Standardizing Soil Moisture Measurements from Cumulative InSAR Closure Phase

FRINGE 2023

Elizabeth Wig, Roger Michaelides, Howard Zebker
Contact: ewig@stanford.edu

Preprint:
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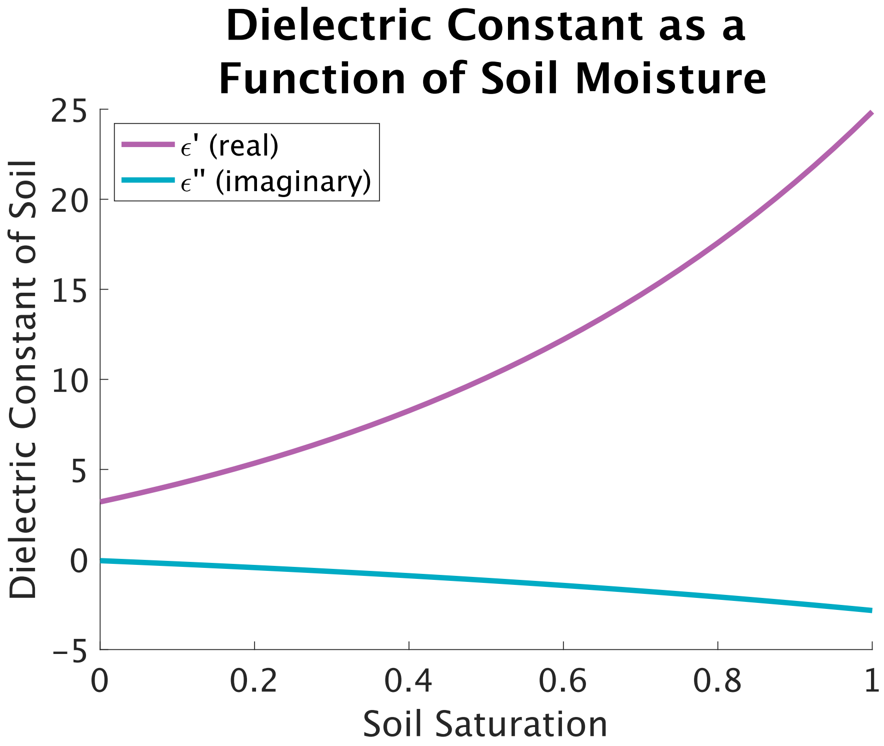
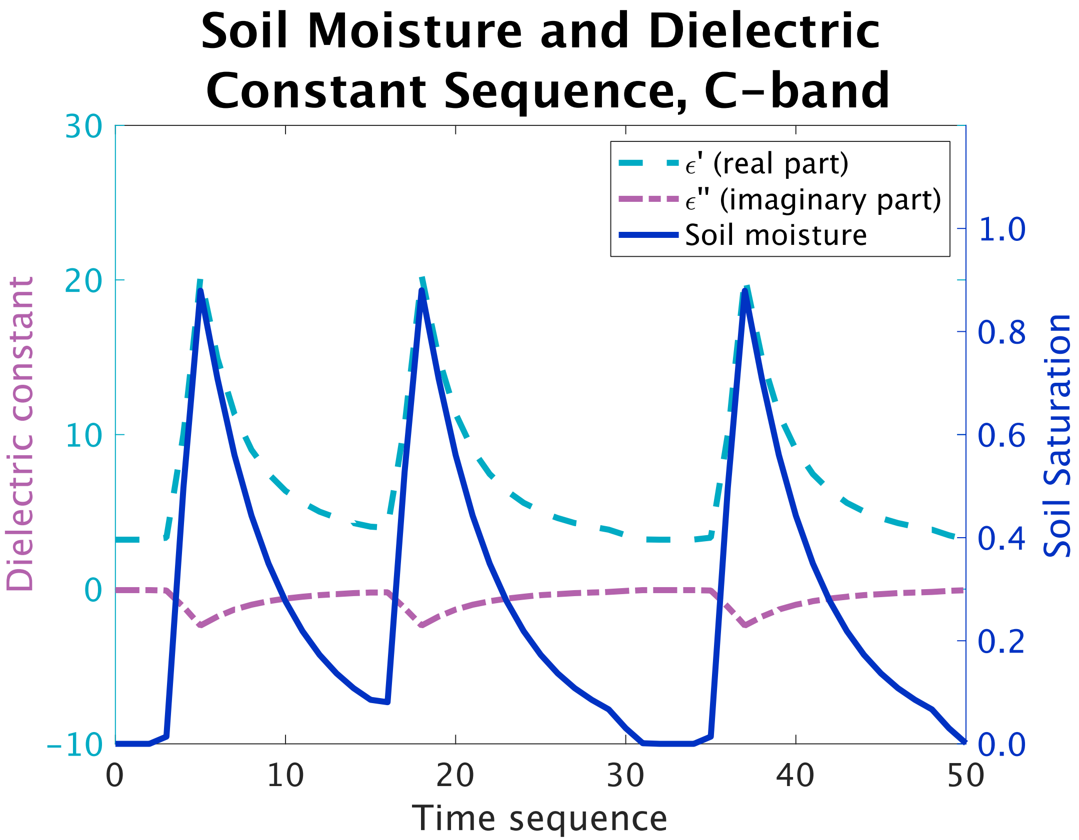
Stanford University

