Water Vapour Bias in Measuring Interseismic Strain Accumulation With InSAR for the Altyn Tagh Fault, N. Tibet

John Elliott

Juliet Biggs, Zhenhong Li, Barry Parsons, Tim Wright
Motivation

• **Principal Aim**
  – Determine fault slip rates through the development of a robust method to mitigate water vapour signals

• **Input for the dynamics of continental deformation**
  – Does the Altyn Tagh Fault have a large control on Tibetan Tectonics

• **Seismic hazard assessment & identification of faults**
  – Production of global strain maps
The Tibetan Plateau

Motivation
Tibet
Water Vapour
Interferograms
Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics &
Monte Carlo
Bias
Atmosphere
Correction
Correlations
Slip Rate
Trade-off
Conclusions
Altyn Tagh Slip Rates

This Study

Motivation
- Tibet
- Water Vapour
- Interferograms
- Stacking
- Errors
- Network
- Orbital
- Corrections
- Rate Map
- Slip Rate
- Synthetics & Monte Carlo
- Bias
- Atmosphere
- Correction
- Correlations
- Slip Rate
- Trade-off
- Conclusions

Geologic Offsets
- 12-23 mm/yr
  - Ryerson 99

Quaternary Offsets
- 4-10 mm/yr
  - Shen 01

Geodetic Rates
- 13-22 mm/yr
  - Peltzer 06
- 20-34 mm/yr
  - Meriaux 04
- 9-15 mm/yr
  - Zhang 07
- 12-16 mm/yr
  - Peltzer 89
- 5-10 mm/yr
  - Xiong 03
- 5-10 mm/yr
  - Zhang 07
- <10 mm/yr
  - Yue 03
- 6.5-11 mm/yr
  - Yue 01

Quaternary Offsets
- 10-20 mm/yr
  - Washburn 03
- 7-9 mm/yr
  - Yin 00
- 20-34 mm/yr
  - Meriaux 04
- 14-20 mm/yr
  - Meriaux 05

Geologic Offsets
- 4-10 mm/yr
  - Shen 01
- 0-10 mm/yr
  - Wright 04
- 20-38 mm/yr
  - Meriaux 04
- 5-13 mm/yr
  - Wallace 04
- 20-38 mm/yr
  - Meriaux 04
- 4-7 mm/yr
  - Zhang 04
- 12-20 mm/yr
  - Zhang 07
- 7-11 mm/yr
  - Zhang 04
- 1-6 mm/yr
  - Zhang 07
- 7-11 mm/yr
  - Yue 02
- 3-7 mm/yr
  - Zhang 04
- 4-14 mm/yr
  - Yue 01
- 12-16 mm/yr
  - Yue 01
- 7-11 mm/yr
  - Chen 00
- 4-8 mm/yr
  - Chen 00
- 10-20 mm/yr
  - Washburn 03
- 4-7 mm/yr
  - Zhang 04
- 5-13 mm/yr
  - Wallace 04
- 20-30 mm/yr
  - Peltzer 89
- 20-38 mm/yr
  - Avouac 93
- 9-15 mm/yr
  - Zhang 07
- 13-22 mm/yr
  - Peltzer 06
- 14-20 mm/yr
  - Meriaux 05
- 7-9 mm/yr
  - Yin 00
- 4-8 mm/yr
  - Zhang 04
Orographic Front

View NE

Tarim Basin

100km

ATF

Tibetan Plateau

4km
Water Vapour Variability

January

Low Water Vapour
Low Variability

July

Effective range change of 30cm

High Water Vapour
High Variability

ECMWF 1 Degree Total Column Water Vapour Data
Baseline - Time Plot for Track 391

- 26 Acquisitions

59 Interferograms

Motivation
Tibet
Water Vapour
Interferograms
Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics &
Monte Carlo
Bias
Atmosphere
Correction
Correlations
Slip Rate
Trade-off
Conclusions
Motivation

