Investigation of Residual Shift Effects in Azimuth Geolocation Results of Sentinel-1 TOPS Data by Leveraging SAR Calibration Sites in Argentina

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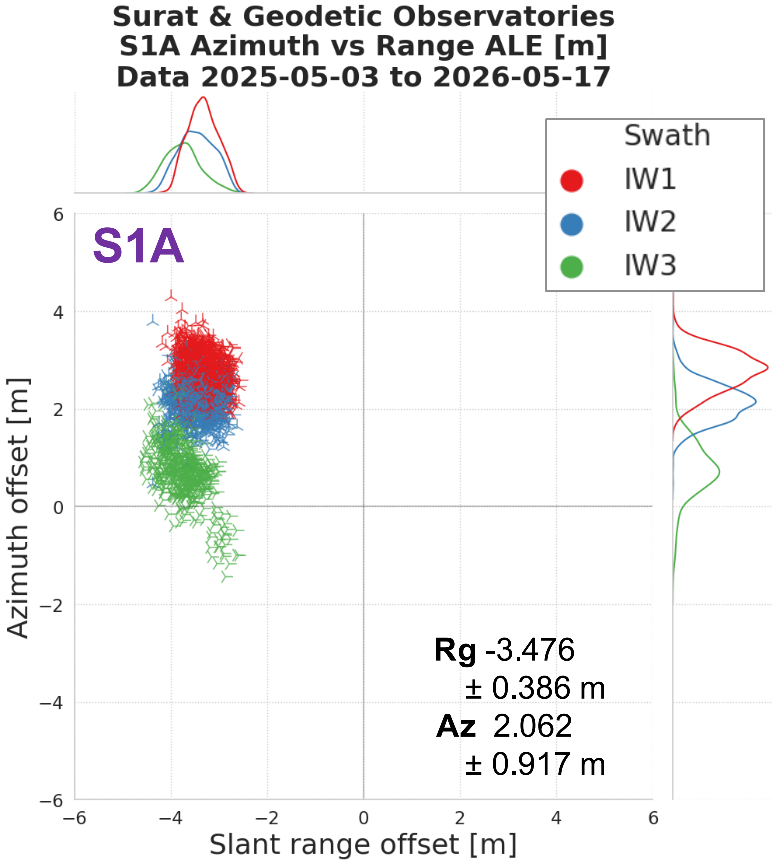
Geolocation with Sentinel-1: Where are we?

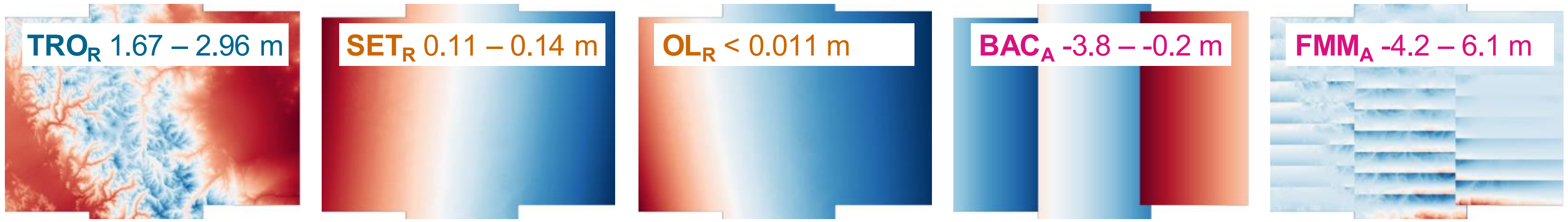
- **ESL Geocal Team at Mission Performance Center** is regularly assessing the geometric performance **of the Sentinel-1 mission over dedicated SAR calibration sites**
  - Nominal L1 product geometric quality

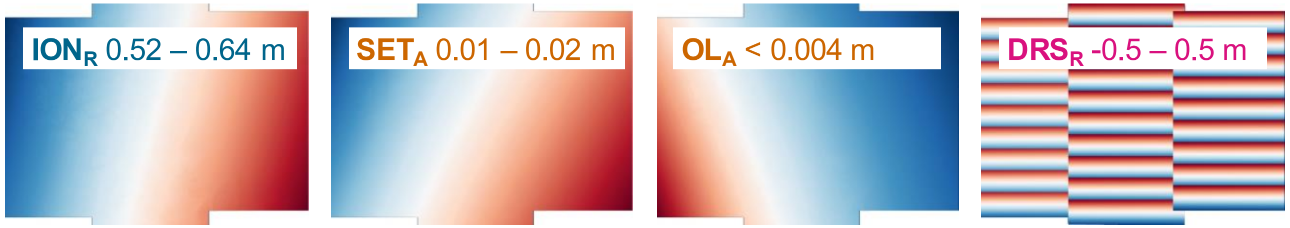


Geolocation with Sentinel-1: Where are we?

- **ESL Geocal Team at Mission Performance Center** is regularly assessing the geometric performance **of the Sentinel-1 mission over dedicated SAR calibration sites**
  - Nominal L1 product geometric quality
  - Optimal L1 product geometric quality
    - *Precise orbit products*
    - *Instrument timing calibration*
    - *Post-processing SAR timings corrections*

→ S-1 Extended Timing Annotation Dataset (ETAD)





S1A_IW_ETA__AXDV_
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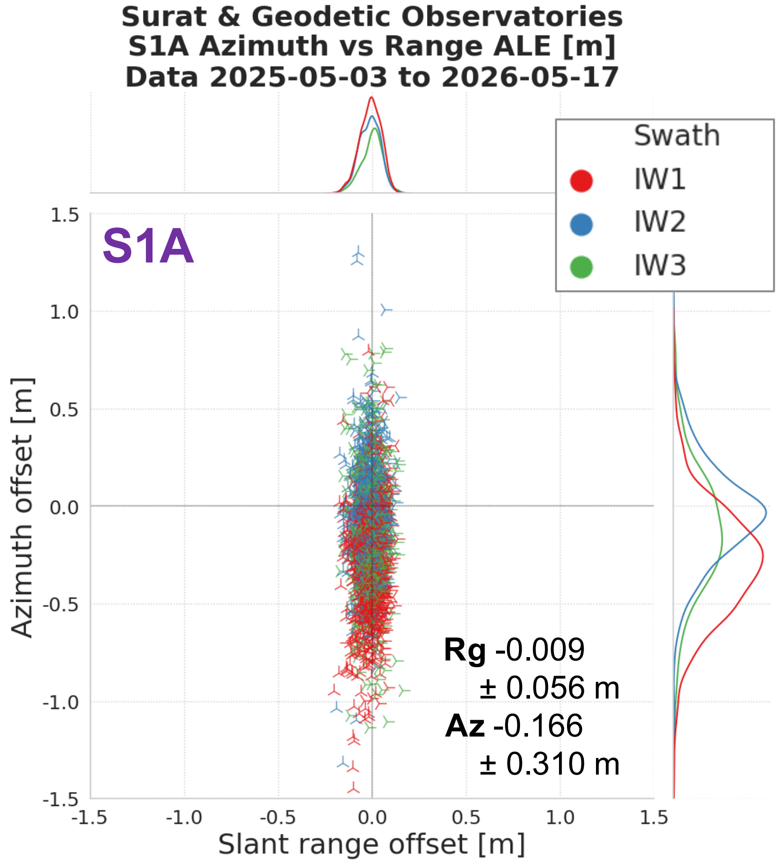
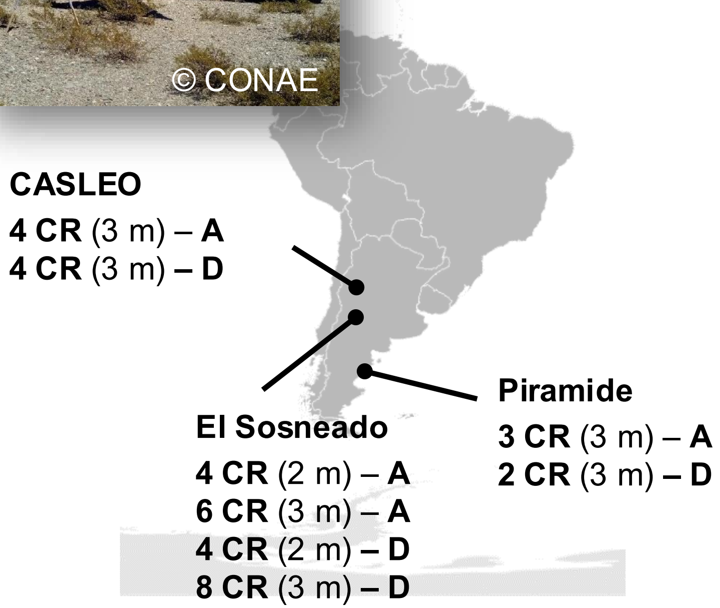
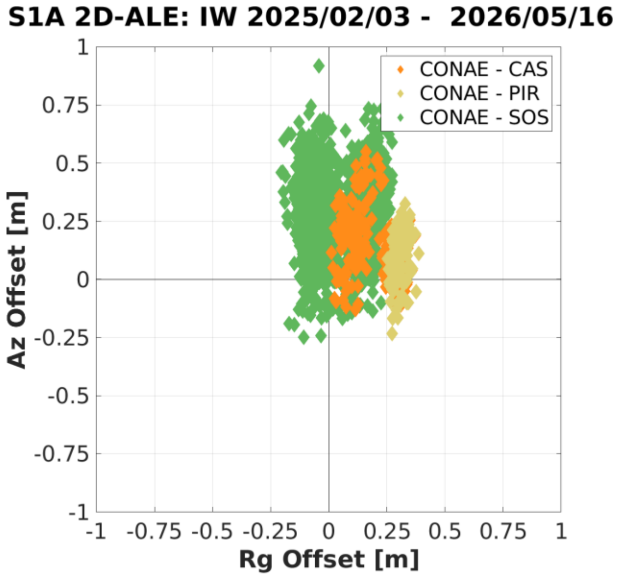
20251231T232802_
062565_07D765_
8C27.SAFE



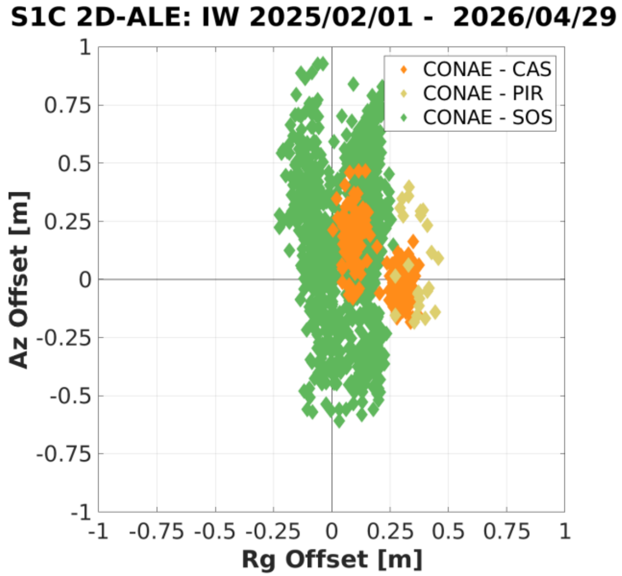
CONAE SAR Calibration Sites

- **Permanent corner reflector installations for Argentina's SAOCOM mission**
  - Fixed installations since November 2018
  - Target information shared via the CEOS SARCalNET initiative: **sarcalnet.org**
    - Sites were used during the S-1C and S-1D In-Orbit Commissioning Phase





Site	Rg ALE [m]	Az ALE [m]
All	0.104 ± 0.131	0.244 ± 0.180
CONAE - CAS	0.192 ± 0.099	0.147 ± 0.139
CONAE - PIR	0.309 ± 0.028	0.094 ± 0.112
CONAE - SOS	0.065 ± 0.115	0.280 ± 0.178



Site	Rg ALE [m]	Az ALE [m]
All	0.089 ± 0.128	0.143 ± 0.291
CONAE - CAS	0.202 ± 0.106	0.072 ± 0.146
CONAE - PIR	0.365 ± 0.052	0.077 ± 0.200
CONAE - SOS	0.060 ± 0.113	0.159 ± 0.312

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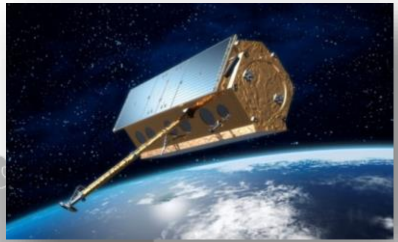


New 3D Positions from TerraSAR-X High-res data → ITRF Coordinates

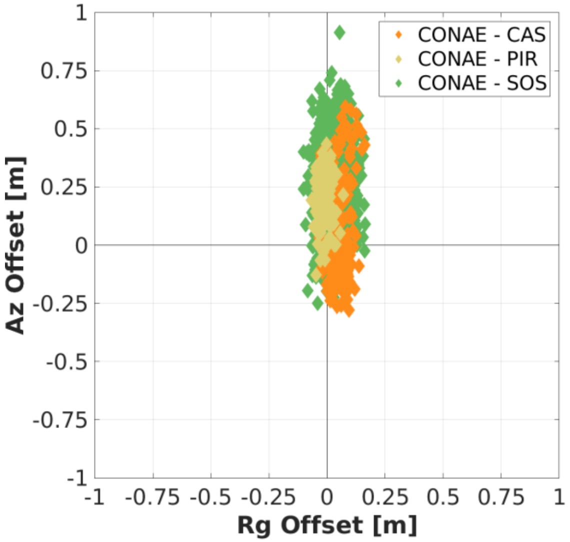
(*Gisinger et al 2015, Precise 3D Stereo* doi 10.1109/TGRS.2014.2348859)

CASLEO
4 CR (3 m) – **A**
4 CR (3 m) **– D**
TSX XYZ (<10cm)

El Sosneado
4 CR (2 m) – **A**
6 CR (3 m) – **A**
4 CR (2 m) **– D**
8 CR (3 m) **– D**
TSX XYZ (<10cm)

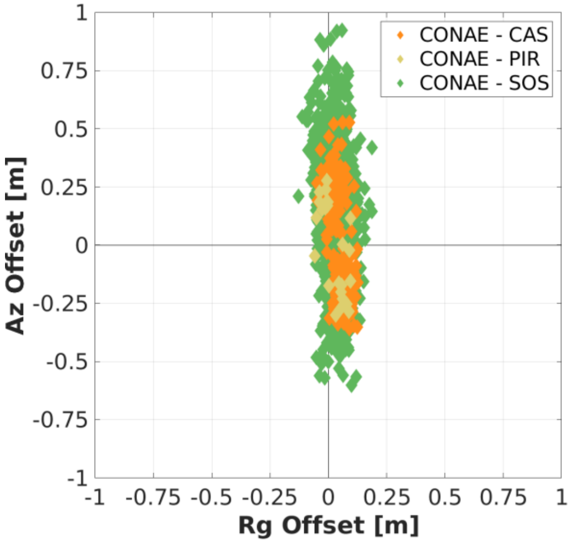
Piramide
3 CR (3 m) – **A**
2 CR (3 m) **– D**
TSX XYZ (<10cm)

