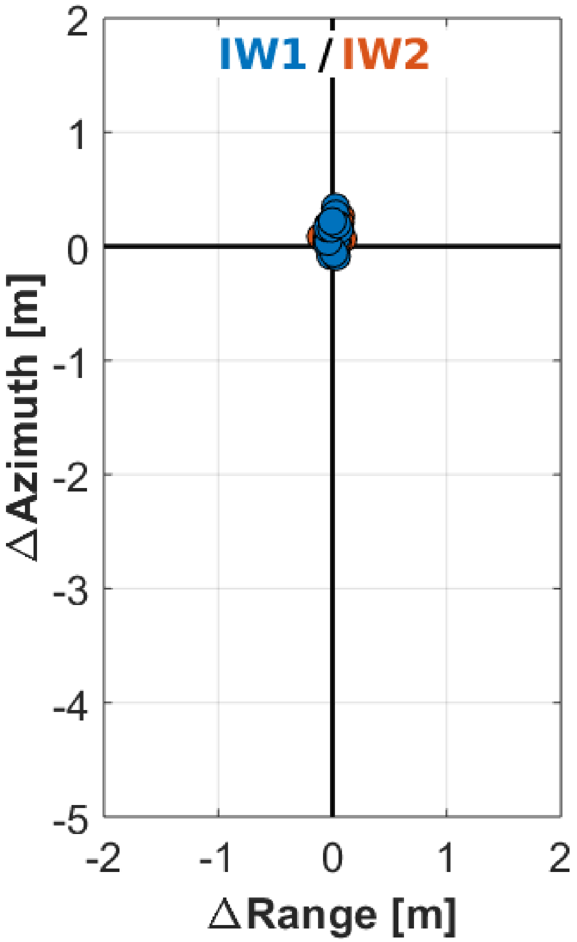

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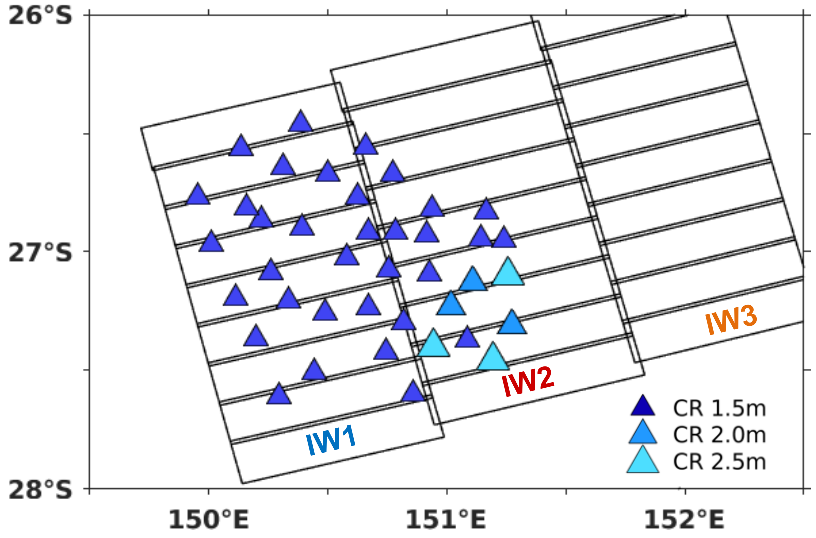

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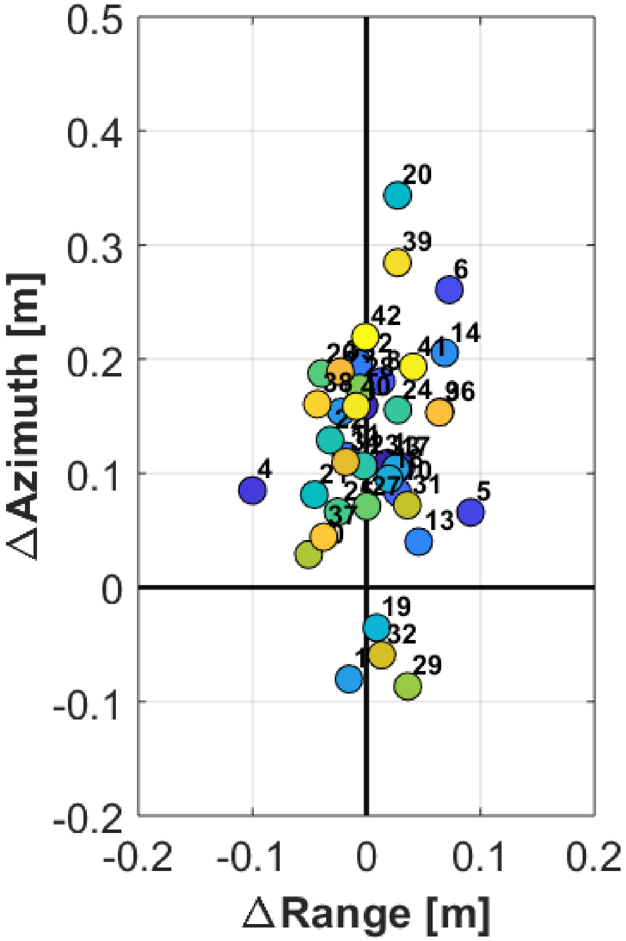

