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Impact of ETAD-like corrections on OPERA Coregistered Single Look Complex products from Sentinel-1 data

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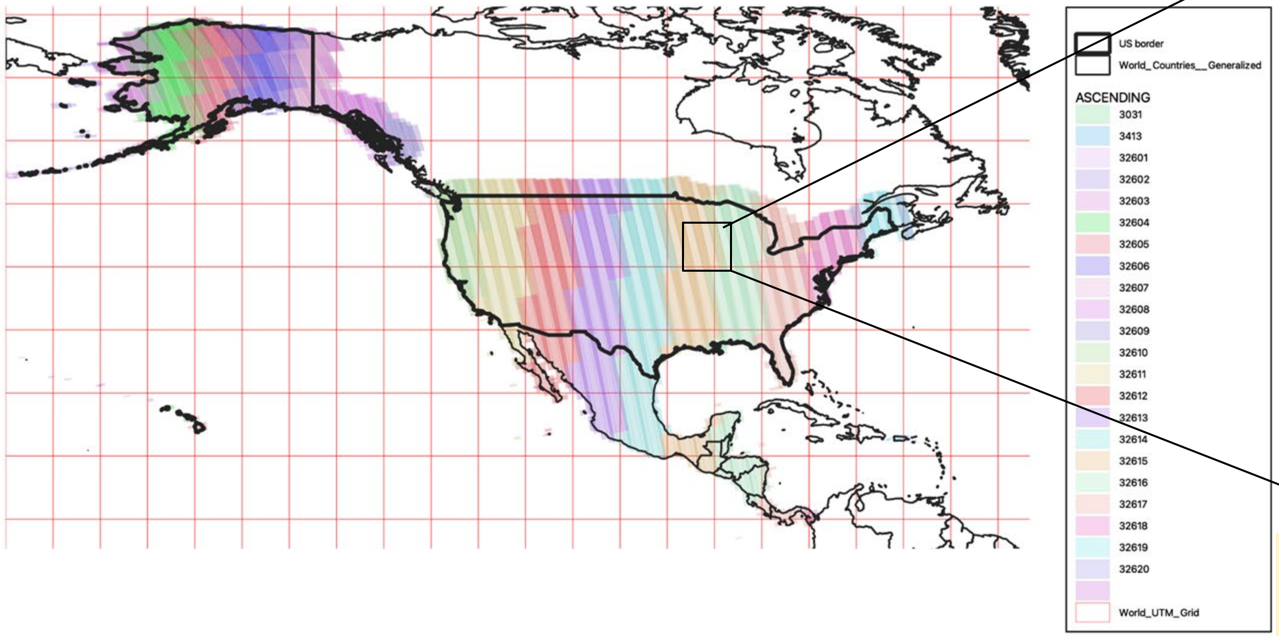
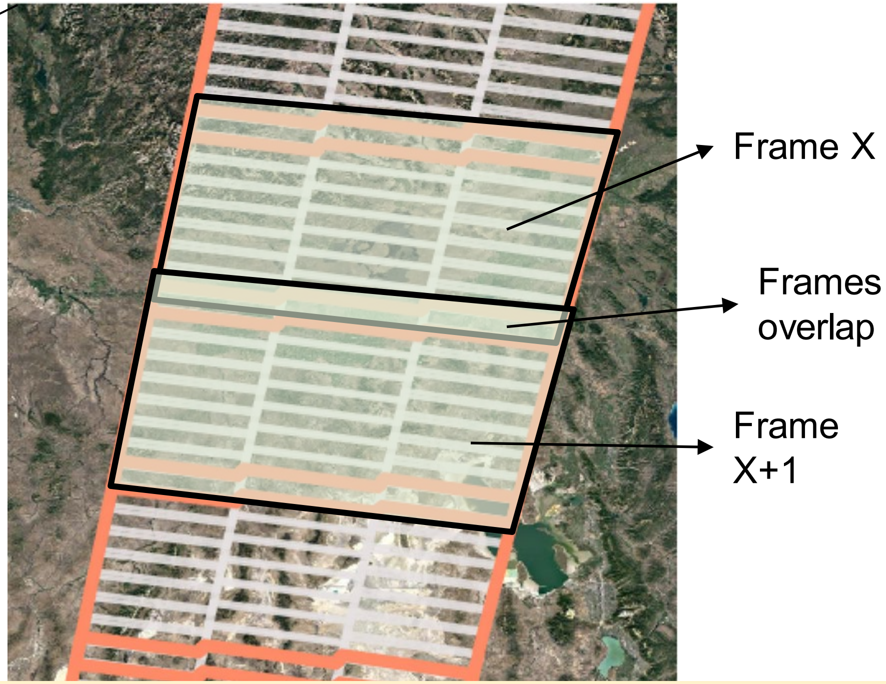
Fringe 2023

Towards North America Surface Displacement product

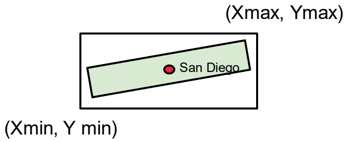
National Aeronautics and Space Administration

Building on the ESA burst map, we created a database, which contains the geocoded grid and map projection for each burst ID



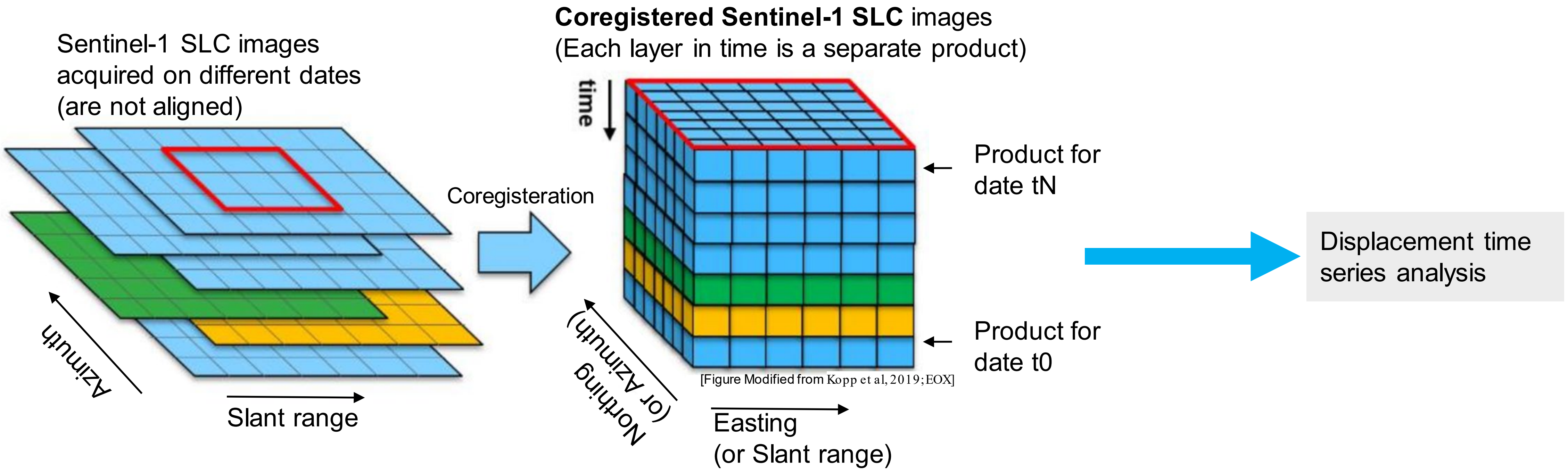


- 1 frame nominally groups together ~27 bursts (~200 km x 240 km)
- **Fixed to the same geographic location for all time**
- Assigning EPSG using frame center
- Tracking if frames intersect with land to avoid mostly-water frames
- Frames overlapping by 1 burst along-track



Each burst is identified with a unique ID and its geocoded output grid is predefined.

Coregistered SLCs



- Sentinel-1 SLC images are not aligned in time
- OPERA Coregistered SLC from Sentinel-1 aligns the SLC products on the same grid
- The Coregistered SLC will be input to the displacement product

Coregistration algorithm (Geocoded SLC)

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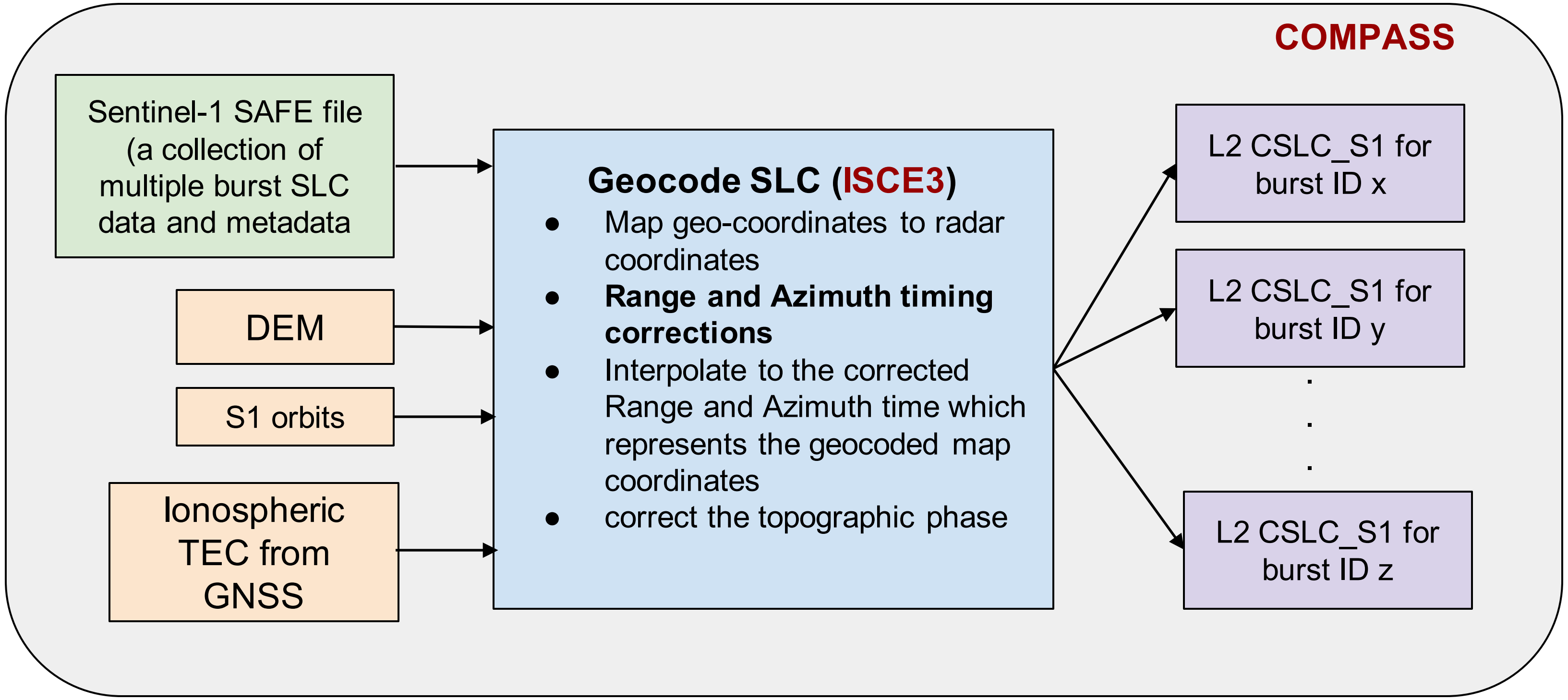
The Coregistration algorithm is a geocode SLC algorithm that takes the level-1 SLC data from Sentinel-1 and geocodes to the same geocoded map coordinates