S1A 2D-ALE: IW 2025/02/03 - 2026/05/16



Site	Rg ALE [m]	Az ALE [m]
All	0.029 ± 0.045	0.235 ± 0.183
CONAE - CAS	0.045 ± 0.040	0.075 ± 0.213
CONAE - PIR	-0.011 ± 0.027	0.198 ± 0.113
CONAE - SOS	0.029 ± 0.045	0.273 ± 0.161

S1C 2D-ALE: IW 2025/02/01 - 2026/04/29



Site	Rg ALE [m]	Az ALE [m]
All	0.029 ± 0.044	0.126 ± 0.277
CONAE - CAS	0.050 ± 0.035	-0.007 ± 0.234
CONAE - PIR	0.022 ± 0.050	-0.011 ± 0.198
CONAE - SOS	0.025 ± 0.045	0.157 ± 0.278

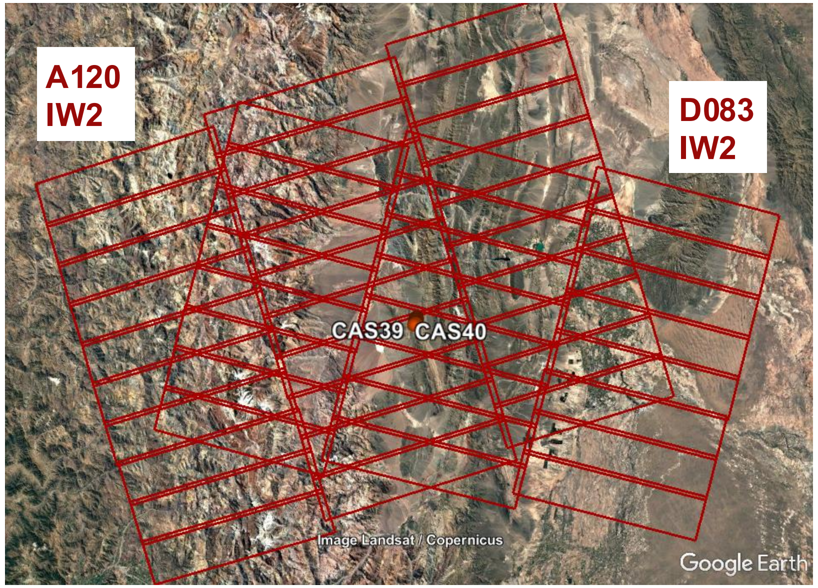
CONAE Sites Sentinel-1 Data Availability

- **We focus on El Sosneado and CASLEO due to the data coverage**
  - Six IW stacks involving all four S-1 sensors S-1A/B/C/D in ascending and descending tracks
  - Ascending *track 120* and descending *track 83* cover both sites less than 1 minute apart
  - In D010-IW3 some El Sosneado targets are located in the along-track burst overlap
- **Important: Only the 3m CRs are used in the following analysis to avoid SCR limitations**

El Sosneado S-1 IW Ascending

El Sosneado S-1 IW Descending

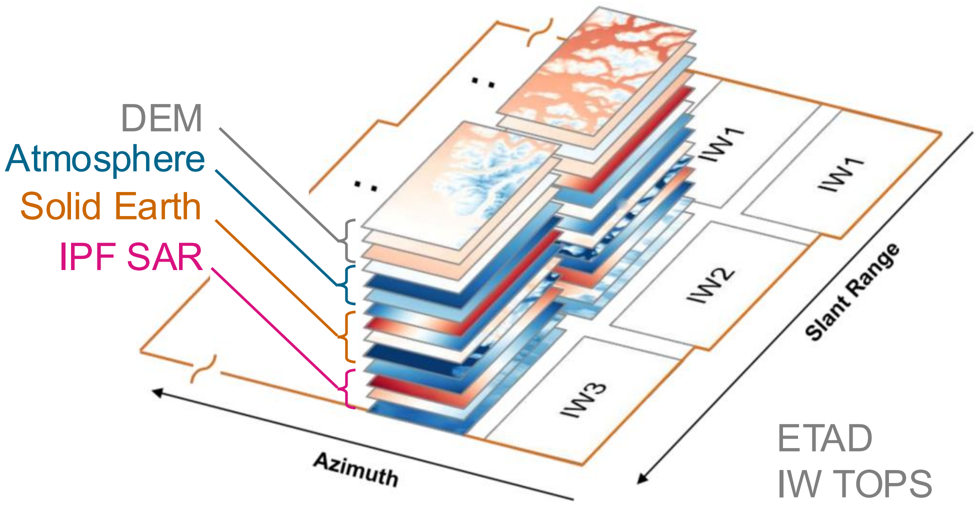
CASLEO S-1 IW



Google Earth Pro, Version 7.1.8.3036. Google, Accessed 12 Jun. 2026. https://www.google.com/earth/

Investigation of Additional SAR Azimuth Effects

- **Azimuth effects already considered in ETAD**
  - Along track shifts from solid Earth deformations
  - Residual bistatic azimuth shifts
  - Shifts from Az FM-rate mismatch due to topography
  - Instrument azimuth time bias



- **Additional effects that could impact S-1 TOPS azimuth geolocation quality**

  1. Azimuth Shifts due to ionosphere TEC gradient
  2. Azimuth antenna patterns phase slope
  3. Beam offset time due to hyperbolic approximation

Azimuth Shifts due to Ionosphere TEC Gradient

- **Basic effect is well understood but handling it in practice is still challenging**
  - TEC variations along the synthetic aperture cause inter alia a shift in focused azimuth data (*see e.g. Gomba et al. 2016, doi: 10.1109/TGRS.2016.2604461*)

  → Modelling using GNSS-based TEC maps is straightforward but limited by their coarse spatial resolution

  → SAR data-driven modelling (e.g. split-spectrum method) is computationally expensive and yields accurate relative results between two dates but requires good coherence

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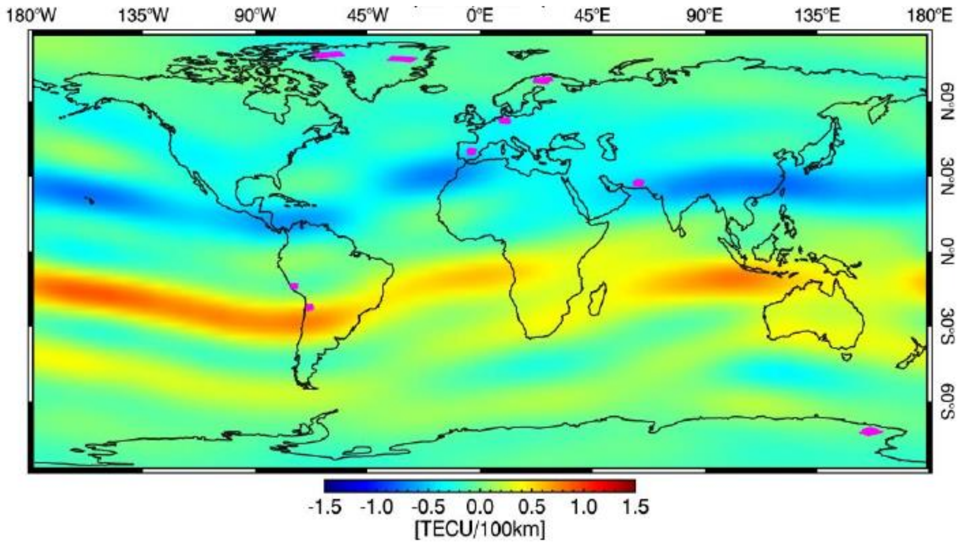
- **Forward modelling with TEC maps**

$$\Delta t_{ION,Az} = -\frac{2 \cdot 40.3e^{16}}{c \cdot f_{SAR}} \cdot \frac{sTEC_{grad}}{k_{a,true}}$$

$sTEC_{grad}$ … *sTEC linear rate along track in TECU/s*

$k_{a,true}$ … *"true" Doppler-rate from sensor to ground geometry*

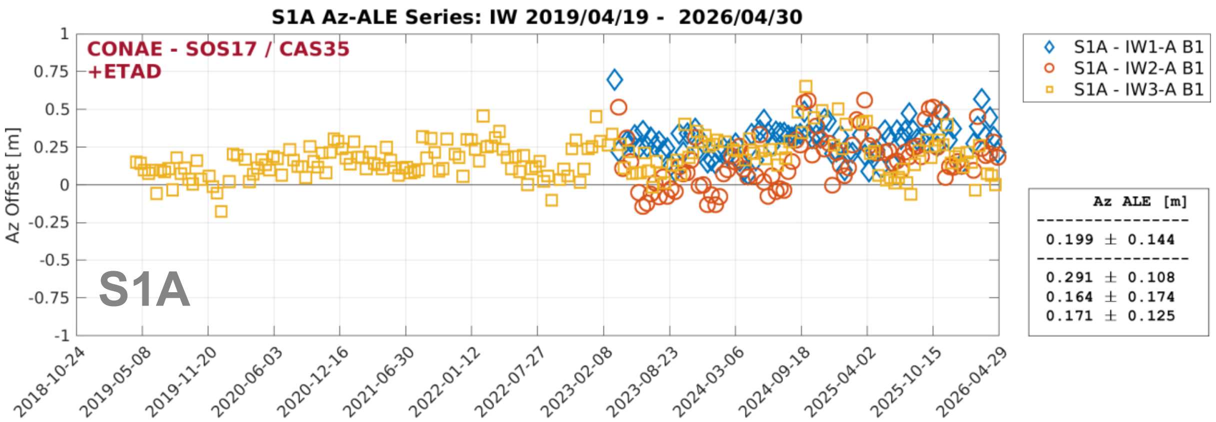


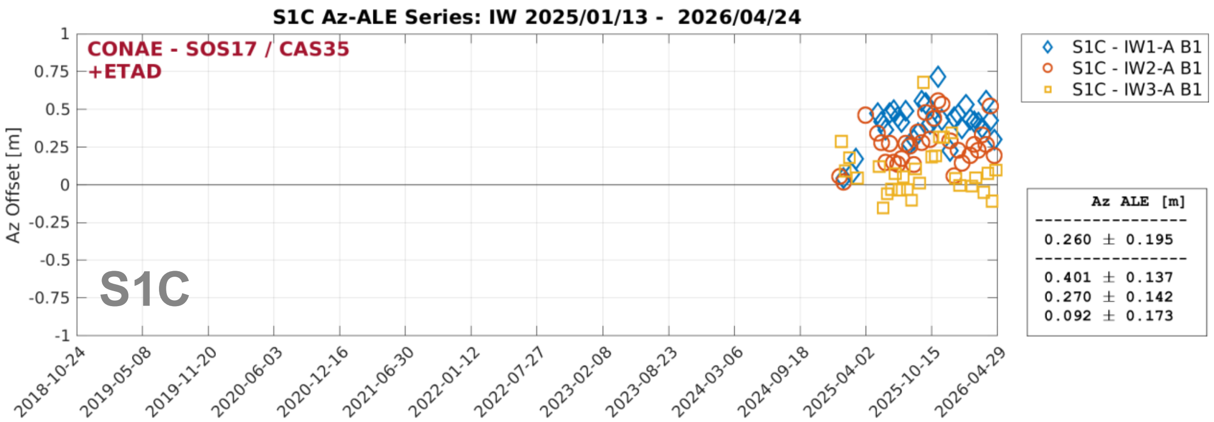
Average Az TEC gradient at 18UTC of 2017 to 2019
(from Gomba et al, SIESTA-Final Report)

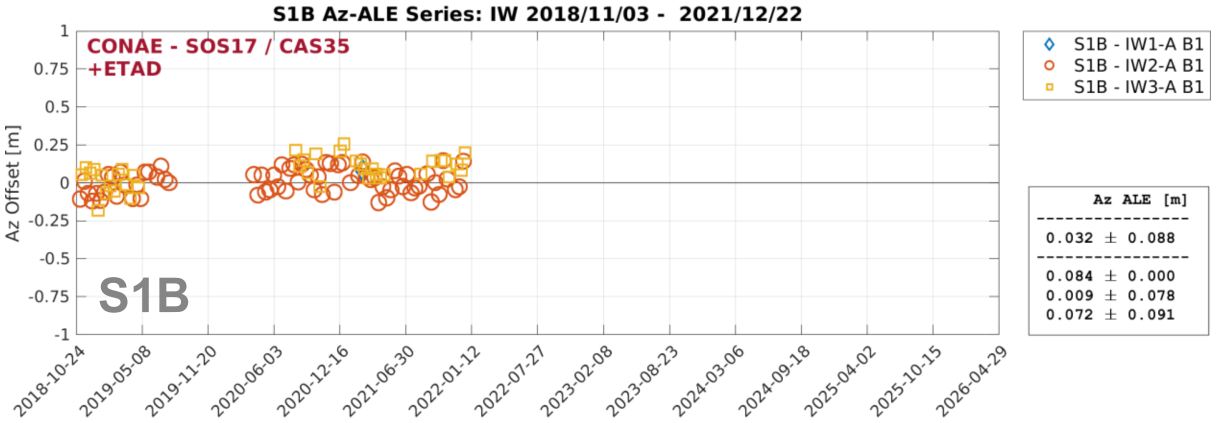
Dominant impact at ±20° along the geo-magnetic equator
- **Up to 1 m in extreme conditions and S-1 Asc passes**
- **Small scale effects not captured**