Tibet

Water Vapour

Interferograms

Stacking

Errors

Network

Orbital

Corrections

Rate Map

Slip Rate

Synthetics & Monte Carlo

Bias

Atmosphere

Correction

Correlations

Slip Rate

Trade-off

Conclusions

Fringe 2007, ESA, Frascati '07

Nadir

Strike 246°

Line Of Profile

Fault

Plan View

Heading 194°

Horizontal

Deformation ~ LOS

cos 38° x sin 23°

~ 3.25 x LOS

Ground

23°

20-26°

LOS

Horizontal

~ 3.25 x LOS

Fringe 2007, ESA, Frascati '07

N

Look Direction

Fault

Strike 246°

Line Of Profile

Satellite

Descending

Track

cos 38° x sin 23°
Interferogram Profiles

Motivation

Tibet
Water Vapour
Interferograms
Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Bias
Atmosphere
Correction
Correlations
Slip Rate
Trade-off
Conclusions
Stacking Interferograms

Baseline - Time Plot for Track 391

Motivation
Tibet
Water Vapour
Interferograms

Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics &
Monte Carlo
Bias
Atmosphere
Correction
Correlations
Slip Rate
Trade-off
Conclusions
6 Interferogram Stack

Motivation
Tibet
Water Vapour
Interferograms
Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Bias
Atmosphere
Correction
Correlations
Slip Rate
Trade-off
Conclusions
Interferogram Errors

Motivation
- Tibet
- Water Vapour
- Interferograms
- Stacking
- Errors
- Network
- Orbital Corrections
- Rate Map
- Slip Rate
- Synthetics & Monte Carlo
- Bias
- Atmosphere Correction
- Correlations
- Slip Rate
- Trade-off
- Conclusions

Water Vapour

Orbital Errors

Decorrelation
**Employing All Interferograms**

**Baseline - Time Plot for Track 391**

- 26 Acquisitions
- 59 Interferograms

**Motivation**
- Tibet
- Water Vapour Interferograms
- Stacking Errors
- Network Orbital Corrections
- Rate Map
- Slip Rate
- Synthetics & Monte Carlo Bias
- Atmosphere Correction
- Correlations
- Slip Rate Trade-off
- Conclusions
Network Orbital Correction

Planar Ramp $ax + by + c$ fitted to South side of Fault (flat topography)

Solve for: $(a_i - a_j)x + (b_i - b_j)y + c_{ij}$ for all Ifgm pairs $ij$ in network

- Design Matrix
  
  $\begin{bmatrix}
  -x_1 & x_1 & 0 & \ldots & -y_1 & y_1 & 0 & \ldots & 1 & 0 & \ldots \\
  -x_2 & x_2 & 0 & \ldots & -y_2 & y_2 & 0 & \ldots & 1 & 0 & \ldots \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  -x_k & x_k & 0 & \ldots & -y_k & y_k & 0 & \ldots & 1 & 0 & \ldots \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  0 & -x_1 & x_1 & 0 & \ldots & -y_1 & y_1 & 0 & \ldots & 1 \\
  0 & -x_2 & x_2 & 0 & \ldots & -y_2 & y_2 & 0 & \ldots & 1 \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  0 & -x_k & x_k & 0 & \ldots & -y_k & y_k & 0 & \ldots & 1 \\
  \end{bmatrix}$

- Parameters
  
  $\begin{bmatrix}
  a_i \\
  a_j \\
  b_i \\
  b_j \\
  c_{12} \\
  \vdots \\
  c_{ij} \\
  \end{bmatrix}$

- Data
  
  $\begin{bmatrix}
  \phi_{1,1} \\
  \phi_{2,1} \\
  \vdots \\
  \phi_{k,n} \\
  \end{bmatrix}$

- Orbit Co-efficients
  
  Offset

- Interferograms
  
  (k pixels*nifgms)
Network Orbital Correction

Motivation
Tibet Water Vapour Interferograms Stacking Errors
Network Orbital Corrections Rate Map Slip Rate Synthetics & Monte Carlo Bias Atmosphere Correction Correlations Slip Rate Trade-off Conclusions

Unflattened Ifgm Orbital Ramp Flattened Ifgm

Fringe 2007, ESA, Frascati '07
Formulating The Rate Map

Baseline - Time Plot for Track 391

Motivation
Tibet
Water Vapour
Interferograms
Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Bias
Atmosphere
Correction
Correlations
Slip Rate
Trade-off
Conclusions
Invert for Rate Map Pixel-by-Pixel Basis

\[
\begin{bmatrix}
  t_2 - t_1 \\
  t_3 - t_1 \\
  \vdots \\
  t_j - t_i \\
\end{bmatrix}
\begin{bmatrix}
  r_1 & r_2 & \cdots & r_k \\
\end{bmatrix}
= \begin{bmatrix}
  d_{12,1} & d_{12,2} & \cdots & d_{12,k} \\
  d_{31,1} & d_{31,2} & \cdots & d_{31,k} \\
  \vdots & \vdots & \ddots & \vdots \\
  d_{ij,1} & d_{ij,2} & \cdots & d_{ij,k} \\
\end{bmatrix}
\]

