GPS Atmospheric Water vapor and Tomography: A review

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And contributions from
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… and many other teams…

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The Atmospheric Water Vapor

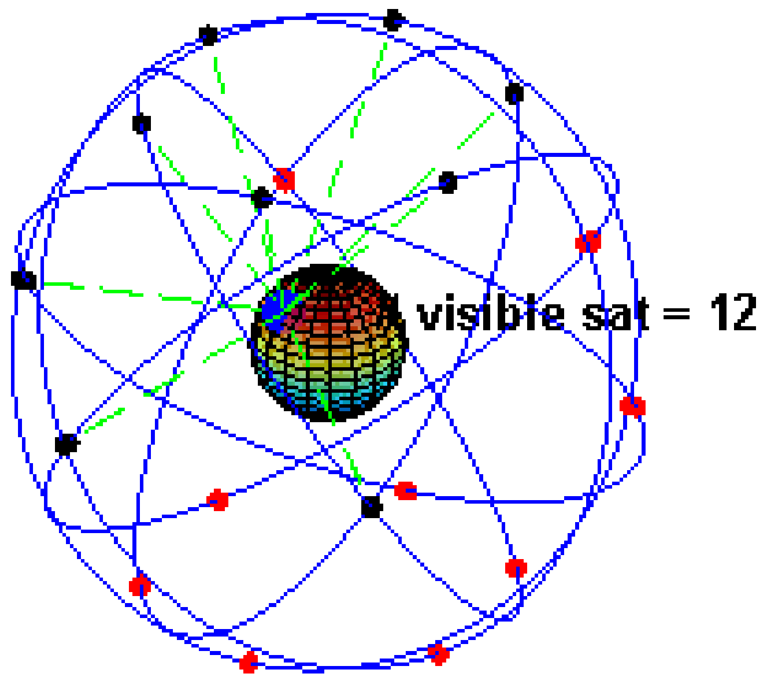
- Water vapor plays a major role in many atmospheric processes concerning physics, thermodynamics and dynamics
- Particularly important for
  - Energy budget and radiative transfer
  - Clouds formation and composition
  - Convective initiation and feeding
  - Precipitation processes
  - Atmospheric chemistry
- Extremely variable both in time and space
- … It is still a physical parameter difficult to measure and characterize

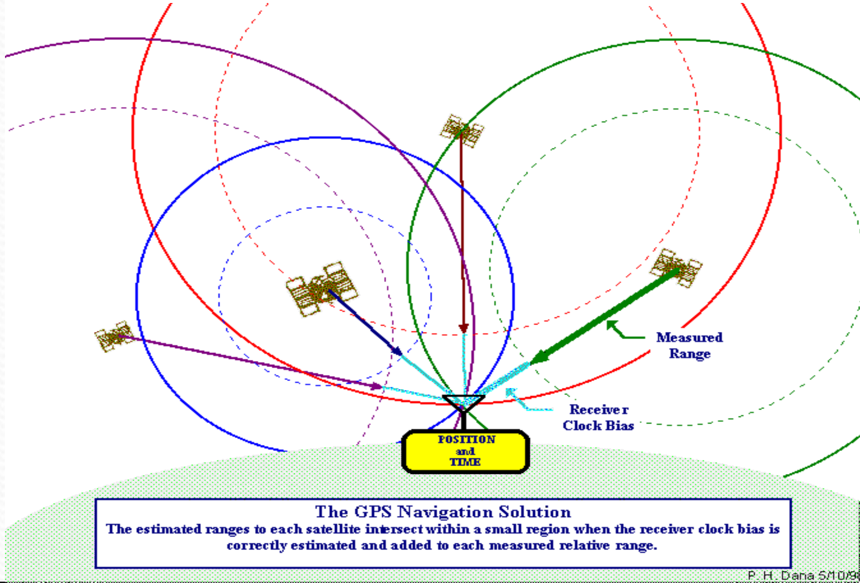
Water Vapor Measurement Methods

- Radiosondes (RS): Time resolution, operation costs
- Microwave Radiometer (MWR): cost, rain, calibration, weighting functions
- Spectrometer : daytime/sun, mapping functions, weighting functions
- Lidars : night time, clear air, cost, operation cost
- ➔ **Interest of GPS**:
  - All weather
  - Continuous unattended operation
  - Good time resolution
  - Ever increasing number of stations

The GPS system

- Space configuration:
  - 24 active 24 satellites
  - Circular orbits at 20200 km
  - 6 orbital planes inclined at 55° with 4 satellites on each
- Any ground station can see between 6 and 12 GPS satellites at any time (average 8) in the absence of masks
- 4 satellites minimum needed to resolve *(x, y, z, t)*



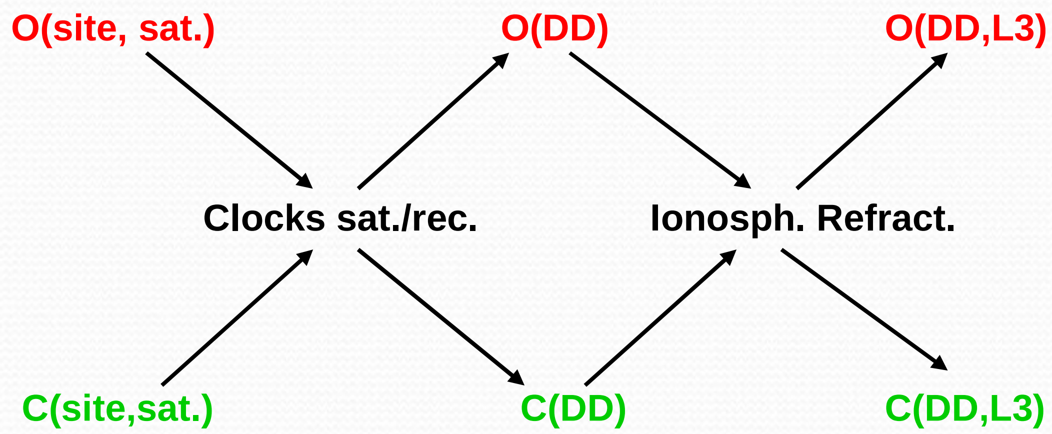


GPS Network resolution

Local Data
IGS Data
(ref. stations)
→ Phase obs.
(L1 et L2)

IGS Orbits
IGS EOPs
→ IGS Products

A priori Coordinates
Phase center var.
Satellite yaw
Solar/lunar tides
Ocean/atm. loading
Mapping functions
→ Models



Observed (DD,L3) – Calculated (DD,L3)

➔ Least square adjustment for
all network parameters

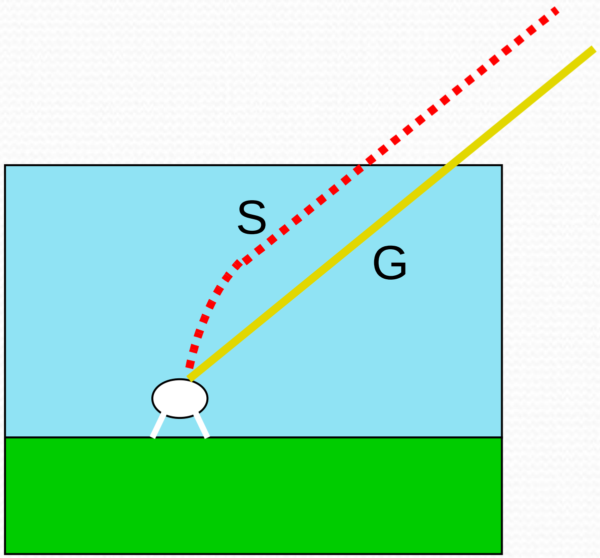
➔ **Station Positionning**

**Tropospheric Parameters
(ZTD and Gradients)**

Atmospheric impact

Tropospheric effect : Path elongation

$$\Delta L = \int_S (n-1).dS + [S-G] \cong \int_S (n-1).dS$$



n : atmospheric refractive index function
of the vertical structure of the atmosphere

$$10^6 (n-1) \cong k_1.\frac{P_d}{T} + k_2.\frac{e}{T} + k_3.\frac{e}{T^2}$$

Total delay (ZTD) $\quad \Delta L = \Delta L_h + \Delta L_w$

Hydrostatic Delay (ZHD)

Wet Delay (ZWD)

IWV calculation

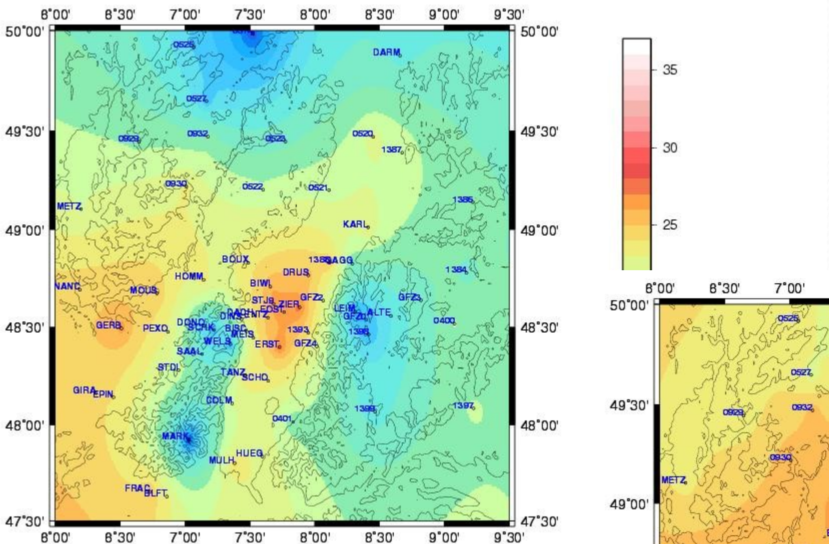
$$ZTD = ZHD + ZWD$$

$$IWV = \frac{10^5}{461.51 \times \left(k_2' + \frac{k_3}{T_m} \right)} \times \left[ZTD - \frac{2.9349\;10^{-5} \times k_1 \times P_S}{\left(1 - 0.00266 \times \cos(2\Psi) - 0.00028 \times H\right)} \right]$$