CR Analysis – Sentinel-1 Azimuth ALE Time Series

IW Ascending: El Sosneado CR 17 and CASLEO CR 35







ETAD Corrections

CR Analysis – Sentinel-1 Azimuth ALE Time Series

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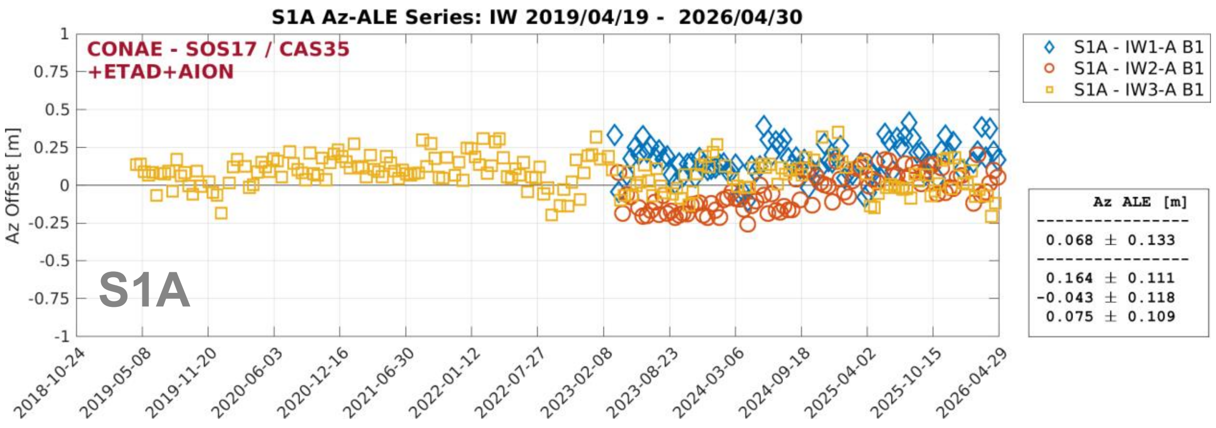
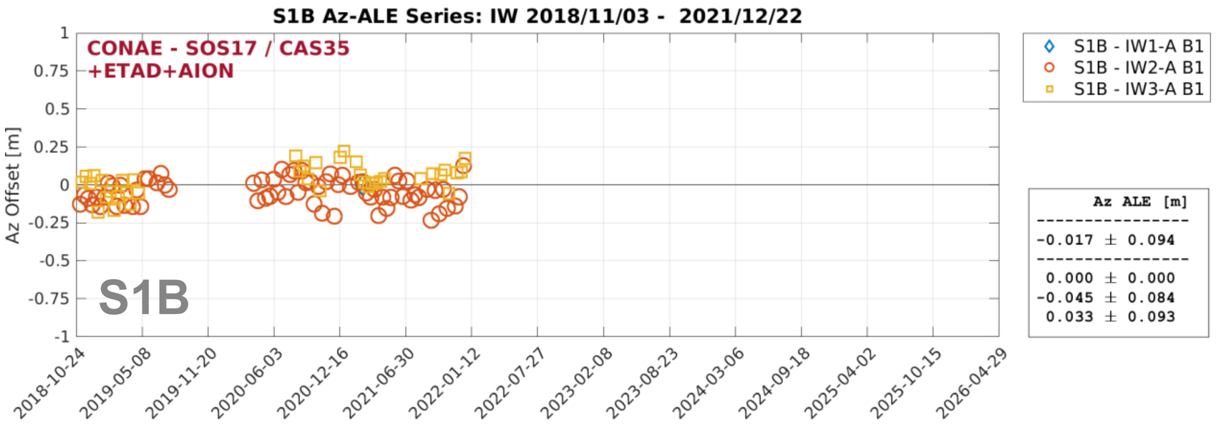




ETAD Corrections & Az Iono (TEC maps)

Beam Offset Time due to Hyperbolic Approximation

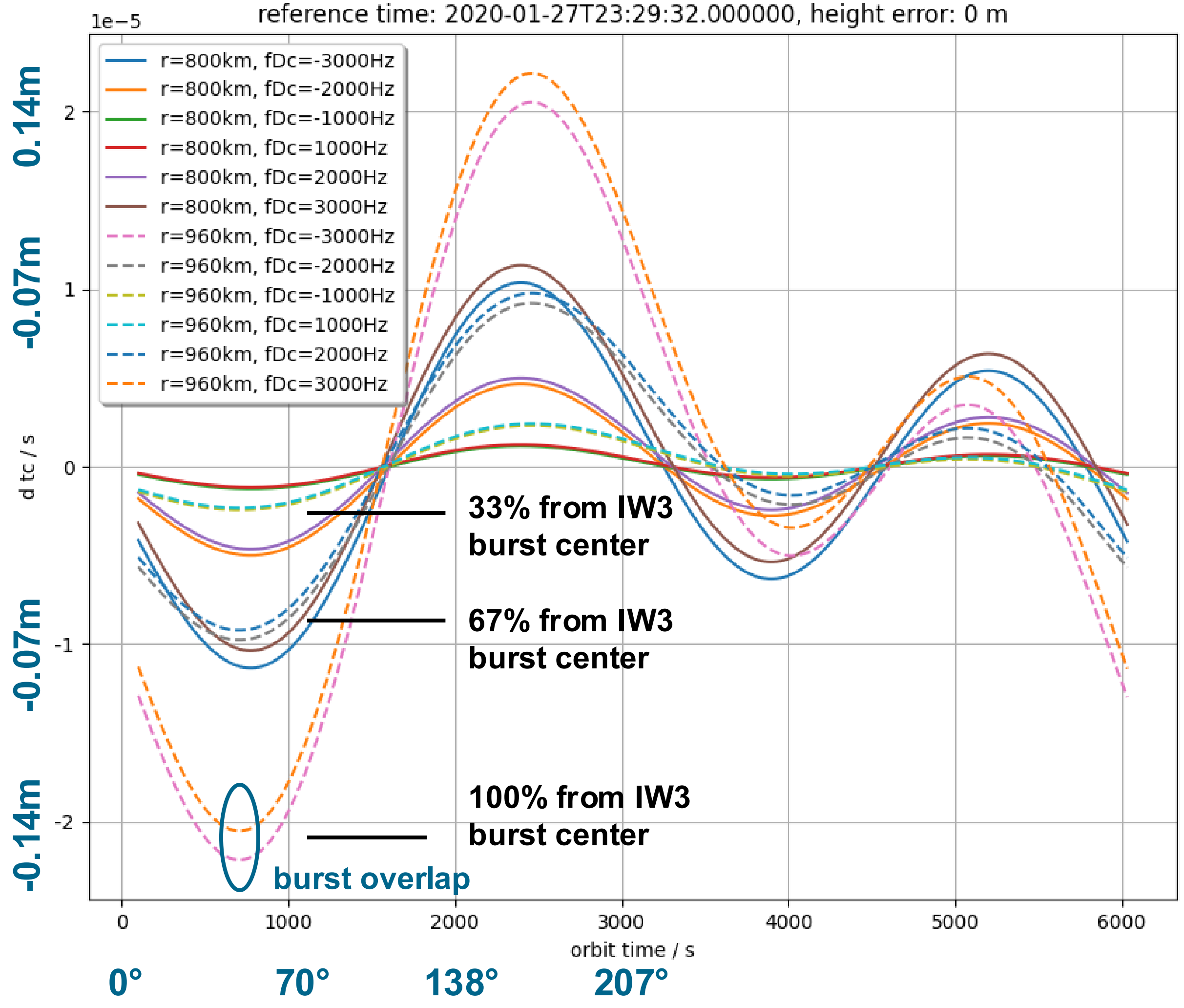
- **Effect associated with L1 SAR data processing**
  - Residual azimuth shift w.r.t. t_{zD} due to assumption of hyperbolic Doppler history in azimuth focusing
  - Correction accounts for time offset between hyperbolic model of IPF and “true” geometric model
  - Effect scales with Doppler and orientation of satellite velocity vector in Earth fixed frame

Effect changes mainly with geographic location and Asc vs Dsc

Assessment Near / Far and Early / Late burst location

- fDC at -3, -2, -1, 1, 2, 3, kHZ
- r = 800 km ≙ IW 1 @ near range
- r = 960 km ≙ IW 3 @ far range

(hyperbolic tc – true tc) in a full S-1 orbit



CR Analysis – Sentinel-1 Azimuth ALE Time Series

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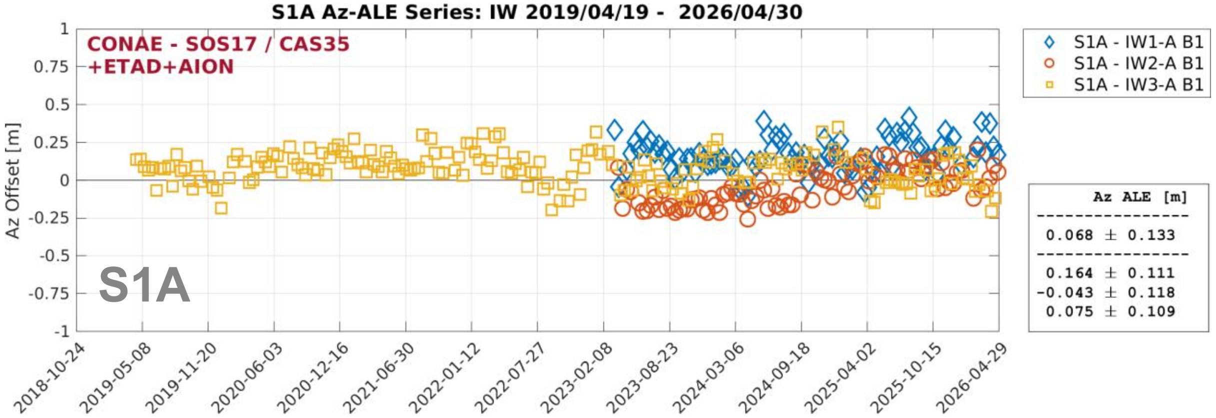

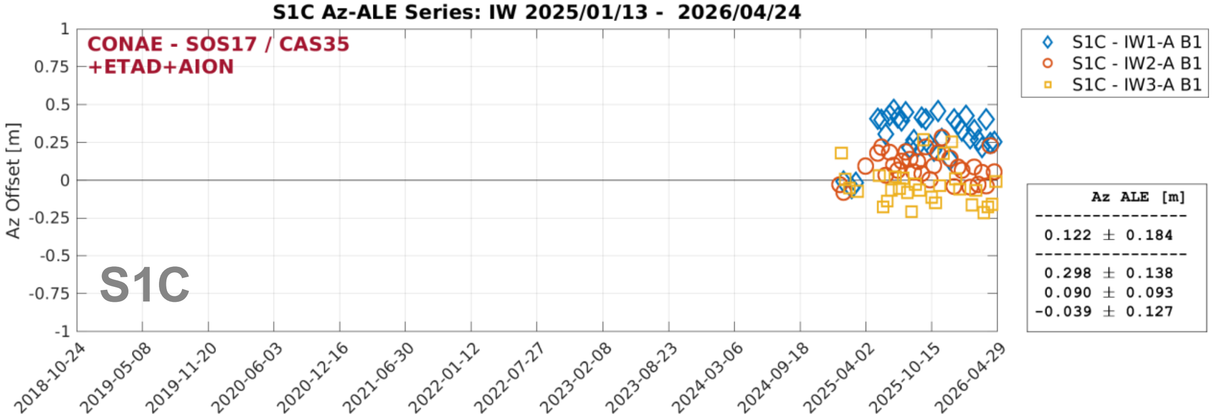

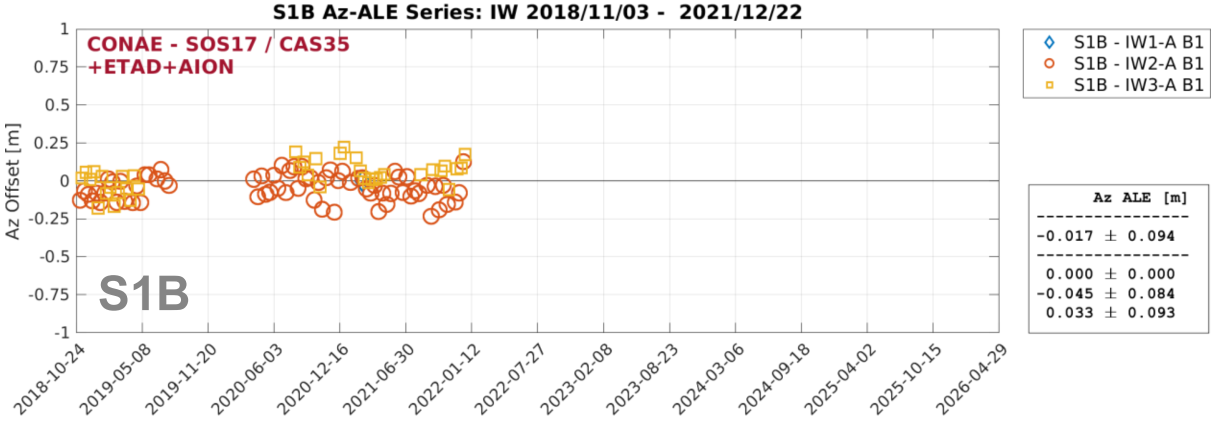

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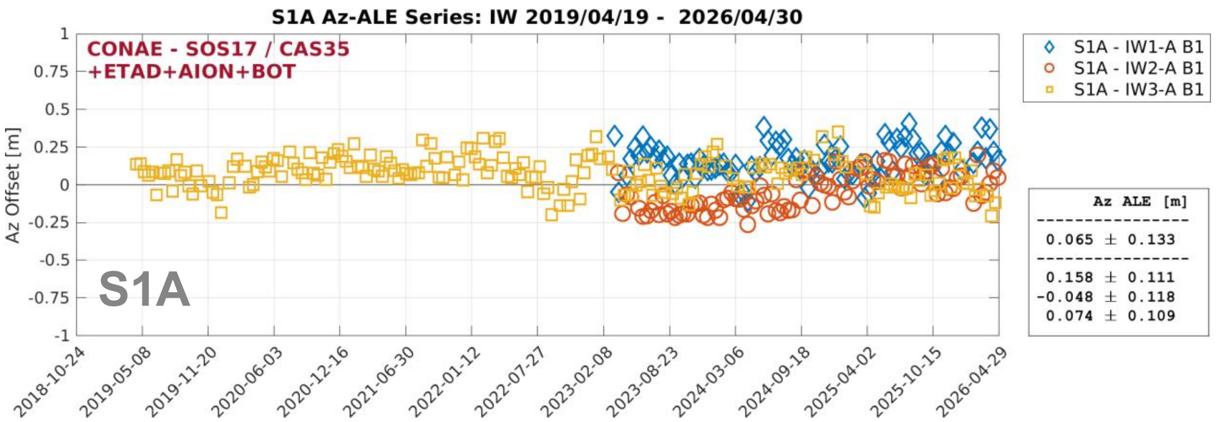
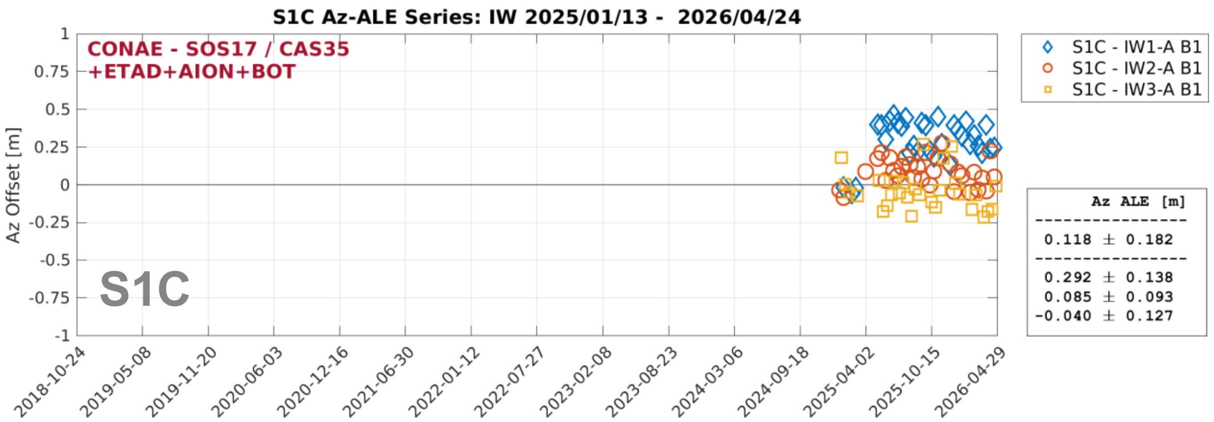
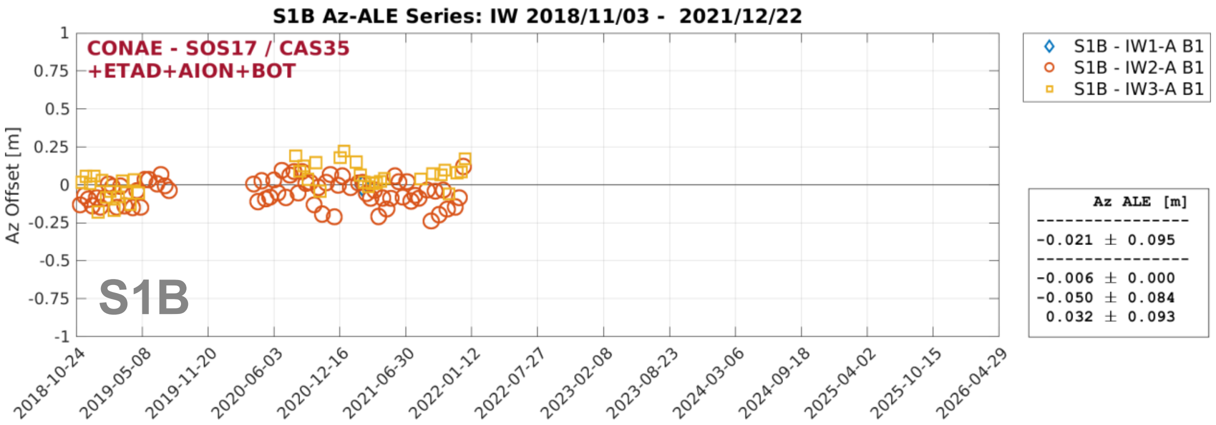