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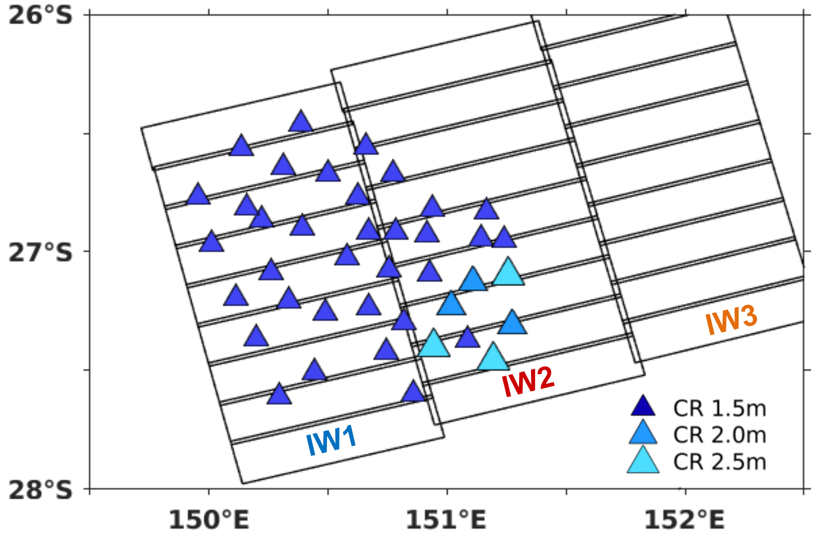
- **CRs updated ITRF coordinates**



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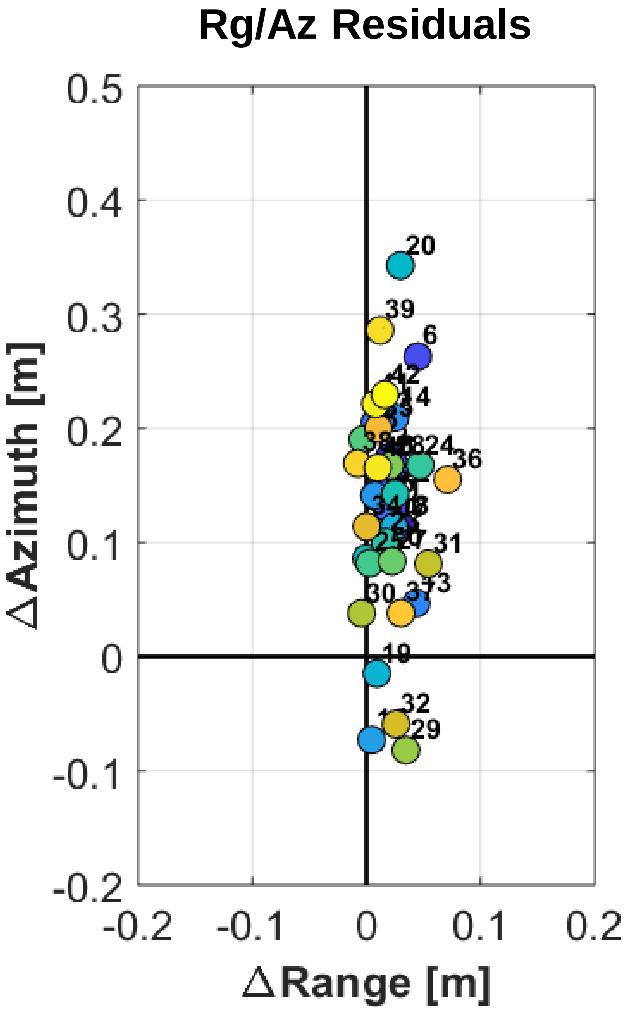
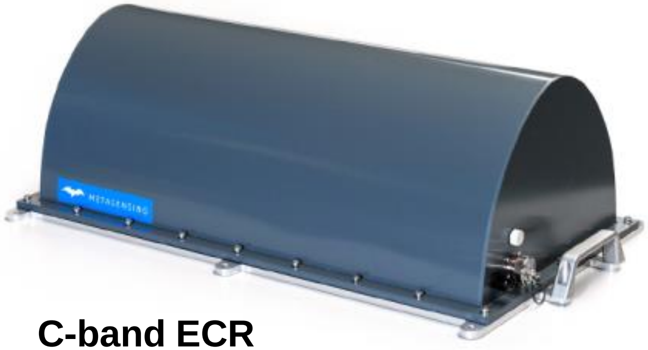
+ Cal&CRs	**0.020 ± 0.043**	**0.131 ± 0.247**

