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

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Abstract

Repeat orbit InSAR serves as a powerful tool to estimate surface deformation caused by tectonic and non-tectonic processes. When aiming at small amplitude tectonic signals, InSAR observations are plagued by propagation delays that correlate with topographic variations. These delays are termed tropostatic delays and are assumed to result from temporal variations in vertical stratification of the troposphere. Assuming a linear model between topography and phase, we present a robust approach to estimating the transfer function K that is relatively insensitive to confounding processes (earthquake deformation, phase ramps from orbital errors or tidal loading, etc.). Our approach takes advantage of a multi-scale perspective by adopting band-pass decomposition of both topography and observed phase. By decomposing topography and observed phase in a given interferogram into several spatial scales, we determine the bands spanning different characteristic length scales wherein correlation between topography and phase is significant and stable. Our approach also uses the inherent redundancy provided by multiple interferograms constructed with common scenes. We define a unique set of component time intervals, ΔT, using a suit of interferometric pairs. The ensemble of interferogram-based transfer function K_{igram} are then combined to estimate consistently the transfer function for each component time interval ($K_{\Delta T}$). The ensemble of $K_{\Delta T}$ are then recombined to predict K_{igram} 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 multi-scale approach provides robust estimates of the transfer function K. We then apply this approach to the 1997-1998 inflation event at Long Valley Caldera. The corrected interferograms show significant improvements in the mountain ranges. We further remove the magmatic inflation signals 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 requires other corrections.

1 The Multi-Scale Approach

The key idea of the approach proposed in this study is that, various topographic length scales (λ) should have different sensitivities to tropospheric stratification. We can take advantage of the multi-scale perspective to robustly estimate a spatially constant K which is less sensitive to other confounding processes. Besides, physiographically there is more short-λ topography than long-λ topography. So in our approach, we also consider that different length scales should contribute differently to the determination of the transfer function K.

To carry out the correction, we decompose both topography and interferogram into different length scales (**Fig. 1**). This is done by applying a series of Guassian 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

$$\Delta\phi(\lambda) = b + K_{igram}h(\lambda)$$
$$[G][K_{\Delta T}] = [K_{igram}]$$

$h(\lambda)$: band-passed topography
$\Delta\phi(\lambda)$: band-passes phase

One Step Inversion

$$\left[\; h_m(\lambda_n), \quad 1 \;\right]\begin{bmatrix} K_{\Delta T} \\ b_{\Delta T}\end{bmatrix} = \left[\; \Delta\phi_m(\lambda_n) \;\right]$$

$h_m(\lambda_n)$: the n selected decomposed bands of topography corresponding to m interferograms
$\Delta\phi_m(\lambda_n)$: the n selected decomposed bands of m interferograms
$K_{\Delta T}$, $b_{\Delta T}$: the transfer function and bias term for each ΔT respectively

Once $K_{\Delta T}$ is solved, a time series of K_T can be formed by choosing an arbitrary series origin and sequentially adding up all $K_{\Delta T}$ values. The K_T time seires allows us to determine the K_{igram} of an interferogram from any arbitrary pair of SAR scenes.

