# Seasonal to Multi-Annual Hydrological Mass Loading Changes a of the Southern Sierra Nevada and Walker Lane Faults from GPS and InSAR Time Series


Aren Crandall-Bear[1] (acrandallbear@unr.edu) and William C. Hammond[1]

(1) Nevada Bureau of Mines and Geology and Department of Geological Sciences, University of Nevada, Reno ,Reno NV, 89557



### Abstract

The stress states on faults and magmatic systems east of the Sierra Nevada Mountains of California and Nevada are sensitive to surface loading from hydrological mass that varies over seasons, drought cycles and climate changes. Recently, three moderate to large earthquakes, the M7.1 2019 Ridgecrest, M6.5 2020 Monte Cristo Range, and M6.0 2021 Antelope Valley earthquakes, occurred near the perimeter of the central and southern Sierra Nevada during the summer months when hydrologic loads were at a minimum. To investigate the specific configuration of strain changes associated with these hydrological loads we use satellite geodesy, including GPS data from the MAGNET and EarthScope Network of the Americas, and Sentinel-1 InSAR data to constrain models of seasonal to multi-annual three-component displacement. A multispectral analysis of snow cover is incorporated into the InSAR analysis to aid in pixel selection in the High Sierra where snow cover can cause radar decorrelation.

We correct the displacement time series for the co- and post-seismic effects from nearby earthquakes and GPS for equipment changes. The InSAR time series are aligned to the GPS, and from the displacement time series we isolate the deformation modes of the phase and amplitude of seasonal variation and long term trends attributable to tectonic deformation.


### Seasonal Methods

Data for GPS time series are downloaded from the Nevada Geodetic Laboratory (NGL) website (http://geodesy.unr.edu/), processed using Blewitt et al., 2018, and detrended with MIDAS robust trend estimator (Blewitt et al., 2016). Data for InSAR is preprocessed interferograms from ARIA service (Buzzanga et al., 2020), hosted at the Alaska Satellite Facility (ASF, https://search.asf.alaska.edu/) and time series processing with MintPy (Yunjun et al., 2019) and atmosphere correction using PyAPS (Jolivet et al., 2011).

Time series parameters for GPS and InSAR are obtained through least squares inversion. Two annual and two semi annual terms are solved for and converted to amplitude and time of year of maximum amplitude. Maximum amplitude is in line of sight (LOS) for InSAR data and three orthogonal directions (east, north, vertical) for GPS stations.

For accurate results in the seasonal parameters, time series are corrected for any steps caused by earthquakes (and equipment changes at GPS stations), as well as any post seismic effects. For both GPS and InSAR, if an earthquake has an effect of the time series is determined by a magnitude (Mw) to distance of zero displacement relationship from Overacker et al., (in prep) (Figure 1) is used. Relaxation terms are added at half this distance, however, the distance relationship for post seismic displacement is still under investigation.

Earthquakes for GPS stations are corrected by adding a damping kernel that damps towards approximate values of displacement from the Overacker et al., method, soon to be available on the NGL website. InSAR time series are corrected by placing the displacement from all earthquakes occurring within the same epoch and spatial area upon the largest earthquake, and then damping towards zero and applying weights (Figure 2).

