OPERA's SAR agnostic, global tropospheric correction dataset from ECMWF high resolution model

David Bekaert, Flemish Institute for Technological Research, California Institute of Technology

Former NASA-JPL OPERA Project Manager, NASA-JPL ARIA PI

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[2]Missouri University of Science and Technology, Missouri, USA

[3]Capella, Louisville, USA

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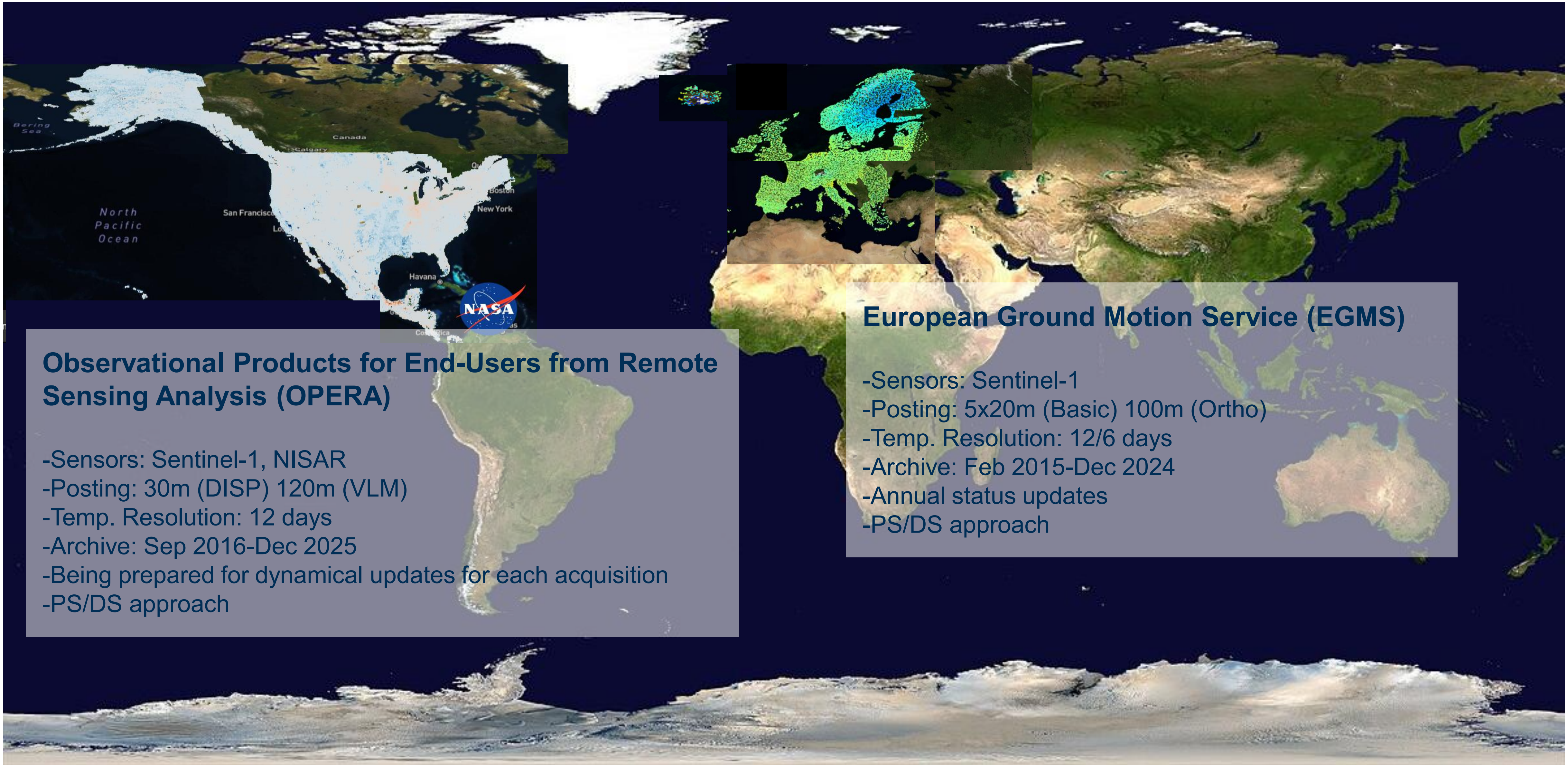
Continental Scale InSAR with GNSS Initiatives

High-resolution Land Subsidence Data



Observational Products for End-Users from Remote Sensing Analysis (OPERA)

-Sensors: Sentinel-1, NISAR
-Posting: 30m (DISP) 120m (VLM)
-Temp. Resolution: 12 days
-Archive: Sep 2016-Dec 2025
-Being prepared for dynamical updates for each acquisition
-PS/DS approach

European Ground Motion Service (EGMS)

-Sensors: Sentinel-1
-Posting: 5x20m (Basic) 100m (Ortho)
-Temp. Resolution: 12/6 days
-Archive: Feb 2015-Dec 2024
-Annual status updates
-PS/DS approach

SAR Agnostic Tropospheric correction products

Global – 6 hourly – Zenith Tropospheric Delays

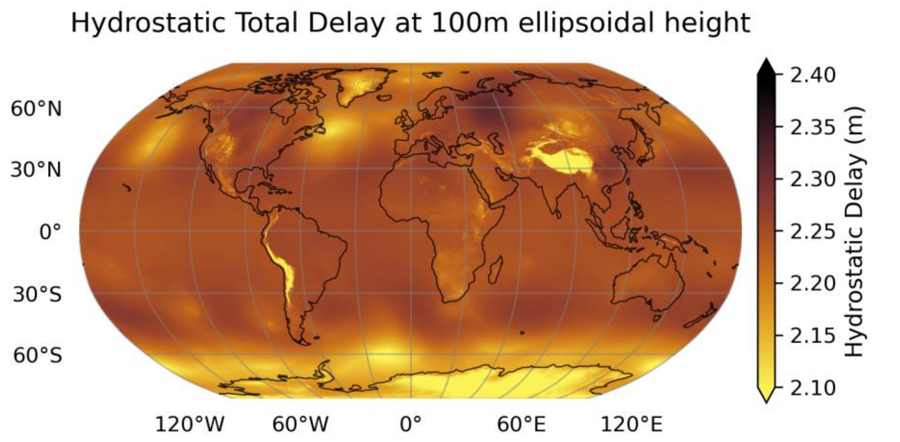
Zenith Hydrostatic and wet delay fields computed by OPERA using the RAiDER software and ECMWF HRES data.

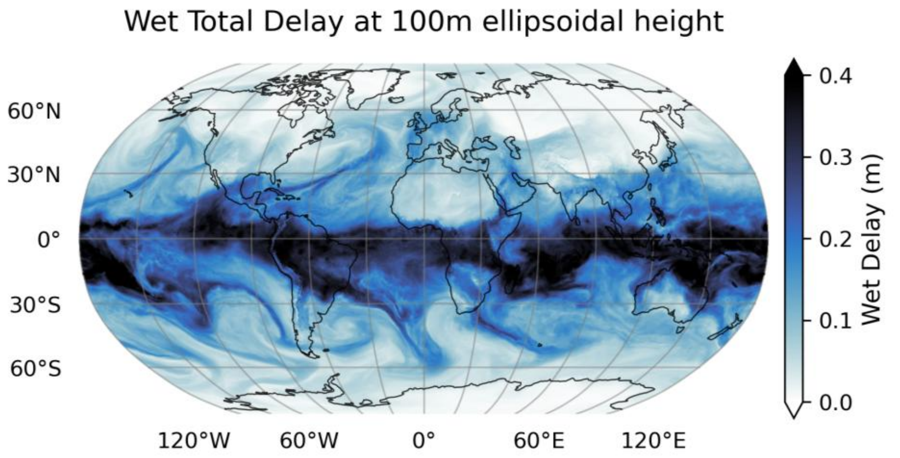
Product features:

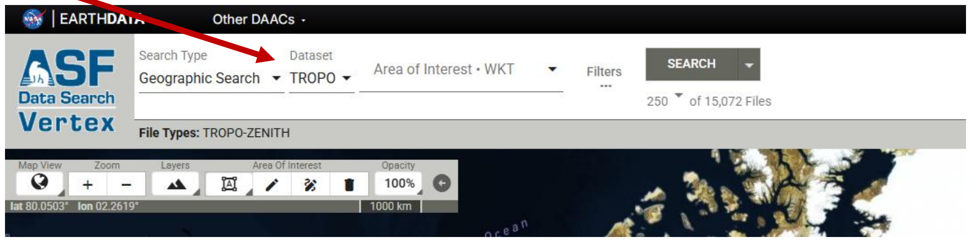
- Global coverage on a ~8 km (0.07°) lat/lon grid
- Delay cubes from –0.5 to ~81 km altitude (145 levels)
- Airborne and space borne radar delay corrections
- CF-1.8–compliant NetCDF format

Free and open data through NASA archives:

- Archive: 2016-currect (daily updates)
- Four epics per day (00, 06, 12, 18 UTC)
- https://www.earthdata.nasa.gov/data/tools/asf-displacement-portal
- Latency ~2-3 days







Why a 3D Zenith tropospheric delay product?