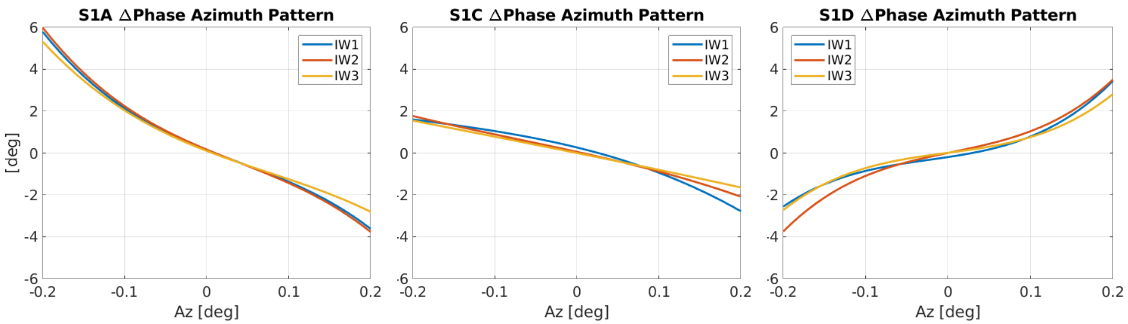
ETAD Corrections & Az Iono (TEC maps) & Beam Offset Time

Azimuth Antenna Patterns Phase Slope

- Azimuth antenna pattern phase contribution over the main lobe → ongoing analysis by ARESYS
  - S-1A: azimuth AAP change due to tile #11 failure in June 2016
  - S-1C: azimuth change due to TRM failures in May 2025
  - S-1D: azimuth change due TRM failures in January 2026
- **Shifts from Azimuth AAP phase slopes**

$$\Delta t_{AAP} = -\underbrace{\left(\frac{k_a(\tau) - k_s}{k_a(\tau)}\right)}_{\text{scaling due to TOPS antenna steering } \alpha_{as}} \cdot s_{AAP} \cdot \frac{\lambda}{4\pi v_s}$$

S-1A/C/D Central Azimuth ΔPattners



First results of IW ΔPhase AAPs from ARESYS documentation

k_a … *Az FM-rate from polynomial used by IPF*

k_s … *Doppler-rate introduced by antenna steering (almost a constant per sub-swath)*

s_{AAP} … *Phase slope from AAPs*

v_s … *Satellite velocity (roughly constant ~7590 m/s)*

Average slope from curves

s_{AAP}	IW1	IW2	IW3
S1A	-15.48	-16.33	-15.10
S1C	-9.58	-8.61	-7.87
S1D	5.94	8.15	5.22

α_{as}	IW1	IW2	IW3
Near Rg	4.28	3.14	4.25
Far Rg	4.50	3.30	4.47

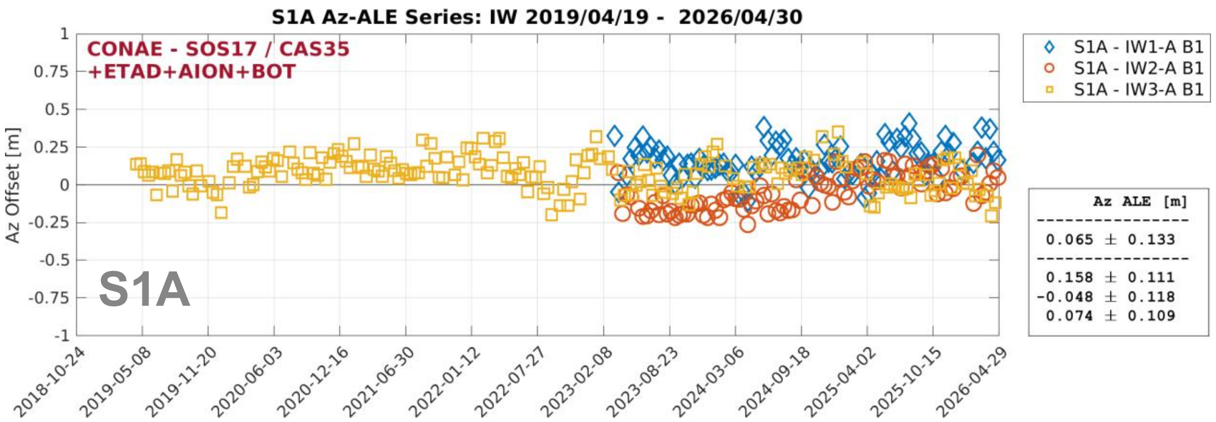
Approximate Estimate
Near / Far in meters

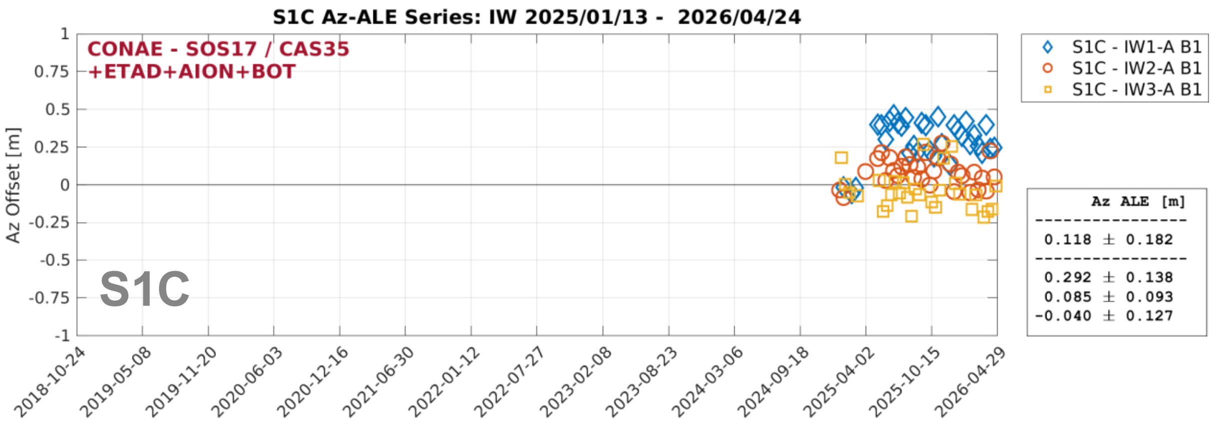
Δt_{AAP}		IW1	IW2	IW3
S1A	Near	0,263	0,204	0,255
	Far	0,277	0,214	0,268
S1C	Near	0,163	0,108	0,133
	Far	0,171	0,113	0,140
S1D	Near	-0,101	-0,102	-0,088
	Far	-0,106	-0,107	-0,093

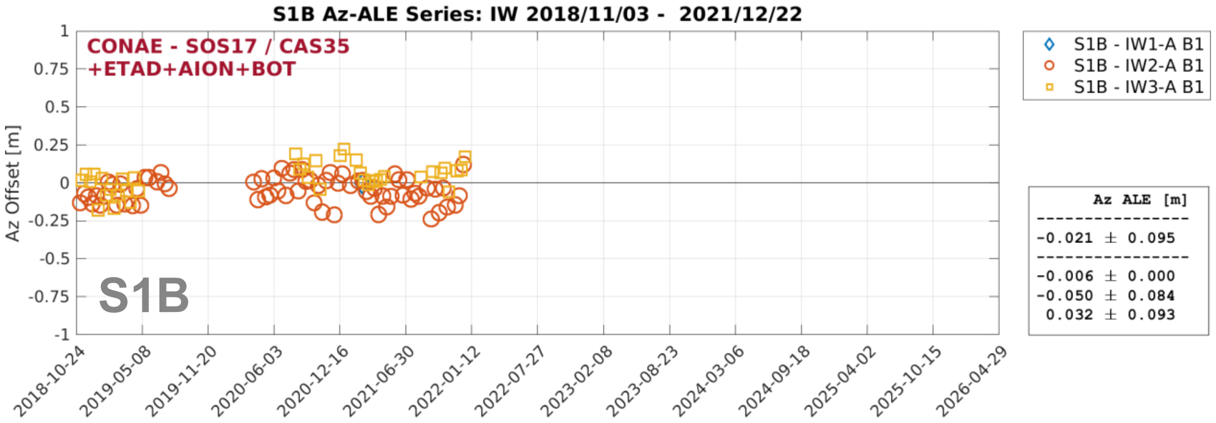
Average already in the AUX ITC (except S-1C) → applying Δt_{AAP} will worsen results for now!

CR Analysis – Sentinel-1 Azimuth ALE Time Series

IW Ascending: El Sosneado CR 17 and CASLEO CR 35







ETAD Corrections & Az Iono (TEC maps) & Beam Offset Time

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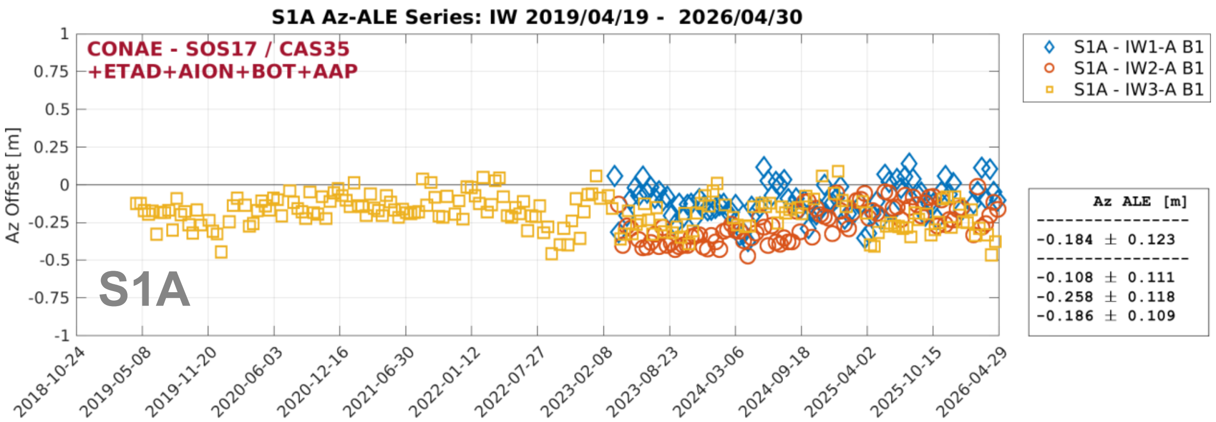
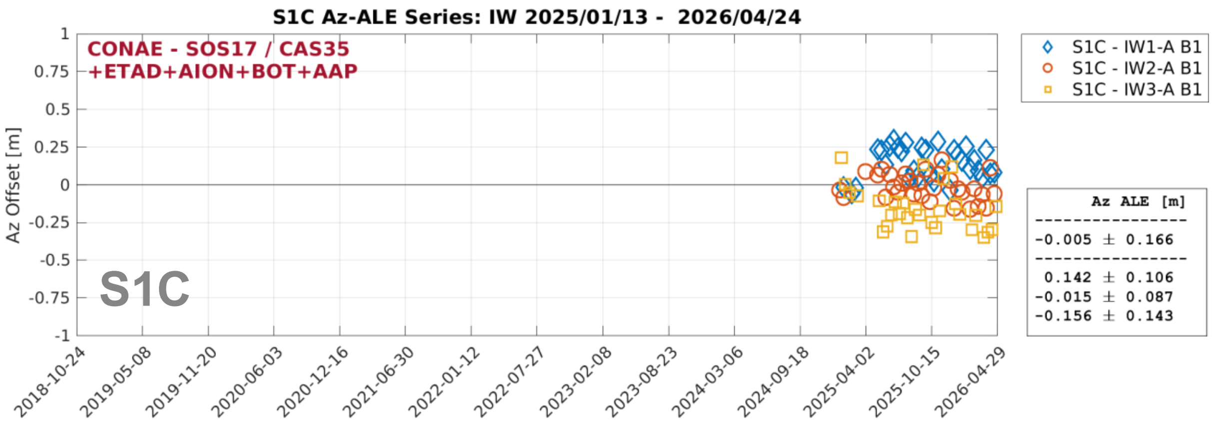
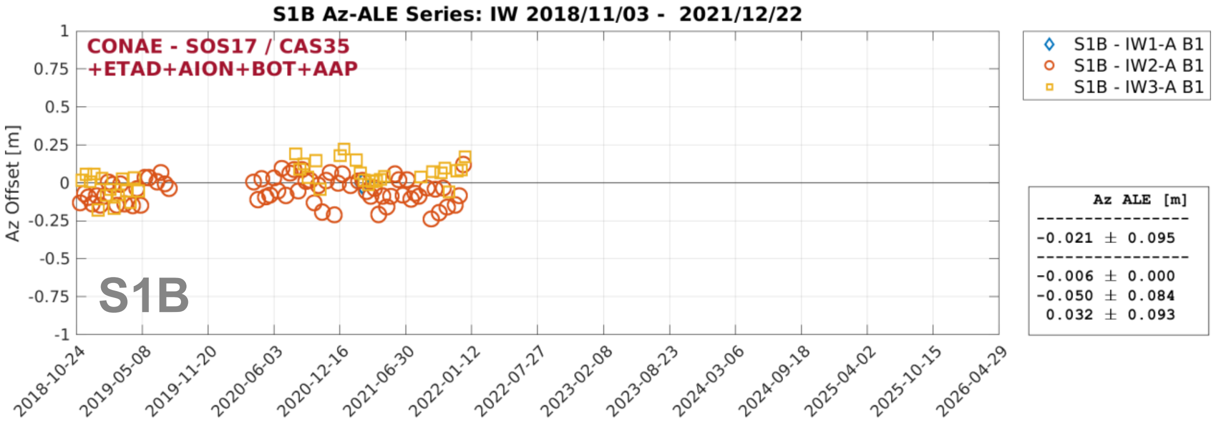