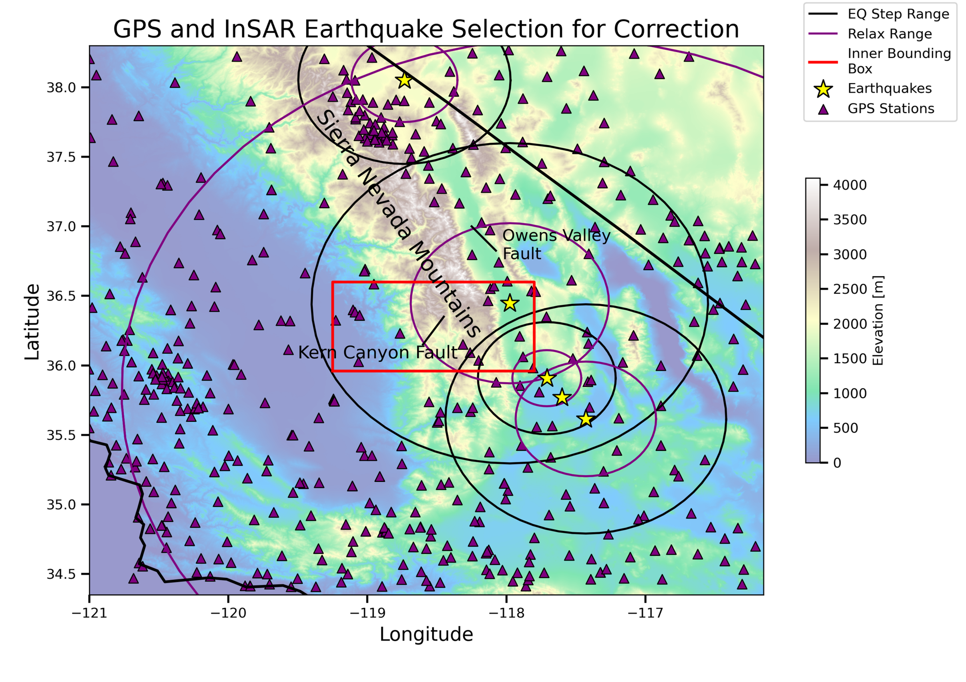


Figure 1: Earthquakes affecting time series (yellow stars) and radius to approximate zero displacement (black circles). Initial distance for post seismic consideration are purple circles. GPS stations are shown in blue triangles, while InSAR bounding boxes are in green. Shows the intersection of GPS stations and InSAR coverage with larger earthquakes in the area that can effect time series. Sierra Nevada mountain range is seen as the higher elevation zone trending west northwest. Bounding box for figure 3 shown in red.