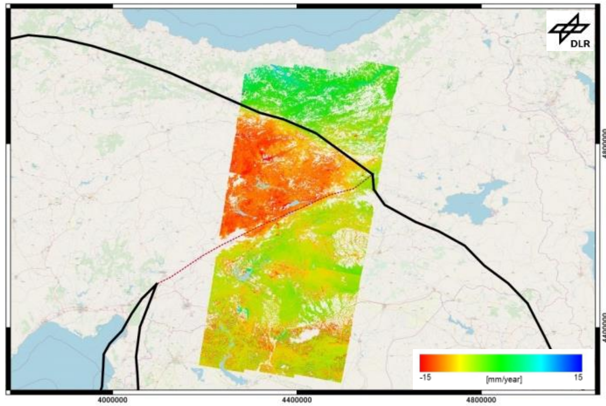


Conclusions

- Extended Time Annotation Dataset that will unlock full potential of Sentinel-1 geolocation capabilities
- Geodetic techniques to compute the corrections for:
  - Tropospheric & Ionospheric path delays
  - Solid Earth tidal deformations
  - Sentinel-1 systematic effects
- In-depth study of tropospheric computation revealed tuneable parameters
- ETAD product with an accuracy of better than 20 cm (rg) and 10 cm (az) for new imaging geodesy applications



C-band ECR



Possibility of phase correction

See e.g. talk of Ansari et al., A Proposal for Interferometric Time Series Product […]

Acknowledgement

- Funded by the EU Commission's Copernicus Programme through the ESA contract 4000126567/19/I-BG
- We thank ESA for supporting this activity
- Disclaimer:

"The views expressed herein can in no way be taken to reflect the official opinion the European Space Agency or the European Union"

