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Near Real Time Estimation of Unbiased Ground Displacement Time-series with InSAR Big Data

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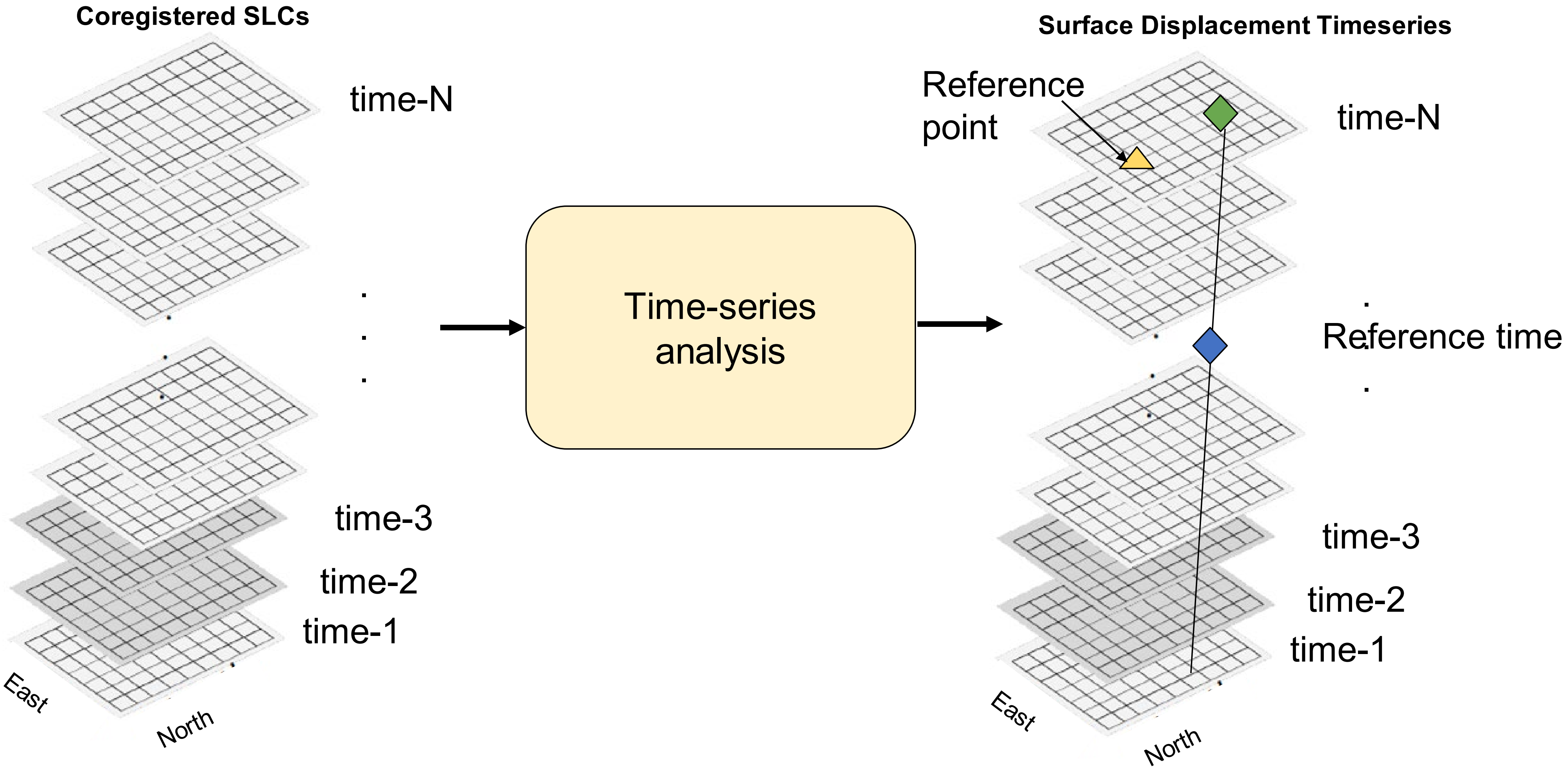
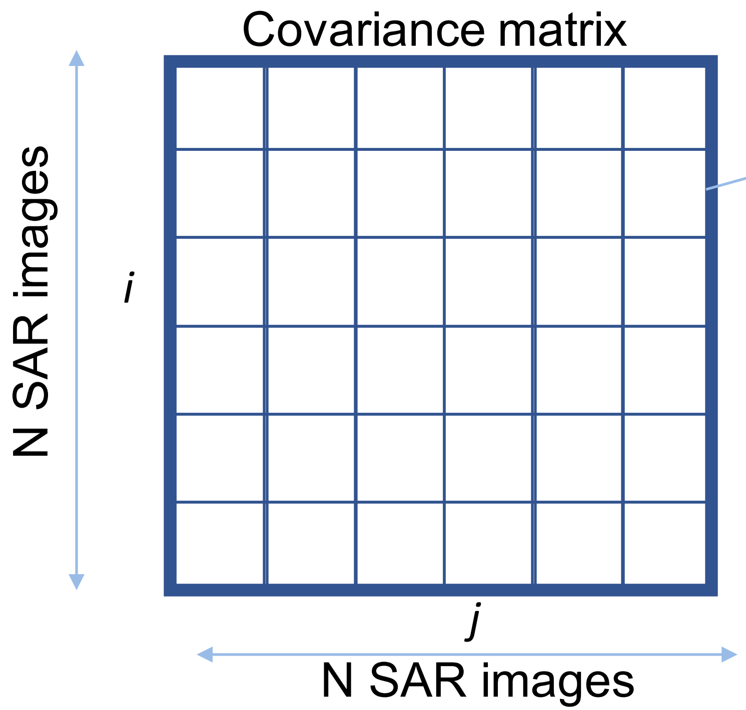
InSAR Displacement Time - series analysis



Covariance-based approach, extracts information from all possible interferometric pairs [Guarnieri & Tebaldini, 2007 and 2008]

Assuming N co-registered SAR images, a NxN covariance matrix can be formed whose elements are multi-looked interferograms



$$\hat{C}_{ij} = \frac{1}{M} \sum_{x \in \Omega} d_x^i {d_x^j}^H$$

- d_x^i A vector of complex SLCs at pixel *x* at time *i*
- H Hermitian conjugate operation
- Ω A neighborhood with M pixels to multi-look interferometric phases

A wrapped phase time-series can be estimated with different algorithms including:

- Maximum Likelihood Estimator (MLE) [Guarnieri & Tebaldini 2008]
- Phase Triangulation Algorithm [Ferretti et al 2011]
- Eigenvalue Decomposition [Fornaro et al, 2015]
- Eigenvalue based MLE (EMI) [Ansari et al, 2018]
- Combined EMI and EVD [Mirzaee et al, 2023]