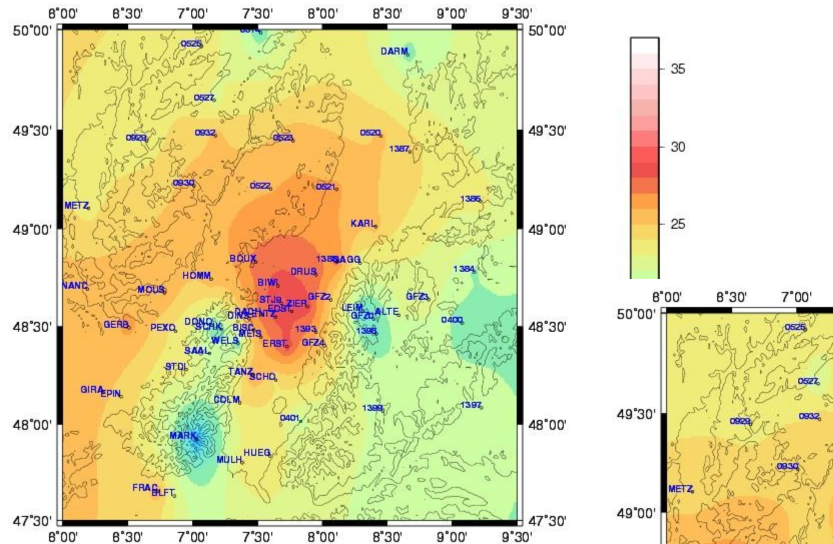
=> **IWV = function**

- **GPS observable**
  - **ZTD**
- **GPS station coordinates**
  - ∀ **Ψ, *H* : latitude & altitude**
- **Ground atmospheric parameters**
  - $\boldsymbol{P_s}$ and $\boldsymbol{T_s}$ **(**to estimate $\boldsymbol{T_m}$**)**

IWV Maps



6°00' 6°30' 7°00' 7°30' 8°00' 8°30' 9°00' 9°30'
50°00' 49°30' 49°00' 48°30' 48°00' 47°30'
35 30 25



6°00' 6°30' 7°00' 7°30' 8°00' 8°30' 9°00' 9°30'
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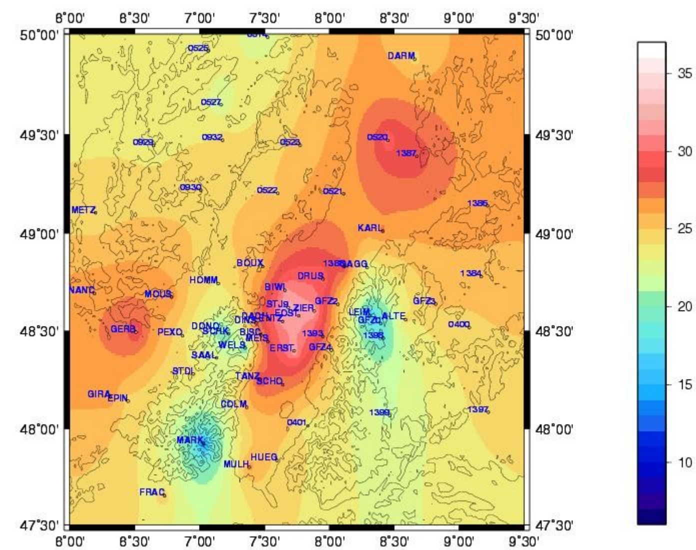
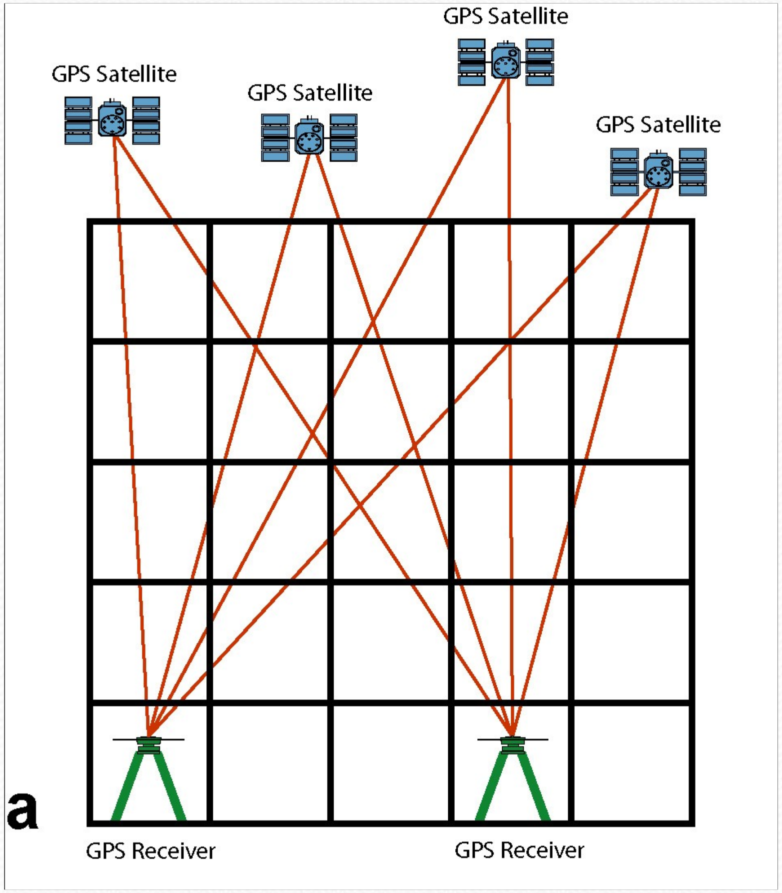
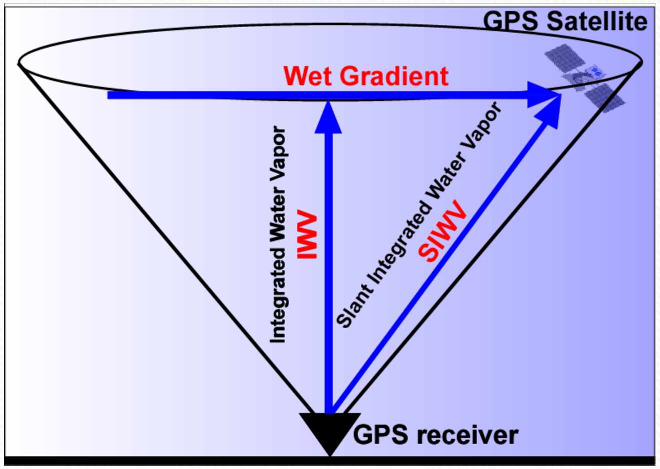


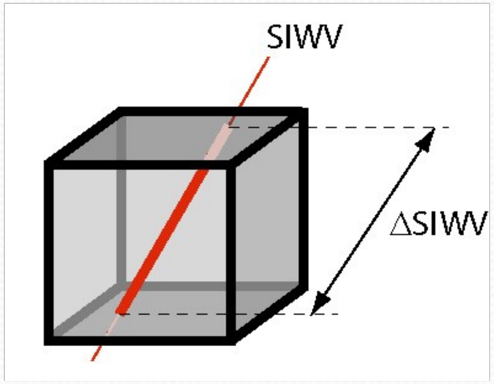
6°00' 6°30' 7°00' 7°30' 8°00' 8°30' 9°00' 9°30'
50°00' 49°30' 49°00' 48°30' 48°00' 47°30'
35 30 25 20 15 10

GPS Water Vapor Tomography

Tomography Principles :







VOXEL

Tomography Equations

$$d = G \times m$$

Data (SIWV)

Model Linear Operator
(SIWV distribution in voxels)

Resulting Estimates
(Unknowns)

