VH-Roda and CEOS SAR Workshop 2019

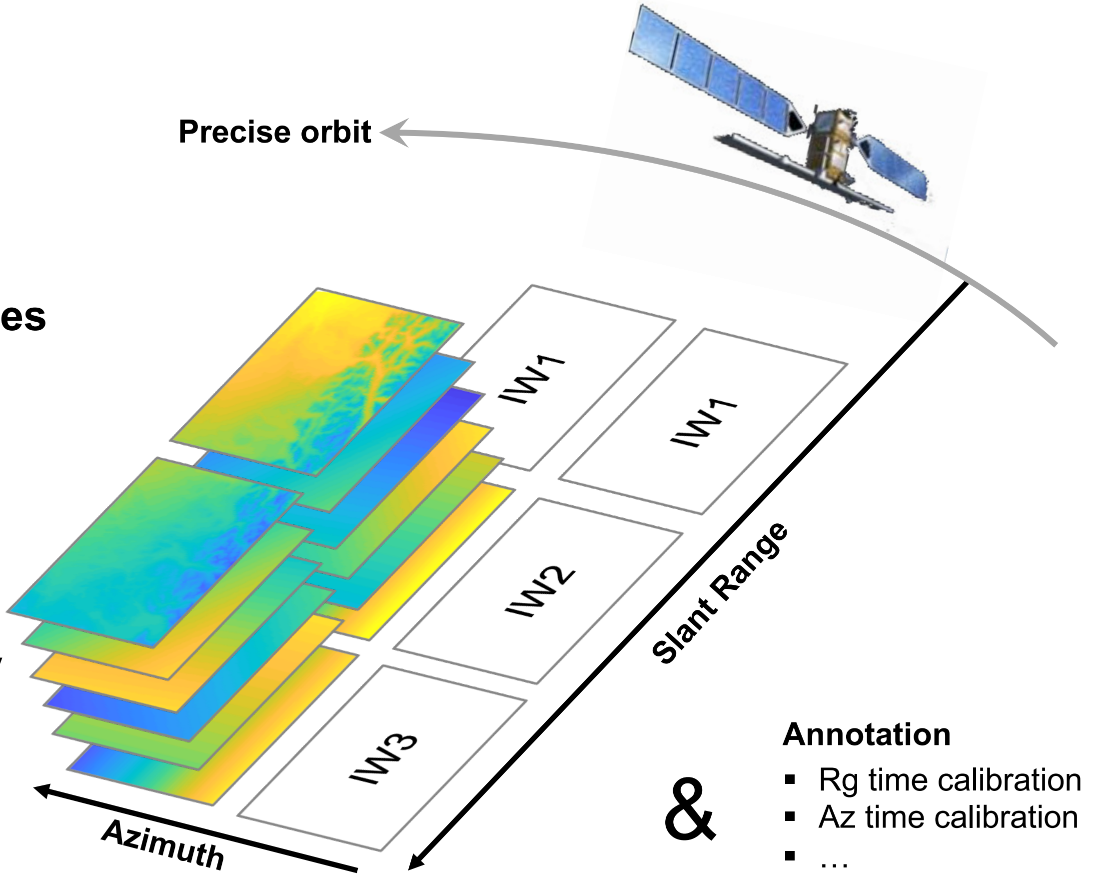
Towards Operational SAR Imaging Geodesy: An Extended Time Annotation Dataset for Sentinel-1 Image Products

C. Gisinger[1], S. Suchandt[1], H. Breit[1], U. Balss[1], M. Lachaise[1],
T. Fritz[1], M. Eineder[1], N. Miranda[2]

[1] German Aerospace Center (DLR)
[2] European Space Agency (ESA)

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

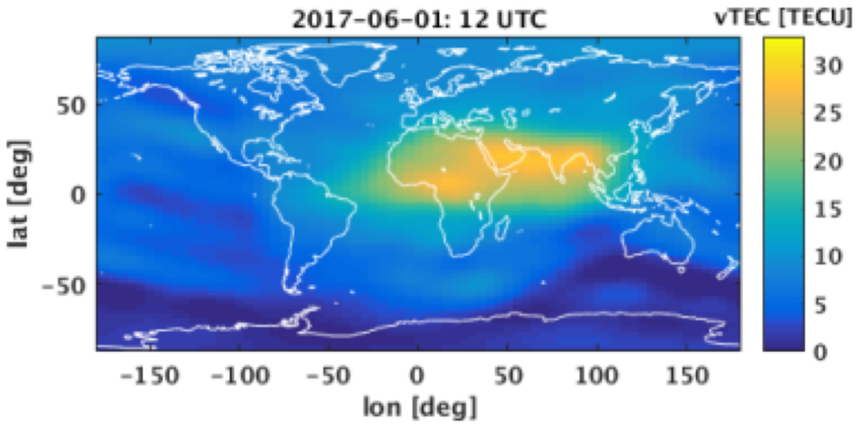


Ionospheric Delay and Solid Earth Tides Corrections

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

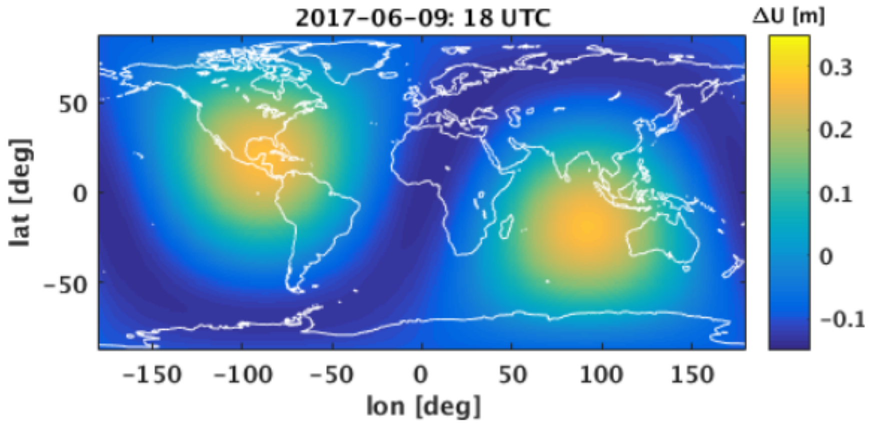
Ionosphere: products by IGS Analysis Centers[1]

- 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] Hernándenz-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

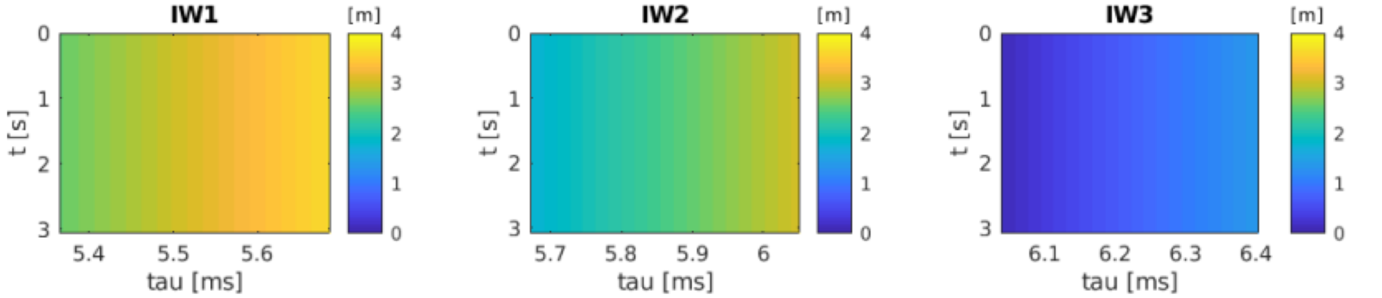
Sentinel-1 SAR System Corrections[1,2]

