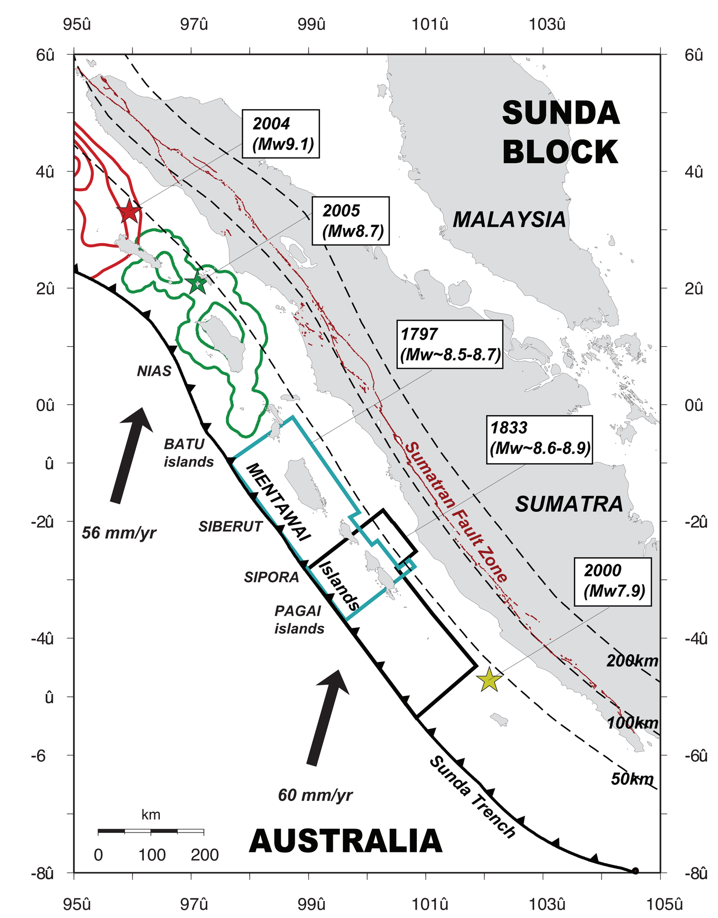
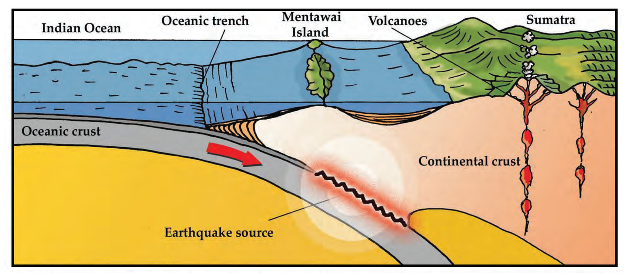
GEOLOGICAL INSPIRATION





Located in Southeast Asia, the Sunda subduction zone lies at the interface between the Sunda block and the Australian plate.

Over the last 200 years, there have been at least five giant earthquakes, including the December 26, 2004 earthquake which caused a tsunami that killed approximately 100,000 people. As such, a detailed understanding how the two plates are slipping past each other can help us understand when and where the next giant earthquake near the Sunda subduction zone is likely to occur.

Temporal Slip Variation:

Principal Component Analysis Based Linear Time Series Inversion On *n*-component Data

A. P. Kositsky
Under the mentorship of J-P. Avouac, T. Schneider, California Institute of Technology, GPS division.
apk@caltech.edu, avouac@gps.caltech.edu
1200 E. California Blvd. Mail Code 100-23 Pasadena CA 91125

ABSTRACT

We demonstrate a robust method of imaging temporal variation of slip at depth using Principal Component Analysis, the backslip model, and inversion of surface displacements for slip at depth using the Okada formulation. With synthetically generated GPS time series, we show how effectively we can invert multi-dimensional We have expanded on our previous work to allow inversion of *n*-dimensional spatiotemporal data such as InSAR or GPS time series for the time dependent slip evolution at depth.