Characteristics of the algorithm

- Scalable
- Capable to meet requirements
- Satisfies downstream displacement needs
- \+ User friendly (Complex SAR data on Map coordinates)

High level coregistered SLC algorithm workflow for Sentinel-1 (selected algorithm 1)



- The core geocoding and interpolation modules are implemented in open source InSAR Scientific Computing Environment, Enhanced Edition (ISCE3) (https://github.com/isce-framework/isce3)
- The workflow for geocoding Sentinel-1 is implemented in open-source COMPASS software (https://github.com/opera-adt/COMPASS)

Coregistration algorithm (Geocoded SLC)

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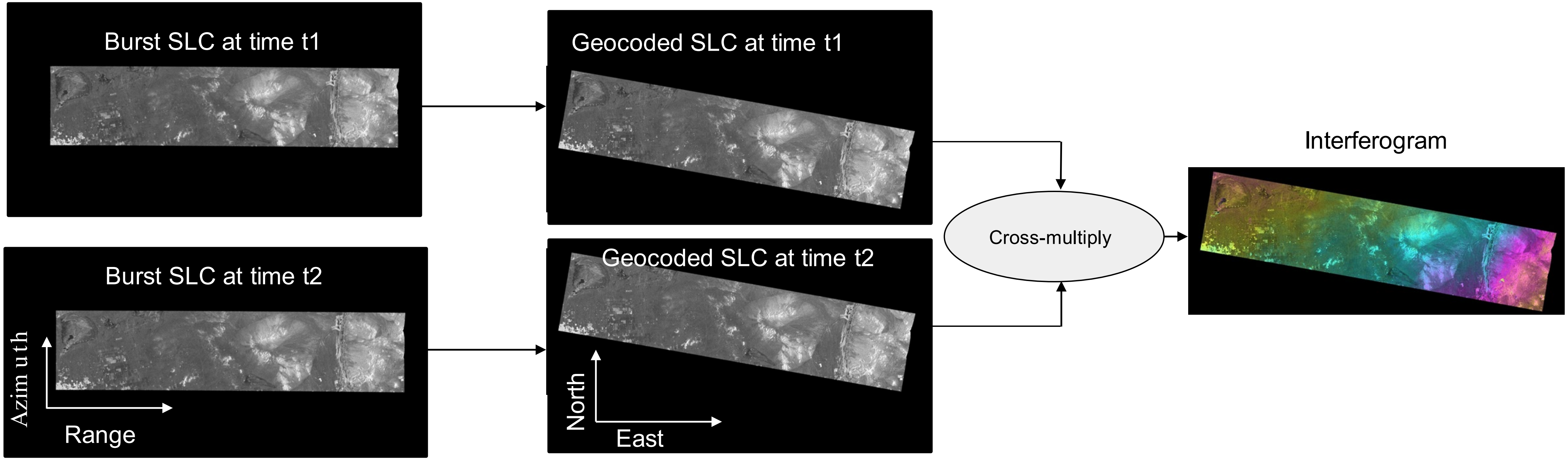
Geocoded SLC simplifies interferometry. However, precise coregistration depends on precise relative geolocation/geocoding accuracy



Specifications and Requirements

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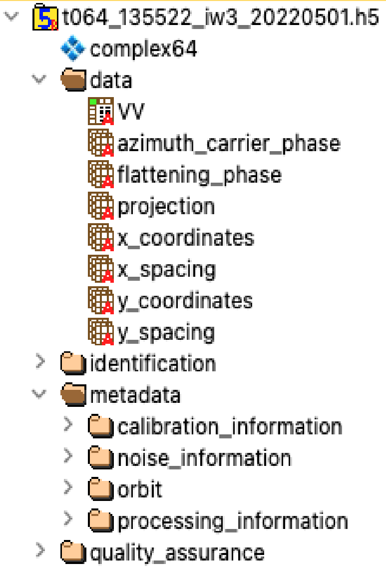
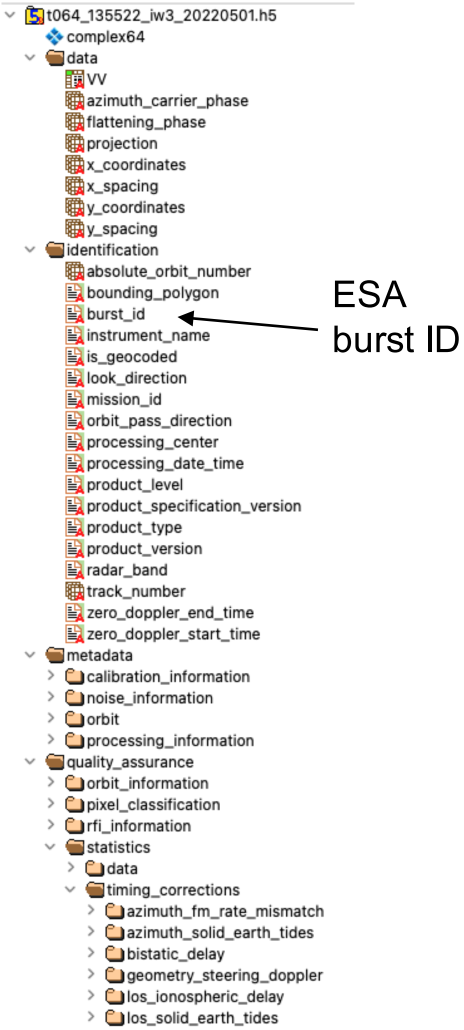
Specification
- 5x10 m product
- Geocoded on UTM projection
- Each product is one geocoded burst SLC
- HDF5 file (CF convention)
- GIS friendly
- Co-pol channel only
- Will be publicly available at ASF DAAC (Oct 2023)





L2 requirement for OPERA CSLC-S1 products

Geolocation accuracy	Ground Range L2 requirement	Azimuth L2 requirement
Relative	**<= 0.5 m**	**<= 0.75 m**
Absolute	**<= 1.5 m**	**<= 1.5 m**

Timing corrections to improve geolocation

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Tropospheric range delay

We use a static model of troposphere to account for the impact of tropospheric delay on geolocation. The same model that is employed for TerraSAR-X annotations [Breit et al., 2010]:

Model parameters are the constant values D0=2.3 m and H=6000 m [Breit et al., 2010]

$$\tau_{atm,ij} = \frac{2}{c}\frac{D_0}{\cos\theta_{inc,ij}}\exp\left(\frac{-h_{ij}}{H}\right)$$

Ionospheric range delay

We use GNSS-based Global Ionospheric Models (GIM) to account for the ionospheric range delay

$$\partial r = K\frac{TEC}{f^2}$$

Stop-and-go approximation or Bistatic delay (ETAD)

- The focusing algorithm assumes that the satellite stops at the pulse transmit time until the echo is received
- In practice the satellite has travelled 10s of meters between the transmit and receive times
- The focused signal should be labeled at midway between transmit and receive
- The azimuth time-tag must be corrected with a range-dependent correction
- The Sentinel-1 SLC processor does not use a range dependent correction. Instead it uses the range to the mid-swath of the TOPS. The corrected time can be obtained as follows [Gisinger et al, 2020]

$$t_{zero\text{-}Doppler}(i,k) = t_{\mathrm{IPF}}(i) + \frac{\tau_{\mathrm{mid}}}{2} + \frac{\tau(k)}{2} - \tau_0$$

Timing corrections to improve geolocation

National Aeronautics and Space Administration

Effect of Doppler shift in range direction (ETAD)

- The motion of the satellite during the transmit and receive of the chirp signal introduces a Doppler shift between the transmitted and received pulses [Prats-Iraola et al, 2014].
- For zero-Doppler SAR data, the Doppler shift changes from positive to negative during sensor approach and sensor recede along the aperture and the effect on range shift cancels out during the range compression. [Prats-Iraola et al, 2014, Gisinger et al, 2020]
- For TOPS, Doppler centroid strongly varies in azimuth. The Doppler shift leads to an azimuth dependent range shift. [Gisinger et al, 2020]

Fast-time shift

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

Doppler centroid frequency

FM-rate of the range chirp

Azimuth FM-rate mismatch (ETAD)

- The azimuth FM-rate depends on the local terrain height. However ESA focuser uses a constant average height across the three sub-swaths with slow update rates (target height deviation of 1000 m is possible in mountainous region) [Gisinger et al, 2020].
- The difference of the true FM-rate and the modeled FM-rate leads to an azimuth shift as

$$\Delta t_{\text{FM-mismatch}} = f_{\text{DC}_{\text{target}}} \cdot \left(\frac{1}{-k_{a_{\text{IPF}}}} - \frac{1}{-k_{a_{\text{geo}}}} \right)$$