OPERA's decision to move from Slant to Zenith product

- Why the decision to go to Zenith and not Slant?
  - Zenith opens the opportunities for SAR agnostic applications
  - No significant qualitative loss in delay estimates
    - The model native resolution (9km) and the thickness of the troposphere don't benefit from ray-tracing
    - The slant correction can be computed straightforward from the projection along incidence angle

- Why provide delays as 3D cubes and not as 2D fields?
  - The NISAR meta-data cubes approach - Data compression and long-term storage benefits
  - Keep the data at the native model nodes (9km); finer and you are storing "interpolated" data
  - You only need to download the layers spanning your vertical range to compute delays!
  - Can be applied for both airborne and spaceborne sensors

OPERA TROPO enabled in MintPy

Miami INSAR Time-series software in Python

Yunjun, Z., Fattahi, H., and Amelung, F. (2019), *Computers & Geosciences*, *133*, 104331.

- Time-series package with support for many input processors including ISCE, SNAP, ARIA, GAMMA
- Widely used in the InSAR community
- **Registration is open for Earthscope summer course!**

README | Code of conduct | Contributing | License

python 3.8+ | docs passing | tests passing | docker passing | conda downloads 67k | version v1.6.3 | forum Google Groups | license GPLv3+ | doi 10.1016/j.cageo.2019.104331

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- Auto search and download from ASF
- Optimized slice and dice through the archive
- No need to wait for computing delay computation

```
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tropospheric delay correction with OPERA ZTD products

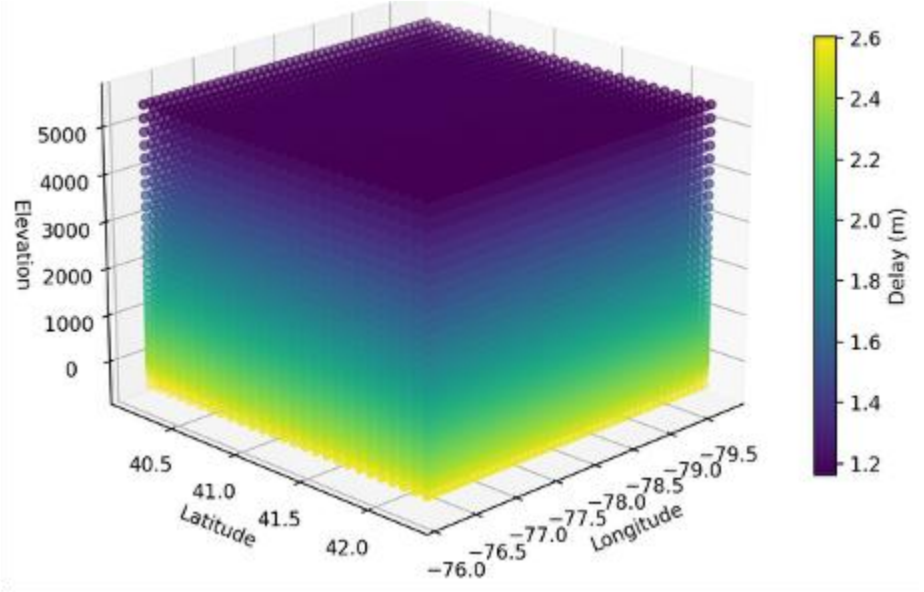
tropo_opera.py -f /scratch/dbekaert/newest/mexico_city/mintpy/timeseries_ion.h5 -g /scratch/dbekaert/newest/mexico_ci
ty/mintpy/inputs/geometryGeo.h5 -o /scratch/dbekaert/newest/mexico_city/mintpy/timeseries_ion_OPERA.h5 --dir ./OPERA
Use OPERA products at directory: /scratch/dbekaert/newest/mexico_city/mintpy/OPERA
tropospheric delay correction with OPERA approach
input displacement file : /scratch/dbekaert/newest/mexico_city/mintpy/timeseries_ion.h5
input geometry file     : /scratch/dbekaert/newest/mexico_city/mintpy/inputs/geometryGeo.h5
input OPERA directory   : /scratch/dbekaert/newest/mexico_city/mintpy/OPERA
output tropo file       : /scratch/dbekaert/newest/mexico_city/mintpy/inputs/OPERA.h5
output corrected file   : /scratch/dbekaert/newest/mexico_city/mintpy/timeseries_ion_OPERA.h5
read date/time info from file: /scratch/dbekaert/newest/mexico_city/mintpy/timeseries_ion.h5
--------------------------------------------------
search/download missing OPERA TROPO-ZENITH products from ASF ...
```

Integrated access to OPERA’s TROPO product though MintPy remove bottlenecks and allows for fast and easy application for community users

RAiDER

Raytracing Atmospheric Delay Estimation for RADAR

- Python-based tropospheric corrections slant and zenith
- Models support (HRRR, ERA, HRES, GMAO) and extensible
- Efficient implementation native to model coordinates



ARIA, OPERA and NISAR

- Underlaying routine for computing tropospheric corrections layers using ECMWF HRES data.
- For ARIA HRRR over US, HRES global

README | Contributing | Apache-2.0 license

RAiDER

Raytracing Atmospheric Delay Estimation for RADAR

python 3.9+ | License Apache 2.0 | PASSED | coverage 50%

RAiDER-tools is a package in Python which contains tools to calculate tropospheric corrections for Radar using a raytracing implementation. Its development was funded under the NASA Sea-level Change Team (NSLCT) program, the Earth Surface and Interior (ESI) program, and the NISAR Science Team (NISAR-ST) (NTR-51433). U.S. Government sponsorship acknowledged.

Basic workflow:

- reader class to implement model-specific APIs and save to NETCDF
- ZTD calculated at the weather model grid nodes in the native projection
- Final output uses fast 3D interpolation from the data cube to a DEM

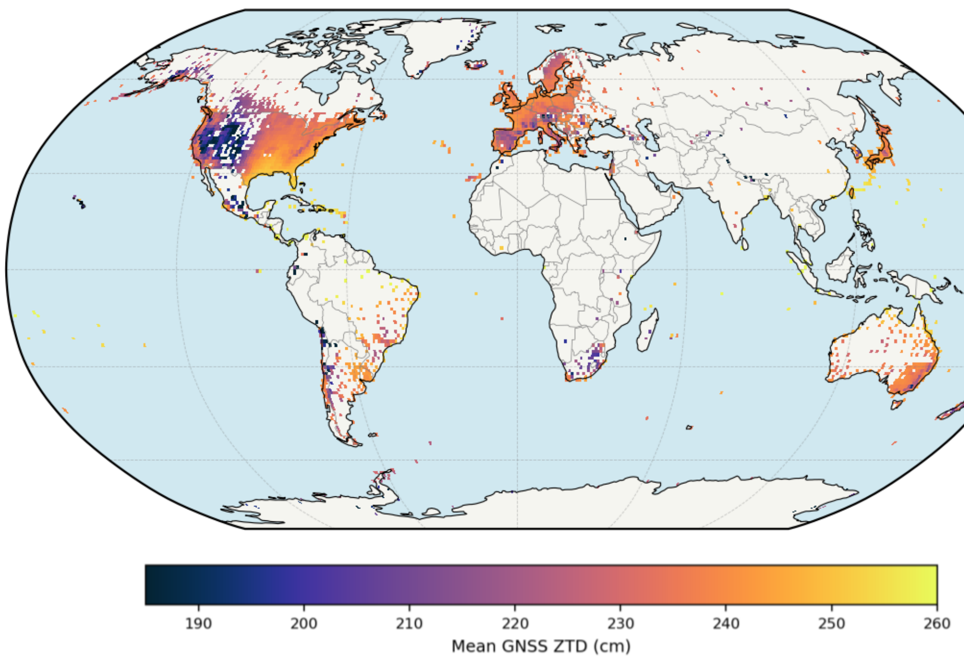
Maurer et al., in prep

Tropospheric delays

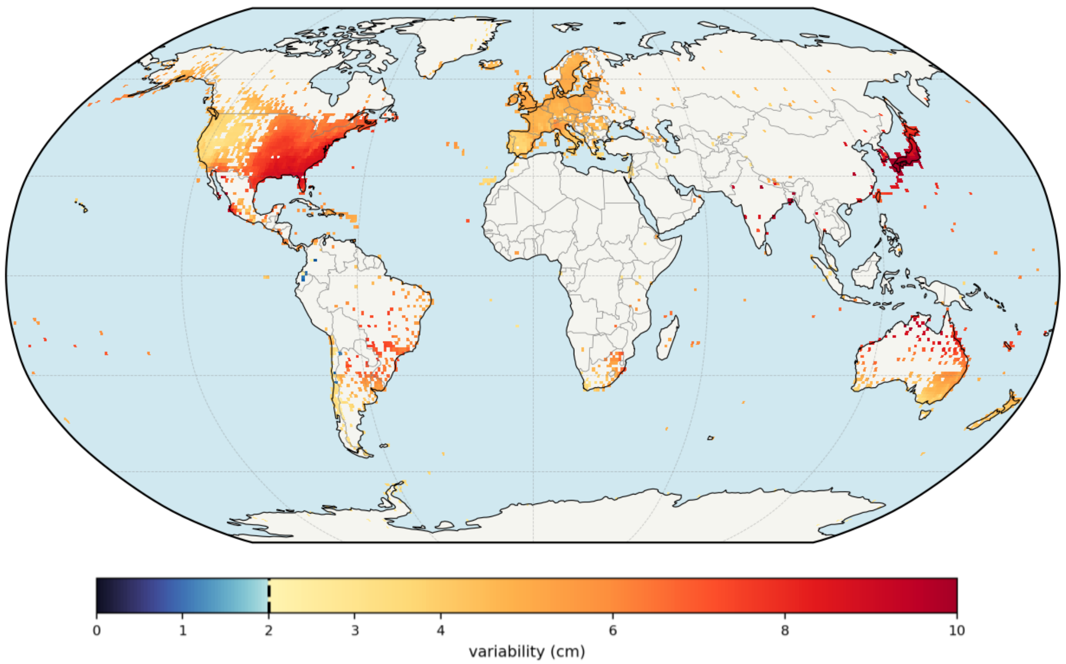
Estimated from GNSS

– 2016-2025 GNSS ZTD
– sampled at 12-day interval
– 6am local time => SAR representative
(Source: University of Reno, Geodetic Laboratory)