INTRODUCTION

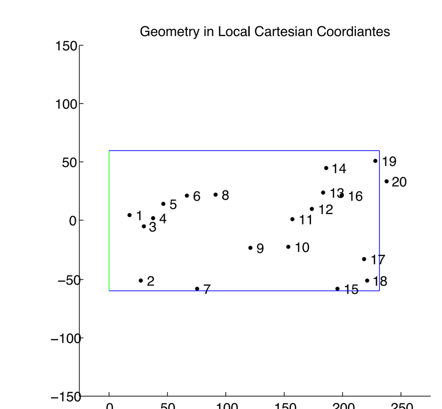
The global positioning satellite (GPS) system makes it possible to monitor deformation of the earth surface along plate boundaries with unprecedented accuracy. In theory, the spatiotemporal evolution of slip on the plate boundary at depth, associated with either seismic of aseismic slip, can be inferred from these measurements. This requires some inversion procedure based on the theory of dislocations in an elastic half space (e.g. Okada, 1994).

The techniques currently used to invert modern geodetic data are computationally intensive. The standard method consists in solving for the incremental fault slip distribution necessary to account for the deformation measured between two successive epochs. When we want to analyze 10 years of daily GPS data from over 1000 GPS stations, the processing time is overwhelming. We propose an alternative approach combining a model-based data extrapolation techniques with principal component analysis (PCA) to decompose the slip into orthogonal components. Reconstruction of the fault slip history requires only the inversion of each Principal Component. We prove that, in the ideal case, the solution space of the standard method and the PCA-based methods are identical. Further, in synthetic tests our method produces comparable results to the standard inversion technique with less computational complexity. This method can be trivially generalized to any linear inversion algorithm.

To test this inversion method, we have put together a representative test case with three spatially distinct time-varying signals on the fault plane:

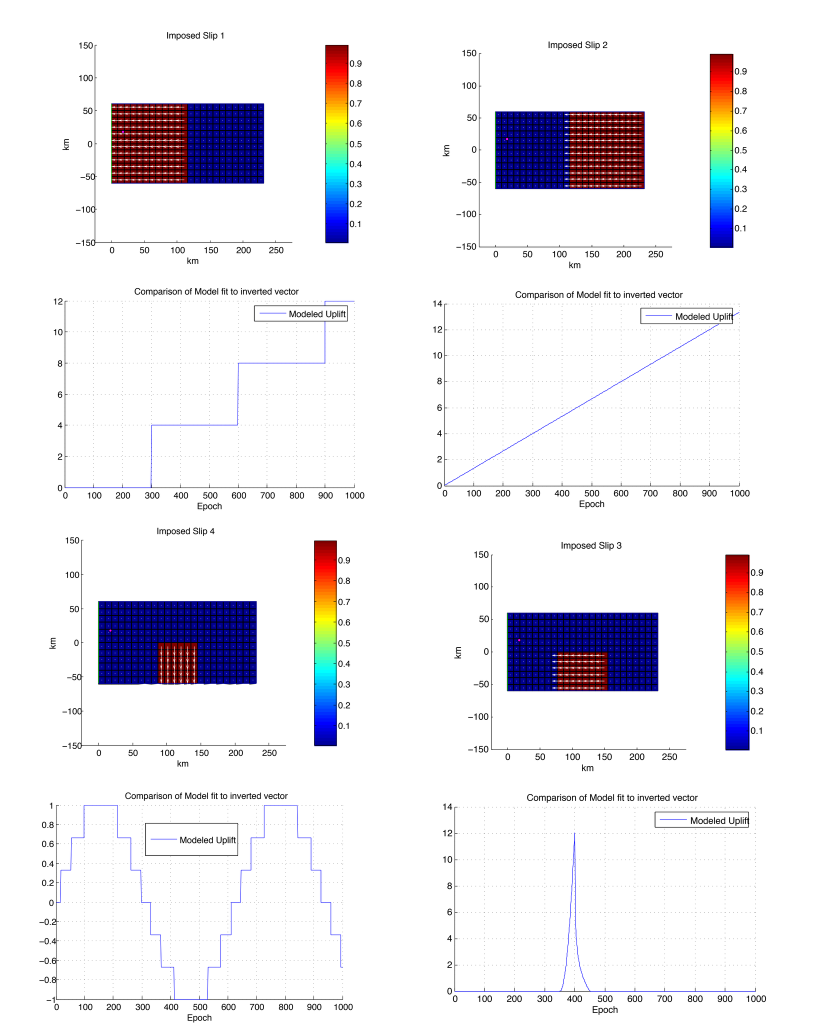
1. Stick-slip above 30 km depth.
2. Constant creep below 30 km depth.
3. A transient slip event at the southern edge of the modeled fault zone.