Validation Approach for CSLC-Sentinel-1

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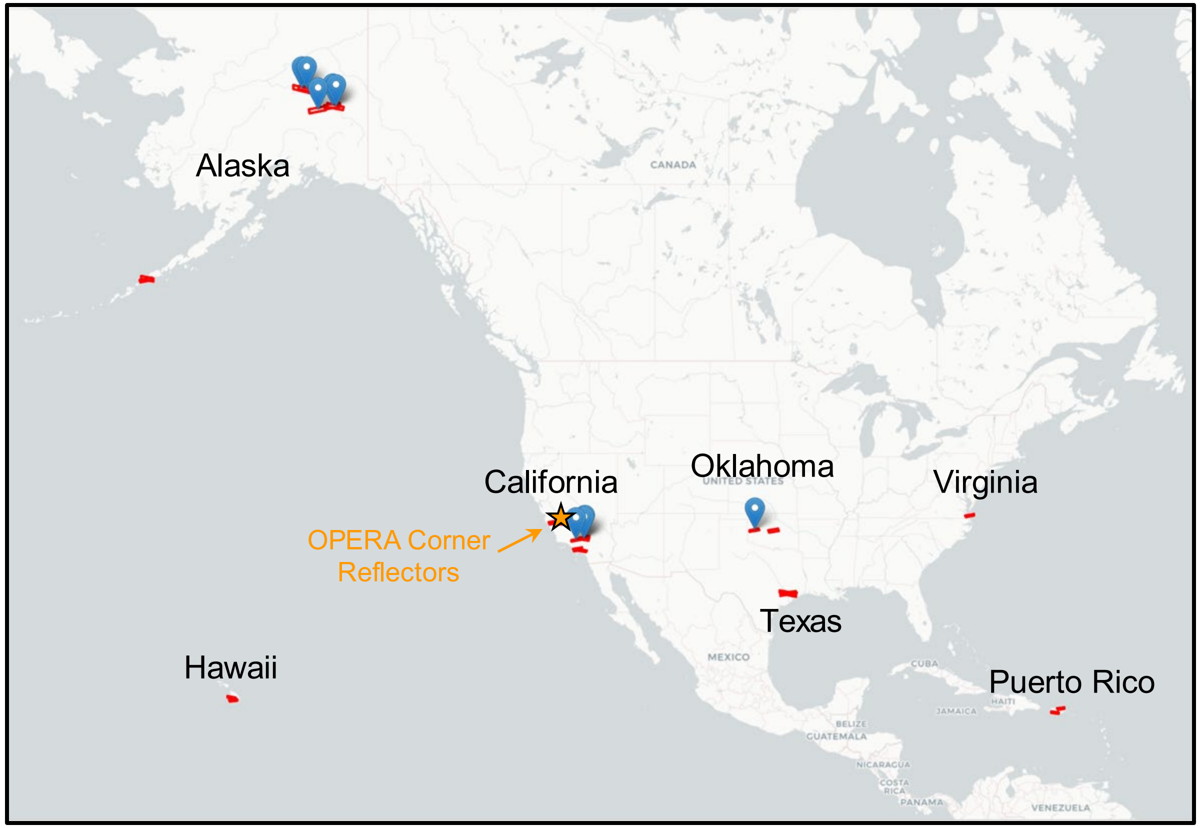
- **<u>Absolute location error estimation</u>** via point-target analysis using corner reflectors ( )
- **<u>Relative location error estimation via</u>** analysis of pixel offsets in an image stack using cross-correlation at cal/val sites ( )
- Approach is documented in the validation plan
- CSLC-S1 validations are implemented in jupyter notebooks available on GitHub: *https://github.com/OPERA-Cal-Val/calval-CSLC*

Validation sites



Geolocation analysis (impact of different corrections)

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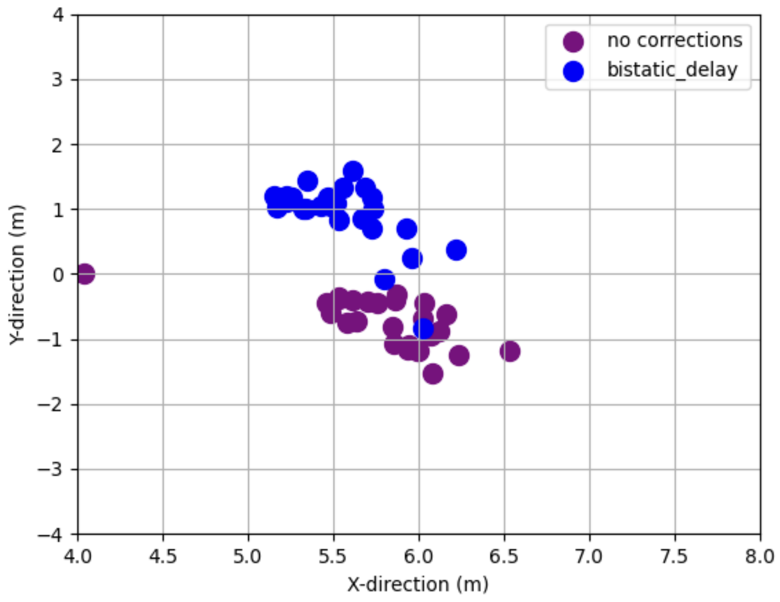
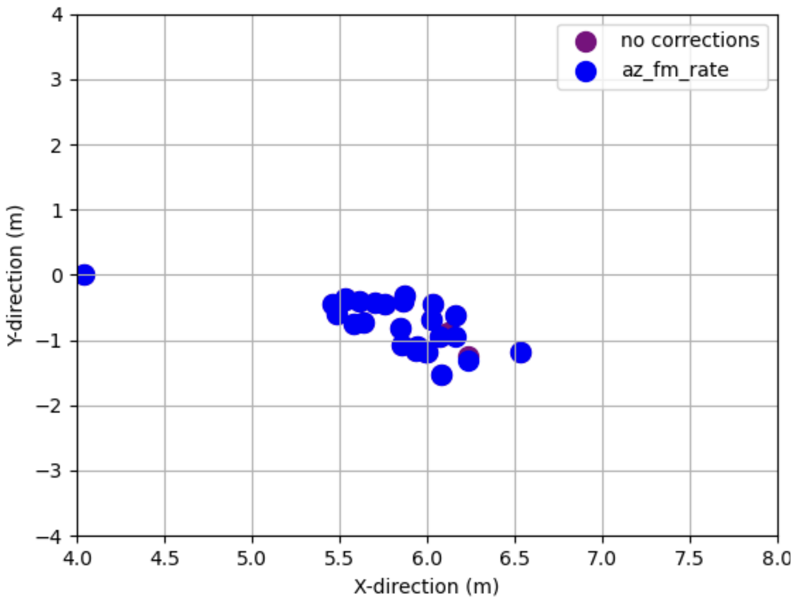
Geolocation analysis over corner reflectors in Rosamond, CA indicates significant improvement of the azimuth geolocation (1-2 m) after Bistatic delay correction using ESA's ETAD algorithm

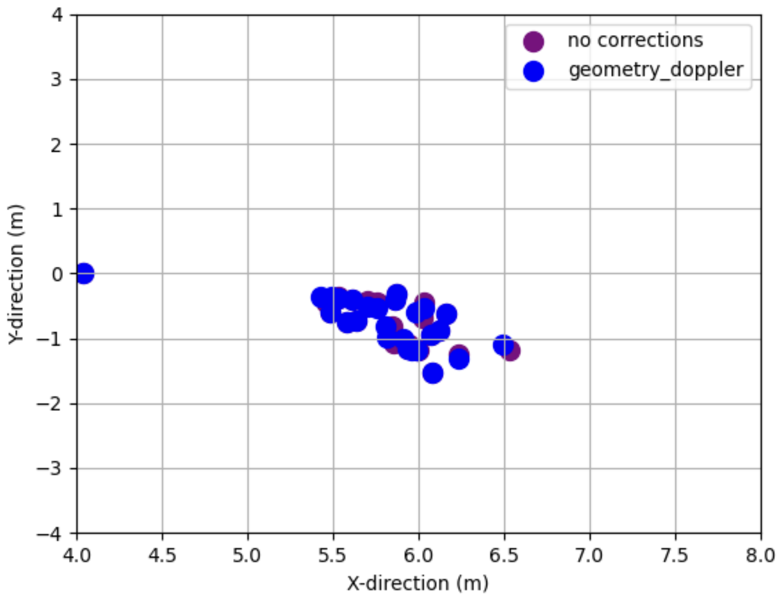
Bistatic delay



Azimuth FM rate



Doppler shift



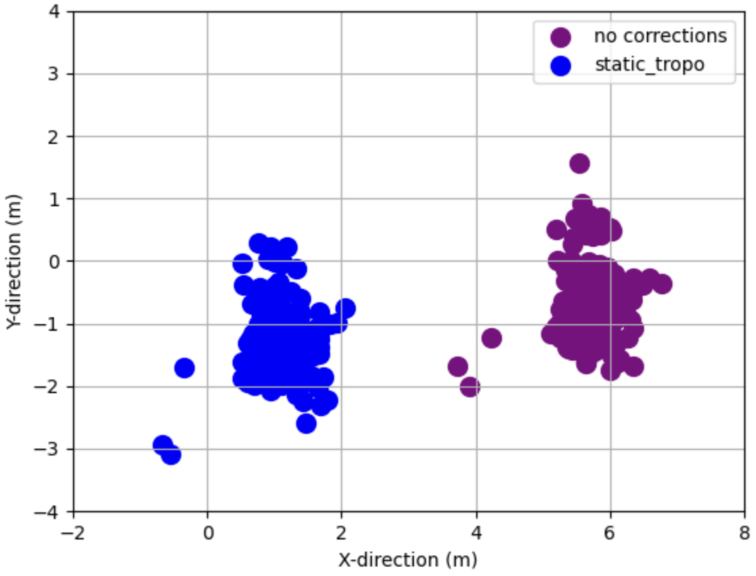
Geolocation analysis (impact of different corrections)

National Aeronautics and
Space Administration

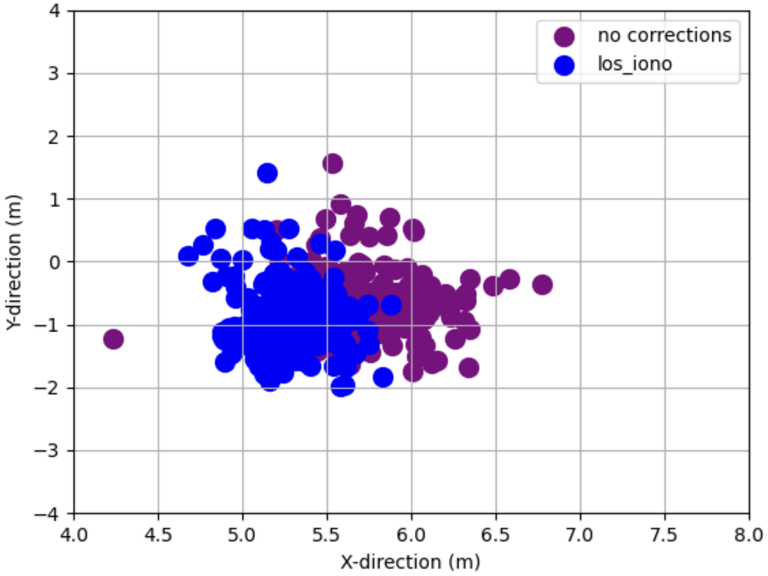
Geolocation analysis over corner reflectors in Rosamond, CA indicates geolocation improvements of ~5 m in east and less than ~1 m in north direction due to tropospheric delay correction

Ionospheric delay correction improves the absolute geolocation by ~ 0.5 over the corner reflectors