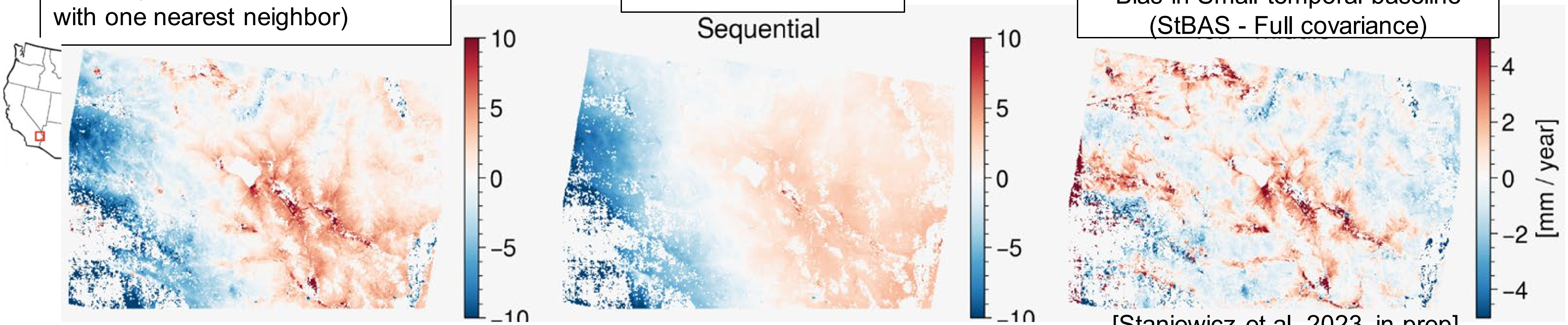
Unbiased displacement estimated from full covariance

National Aeronautics and Space Administration

StBAS (Small temporal Baseline with one nearest neighbor)

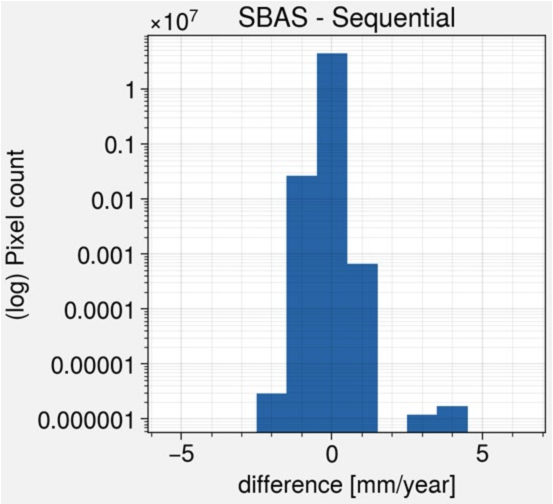
Full covariance

Bias in Small temporal baseline (StBAS - Full covariance)



[Staniewicz et al, 2023, in prep]

- Rate of displacement for a stack of Sentinel-1 data over Mojave desert was estimated from displacement timeseries derived with two algorithms:
  - Left: StBAS with one nearest neighbor interferometric pairs
  - Middle: Full covariance based using Sequential estimator
- The difference between the StBAS with one nearest neighbor and Full covariance indicates the bias in the StBAS results caused by non-zero closure phase
- Full-covariance based algorithm reduces a bias of up to ~5 mm/yr in the rate of displacement time-series
- Confirming similar observation reported by Ansari et al, 2021 and Zheng et al 2022



Big - data problem for full covariance based estimators

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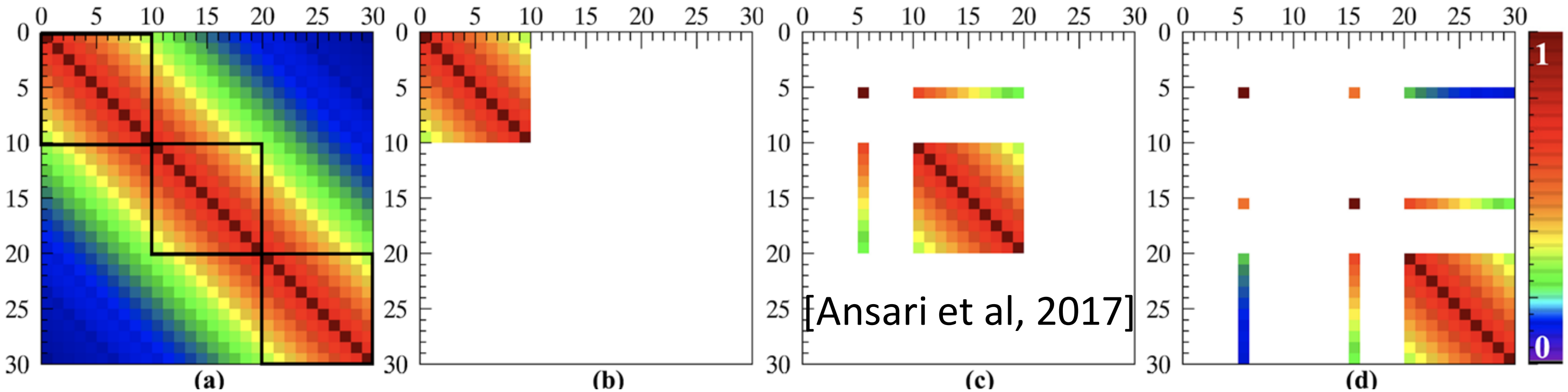
Estimating the wrapped phase time-series from a **full covariance matrix** formed from a large stack of SLCs (10s or 100s of SLCs) **is an expensive operation**

Ansari et al, 2017 proposed Sequential Estimator algorithm which processes a covariance matrix in batch and allows to update an existing time-series without processing the full covariance matrix.