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

  - **Bistatic Az Correction**

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

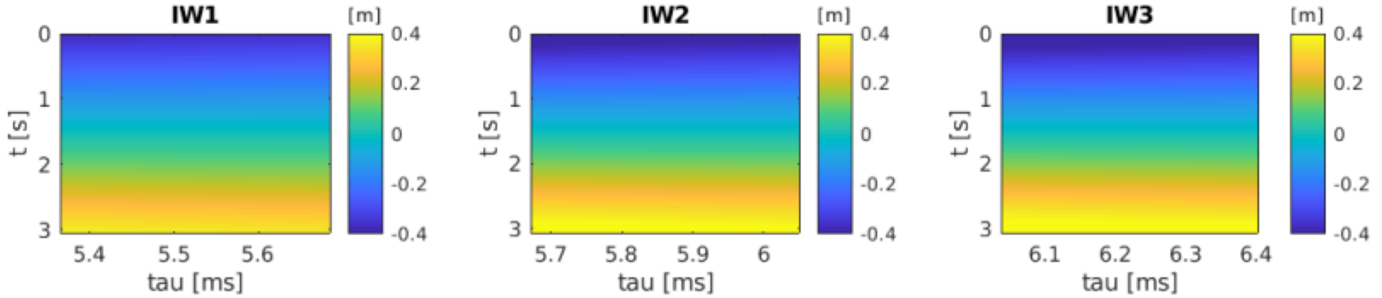
    τ_0 ... rank · PRI



  - **Doppler Shift Rg Correction**

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

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



  - **FM-rate Mismatch Az Correction**

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

    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

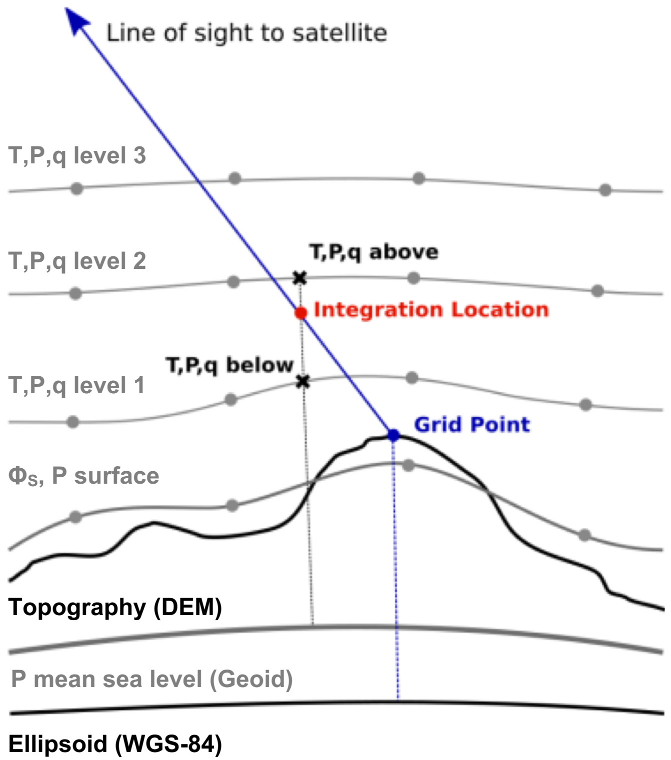
[2] Piantanida et al. 2018, *Accurate Geometric Calibration of Sentinel-1 Data*, Proc. EUSAR 2018

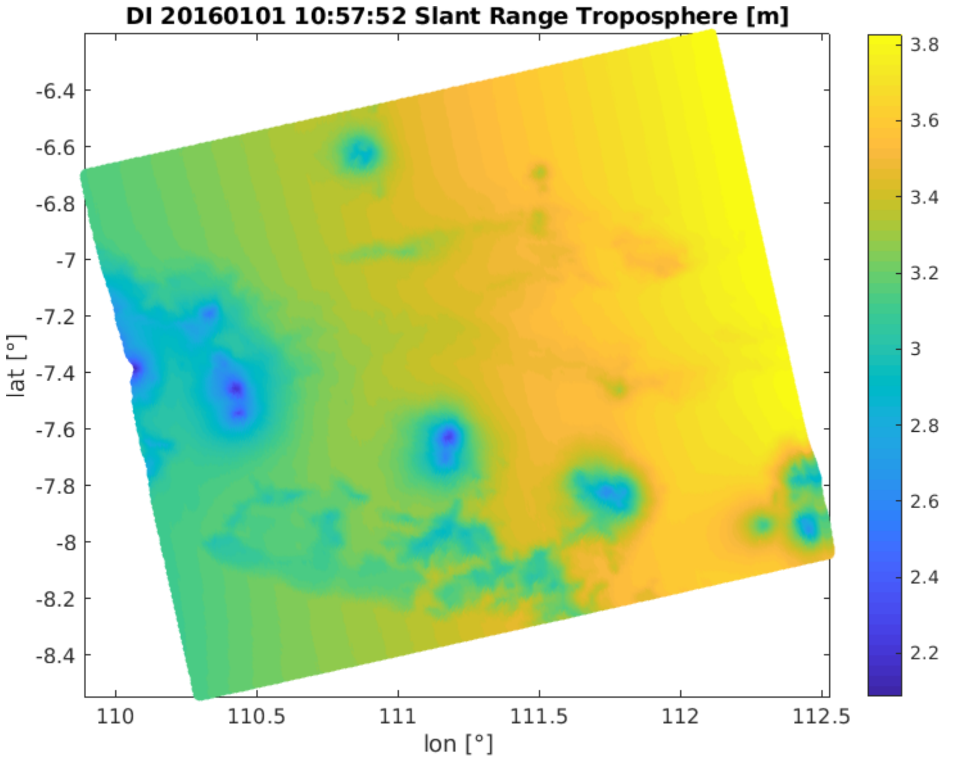
Tropospheric Delay: Direct Integration of ECMWF NWP Data[1]

- 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

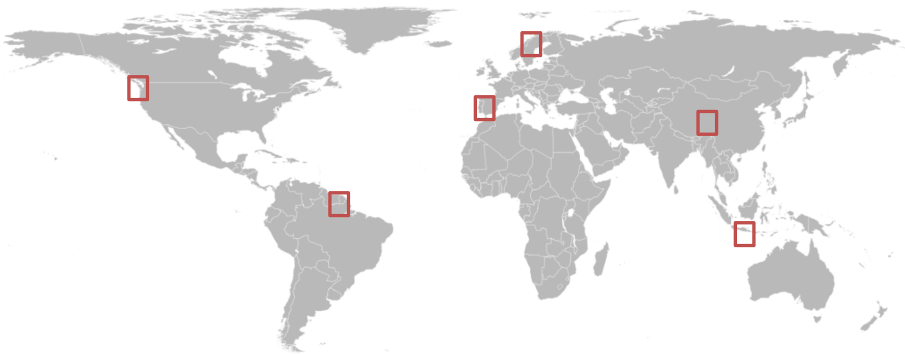
[1] Cong et al. 2018, *Mitigation of Tropospheric Delay in SAR and InSAR Using NWP Data*, Remote Sensing

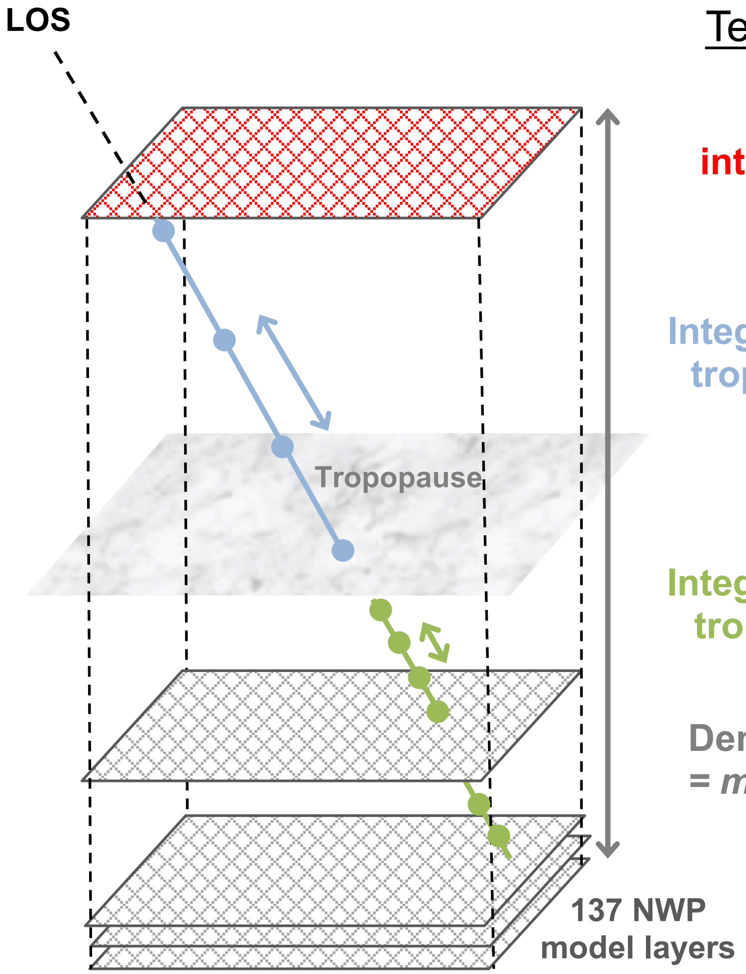
Sensitivity Analysis of Path Delay Integration