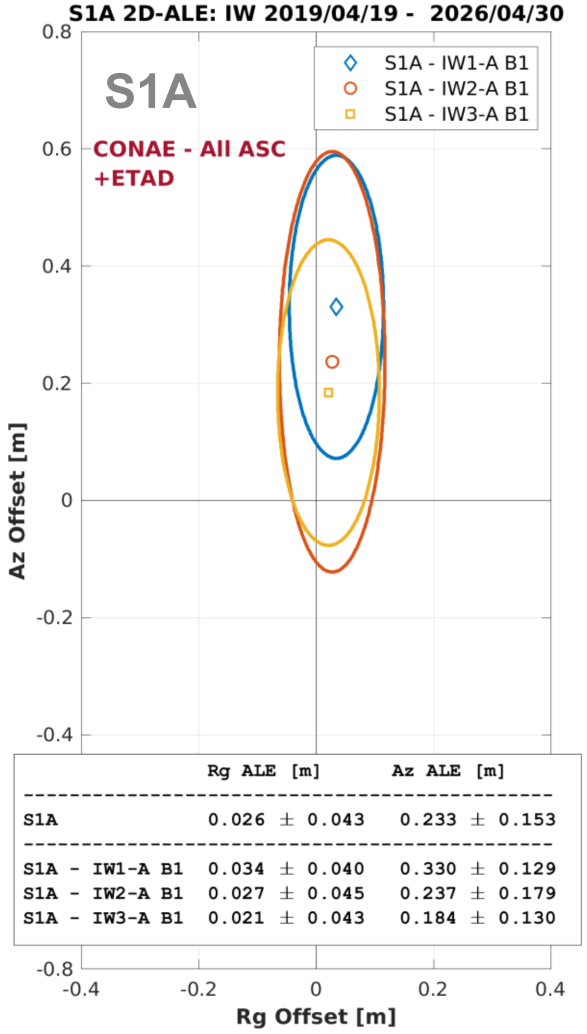


ETAD Corrections & Az Iono (TEC maps) & Beam Offset Time & Az AAP Phase

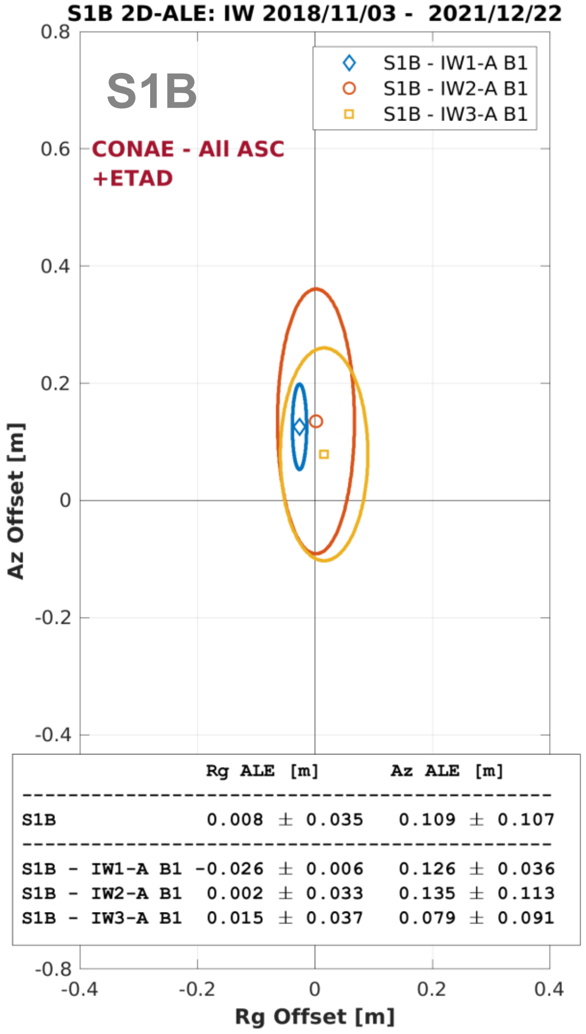
Overall CONAE El Sosneado and CASLEO Az-ALE Results

Overall Site Results – ASCENDING 2D ALE

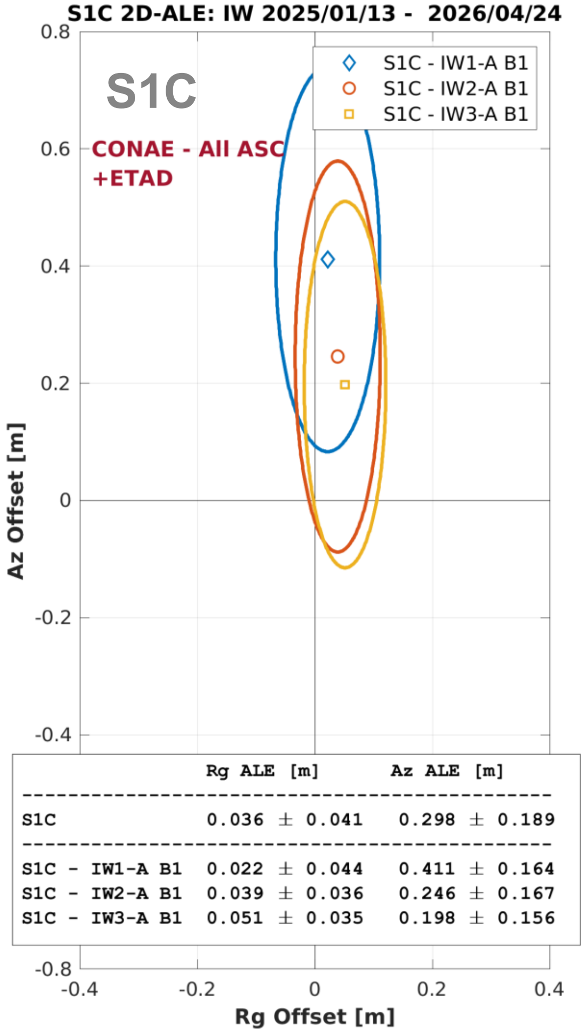
Per stack: Residual means and 2 x STD (= 95% ellipse)



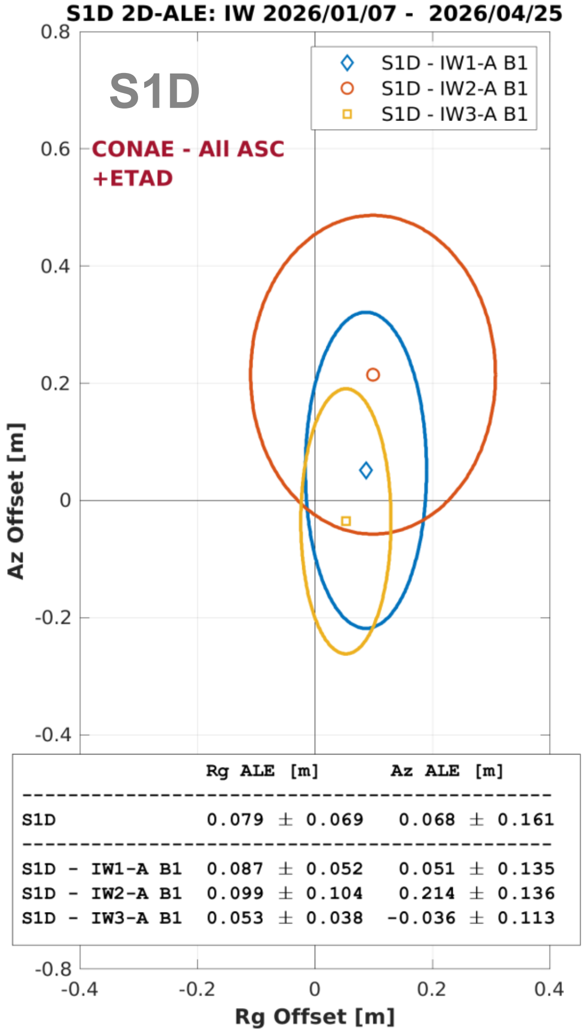
	Rg ALE [m]	Az ALE [m]
S1A	0.026 ± 0.043	0.233 ± 0.153
S1A - IW1-A B1	0.034 ± 0.040	0.330 ± 0.129
S1A - IW2-A B1	0.027 ± 0.045	0.237 ± 0.179
S1A - IW3-A B1	0.021 ± 0.043	0.184 ± 0.130



	Rg ALE [m]	Az ALE [m]
S1B	0.008 ± 0.035	0.109 ± 0.107
S1B - IW1-A B1	-0.026 ± 0.006	0.126 ± 0.036
S1B - IW2-A B1	0.002 ± 0.033	0.135 ± 0.113
S1B - IW3-A B1	0.015 ± 0.037	0.079 ± 0.091



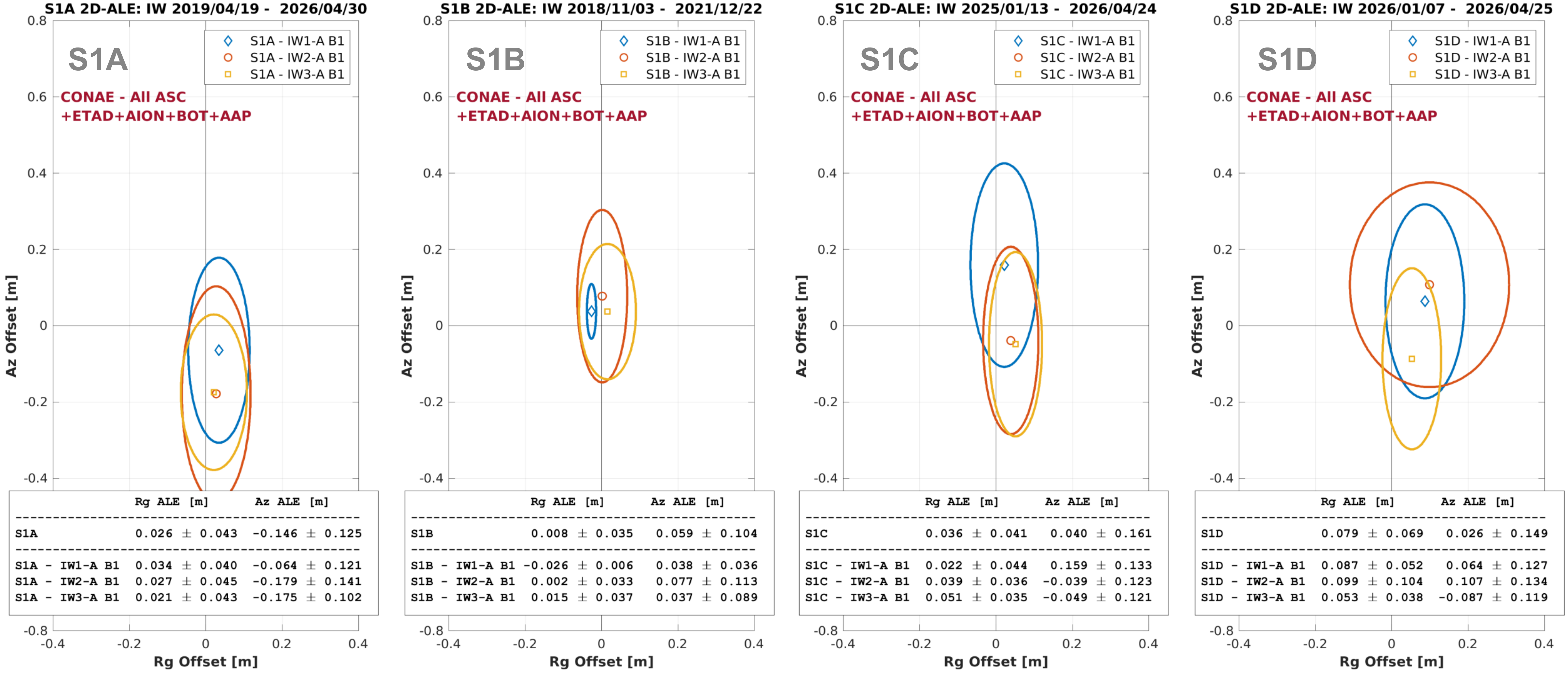
	Rg ALE [m]	Az ALE [m]
S1C	0.036 ± 0.041	0.298 ± 0.189
S1C - IW1-A B1	0.022 ± 0.044	0.411 ± 0.164
S1C - IW2-A B1	0.039 ± 0.036	0.246 ± 0.167
S1C - IW3-A B1	0.051 ± 0.035	0.198 ± 0.156



	Rg ALE [m]	Az ALE [m]
S1D	0.079 ± 0.069	0.068 ± 0.161
S1D - IW1-A B1	0.087 ± 0.052	0.051 ± 0.135
S1D - IW2-A B1	0.099 ± 0.104	0.214 ± 0.136
S1D - IW3-A B1	0.053 ± 0.038	-0.036 ± 0.113

Overall Site Results – Ascending 2D ALE

Per stack: Residual means and 2 x STD (= 95% ellipse)