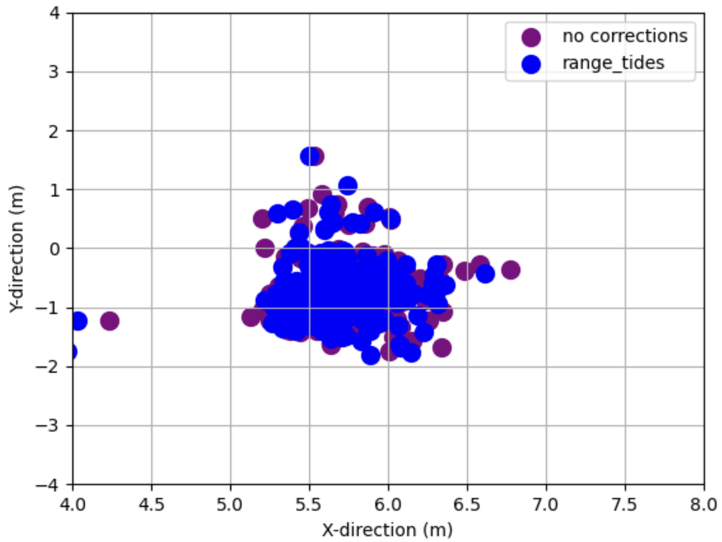
Troposphere



Ionosphere



Solid earth tide (range)



Geolocation accuracy of geocoded SLC (preliminary results)

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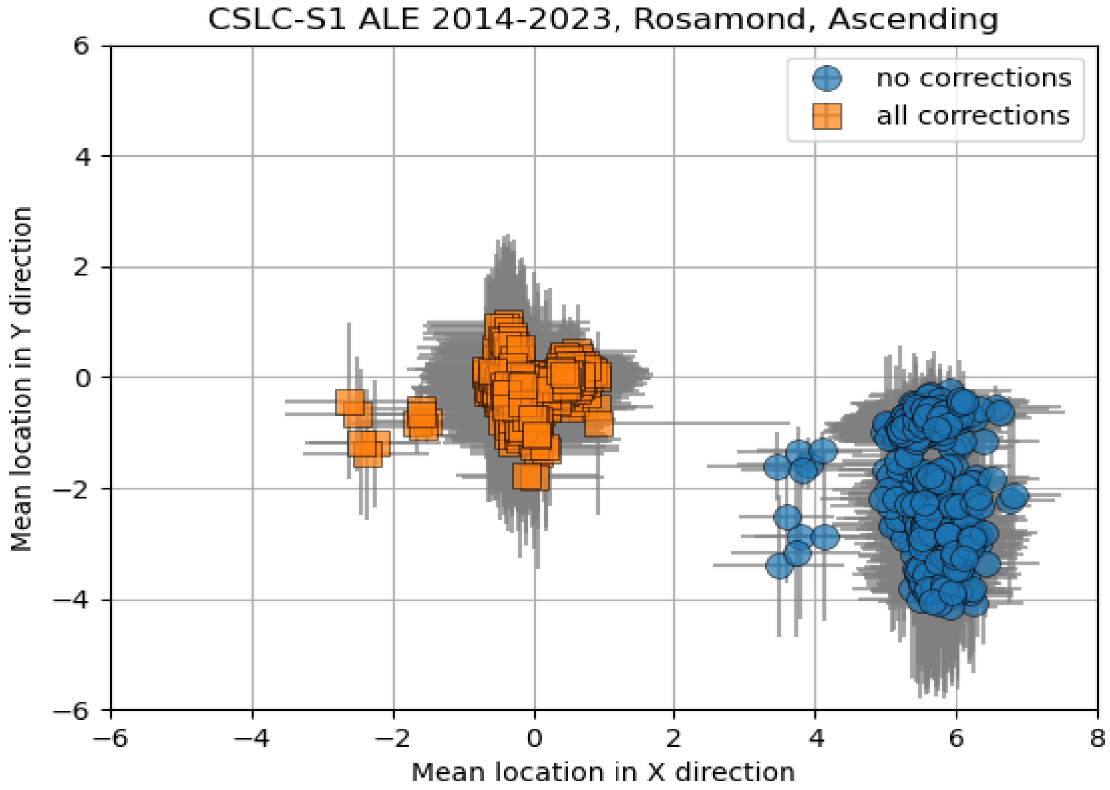
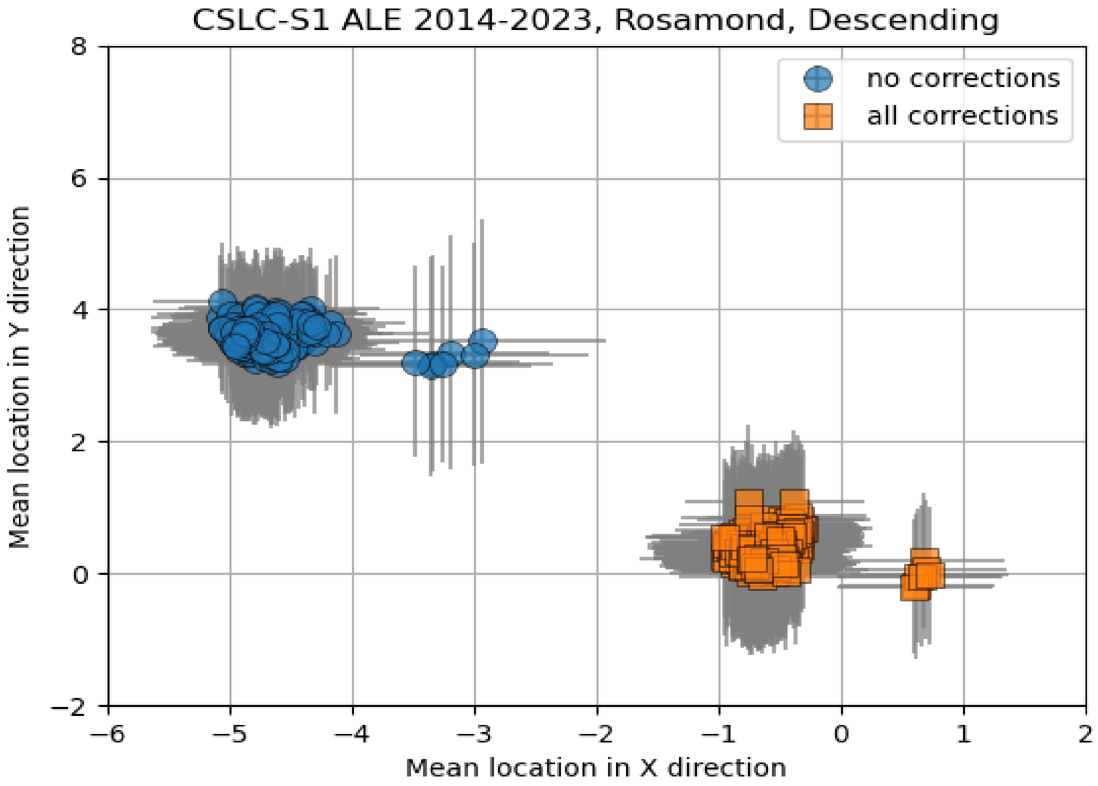


	Without timing corrections	With timing corrections
East (X)	5.6 m +/- 0.6 m	-0.1 m +/- 0.3 m
North (Y)	-2.9 m +/- 0.43	-0.2 m +/- 0.3 m



	Without timing corrections	With timing corrections
East (X)	4.7 m +/- 0.6 m	0.6 m +/- 0.3 m
North (Y)	2.9 m +/- 0.43	0.3 m +/- 0.3 m

CSLC-S1 Validation Example (Preliminary results)

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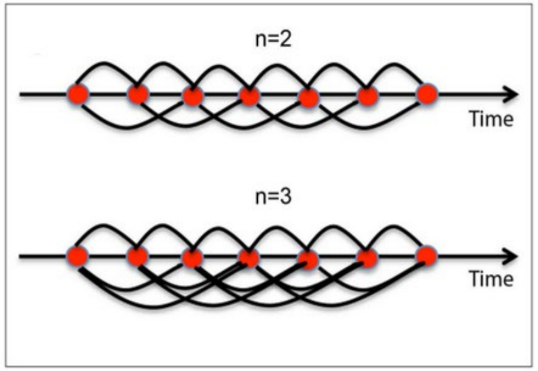
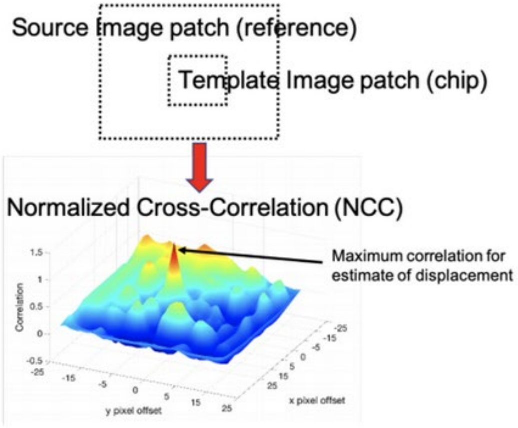
Image Cross Correlation for Relative Location Error

- Construct a stack of CSLCs with a pairing n=3
- Perform cross-correlation
- Estimate mean and standard deviation of the offsets