Copernicus
Europe's eyes on Earth

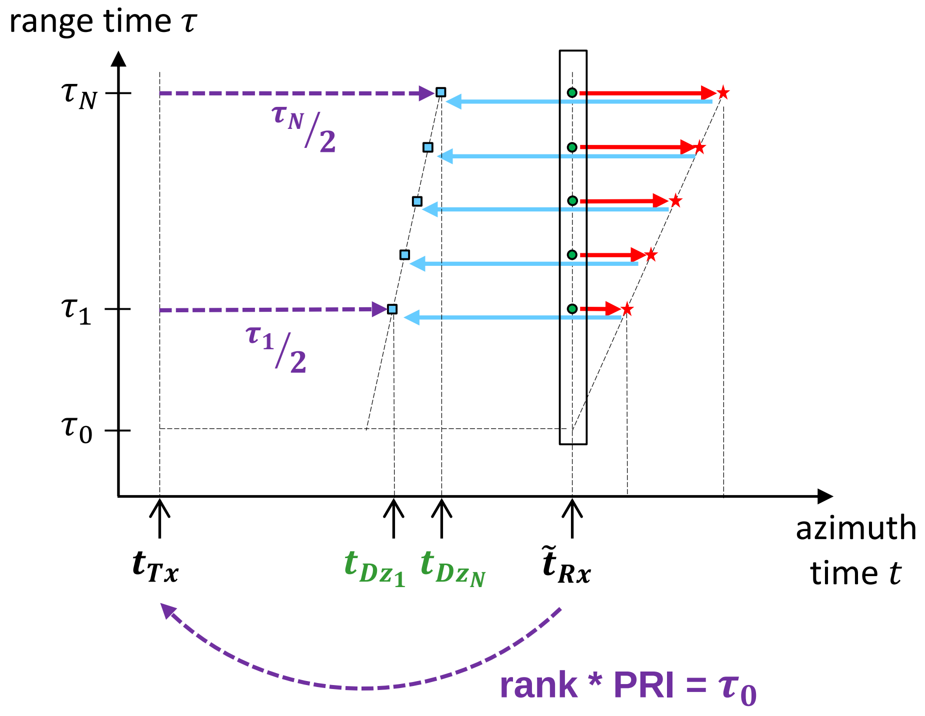
DLR esa

Sentinel-1 Bistatic Azimuth Correction

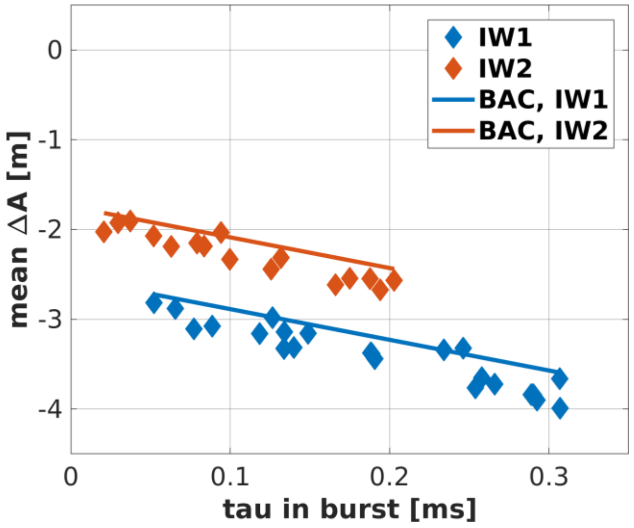
- Remove the IPF bulk contribution and apply the total bistatic azimuth correction

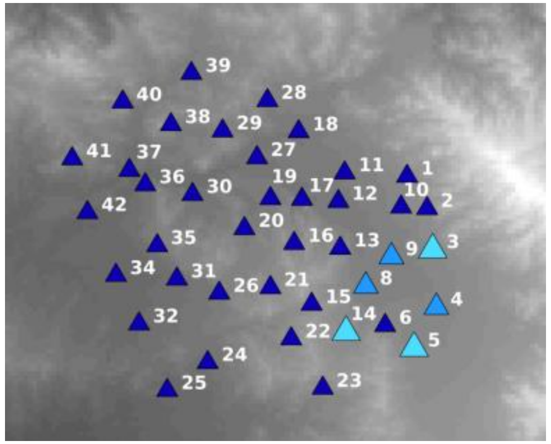
$$t_{Doppler-zero} = \tilde{t}_{Rx} - \frac{\tau_{mid,IW2}}{2} + \boxed{\frac{\tau_{mid,IW2}}{2} + \frac{\tau}{2} - \tau_0}$$

S-1 specific bistatic azimuth correction



Sentinel-1B: ΔAzimuth vs. τ



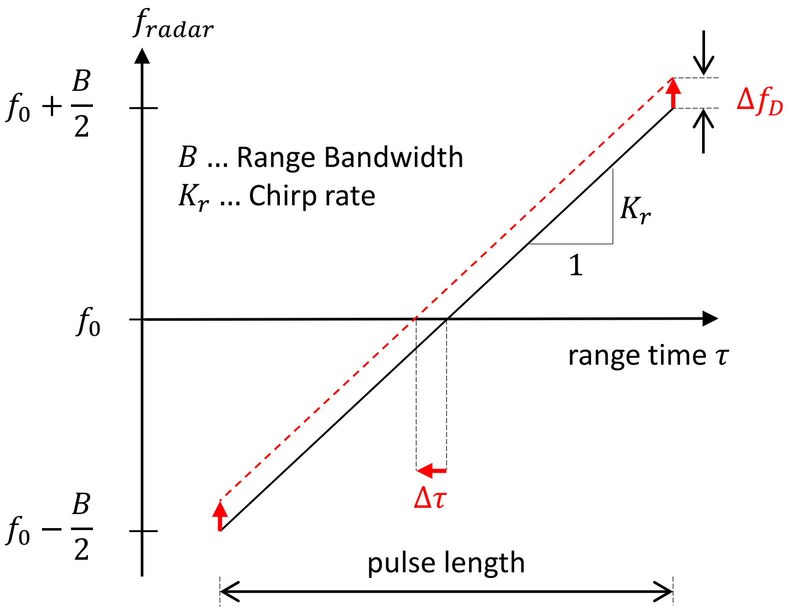


– “Bulk correction” is not a correction!