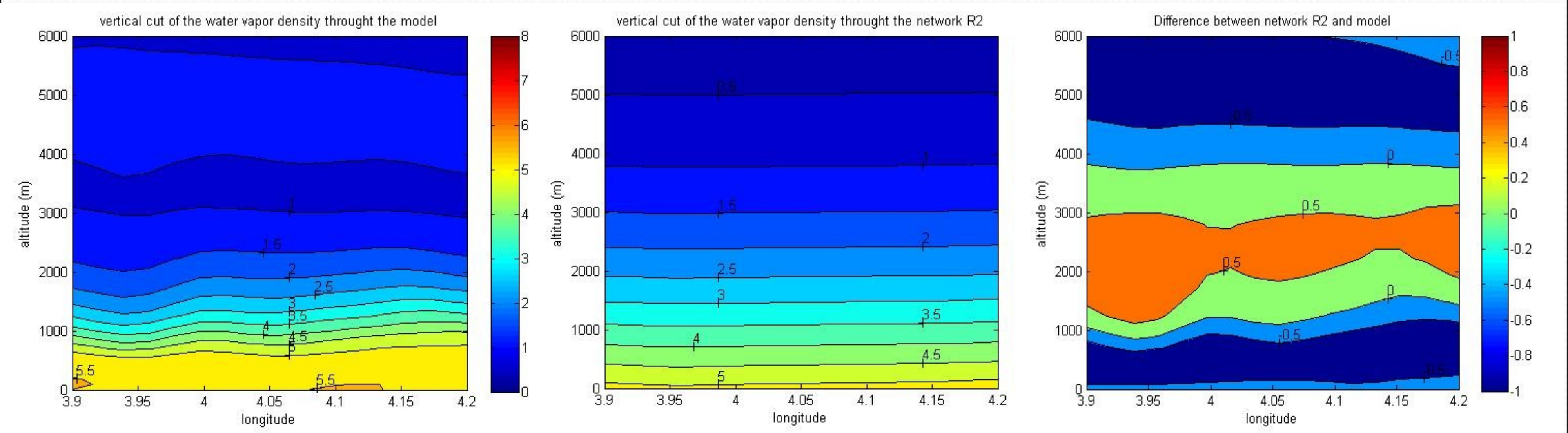
<u>Inversion :</u>

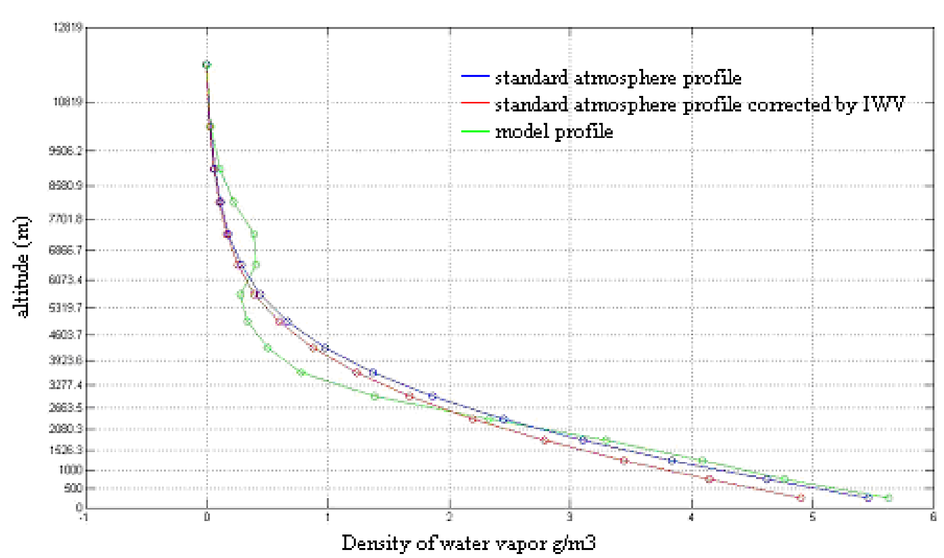
$$m^{est} = m_0 + L \times \left(d - G \times m_0\right)$$

With

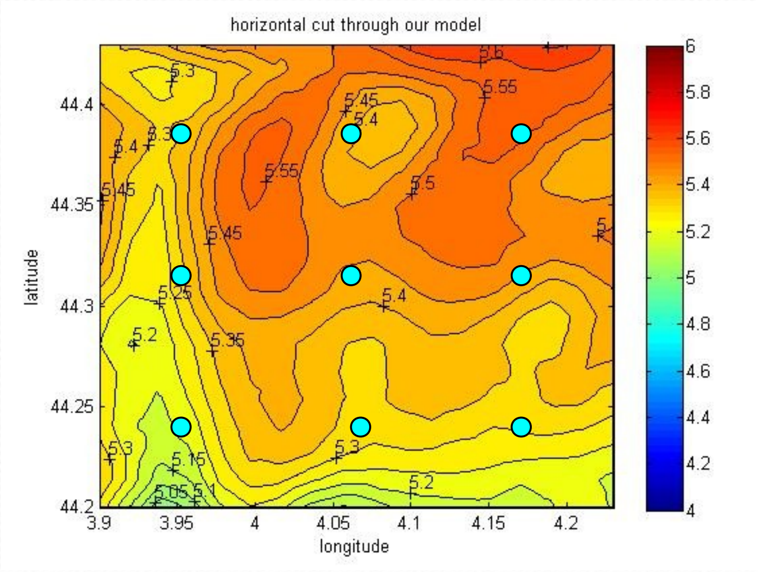
- m_0 = *initialization matrix*
- $$L = \left(G' \times W_e \times G + \alpha^2 \times W_m\right)^{-1} \times G' \times W_e$$
- *W = variances/covariances* inverse *matrices*
- α = weighting factor