Soil Moisture Changes Soil Dielectric Constant

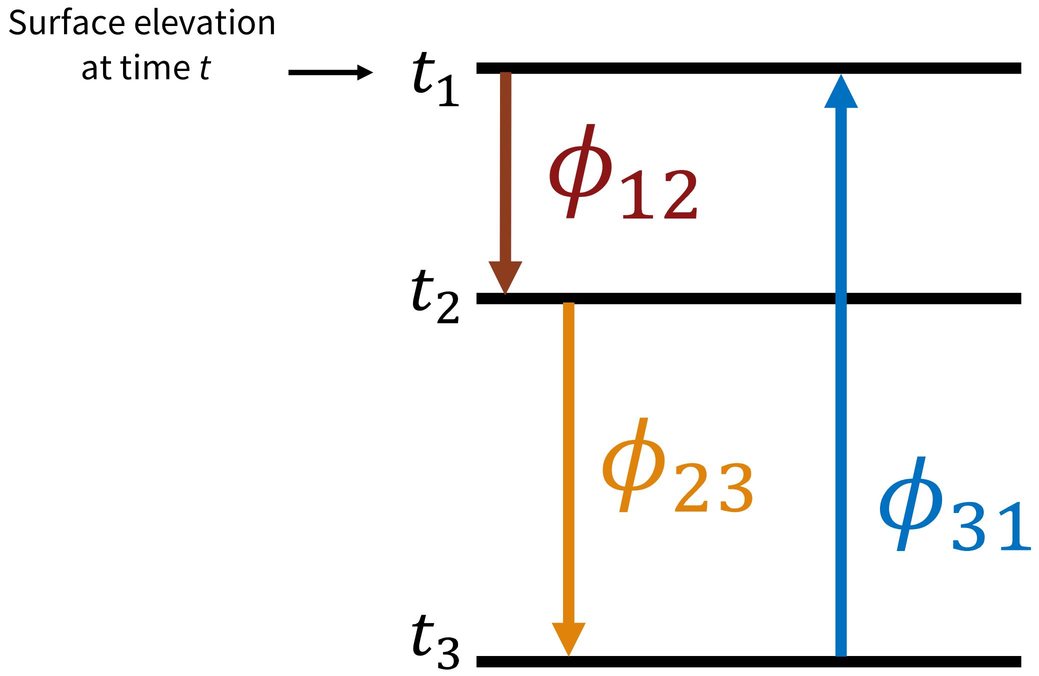




Soil Moisture dielectric constant from Cihlar and Ulaby 1974

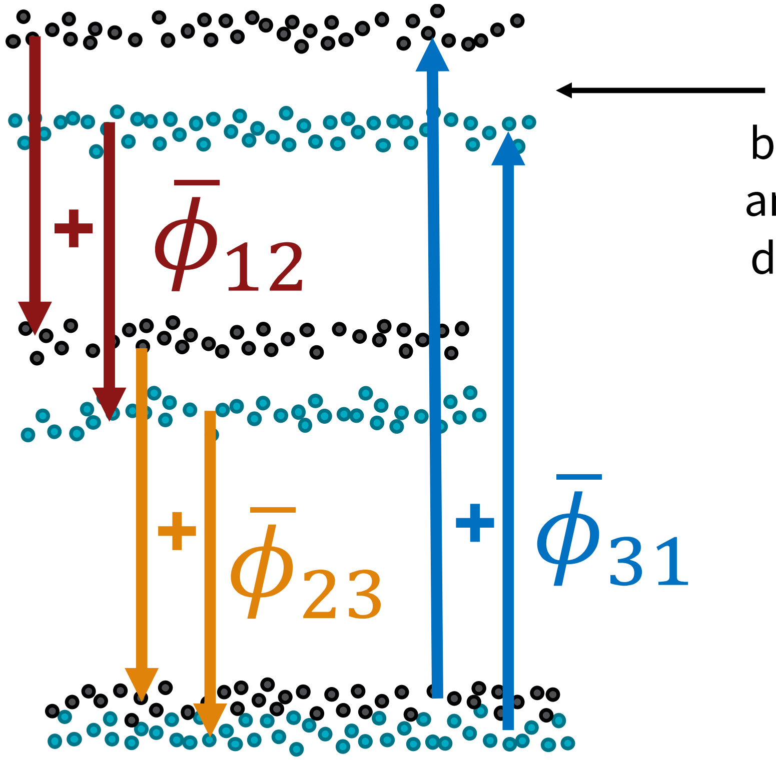
Background

Surface scattering only



$$\phi_{12} + \phi_{23} + \phi_{31} = 0$$

Surface and subsurface scattering

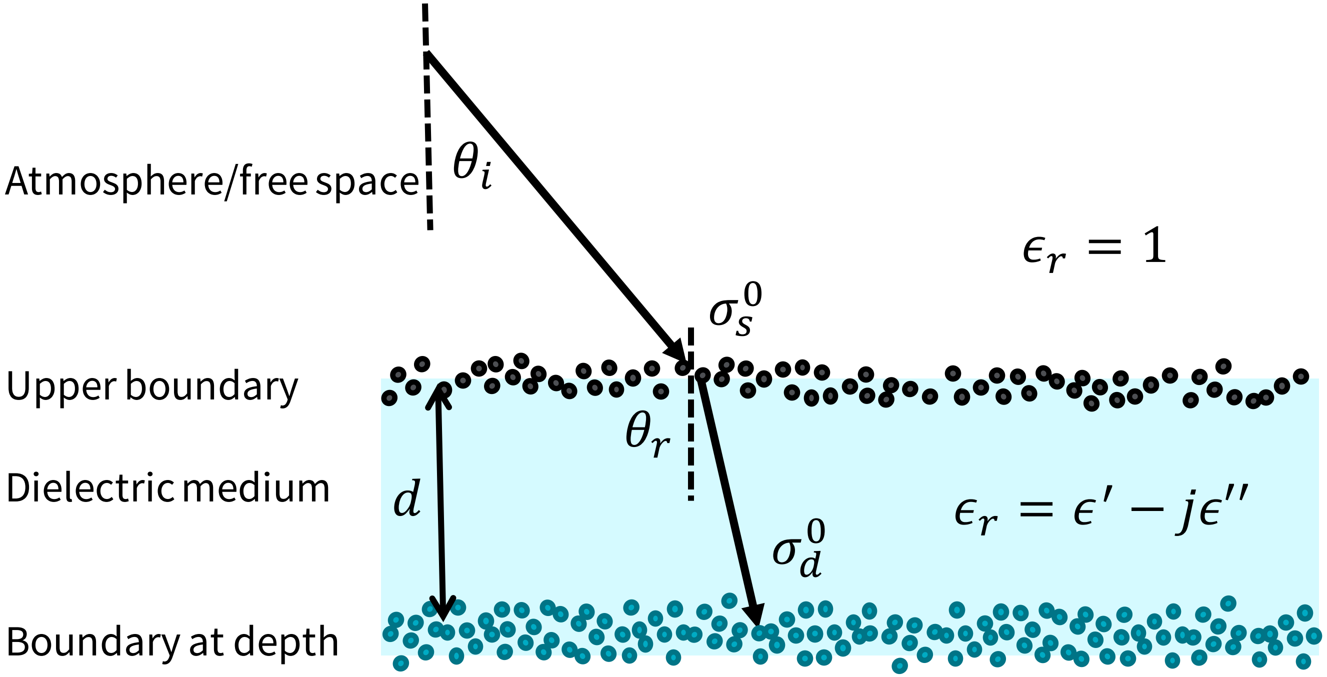


Interference between surface and time-varying depth scatterers

$$\phi_{123} = \bar{\phi}_{12} + \bar{\phi}_{23} + \bar{\phi}_{31} \overset{may}{\neq} 0$$

Scattering Model

Received radar echo is sum of surface and subsurface signals



Received echo:

$$s = s_s + s_d e^{-j\frac{4\pi}{\lambda}n\frac{d}{\cos\theta_r}}$$

s_s, s_d random complex Gaussian, variance σ^0

$$n = \sqrt{\epsilon_r}$$

Spatial averaging (multilooking) simplifies terms

- For notation: depth $x = \frac{4\pi}{\lambda} d$ dielectric constant $\tilde{n} = \frac{n}{\cos\theta_r}$
- Then interferogram is:

$$s_1 s_2^* = \left(s_s + s_d e^{-j\tilde{n}_1 x}\right)\left(s_s^* + s_d^* e^{j\tilde{n}_2^* x}\right)$$

$$= s_s s_s^* + s_s s_d^* e^{j\,\tilde{n}_2^* x} + s_d s_s^* e^{-j\tilde{n}_1 x} + s_d s_d^* e^{-j\tilde{n}_1 x + j\tilde{n}_2^* x}$$

- Multilooking removes cross terms, results in:

$$< s_1 s_2^* > = \sigma_s^0 + \sigma_d^0 e^{-j\tilde{n}_1 x + j\tilde{n}_2^* x}$$

← Note: needs only radar cross section and angle-adjusted dielectric constant

Closure phase messy but readily found

$$\langle s_1 s_2^* \rangle \langle s_2 s_3^* \rangle \langle s_3 s_1^* \rangle = \left(\sigma_s^0\right)^3 + \left(\sigma_s^0\right)^2 \left(\sigma_d^0\right) \left[e^{-j(\tilde{n}_2 - \tilde{n}_3^*)x} + e^{-j(\tilde{n}_1 - \tilde{n}_2^*)x} + e^{-j(\tilde{n}_3 - \tilde{n}_1^*)x} \right] +$$

$$\left(\sigma_d^0\right)^2 \left(\sigma_s^0\right) \left[e^{-j(\tilde{n}_1 - \tilde{n}_2^* + \tilde{n}_2 - \tilde{n}_3^*)x} + e^{-j(\tilde{n}_2 - \tilde{n}_3^* + \tilde{n}_3 - \tilde{n}_1^*)x} + e^{-j(\tilde{n}_3 - \tilde{n}_1^* + \tilde{n}_1 - \tilde{n}_2^*)x} \right] +$$

$$\left(\sigma_d^0\right)^3 e^{-j(\tilde{n}_1 - \tilde{n}_2^* + \tilde{n}_2 - \tilde{n}_3^* + \tilde{n}_3 - \tilde{n}_1^*)x}$$

Multilooking (by finding expected value) reduces number of terms to 8 from 64

Needs only radar cross-section, angle-adjusted dielectric constant

This model is **nonlinear**[1]

A Taylor expansion of the exponential, as:

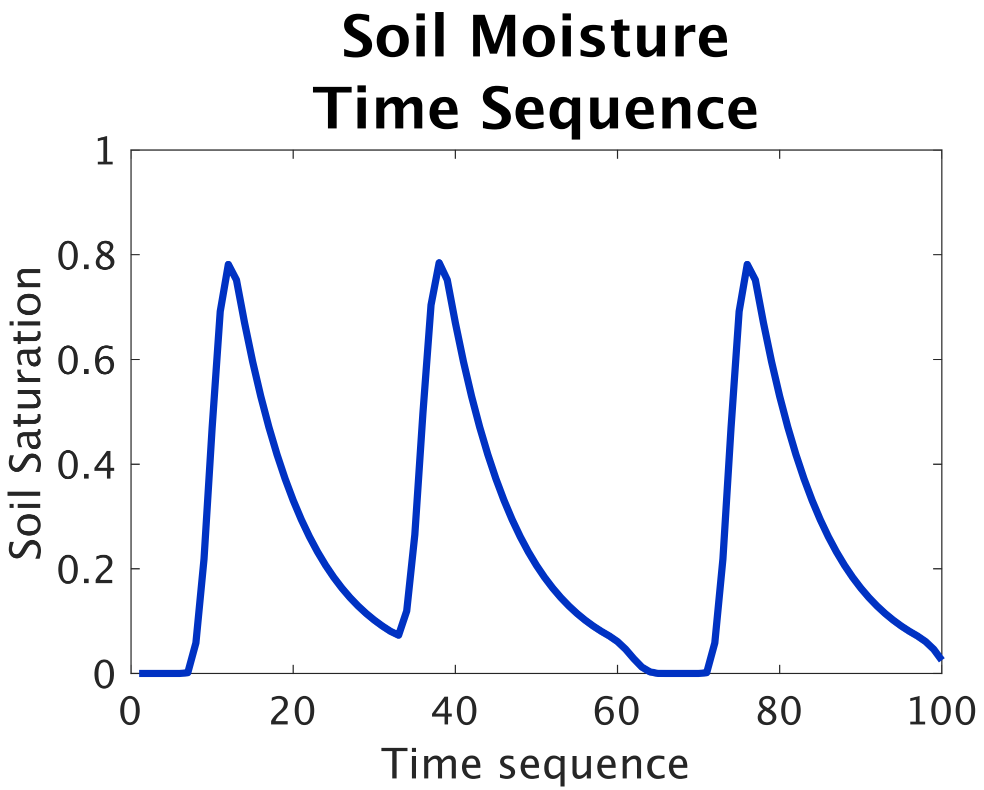
$$e^{x} \cong 1 - x + \frac{x^{2}}{2} - \cdots$$

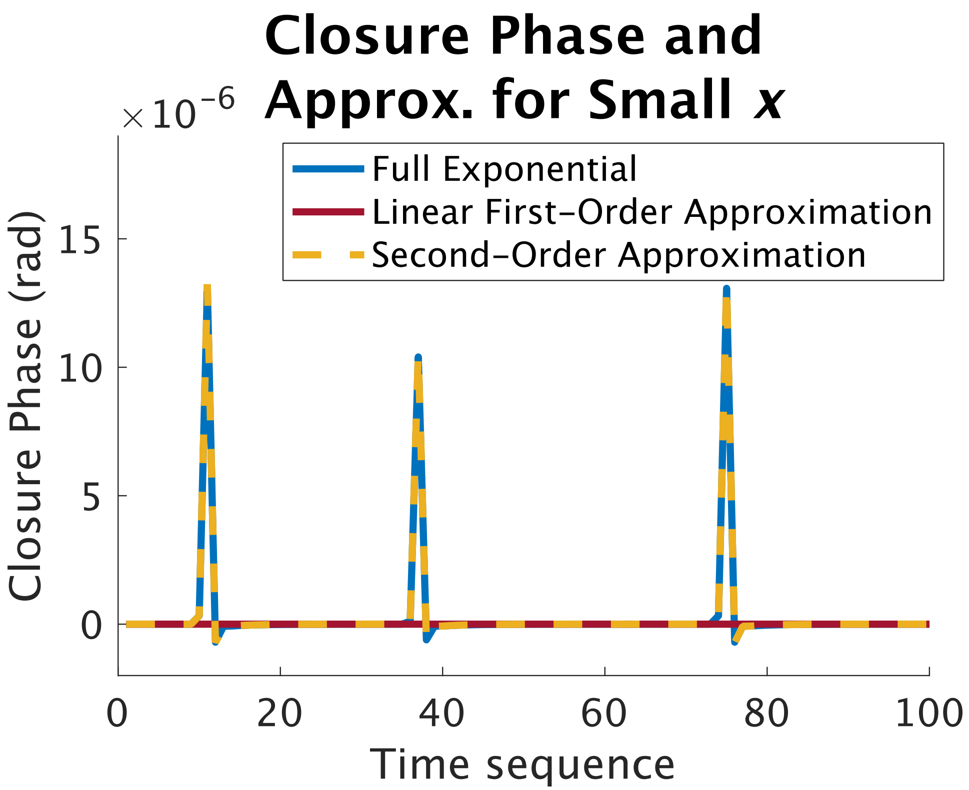
Linearizing by taking only the first two terms, the model prediction is entirely real & produces zero closure phase.

Only higher-order terms $\left(\frac{x^{2}}{2} - \cdots\right)$ produce an imaginary component.