– Echo window start and PRI adaption lead to staggered subwaths

Sentinel-1 Doppler-Shifts in Range

- The sensor movement leads to Doppler-shifts Δf_D in the radar pulses
  - Echo separation in azimuth → basic SAR principle
  - But t - dependent range shifts in TOPS SAR if not corrected after range compression



1. Doppler in SAR

$$\Delta f_D = -\frac{2\dot{r}(t)}{c} f_{radar}$$

2. Shift

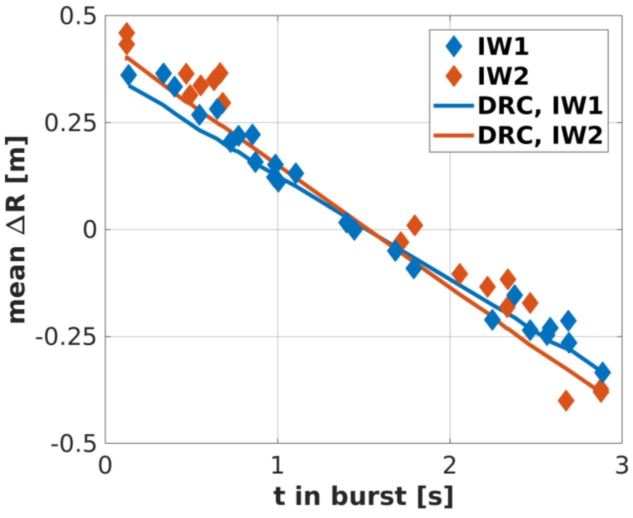
$$\Delta\tau = -\frac{\Delta f_D}{K_r}$$