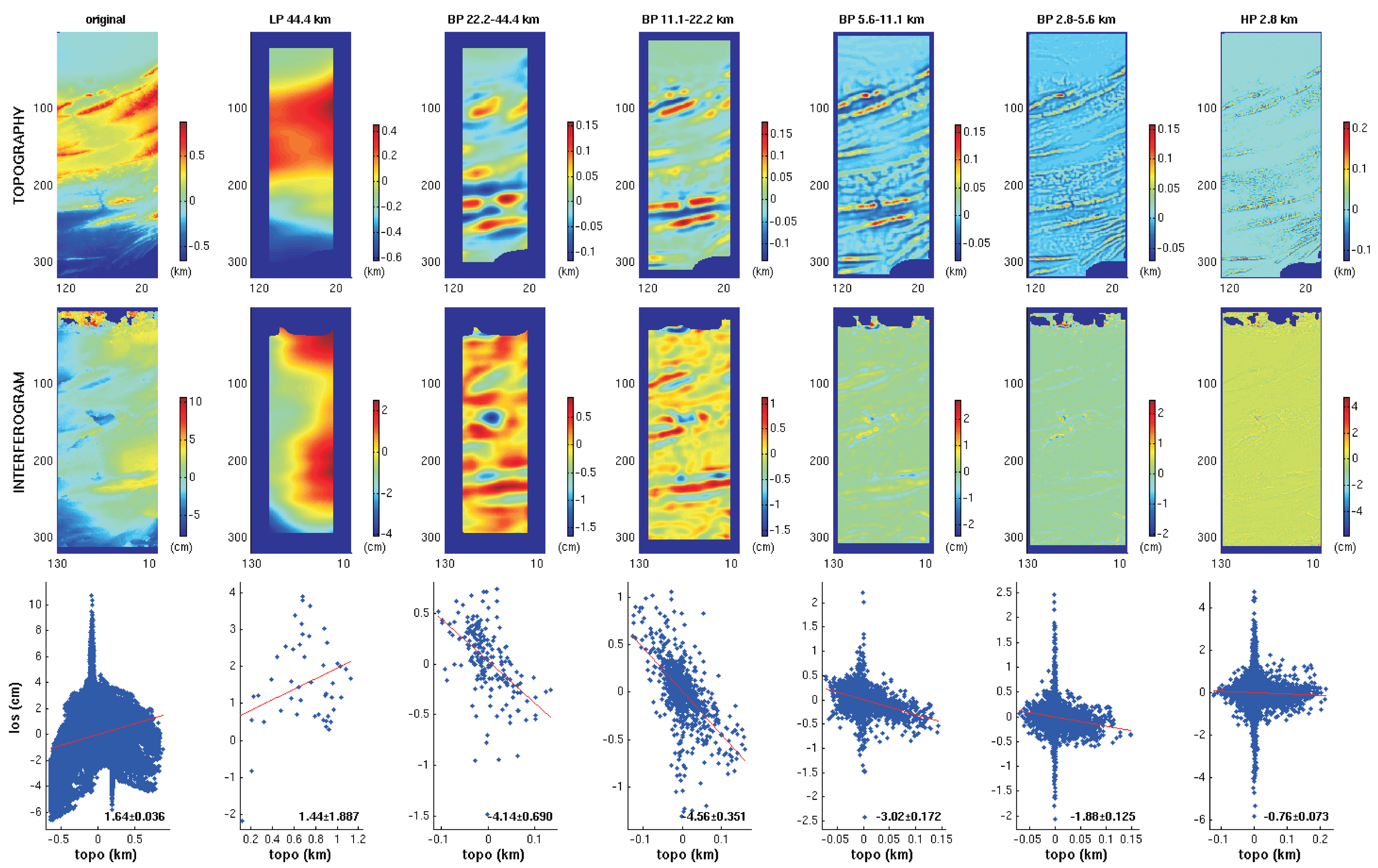


Fig. 1 Original and decomposed topography (upper panel) and interferogram (middle panel). LP, BP and HP represent low-pass, band-pass and high-pass respectively. The scatter plots of each decomposed band are in the lower panel. The interferogram are produced from the two ENVISAT ASAR images acquired on 2004/05/14 and 2008/10/04 in the Makran subduction zone

2 Synthetic example: Makran subduction zone

We select the Makran subduction zone to carry out a synthetic example test. The 1945 Balochistan earthquake (Mw 8.1) took place on the megathrust (**Fig. 2**), with its 150-km long rupture generating tsunami waves along the coastal region in Makran and surrounding Indian Ocean countries. This remote area demonstrates a good example where InSAR data is the only available geodetic data for us to exploit. Back-slip dislocation model shows that the interseismic uplift rate is ~4.8 mm/yr. This small-amplitude signal can be easily messed up by atmospheric delays. Since we do not have an atmosphere-free geodetic 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 multi-scale approach works.