Mean delay



Standard Dev. of delay



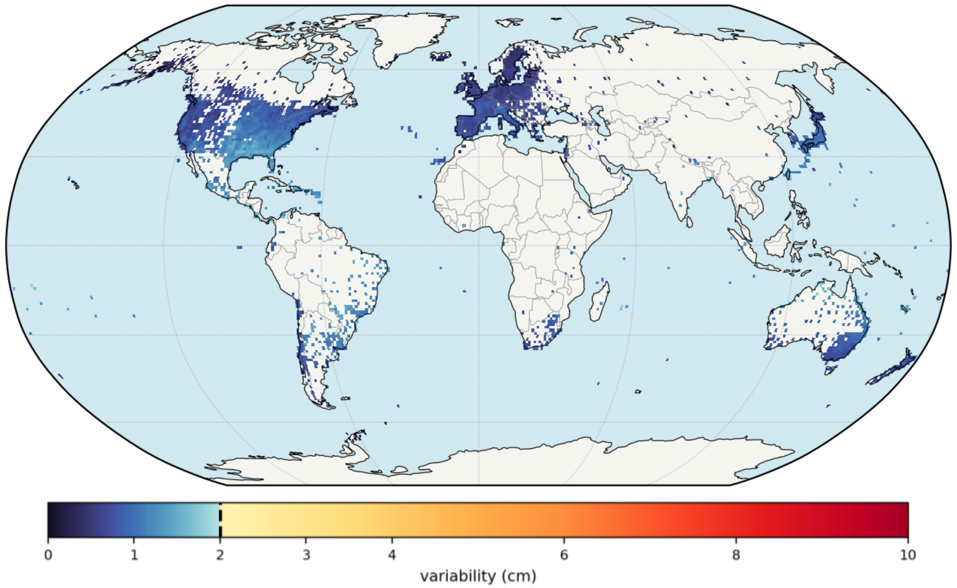
- UNR GNSS ZTD accuracy is ~5mm

- This is the variability between acquisitions
  → **Signal to correct for InSAR**

Bekaert et al., in prep

TROPO performance against GNSS – 2016-2025 @ 6am

Standard Dev of residual (GNSS-TROPO)



- TROPO performance:
  - At ~25km (limited by GNSS station distribution)
  - Residuals do not clearly correlate with topography
  - 6AM slightly worse than 6PM (~0.1cm)
  - European continent performs best,
  - US potentially impacted my low-level jet stream/ complex moisture transportation from the Gulf of Mexico

Bekaert et al., in prep

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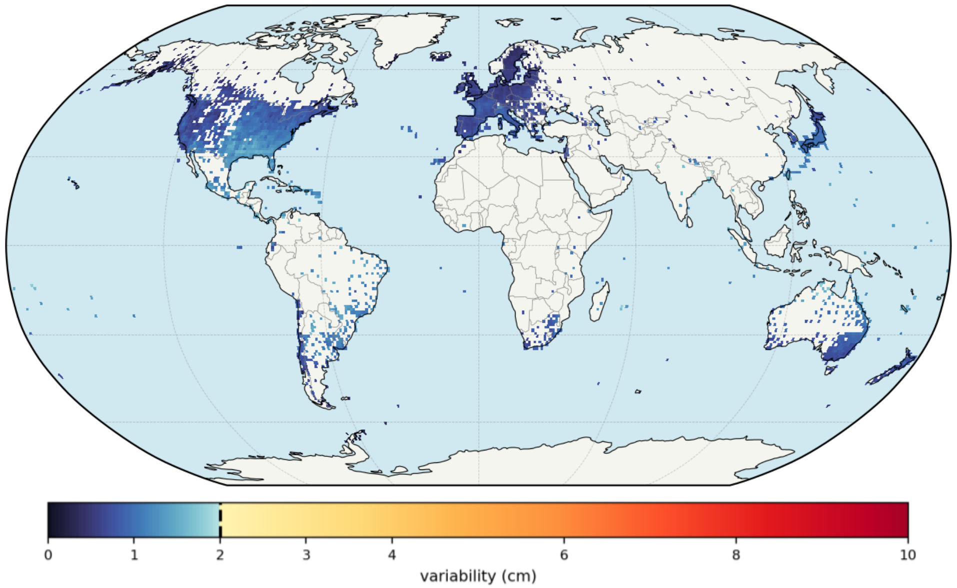

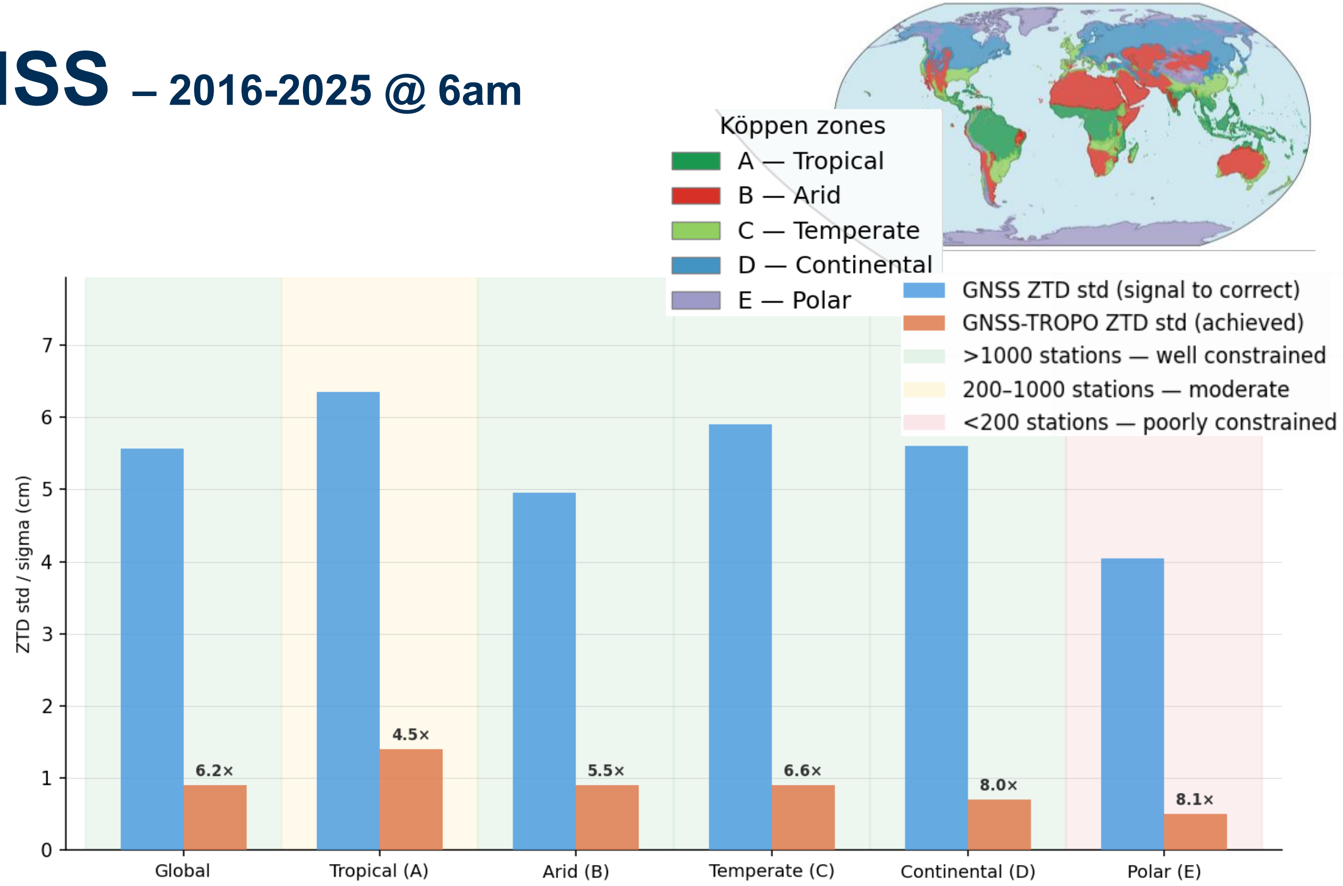

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- Performance in context of Koppen Climate zones
  - A - Tropical (not well sampled) – deep convection
  - B – Arid – Low IWV; tends towards hydrostatic
  - C – Temperate – Dense radio sound constraint
  - D – Continental – predictable seasonal cycles
  - E – Polar (not well sampled)

