GACOS-Assisted InSAR Time Series Technique

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Basic Structure of the Atmosphere

- **Troposphere:**
  - Contains 80% of air mass
  - Contains 99% of water vapour
  - Air temperature decreases with altitude
  - ~12 km thick on average
  - ~16 km in the Tropics
  - ~9 km in the Polar Regions
  - Not dispersive (up to 30 GHz)

We focus on **Troposphere** today…
• Spatiotemporal variations in Troposphere represent one of the major limitations of repeat-pass InSAR.
Water vapour effects on InSAR measurements

- Higher altitude, Lower PWV

ZPDDM
- Max: 7.8 cm
- Min: -5.2 cm
- Mean: -0.9 cm
- StdDev: 1.0 cm

- 1 mm of PWV => ~6.2 mm of ZPD
- ZPDDM: Zenith Path Delay Difference Map
Higher altitude, Lower PWV

Southern California (07 Aug 2004 – 09 Apr 2005)

ZPDDM:
Max: 2.7 cm
Min: -12.8 cm
Mean: -2.9 cm
StdDev: 2.9 cm

N.B. Strong gradient in Figure (a)
Space-based water vapour measurements

- **Limitations**: Sensitive to the presence of clouds;
  Available in the daytime only;
  Time differences between radar and PWV data

Ground-based measurements

- **Limitations**: Coverage + Density + Distribution

Numerical Weather Models (NWM)

- Global/regional/local coverage
- High-resolution (relatively)
- Non-continuous but regular
- Insensitive to the presence of clouds
Key Questions

1. How to generate high resolution (e.g. 90m) and precise (e.g. 1-2 mm) water vapour maps from sparse observations (e.g. GPS derived PWVs)?

2. Which numerical weather model can be used to generate high resolution (e.g. 90m) and precise (e.g. 1-2 mm) water vapour maps?

3. Is it feasible to integrate multiple sources with different resolutions to produce high resolution (e.g. 90m) and precise (e.g. 1-2 mm) water vapour maps?

N.B. 1 mm of PWV => 6.2 mm of Phase Delay
Tropospheric delays can be calculated as follows:

\[ \Delta S = 10^{-6} \int_{\mathcal{S}} N \cdot ds \]

where \( N \) is refractivity: \( N = (n - 1) \times 10^{-6} \)

The refractivity of the troposphere is given by

\[
N = k_1 \left( \frac{P_d}{T} \right) Z_d^{-1} + k_2 \left( \frac{P_w}{T} \right) Z_d^{-1} + k_3 \left( \frac{P_w}{T^2} \right) Z_d^{-1}
\]

- \( k_1 = 77.60 \pm 0.05 \) K/mbar
- \( k_2 = 70.4 \pm 2.2 \) K/mbar
- \( k_3 = (3.739 \pm 0.012) \times 10^5 \) K²/mbar
The refractivity of the troposphere is **COMMONLY** written as

\[ N = N_h + N_w \]

Assuming a spherically symmetric atmosphere, the zenith tropospheric delay (ZTD) can be expressed as:

\[ ZTD = ZHD + ZWD \]

- **ZHD**: Zenith Hydrostatic Delay
- **ZWD**: Zenith Wet Delay
Tropospheric delays include:

- **Stratified**: Topography-dependent component
- **Turbulent**: Topography-independent component resulting from turbulent processes

\[ V L_{ij}^k = T(x^k) + L_0 e^{-\beta h^k} + \varepsilon \]

Turbulent  Stratified  Unmodelled error
The turbulent and stratified components are modeled with **IDW** and **exponential functions**, respectively.

ITDM reduces the **turbulence effects** on the estimation of height scaling.
Atmospheric Correction Model: Iterative Tropospheric Decomposition Model (ITDM)

ITDM leads to 45–78% of noise reduction even with a sparse (~50–80 km station spacing) GPS network and/or with strong and non-random tropospheric turbulence.

(Yu et al., 2018, RSE)
## Comparison between HRES ECMWF and ERA-Interim

<table>
<thead>
<tr>
<th></th>
<th>HRES-ECMWF</th>
<th>ERA-Interim</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizontal Resolution</strong></td>
<td>9~16 km</td>
<td>75 km</td>
</tr>
<tr>
<td><strong>Vertical Resolution</strong></td>
<td>137 levels</td>
<td>61 levels</td>
</tr>
<tr>
<td><strong>Output frequency</strong></td>
<td>00,06,12,18 UTC</td>
<td>00,06,12,18 UTC</td>
</tr>
<tr>
<td><strong>Data availability</strong></td>
<td>Near real-time</td>
<td>Delayed 3-4 months</td>
</tr>
<tr>
<td><strong>Data access</strong></td>
<td>Free with authorization</td>
<td>Free</td>
</tr>
</tbody>
</table>

(a) California

(b) United Kingdom

(c) $\sigma = 1.07 \text{ cm}$

(d) $\sigma = 0.88 \text{ cm}$
GPS and HRES-ECMWF are integrated with proper weighting to generate reliable ZTD correction maps.

The relative weighting between GPS and HRES-ECMWF are controlled by the precision and station distribution of GPS.