Interferogram Time Span
Rate Map Pixel-by-Pixel
Flattened Interferograms (k pixels) * (n ifgms)
$T = \text{vector of interferogram timespans},$

$d = \text{matrix of interferograms},$

$r = \text{rate map (on a pixel-by-pixel basis)},$

$\Sigma_d = \text{variance-covariance matrix}$
Solve for Slip Rate & Orbits

- Design Matrix:
  \[
  \begin{bmatrix}
  g_1 & x_1 & y_1 & 1 \\
  g_2 & x_2 & y_2 & 1 \\
  \vdots & \vdots & \vdots & \vdots \\
  g_k & x_k & y_k & 1 \\
  \end{bmatrix}
  \]

- Parameters:
  \[
  \begin{bmatrix}
  s \\
  a \\
  b \\
  c \\
  \end{bmatrix}
  \]

- Data:
  \[
  \begin{bmatrix}
  r_1 \\
  r_2 \\
  \vdots \\
  r_k \\
  \end{bmatrix}
  \]

Green’s Functions
X & Y Co-ordinates
& Column of Ones

Slip Rate
Ramp
Offset

Rate Map (k pixels)

Motivation
Tibet
Water Vapour
Interferograms
Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Bias
Atmosphere
Correction
Correlations
Slip Rate
Trade-off
Conclusions
Slip Rate & Formal Error

**Motivation**
- Tibet
- Water Vapour Interferograms
- Stacking Errors
- Network Orbital Corrections
- Rate Map
- **Slip Rate**
- Synthetics & Monte Carlo
- Bias
- Atmosphere Correction
- Correlations
- Slip Rate
- Trade-off
- Conclusions

**Slip Rate**

*Model Map for Slip Rate 35 mm/yr*

*Residuals Map*

*Elevation (km)*

**Profile of Rate Map (LOS) for Altyn Tagh Fault, Track 391, 85degE**

**Slip Rate = 35 ±1σ 3 mm/yr**

*Rate Map*

*Rate Map*
Tropospheric Water Vapour

- Previous estimates take account of general atmospheric noise

- The large relief across the Altyn Tagh Fault requires that topographic water vapour signal to be modelled as well

- No contemporaneous measurements of water vapour exist for ERS data

- Used ECMWF weather model data from 1993-2000 for the total column water vapour
Monte Carlo Estimates of Error

- Formal inversion error underestimates true error in slip rate

- Create synthetic data and run inversion many times with perturbed datasets based upon
  - realistic spatially correlated noise
  - planar orbital errors
  - interseismic deformation of an elastic half-space
  - use of the same distribution of epoch acquisitions and coherence masks
Synthetic Data

Motivation
- Tibet
- Water Vapour Interferograms
- Stacking Errors
- Network Orbital Corrections
- Rate Map
- Slip Rate

Synthetics & Monte Carlo
- Bias
- Atmosphere Correction
- Correlations
- Slip Rate
- Trade-off
- Conclusions

Epoch 1
- Deformation

Epoch 2
- Orbital Error

Atmospheric Noise
Monte Carlo Estimate

Histogram of Slip Rate (mm/yr)

- Tectonic Signal = 20 mm/yr
- Monte Carlo returns 25 mm/yr
- Standard Deviation = 5.6 mm/yr

Bias 5 mm/yr
Systematic Shift in Epochs

Baselne - Time Plot for Track 391

Perpendicular Baseline (m)

Time


Bias
Atmosphere Correction
Correlations
Slip Rate
Trade-off
Conclusions
Systematic Bias in Monte Carlo Estimate

Motivation
Tibet
Water Vapour
Interferograms
Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo

Bias
Atmosphere
Correction
Correlations
Slip Rate
Trade-off
Conclusions
Network Atmospheric Correction