We are able to effectively recover the slip history despite noise. It is apparent that the recovery does not depend on the particular functional forms of the imposed slip.



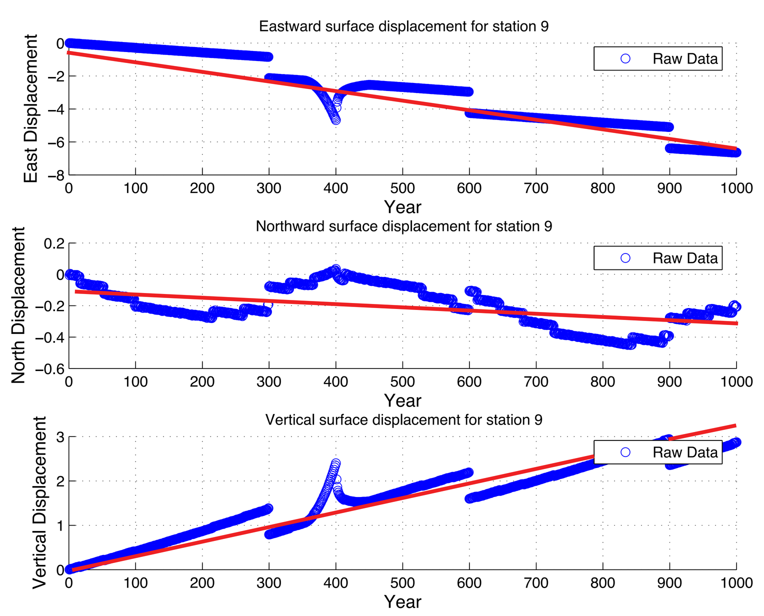
Synthetic Scenario Summary

Station Distribution:	Random (Even Distribution)
Number of Stations:	20
Number of Epochs:	1000
Number of Readings/Epoch:	3 (GPS)
Number of Components:	6
Significant Components:	3-4
Variance Explained:	0.968-0.985
Noise Magnitude:	0.010 cm
Signal Magnitude:	~5-10cm/1000 epochs
Size of Fault Zone:	120 km x 240 km
Origin:	(0,0) (Lat, Long)
Nu:	0.25
Number of Patches:	6 x 12 = 72
Dip Imposed:	15 degrees (dipping East)
Azimuth Imposed:	0 degrees CW of North
Decomposition of data:	Centered SVD
Inversion Method Used:	Okada Formulation
Strength of Laplacian:	0.20