[1]De Zan 2015 finds similar results

Linearized model shows no closure phase





Why Cumulatively Sum Closure Phase?

with interferometric phase:

Changing elevation of ground → Non-zero interferometric phase corresponding to change → Cumulative sum of interferometric phase → Time-series of displacement

$\phi_{12} + \phi_{23} + \phi_{34} + \cdots$

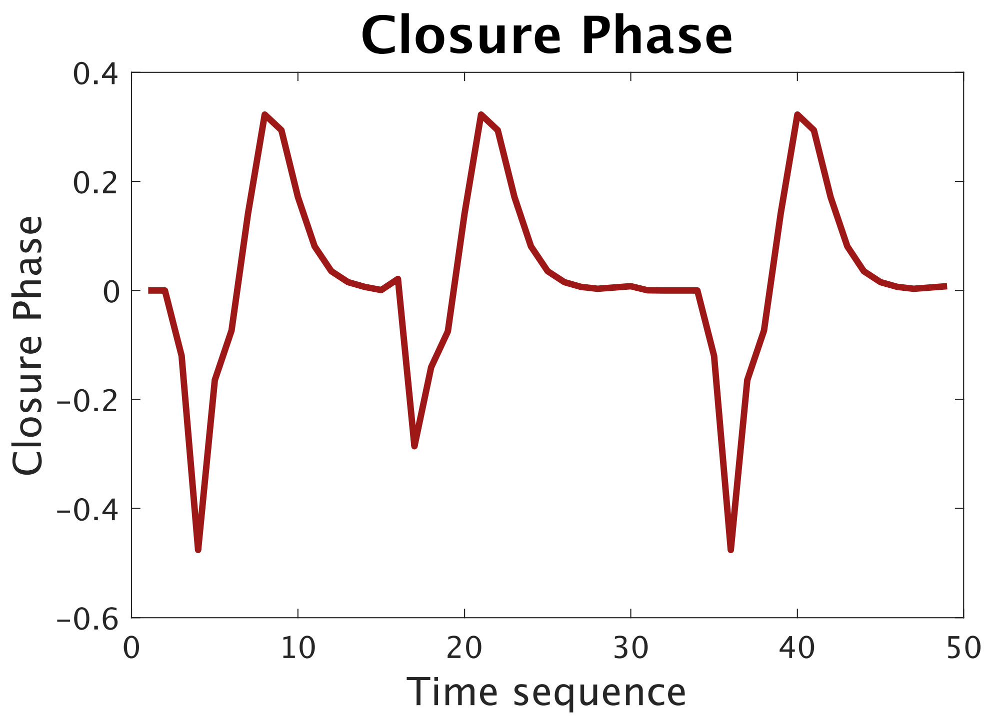
with closure phase:

Changing dielectric properties of ground → Non-zero closure phase corresponding to change → Cumulative sum of closure phase → Time-series of dielectric properties

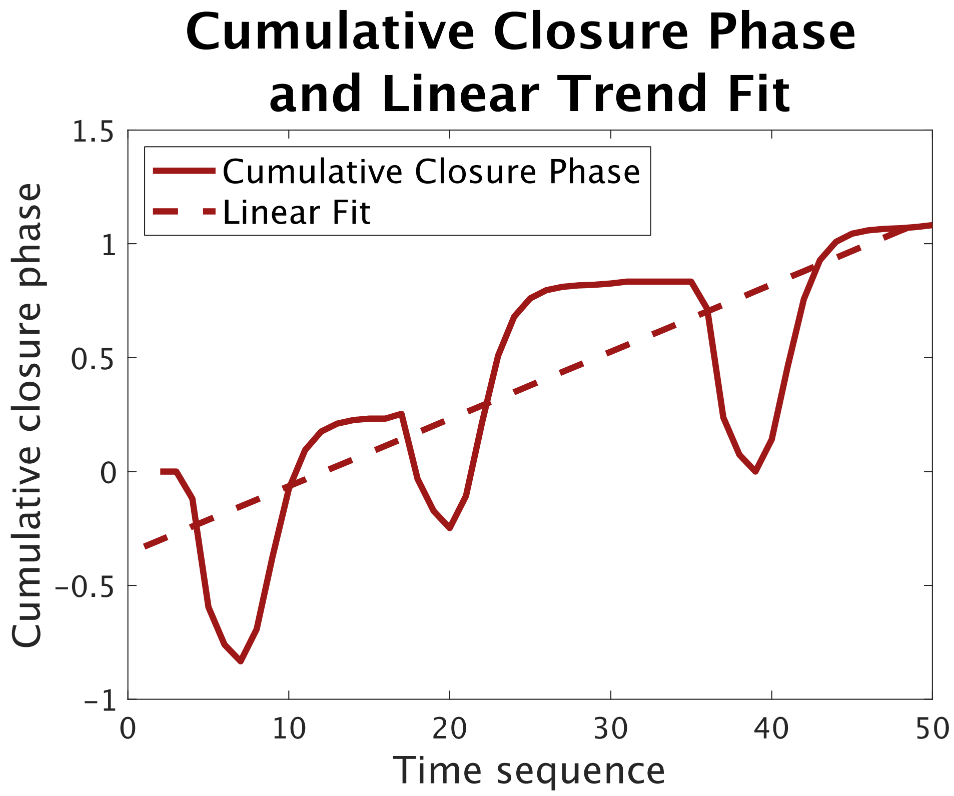
$\phi_{123} + \phi_{234} + \phi_{345} + \cdots$

e.g. soil moisture!

If soil moisture changes asymmetrically (e.g., increases more rapidly than decreases), model predicts a trend or **bias**[1] over time



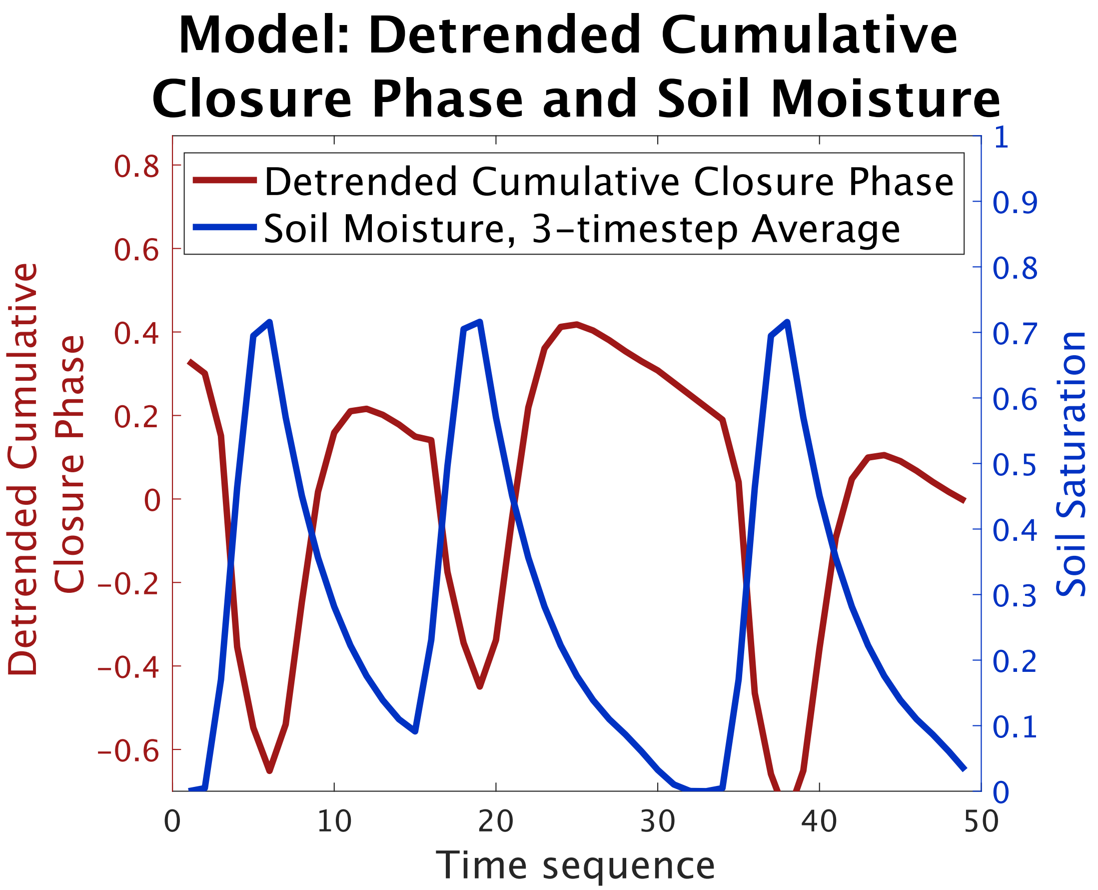
Closure phase yields change in moisture



- Cumulatively sum to get moisture
- Nonlinearity leads to bias with time so detrend measurements before solution

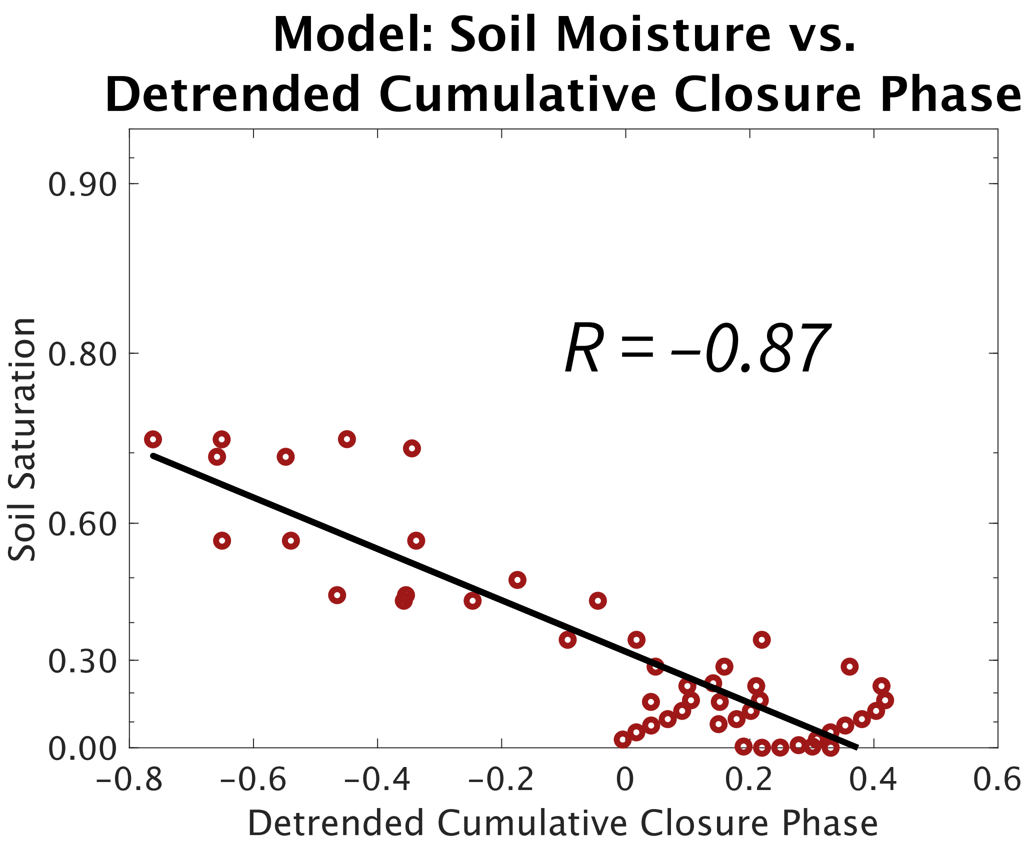
[1]Ansari et al. 2021 found a systematic bias that may derive from this source