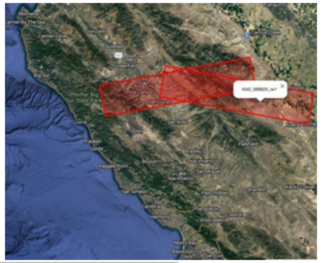


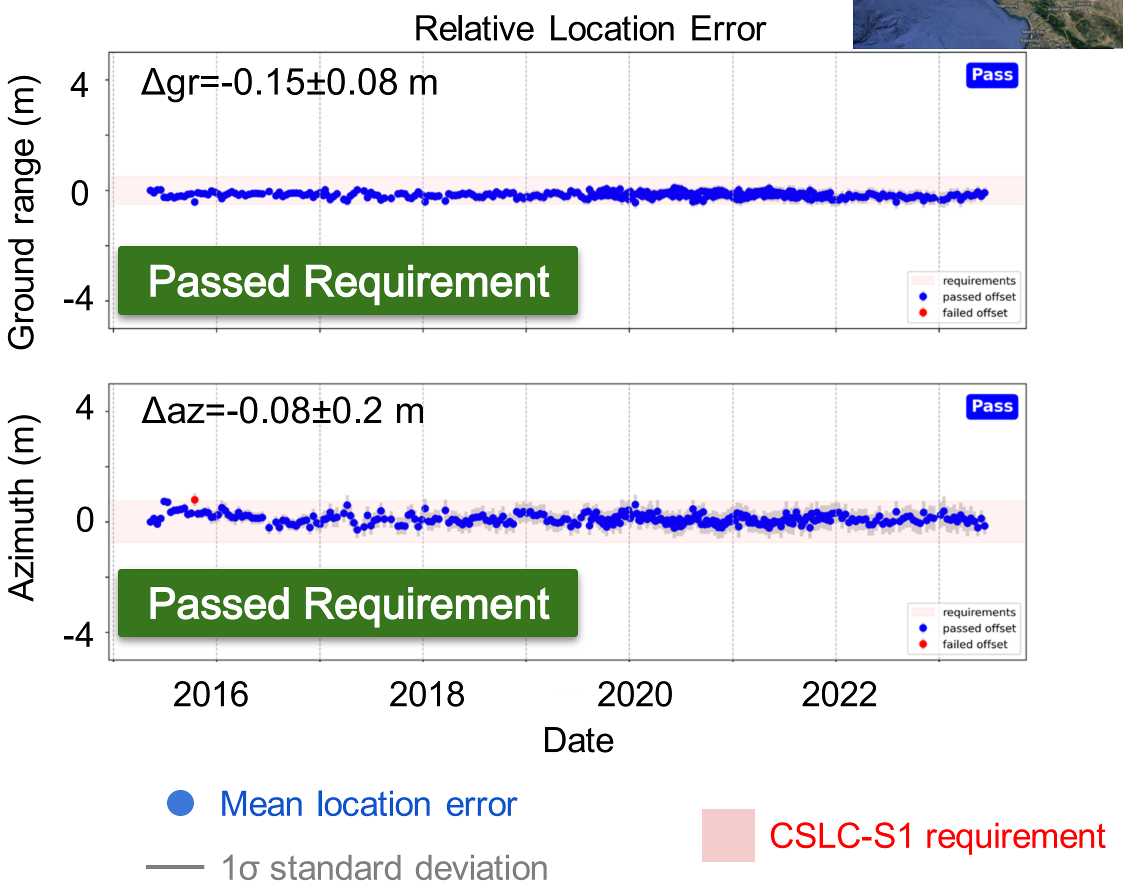
(a)



(b)

Time-series over central California





Sources of residual geolocation errors

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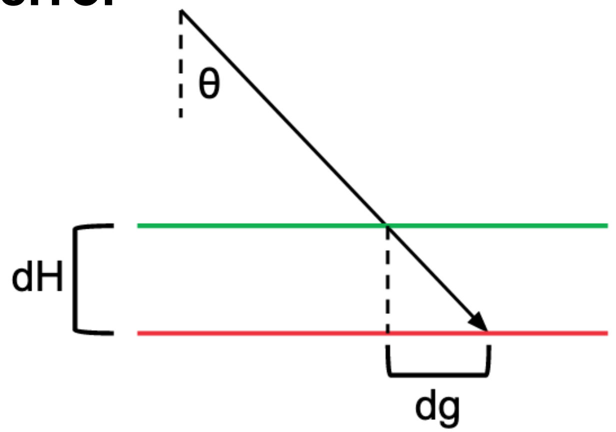
1- DEM error



A DEM error of dH introduces a ground range error of dg:

$$dg = dH/\tan(\theta)$$

Which translates to errors in east and north direction

$$dE = dg * \cos(\alpha)$$
$$dN = -dg * \sin(\alpha)$$

A DEM error of 1 m results in ~1.4 m and ~0.25 m geolocation errors in east and north directions

The small orbital tube of Sentinel-1 satellites minimizes the temporal variability of absolute geolocation errors due to DEM errors

2- Ionospheric residuals

2-1 Ionosphere induces azimuth geolocation errors

Ionospheric TEC gradient in azimuth direction results in a Doppler shift which leads to a time-shift in azimuth direction
A TEC gradient of 0.1 TECU over 30 sec (0.0033 TECU/sec) results in 7e-7 sec time shift (~5 mm)

2-2 TEC models inaccuracy (~2-4 TECU)

2-3 Topside TEC

3- Tropospheric residuals

We have used a static model for tropospheric delay correction (i.e., no variation over time). However troposphere may vary by ~20-30 cm over time.

4- Uncertainty of corener reflector peak detection

Geocoded Single Look Complex from NISAR and Sentinel - 1

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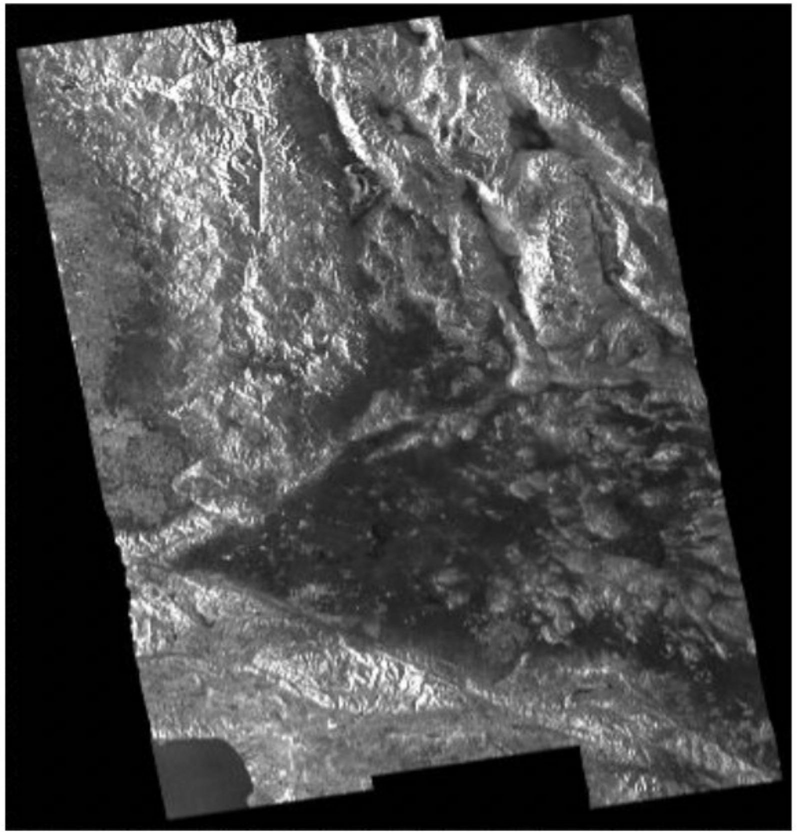
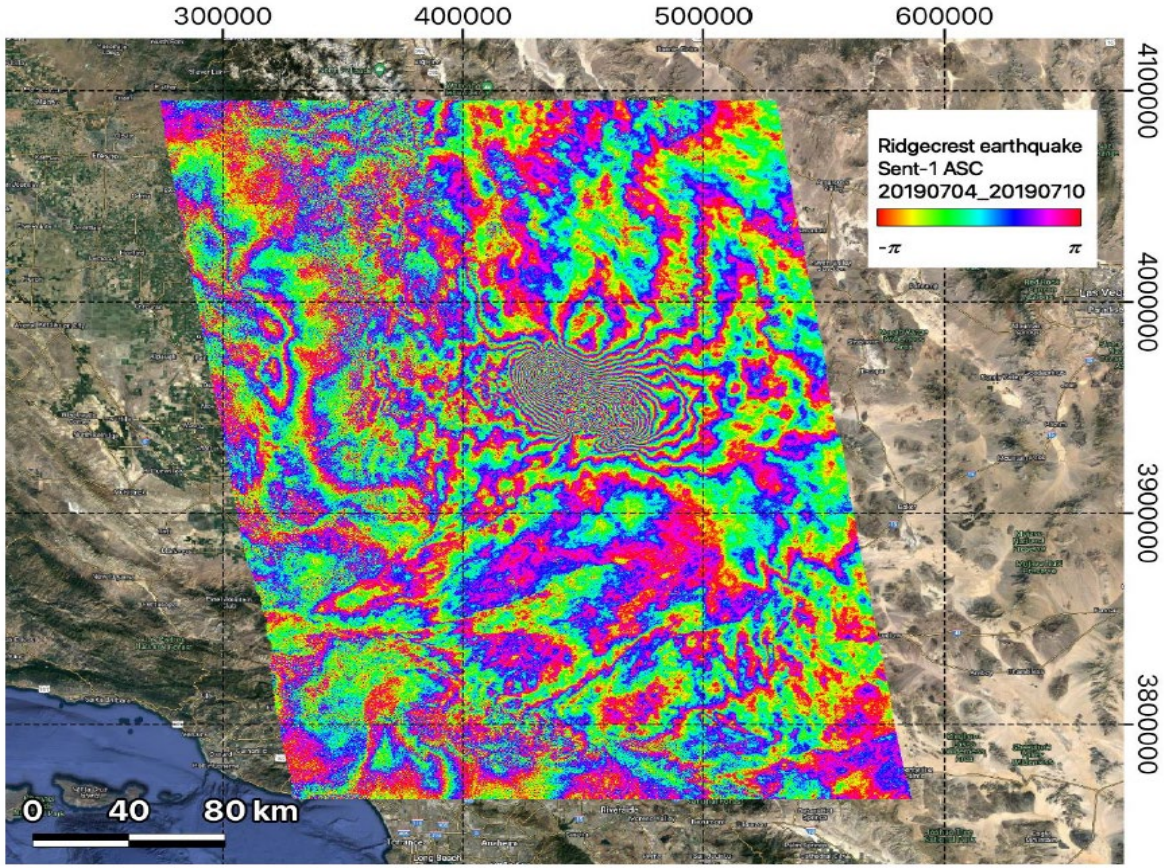
Absence of burst boundaries in sample interferograms in different regions indicate precises coregistration of geocoded SLCs