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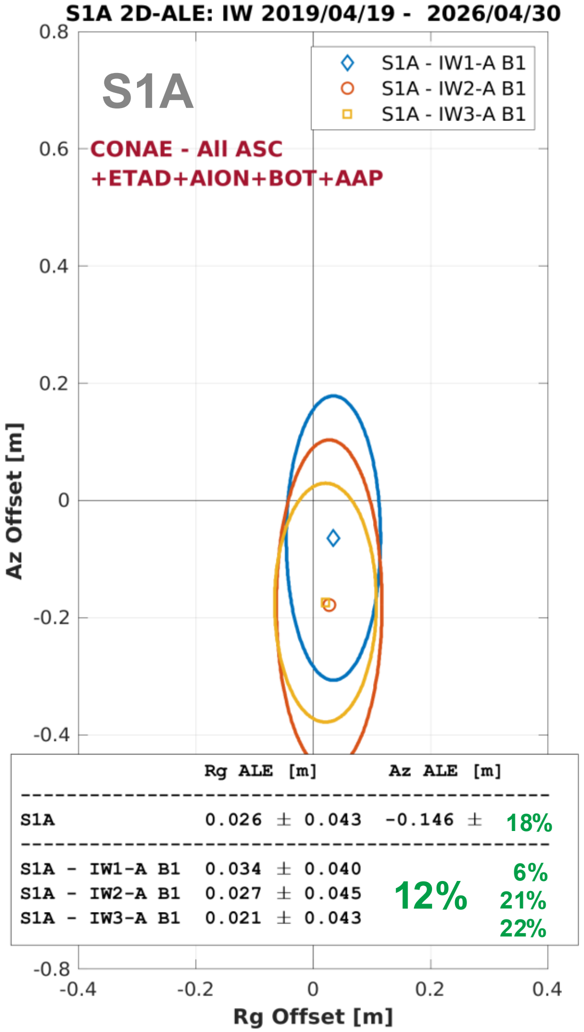
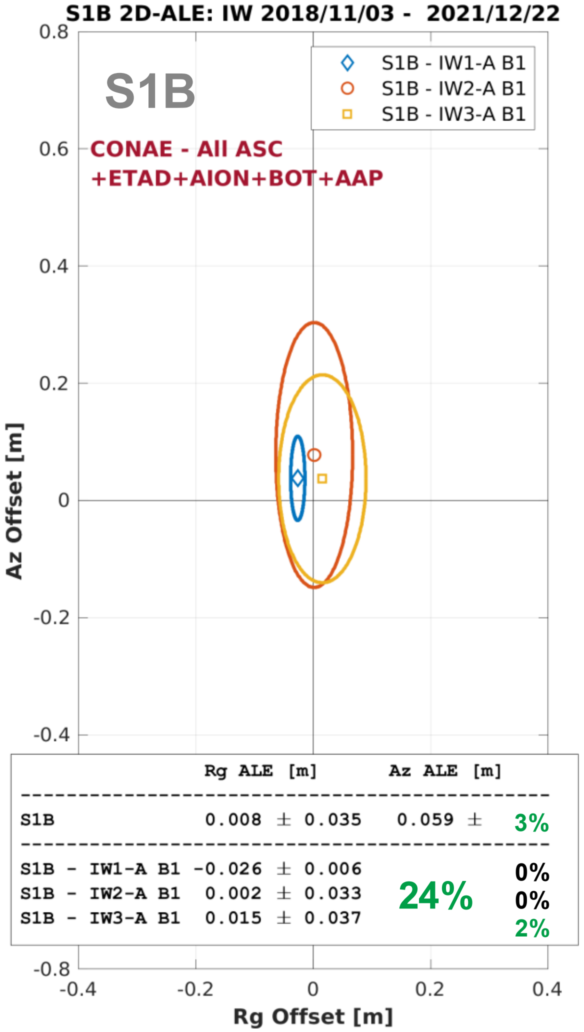
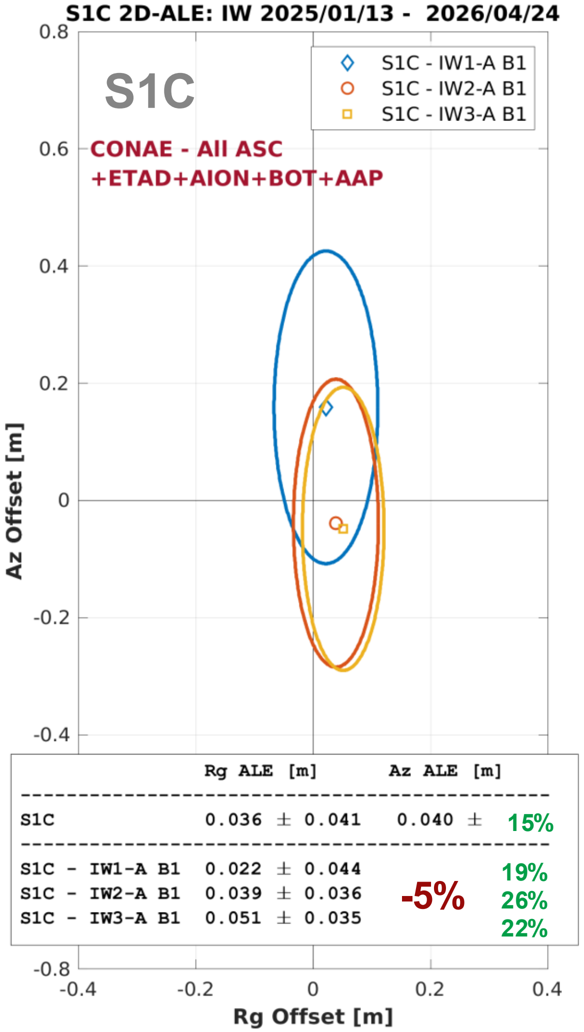
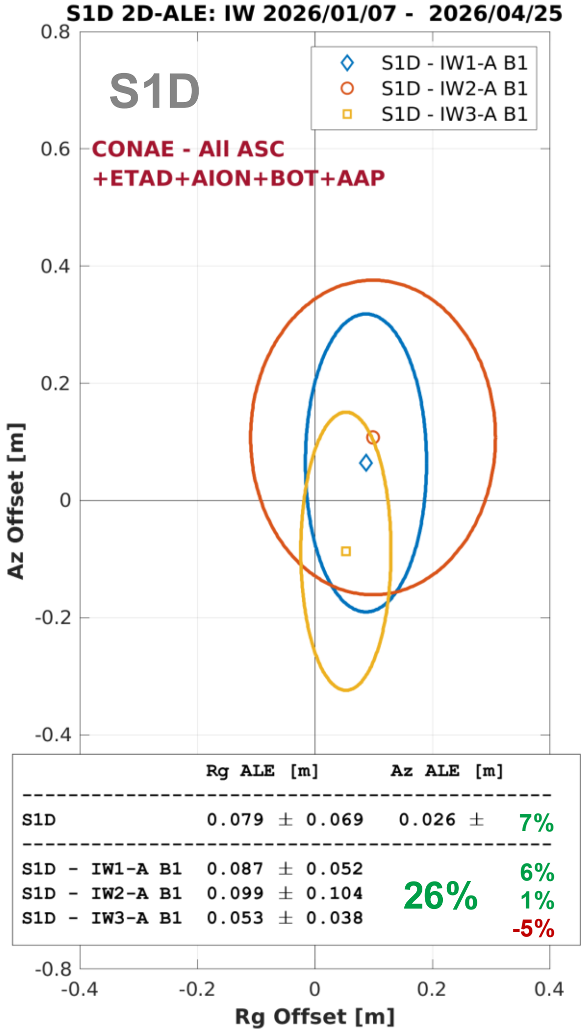


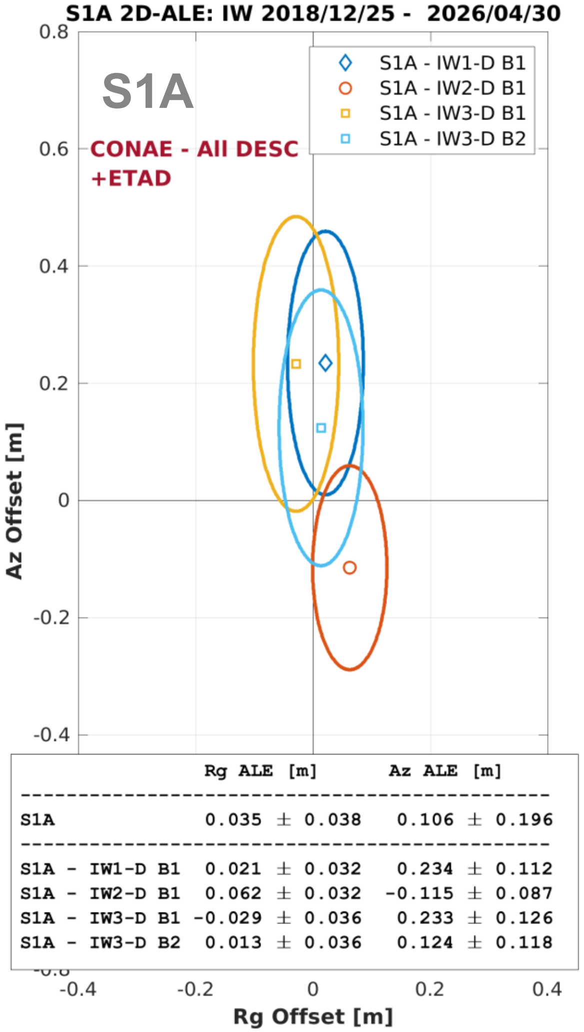




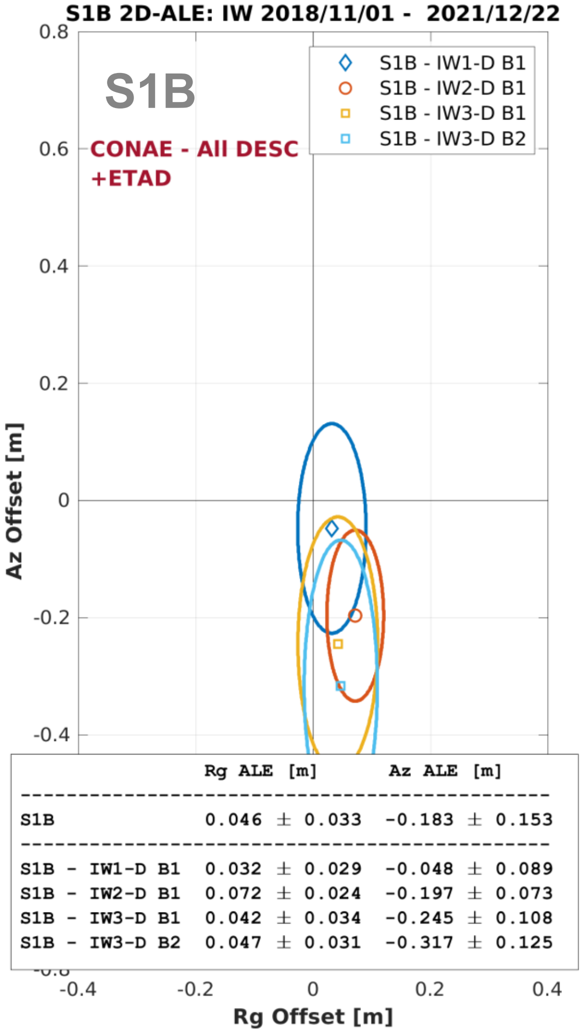


Overall Site Results – Descending 2D ALE

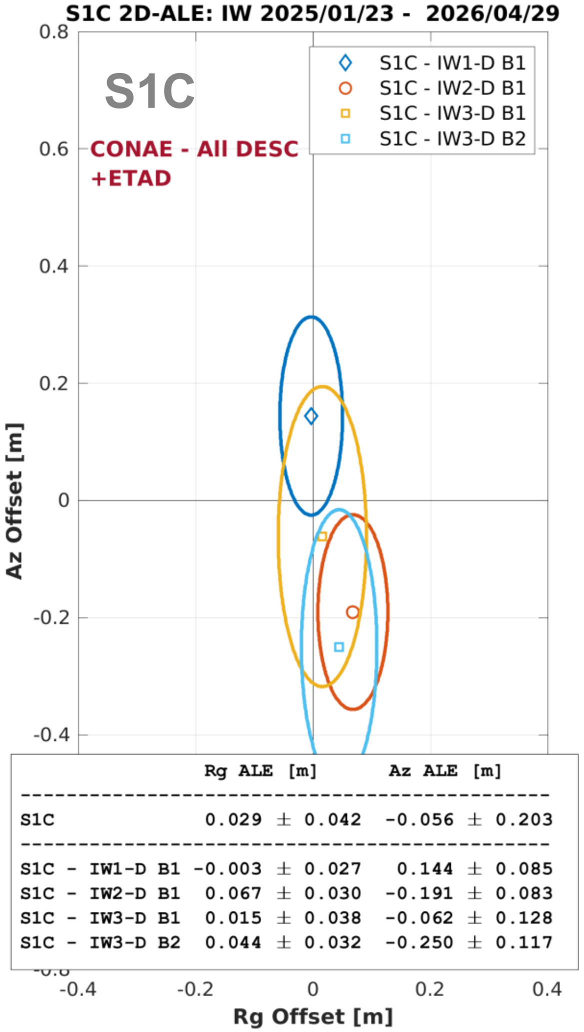
Per stack: Residual means and 2 x STD (= 95% ellipse)



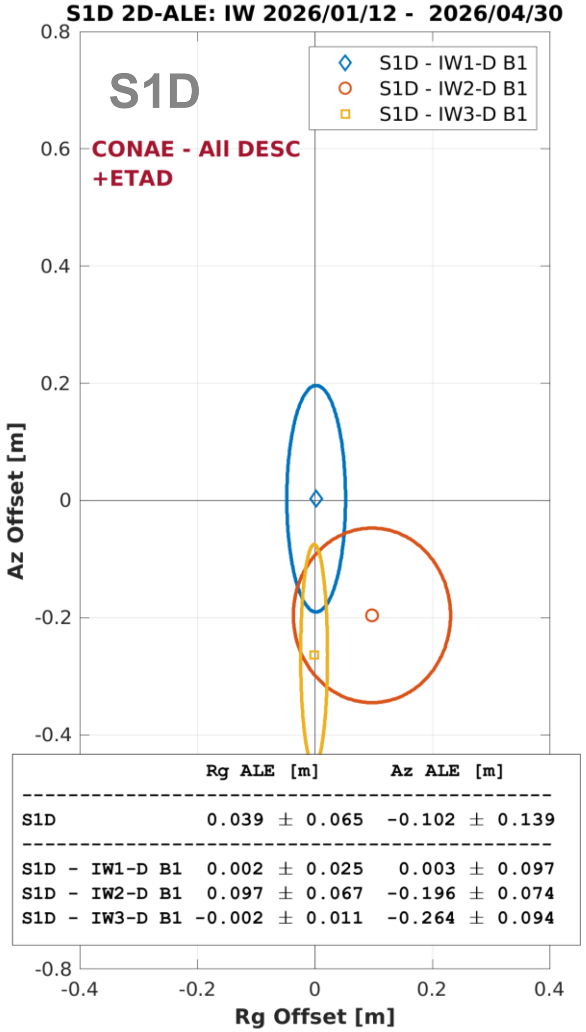
	Rg ALE [m]	Az ALE [m]
S1A	0.035 ± 0.038	0.106 ± 0.196
S1A - IW1-D B1	0.021 ± 0.032	0.234 ± 0.112
S1A - IW2-D B1	0.062 ± 0.032	-0.115 ± 0.087
S1A - IW3-D B1	-0.029 ± 0.036	0.233 ± 0.126
S1A - IW3-D B2	0.013 ± 0.036	0.124 ± 0.118



	Rg ALE [m]	Az ALE [m]
S1B	0.046 ± 0.033	-0.183 ± 0.153
S1B - IW1-D B1	0.032 ± 0.029	-0.048 ± 0.089
S1B - IW2-D B1	0.072 ± 0.024	-0.197 ± 0.073
S1B - IW3-D B1	0.042 ± 0.034	-0.245 ± 0.108
S1B - IW3-D B2	0.047 ± 0.031	-0.317 ± 0.125