Limitations of the Sequential estimator

1- Long latency (up to few months):
With the arrival of a new acquisition the estimator needs to wait until enough new acquisitions exist to form a mini-stack

2- Not an operation-friendly algorithm: The mini-stack adjustment is not operation friendly

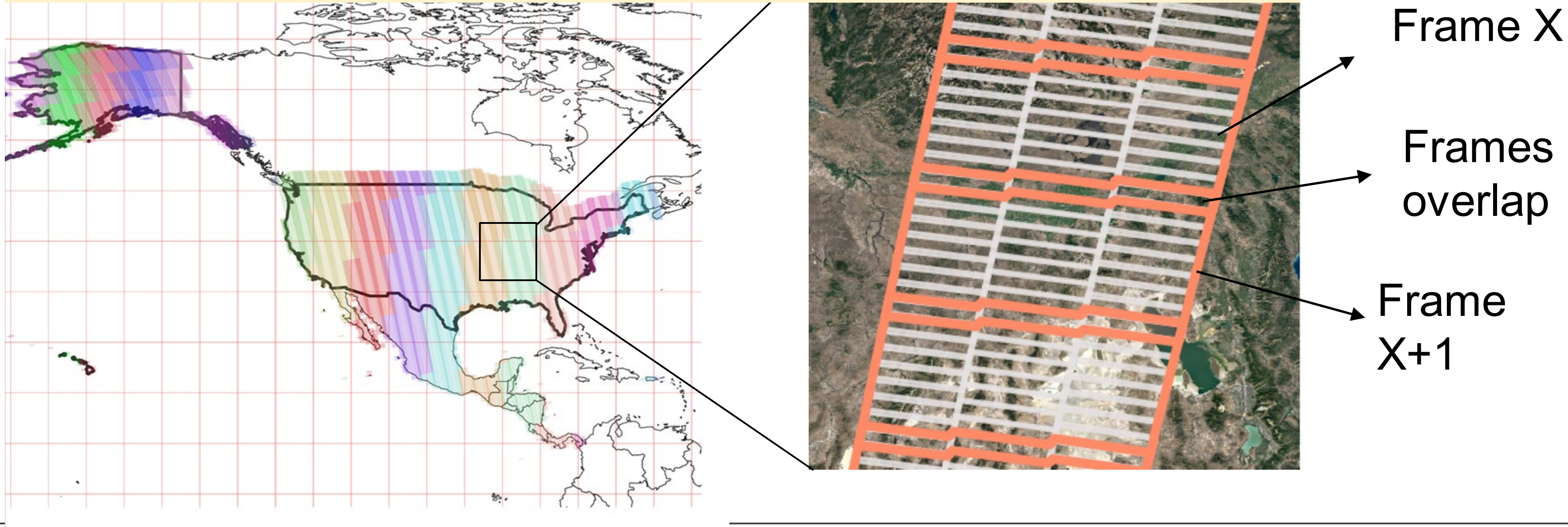
Surface Displacement Time - series over United States

National Aeronautics and Space Administration

NASA has planned producing surface displacement products from Sentinel-1 and NISAR over North America
OPERA project at JPL is assigned to produce the displacement time-series. Driving requirements include:

- 30 m spacing or better
- Displacement in radar Line Of Sight (LOS)
- **72 hours latency (since the time that all inputs are available)**
- **Displacement uncertainty of 5 mm/yr or better** over length scales within 0.1 km < L < 50 km

The product's spatial coverage includes 50 states of USA, all official 14 US Territories, all mainland countries between US CONUS south to and including Panama, and Canada within 200 km from US border

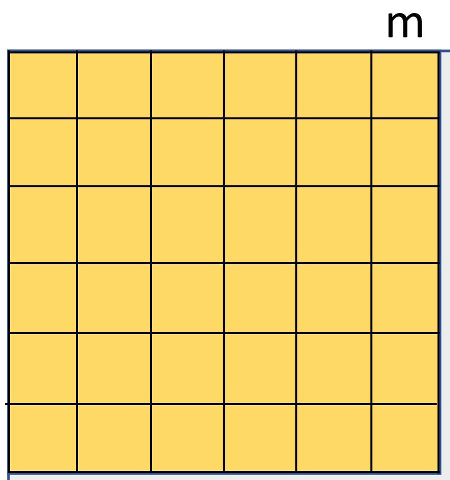


- Each frame is a group of ~27 bursts (~200 km x 240 km)
- Frames are fixed through time
- Frames are overlapping by one burst

Incremental Estimator

In order to reduce the latency of the full-covariance based estimation of the interferometric wrapped phase time-series, we introduce the “**incremental estimator”** with the following characteristics:

- Estimates the wrapped phase series using a full covariance matrix
- Allows for short latency upon arrival of new acquisitions
- Is significantly more operation-friendly compared to sequential estimator (does not require datum adjustment)

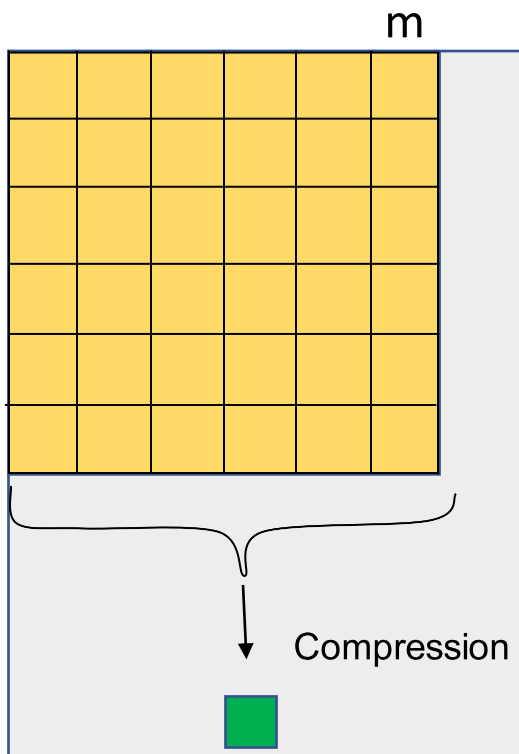


Estimate phase series for the first ministack

Compress the first ministack in one compressed SLC

Archive:

- $d_{1,2}, d_{1,3}, \dots d_{1,m}$
- First compressed slc



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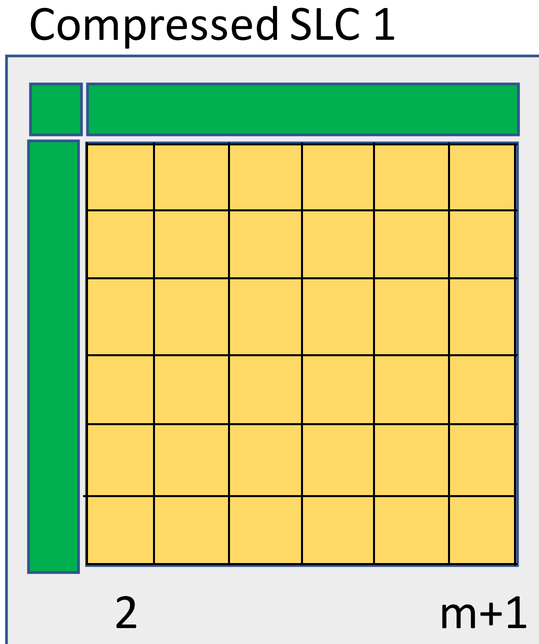