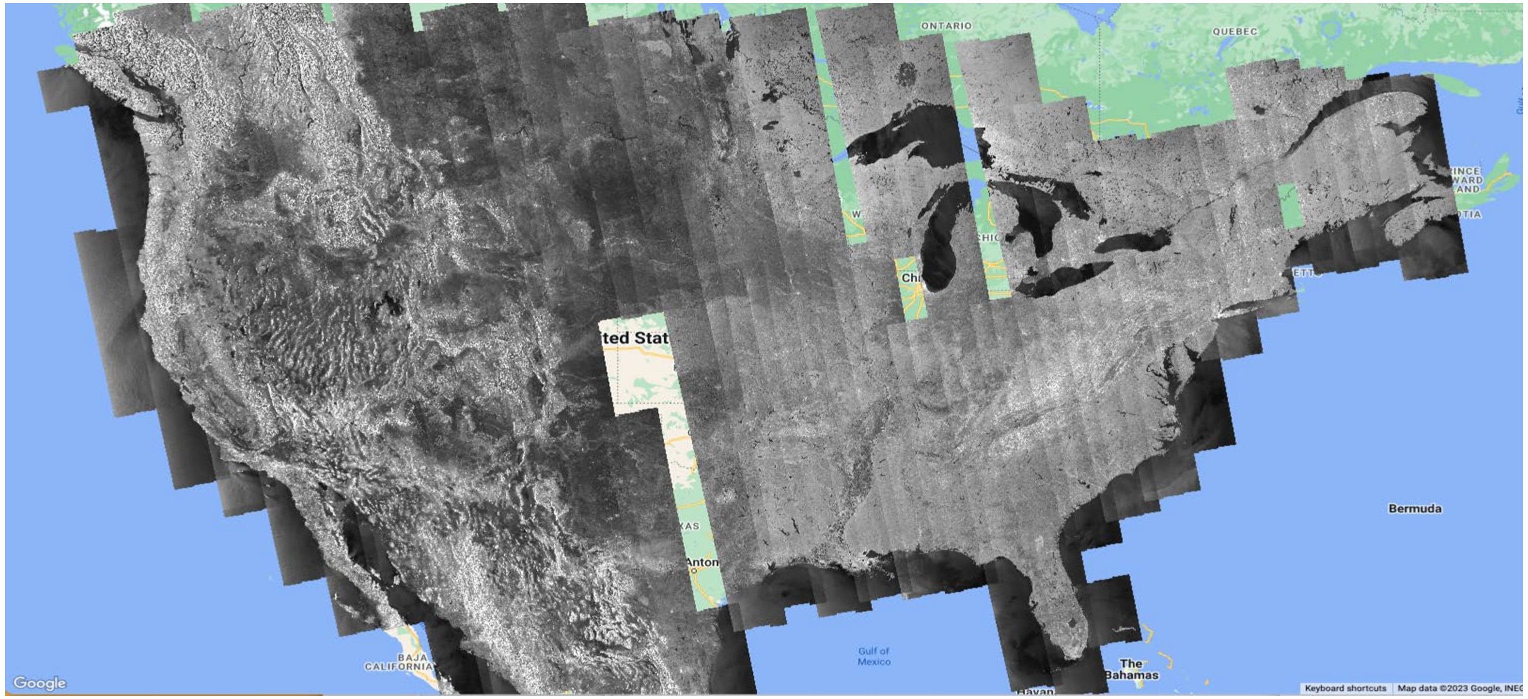


Ridgecrest earthquake, July 2019



Geocoded SLC from Sentinel - 1

Mosaic of ISCE3-based geocoded SLC from Sentinel-1 (OPERA CSLC-S1) backscatter amplitude for one cycle of Sentinel-1 data scaled over US by the OPERA data system



InSAR displacement time - series derived from geocoded SLCs

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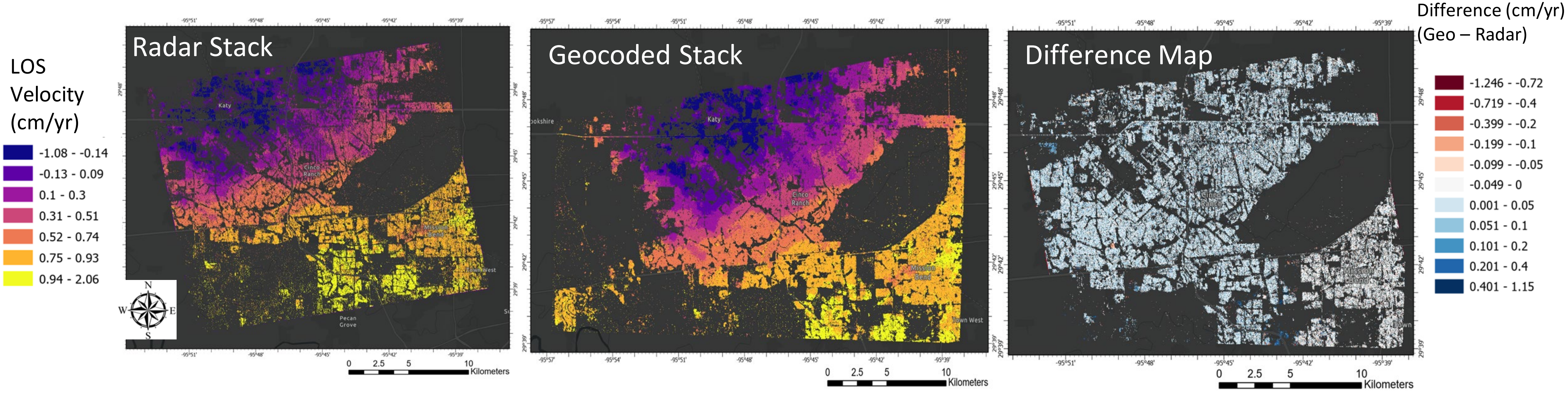

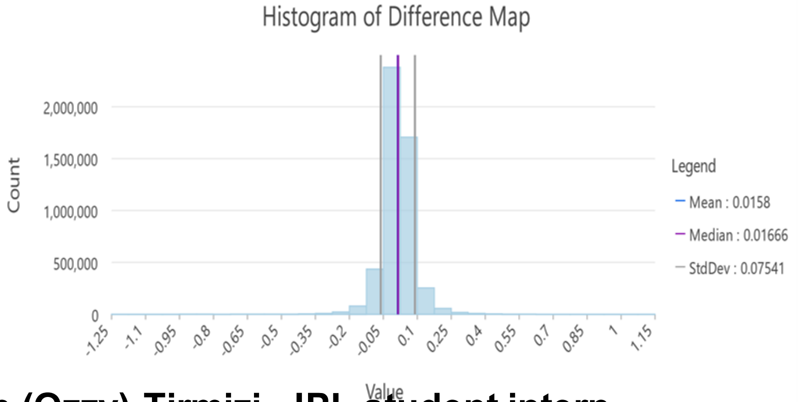

A stack of Sentinel-1 SLCs, over Houston Tx were coregistered with both traditional coregistration in range-Doppler coordinates and in geocoded coordinates (geocoded SLCs)

A full covariance based (combined PS-DS) time-series applied on both stacks

The estimated rate of displacement from the two stacks are consistent

The difference between two velocity fields shows 0.15 +/- 0.7 mm/yr

[Osman (Ozzy) Tirmizi, JPL student intern, Uni of Houston, TX]

InSAR displacement time - series derived from geocoded SLCs

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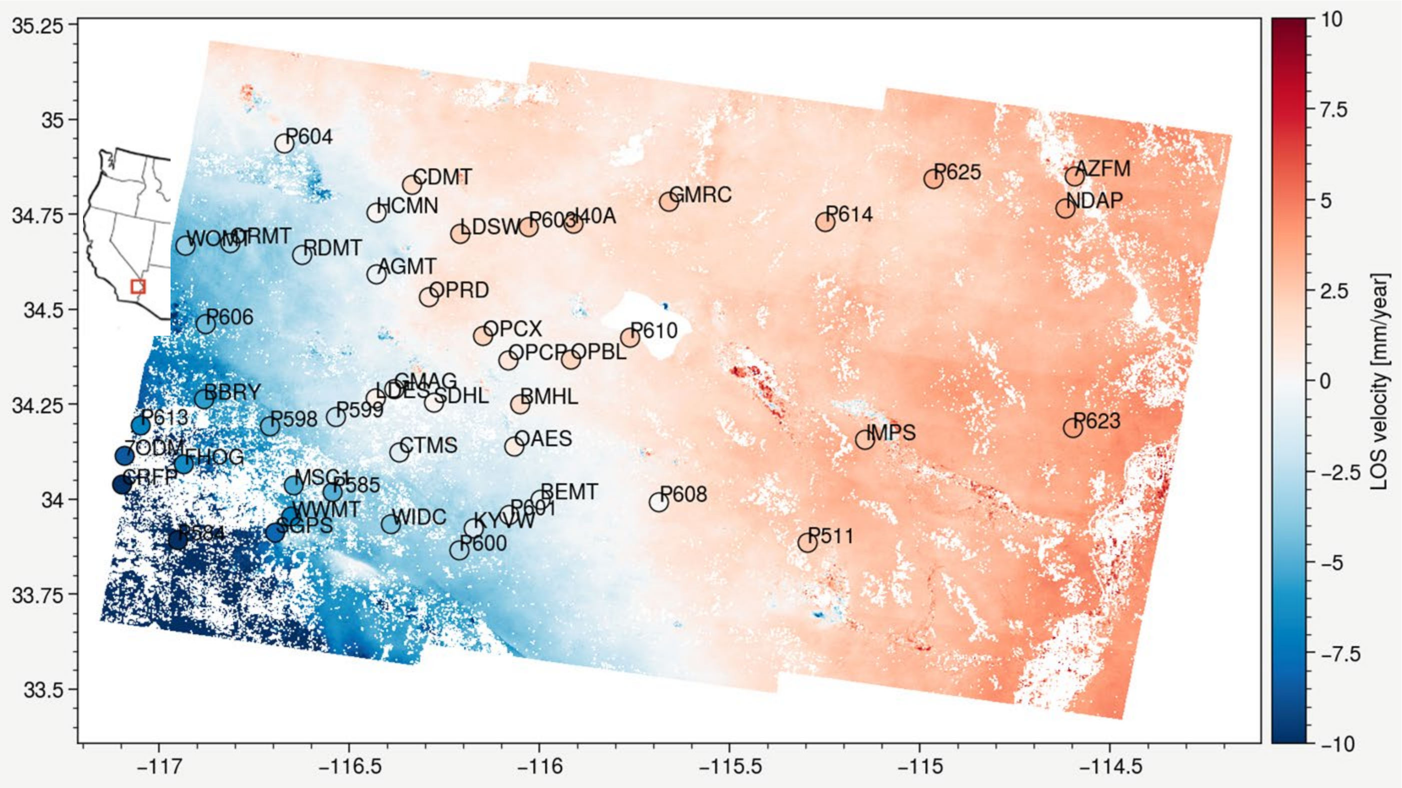
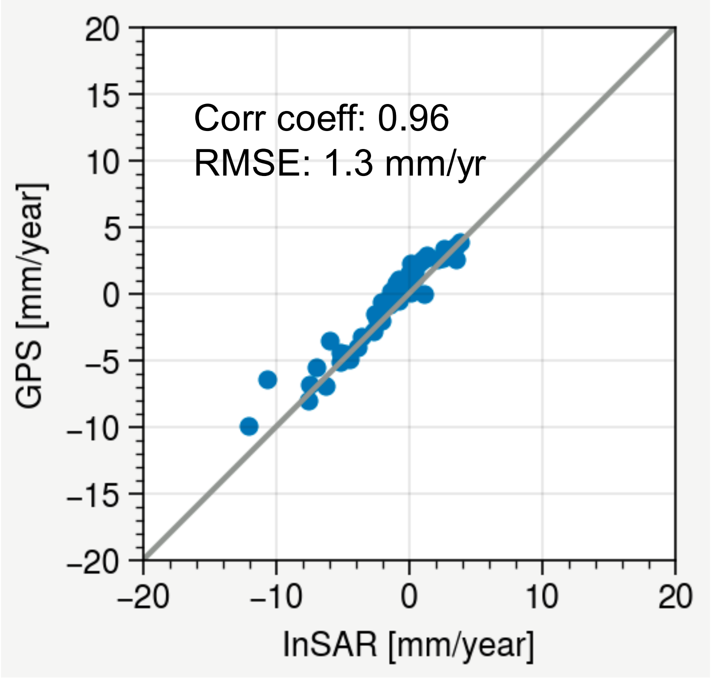
Comparing rate of ground displacement from InSAR time-series with the GNSS data indicates consistency between InSAR derived displacement from Geocoded SLCs with GNSS data