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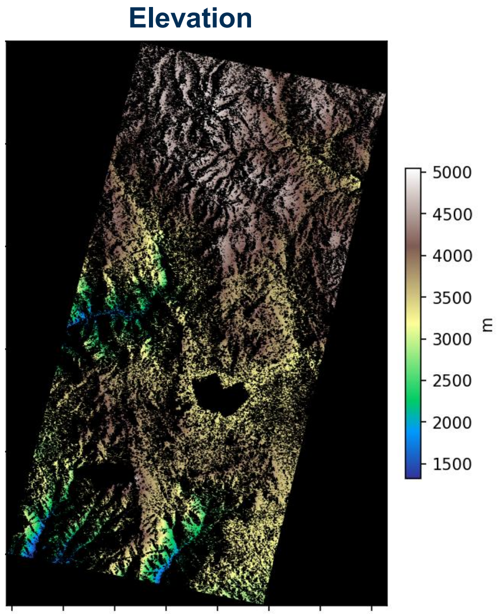
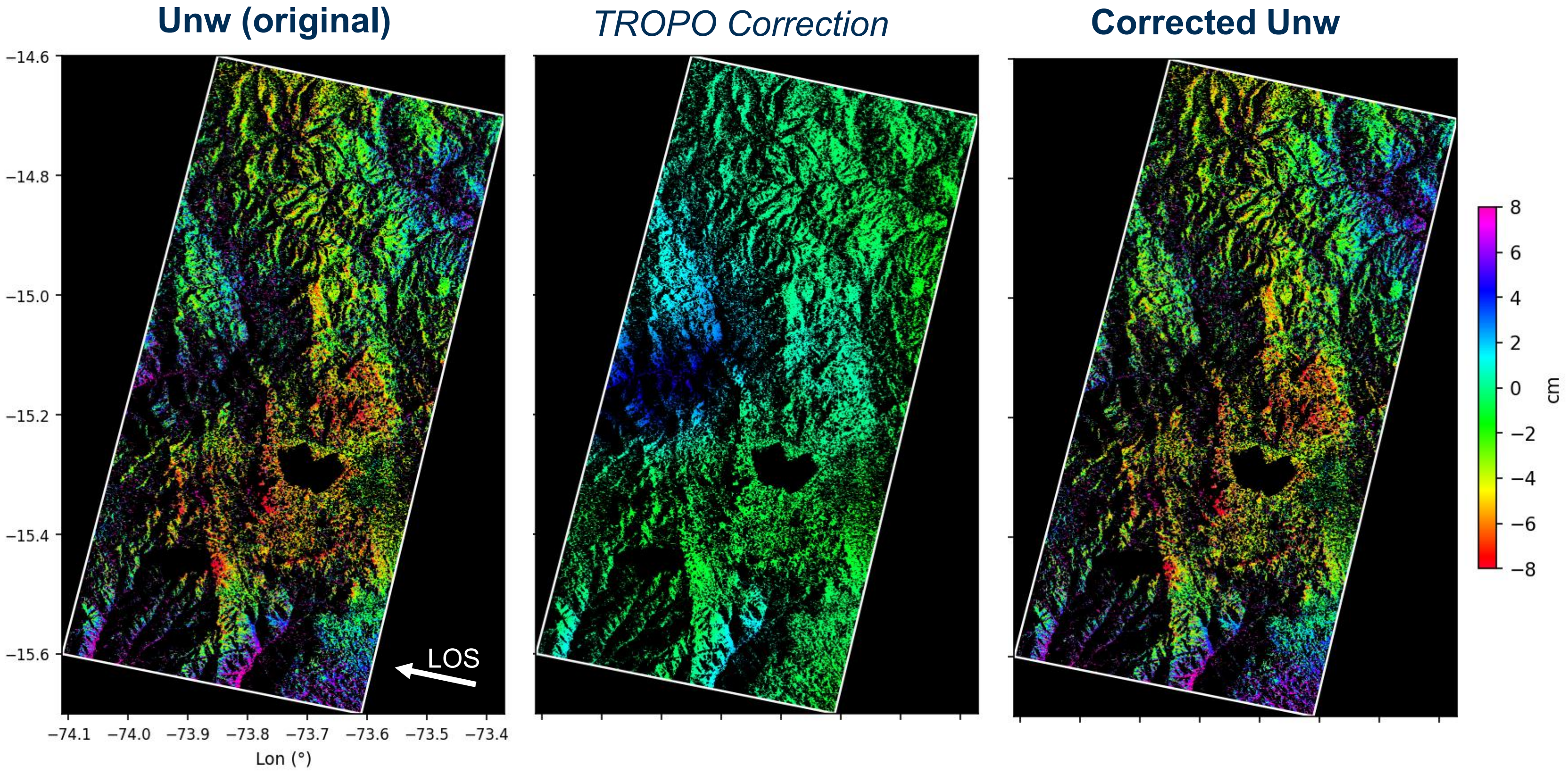
Bekaert et al., in prep

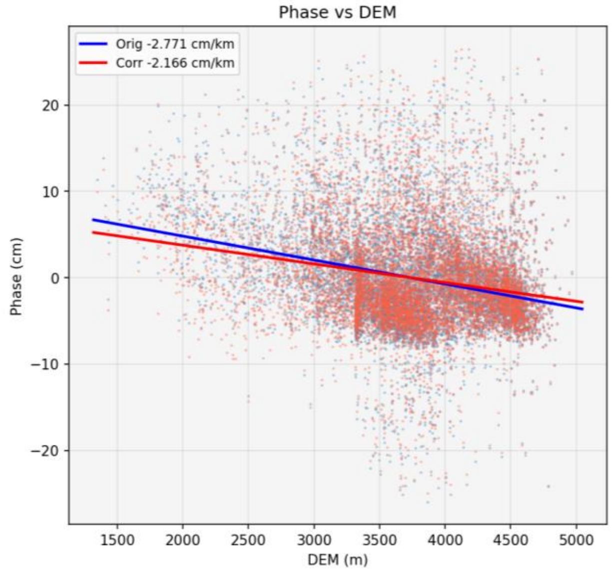
TROPO applied to BIOMASS L1C

P-band

- *20260503-20260512*
- *Bperp -2738m*
- *~80km swath width*
- *Level S1C product*
- *Corrected with embedded Iono layer*
- *Incidence angle: 22.3°– 27.9°*







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Bekaert et al., in prep

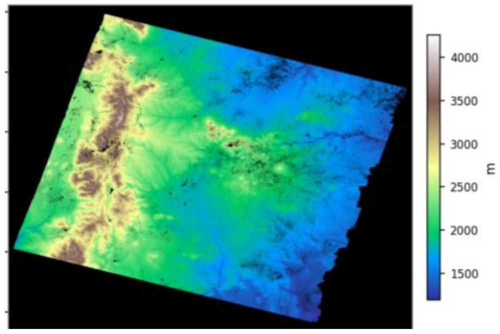
TROPO applied to NISAR GUNW

L-band

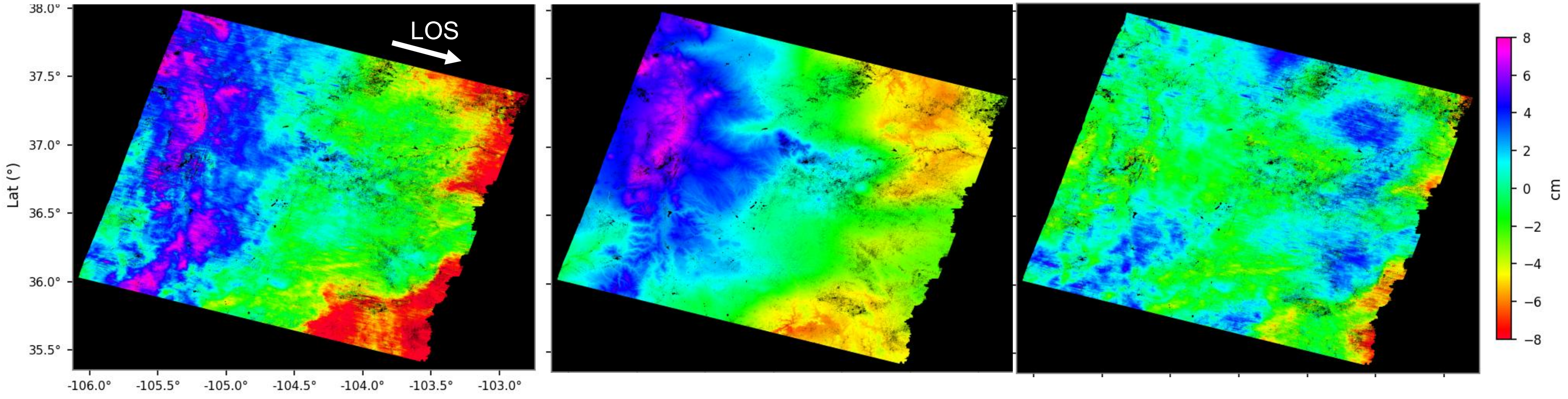
- *20251024-20251105*
- *~250km swath width*
- *Incidence angle: ~33°– 47°*
- *Level 2 GUNW product*
- *Corrected with embedded Iono layer*

