

Wavelet methods for detecting slow slip events in GNSS recordings

Ariane Ducellier¹, Kenneth Creager², and David Schmidt¹

¹University of Washington

²Univ Washington

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Abstract

Slow slip events were discovered in many subduction zones during the last two decades thanks to recordings of the displacement of Earth's surface by dense GNSS networks. Slow slip can last from a few days to several years and have a relatively short recurrence time (months to years), compared to the recurrence time of regular earthquakes (up to several hundreds of years), allowing scientists to observe and study many complete event cycles. In many places, tectonic tremor is also observed in relation to slow slip and can be used as a proxy to study slow slip events of moderate magnitude where surface deformation is hidden in GNSS noise. However, in subduction zones where no clear relationship between tremor and slow slip occurrence is observed, these methods cannot be applied, and we need other methods to be able to better detect and quantify slow slip. Wavelets methods such as the Discrete Wavelet Transform (DWT) and the Maximal Overlap Discrete Wavelet Transform (MODWT) are mathematical tools for analyzing time series simultaneously in the time and the frequency domain by observing how weighted averages of a time series vary from one averaging period to the next. In this study, we use wavelet methods to analyze GPS time series and seismic recordings of slow slip events in Cascadia. We use detrended GPS data, apply the MODWT transform and stack the wavelet details over several nearby GPS stations. As an independent check on the timing of slow slip events, we also compute the cumulative number of tremors in the vicinity of the GPS stations, detrend this signal, and apply the MODWT transform. In both time series, we can then see simultaneous waveforms whose timing corresponds to the timing of slow slip events. We assume that there is a slow slip event whenever there is a peak in the wavelet signal. We verify that there is a good correlation between slow slip events detected with only GPS data, and slow slip events detected with only seismic data. The wavelet-based detection method detects all events of magnitude higher than 6 as determined by independent event catalogs (e.g. Michel et al., 2019, Pure Appl. Geophys.).



1. Slow slip events

- Duration: Several days to several years. Recurrence time: Months to years.
- Generate much weaker seismic waves than ordinary earthquakes.
- Observed in many subduction zones and some transform fault zones (Beroza and Ide, 2011 [2]; Audet and Kim, 2016 [1]).
- In some places, slow slip events are spatially and temporally correlated with tectonic tremor events (Episodic Tremor and Slip in Cascadia and Nankai).

We explore whether the wavelet decomposition of GNSS time series can be used to detect slow slip events, which would be useful for systems where tremor is not abundant or detected.

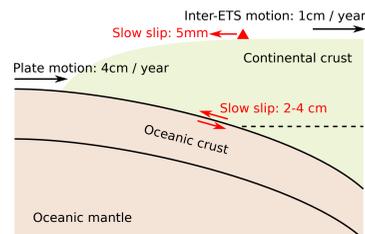


Figure 1: Slow slip event in northern Cascadia.

2. Wavelet decomposition

Maximal Overlap Discrete Wavelet Transform (MODWT)

X_t (length N) \rightarrow J wavelet vectors W_j ($j = 1, \dots, J$) of length $N \rightarrow J$ details D_j ($j = 1, \dots, J$) of length N and one smooth S_J of length N . Each wavelet vector W_j and each detail D_j is associated with changes on time scale $\tau_j = dt2^{j-1}$, where dt is the time step of the time series, and corresponds to a bandpass filter of the original GPS time series X_t between frequencies $\frac{1}{dt2^{j+1}}$ and $\frac{1}{dt2^j}$.

J = Level of the wavelet decomposition (Percival and Walden, 2000 [4]).

Multiresolution analysis (MRA): $X = \sum_{j=1}^J D_j + S_J$.