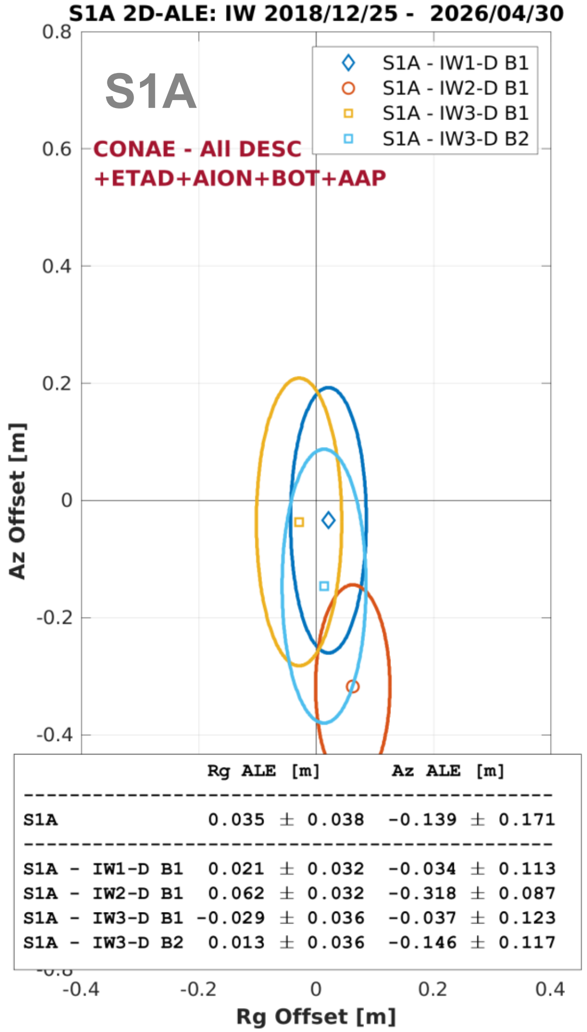
	Rg ALE [m]	Az ALE [m]
S1C	0.029 ± 0.042	-0.056 ± 0.203
S1C - IW1-D B1	-0.003 ± 0.027	0.144 ± 0.085
S1C - IW2-D B1	0.067 ± 0.030	-0.191 ± 0.083
S1C - IW3-D B1	0.015 ± 0.038	-0.062 ± 0.128
S1C - IW3-D B2	0.044 ± 0.032	-0.250 ± 0.117



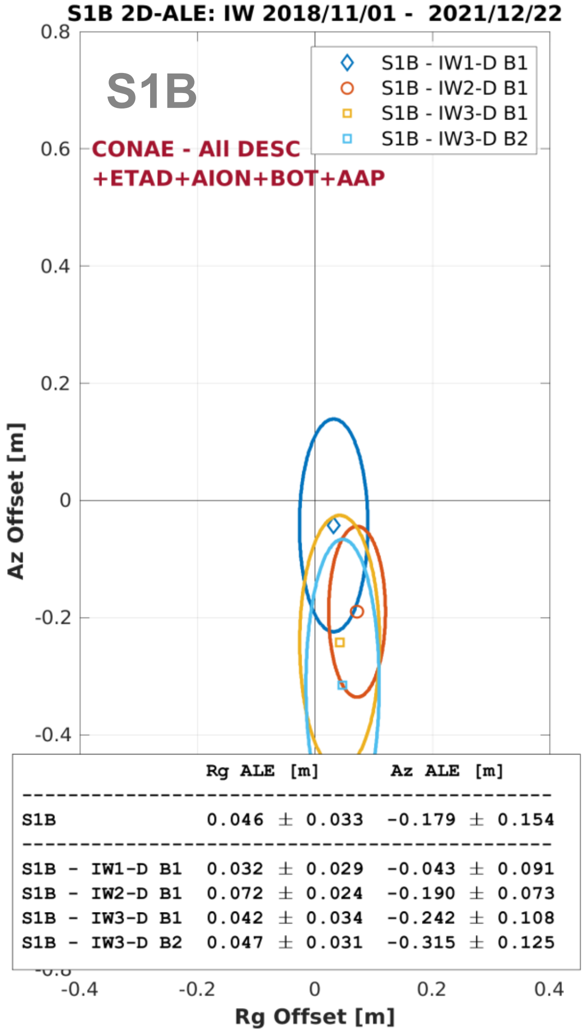
	Rg ALE [m]	Az ALE [m]
S1D	0.039 ± 0.065	-0.102 ± 0.139
S1D - IW1-D B1	0.002 ± 0.025	0.003 ± 0.097
S1D - IW2-D B1	0.097 ± 0.067	-0.196 ± 0.074
S1D - IW3-D B1	-0.002 ± 0.011	-0.264 ± 0.094

Overall Site Results – Descending 2D ALE

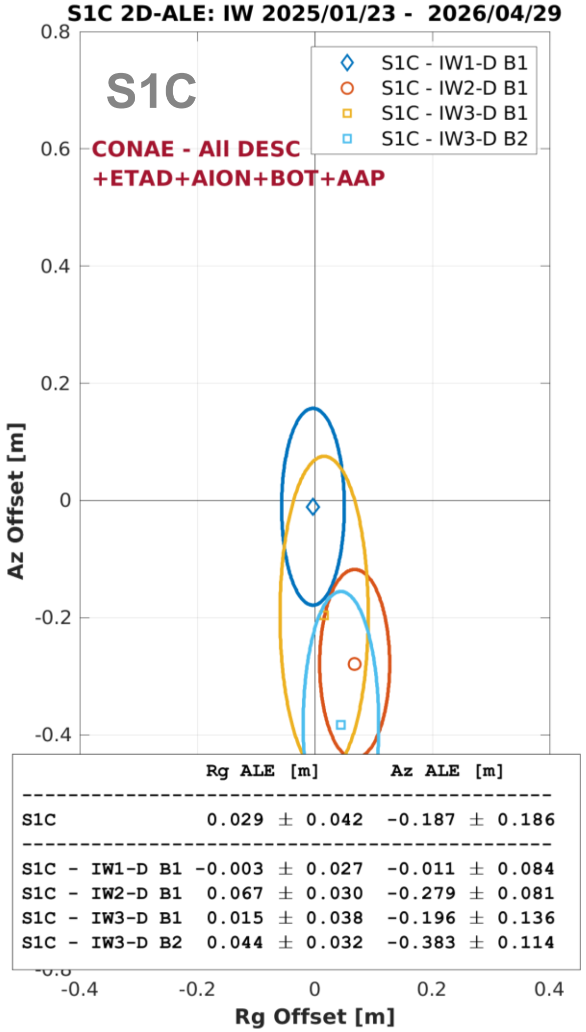
Per stack: Residual means and 2 x STD (= 95% ellipse)



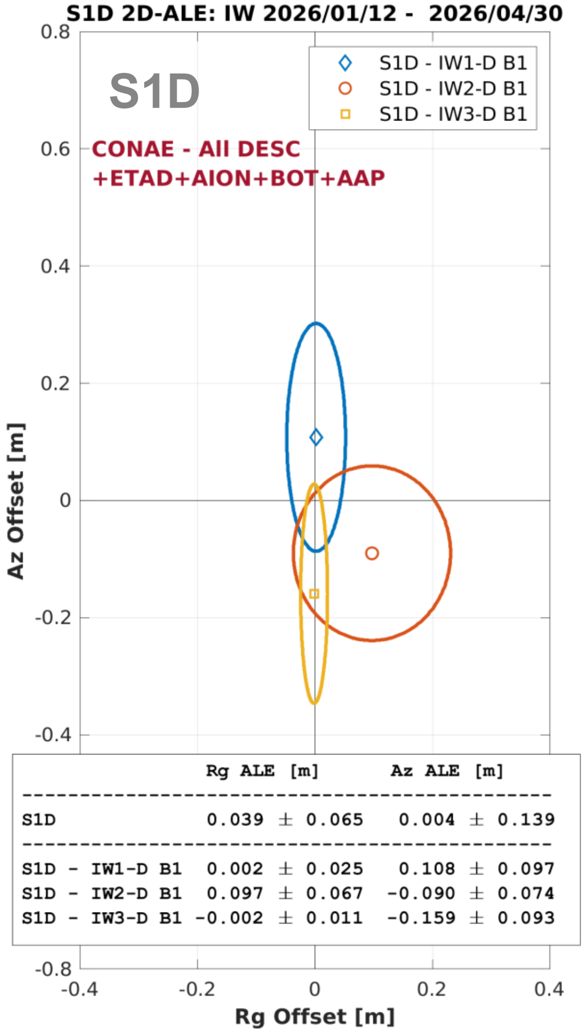
	Rg ALE [m]	Az ALE [m]
S1A	0.035 ± 0.038	-0.139 ± 0.171
S1A - IW1-D B1	0.021 ± 0.032	-0.034 ± 0.113
S1A - IW2-D B1	0.062 ± 0.032	-0.318 ± 0.087
S1A - IW3-D B1	-0.029 ± 0.036	-0.037 ± 0.123
S1A - IW3-D B2	0.013 ± 0.036	-0.146 ± 0.117



	Rg ALE [m]	Az ALE [m]
S1B	0.046 ± 0.033	-0.179 ± 0.154
S1B - IW1-D B1	0.032 ± 0.029	-0.043 ± 0.091
S1B - IW2-D B1	0.072 ± 0.024	-0.190 ± 0.073
S1B - IW3-D B1	0.042 ± 0.034	-0.242 ± 0.108
S1B - IW3-D B2	0.047 ± 0.031	-0.315 ± 0.125



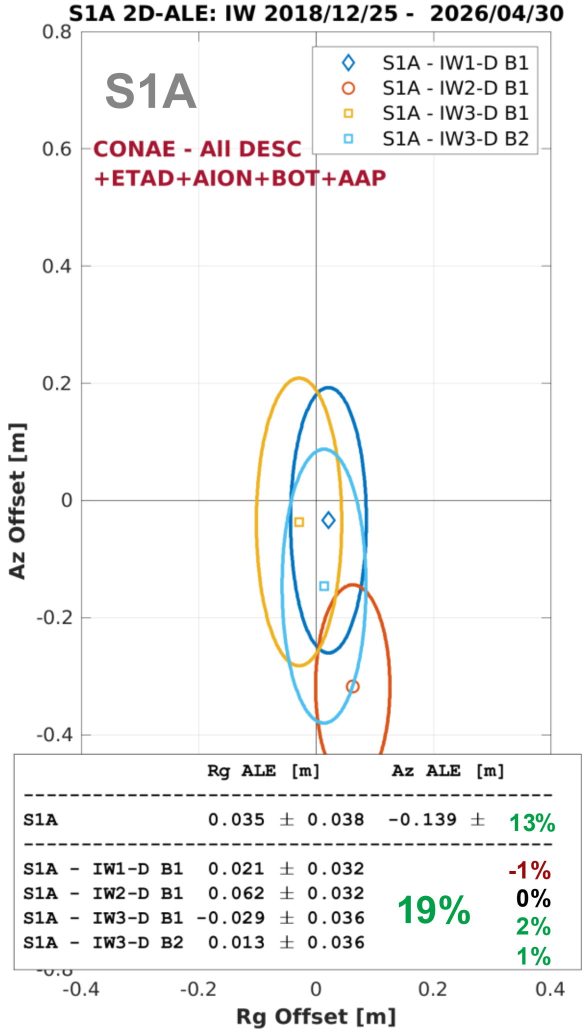
	Rg ALE [m]	Az ALE [m]
S1C	0.029 ± 0.042	-0.187 ± 0.186
S1C - IW1-D B1	-0.003 ± 0.027	-0.011 ± 0.084
S1C - IW2-D B1	0.067 ± 0.030	-0.279 ± 0.081
S1C - IW3-D B1	0.015 ± 0.038	-0.196 ± 0.136
S1C - IW3-D B2	0.044 ± 0.032	-0.383 ± 0.114



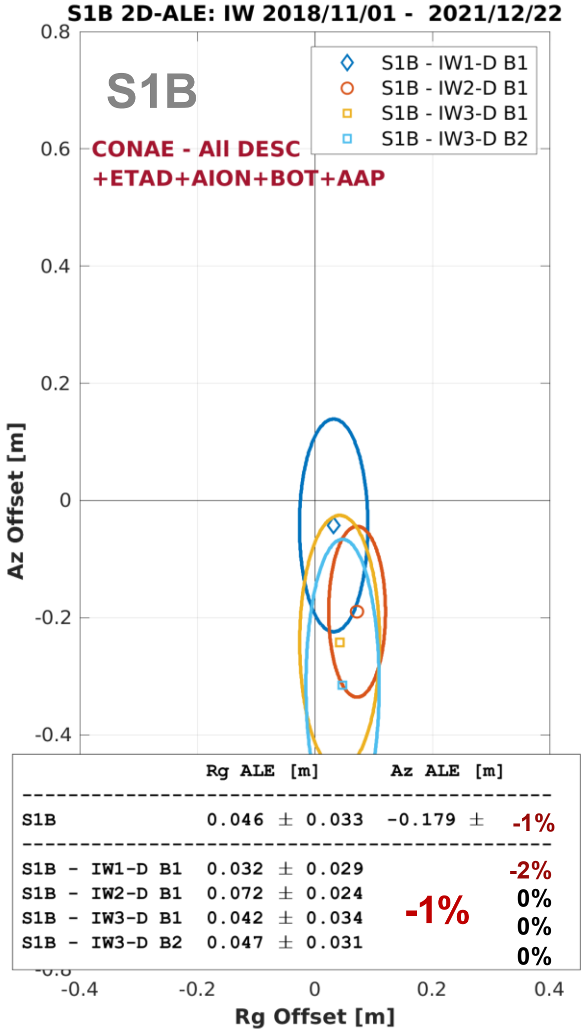
	Rg ALE [m]	Az ALE [m]
S1D	0.039 ± 0.065	0.004 ± 0.139
S1D - IW1-D B1	0.002 ± 0.025	0.108 ± 0.097
S1D - IW2-D B1	0.097 ± 0.067	-0.090 ± 0.074
S1D - IW3-D B1	-0.002 ± 0.011	-0.159 ± 0.093

Overall Site Results – Descending 2D ALE

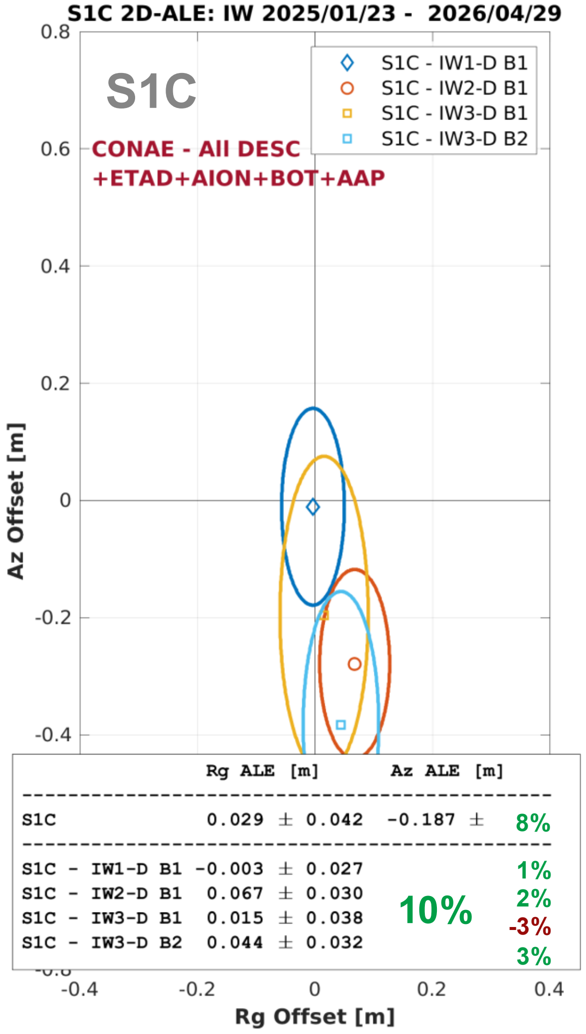
Per stack: Residual means and 2 x STD (= 95% ellipse)