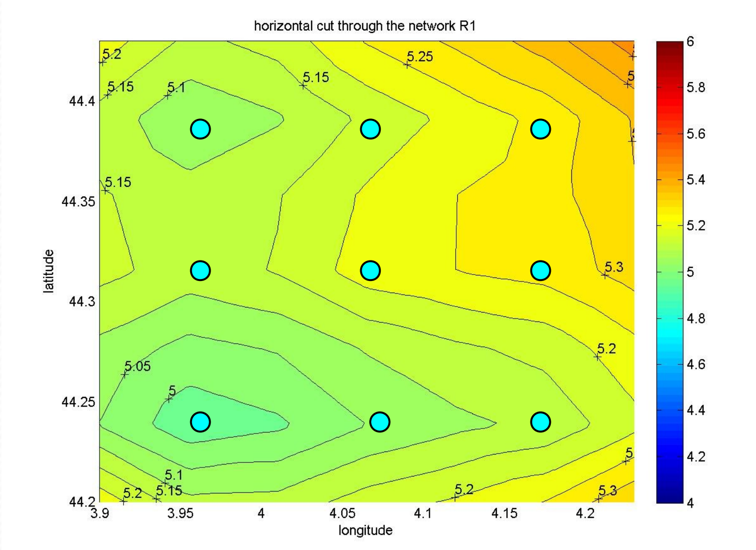
Sensitivity Tests : Initialization

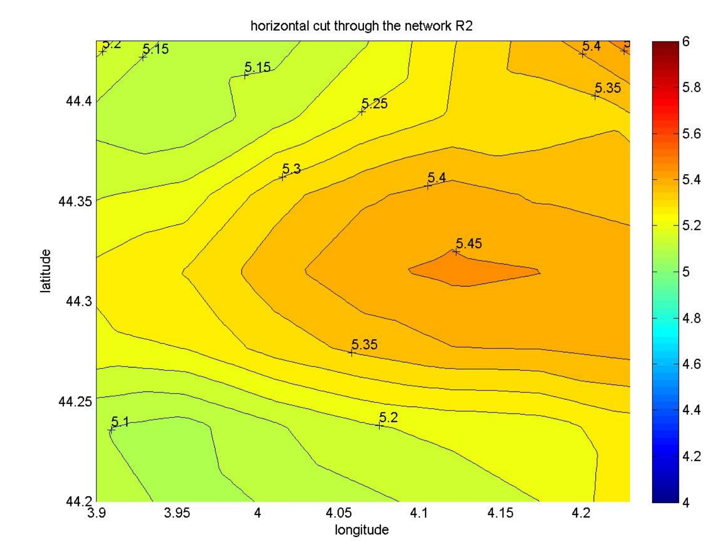


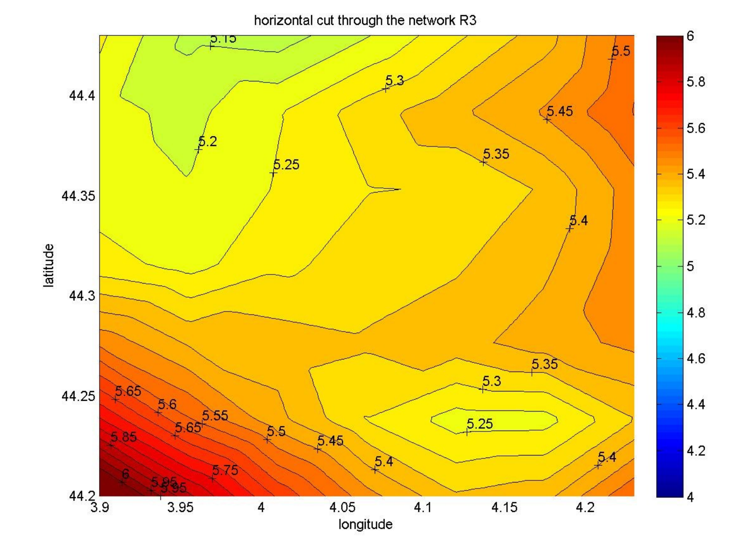


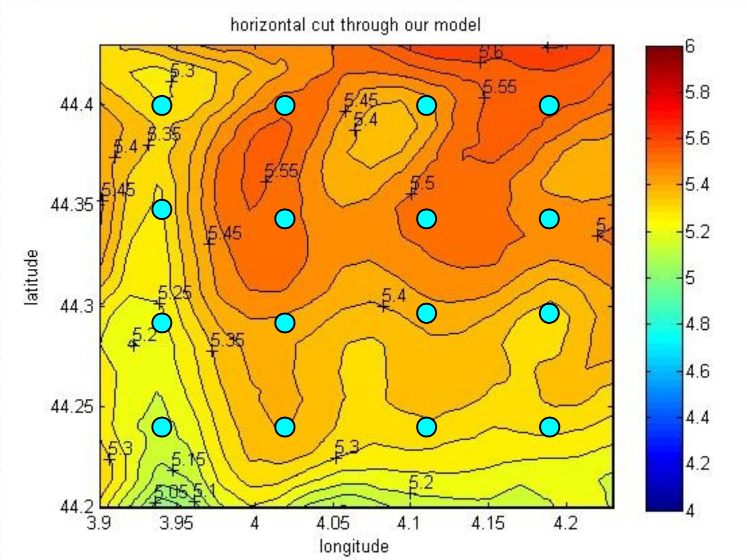
Sensitivity Tests : Network Geometry

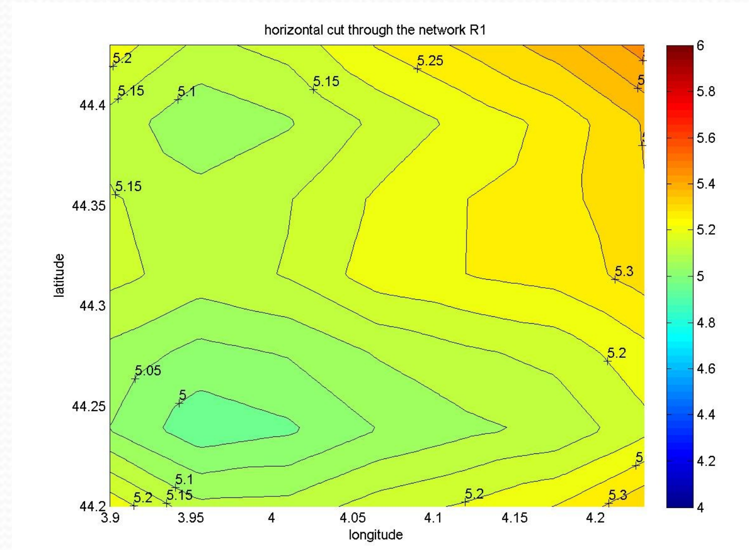


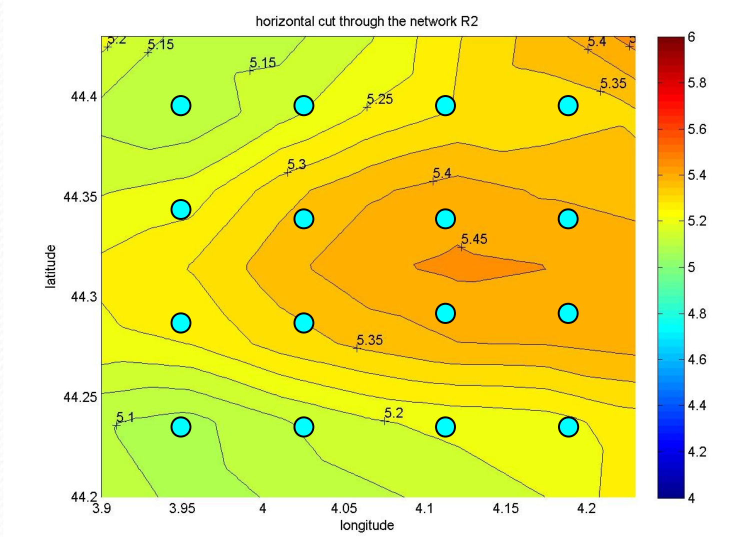


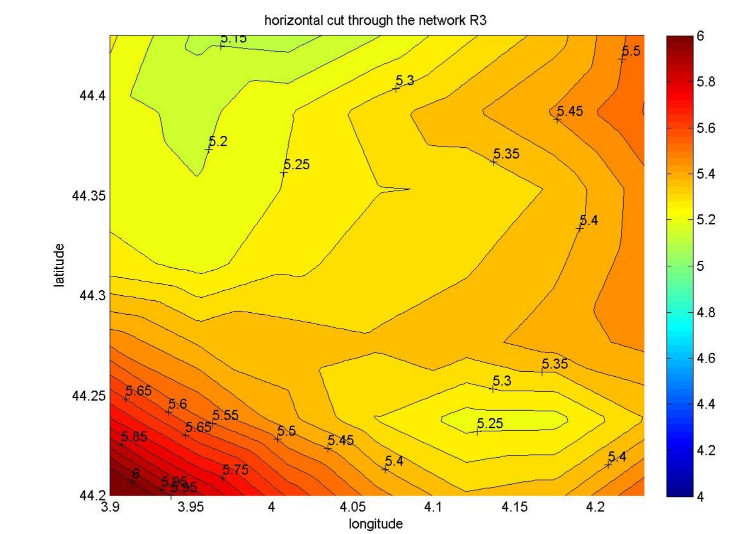


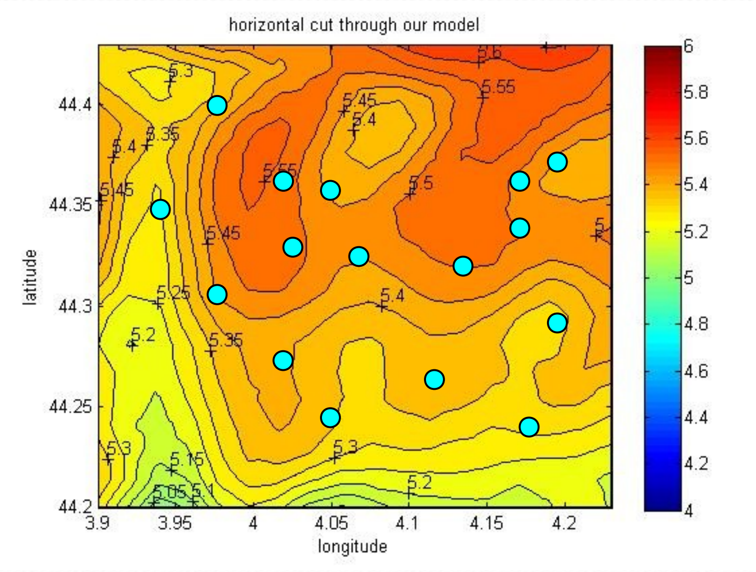


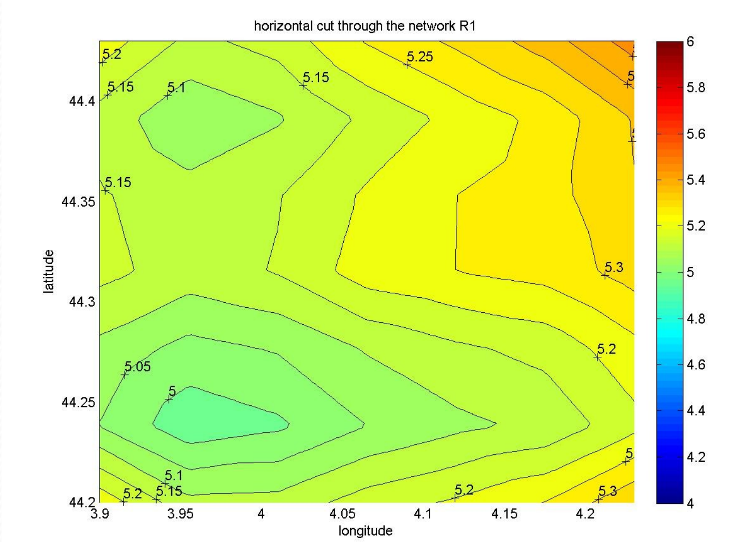

horizontal cut through our model
latitude
longitude

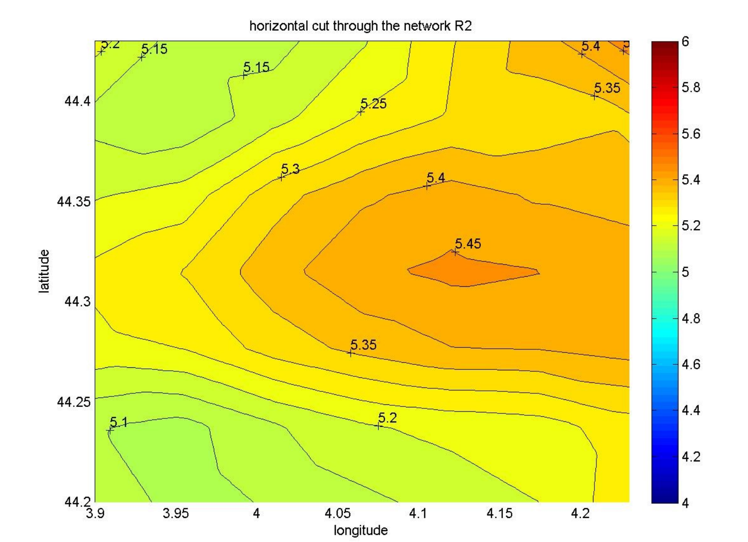

horizontal cut through the network R1
latitude
longitude

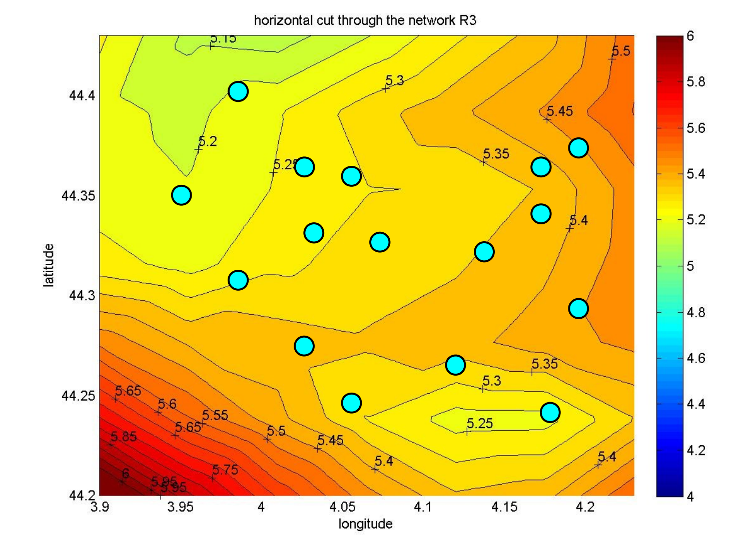

horizontal cut through the network R2
latitude
longitude


horizontal cut through the network R3
latitude
longitude


horizontal cut through our model