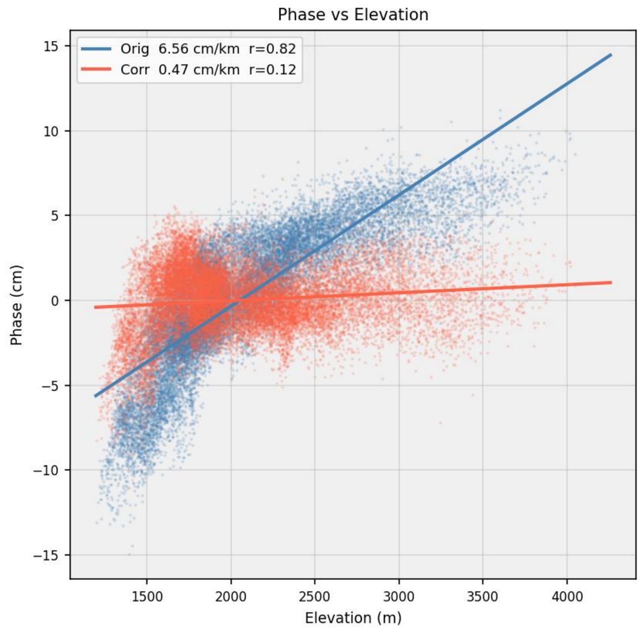
New Mexico

Elevation



Unw (original) — *TROPO Correction* — **Corrected Unw**





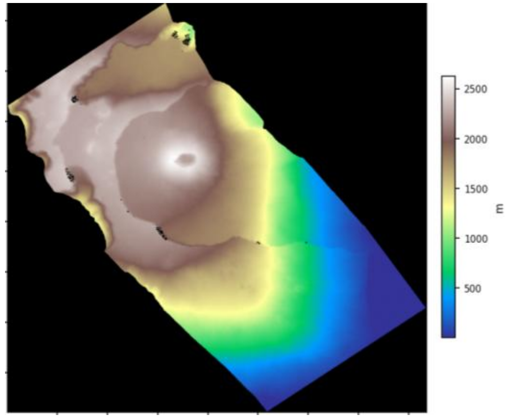
TROPO applied to Capella-13 Stripmap

X-band

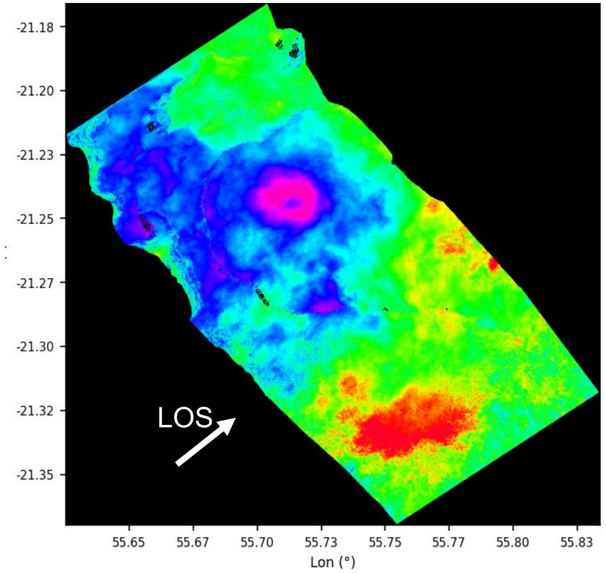
– *20251203-20251212*
– *Derived from mid-inclination C13 stripmap time series over* Piton de la Fournaise
– *Acquisition time of day variable (16:48 and 13:38 UTC)*
– *Incidence angle: 38 degrees (less than 1 degree of variation)*
– *Perpendicular baseline: 258 m*
– *Swath width 10 km*

Piton de la Fournaise

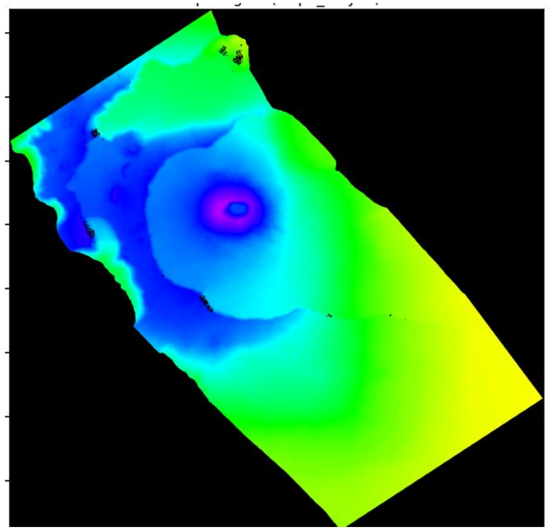
Elevation



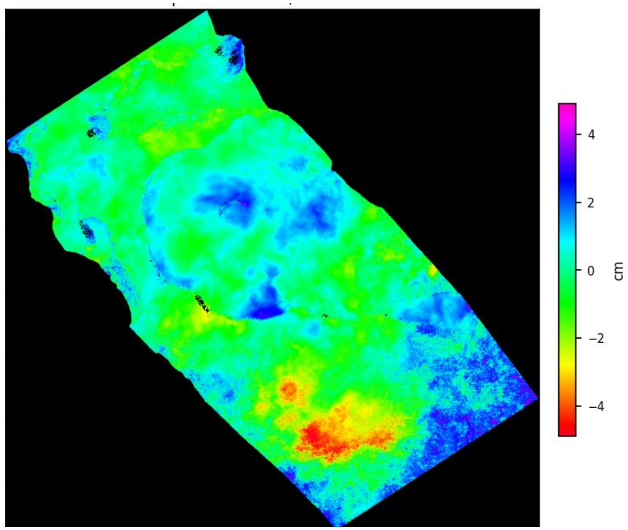
Unw (original)

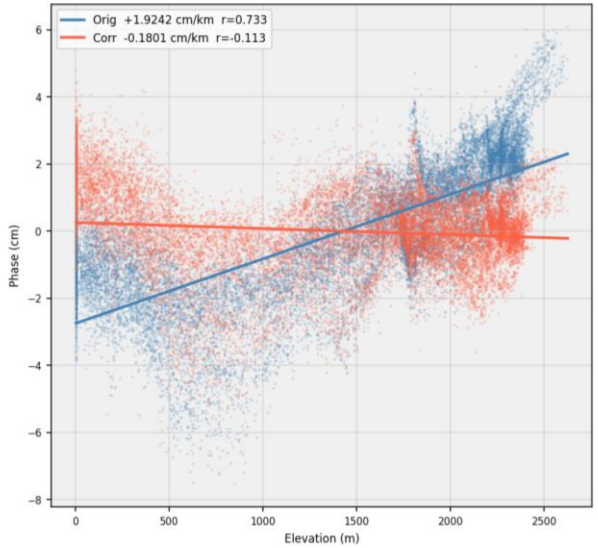


TROPO Correction



Corrected Unw





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(Data and processing by Scott Staniewicks - Capella)