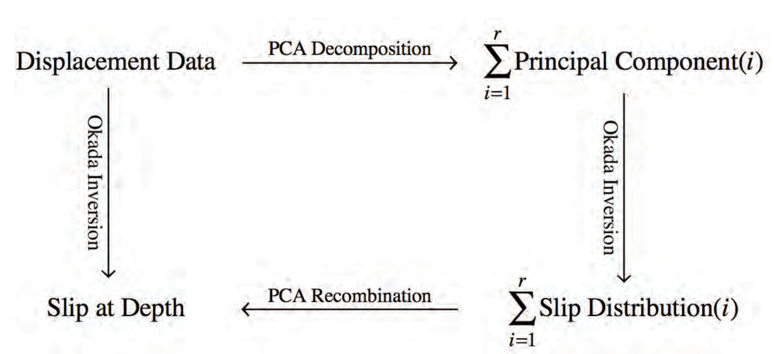


We set up a scenario where there is a known amount of slip at depth and attempt to use the resulting surface displacements to invert for slip at depth. We input 4 spatially and temporally different signals as described above. The cumulative slip at any given epoch t is the sum over the four slip distributions of time function at time t times the spatial signal. We add noise in order to make the model more realistic.

METHODS



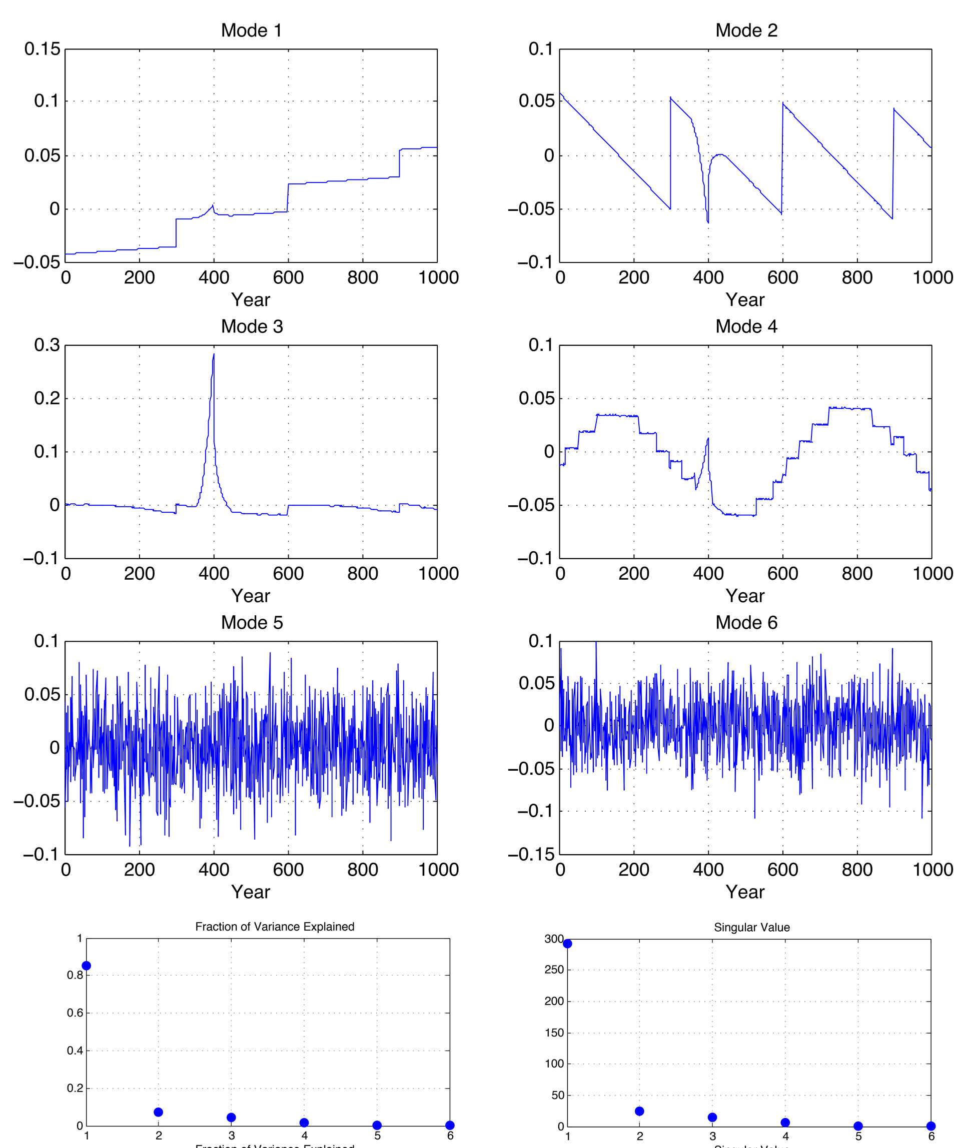
The most straightforward model is one that is linear with time. That is, the rate of displacement (vertical displacement in this case) at the surface is constant. This allows us to explain most of the first-order features of the data (no pun intended.) However, it is clear that there is some unexplained variability in the data.