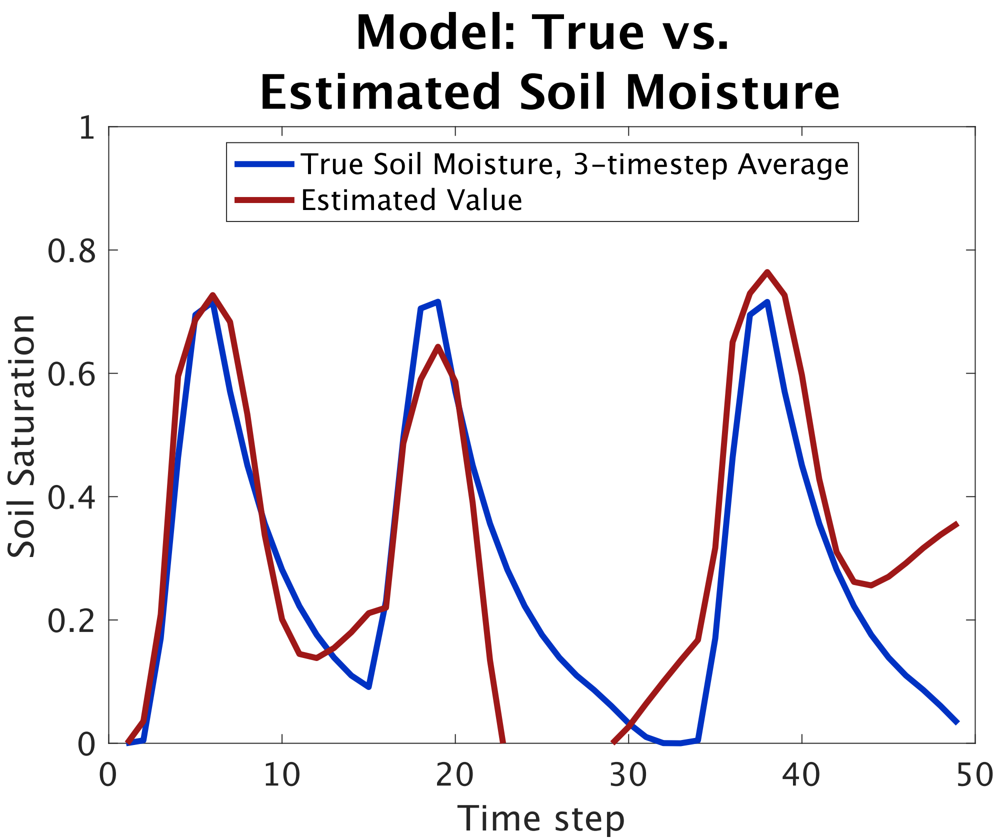
We remove trend to find soil moisture estimate



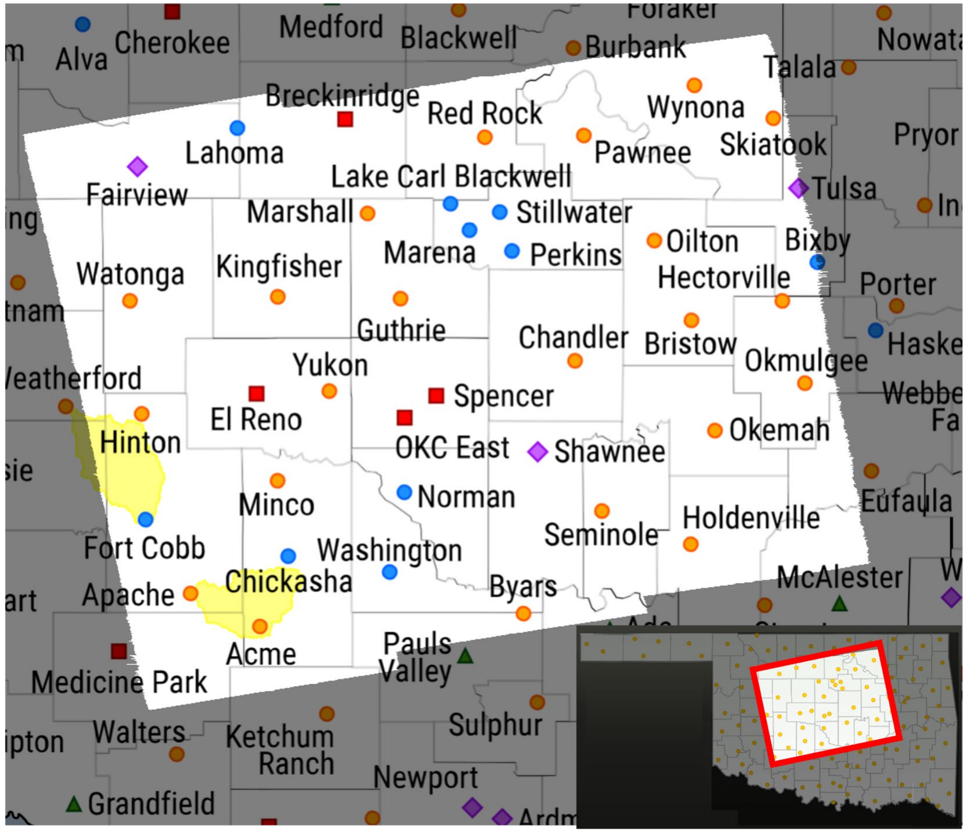
Anticorrelation between soil moisture and detrended cumulative closure phase

Use detrended cumulative closure phase to find soil moisture





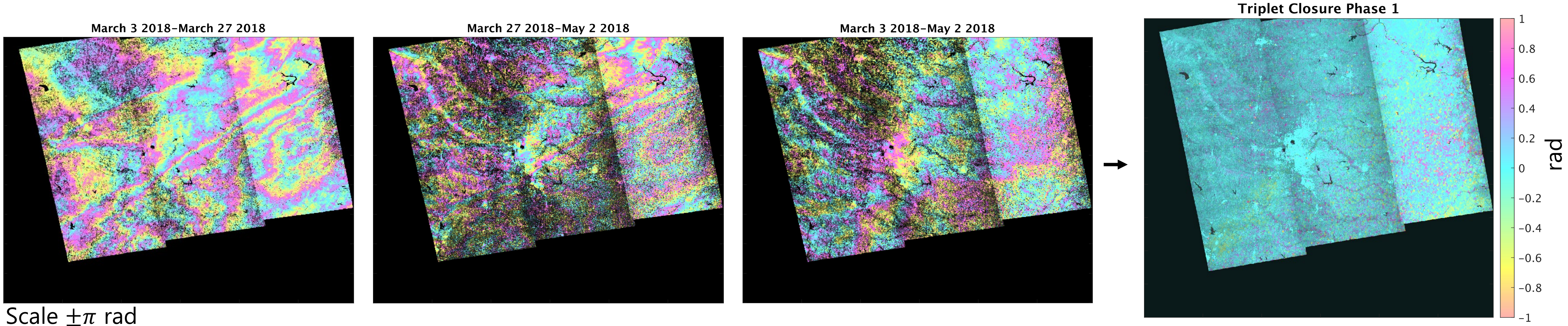
Validation with in situ soil moisture probes
State of Oklahoma, USA



- 37 soil moisture probes at named locations
- *In situ* measurements at 5 cm depth
- Compare to Sentinel-1 InSAR swath, multilooked to <1km pixels

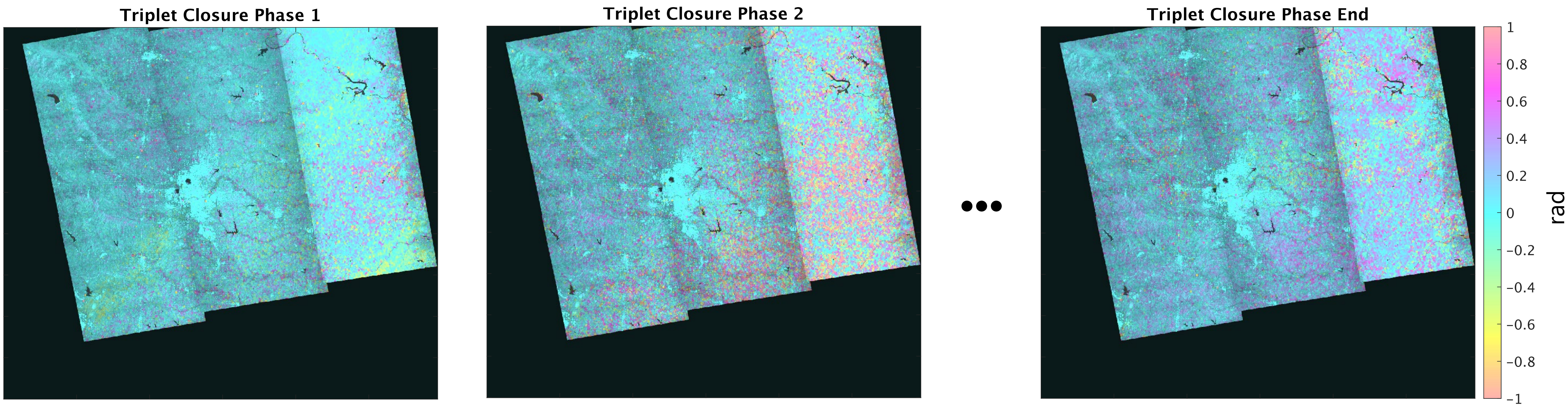
Three interferograms yield one closure image

