Multi-scale analysis of InSAR time series to estimate variations in topographically correlated propagation delays

Yu-nung Nina Lin*, Mark Simons1, Eric Hetland2, Pablo Musso3 and Christopher DiCaprio1

1Division of Geological and Planetary Sciences, California Institute of Technology 2Department of Geological Sciences, University of Michigan 3Department of Image and Signal Processing, Facultad de Ingenieria, Universidad de la Republica, Uruguay

Abstract

Repeat orbit InSAR serves as a powerful tool to estimate surface deformation caused by tectonic and neotectonic processes. When analyzing small-amplitude tectonic signals, InSAR observations are plagued by propagation delays that correlate with topographic variations. These delays are termed topographic delays and are assumed to result from temporal variances in vertical stratification of the troposphere. Assuming a linear model between topography and phase, we present a robust approach to estimating this transfer function K that is relatively insensitive to non-propagating processes (earthquake deformation, phase ramps from orbital errors or tidal loading, etc.). Our approach takes advantage of a multiscale property by adopting bandpass decomposition of both topography and observed phases. By decomposing topography and observed phases in a given interferogram into several spatial scales, we determine the bands spanning different characteristic length scales whereas correlation between topography and phase is significant and stable. Our approach also uses the inherent redundancy provided by multiple interferograms constructed with common sources. We define a unique set of component time intervals, \( \Delta T \), using a suit of interferometric pairs. The ensemble of interferometric transfer function \( K_{\text{enm}} \) are then combined to estimate consistently the transfer function for each component time interval \( K_{\text{time}} \). The ensemble of \( K_{\text{enm}} \) are then recombined to predict \( K_{\text{inm}} \) in order to correct any arbitrary interferometric pair. We test our approach in a synthetic example of the Makran subduction zone, and prove that the multiscale approach provides robust estimates of the transfer function \( K \). We then apply this approach to the 1997-1999 inflation event at Long Valley Caldera. The corrected interferograms show significant improvement in the mountain ranges. We further remove the atmospheric phase noise from the original interferograms and still derive the same values of transfer functions. The remaining uncorrected signals may be caused by heterogeneous water vapor distribution that require other corrections.

1 The Multi-scale Approach

The key idea of the approach proposed in this study is that, various topographic length scales \((L_i)\) should have different sensitivities to topographic stratification. We can take advantage of the multiscale property to robustly estimate a spatially constant \( K \) which is less sensitive to other confounding processes. Besides, physically there is more about topography than a topographic length scale, so in our approach, we also consider that different length scales would contribute differently to the determination of the transfer function \( K \). To carry out the correction, we decompose both topography and interferograms into different length scales (Fig. 1). This is done by applying a series of Gaussian filters with different spatial scales and taking the difference between two subsequent scales. Next, we propose two different algorithms to solve our linear equation.

Two Step Inversion

\[
\Delta \omega_{\text{filt}} = \hat{K}_{\text{enm}(t)} = \hat{K}_{\text{inm}(t)}
\]

\( \Delta \omega_{\text{filt}} \) is the selected decomposed bands of topography corresponding to interferograms \( \omega_{\text{filt}} \). \( \Delta \omega_{\text{filt}} \) is the selected decomposed bands of interferograms \( \omega_{\text{filt}} \). \( \hat{K}_{\text{enm}(t)} \) is the transfer function in line with each of \( \hat{K}_{\text{enm}(t)} \) respectively.

Once \( \hat{K}_{\text{enm}(t)} \) is solved, a time series of \( K \) can be formed by choosing an arbitrary source origin and sequentially adding up all \( K_{\text{time}} \) values. The \( K \) time series allows us to determine the \( \hat{K}_{\text{inm}(t)} \) of an interferogram from any arbitrary pair of SAR scenes.

One Step Inversion

\[
\hat{K}_{\text{enm}(t)} = \left[ \hat{K}_{\text{enm}(t)} \right] = \left[ \hat{K}_{\text{inm}(t)} \right] = \left[ \hat{K}_{\text{enm}(t)} \right] = \left[ \hat{K}_{\text{inm}(t)} \right]
\]

\( \hat{K}_{\text{enm}(t)} \) is the selected decomposed bands of topography corresponding to interferograms \( \omega_{\text{filt}} \). \( \hat{K}_{\text{inm}(t)} \) is the selected decomposed bands of interferograms \( \omega_{\text{filt}} \). \( \hat{K}_{\text{enm}(t)} \) is the transfer function in line with each of \( \hat{K}_{\text{enm}(t)} \) respectively.

Once \( \hat{K}_{\text{enm}(t)} \) is solved, a time series of \( K \) can be formed by choosing an arbitrary source origin and sequentially adding up all \( K_{\text{time}} \) values. The \( K \) time series allows us to determine the \( \hat{K}_{\text{enm}(t)} \) of an interferogram from any arbitrary pair of SAR scenes.

2 Synthetic example: Makran subduction zone

We select the Makran subduction zone to carry out a synthetic example test. The 1995 Pakistan earthquake and tsunami occurred along the coastal region in Makran and surrounding Indian Ocean countries. This remote area demonstrates a good example where InSAR can reveal the topographically correlated data for us to exploit. Backward difference model shows that the isotropic slip rate is \( \sim 0.5 \text{ mm/yr} \). The small amplitude signal can be easily masked by atmospheric delays. Since we do not have an atmosphere-free geometric data to compare with, we decide to build a synthetic interferogram to see how atmospheric signals may affect the detection of tectonic signals and how our multiscale approach works.

![Fig. 1](image1.png) Original and decomposed topography (upper panel) and interferograms (middle panel). LP, MP and HP represent lowpass, bandpass and highpass respectively. The scatter plots of each decomposed band are in the lower panel. The interferograms are from the two ENVISAT ASAR images acquired on 2004/01/14 and 2006/06/14 in the Makran subduction zone.

![Fig. 2](image2.png) (A) Makran subduction zone is located between the western Pakistan and eastern Iran, where the Arabian Plate subducts under the Eurasian Plate. (B) Topographic and major structure of the Makran subduction zone. White arrows with two numbers are plots corresponding vectors in (A). (C) Black squares are the three frames of ENVISAT descending track 409 with which we synthesize this study. We used the Geographical Information System standard deviation \( \pm 2.5 \text{ cm} \).

![Fig. 3](image3.png) Alternating interferograms with ramp removed. (A) Synthetic Interferogram (B) Topographic (C) Interferogram (D) Multi-scale interferogram derivative (E) Interferogram derivative with ramp. The beat frequency is \( \Delta f = 4 \) with \( f_{\text{cyc}} = 25 \text{ cm} \). The ramp is \( \Delta f \). The ramp removal increases the resolution of interferogram.

![Fig. 4](image4.png) (A) Synthetic interferograms, interferogram with ramp, interferogram with ramp removed. (B) Synthetic interferograms, interferogram with ramp, interferogram with ramp removed. (C) Synthetic interferograms, interferogram with ramp, interferogram with ramp removed. (D) Synthetic interferograms, interferogram with ramp, interferogram with ramp removed. (E) Synthetic interferograms, interferogram with ramp, interferogram with ramp removed.

3 Case study: Long Valley Caldera

Now that we have the multiscale approach as a robust tool to estimate \( K \), we turn to the Long Valley Caldera, located in the eastern California region just west of Mammoth Lakes, California. Using the 1997-1999 data, we first gather an exceptional growth in multi-scale and an exponential growth in long distance data. The result degrades seriously with large ramp.

![Fig. 5](image5.png) The location of the Long Valley Caldera and its surrounding areas during the 1997-1999 inflation event.