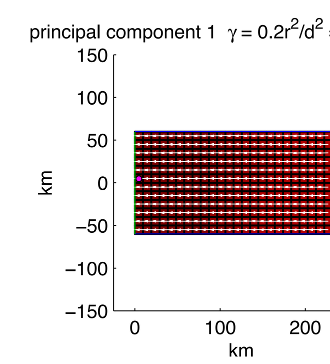
In order to try to better understand the unexplained variability, we will process and invert the data using the above diagram. Instead of inverting directly using Okada Inversion we first transform our displacement data into principal components and their weightings by significance and by time using a technique called singular value decomposition:

$$X = USV^t$$

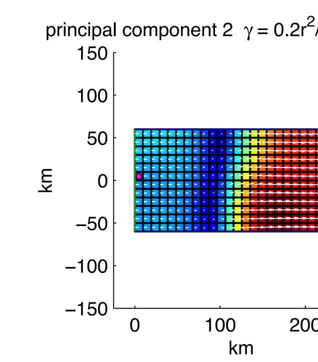
This construction leads to a small number of significant principal components which we then invert for slip at depth. Finally, we recombine the inverted components with their significance and time weightings (called singular values and modes, respectively.) The application of singular value decomposition in this context is called principal component analysis (PCA).



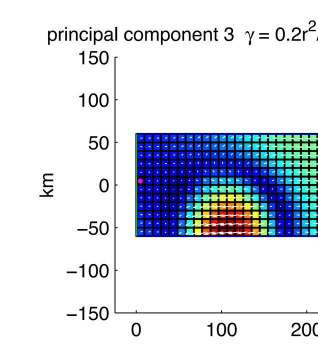
The so-called principal component vectors are chosen and ordered such that the first principal component vector explains as much variability of the data as possible. The second principal component vector explains as much variability of the data as possible given that the variability associated with the first component has been removed. The third principal component vector explains as much data as possible given the variability explained by the first two principal components, and so on. We show the first six here.



The slip associated with the first principal component is nearly constant across the entire fault plane. It explains much more variance than the other components.