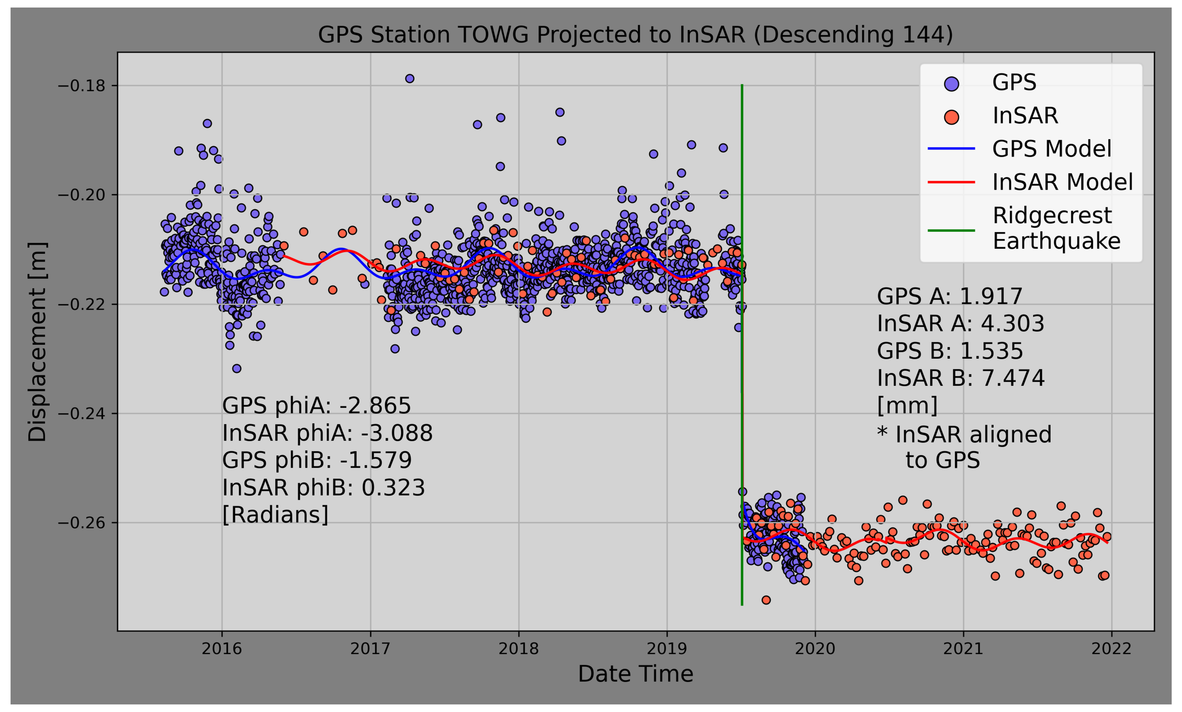


Figure 2: Time series for GPS (blue) and InSAR (orange). Seasonal terms are solved for with Ridgecrest earthquake (green) within the model. InSAR time series has been aligned to the GPS. Parameter values, amplitudes A (annual) and B (semi annual) and phases, phiA (annual), and phiB (semi annual) are listed. Parameter values show good match between annual phase, but poor fit to semi annual phase.