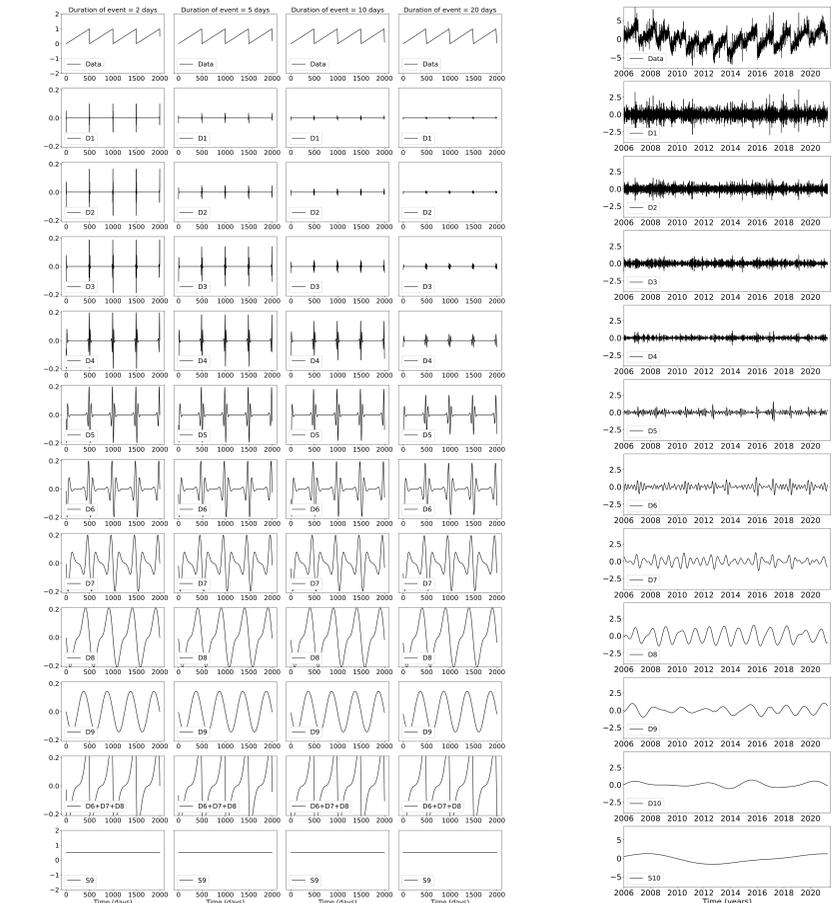


Figure 2: Demonstration of a wavelet decomposition for a synthetic dataset. A synthetic time series is created (top row) with steps of period 500 days, and transient durations of 2 days, 5 days, 10 days, and 20 days (right). The resulting details and smooths are shown in increasing level. The amplitude of the synthetic time series is normalized to 1, and the details and smooths show the relative amplitude.

Figure 3: Top: Longitudinal displacement recorded at GPS station PGC5. The resulting details and smooths of the wavelet decomposition are shown in increasing level.

3. Slow slip detection and comparison with tremor

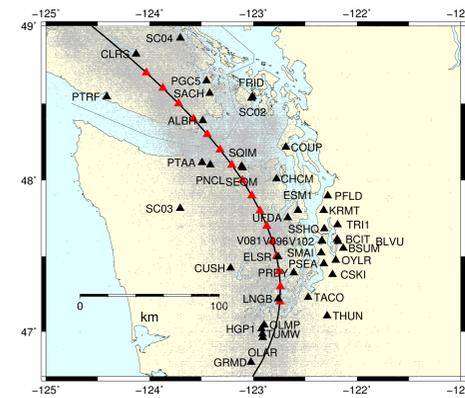


Figure 4: GPS stations used in this study (black triangles). The black line represents the 40 km depth contour of the plate boundary model by Preston *et al.* (2003 [5]). The red triangles are the locations where we stack the GPS data. The small grey dots are all the tremor locations from the PNSN catalog.

Signal processing for the GPS data

- Take points along the 40km depth contour of the plate boundary.
- Take all GPS stations in a 50 kilometers radius.
- Compute the MODWT for all the stations
- Stack each detail over all the stations.
- Sum the 6th, 7th and 8th levels details together (corresponds to periods 64 to 512 days).

Signal processing for the tremor data

- Compute the cumulative number of tremor in a 50 kilometers radius.
- Remove the trend.
- Compute the MODWT.
- Multiply by -1 for easier comparison.
- Sum the 6th, 7th and 8th levels details together.

- Red rectangles = Sum of details $> D_{cut}$ \rightarrow Replace by 1
- Blue rectangles = Sum of details $< -D_{cut}$ \rightarrow Replace by -1
- $-D_{cut} <$ Sum of details $< D_{cut}$ \rightarrow Replace by 0

- True positive (TP) = Value equal to 1 for both GPS and tremor / Value equal to -1 for both GPS and tremor
- False positive (FP) = Absolute value of GPS equal to 1 but value of tremor equal to 0 / Values of GPS and tremor have opposite signs
- True negative (TN) = Value equal to 0 for both GPS and tremor
- False negative (FN) = Value of GPS equal to 0 but value of tremor equal to 1 or -1

The receiver operating characteristic curve (ROC curve) is widely used for binary classification problems in statistics and machine learning.

$$\text{sensitivity} = \frac{TP}{TP + FN} = \text{True positive rate}$$

$$\text{specificity} = \frac{TN}{TN + FP} = 1 - \text{False positive rate}$$

- Vary the value of D_{cut} for both the GPS and the tremor data.
- Compute the corresponding sensitivity and specificity and add to ROC curve.
- Choose the values of the threshold that maximize the sensitivity while keeping the specificity large enough.