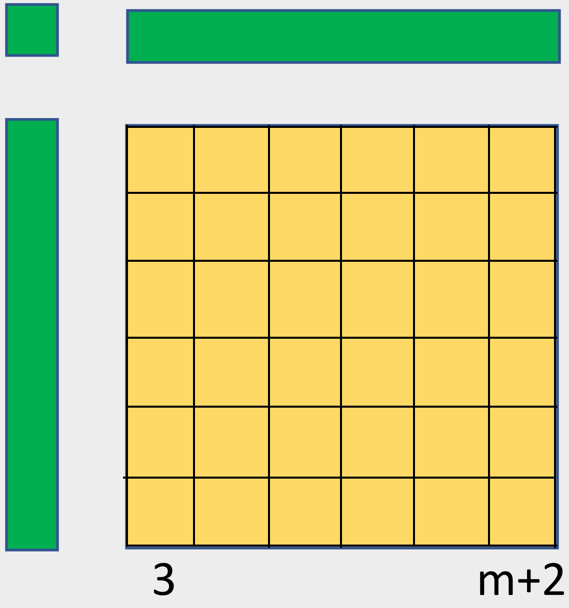
The newest acquisition comes in: $m+1$

Use m most recent real SLCs, plus the compressed SLC

Estimate phase series

Archive:

$$d_{1,m+1}$$

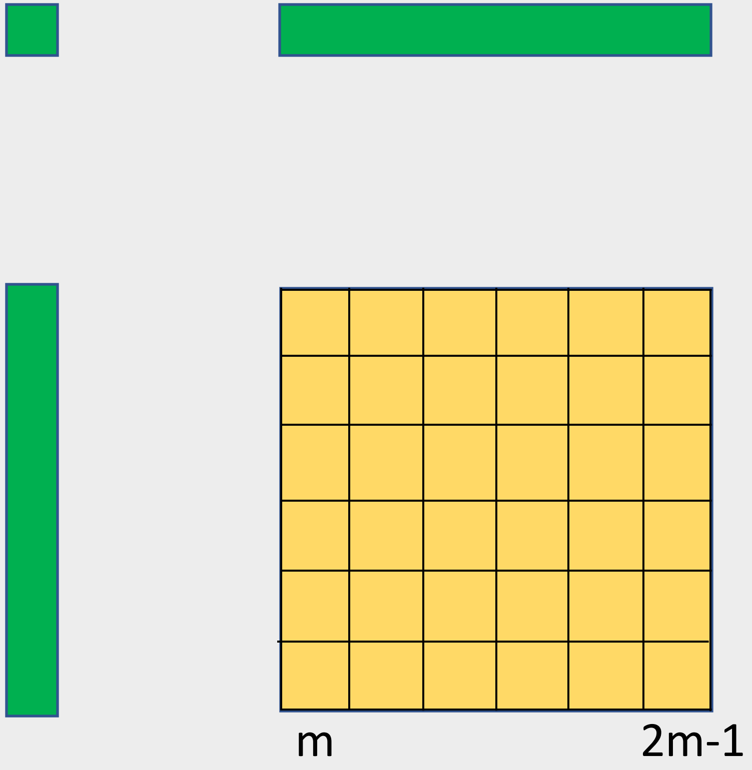


The newest acquisition comes in $m + 2$

Estimate phase series

Archive

$d_{1,m+2}$

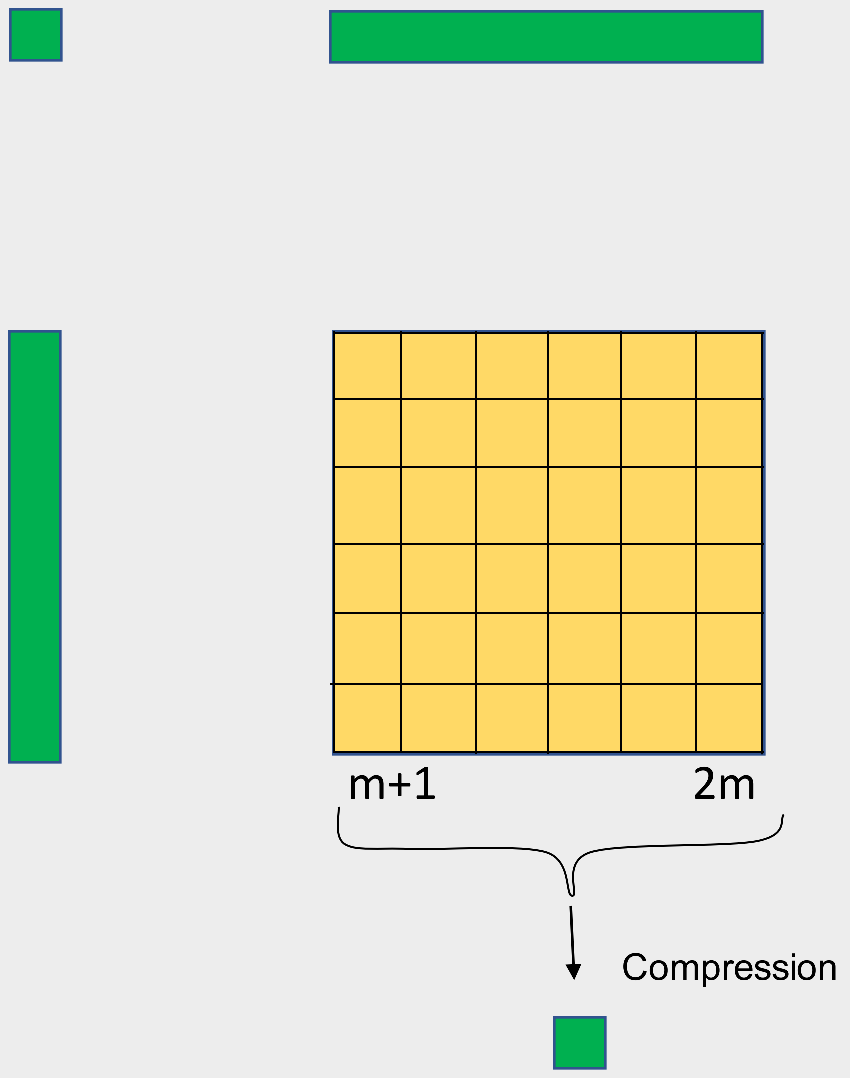


The newest acquisition comes in: $2m - 1$

Estimate phase series

Archive

$d_{1,2m-1}$



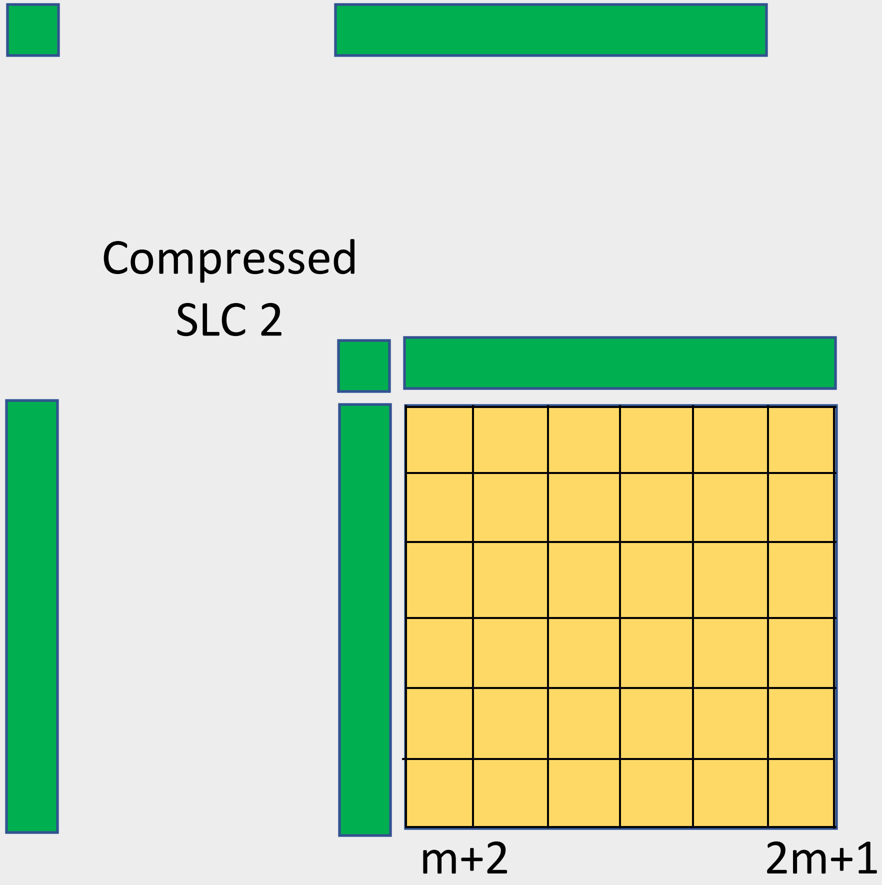
The newest acquisition comes in: $2m$

Estimate phase series

Compress the ministack in the 2nd compressed SLC

Archive:

- Phase $d_{1,2m}$
- Compressed SLC 2



The newest acquisition comes in $2m + 1$

Estimate phase series using m real SLCs and 2 compressed SLCs

Archive

$d_{1,2m+1}$

SLC Compression Details

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- Let $\boldsymbol{z}_{1,m}$ be the original SLCs from dates (1, … m)
- Let $\tilde{\boldsymbol{z}}_{1,m}$ be the optimized vector after phase linking
  - This vector has an arbitrary offset. Multiply all elements by $\tilde{x}_1^*$ so the first element's phase = 0

$$\boldsymbol{z}_{1,m} = [x_1, x_2, \dots x_m]^T$$

$$\tilde{\boldsymbol{z}}_{1,m} = [\tilde{x}_1 \cdot \tilde{x}_1^*, \dots \tilde{x}_m \cdot \tilde{x}_1^*]^T$$

- The first compressed SLC c_1 is **the inner product** of the original SLCs and the optimized SLCs

$$c_1 = < \boldsymbol{z}_{1,m}, \tilde{\boldsymbol{z}}_{1,m} >$$

$$= \sum_{k=1}^{m} x_k \, (\tilde{x}_k \tilde{x}_1^*)^*$$

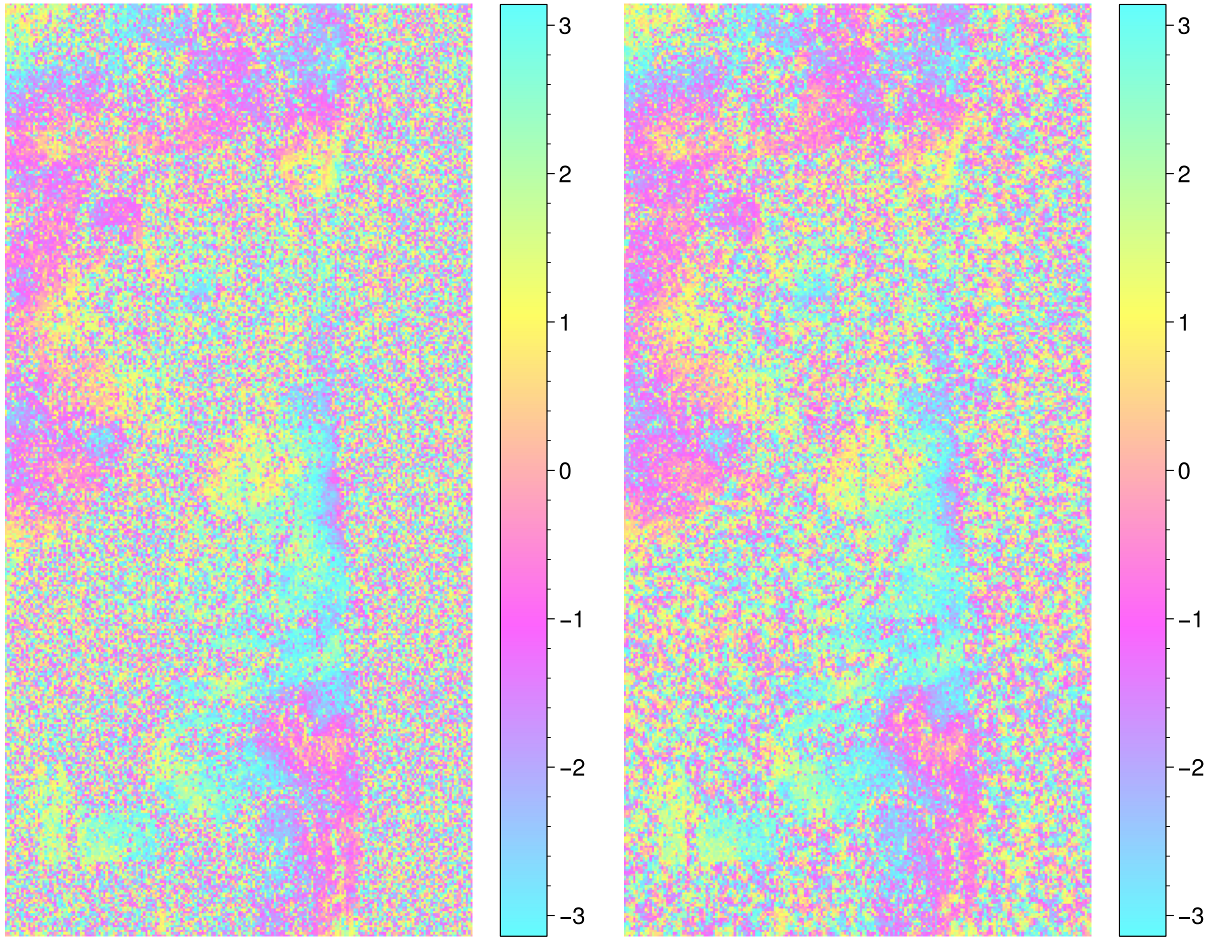
$$= \tilde{x}_1 \sum_{k=1}^{m} x_k \tilde{x}_k^*$$