- 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*

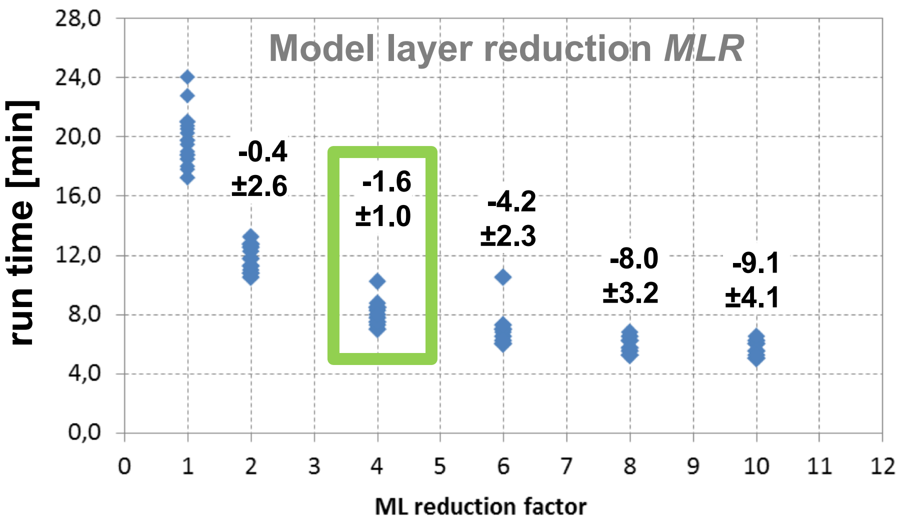
Integration interval above tropopause *int2 =100m*

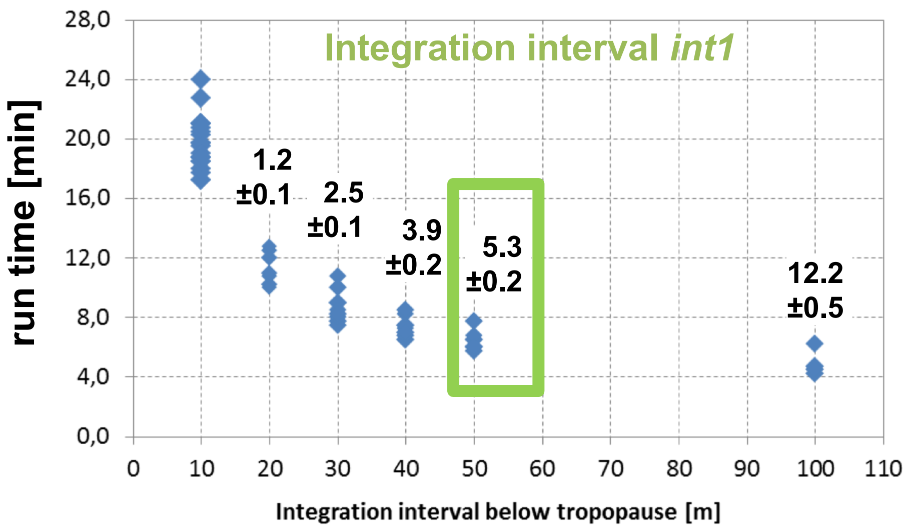
Integration interval below tropopause *int1 = 10m*

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

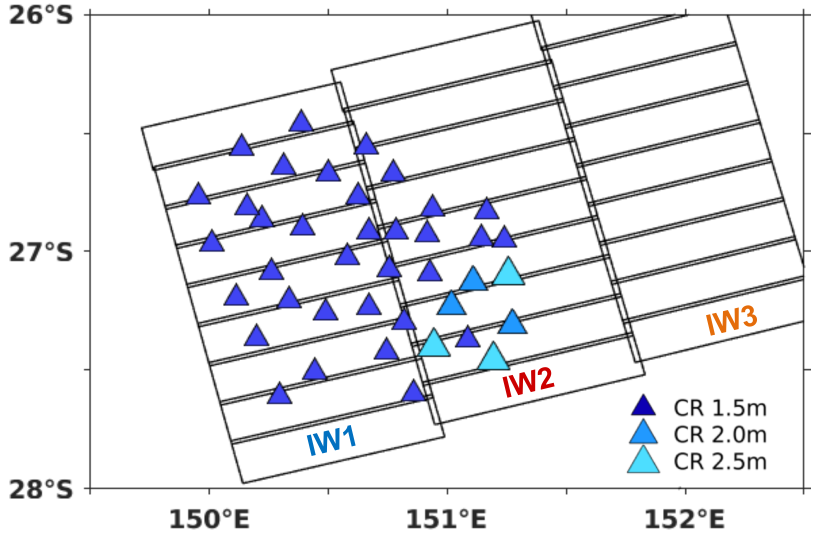
- Combination of all tunable parameters: changes with respect to default

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

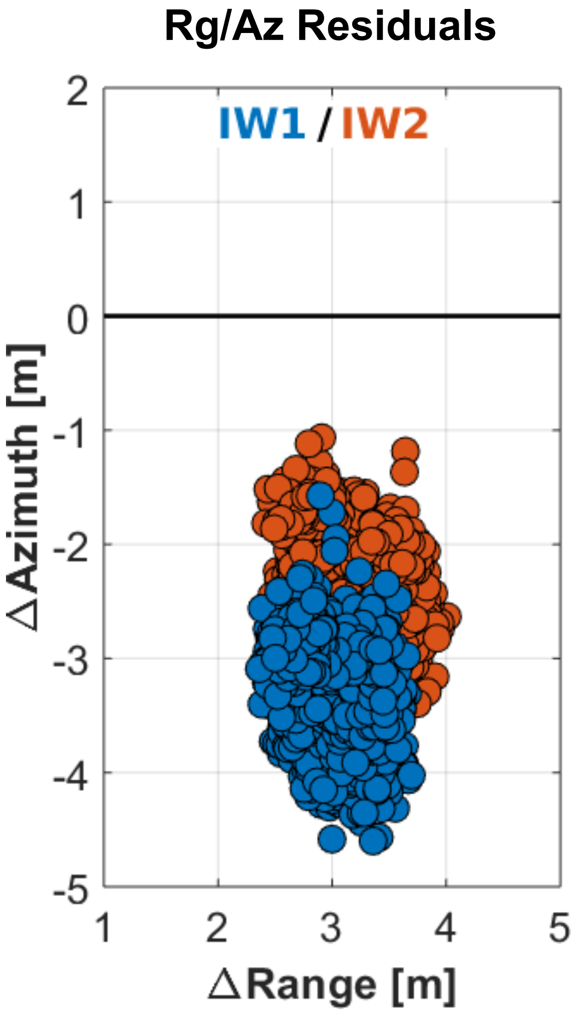
⇨ ***Our basis for further code optimizations***

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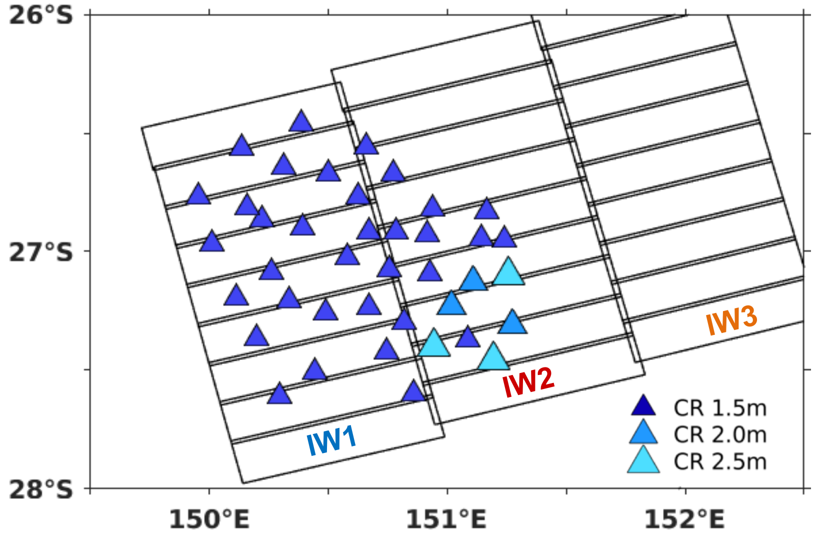
  - **Tropospheric delays (VMF3)[1]**