Sequence of three interferograms → Closure Image

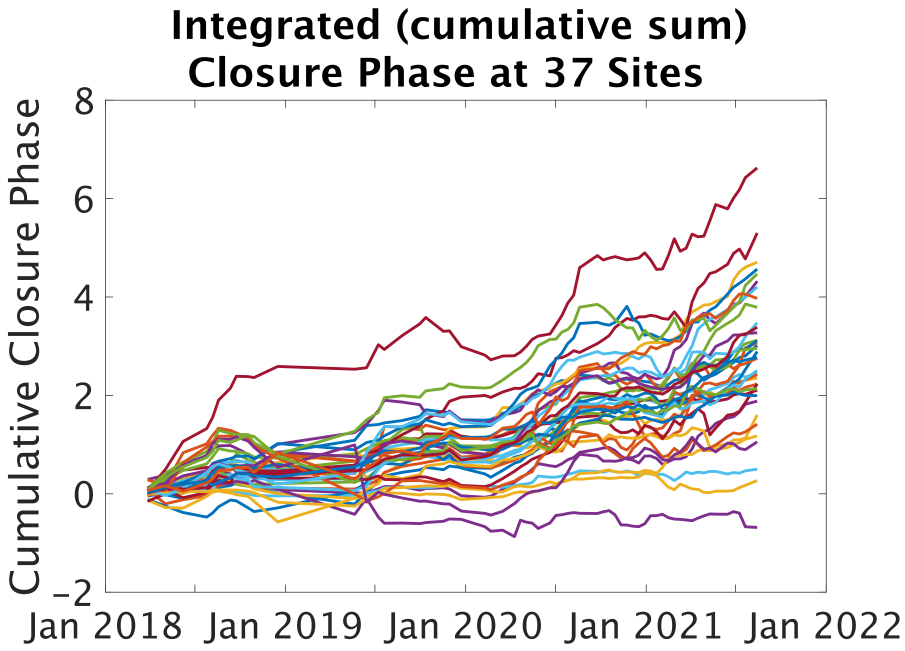


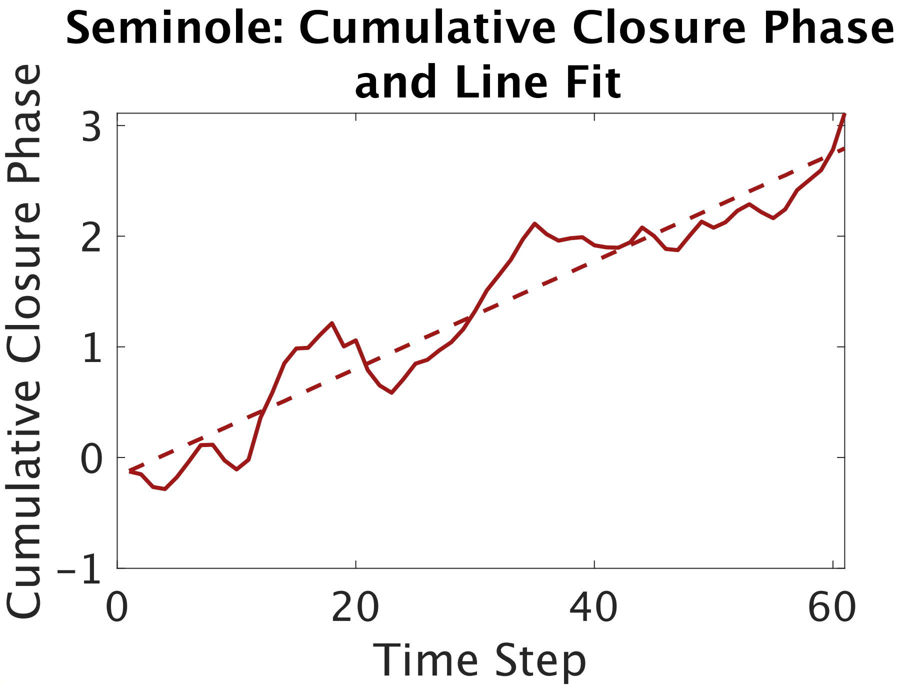
Scale $\pm\pi$ rad

Create sequence of interferogram triplets



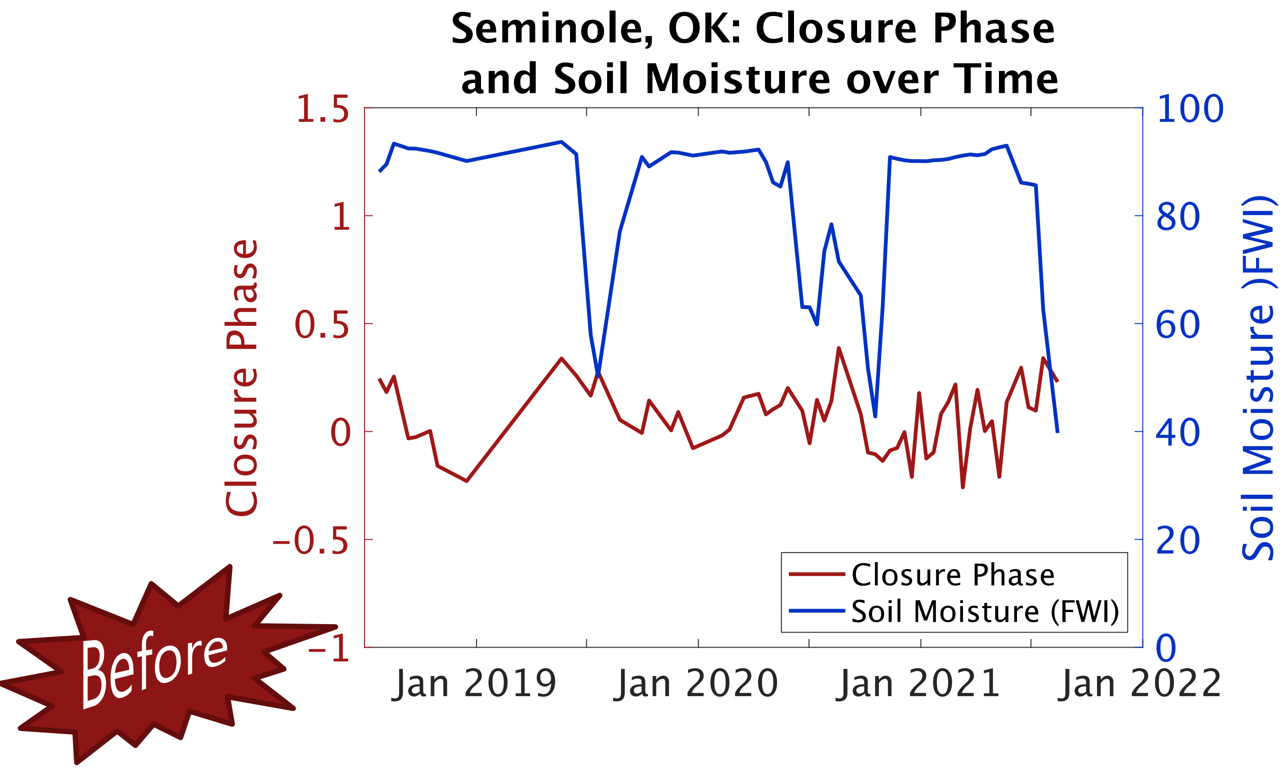
Data reduction approach
Cumulative sum of closure phase leads to trend