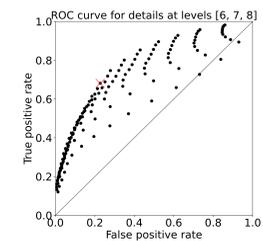
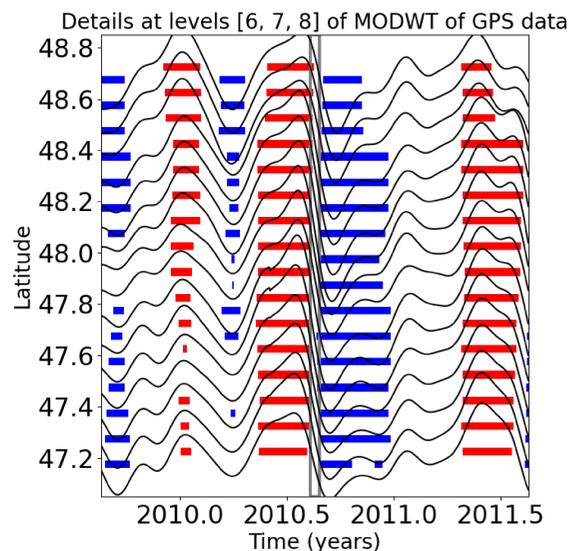


Figure 6: ROC curve for the sum of the 6th, 7th, and 8th level details of the wavelet decomposition. Each black dot represents the true positive rate of event detections and the false positive rate of event detections for a given pair of thresholds (for the GPS and for the tremor). The red cross marks the true positive rate and the false positive rate obtained with the thresholds used to make Figure 5.

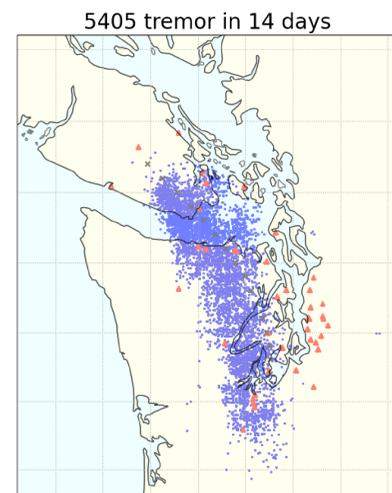
4. An example: the 2010 slow slip event



Left panel: Same as top panel of Figure 5, but zoomed over a shorter time window.

Right panel: Location of the tremor occurring during a 14 days period centered on the middle of the time window from the left panel (marked as a grey rectangle).

An animated version of this figure is available on the online version of the poster.



5. Summary

- In many subduction zones, tectonic tremor is observed in relation to slow slip \rightarrow Tremor can be used as a proxy to study slow slip events where surface deformation is hidden in GNSS noise.
- In some subduction zones, no clear relationship between tremor and slow slip occurrence \rightarrow This method cannot be applied.
- DWT and MODWT: Analyze time series simultaneously in the time and the frequency domain.
- Project objective: Use wavelet methods to analyze GNSS time series and seismic recordings of slow slip events in northern Cascadia.
- Detrended GNSS data \rightarrow MODWT transform \rightarrow Stack wavelet details over several nearby GNSS stations.
- Cumulative number of tremor in the vicinity of the GNSS stations \rightarrow Detrend \rightarrow MODWT transform.

Findings

- Timing of waveforms corresponds to the timing of slow slip events.
- Slow slip event = Positive peak followed by a negative peak.
- Good correlation between slow slip events detected with only GNSS data, and slow slip events detected with only tremor data for northern Cascadia.

6. References

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7. Acknowledgements

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The GPS recordings used for this analysis can be downloaded from the PANGA website [3] <http://www.panga.cwu.edu/>. The Python scripts used to analyze the data and make the figures can be found on the first author's Github account <https://github.com/ArianeDucellier/slowslip>. Figure 4 was created using GMT [6]. This work was funded by the grant from the National Science Foundation EAR-1358512. A.D. would like to thank Professor Donald Percival for introducing her to wavelet methods during his excellent class on Wavelets: Data Analysis, Algorithms and Theory taught at University of Washington.