For more details about the algorithm for InSAR displacement time-series analysis please see the presentation
ID 227 entitled **"Near Real Time Estimation of Unbiased Ground Displacement Time-Series With InSAR Big Data" ,**
InSAR methods session, Sep 12, 11:10 am – 12:50 pm

Radiometric Terrain Corrected from Sentinel - 1

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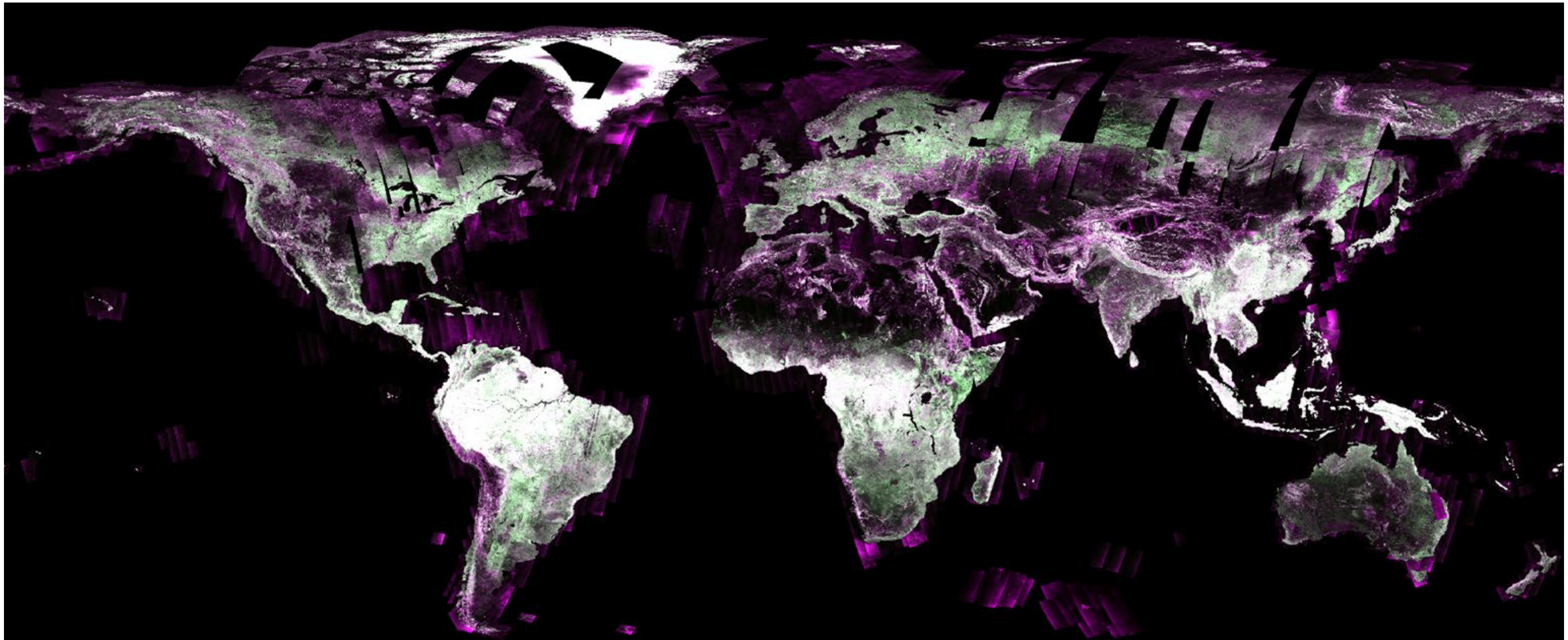
ISCE3 based RTC products from Sentinel-1 scaled to globe by the OPERA data system

One cycle of Sentinel-1 SLC imagery was processed to burst RTC products by the OPERA data system

A total ~270K products were generated



[Gustavo H. X. Shiroma, Heresh Fattahi, Franz Meyer, Seongsu Jeong, Luca Cinquini, Scott Collins, Bruce Chapman, Steven K. Chan, Alexander L. Handwerger, David Bekaert, The OPERA Radiometric Terrain Corrected SAR Backscatter From Sentinel-1 (RTC-S1) Product, IGARSS 2023]

For more details about RTC product from Sentinel-1 data please see the poster presentation
ID 445 "OPERA RTC-S1 Product, Algorithm, and Validation Plan”

Burst ID determination for Sentinel - 1 burst - based products

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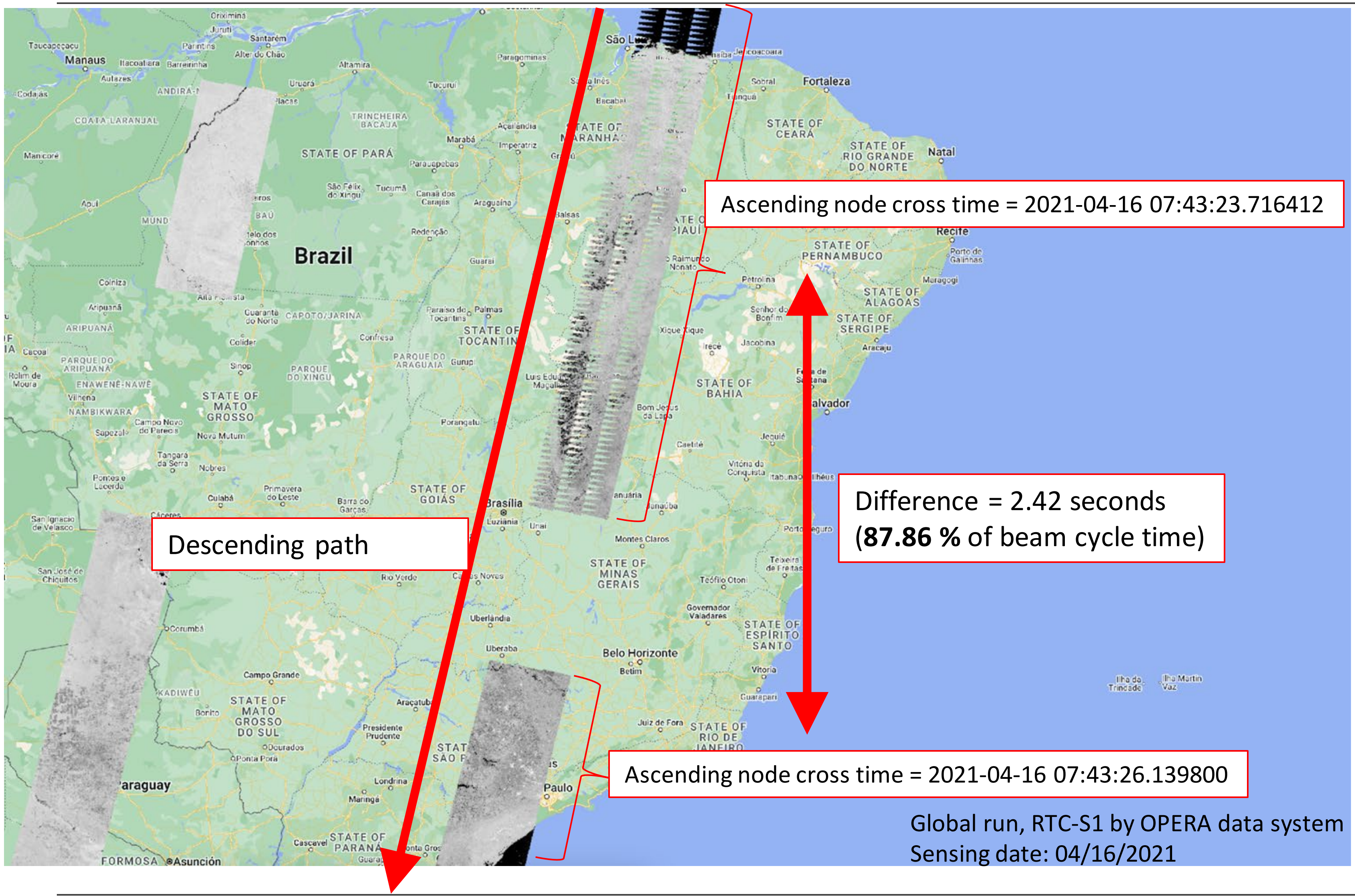
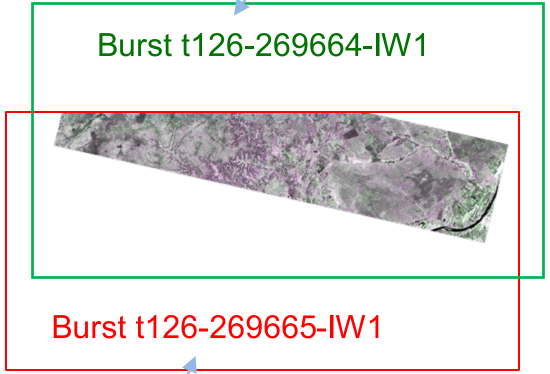
Space Administration