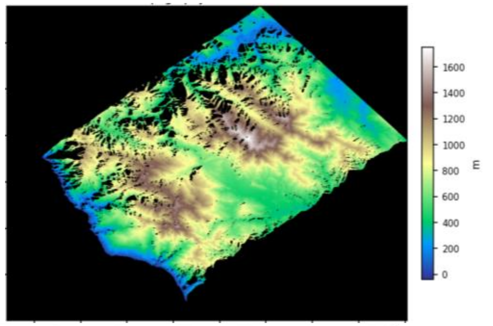
TROPO applied to UAVSAR

L-band

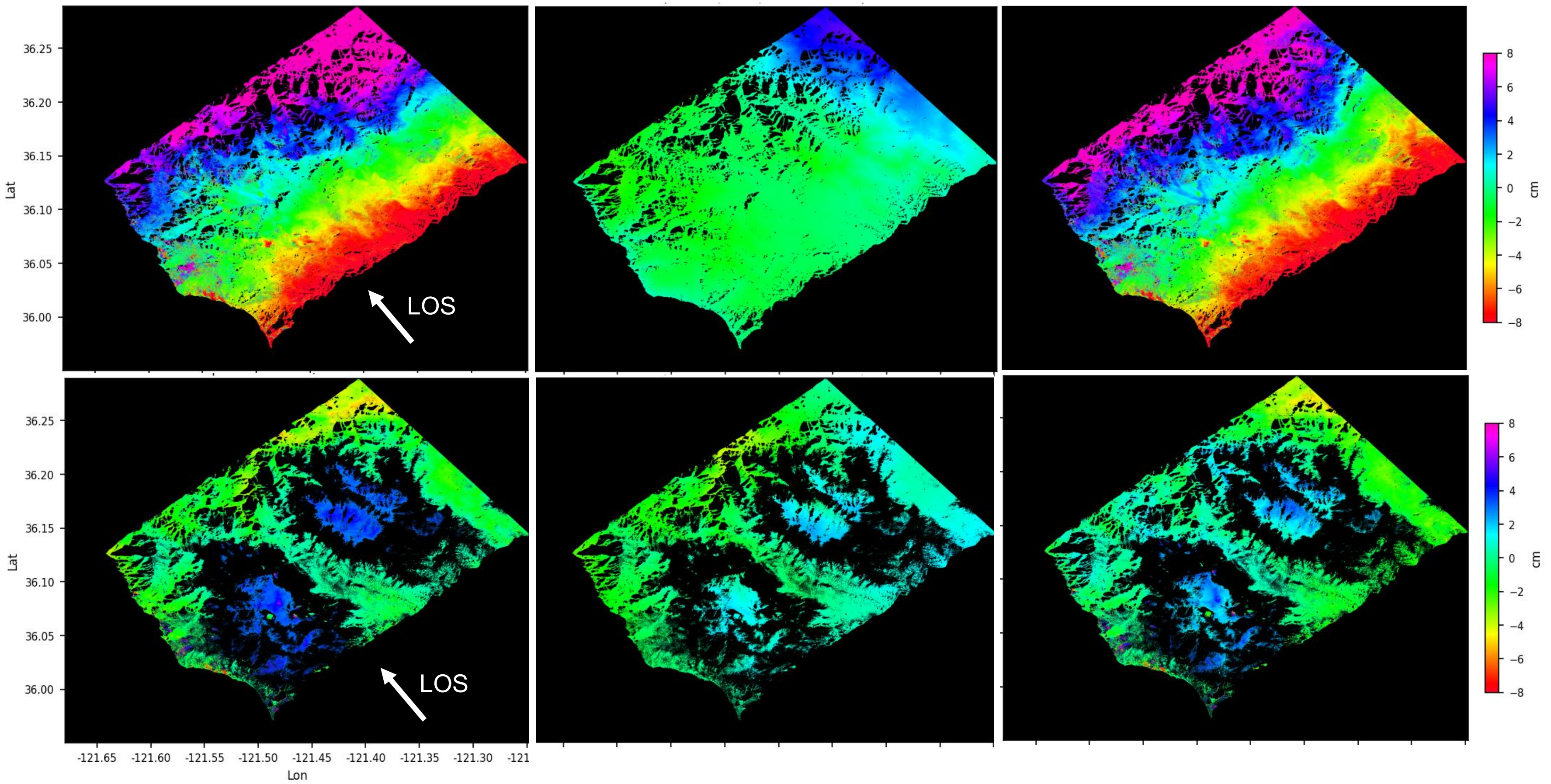
- *20161027-20200918 (top) & 20161027-20180808 (bottom)*
- *acquisition time is variable*
- *Aircraft altitude: ~12500 m*
- *SLCs (baseline uncorrected) products*
  (Unw processing shared by Alex Handwerger - JPL)
- *Incidence angle: 21.5°– 67.8 °*

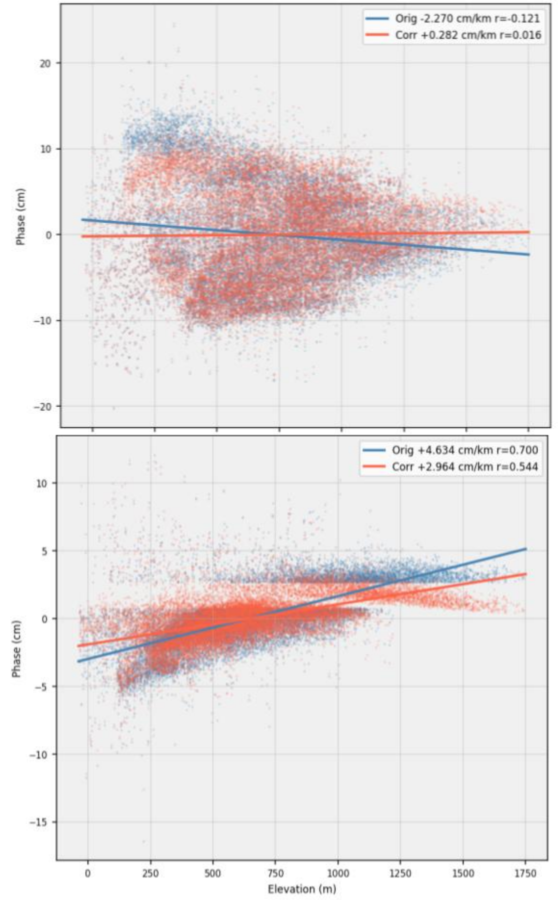
Big Sur

Elevation



Unw (original) | *TROPO Correction* | **Corrected Unw**





❖ TROPO product suitable for airborne tropospheric corrections (ground-platform; variable UTC)
❖ Tropospheric noise correction to be applied prior to residual baseline corrections

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Bekaert et al., in prep

OPERA TROPO enabled in MintPy

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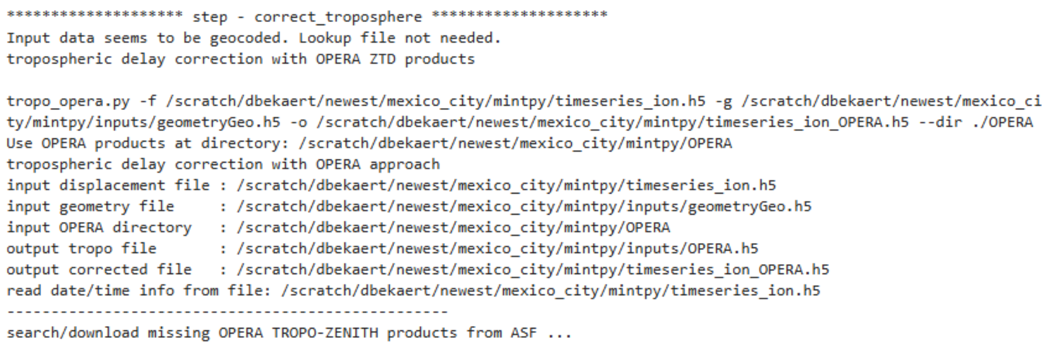

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ty/mintpy/inputs/geometryGeo.h5 -o /scratch/dbekaert/newest/mexico_city/mintpy/timeseries_ion_OPERA.h5 --dir ./OPERA
Use OPERA products at directory: /scratch/dbekaert/newest/mexico_city/mintpy/OPERA
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input geometry file     : /scratch/dbekaert/newest/mexico_city/mintpy/inputs/geometryGeo.h5
input OPERA directory   : /scratch/dbekaert/newest/mexico_city/mintpy/OPERA
output tropo file       : /scratch/dbekaert/newest/mexico_city/mintpy/inputs/OPERA.h5
output corrected file   : /scratch/dbekaert/newest/mexico_city/mintpy/timeseries_ion_OPERA.h5
read date/time info from file: /scratch/dbekaert/newest/mexico_city/mintpy/timeseries_ion.h5
--------------------------------------------------
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```

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TROPO applied to NISAR time-series

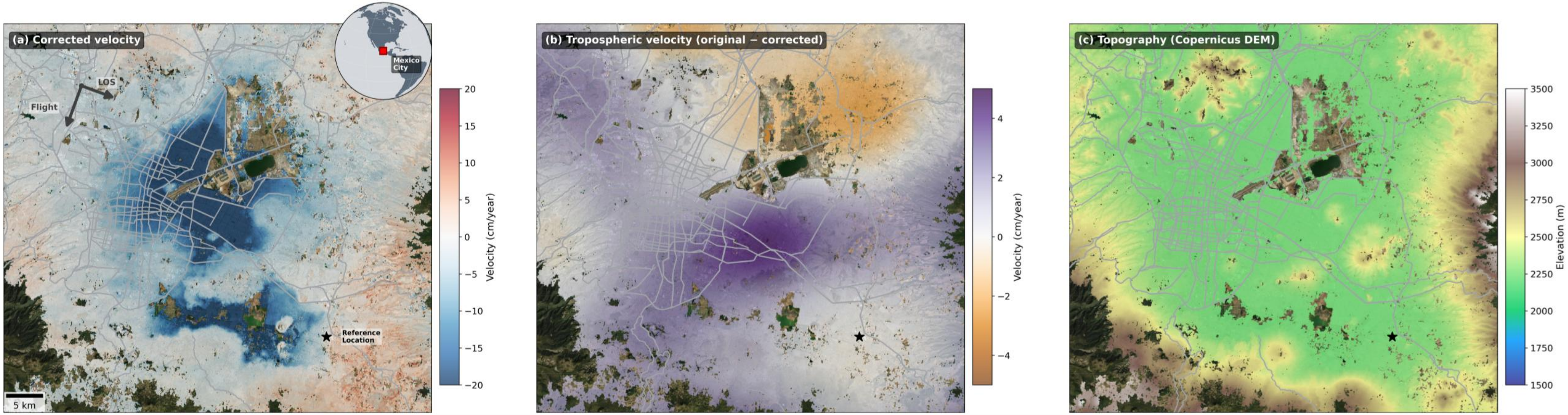
L-band

Mexico City:

– 2025-10-25 to 2026-05-17
– time-series analysis (18 acquisitions)

– L2 NISAR GUNW (pre-calibrated data)
– Corrected with embedded Iono layer

– Processed with ARIA-tools and MintPY (both support NISAR!)



- ❖ OPERA TROPO corrections reduces noise in order of 10cm/yr over 50km length scale
- ❖ NISAR also has embedded tropospheric correction layer (already in slant); both OPERA and NISAR are consistent!