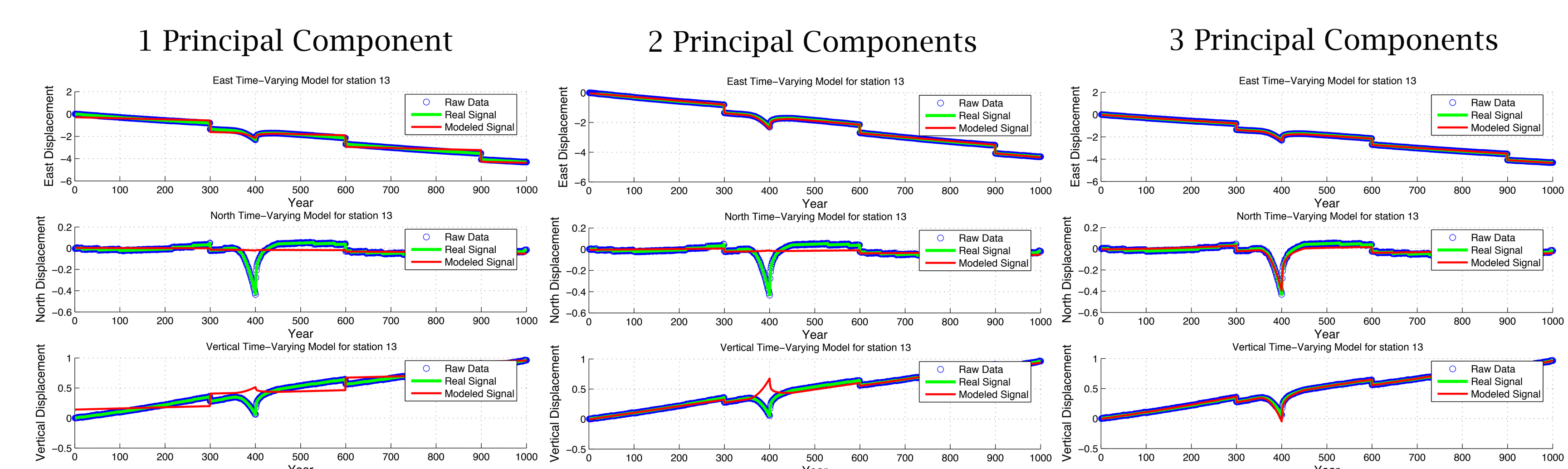


The slip associated with the second principal component has a sharp divide at 120 km, precisely where there is a separation between creeping and stick-slip behavior.



The slip associated with the third principal component is less homogeneous than the other first two. This reflects that the lower order components are more spatially coherent signals.

Each principal component has a weight corresponding to each station. These weights represent how strongly a principal component is represented in the time series of that particular station. Displacement from each component is proportional to its weight for that station, allowing inversion via the Okada formulation. We only need to perform inversion on the significant components, ones that explain signal and not noise. In this case there are four significant components.