latitude
longitude

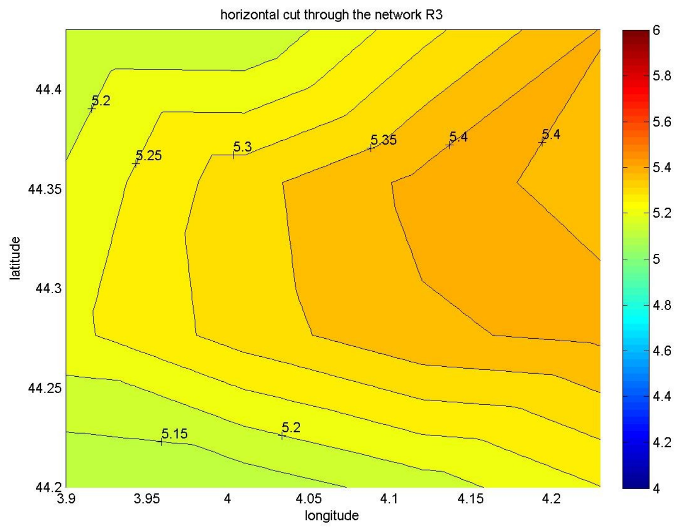

horizontal cut through the network R1
latitude
longitude


horizontal cut through the network R2
latitude
longitude

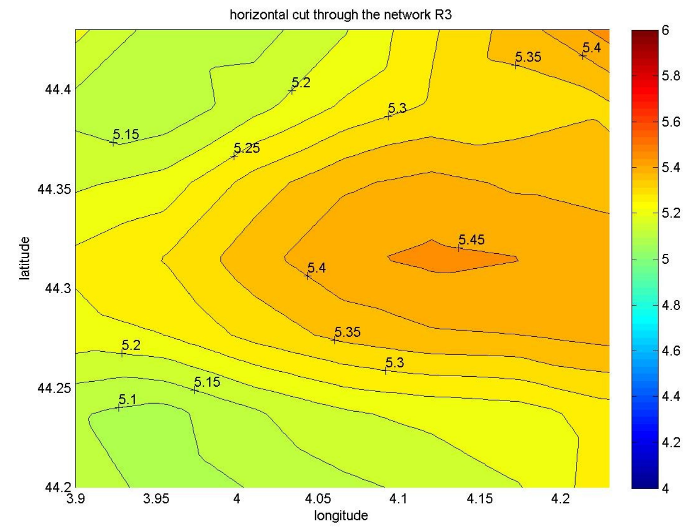

horizontal cut through the network R3
latitude
longitude

Sensitivity Tests : Voxel Size (resolution)

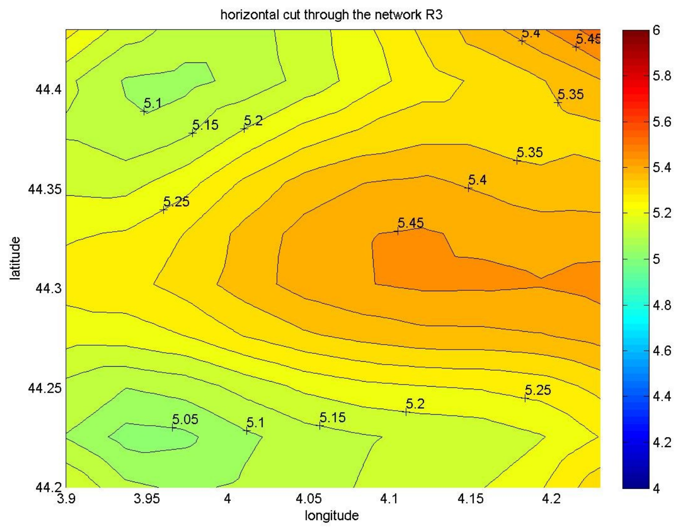
4 x 4



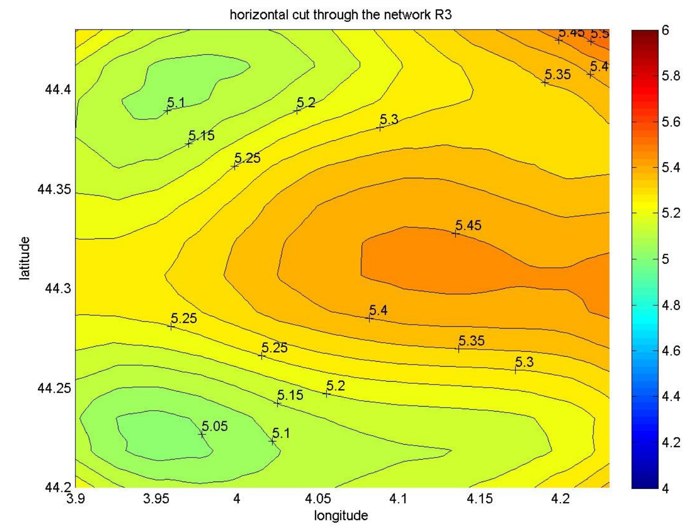
7 x 7



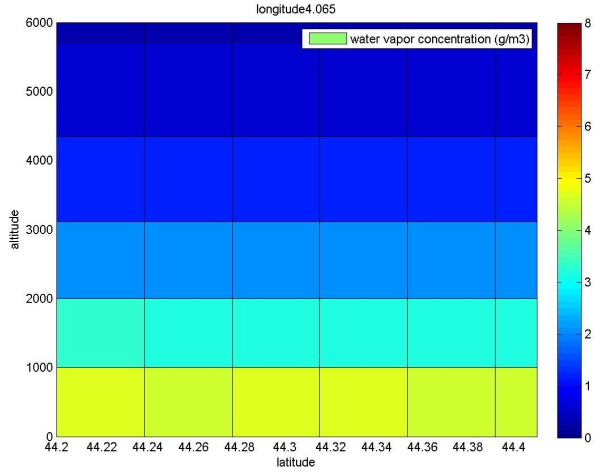
10 x 10



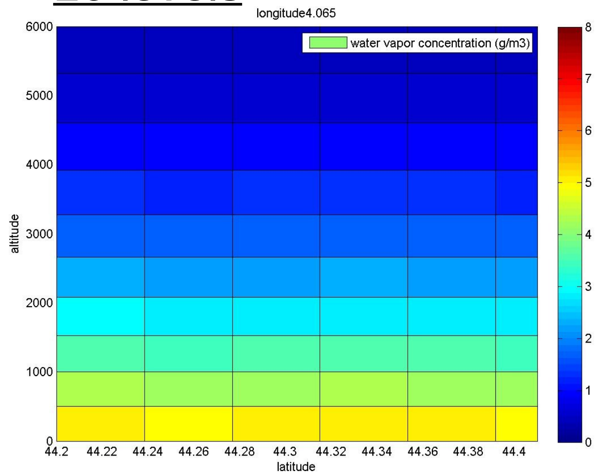
14 x 14



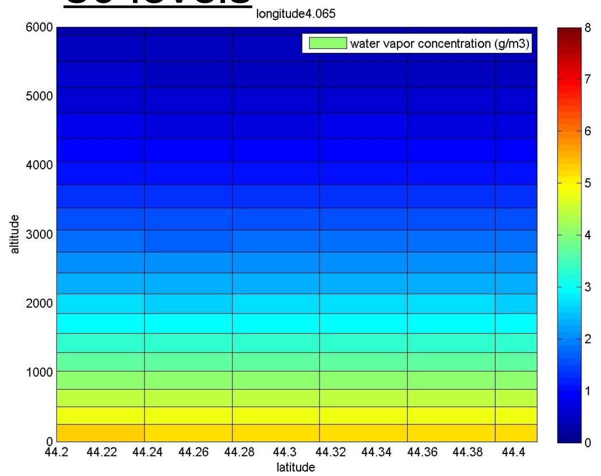
9 levels



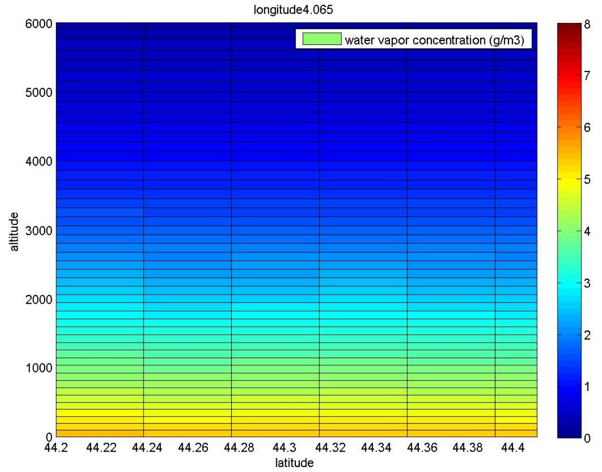
16 levels



30 levels

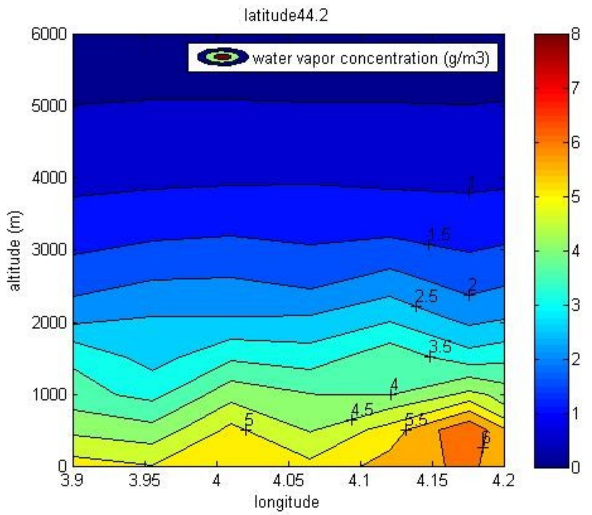


72 levels

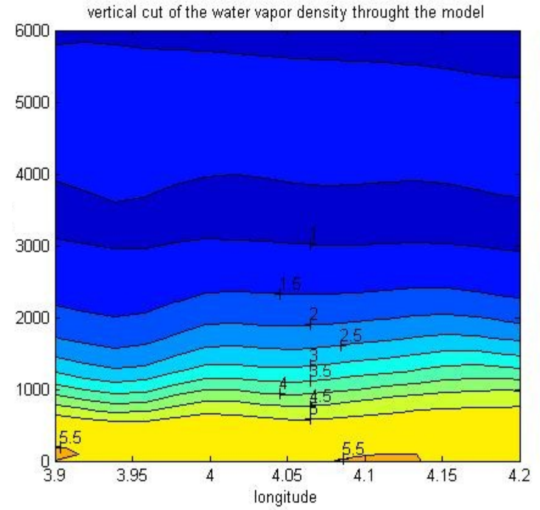


Sensitivity Tests : weighting coefficient (α)