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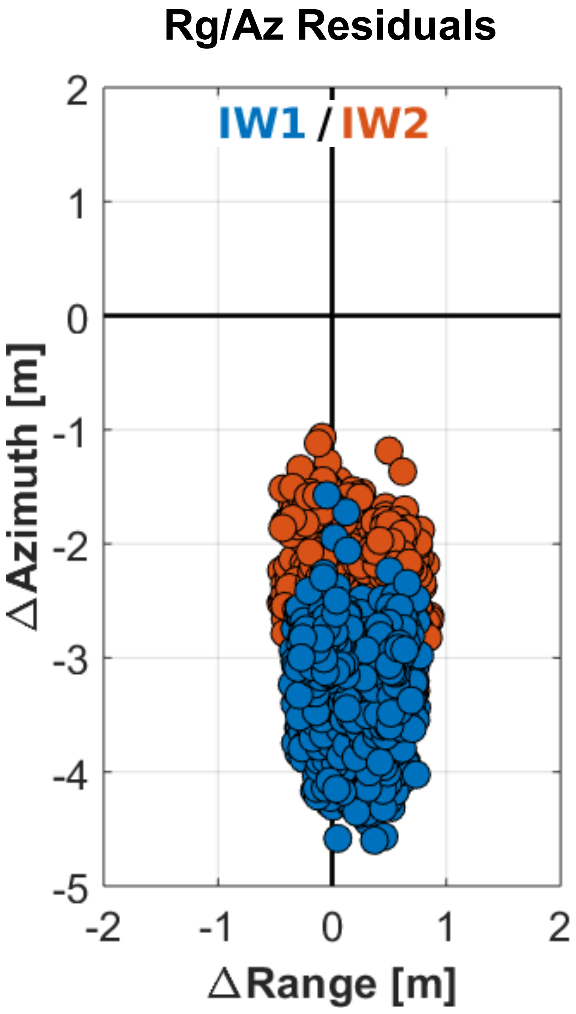

[1] Landskron and Böhm 2017, *VMF3/GPT3: refined discrete and empirical troposphere mapping functions*, J. Geod.

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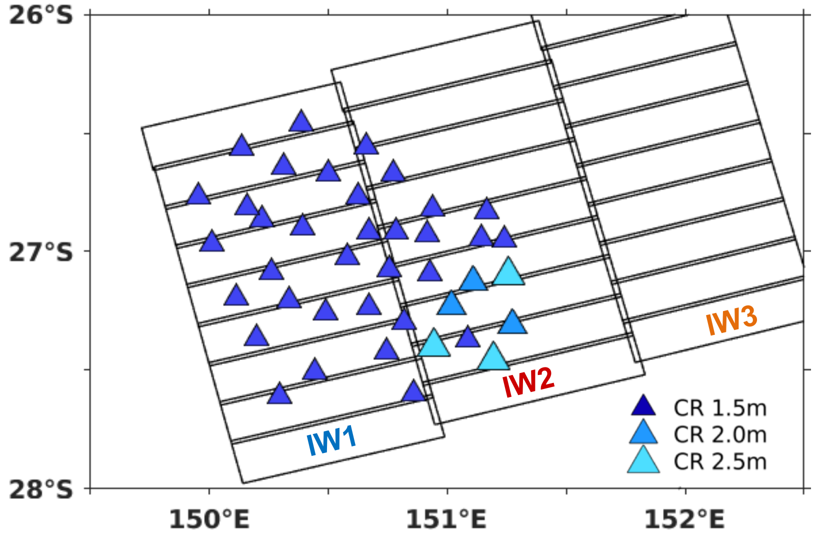

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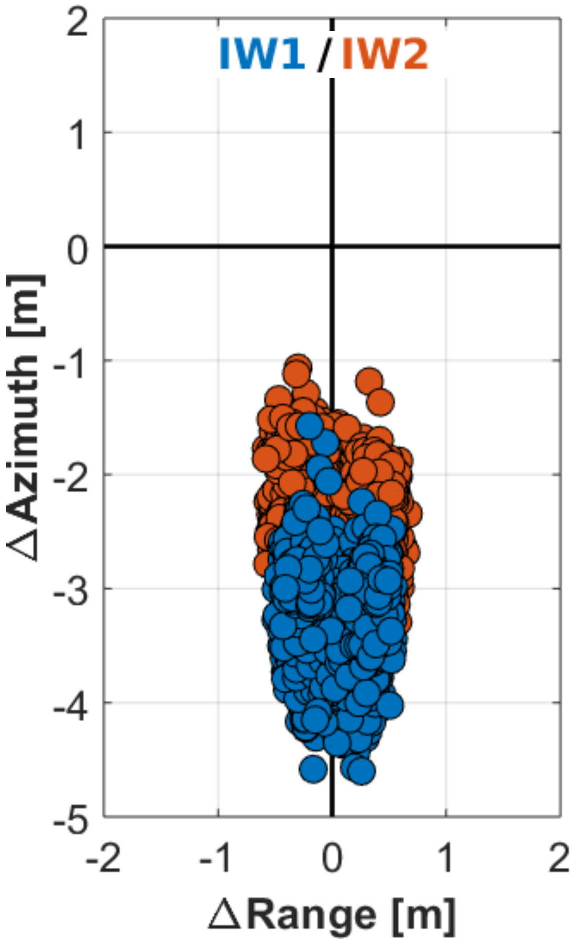
Rg/Az Residuals



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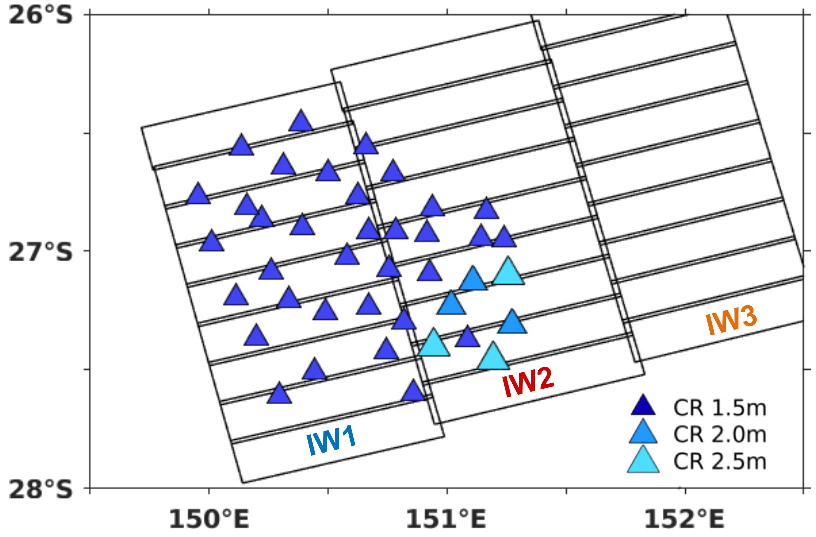

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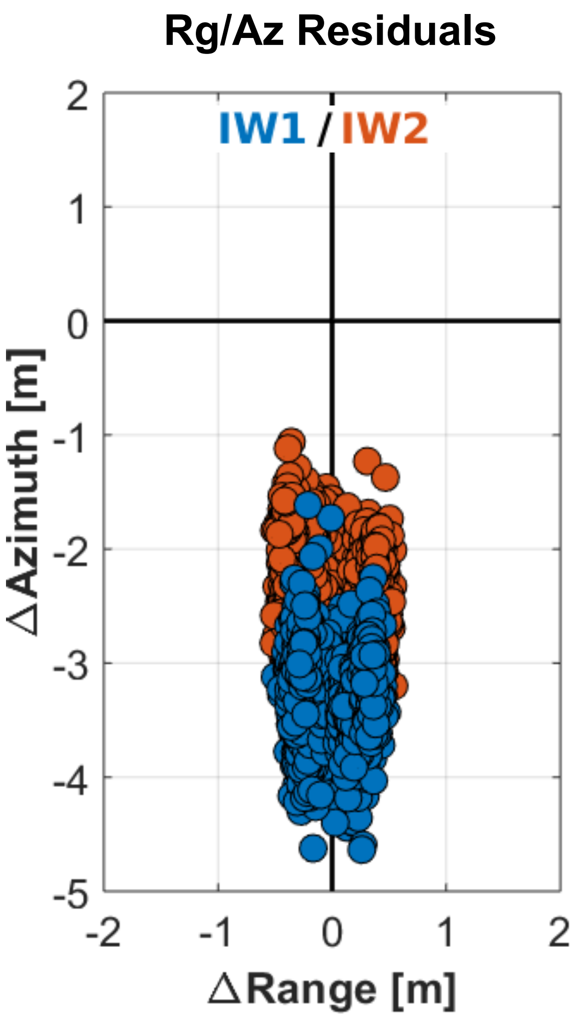