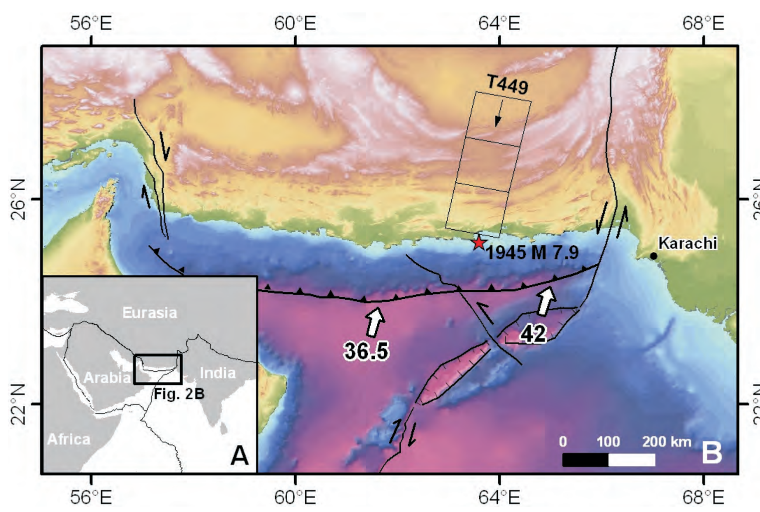


Fig. 2 (A) Makran subduction zone is located between western Pakistan and eastern Iran, where the Arabian plate subducts underneath the Eurasian plate. (B) Topography and major structures of the Makran subduction zone. White arrows with numbers are plate convergence vectors in mm (*DeMets et al.*, 1990). Black squares are the three frames of ENVISAT descending track 449 which we synthesize in this study. Red star represents the epicenter of the 1945 M 7.9 Balochistan earthquake (*Byrne et al.*, 1992).

Components of Synthetic Interferogram

(A) topography (Fig. 3)
(used to build (B) and (C); not directly included in the synthetic)

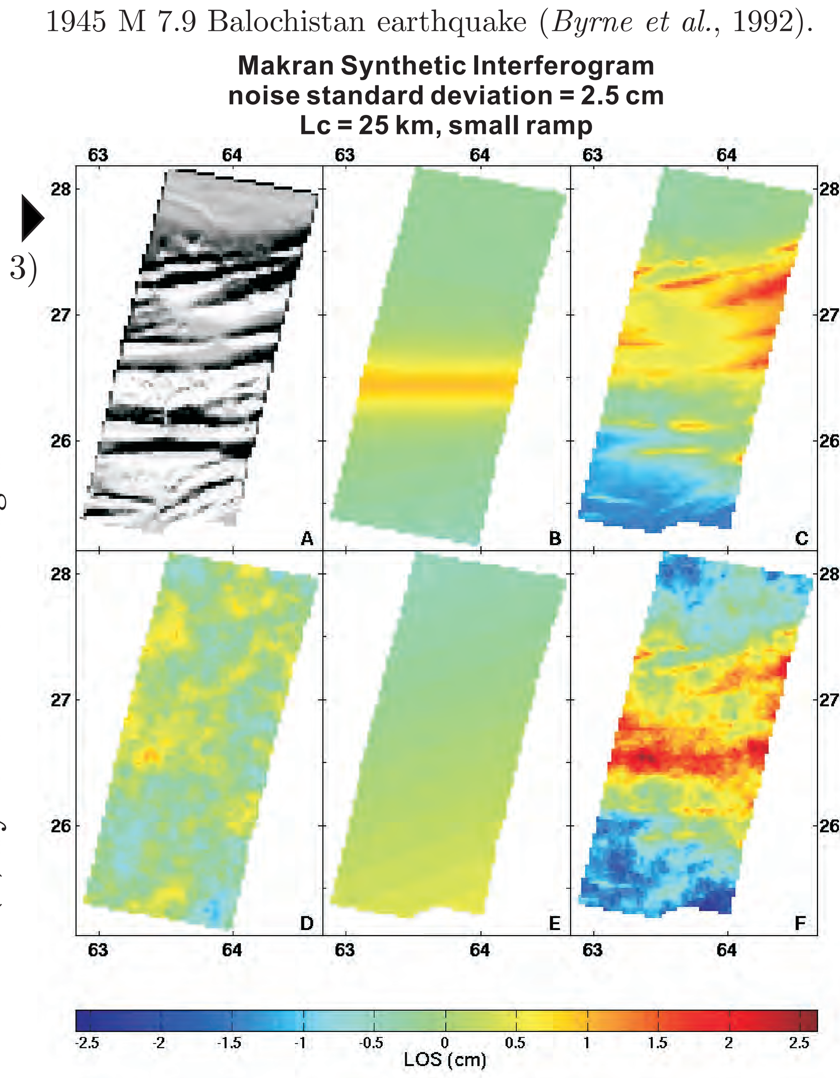
(B) tectonic (interseismic)