- Because we refence to $\tilde{x}_1^*$, the compressed SLC consists of
  - A phase close to the first SLC as the dominant term
  - A "weighting" term from the dot product sum

SLC Compression Details

- Qualitative comparison of interferogram formed using first compressed SLC
- The phase of c_1 can be though of as a **filtered phase** of the first real SLC

Normal multi-looked ifg. $x_1 \cdot x_2^*$ Ifg. using compressed SLC $c_1 \cdot x_2^*$



Using compressed SLCs without ”Datum Adjustment”

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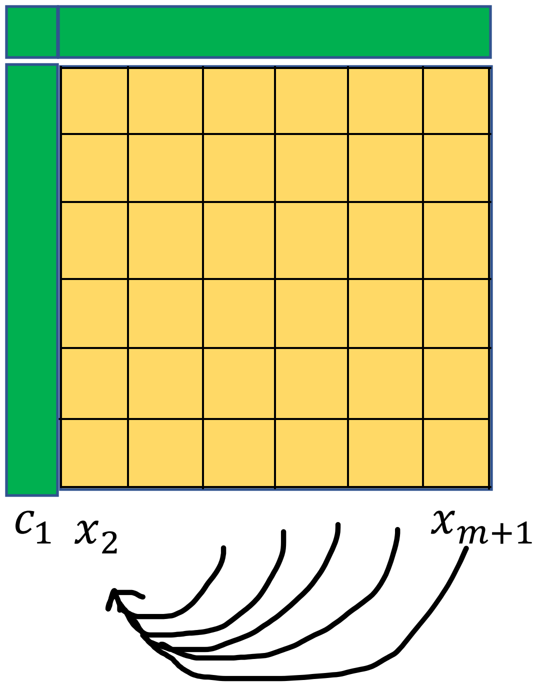


Multiply by x_2^*

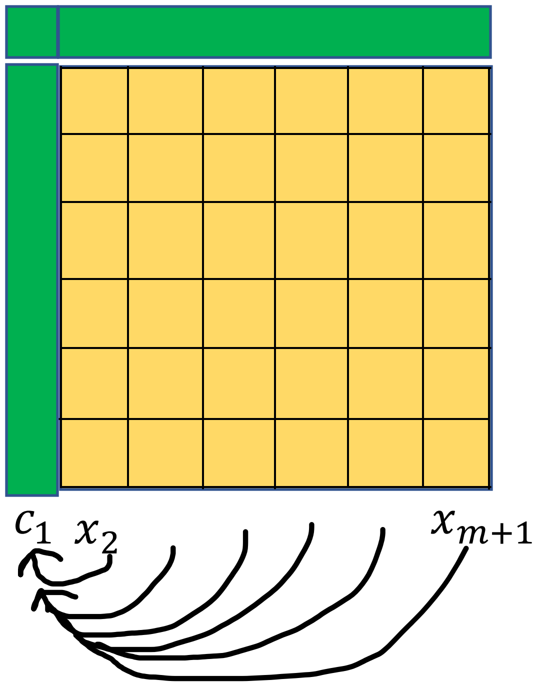
Let c_1 be the first compressed SLC, and x_i be the measurement from real SLC i.

The complex measurement vector for this iteration is
$Z = [c_1, x_2, \dots x_{m+1}]^T$

After phase linking, we get an optimized vector $\tilde{Z} \in \mathcal{C}^{m+1}$ whose phase must be referenced to some date (multiplying each entry in the vector by a complex conjugate).

In Ansari, 2017, the phase is referenced to the **first real SLC** in the ministack (here, x_2^*). This leads to an offset disconnecting adjacent ministacks.

Using compressed SLCs without "Datum Adjustment"



Multiply by c_1^*

Let c_1 be the first compressed SLC, and x_i be the measurement from real SLC i.

The complex measurement vector for this iteration is
$Z = [c_1, x_2, \ldots x_{m+1}]^T$

After phase linking, we get an optimized vector $\tilde{Z} \in \mathcal{C}^{m+1}$ whose phase must be referenced to some date (multiplying each entry in the vector by a complex conjugate).

Instead of using x_2^*, **we use c_1^***
This makes all entries $\tilde{Z}$ relative to day 1, even though the real SLC 1 is not in the ministack.