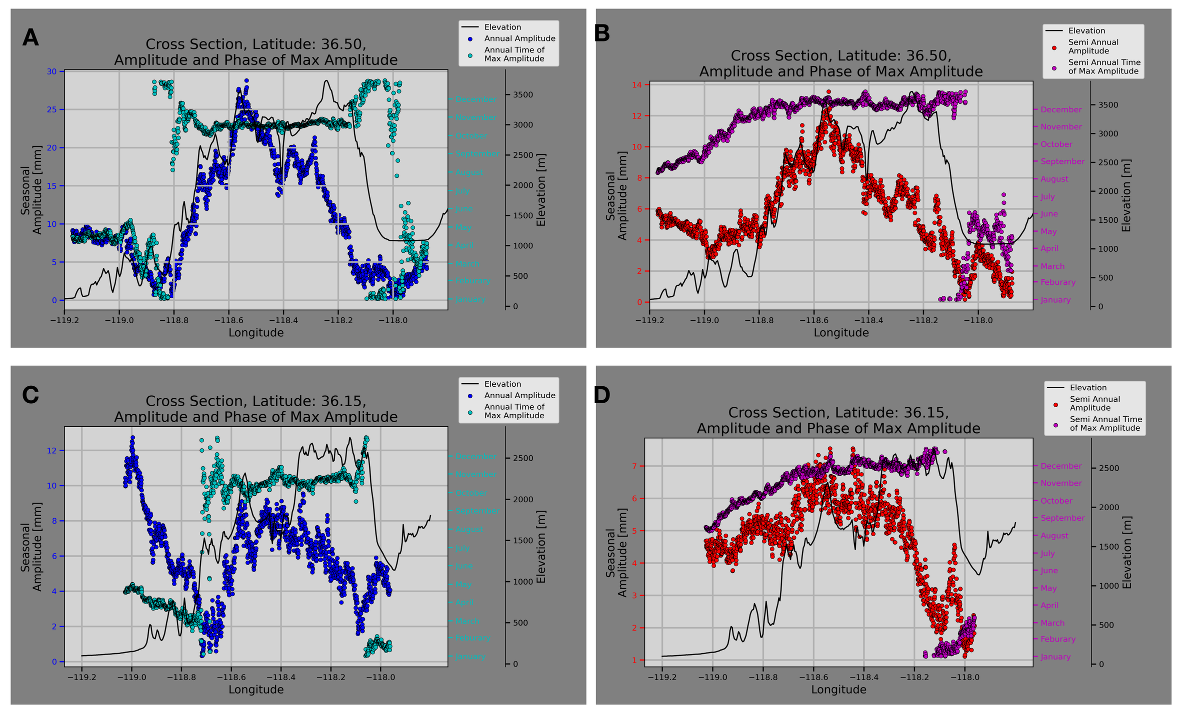


Figure 4: Figure 4a, cross section at 36.5 latitude, showing annual max amplitude in blue, and timing (phase) of max amplitude in cyan. In figure 4b, the semi annual amplitude is shown in red, and the timing of the max amplitude is shown in magenta. Elevation is shown in black. Figure 4c and 4d, similar graph to figure 4a and 4b, but cross section taken at 36.15 latitude. 4A and 4C clearly show a very abrupt transition between the loading domain (time of max late fall) and the poroelastic domain in the Central Valley.

### Results

Seasonal results from InSAR time series analysis show interesting patterns across the Sierra. The annual amplitude (Figure 3a) shows a maximum at higher elevations of the mountain, but also a zone of minimum amplitude between the mountains and valley to the west. This zone of minimum amplitude corresponds to the change in phase of the time of maximum amplitude, which is around October for the higher elevation mountain, and around May for the lower elevation valley (Figure 3c). The eastern side of the Sierra has a transition from October at the peak of the mountain to January as you go eastward, before transitioning to May, seen in the northeast of figure 3c. Results from GPS annual amplitudes are all low compared to InSAR results, likely due to the higher precision of the GPS system, but do align in some areas.

No GPS stations are available in the high Sierra to compare with the peak amplitude of the InSAR. Phase of the GPS agree with InSAR in areas such as the Sierra and valley areas, and disagree in areas of where the elevation is changing between the Sierra and valley. The semi annual amplitude (Figure 3b) is smaller from the annual amplitude, which is expected. There is a smoother transition on the western side, compared to the annual phase. The phase at the top of the mountain, occurring in December, transitions smoothly to the valley below, which peaks in September (Figure 3d). There is a sharper transition of phase on the eastern side of the Sierra, which corresponds to a minimum in the semi annual amplitude.

The semi annual GPS amplitude is very low compared to the InSAR results. The phase of maximum amplitude matches the InSAR at several stations, but in general has a less good fit compared to the annual terms. While the fit is poor between GPS and InSAR in the semi annual terms, the InSAR showing smooth transitions between low elevations and mountainous regions indicate that the signal seen is likely more than noise. This indicates that improvement could be made in the modeling to better constrain the semi annual parameter. Results from cross sections show that amplitude does not always correlate with elevation, ass seen in figure 4c. This indicates that other processes are affecting the amplitude of seasonality besides the loading from snow at the higher elevations. The timing or phase of the annual term does correlate with elevation, or the boundary between mountains and lower elevations indicating the annual phase is controlled by elevation. The semi annual phase shows a distinct change once on the east side of the Sierra (figure 4d).