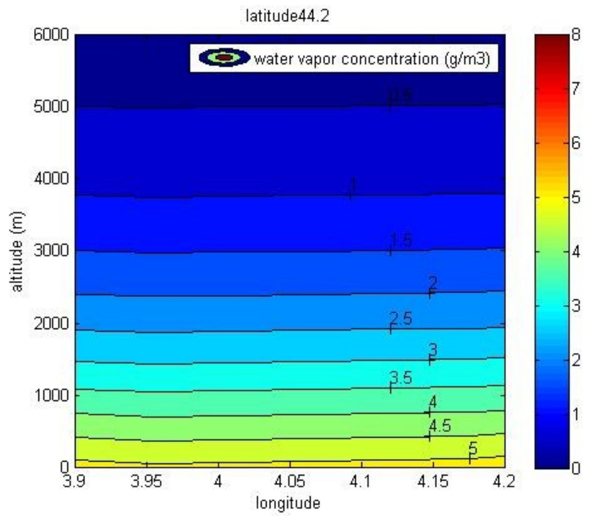
α = 0.03



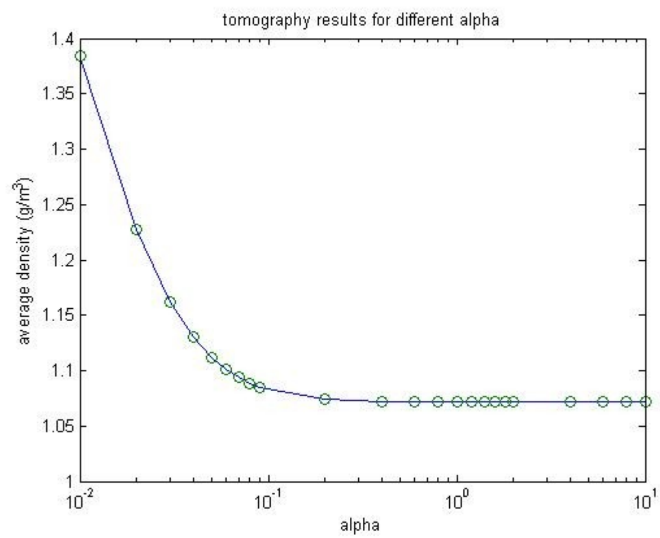
synthetic



α = 2.0



α < 1 : more weight to data

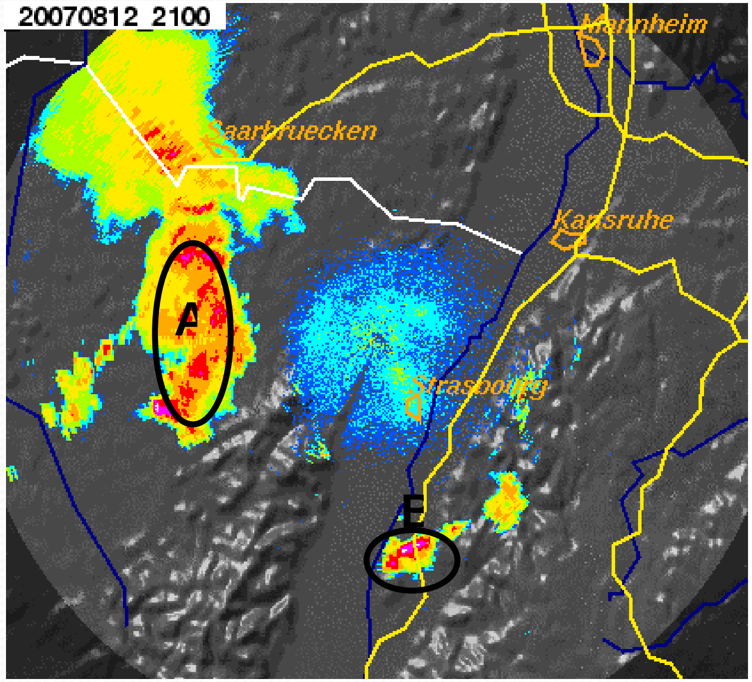


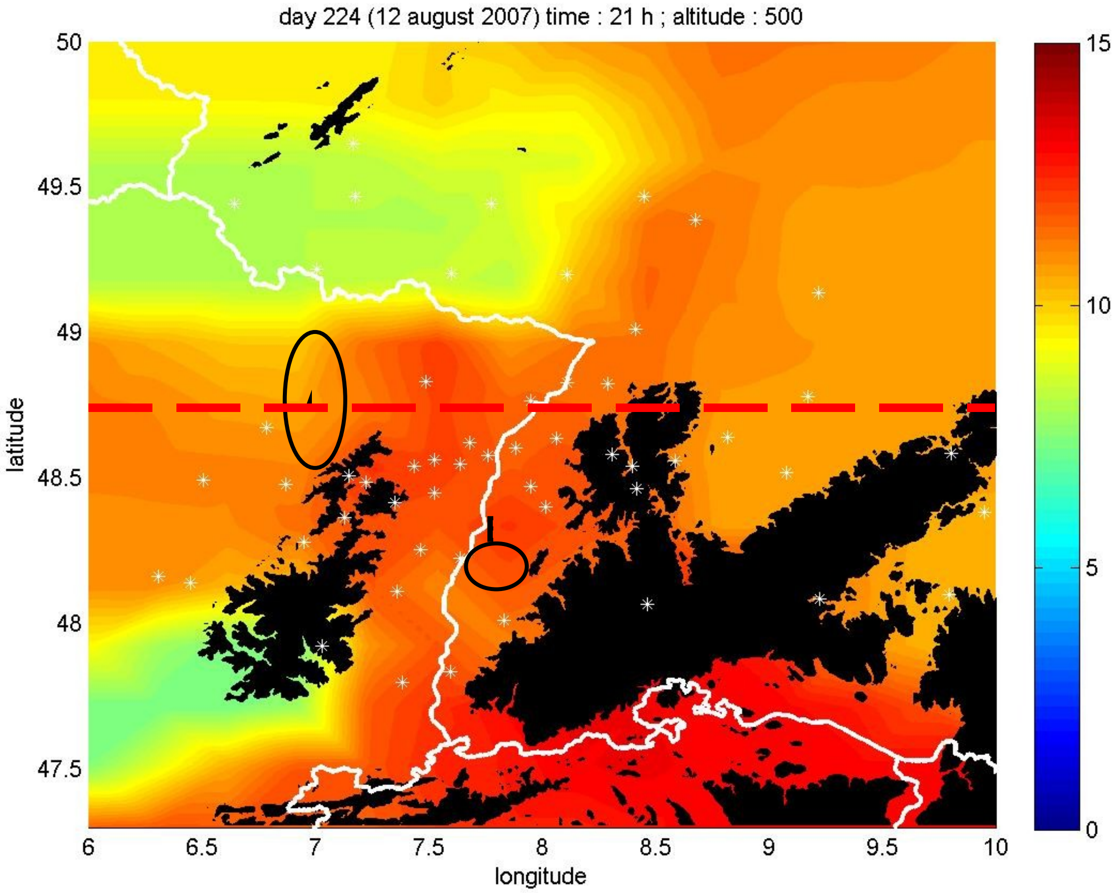
α > 1 : more weight to initial model

GPS Water vapor tomography results