Linear Water Vapour with Height

Solve for: \((w_i - w_j)x + c_{ij}\) for all Ifgm pairs \(ij\) in network

Design Matrix

\[
\begin{bmatrix}
-h_1 & h_1 & 0 & \ldots & 1 & 0 & \ldots \\
-h_2 & h_2 & 0 & \ldots & 1 & 0 & \ldots \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots \\
-h_k & h_k & 0 & \ldots & 1 & 0 & \ldots \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots \\
0 & -h_1 & h_1 & 0 & \ldots & 1 \\
0 & -h_2 & h_2 & 0 & \ldots & 1 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots \\
0 & -h_k & h_k & 0 & \ldots & 1
\end{bmatrix}
\]

Heights & Column of Ones For each interferogram

Parameters

\[
\begin{bmatrix}
w_i \\
w_j \\
c_{12} \\
c_{ij}
\end{bmatrix}
\]

Water Co-efficients

Offset

Data

\[
\begin{bmatrix}
\phi_{1,1} \\
\phi_{2,1} \\
\vdots \\
\phi_{k,n}
\end{bmatrix}
\]

Flattened Interferograms

(k pixels*nifgms)
Atmospheric Correction

Motivation
Tibet
Water Vapour Interferograms
Stacking Errors
Network Orbital Corrections
Rate Map
Slip Rate Synthetics & Monte Carlo
Bias Atmosphere Correction
Correlations Slip Rate Trade-off
Conclusions
Water Vapour Correlation

Motivation

Tibet

Water Vapour

Interferograms

Stacking

Errors

Network

Orbital

Corrections

Rate Map

Slip Rate

Synthetics & Monte Carlo

Bias

Atmosphere

Correction

Correlations

Slip Rate

Trade-off

Conclusions

\[ n = 59, \quad r^2 = 0.42 \]
\[ r = 0.65, \quad (0.57 - 0.72)_{2\alpha} \]
\[ \text{slope} = 0.73 \pm_{2\alpha} 0.11 \]
\[ \text{intercept} = -6.1 \pm_{2\alpha} 3.64 \]
Hydrostatic Correlation

- Motivation
- Tibet
- Water Vapour Interferograms
- Stacking Errors
- Network Orbital Corrections
- Rate Map
- Slip Rate
- Synthetics & Monte Carlo Bias
- Atmosphere Correction
- Correlations
- Slip Rate
- Trade-off
- Conclusions

---

Graph: Scatter plot with linear regression line. 

- $n = 59$, $r^2 = 0.02$
- $r = 0.14$, $(-0.12 \pm 0.38)_{2\sigma}$
- slope $= 0.21 \pm 0.4$
- intercept $= -9.39 \pm 9.7$

---
Combined Correlation

- Motivation
- Tibet
- Water Vapour
- Interferograms
- Stacking
- Errors
- Network
- Orbital
- Corrections
- Rate Map
- Slip Rate
- Synthetics &
- Monte Carlo
- Bias
- Atmosphere
- Correction

**Correlations**
- Slip Rate
- Trade-off
- Conclusions

$n = 59, \ r^2 = 0.74$

$r = 0.86, (0.78-0.92)_{2\sigma}$

$slope = 1.11 \pm 0.17$

$intercept = -3.95 \pm 4.94$
Solve for Slip Rate & Orbits

Design Matrix

\[
\begin{bmatrix}
g_1 & x_1 & y_1 & 1 & h_1 \\
g_2 & x_2 & y_2 & 1 & h_2 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
g_k & x_k & y_k & 1 & h_k \\
\end{bmatrix}
\]

Parameters

\[
\begin{bmatrix}
s \\
a \\
b \\
c \\
w \\
\end{bmatrix}
\]

Data

\[
\begin{bmatrix}
r_1 \\
r_2 \\
\vdots \\
r_k \\
\end{bmatrix}
\]

Green’s Functions, X & Y Coordinates, Column of Ones, DEM heights

Slip Rate
Ramp
Offset
Vapour

Rate Map
(k pixels)

Motivation
Tibet
Water Vapour
Interferograms
Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Bias
Atmosphere
Correction
Correlations
Slip Rate
Trade-off
Conclusions
Monte Carlo Estimates

Histogram of Slip Rate (mm/yr)