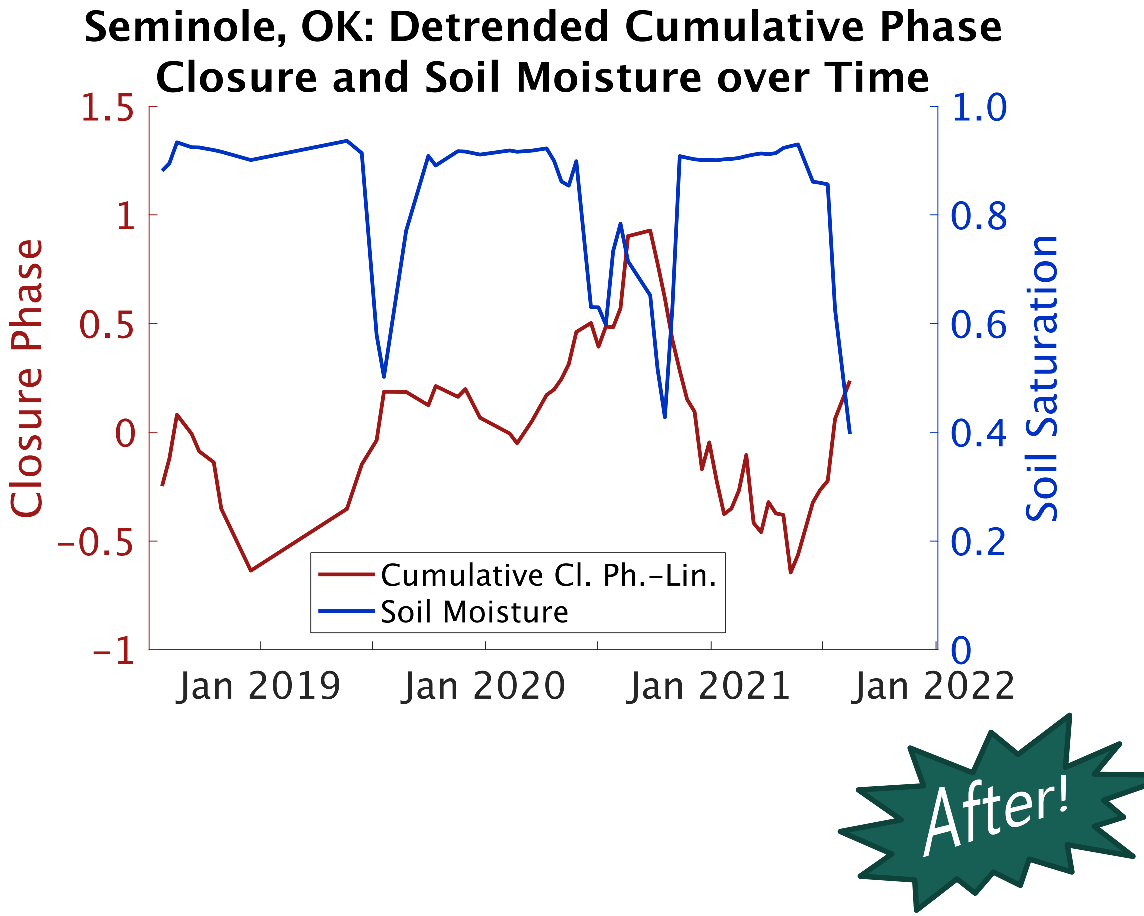




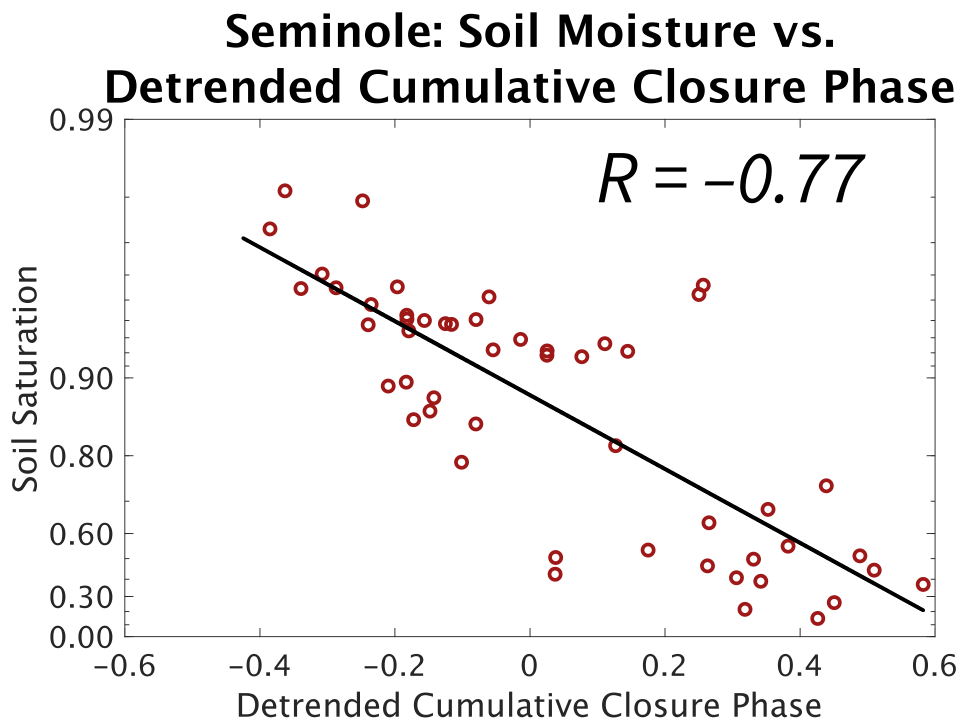
Result

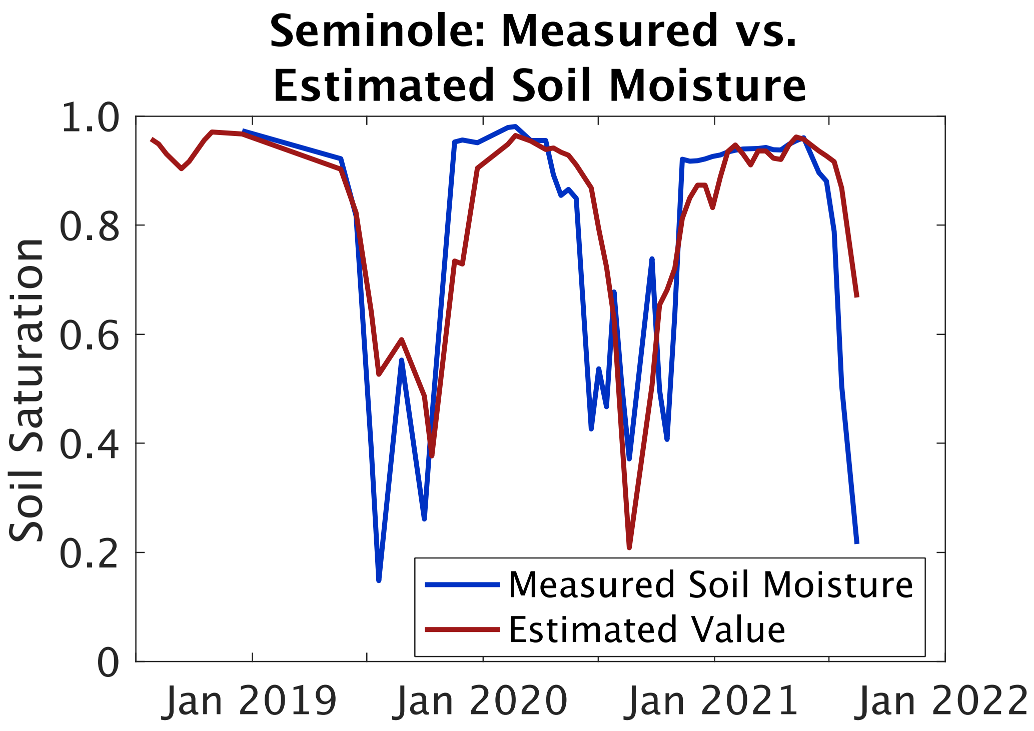
Detrended cumulative closure phase tracks soil moisture



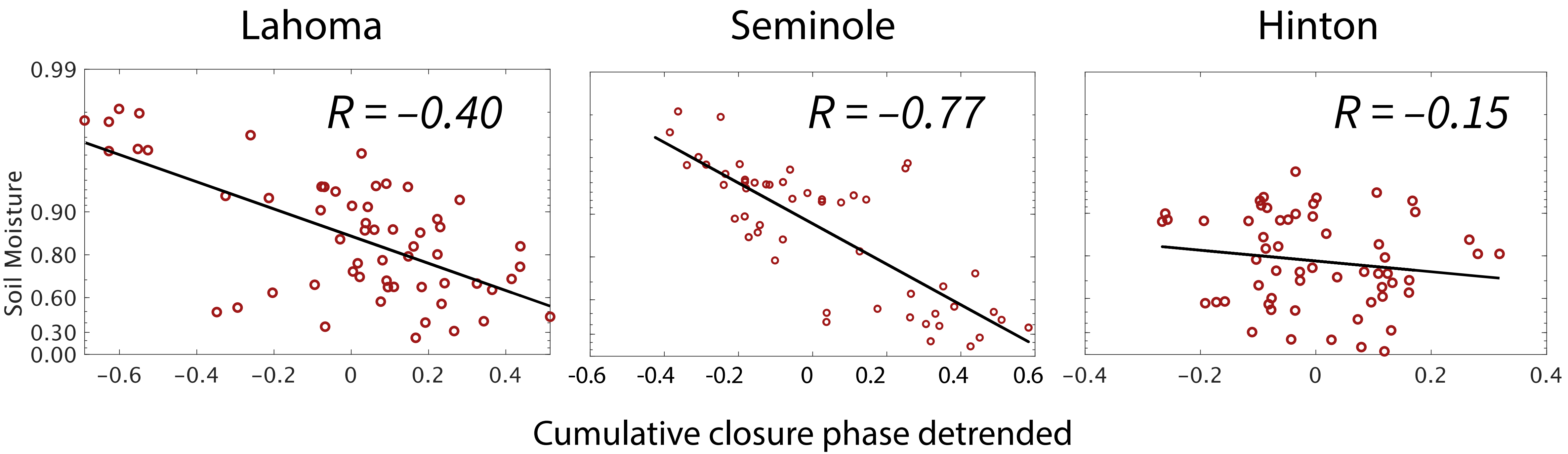


Linear relationship between soil moisture and cumulative closure phase – enabling prediction