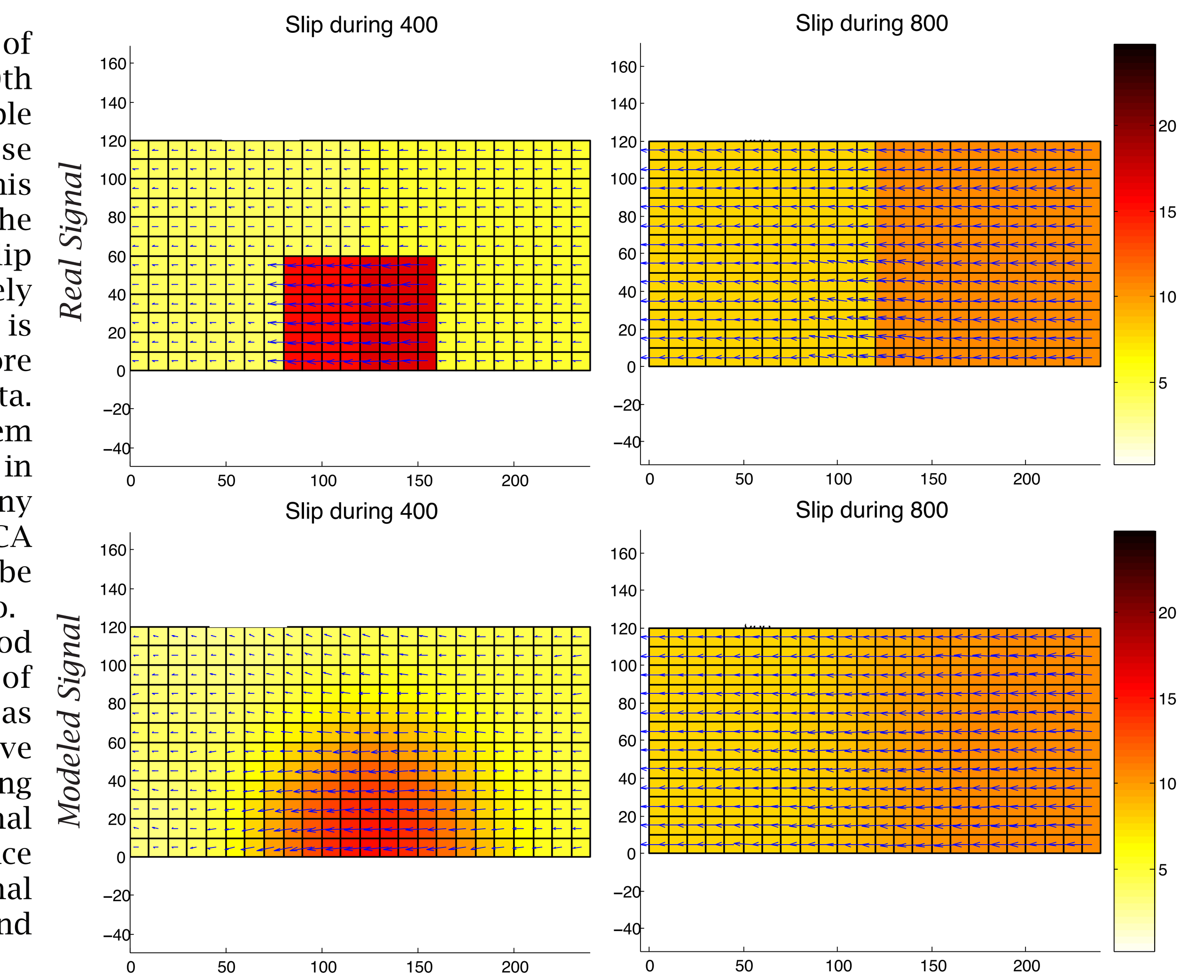


In this particular case, there are 60 principal component vectors in total. Most of the stations (such as 13 depicted above) have their signal explained within the first 3 components. The first component explains most of the variability in the data, the second slightly more, and the third tops off the fit.

RESULTS AND DISCUSSION

The figures to the right are examples of cumulative slip distributions at the 800th and 400th epochs. We see that we are able to faithfully reproduce both of these signals up to a smoothing factor. This smoothing factor is a result of the necessary condition that the slip distribution on the fault be relatively smooth; the problem we wish to solve is "ill-posed," meaning that there are more free parameters in our model than data. This is realistic since the same problem arises in nearly all inversion problems in geophysics. We can infer that any computation performed using the PCA inversion technique described here will be a smoothed version of the "real" scenario.

The computational benefits of this method are vast in this story. Instead of performing 999 day-by-day inversions as current methods must do, we have recovered most of the signal performing only 4 inversion. The computational savings are on the order of 100 times once we take into account the additional computation required to decompose and recompose the data matrix.



CONCLUSIONS AND FUTURE WORK

In summary, we have created an analytic method through which it is possible to invert surface displacement time series for temporally changing slip distributions at depth using multi-component data. In this particular demonstration, we used three component GPS data, but there is no reason we must restrict ourselves to such data. If we find a way to have 4 or 5 component data or are restricted to one or two component data, this methodology as described can use that information efficiently.

There are three major obstacles we aim to tackle:

1. Incomplete Data Sets
2. Multiple Data Types
3. Adaptation to Independent Component Analysis, Wavelets, and Other Linear Beasts

We plan to use recursive model-based imputation to deal with (1). By iteratively inverting complete subsets of the data, the expectation of the value at the missing points does not change as we "fill in" the "holes" in an incomplete data set.

Because everything is linear, we can simultaneously invert all of the principal components at once and add in linear equality or inequality constraints to solve (2.). In the case of linear inequality constraints, the method will have to run iteratively, reducing the computational advantage of the method.

We are still looking into computationally efficient ways to use decomposition methods other than singular value decomposition, but this remains an area of active research.

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