Analysis by D.Bekaert as part of the NISAR Science team activities.
Derived from pre-calibrated data.

Discussion

Do tropospheric correction always work?

- model-based, with performance depending on local weather dynamics and model physics .
- Weather modeling is an active field of research
- On average, applying corrections lead to InSAR measurement improvements.

Are higher resolution models better?

- Most Numerical WM capture long-wavelength signals (>50km) well.
- Higher resolution can better capture hydrostatic correlation with topography.
- Localized wet delays are difficult to model and may introduce artifact if timing is inaccurate.

Expected benefits

- Reduces tropospheric noise in InSAR time series.
- Improves time-series analysis and detection of transient and seasonal deformation signals.
- Benefits may be smaller for localized study areas, and on linear rates estimates from long records.

Summary

OPERA has released a TROPO product

- Derived from HRES ECWMF data at 00, 06, 12 and 18 UTC.
- Record 2016-current and up to date.
- Free and open access through the NASA ASF DAAC
- 3D cube (~9km lateral, 145 height levels)

SAR agnostic

- Can be applied to airborne and spaceborne missions.
- Flexibility to varying acquisitions times

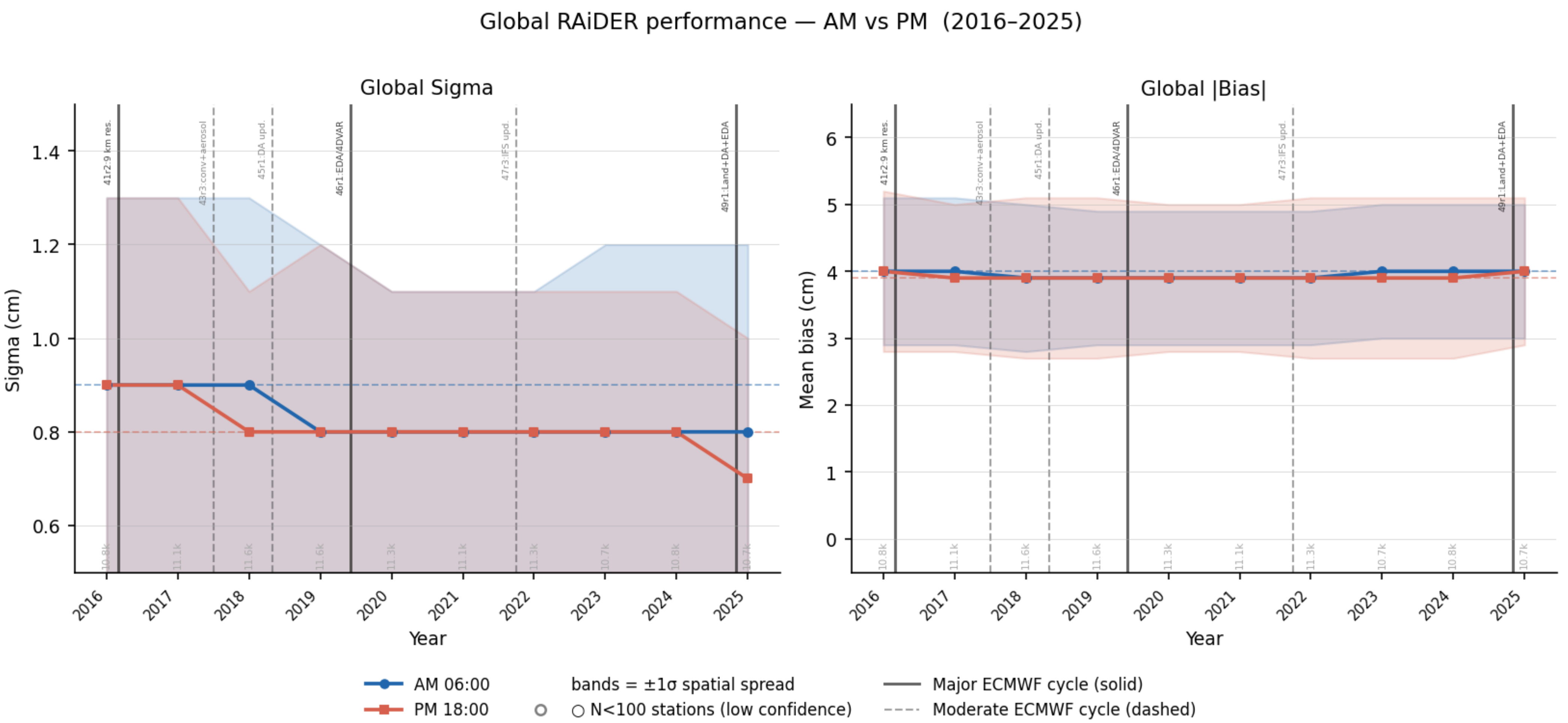
Demonstrated TROPO application to various SAR sensors

- Biomass, NISAR, UAVSAR, Capella, Sentinel-1
- SAR and time-series examples included
- In general, tropospheric corrections do reduce noise

TROPO support enabled in Mintpy package

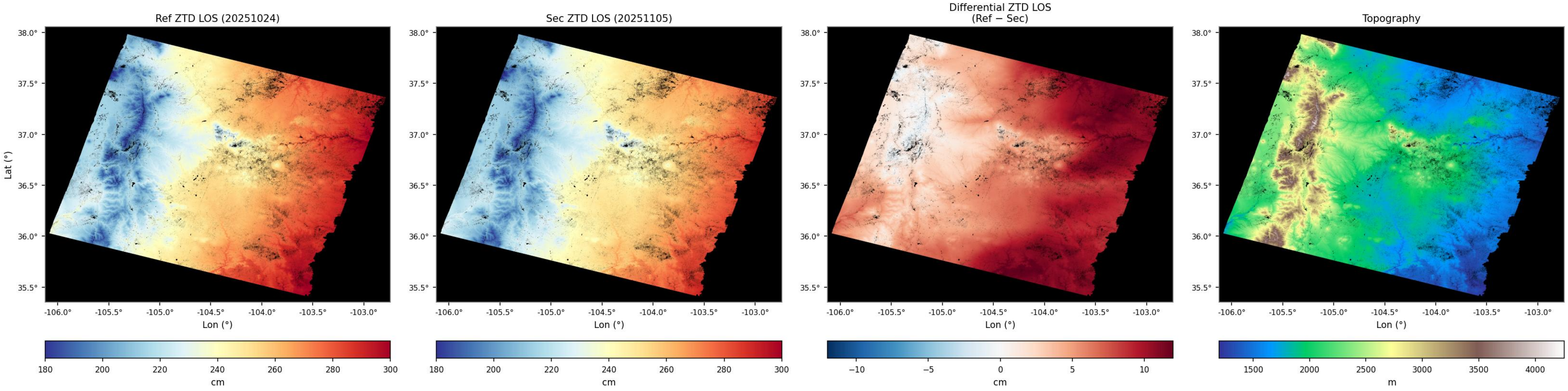
Backup

ECMWF HRES model improvement impact



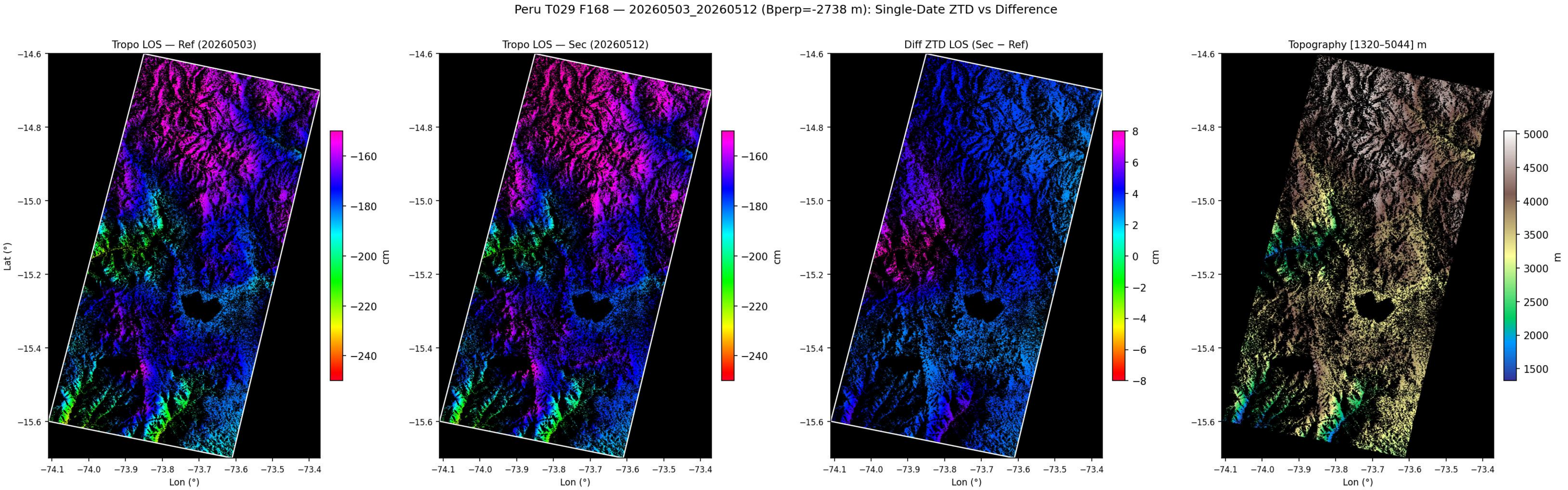
TROPO for New Mexico Example

20251024-20251105



TROPO for Peru Example

20260503-20260512



OPERA’s North America Displacement Product from InSAR

Continental scale mapping with Sentinel-1 operational, NISAR to follow soon

Kept up to date:

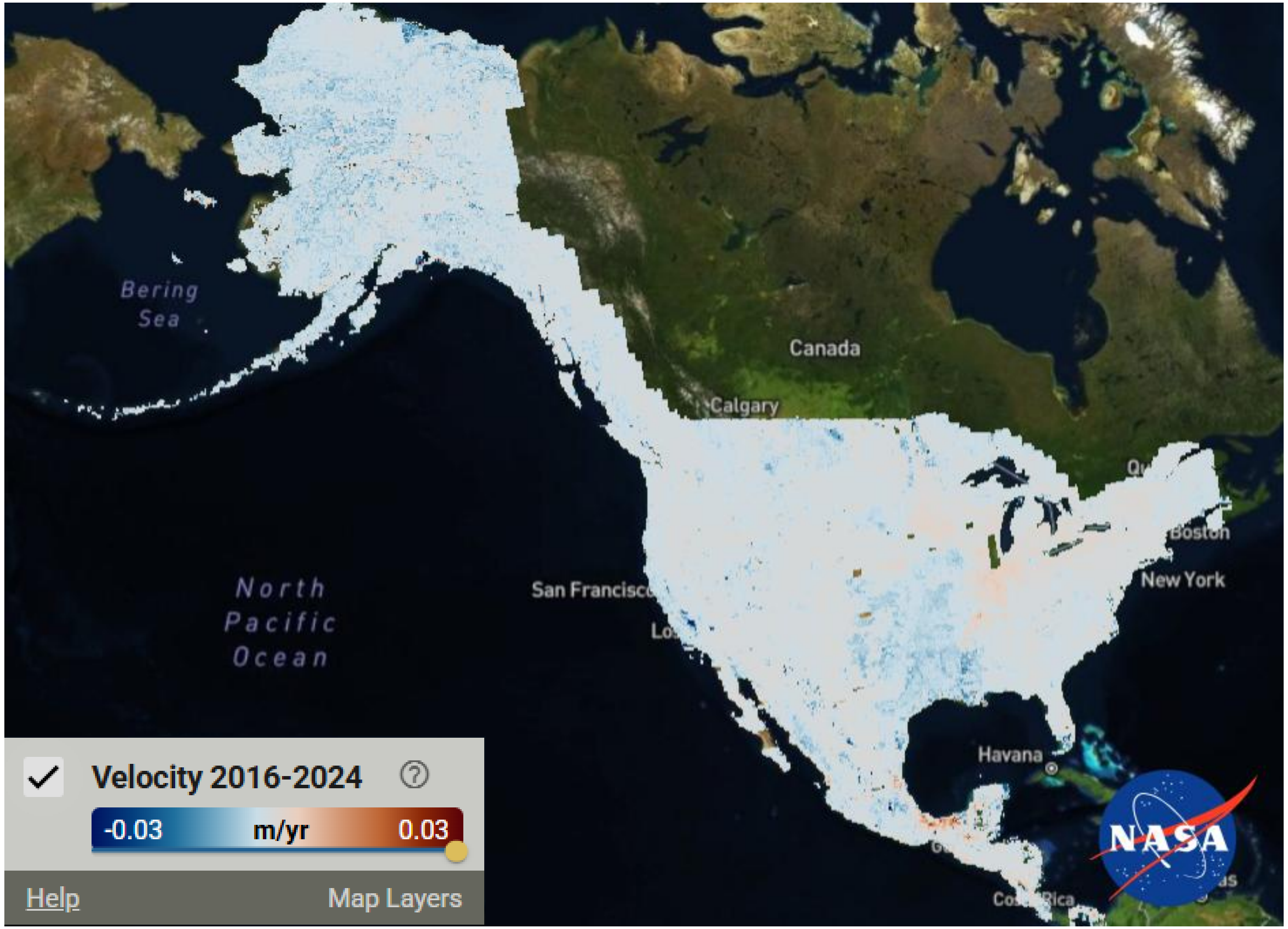
- Planned for update on each pass
- Products added as soon as is processed (*OPERA has no latency requirements*).

Free and open data through NASA archives:

- https://www.earthdata.nasa.gov/data/tools/asf-displacement-portal

Algorithm and product design suitable to cover varied terrain types and climatology

- e.g. coastal, vegetated, snow
- complementing Sentinel-1 (C-band) with NISAR (L band)



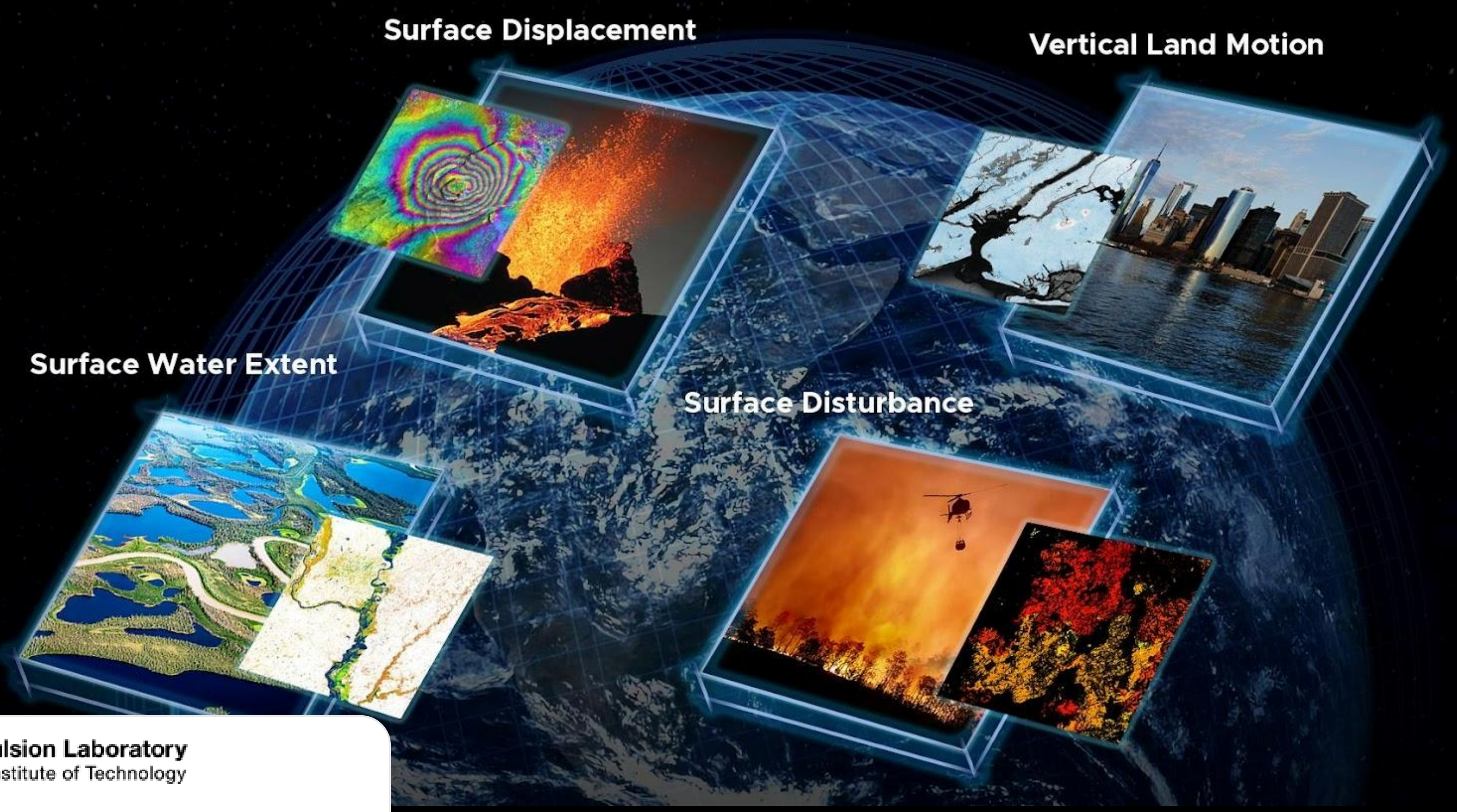
(Staniewicz et al., TGRS, April 2026)

Observational Products for End Users from Remote Sensing Analysis

National Aeronautics and Space Administration

OPERA was selected as part of the 2018/2020 Satellite Needs Working Group (SNWG) Assessment to create **analysis ready *data products*** that directly address the needs of multiple U.S. Federal Agencies.

OPERA is spearheading an innovative model within NASA to go beyond a single-mission and developing multiple product lines



Jet Propulsion Laboratory
California Institute of Technology

USGS · Goddard Space Flight Center · UAF University of Alaska Fairbanks · SMU · EarthScope Consortium · GLAD

For more information see: https://www.jpl.nasa.gov/go/opera/