Tectonic Signal = 20 mm/yr
Monte Carlo returns 20 mm/yr

Standard Deviation = 5 mm/yr
c.f. formal error 3.4 mm/yr
Slip Rate & Formal Error

Slip Rate = 10.6 ± 1σ 3.4 mm/yr

Profile of Rate Map (LOS) for Altyn Tagh Fault, Track 391, 85degE

Motivation
- Tibet
- Water Vapour Interferograms
- Stacking Errors
- Network Orbital Corrections
- Rate Map
- Slip Rate
- Synthetics & Monte Carlo
- Bias
- Atmosphere Correction
- Correlations

Slip Rate
- Trade-off
- Conclusions

Rate Map

Model Rate Map for 10.6 mm/yr

Residuals Map

Elevation

Fringe 2007, ESA, Frascati '07
Slip Rate & Formal Error

Motivation
- Tibet
- Water Vapour Interferograms
- Stacking Errors
- Network Orbital Corrections
- Rate Map
- Slip Rate
- Synthetics & Monte Carlo Bias
- Atmosphere Correction
- Correlations
- Slip Rate Trade-off
- Conclusions

Corrected Rate Map

Profile of Corrected Rate Map (LOS) for Altyn Tagh Fault, Track 391, 85degE

Slip Rate = 10.6 ±1σ 3.4 mm/yr

Model Rate Map for 10.6 mm/yr

Residuals Map

rms = 0.53 mm/yr

Elevation

Fringe 2007, ESA, Frascati '07
Fault Depth & Slip Rate Trade-Offs

Motivation
Tibet
Water Vapour Interferograms
Stacking Errors
Network Orbital Corrections
Rate Map Slip Rate
Synthetics & Monte Carlo Bias
Atmosphere Correction
Correlations Slip Rate
Trade-off
Conclusions
Fault Depth & Slip Rate Trade-Offs

Motivation

Tibet
Water Vapour
Interferograms
Stacking
Errors
Network
Orbital
Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Bias
Atmosphere Correction
Correlations
Slip Rate
Trade-off
Conclusions
Conclusions

• Water vapour is the largest source of error in determining slip rates on faults with large topographic steps – but evidence for hydrostatic delay also

• Accurate slip rate determination using ERS data will continue to be difficult due to the lack of independent water vapour measurements

• A bias slip rate estimates exists due to the non-uniform distribution of epochs

• A preliminary estimate for the slip rate of the Altyn Tagh fault at 85°E is 11 ± 5 mm/yr
Thank you for your attention

Any Questions?
Introduction

• Introductory Section
  – Motivation
  – InSAR
  – Altyn Tagh Fault & Published Slip Rates

• Detailed Section
  – Location of Study
  – Stacking Interferograms
  – Solving for Orbital Errors & Water Vapour
  – Monte Carlo Estimates of Errors
Co-Seismic vs Interseismic

**Coseismic**
- Timescales of seconds
- Metre Scale Offsets

**Interseismic**
- Timescales of Centuries
- Measuring mm’s per year

Metres of interseismic deformation

But over Timescales of Centuries
Line of Sight Displacement

Half a Wavelength ($\lambda/2 = 2.8$ cm)
Increased atmosphere refractivity results in path delay

Line of Sight Path Delay

Half a Wavelength ($\lambda/2 = 2.8$ cm)
Alpine-Himalayan Belt

Introduction
Motivation
InSAR
Slip Rates
Water Vapour
Altyn Tagh
Interferograms
Stacking
Interseismic
Strain
Initial Result
Problems
Network Orbital
Corrections
Rate Map
Slip Rate
Synthetics &
Monte Carlo
Water
Correction
Conclusions
Future Work
Previous Slip Rates by Publication Date

Altn Tagh Fault Slip Rate (mm/yr) – Descending By Publication Date

- Peltzer et al. 1989
- Avouac & Tapponier 1993
- Meyer et al. 1996
- Ryerson et al. 1999
- Yin & Harrison 2000
- Bendick et al. 2000
- Chen et al. 2000
- Chen et al. 2000
- Shen et al. 2001
- Shen et al. 2001
- Yue et al. 2001
- Yin et al. 2002
- Washburn et al. 2003
- Xiong et al. 2003
- Yue et al. 2003
- Ryerson et al. 2003
- Zhang et al. 2004
- Zhang et al. 2004
- Wallace et al. 2004
- Wright et al. 2004
- Meriaux et al. 2004
- Meriaux et al. 2005
- Peltzer et al. 2006