(C) tropostatic
$$\Delta\phi = b + Kh$$
K is set to be 2.3 cm/km

(D) turbulent mixing
$$C_d^{ij} = e^{-L_{ij}/L_c}$$
$$n_c = vu^{1/2}n_n$$
C_d^{ij}: covariance between the ith and jth points
L_{ij}: distance between the ith and jth points
L_c: turbulent spatial scale
n_n: uncorrelated nois
v, u: matrices of eigenvectors and eigenvalues of C_d

(E) ramp signals
$$\phi_{ramp} = a_1 + a_2X + a_3Y + a_4XY$$

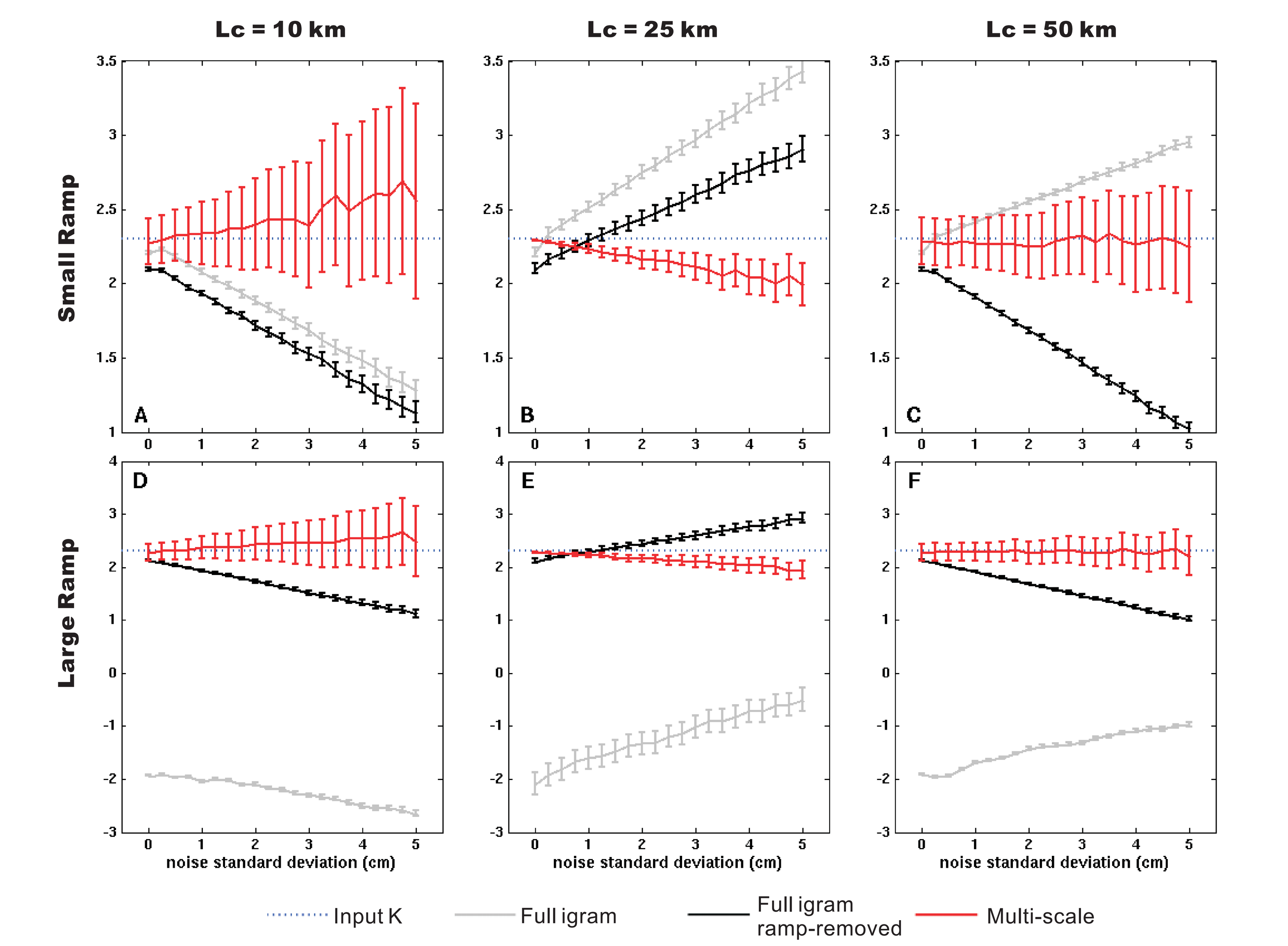
(F) Synthetic Interferogram



Testing Variables

σ_{noise}	1 - 5 cm
L_c	10 km, 25 km, 50 km
$ramp$	Small (-0.5~0.5 cm), Large (-5 ~ 5 cm) N-S gradient

Fig. 4 Comparison of K values calculated by using full interferogram correlation (gray lines), deramped interferogram correlation (black lines) and multi-scale analysis (red lines). All methods show that the retrieved K degrades from the input K as the noise standard deviation increases, but the multi-scale approach yields K values that decay less than the other two method.



Summary from Synthetics

	Multi-scale	Full igram with ramp	Full igram deramped
σ_{noise}	~ $\pm 0.06K$ per unit increase of σ_{noise} when Lc is within the bandpass wavelength	result degrades as σ_{noise} increases	
L_c		when ramp is small, gives better result than deramped igram	when ramp is small, Lc may cause inappropriate fitting of ramp so result degrades
$ramp$	not sensitive to ramp amplitude	result degrades seriously with large ramp	not sensitive to ramp amplitude

3 Case study: Long Valley Caldera

Now that we prove the multi-scale approach as a more robust tool to estimate K, we turn to the Long Valley Caldera (**Fig. 5**) where a large inflation event occurred between mid-April and late June 1997. This episode is one of the five inflation events through the past 30 years. During the 1997 episode, it first showed an exponential growth increase in mid-April, and an exponential growth decay in late November 1997, cumulating in ~10 cm of uplift (*Newman et al.*, 2001; *Hill et al.*, 2003).