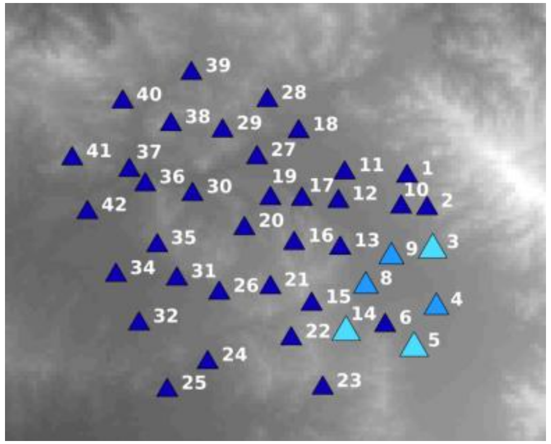
3. Correction in TOPS

$$\tau_{corr} = \tau_{IPF} + \boxed{\frac{f_{DC}(\tau, t)}{K_r}}$$

f_{DC} ... Doppler Centroid; includes the TOPS beam steering

Sentinel-1B: ΔRange vs. t

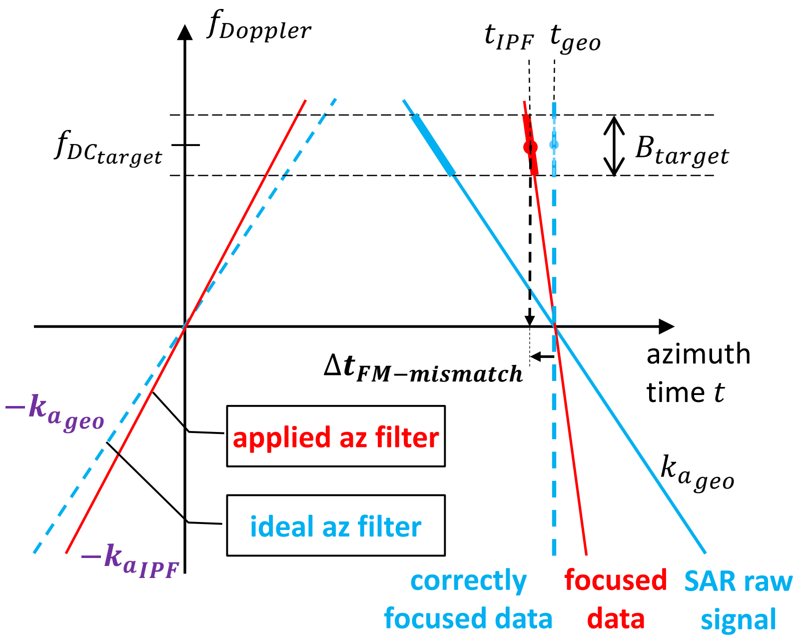




S-1 specific range correction

Sentinel-1 Azimuth FM-rate Mismatch due to Topography

- The azimuth filter construction uses an effective velocity parameter v_e which
  - depends on topography (sensor X_s to target X_T geometry)
  - is usually assumed constant over large blocks of azimuth data (e.g. burst wise)
- Az Doppler FM-rate k_a of the filter may not matches true signal → issue for TOPS[1]



1. Effective Velocity

$$k_{a_{IPF}} = -\frac{2v_e^2}{\lambda \cdot r_0}$$

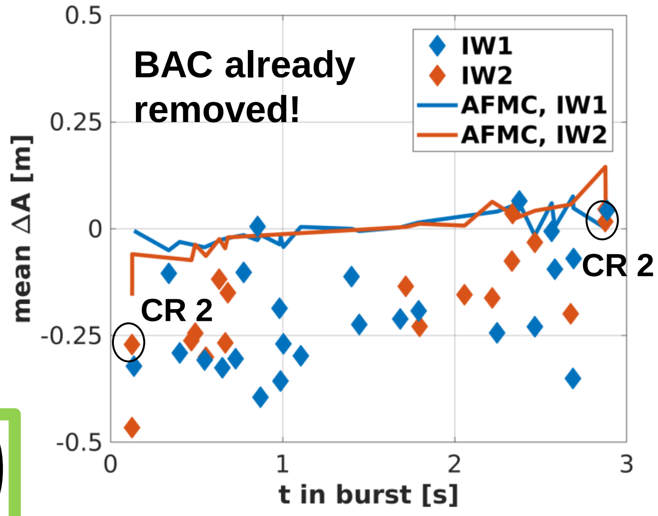
$$v_e^2 = \dot{X}_s \cdot \dot{X}_s - \ddot{X}_s \cdot (X_s - X_T)$$

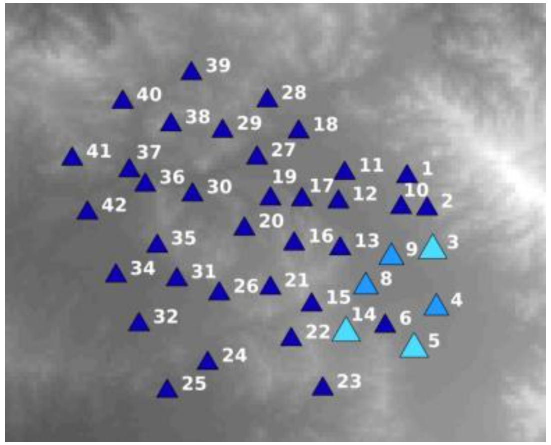
2. Correction in TOPS

$$t_{geo} = t_{IPF} + \Delta t_{FMC}$$

$$\Delta t_{FMC} = f_{DC} \cdot \left(\frac{1}{-k_{a_{geo}}} - \frac{1}{-k_{a_{IPF}}} \right)$$

Sentinel-1B: ΔAzimuth vs. t





S-1 specific FM-mismatch correction

Sentinel-1 Azimuth FM-rate Mismatch due to Topography

- Practical example for an extreme case: CR at *Torny-Le-Grand* (CH) that is
  - located at the very border of an IW product which includes the Alps
  - and lies at the edge of a burst

*S1A_IW_SLC__1SDV_**20160707**T053457_20160707T053524_012038_0129AA_34F1.SAFE*

f_{DC} = 1576.0016 Hz

$k_{a\ geo}$ = -1927.**0241** Hz/s

$k_{a\ IPF}$ = -1927.**4002** Hz/s

Δt_{FMC} = 0.0001596 s ≈ **1.085 m**