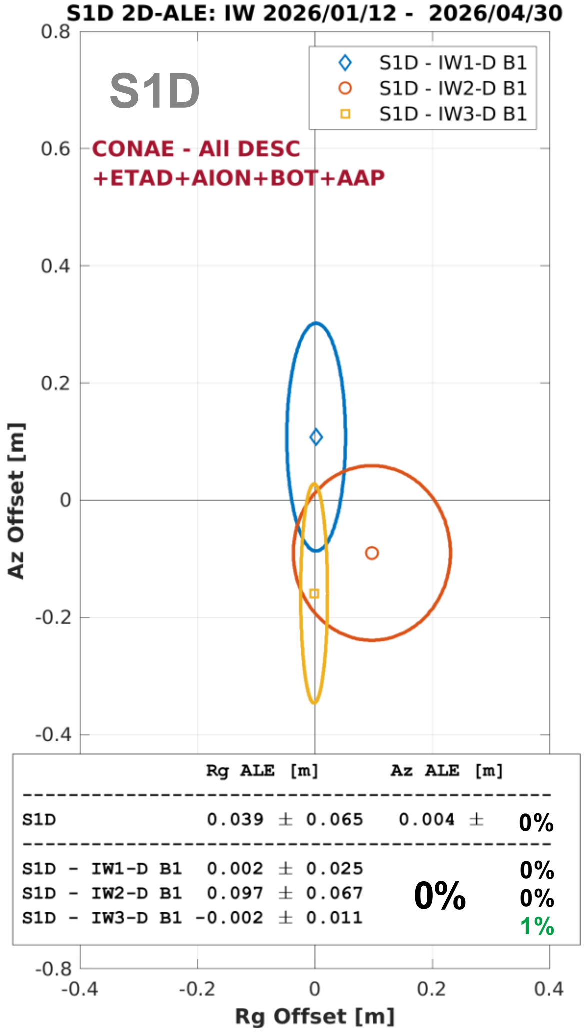
	Rg ALE [m]	Az ALE [m]	
S1A	0.035 ± 0.038	-0.139 ±	13%
S1A - IW1-D B1	0.021 ± 0.032	19%	-1%
S1A - IW2-D B1	0.062 ± 0.032		0%
S1A - IW3-D B1	-0.029 ± 0.036		2%
S1A - IW3-D B2	0.013 ± 0.036		1%



	Rg ALE [m]	Az ALE [m]	
S1B	0.046 ± 0.033	-0.179 ±	-1%
S1B - IW1-D B1	0.032 ± 0.029	-1%	-2%
S1B - IW2-D B1	0.072 ± 0.024		0%
S1B - IW3-D B1	0.042 ± 0.034		0%
S1B - IW3-D B2	0.047 ± 0.031		0%



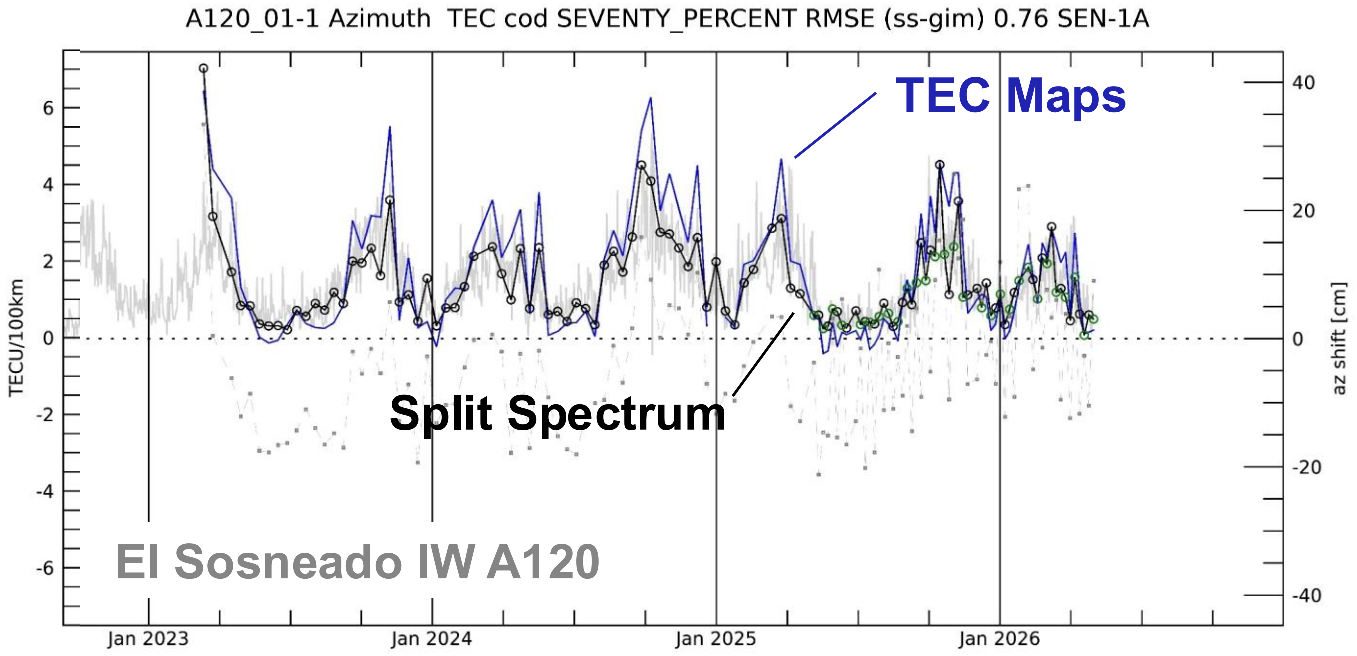
	Rg ALE [m]	Az ALE [m]	
S1C	0.029 ± 0.042	-0.187 ±	8%
S1C - IW1-D B1	-0.003 ± 0.027	10%	1%
S1C - IW2-D B1	0.067 ± 0.030		2%
S1C - IW3-D B1	0.015 ± 0.038		-3%
S1C - IW3-D B2	0.044 ± 0.032		3%



	Rg ALE [m]	Az ALE [m]	
S1D	0.039 ± 0.065	0.004 ±	0%
S1D - IW1-D B1	0.002 ± 0.025	0%	0%
S1D - IW2-D B1	0.097 ± 0.067		0%
S1D - IW3-D B1	-0.002 ± 0.011		1%

Next Steps: Split-Spectrum and Detailed AAPs

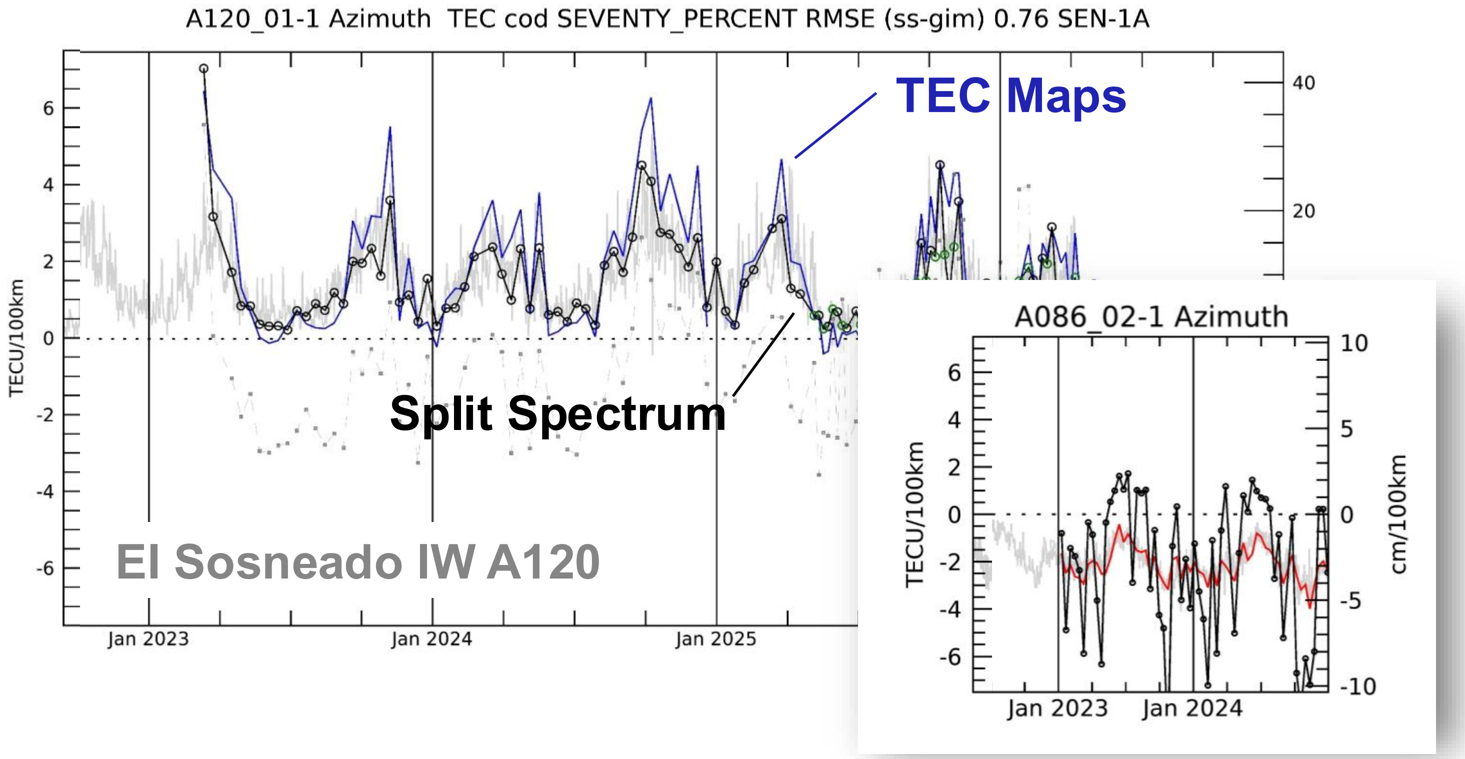
Local ionosphere **gradient from Split-Spectrum method** for each scene aligned to average TEC map gradient → **more precise results?**

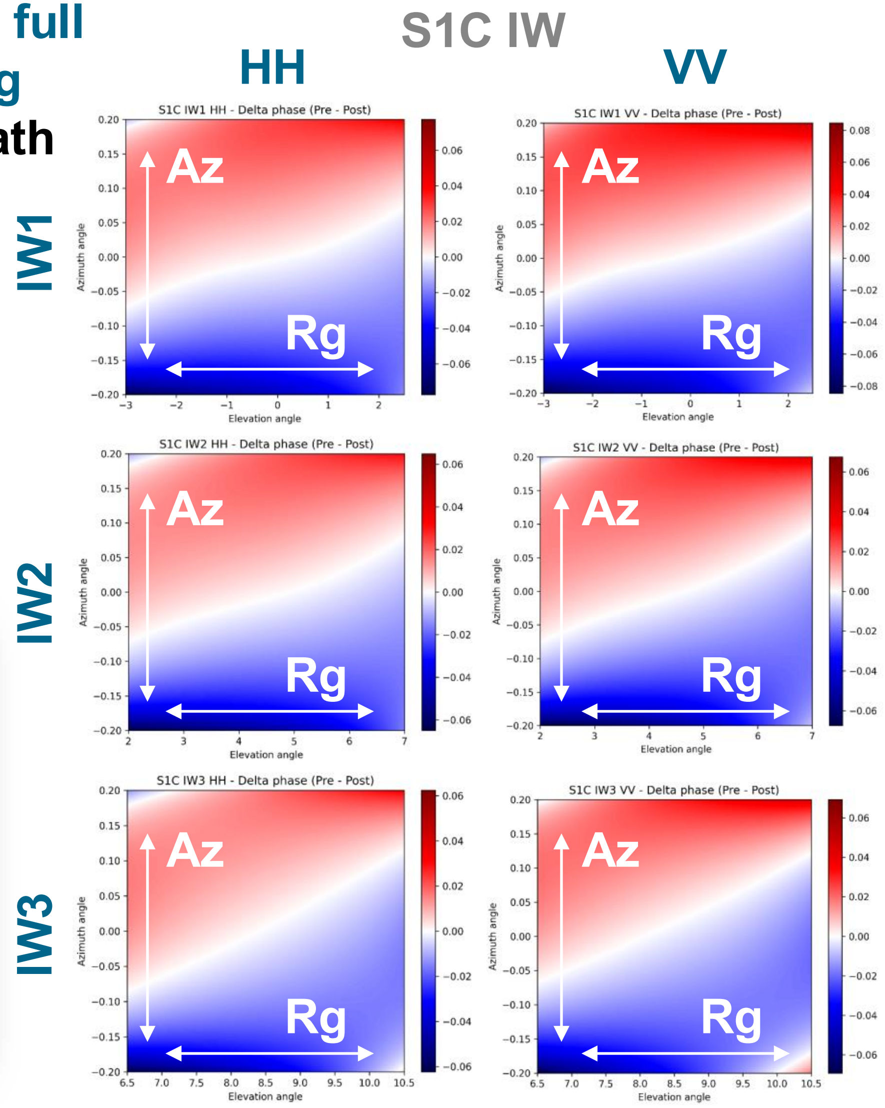


Next Steps: Split-Spectrum and Detailed AAPs

Local ionosphere **gradient from Split-Spectrum method** for each scene aligned to average TEC map gradient → **more precise results?**

2D Azimuth Antenna Phase Patterns + full TopSAR scanning → better sub-swath alignment?





Summary

- Sentinel-1 has very good geolocation capabilities across all the S-1A/B/C/D units
- Excellent agreement with TerraSAR-X → **standardized correction methods (ETAD) are useful**
- Large CRs at CONAE sites allow for detailed Sentinel-1 azimuth data assessment
  - **Three additional azimuth shift effects studied**
    - **Along-track ionosphere gradients** → **clear improvement of azimuth ALE even with TEC maps data**
    - **Hyperbolic model beam-offset time** → no impact at CONAE sites but some effect across our global sites
    - **Differential azimuth antenna phase patterns** → **positive effect demonstrated (S-1A and S-1C)**
  - **But tackling the Sentinel-1 IW sub-swath effects remains a challenge**
    - **Still some 1-3 dcm relative biases between IW1/2/3**
    - **Discrepancies between Ascending and Descending stacks**
- **Next steps**
  - Detailed antenna phase patterns for each sensor / mode / polarization
  - More accurate ionosphere TEC gradients from split-spectrum methods

→ The S-1 ETAD product will be extended depending on the outcomes

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