New insights into the nature and effects of the water vapour field on InSAR measurements over Etna

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Overview

• Atmospheric modelling technique

• New insights:
  • Scaling factor for radar delay conversion
  • Effect of liquid and solid water on radar delay
  • Vertical and horizontal heterogeneity of PWV
  • Spectral analysis of PWV field

• Interferogram correction – Etna 04-05 eruption
Atmospheric noise in InSAR

- Noise caused by water vapour variability from one date to another are a well-known problem for InSAR particularly in areas of high relief.

- Interferogram of Etna from 5-6th Sept 1995 shows atmospheric fringes surrounding summit

- Etna is a good location for studying this problem due to high relief and coastal climate
Apparent ground deformation

Slave PWV gradient steeper than master: apparent uplift

Slave gradient shallower than master: apparent subsidence
Advantages of modelling approach

• Requires no field presence, data archive or specific weather conditions

• Potentially applicable anywhere in the world

• Captures the dynamic, local features of atmospheric flow over and around mountains

Above: Cloud covered MERIS image; Below: GPS installation on Mt St Helens (USGS/Mike Poland)
Unified Model set-up

- Nested domain scheme, outer domains provide initial state and boundary conditions for the higher resolution domains nested within.
- Model physics includes land surface, planetary boundary layer, radiation, cloud microphysics.

<table>
<thead>
<tr>
<th></th>
<th>Global</th>
<th>60 km</th>
<th>12 km</th>
<th>4 km</th>
<th>1 km</th>
<th>300 m</th>
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<tbody>
<tr>
<td>Grid length</td>
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<tr>
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<td>5 min</td>
<td>1.33 min</td>
<td>30 sec</td>
<td>10 sec</td>
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<td>Boundary update</td>
<td>1 hour</td>
<td>1 hour</td>
<td>15 min</td>
<td>15 min</td>
<td></td>
<td></td>
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</tbody>
</table>
Unified Model set-up

- Initialisation data, European Centre for Medium-Range Weather Forecasts (ECMWF) global atmospheric analysis

- Initialisation time, 06 UTC and 18 UTC for radar descending pass (09:11 UTC) and ascending pass (20:46 UTC) respectively

- 300 m orography from SRTM DEM

- 300 m domain land-use and vegetation, derived from the IGBP 1 km dataset

- Run time - 6 hour model integration finishes within 1 hour on HPCx if using > 32 processors
Unified Model Outputs

- Model outputs include 3D fields of:
  - Temperature
  - Pressure
  - Water vapour
  - Liquid cloudwater
  - Solid cloudwater
  - Wind speed and direction

*Top: Cross section of wind (m/s, stream lines) and mixing ratio (g/kg, shaded) at 0900 UTC 24 November 2004.*
*Bottom: horizontal slice at 1500m asl, showing line of cross-section A-B.*
Model Validation

- Validation against MERIS data for several test cases showed rms misfit between the two was ≤1.6mm, approximately the accuracy level of the MERIS data.

Data for 24/11/04 (above) and 25/06/06, showing MERIS (a,e), model (b,f), difference (c,g) and plot of modelled vs observed PW (d,h). (Zhu et al 07)
Atmospheric refractivity

- InSAR atmospheric errors are caused by factors which affect the refractivity of the atmosphere.

- Main contributions to refractivity (Hanssen 01):

\[ N = \left( k_1 \frac{P}{T} \right) + \left( -4.028 \times 10^7 \frac{n_e}{f^2} \right) + \left( k'_2 \frac{e}{T} + k_3 \frac{e}{T} \right) + 1.45W \]

Hydrostatic  Ionospheric  Water vapour  Liquid water

\( k_1 = 77.6 \text{ K kPa}^{-1} \),
\( P = \text{total atmospheric pressure in hPa} \)
\( T = \text{absolute temperature in K} \)
\( K'_2 = 23.3 \text{ K hPa}^{-1} \),
\( e = \text{partial pressure of water vapour in hPa} \),
\( n_e = \text{electron density per cubic metre} \),
\( f = \text{radar frequency (XXX Ghz)} \),
\( W = \text{liquid water content in gm}^3 \).
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Hydrostatic
- Dry correction

Ionospheric
- Long wavelength

Water vapour
- Q factor

Liquid water
- Neglected?