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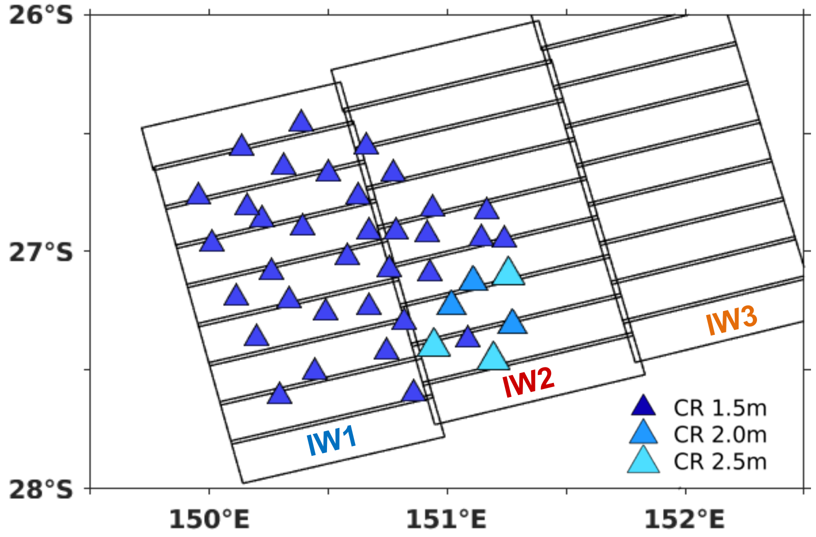

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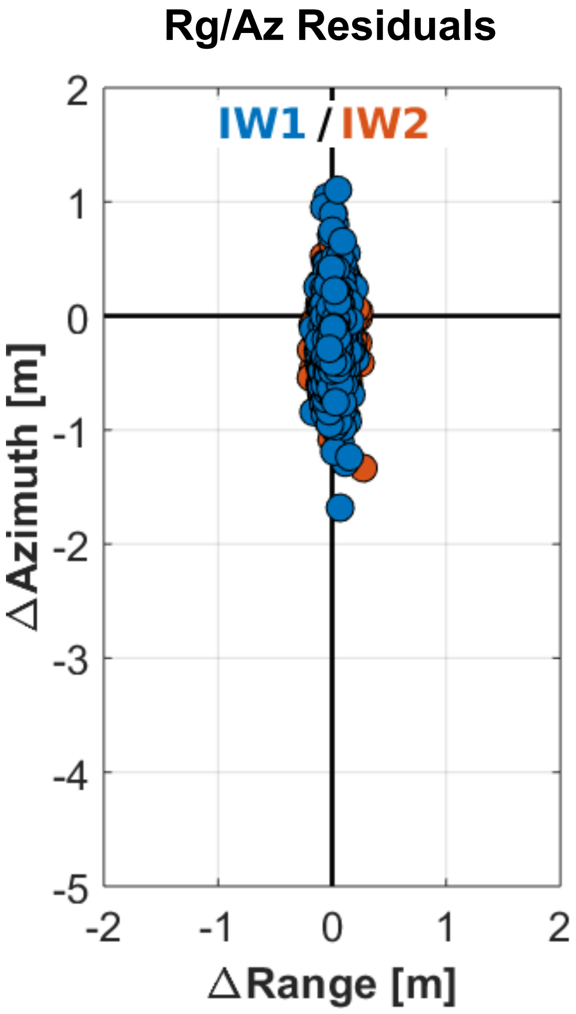
+ System	**0.018 ± 0.054**	**-0.195 ± 0.248**



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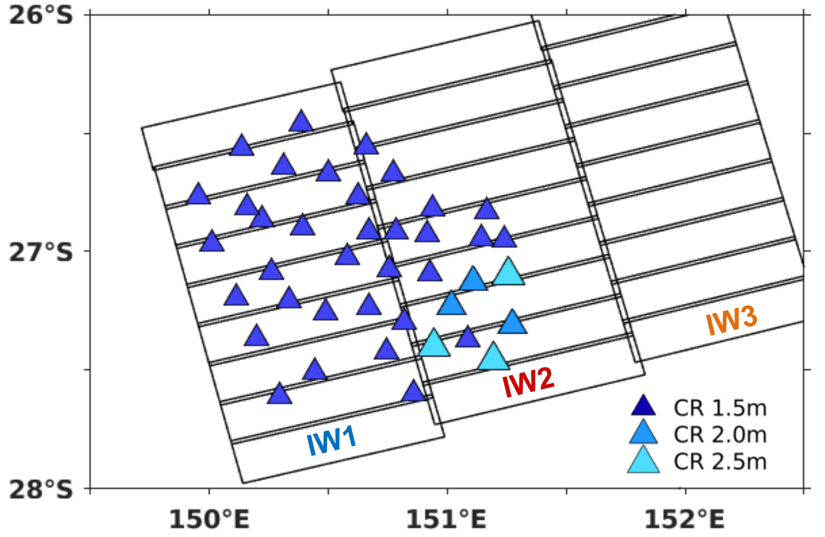

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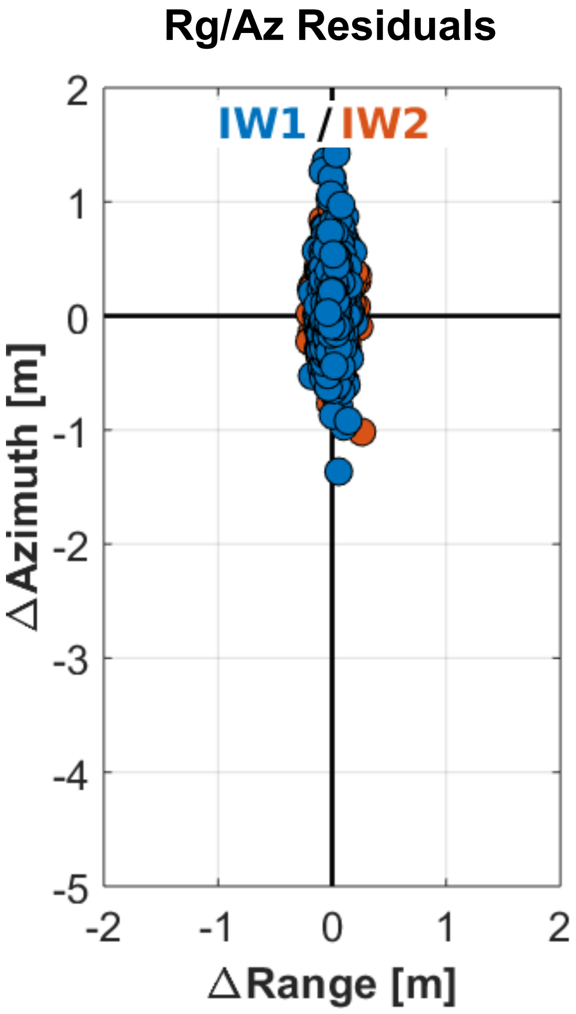

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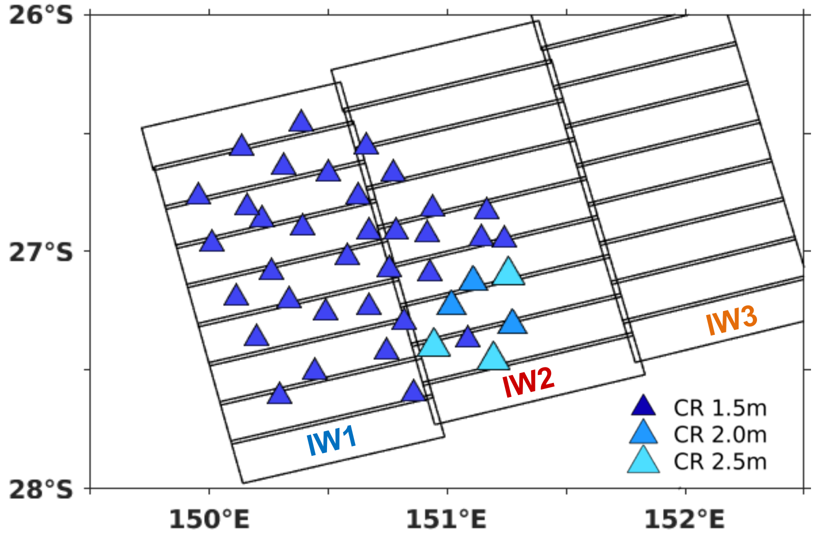