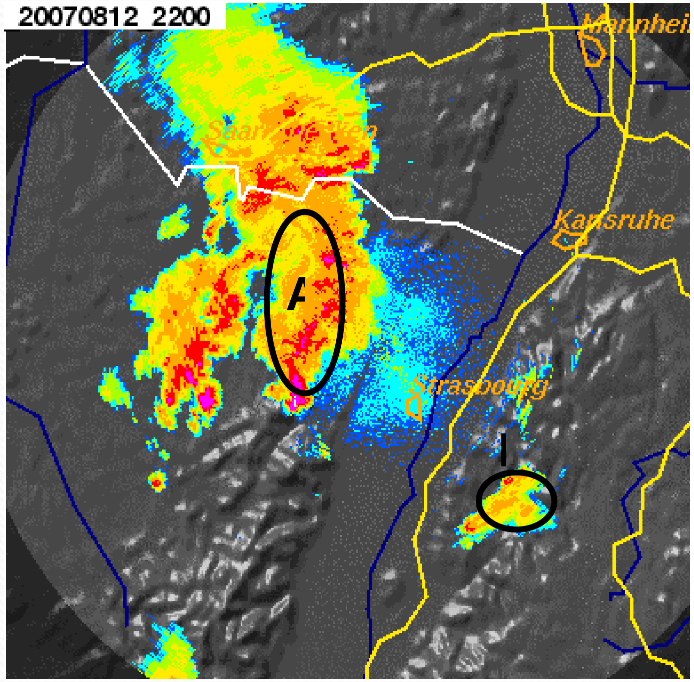
COPS campaign

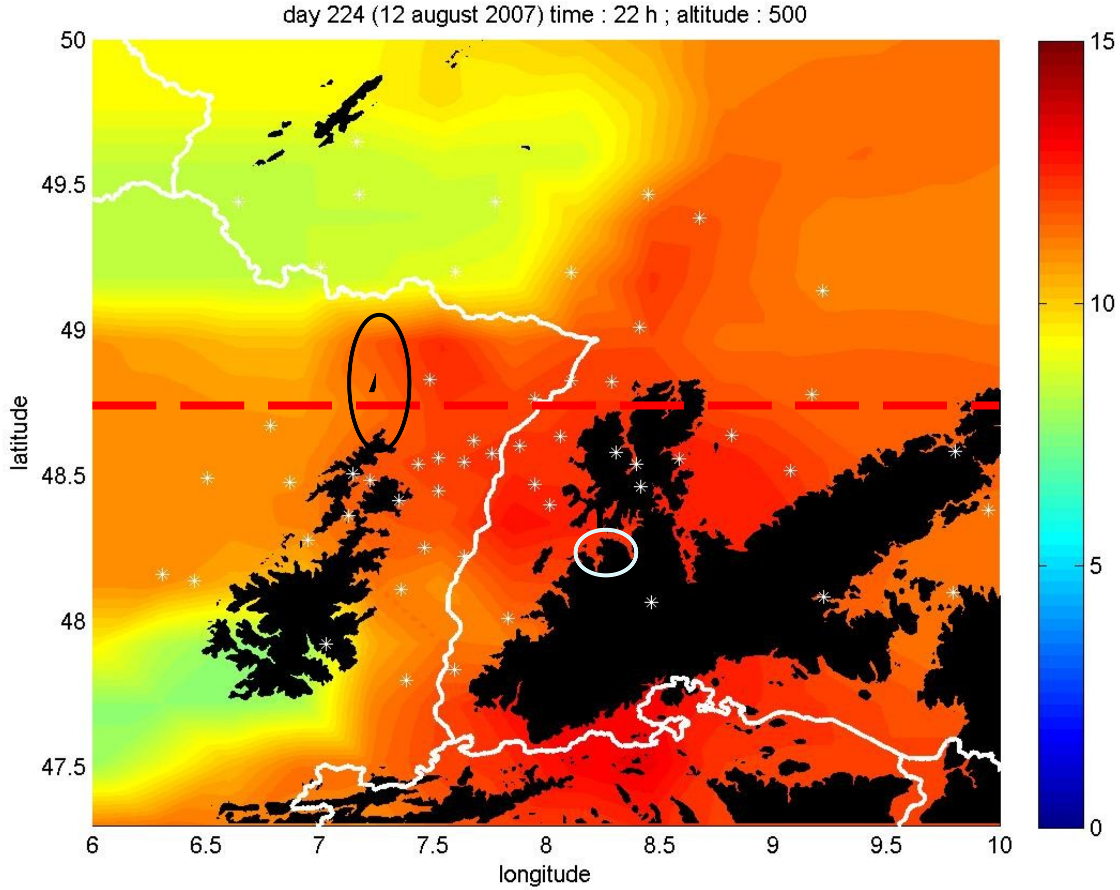
12 AUG. 2007, 21:00 UTC



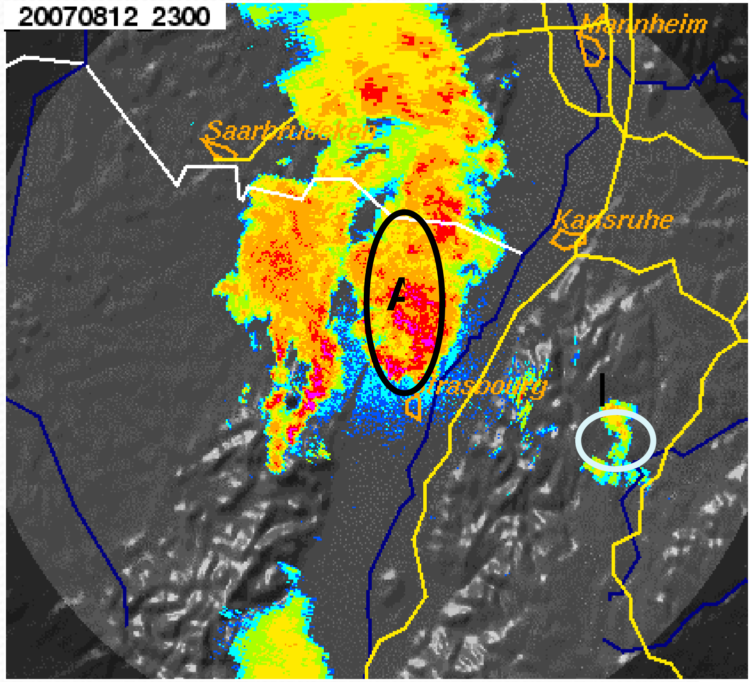


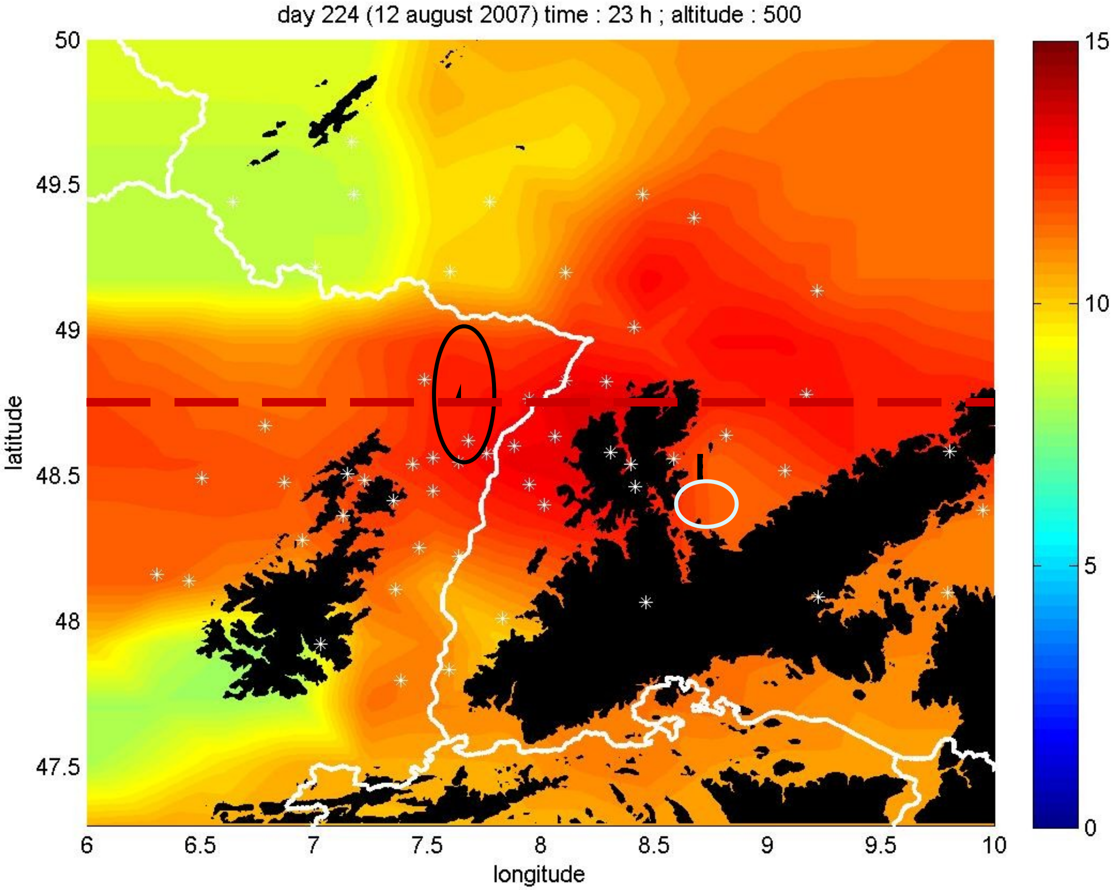
12 AUG. 2007, 22:00 UTC



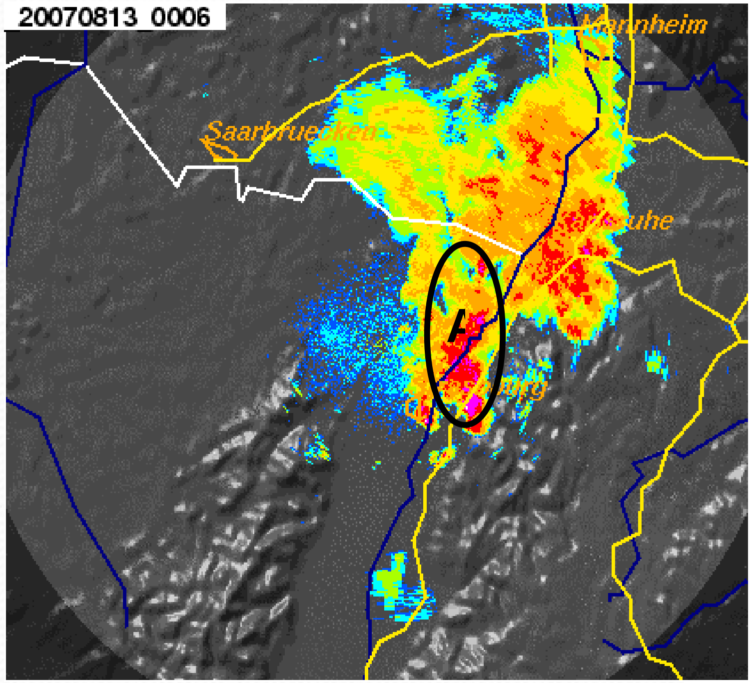


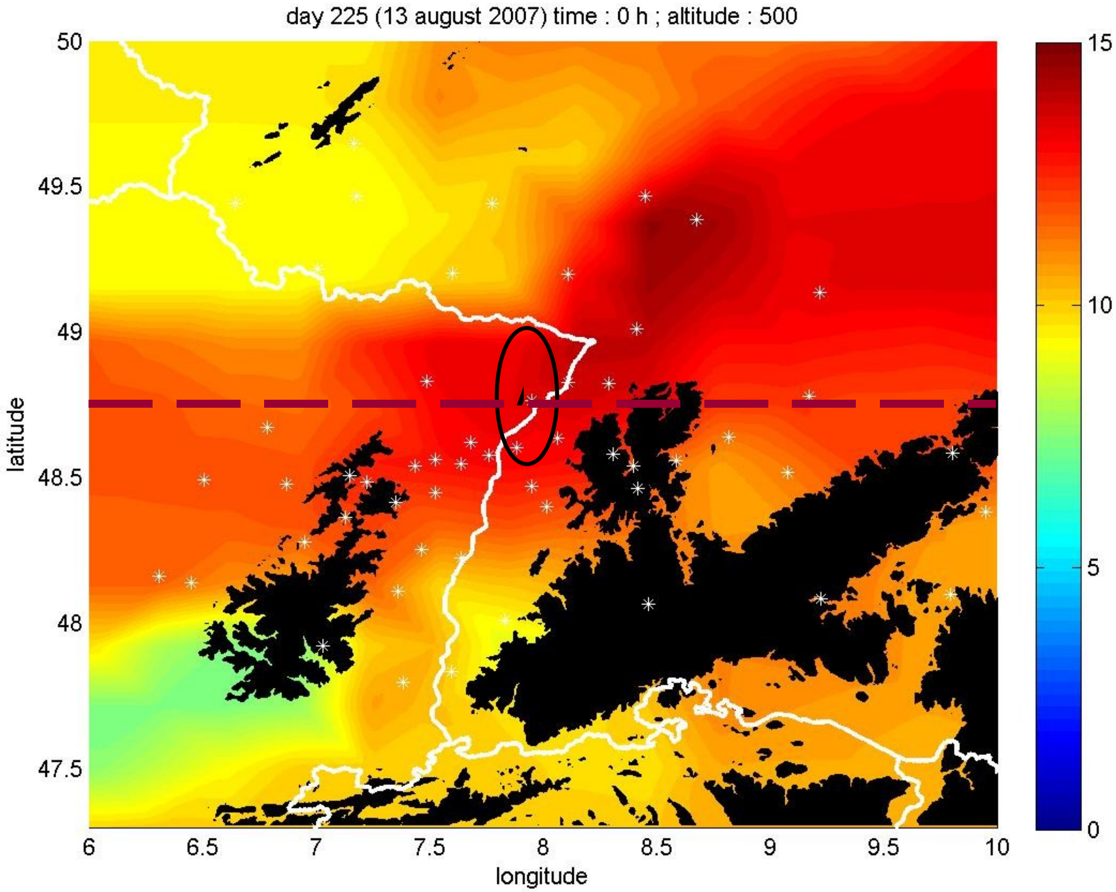
12 AUG. 2007, 23:00 UTC