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Conversion to Radio Wave Delay

- Calculate integrated water vapour (IWV) along radar lines of sight
- Calculate a scaling factor (Q), a function of the mean atmospheric temperature ($T_m$) along the line of sight, which can be obtained from the model.
- Use these to calculate the radar delay ($\delta$) for each pixel:

$$\delta = Q \times IWV$$

$$Q = 10^{-8} \rho R_v \left[\left(k_3 / T_m\right) + k_2'\right]$$

$\rho$ = density of liquid water
$R_v$ = Specific gas constant of water vapour (461.524 J kg$^{-1}$K$^{-1}$)
$k_3 = 3.7 \times 10^5$ K$^2$ mbar$^{-1}$
$k_2' = 22$ K mbar$^{-1}$

$$T_m = \frac{\int \rho_v \, dz}{\int \left(\rho_v / T\right) \, dz}$$

$\rho_v$ = water vapour density
$T$ = temperature
$V$ = vertical co-ordinate
Seasonal variation in Q

- Typical seasonal variability of Q at Etna, calculated from UM model
- Using a constant value of $Q=6.3$ can introduce up to 10-15% error in delay, relative to the explicitly calculated Q value.
Atmospheric refractivity

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Dry correction
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Liquid and solid water

- 2nd of February 2005, 0900 UTC, UM 1km domain
- 25mm variation in PWV
Liquid and solid water

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- ~3mm variation in PLW (precipitable liquid water), <0.2 fringes
Liquid and solid water

- 2nd of February 2005, 0900 UTC, UM 1km domain
- 25mm variation in PWV
- ~3mm variation in PLW (precipitable liquid water), <0.2 fringes
- >3mm variation in PSW (precipitable solid water)
- This case lacked large cumulous, where effect is expected to be greater
Vertical and horizontal heterogeneity

- Advantage of model is explicit representation of turbulent, non-stratified component of flow around topography
- However the most obvious effect in PWV signal comes from the interaction of the vertical PWV gradient with the topography.

MODIS data 1020 UTC 27 July 2005.

Left: Cross section of wind (m/s, stream lines) and mixing ratio (g/kg, shaded) at 0900 UTC 24 November 2004.
Right: horizontal slice at 1500m asl, showing line of cross-section A-B.
Vertical and horizontal heterogeneity

- Since the vertical PWV gradient is approximately exponential, these contributions can be separated by subtracting a regression curve.
- The horizontal perturbation field is represented by the departure of the full field from the curve.

MODIS data 1020 UTC 27 July 2005.
Comparison with MODIS

- Comparison of separated components shows good agreement of UM model with MODIS data.

**Comparison of separated components shows good agreement of UM model with MODIS data.**
PVW Power spectra

Power spectra of spatial variability of the PWV field, showing MODIS (circle) and modelled (open circle).

Full PW field (a), horizontal mean component (b), horizontal perturbation component (c) and surface elevation (d). The grey lines have slopes of –3 and –5/3.
Interferogram correction

- 3d fields of water vapour cause a temporal difference in radar LOS delay field
- Difference field can be removed from the interferogram

SAR Data

- ASAR1
- ASAR2

Interferogram

Unified Model

- LOS PW1
- LOS PW2
- Q factor

PWV difference

Delay difference map

Corrected interferogram
Corrected interferograms

Interferogram  Model  Corrected Interferogram

Unwrapped interferogram (left), model (middle) and corrected interferogram (right), for 17th Nov 04 – 24th Aug 05, in mm of ascending-pass line-of-sight apparent deformation. Deformation normalised assuming zero motion at a point away from the volcano (white circle).
2004-2005 Corrected Interferograms

<table>
<thead>
<tr>
<th>Period</th>
<th>Days</th>
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<tbody>
<tr>
<td>Dec – Mar</td>
<td>70</td>
</tr>
<tr>
<td>Jan – Apr</td>
<td>70</td>
</tr>
<tr>
<td>Nov – Mar</td>
<td>105</td>
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<td>Apr – Jul</td>
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<td>Jan – Jul</td>
<td>175</td>
</tr>
<tr>
<td>Mar – Aug</td>
<td>175</td>
</tr>
<tr>
<td>Nov – Aug</td>
<td>280</td>
</tr>
</tbody>
</table>

Unwrapped interferogram (top), model (middle) and corrected interferogram (bottom), for seven ascending track interferograms.
Etna 2004-2006

“silent” SE Crater eruption
\[ V = 18 - 32 \text{ Mm}^3 \]

Corrected interferograms

SE Crater eruptions
Etna 2004-2006

![Graph showing data from 2004 to 2006 for Etna. The graph indicates a peak in activity around 2005.](image-url)
Etna 2004-2006
Etna 2004-2006
Etna 2004-2006
Etna 2004-2006
Etna 2004-2006
Conclusions

- Atmospheric modelling has ability to represent dynamic PWV fields, and allows interferogram correction
- Reduction in delay error from explicit Q calculation
- Some indication that we need to consider taking delays from liquid and solid water into account
- Spatial structure shows importance of turbulent flow and coastal effects