Legend:
- Red: Geologic Offsets
- Green: Quaternary Offsets
- Blue: Geodetic Rates
Northern Tibet
6 Interferogram Stack

Rate Map from a Stack of 6 Interferograms

Profile of Rate Map (LOS) for Altyn Tagh Fault, Track 391, 85degE

How To Model The Signal?
Interseismic Strain Accumulation

- Elastic Strain Dislocation Model

\[ y = \frac{s}{\pi} \tan^{-1} \frac{x}{d} \]

- for a vertical strike slip fault

\[ s = 1 \text{ m} \]
\[ d = 15 \text{ km} \]

Savage & Burford (1973)
Modelled Data

- Modelled Line of Sight from forward elastic model
Invert for Slip Rate using Rate Map

\[
\begin{bmatrix}
g_1 & 1 \\
g_2 & 1 \\
\vdots & \vdots \\
g_k & 1 \\
\end{bmatrix}
\begin{bmatrix}
s \\
c \\
\vdots \\
r_k \\
\end{bmatrix}
= 
\begin{bmatrix}
r_1 \\
r_2 \\
\vdots \\
r_k \\
\end{bmatrix}
\]

Green’s Functions from Okada (1985) & Slip Rate Offset & Rate Map (k pixels)

Model & Design Matrix & Parameters & Data

Introduction
Motivation
InSAR
Slip Rates
Water Vapour
Altyn Tagh
Interferograms
Stacking
Interseismic
Strain
Initial Result
Problems
Network Orbital
Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Water
Correction
Conclusions
Future Work
Weighting In The Inversion

- Variance Co-Variance Matrix based on Master-Slave Combinations & Median Maximum Variance of Ifgms

\[
\sigma^2 = \sigma_{\text{max}}^2 \exp(\text{dist}/d_c)
\]

\[
\sigma_{\text{median}}^2 = 65 \text{ mm}^2
\]

\[
VCM (\Sigma_d) = \sigma^2 \begin{bmatrix}
1 & 0.5 & -0.5 & \text{ifgm1} \\
0.5 & 1 & -0.5 & \text{ifgm2} \\
-0.5 & -0.5 & 1 & \text{ifgm3 etc}
\end{bmatrix}
\]
Variance-Covariance Matrix

- 1D Covariance Function used to create VCM to account for Spatial Correlation of Pixels

$$\sigma^2 = \sigma_{\text{max}}^2 \exp(\text{dist}/d_c)$$

**Characteristic Distance,** \(d_c = 28\text{km}\)

**Rate Map Error,** \(\Sigma_r = 0.42\text{ mm/yr}\)
Synthetic Data

Epoch 1
Deformation
Epoch 2
Monte Carlo Estimates & Trade-Offs

Histogram of Slip Rate (mm/yr)

Model Input = 20 mm/yr
Standard Deviation = 4 mm/yr
Systematic Bias in Monte Carlo Estimate

Number of Days Epoch Shifted

Monte Carlo Slip Rate based upon 20 mm/yr Input

Introduction
Motivation
InSAR
Slip Rates
Water Vapour
Altyn Tagh
Interferograms
Stacking
Interseismic Strain
Initial Result
Problems
Network Orbital Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Water Correction
Conclusions
Future Work

15 day Increments
Future Water Vapour Mitigation Work

- Process ENVISAT data on Altyn Tagh using MERIS water vapour product

- Possible investigate along strike variations in slip rate
Previous Slip Rates East-West

Altn Tagh Fault Slip Rate (mm/yr) – Descending East to West

- Ryerson et al. 1999
- Shen et al. 2001
- Wright et al. 2004
- Peltzer et al. 1989
- Mériaux et al. 2004
- Avouac & Tapponier 1993
- Xiong et al. 2003
- Elliott et al. 2008
- Peltzer et al. 2006
- Wallace et al. 2004
- Bendick et al. 2000
- Shen et al. 2001
- Zhang et al. 2004
- Yue et al. 2003
- Yue et al. 2001
- Washburn et al. 2003
- Chen et al. 2000
- Yin et al. 2002
- Chen et al. 2000
- Yin & Harrison 2000
- Zhang et al. 2004
- Mériaux et al. 2005
- Ryerson et al. 2003
- Meyer et al. 1996