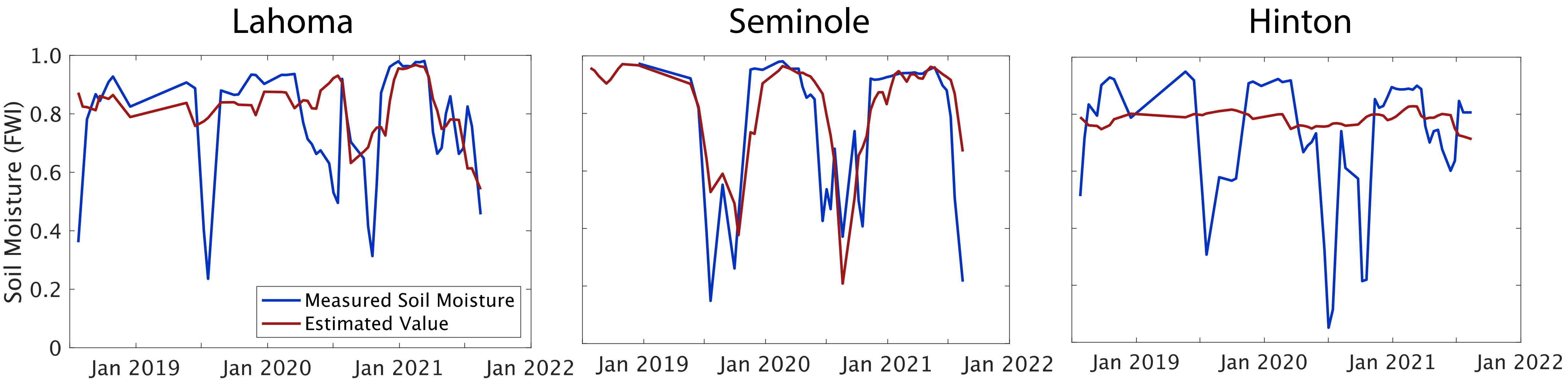




Soil moisture vs. detrended cumulative phase

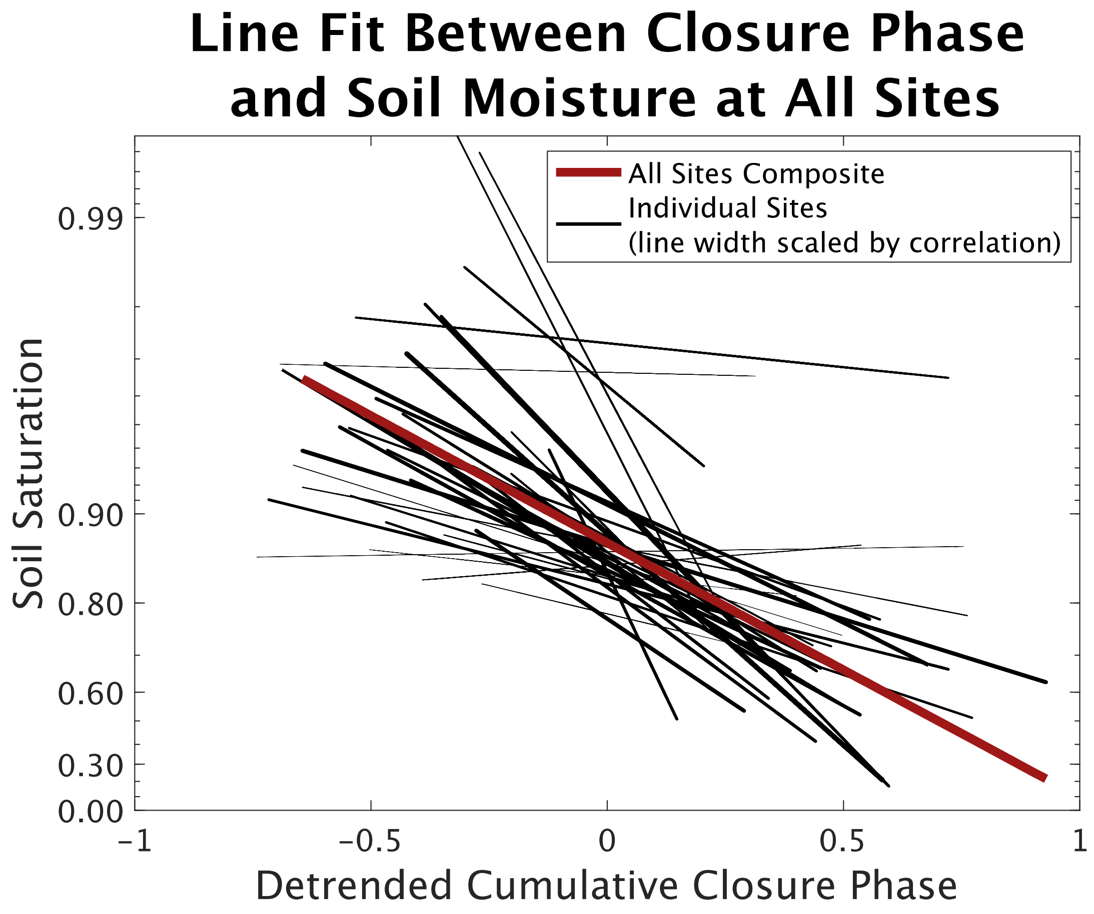


Estimated soil moisture at sites



We compared all fit lines to find a universal* trend

*within this swath



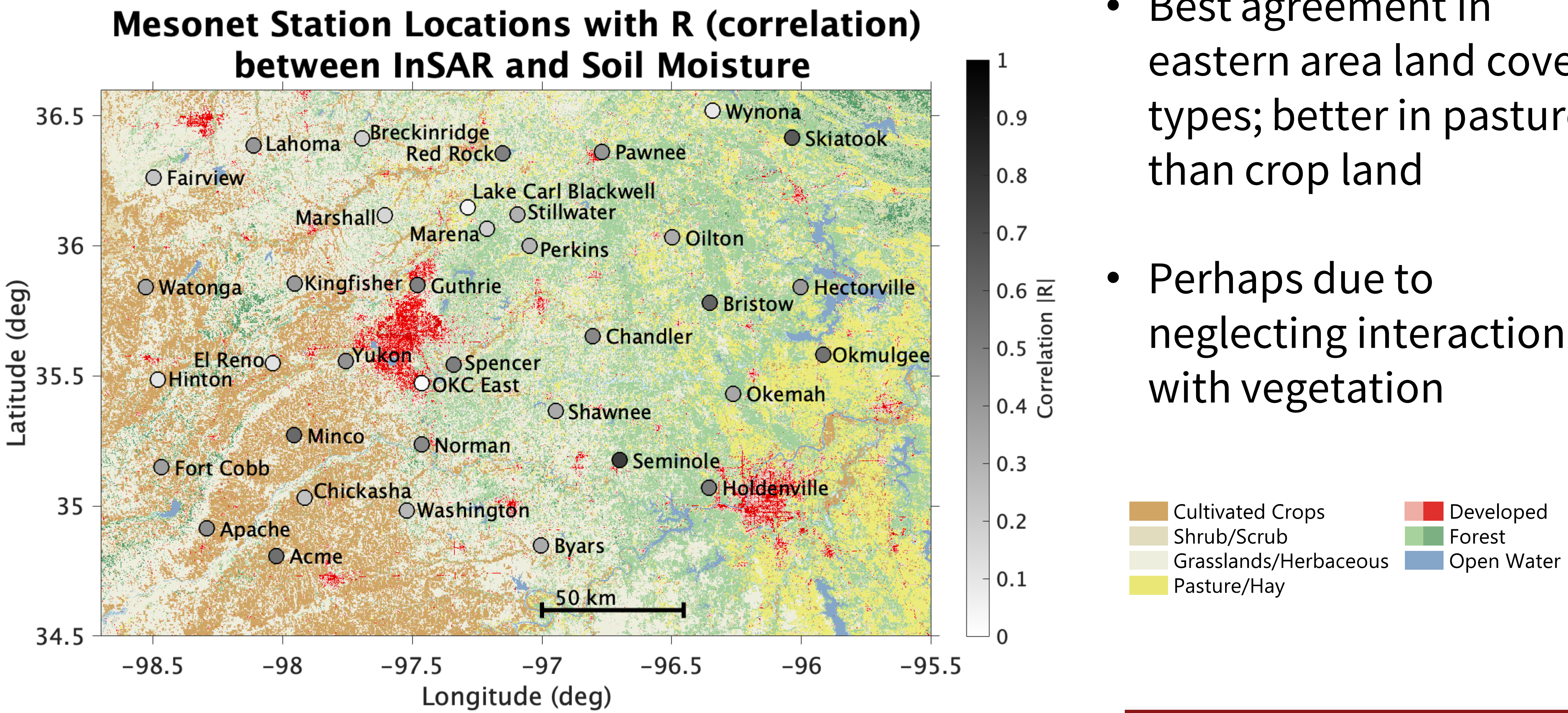
Mean correlation coefficient between measured and estimated soil moisture using **each site's best-fit line**

At all sites	At the 5 best-correlated sites
0.36	0.63

Mean correlation coefficient between measured, estimated soil moisture using the **universal best-fit line for all sites**

At all sites	At the 5 best-correlated sites
0.36	0.63

Accuracy appears correlated with surface type



- Best agreement in eastern area land cover types; better in pasture than crop land
- Perhaps due to neglecting interaction with vegetation

Conclusion

- Time-varying interference of surface and depth scatterers produces a closure phase
- Detrended cumulative closure phase agrees with in situ soil moisture
- Agreement varies with terrain
- Method could yield soil moisture at fine resolution

Fine-Resolution Measurement of Soil Moisture from Cumulative InSAR Closure Phase

Elizabeth Wig, *Student Member, IEEE*, Roger Michaelides *Member, IEEE*, Howard Zebker, *Fellow, IEEE*

Abstract—Soil moisture can vary sp agricultural fields (~ 10 – 100 m), which resolve using passive radiometric methods an opportunity for finer resolution measu the interferometric synthetic aperture phase parameter is sensitive to changing

CKGROUND

water in soil can be measured avimetric soil moisture compares to the weight of dry soil, while

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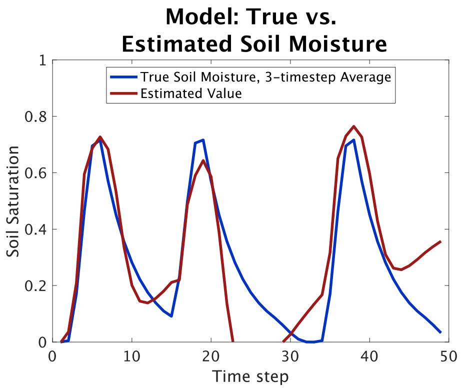

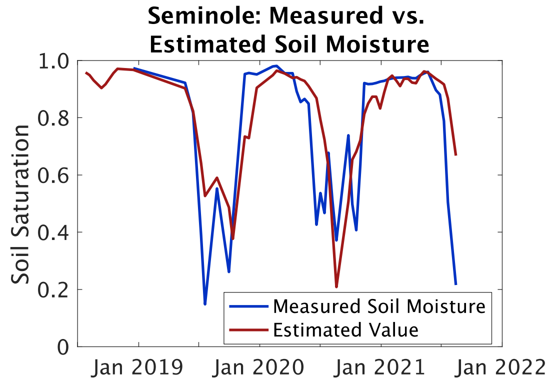

Contact: ewig@stanford.edu

Thanks for listening!

References & Data Sources

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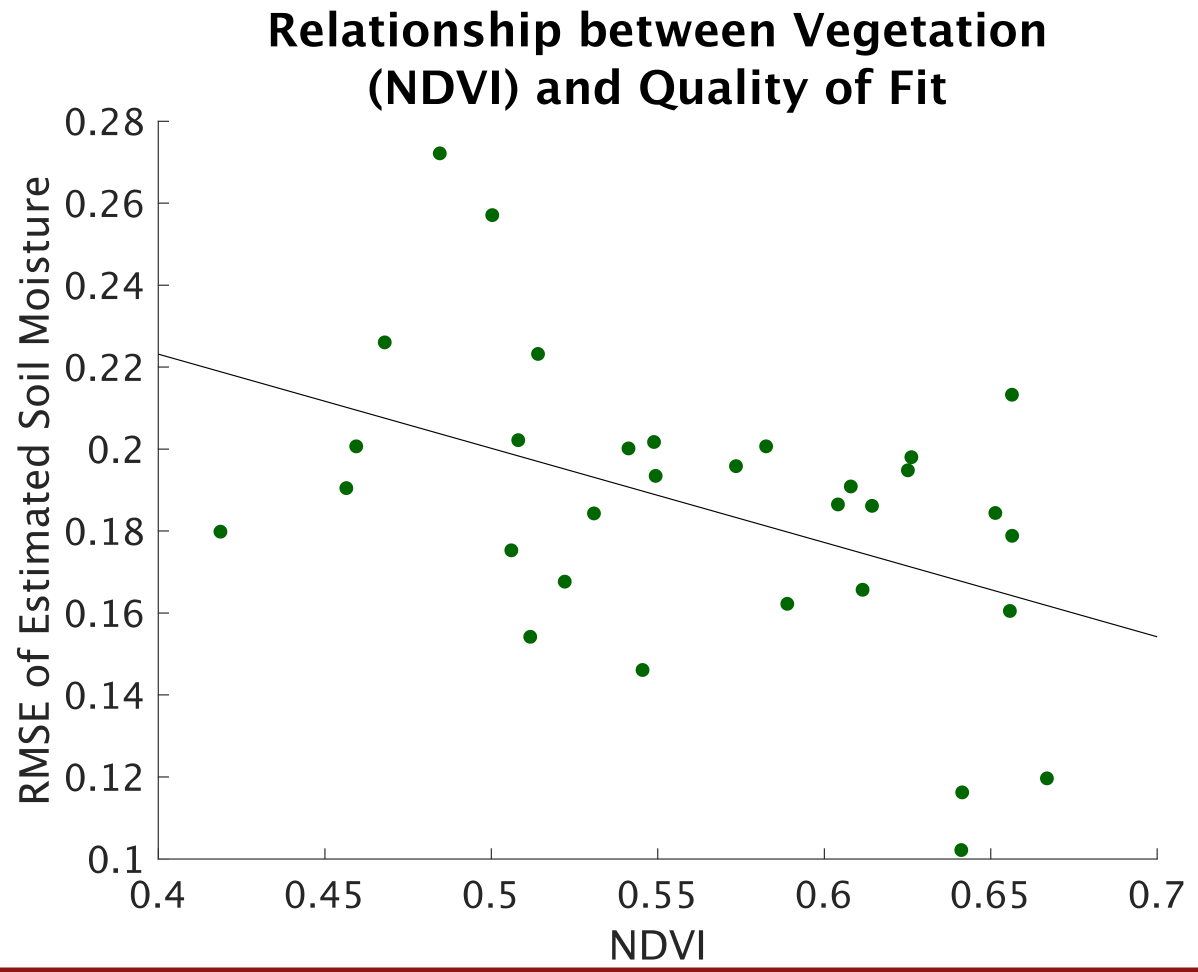
8. Copernicus Sentinel data 2018-2021. Retrieved from ASF DAAC, some processing by ESA.
9. "Evaluation of greenness by NDVI at Oklahoma Mesonet stations." NDVI map package on Arcgis.com from user pblankenau2