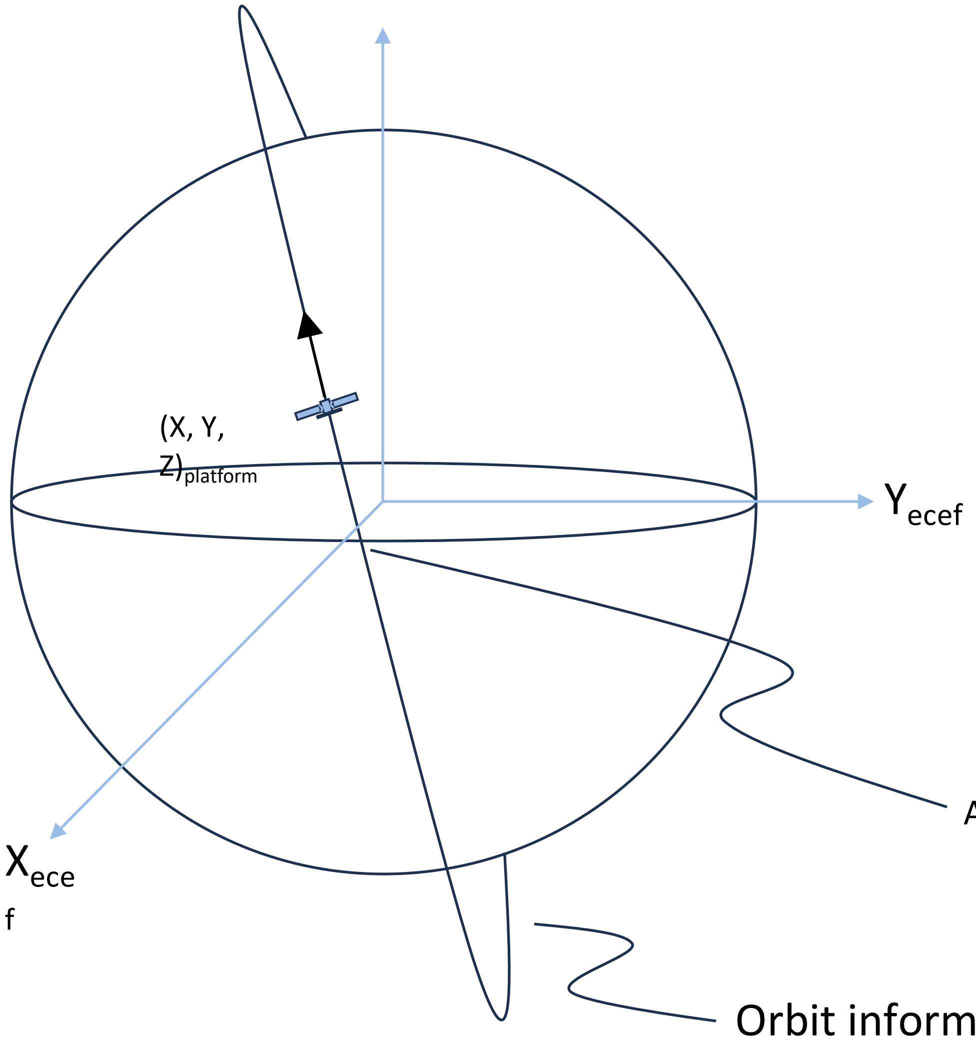
True burst ID and
bounding box



Computed burst ID using
ESA's metadata for
Ascending node time

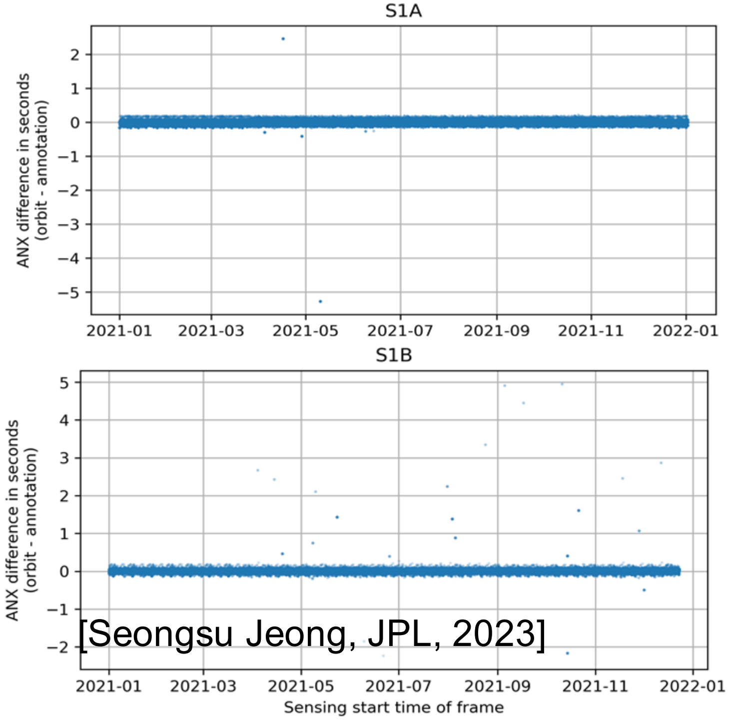
Burst ID determination for Sentinel - 1 burst - based products

National Aeronautics and Space Administration



Ascending node crossing time = t($Z_{platform}$ = 0.0)

Orbit information: $(X, Y, Z, V_X, V_Y, V_Z)_{platform,\ t}$



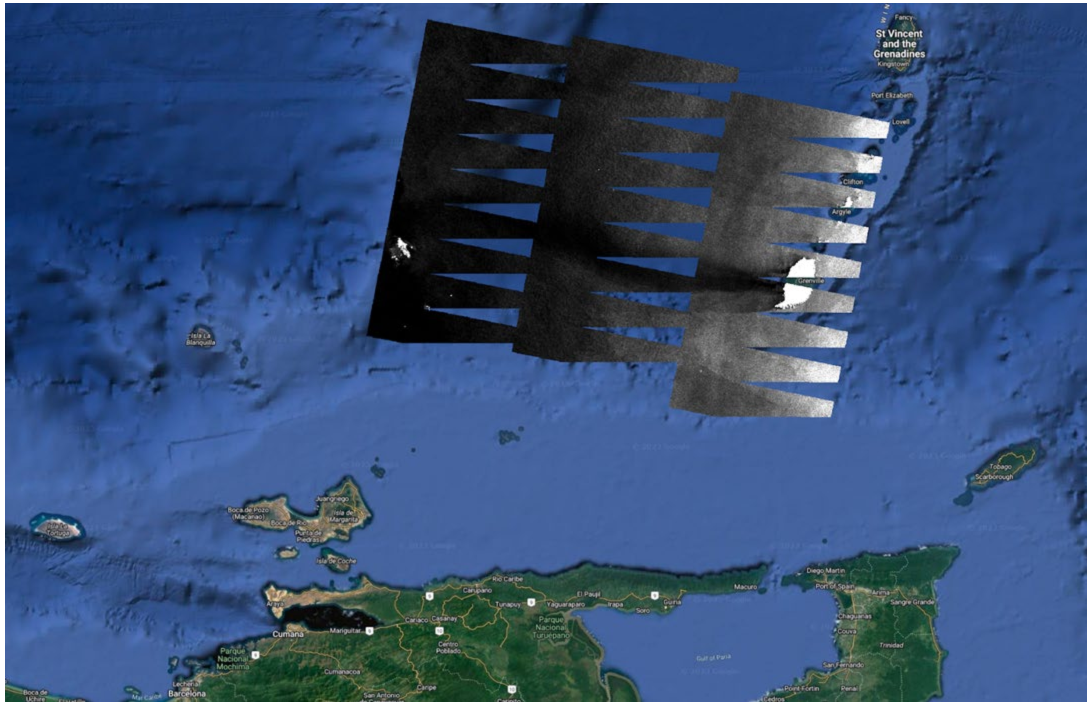
Number of frames with ANX time error larger than 1.0 seconds in year 2021 over the globe:

Sentinel-1A:
22 frames out of 189,080 (0.0116%)

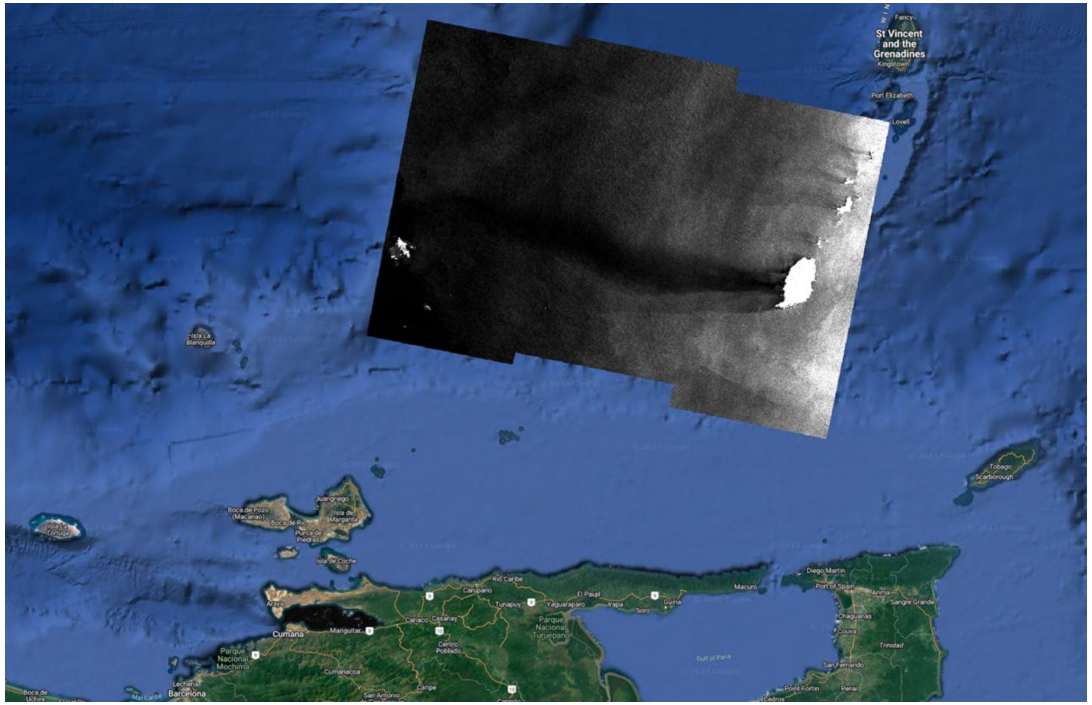
Sentinel-1B:
61 frames out of 144,809 (0.0421%)

Burst ID determination for Sentinel - 1 burst - based products

Using ANX time in Sentinel-1 SLCs metadata



Using ANX time determined from orbit



Summary

- We developed a workflow to generate Coregistered Single Look Complex from Sentinel-1 by geocoding each burst SLC to pre-fixed geocoded map coordinates

- Geolocation analysis over corner reflectors indicates achievable absolute geolocation accuracy better than 0.75 m and 1.5 m in east and north directions after multiple correction including the ETAD timing corrections

- The absence of burst boundaries in sample interferograms in different regions indicates precise coregistration of the geocoded burst SLC products

- InSAR displacement time-series derived from stacks of coregistered SLCs in radar and geocoded coordinates are consistent with a difference of 0.15 +/- 0.7 mm/yr

- InSAR displacement time-series (from geocoded SLCs) compared with GNSS data indicates an RMSE of ~1 mm/yr over 200 km

Thank you!