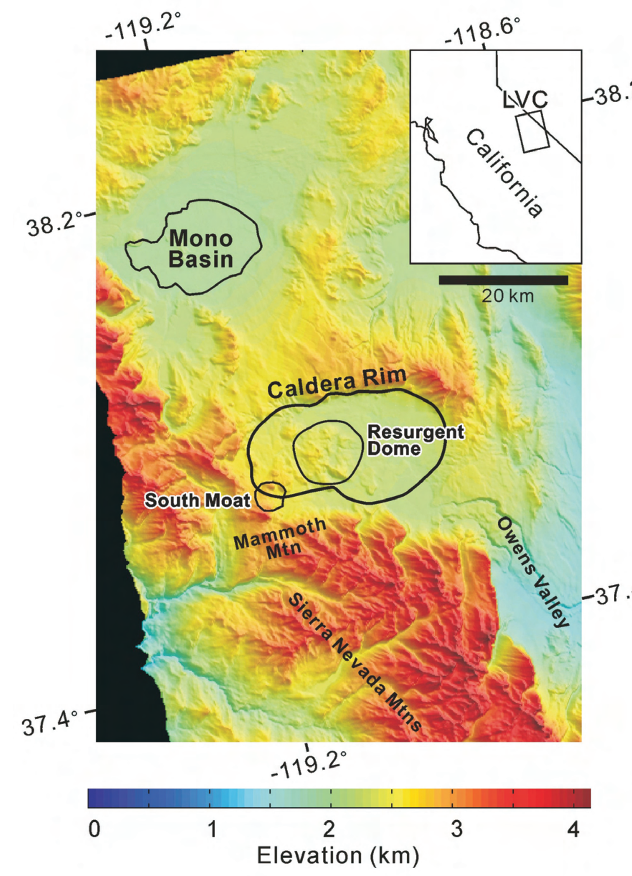


Fig. 5 The basemap of the Long Valley Caldera and the resurgent dome during the 1997-98 inflation episode.

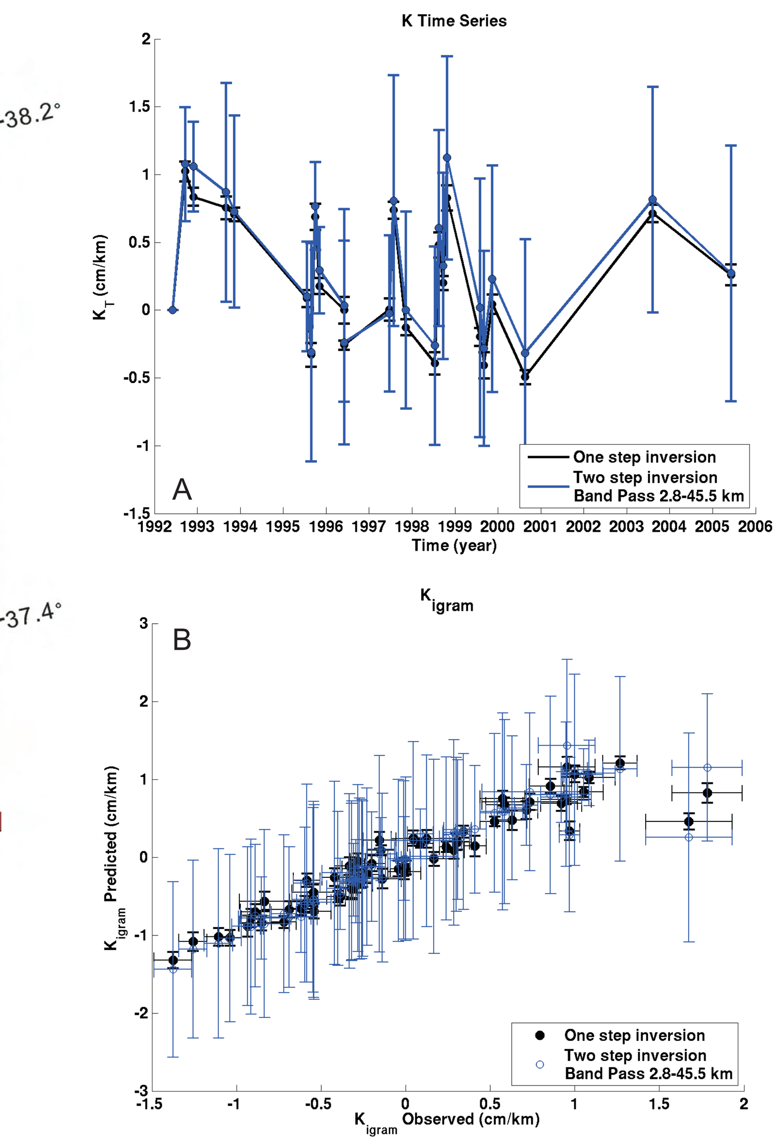


Fig. 6 (A) Comparison of K_T time series derived from one-step inversion (black line) and two-step inversion (blue line). (B) Comparison between observed K_{igram}, calculated directly from the phase-topography correlation of each interferogram, and predicted K_{igram}, derived from the K time series by using one-step and two-step inversion.