Simulation

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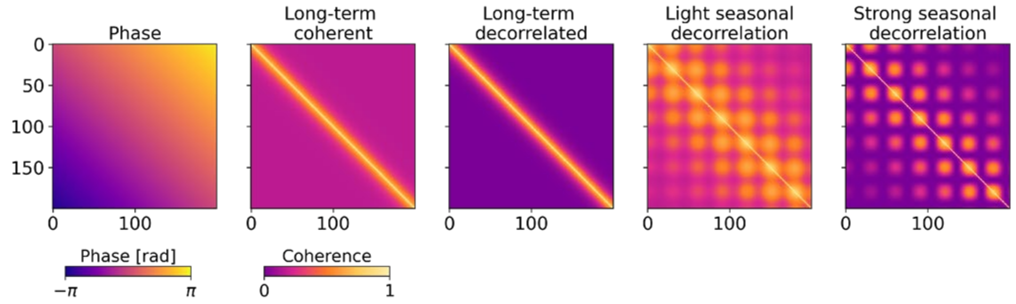
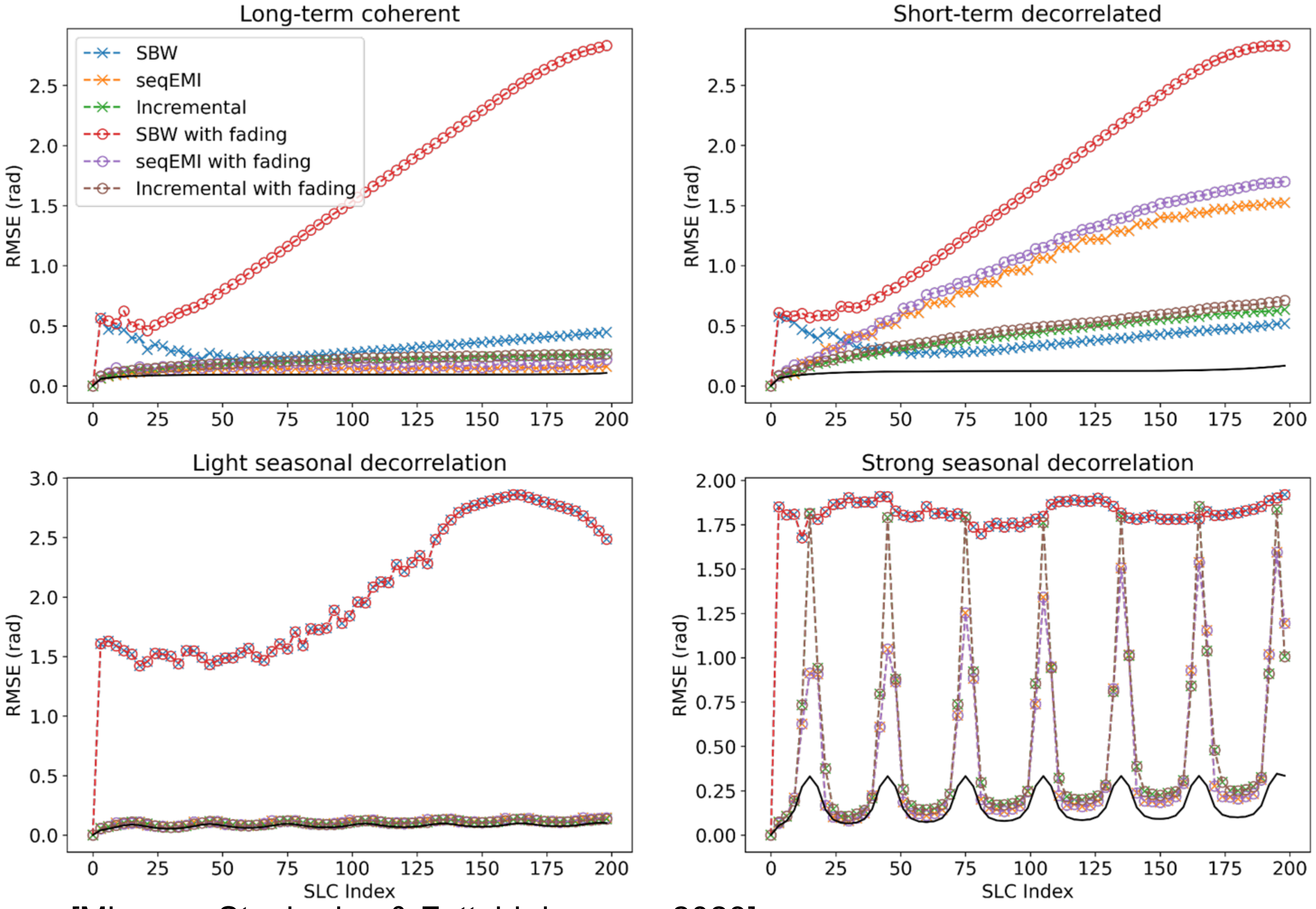




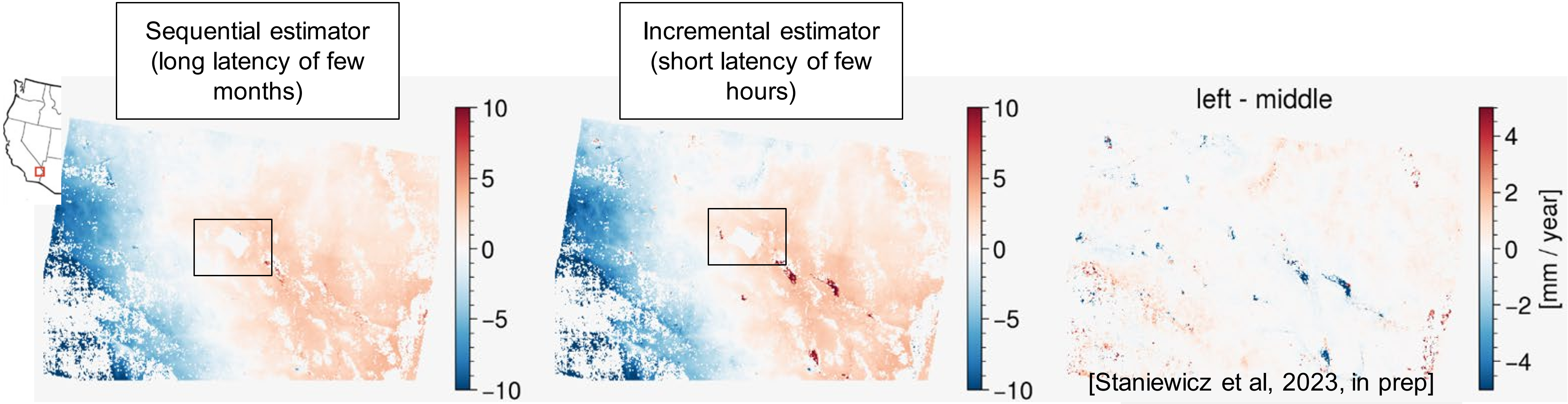
- Phase residuals for Short bandwidth, sequential EMI and Incremental time-series techniques for four decorrelation scenarios: (a) Long term coherent, (b) long term decorrelated, (c) light seasonal decorrelated and (d) strong seasonal decorrelated

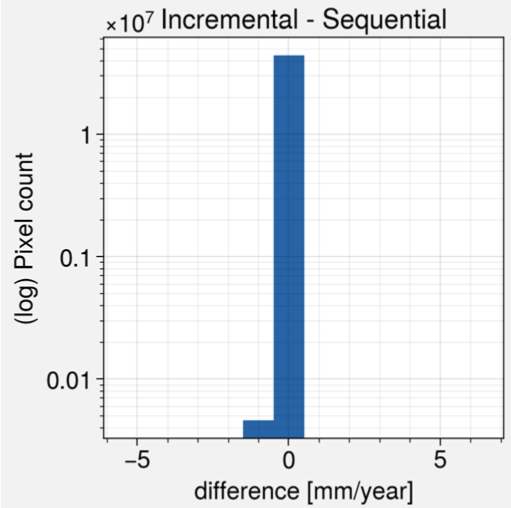
- The RMSE of 1000 realization for incremental estimator is low in all decorrelation scenarios compared to other algorithms

- The impact of non-zero closure phase on the proposed incremental estimator is minimal

[Mirzaee, Staniewicz & Fattahi, in prep, 2023]

Real data (Mojave Desert)





- The difference between the rate of displacement obtained from incremental estimator compared with Sequential estimator is within ~1 mm/yr
- The incremental estimator is capable of meeting short latency requirement for product generation and producing unbiased displacement time-series