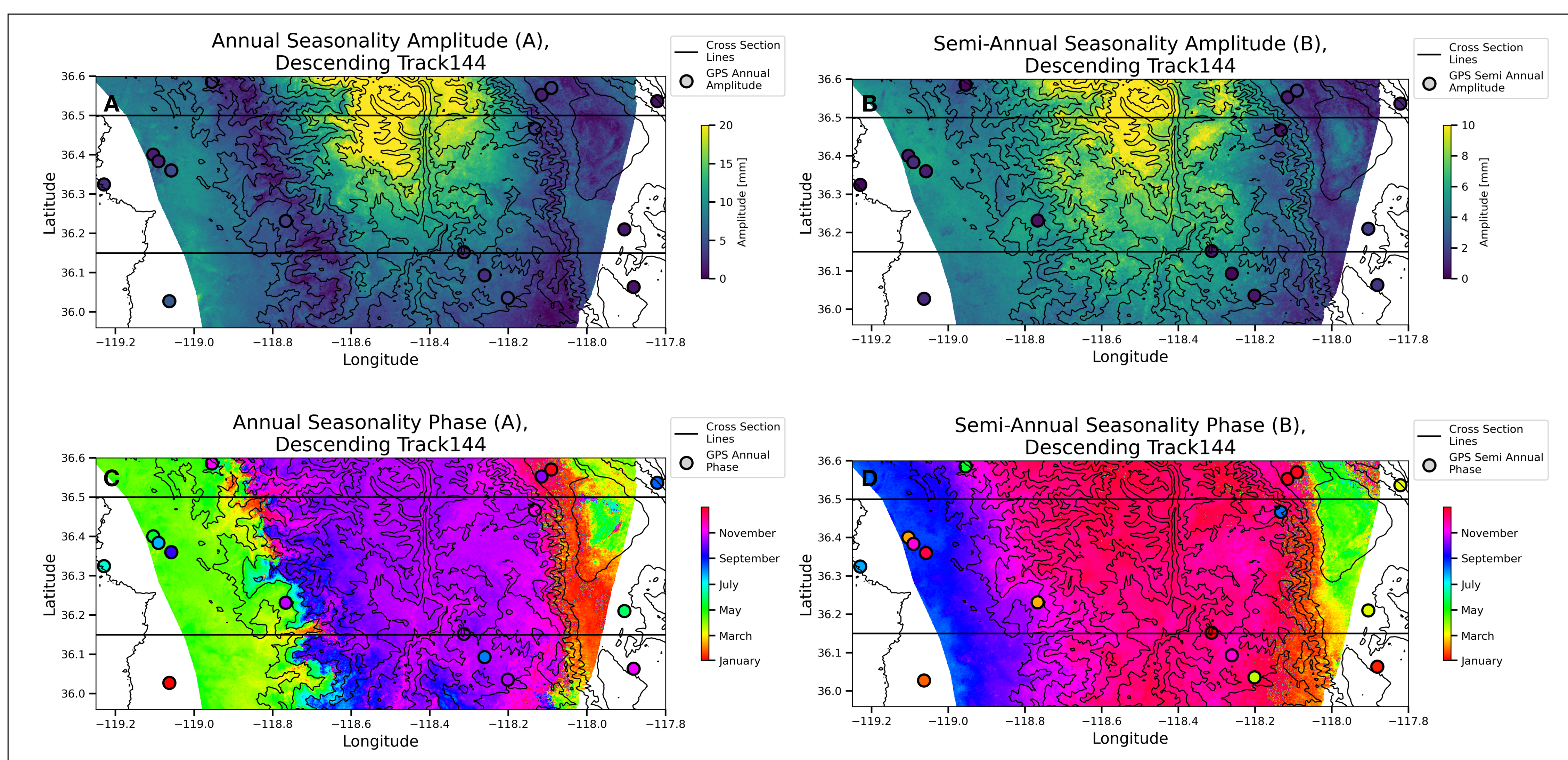


Figure 3: Figure 3a, maximum amplitude of the annual term solved across the InSAR time series. GPS stations are shown as circles, colored by similar amplitude. Cross section lines shown at 36.50 and 36.15 degrees latitude. Figure 3b, a similar image, but colored by the semi annual term. Figure 3c, time of year (phase) of the maximum amplitude, GPS stations shown as circles, colored by annual phase. Figure 3d, same as 3c, but colored by semi annual phase.

### Conclusions

The general agreement between amplitudes and phase for the annual terms between GPS and InSAR is promising. The agreement for the semi annual terms is not as good, possibly because the second harmonic is too small to accurately estimate. These results indicate the second term can possibly be dropped from the inversions, unless some other correction can be made to enhance the signal.

The patterns of amplitude and phase across the Sierra show clear patterns, with the mountain moving in a different phase than the valley below. The amplitudes show peaks in the valley and the mountain, with a zone of low amplitude between the zones, where the phase changes, in some areas with a sharp distinct boundary. These indicate differing controls on seasonal load, likely snow in the Sierra and water in the valley.

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