- Red: Geologic Offsets
- Green: Quaternary Offsets
- Blue: Geodetic Rates
Interferometric Synthetic Aperture Radar

- Near Global Coverage
  - Useful for Remote Areas

- High Resolution & Large Spatial Scale
Altyn Tagh Slip Rates

Introduction

Motivation

InSAR

Slip Rates

Water Vapour

Altyn Tagh

Interferograms

Stacking

Interseismic

Strain

Initial Result

Problems

Network Orbital

Corrections

Rate Map

Slip Rate

Synthetics &

Monte Carlo

Water

Correction

Conclusions

Future Work
Previous Work

Introduction

Motivation

InSAR

Slip Rates

Water Vapour

Alyn Tagh

Interferograms

Stacking

Interseismic

Strain

Initial Result

Problems

Network Orbital

Corrections

Rate Map

Slip Rate

Synthetics &

Monte Carlo

Water

Correction

Conclusions

Future Work

Wright et al., Science 2004

Fringe 2007, ESA, Frascati '07
Water Vapour Variability

Tibetan Plateau (South)

Tarim Basin (North)

Introduction
Motivation
InSAR
Slip Rates
Water Vapour
Altyz Tagh
Interferograms
Stacking
Interseismic
Strain
Initial Result
Problems
Network Orbital
Corrections
Rate Map
Slip Rate
Synthetics &
Monte Carlo
Water
Correction
Conclusions
Future Work
Interferogram Profiles

Weighted Histogram of Ifgm LOS Displacement Rates

LOS Displacement Rate (mm/yr)
Cumulative Timespan of Coherent Pixels

- Some Pixels Remain Coherent Through All Interferograms
  - Alluvial fans

- Other Areas Remain Incoherent in All Interferograms
  - Steep Mountain Sides
Adding more ifgms reduces number of common pixels remaining coherent
Stacking Interferograms

Baseline - Time Plot for Track 391

Perpendicular Baseline (m)

Time

12 Interferogram Stack

Introduction
Motivation
InSAR
Slip Rates
Water Vapour
Altyn Tagh
Interferograms
Stacking
Interseismic Strain
Initial Result
Problems
Network Orbital Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Water Correction
Conclusions
Future Work

Rate Map from a Stack of 12 Interferograms
Profile of Rate Map (LOS) for Altyn Tagh Fault, Track 391, 85degE

Slip Rate = 37 mm/yr

Model Map for Slip Rate 37 mm/yr
Residuals Map
Elevation (km)
Monte Carlo Estimates & Trade-Offs

Introduction
Motivation
InSAR
Slip Rates
Water Vapour
Altyn Tagh
Interferograms
Stacking
Interseismic Strain
Initial Result
Problems
Network Orbital Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Water Correction
Conclusions
Future Work
Monte Carlo Trade-Offs (Vapour)

Introduction

Motivation

InSAR

Slip Rates

Water Vapour

Altyn Tagh

Interferograms

Stacking

Interseismic Strain

Initial Result

Problems

Network Orbital Corrections

Rate Map

Slip Rate

Synthetics & Monte Carlo

Water Correction

Conclusions

Future Work
Slip Rate & Formal Error

Introduction
Motivation
InSAR
Slip Rates
Water Vapour
Altyn Tagh
Interferograms
Stacking
Interseismic Strain
Initial Result
Problems
Network Orbital Corrections
Rate Map
Slip Rate
Synthetics & Monte Carlo
Water Correction
Conclusions
Future Work

Rate Map

Profile of Rate Map (LOS) for Altyn Tagh Fault, Track 391, 85degE

Slip Rate = 14 ±1σ 3 mm/yr

slip rate - 5 mm/yr
slip rate + 5 mm/yr

LOS Displacement Rate (mm/yr)

Distance from Fault (km)

Model Map for Slip Rate 14 mm/yr

Residuals Map

Elevation (km)