(Yu et al., 2018, in press for JGR)
GACOS: Generic Atmospheric Correction Online Service for InSAR

- Global coverage
- Operational in near real time
- Easy to implement
- Performance indicators

- High Resolution ECMWF (0.125, 6 hours);
- GNSS (soon to be released)
- 90m SRTM and ASTER GDEM

Launched in the 2017 Fringe Workshop on 6 Jun 2017
N.B. RMS difference (InSAR vs GPS): 2.43 cm -> 0.72 cm

(Yu et al., 2018, in press for JGR)
Case studies: Northern Tibet/Nepal

**Raw IFGs**

- **Northern Tibet**
  - STD=1.15 mm

- **Nepal**
  - STD=1.83 mm

**ZTD maps**

- **Northern Tibet**
  - STD=0.45 mm

- **Nepal**
  - STD=1.11 mm

**Corrected IFGs**
Case study: Maoxian Landslide, China

The 24 June 2017 Maoxian (China) Landslide (Sentinel-1A 20170131-20170531)
Performance Matrix (Indicators)

- Cross RMS
- Correlation coefficients
- ECMWF time difference
- Topography variation
Performance indicator: Cross RMS

UK Network (> 50 km)
RMS = 9.7 mm

California Network (~ 10 km)
RMS = 6.2 mm

- Model performance decreases whilst Cross RMS increases.
Parameters to be estimated:

- Displacement time series
- Mean velocity
- DEM error
- Orbital ramps + Atmospheric effects (Atmospheric Phase Screen, APS)
Fundamental assumptions:

- Deformation signals are correlated in time and in space (✓)
- APS signals are correlated in space, but NOT in time (?)

Our solution:

- Apply GACOS correction for every interferogram
- Identify the dates with poor GACOS correction according to GACOS performance indicators
- Estimate APS for those dates using a sub-network approach (Li et al., 2009, IEEE TGRS)
- Perform standard time series inversion…
Sub-network for APS Estimation: Envisat over Bam

- Descending track 120
- 25 dates: APS OK
- 2 dates: APS to be estimated
- 130 interferograms
- Small Perp baseline: < 400 m
- Network inversion:
  - 109 cloud-free pairs
  (Li et al., 2009)
Sub-network for APS Estimation: Envisat over Bam

Date: 050503

Perp baseline: < 400 m

Red: 10 Single-PWV-corrected Infms

Blue: 38 ZPDDM-corrected Infms

(Li et al., 2009, IEEE TGRS)
Postseismic motion after the 2016 Kaikōura, New Zealand, earthquake
Co-seismic displacements

(Ian J. Hamling et al. Science 2017)
Co- & Post-seismic displacements
From GPS

Co-seismic
(Horiz. + Vert.)

Post-seismic
New Zealand Post-seismic time series

Ascending
33 images
(2016.11–2017.12)
550 interferograms
Small Perp baseline:<200m
200 km by 200 km

Ascending
35 images
(2016.11–2017.12)
559 interferograms
Small Perp baseline:<200m
150 km by 100 km
S-1 Interferograms with or without GACOS correction

(a) Before Correction

20161127  20161203  20170207

20170309  20170426  20170812

20170824  20170929  20171104

(b) After Correction

20161127  20161203  20170207

20170309  20170426  20170812

20170824  20170929  20171104

LOD Disp (cm)
-9 -6 -3 0 3 6 9
GACOS Performance Indicator(s)

Atmospheric Correction Quality Control
Rejection threshold = Mean + 2\sigma = 5.6 \text{ mm}

Rejected (5.8%)
Accepted (94.2%)

Cross Test RMS (mm)

Days after mainshock

Summer
Winter

T52
T154
InSAR time series results

T52

(a) SBAS
(b) SBAS-GACOS
(c) SBAS-APS
(d) SBAS-GACOS-APS

T154

(a) SBAS
(b) SBAS-GACOS
(c) SBAS-APS
(d) SBAS-GACOS-APS
Cumulative Displacements

(a) SBAS
(b) SBAS-GACOS
(c) SBAS-APS
(d) SBAS-GACOS-APS

LOS Disp. (cm)

Days after mainshock
InSAR vs GPS displacements

RMS Difference

(a) 1.95 cm

(b) 1.65 cm

(c) 0.77 cm

(d) 0.72 cm
2D spectral analysis

(a) SBAS

(b) SBAS-GACOS

(c) SBAS-APS

(d) SBAS-GACOS-APS
Model 1: Best-fitting crustal fault model

(Ian J. Hamling et al. Science 2017)
NB. Given the proximity of the event and the location of the southern end of the Hikurangi subduction zone, an interface was introduced in Model 2.
Best-fitting afterslip model
Best-fitting afterslip model

Observed  Modeled  Residual
Afterslip time series

(a) Co-located co-seismic slip and afterslip on subduction interface
GACOS is freely available for the InSAR research community (http://ceg-research.ncl.ac.uk/v2/gacos/ Version 2 will be released in Oct 2018.

The assumption on APS being uncorrelated in time does not hold.

GACOS-assisted InSAR TS is demonstrated, and outperform other TS techniques.

Our preliminary afterslip model suggests that the 2nd co-seismic model including an interface source is preferred, i.e. the subduction slab moved during the co-seismic period and continues to move afterwards.