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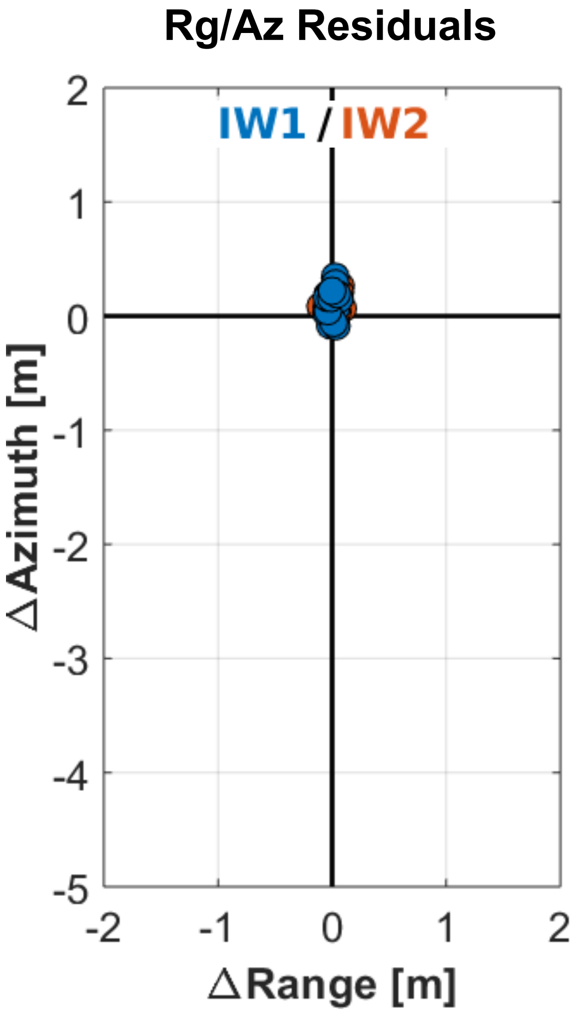

DLR esa

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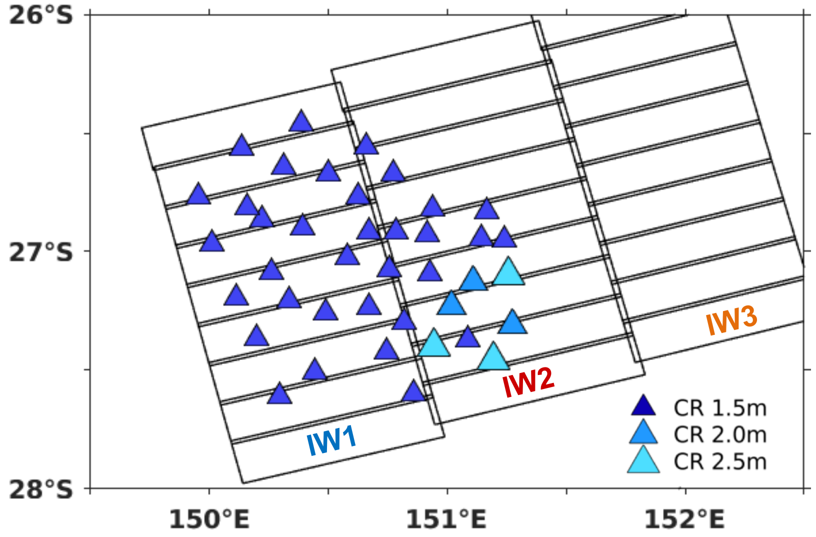

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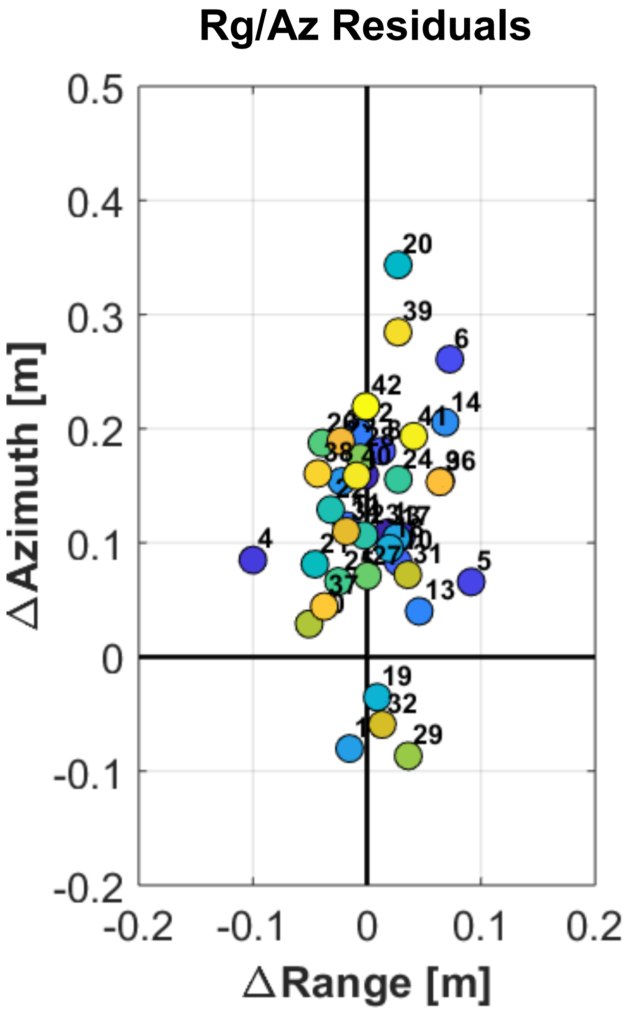

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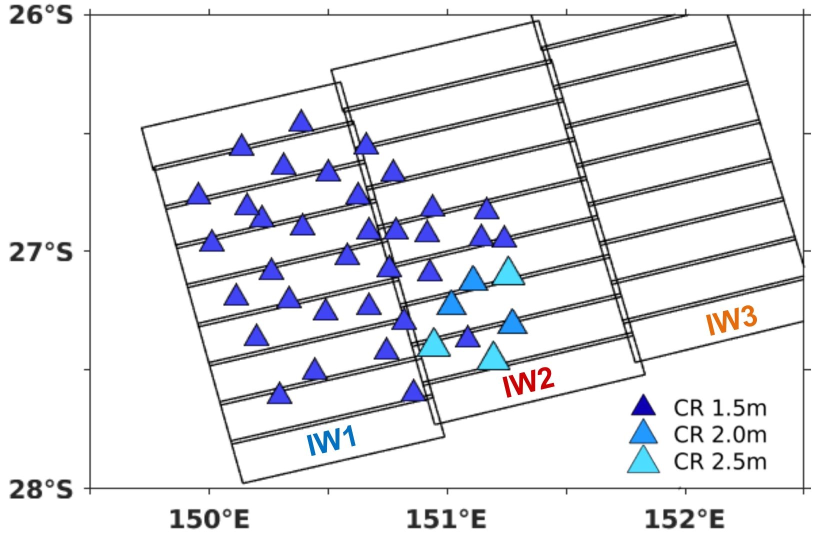
- **Temporal filtering: mean per CR**
- **CRs updated ITRF coordinates**