20 km

20 km

0.5

1

1.5

2

2.5

3

3.5

4

4.5

5

5.5

0

0.5

1

1.5

2

2.5

3

3.5

4

4.5

5

5.5

1.5 km

rms = 0.5 mm/yr

Fringe 2007, ESA, Frascati '07
Parameter Trade-Offs

- Water vapour w vs. orbital a co-eff: correlation = 0.47323
- Water vapour w vs. orbital b co-eff: correlation = 0.12131
- Slip (mm/yr) vs. orbital a co-eff: correlation = -0.47261
- Slip (mm/yr) vs. orbital b co-eff: correlation = -0.82567
- Offset c vs. orbital a co-eff: correlation = -0.62207
- Offset c vs. orbital b co-eff: correlation = 0.14898
Data Availability

- Data Selection strongly dictated by perpendicular baseline and timespan
Interferograms

Introduction
Motivation
Earthquake Cycle
InSAR
Tibet
Slip Rates
Previous Work
Elevation
Water Vapour Variability
Data Availability

Interferograms

Interseismic Strain
Modelled Data
Result
Comparison
Water Vapour Differences
Conclusions
Future Work
Interferograms

Introduction
Motivation
Earthquake Cycle
InSAR
Tibet
Slip Rates
Previous Work
Elevation
Water Vapour Variability
Data Availability

Interferograms
Interseismic Strain
Modelled Data
Result
Comparison
Water Vapour Differences
Conclusions
Future Work
Interferograms

Introduction

Motivation

Earthquake Cycle

InSAR

Tibet

Slip Rates

Previous Work

Elevation

Water Vapour Variability

Data

Availability

Interferograms

Interseismic Strain

Modelled Data

Result

Comparison

Water Vapour Differences

Conclusions

Future Work

Fringe 2007, ESA, Frascati '07
Stacked Interferograms

Introduction

Motivation

Earthquake Cycle

InSAR

Tibet

Slip Rates

Previous Work

Elevation

Water Vapour Variability

Data Availability

Interferograms

Interseismic Strain

Modelled Data

Result

Comparison

Water Vapour Differences

Conclusions

Future Work

Fringe 2007, ESA, Frascati '07
The Answer?

Introduction
Motivation
Earthquake Cycle
InSAR
Tibet Slip Rates
Previous Work
Elevation
Water Vapour Variability
Data Availability
Interferograms
Interseismic Strain
Modelled Data
Result
Comparison
Water Vapour Differences
Conclusions
Future Work
Comparison

Peltzer et al. (1989)
Avouac and Tapponnier (west) (1993)
Avouac and Tapponnier (central) (1993)
Yin and Harrison (2000)
Bendick et al. (2000)
Yue et al. (2001)
Shen et al. (west) (2001)
Shen et al. (central) (2001)
Yin et al. (2002)
Yue et al. (2003)
Wallace et al. (2004)
Zhang et al. (2004)
Mereaux et al. (2004)
Wright et al. (2004)

Elliott et al. ??

Introduction
Motivation
Earthquake Cycle
InSAR
Tibet
Slip Rates
Previous Work
Elevation
Water Vapour Variability
Data Availability
Interferograms
Interseismic Strain
Modelled Data
Result
Comparison
Water Vapour Differences
Conclusions
Future Work
Introduction
Motivation
Earthquake Cycle
InSAR Tibet
Slip Rates
Previous Work
Elevation
Water Vapour Variability
Data Availability
Interferograms
Interseismic Strain
Modelled Data
Result
Comparison
Water Vapour Differences
Conclusions
Future Work

Altyn Tagh Topographic Profile
Water Vapour Differences

July

January

Date 2 minus Date 1

Introduction
Motivation
Earthquake Cycle
InSAR
Tibet
Slip Rates
Previous Work
Elevation
Water Vapour Variability
Data Availability
Interferograms
Interseismic Strain
Modelled Data
Result
Comparison
Water Vapour Differences
Conclusions
Future Work
Water Vapour Differences

Mean difference of 0.4cm/yr
Over spatial scale of interferogram

With up to 1.4cm/yr within 2 sigma variation
Water Vapour Contribution

- Removal of 0.4 cm/yr water vapour contribution
- Removal of 0.7 cm/yr water vapour contribution
- Removal of 1.4 cm/yr water vapour contribution

Introduction

Motivation

Earthquake Cycle

InSAR

Tibet

Slip Rates

Previous Work

Elevation

Water Vapour Variability

Data Availability

Interferograms

Interseismic Strain

Modelled Data

Result

Comparison

Water Vapour Differences

Conclusions

Future Work