Real data (Mojave Desert) – Validation with GPS

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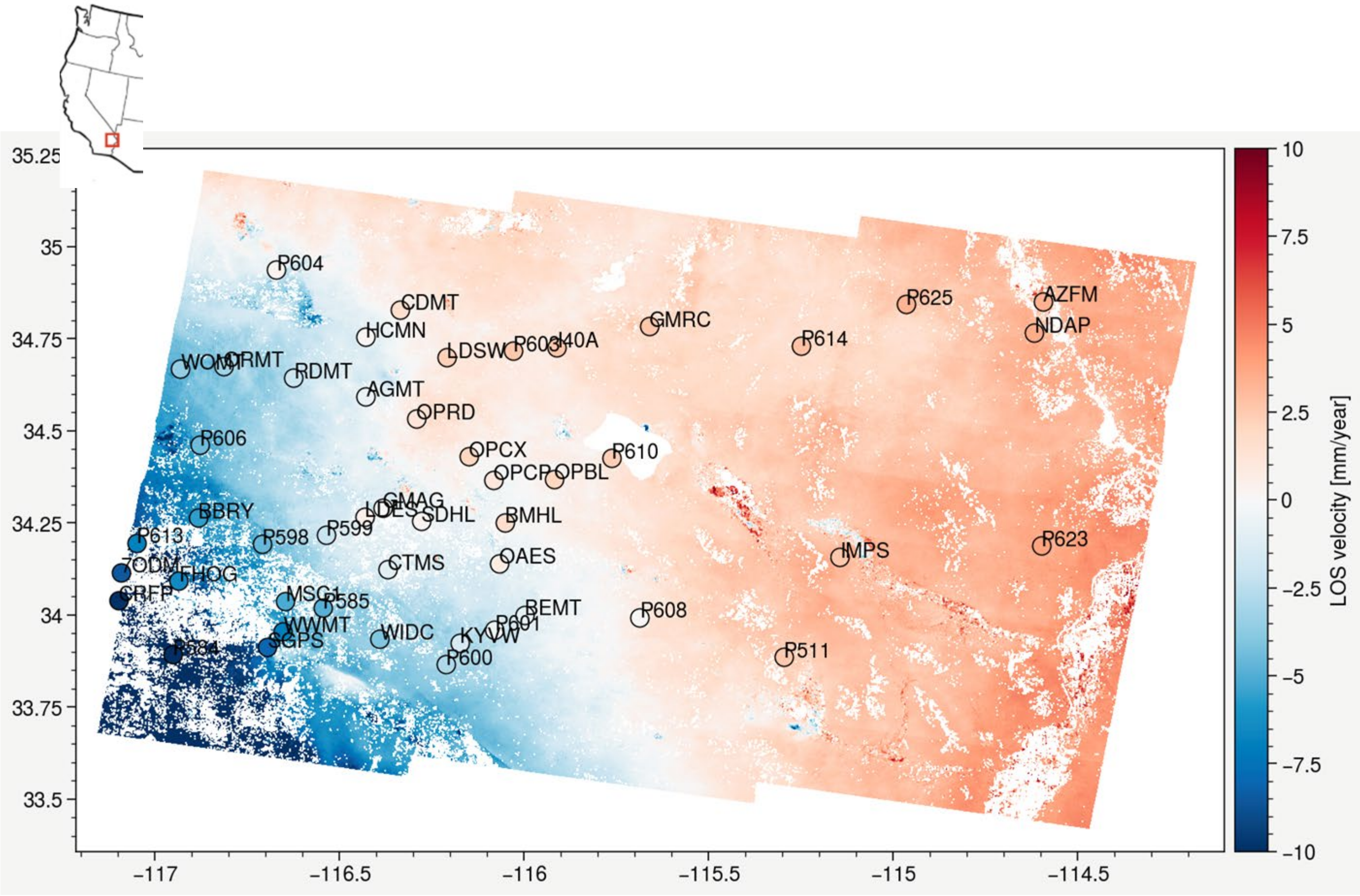
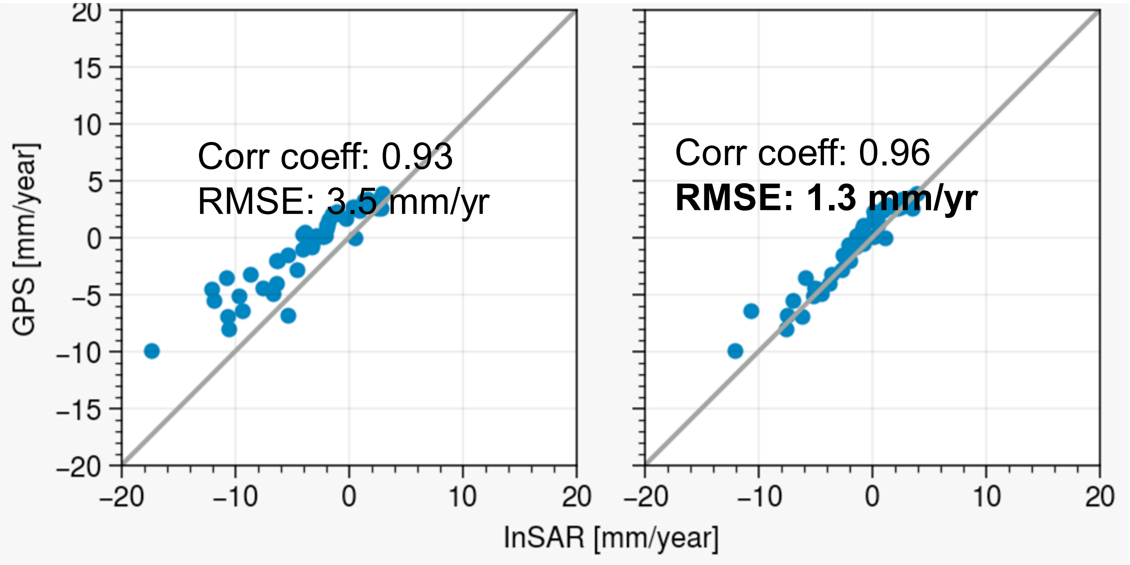


Without tropospheric delay correction

With tropospheric delay correction (using ERA-5)



Summary

- We introduced the "**Incremental Estimator**", a novel algorithm enabling near real-time generation of displacement time-series
- The "**Incremental Estimator**" significantly reduces the product generation latency from few months to hours compared to the state-of-the-art full-covariance and big-data friendly algorithms
- The "**modified Sequential Estimator**" may be used to process historical stacks of data *without* a final Datum Adjustment step
- **Through Simulations** incorporating different decorrelation scenarios and the presence or absence of short-lived signals from non-closing phase triplets, the Incremental Estimator demonstrates superior performance compared to existing algorithms
- Using real-data over Mojave Desert shows that the Incremental Estimator is not affected by displacement bias caused by closure phase
- For more on PS/SHP selection, see our poster: *"Detecting Persistent and Distributed Scatterer Changes in Geocoded Single Look Complex Images for Near-Real-Time InSAR Processing"*