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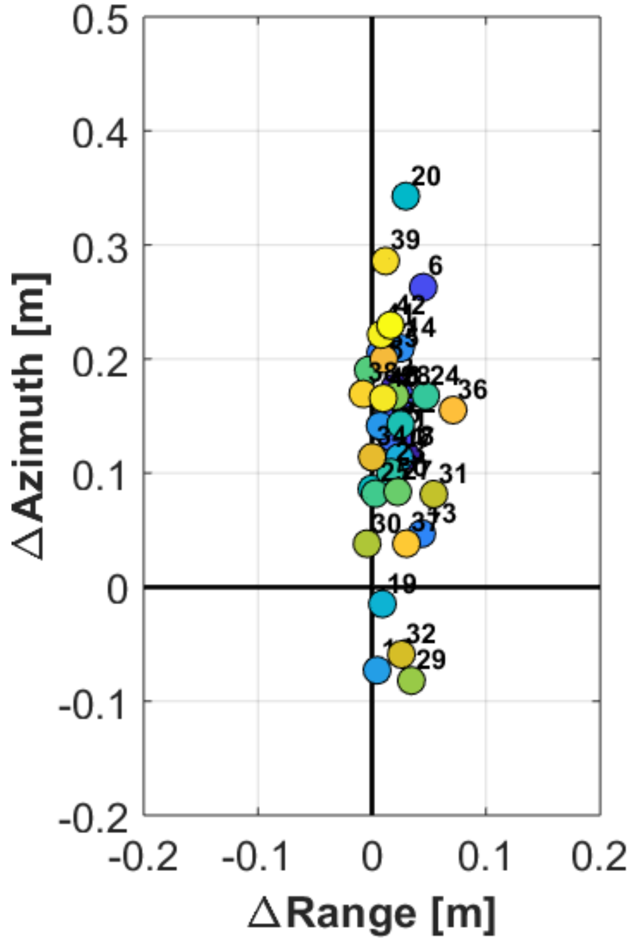
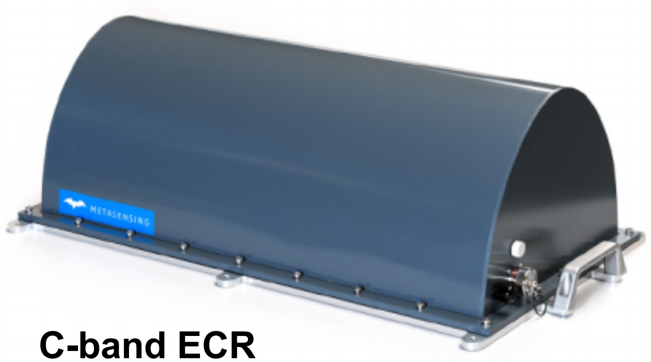
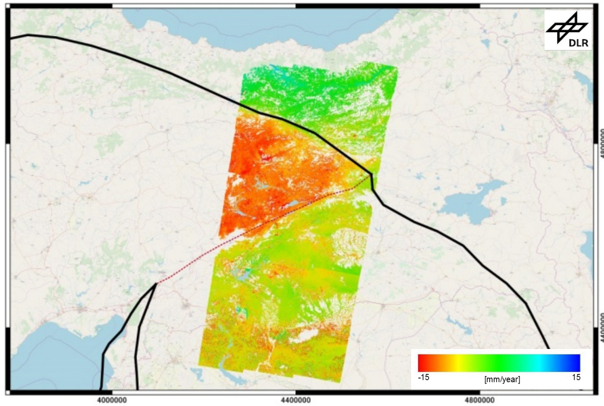
+ Cal&CRs	**0.020 ± 0.043**	**0.131 ± 0.247**



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"

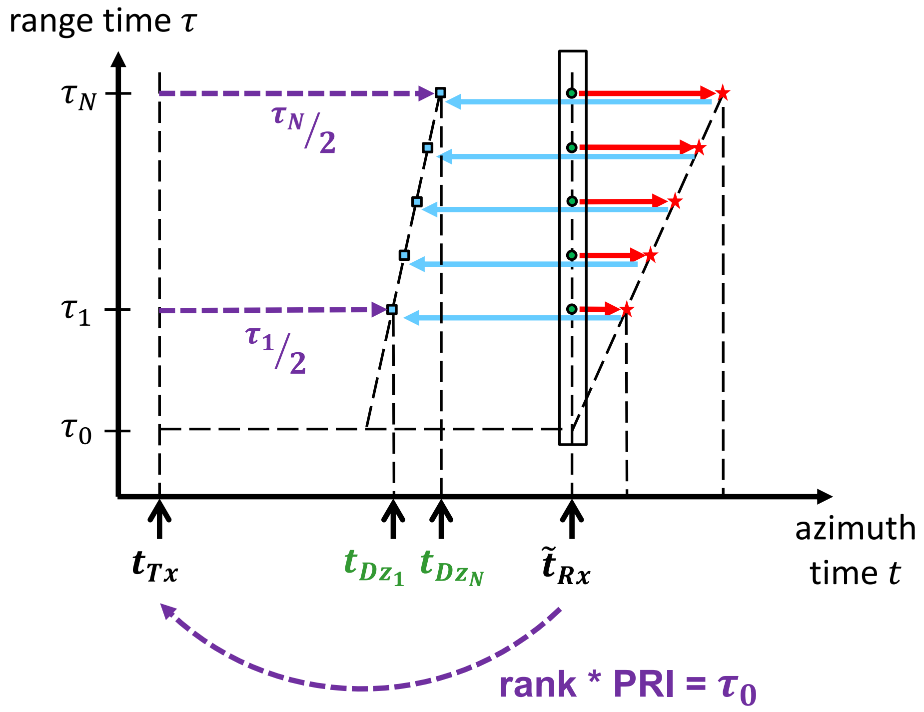
Europe's eyes on Earth

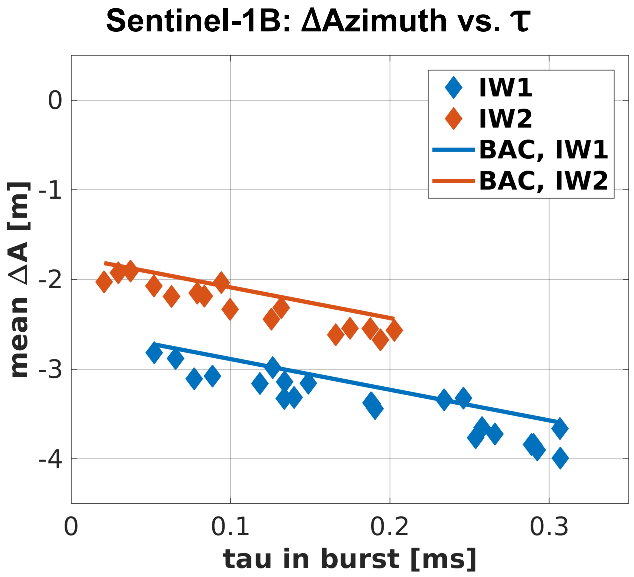
Sentinel-1 Bistatic Azimuth Correction

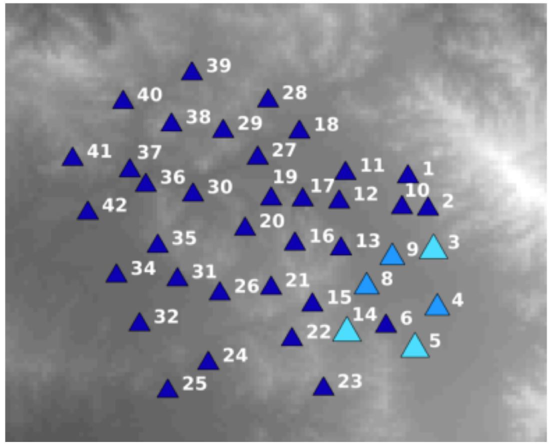
- Remove the IPF bulk contribution and apply the total bistatic azimuth correction

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

S-1 specific bistatic azimuth correction





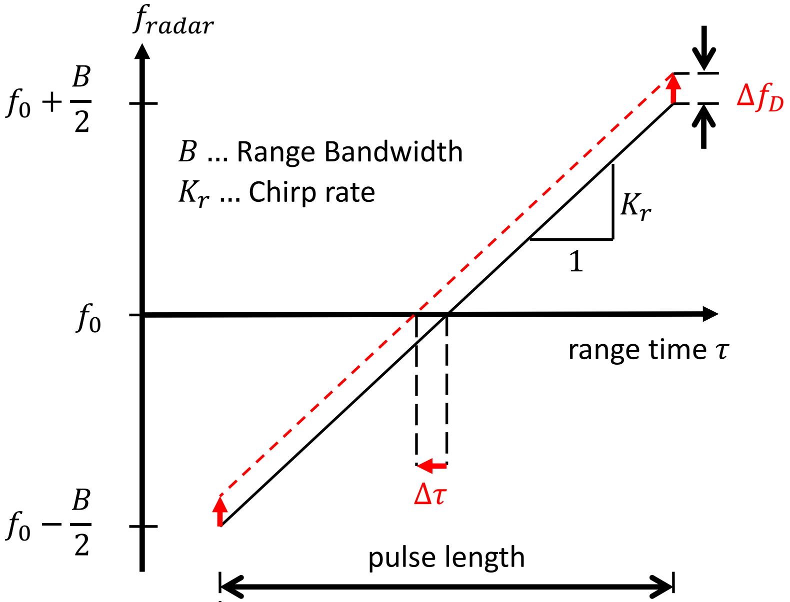


– “Bulk correction” is not a correction!