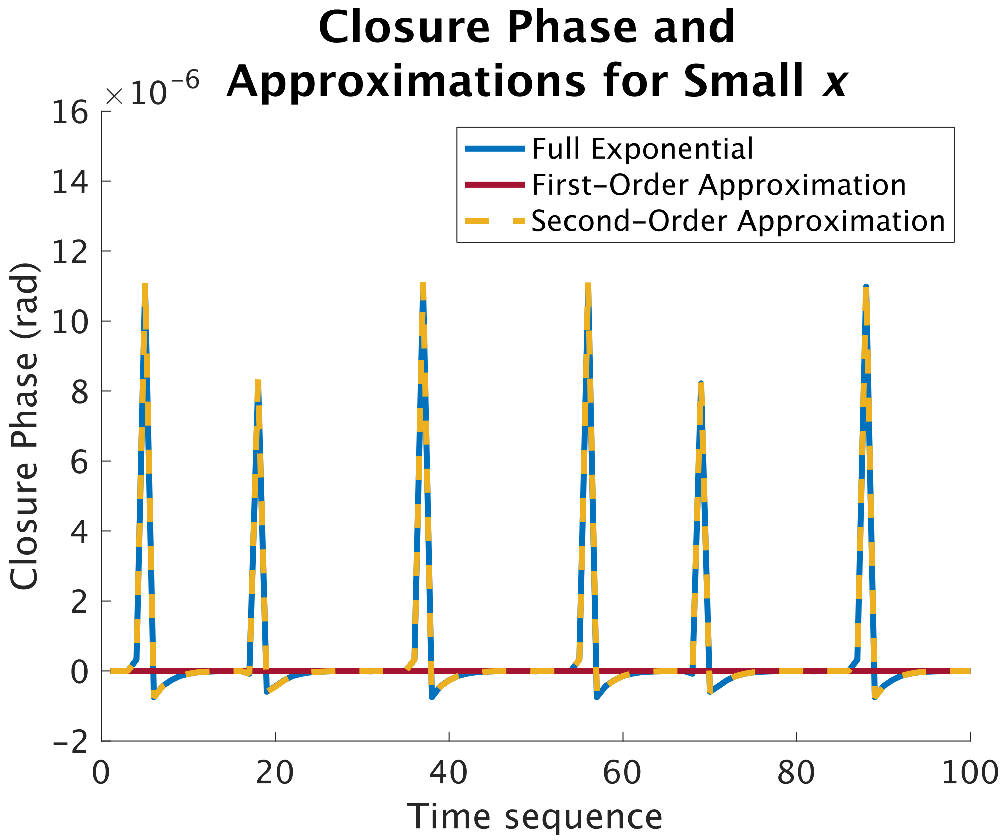
Contact: ewig@stanford.edu

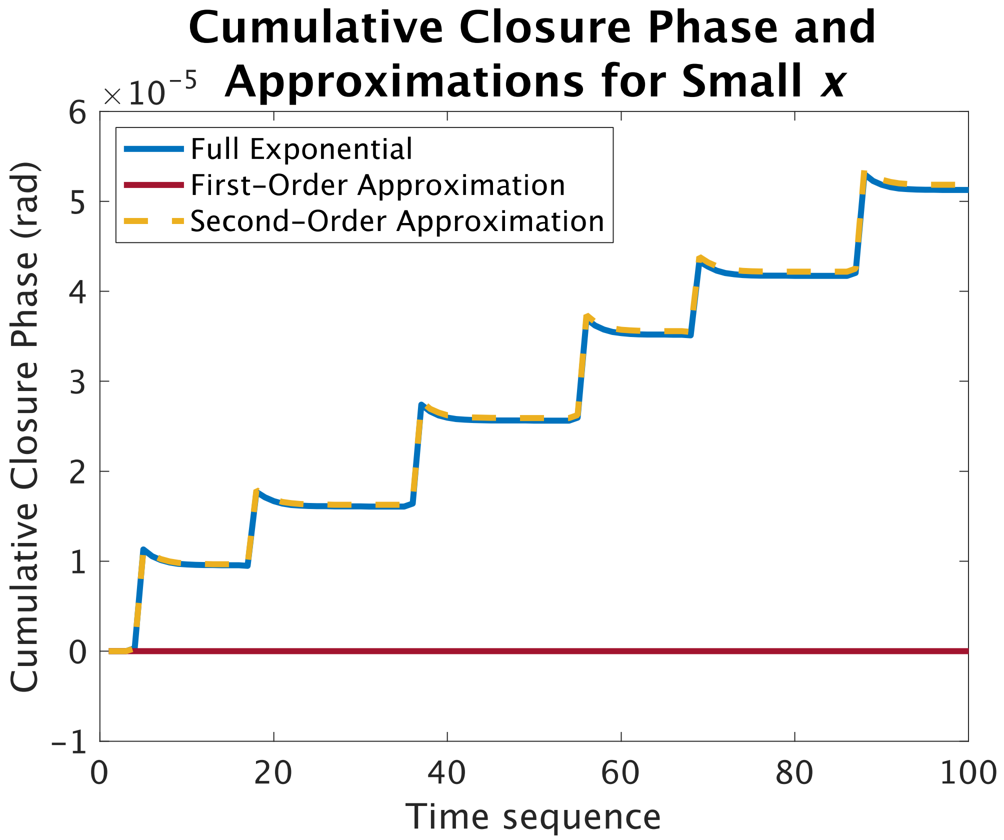
Backup Slides

Slight correlation of quality of fit with vegetation density (measured as NDVI)



Cumulative sum of modeled closure phase and Taylor approximation



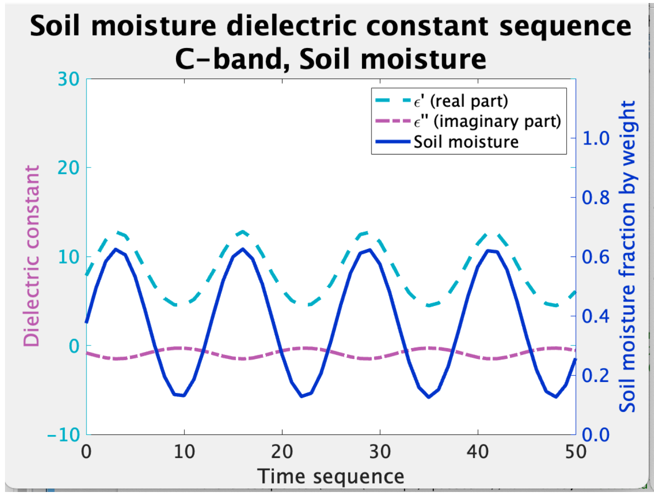


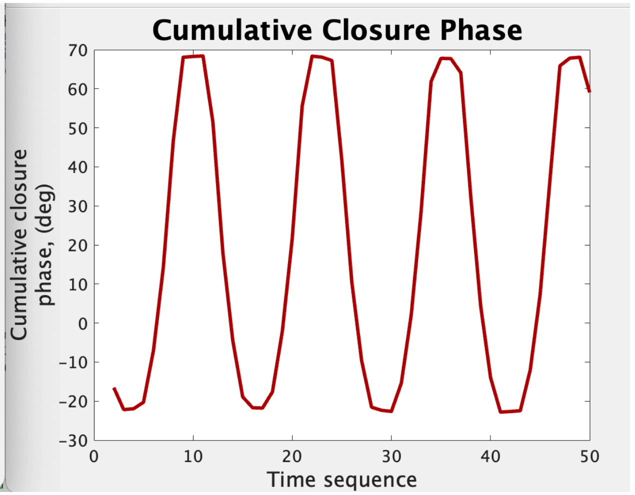
Asymmetry leads to systematic bias

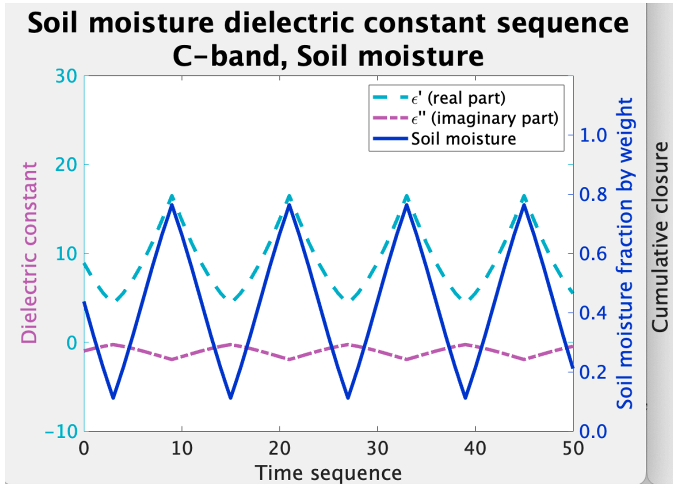
Trivially, a completely symmetric time series of soil moisture will produce no trend, because any positive soil moisture producing ϕ_{123} will be cancelled by the negative soil moisture producing ϕ_{321}.

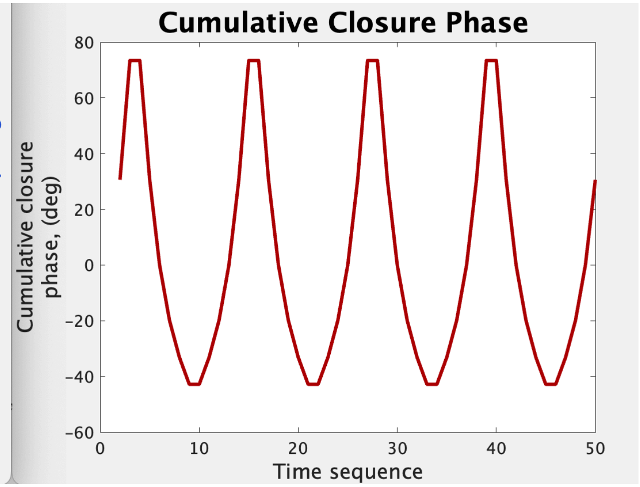
$$\phi_{123} = -\phi_{321}$$

We find this principle also applies to time series with same-size steps, e.g. sine and triangle waves – no bias, and no trend in cumulative closure phase









Asymmetry leads to systematic bias

Bias emerges when either increase and decrease in soil moisture has larger changes relative to the other, consistently over a time series.

Here we show a trend in cumulative closure phase for soil moisture with rapid increase/slow decrease, and the opposite.