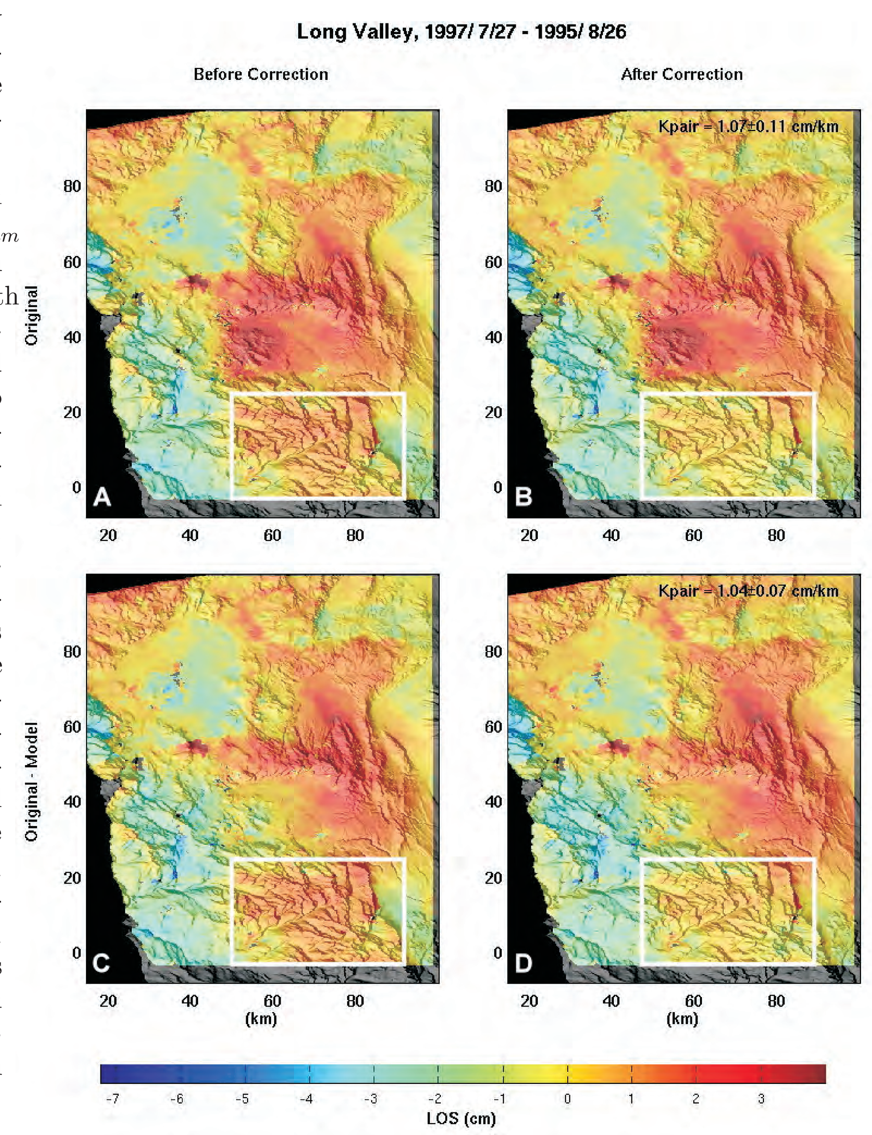


Fig. 7 We apply our two-step inversion approach as describd earlier to derive K_{igram} and K_T. **Fig.6** shows that the results from two-step and one-step approaches agree with each other very well, and the predicted values are almost identical with the observed K_{igram} values. In this case study, we also want to test the sensitivity of our multi-scale approach to confounding tectonic signals. We modeled the 1997-1998 inflation episode by using mogi model (*Mogi*, 1958). We derive the best fit of depth by calculating the least square error between models and interferograms. The result gives 10.5-km depth as the best fit. We assume that the source depth remains fixed during the whole inflation episode, with inflation volume as the only changing parameter. We then remove models from original interferograms, and carry out multi-scale decomposition and calculated the K_{igram} value again. The K_{igram} values thus derived are almost identical to the K_{igram} values derived before model removal. This validates our idea of multi-scale approach as a robust way to separate the elevation-phase correlated trapostatic delays from other non-correlated signals.