– 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

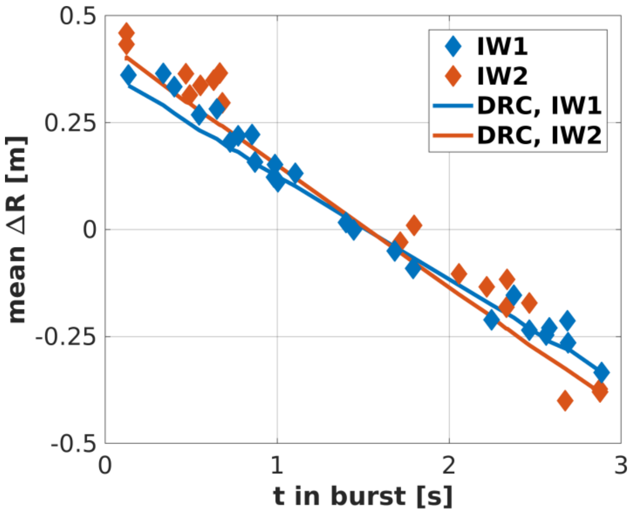
$$\Delta\tau = -\frac{\Delta f_D}{K_r}$$

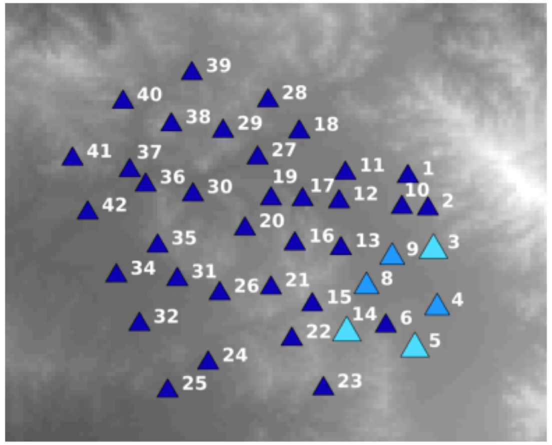
3. Correction in TOPS

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

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

Sentinel-1B: ΔRange vs. t

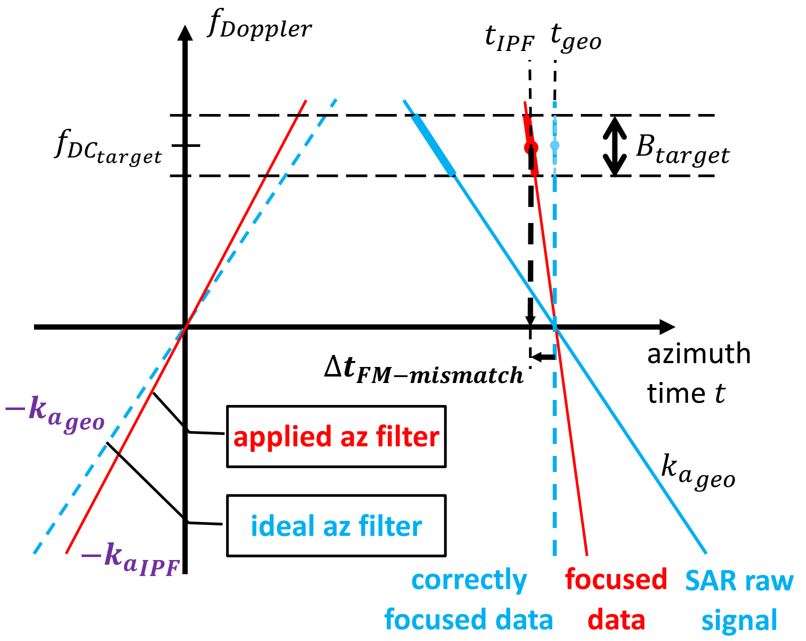




S-1 specific range correction

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

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

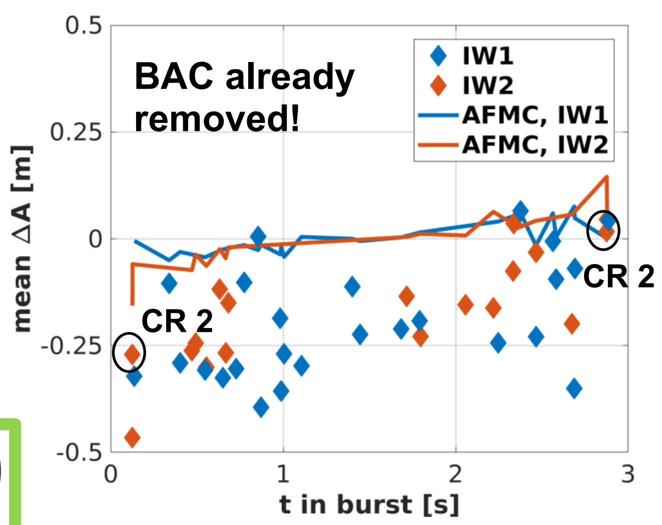
$$v_e^2 = \dot{X}_s \cdot \dot{X}_s - \ddot{X}_s \cdot (X_s - X_T)$$

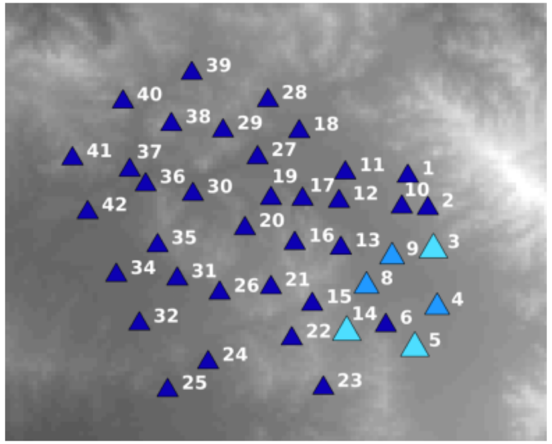
2. Correction in TOPS

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

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

Sentinel-1B: ΔAzimuth vs. t

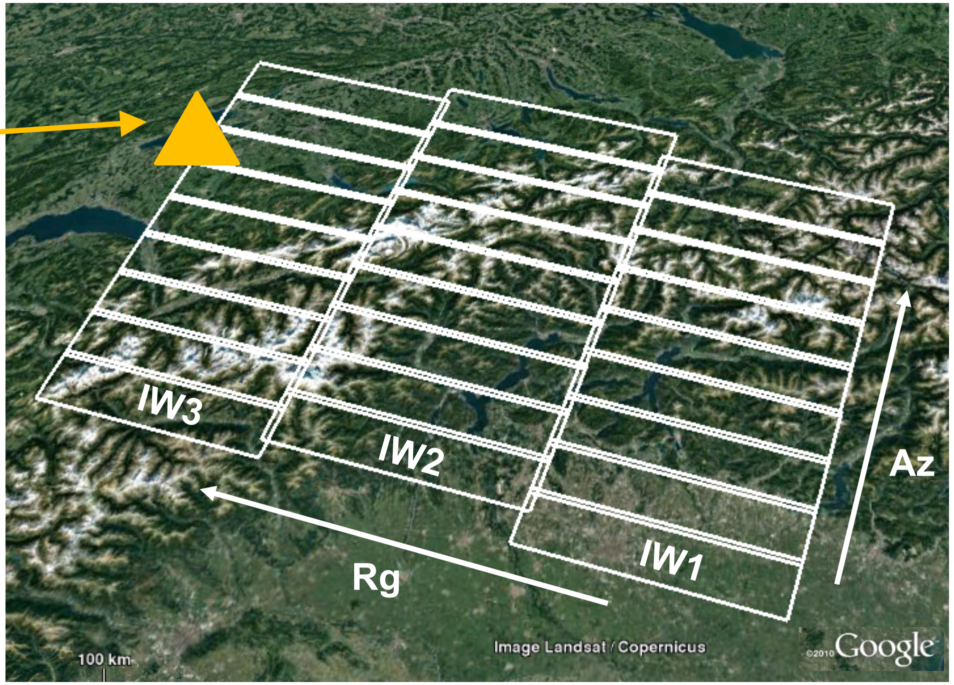




S-1 specific FM-mismatch correction

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**