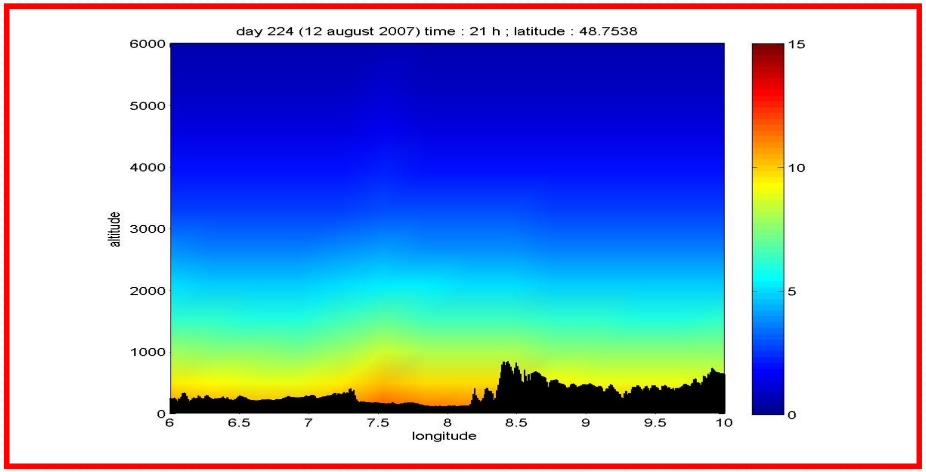


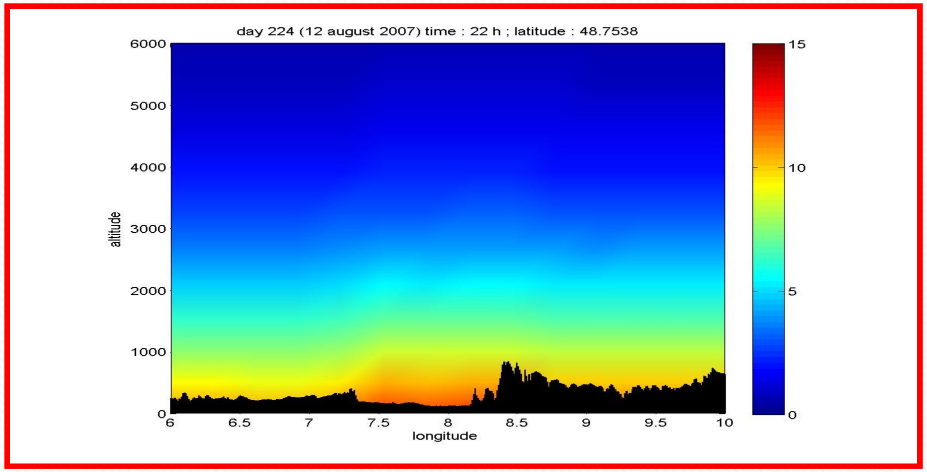
13 AUG. 2007, 00:00 UTC

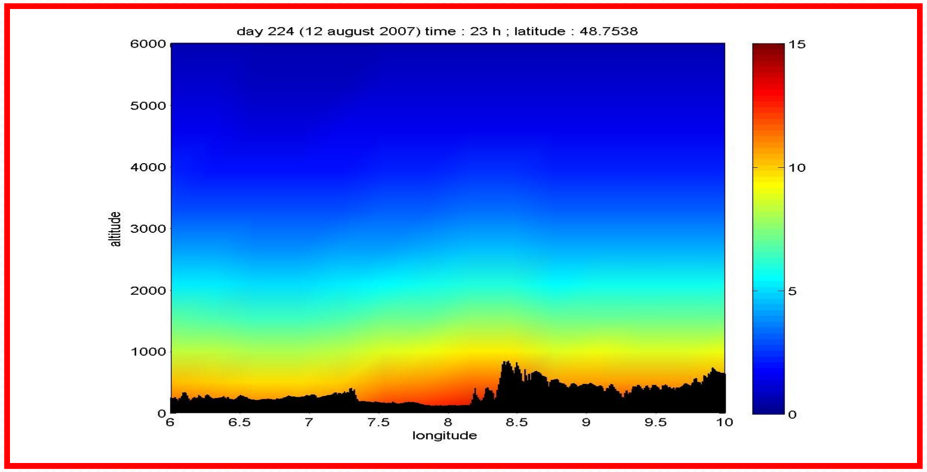


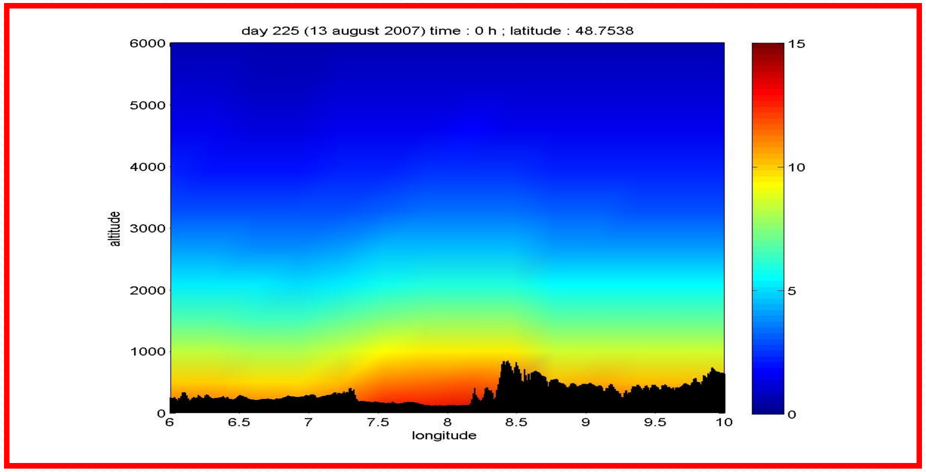


Vertical cut time series









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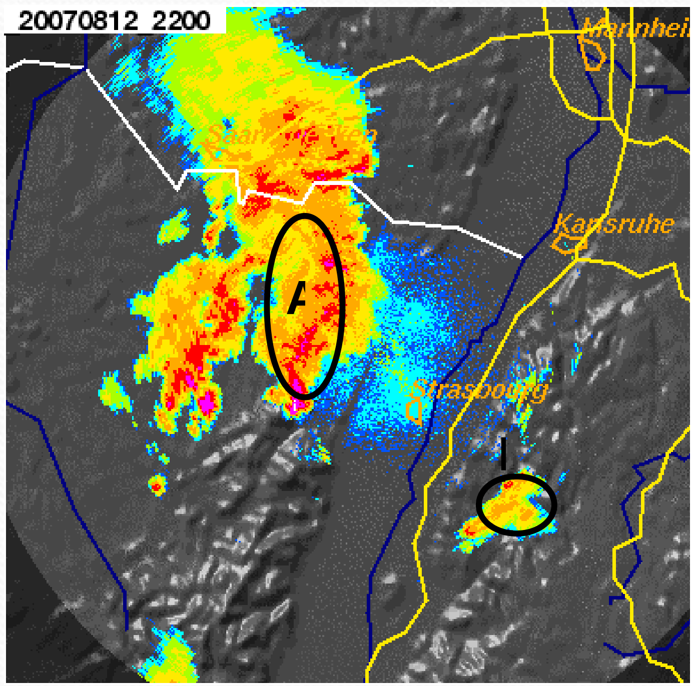
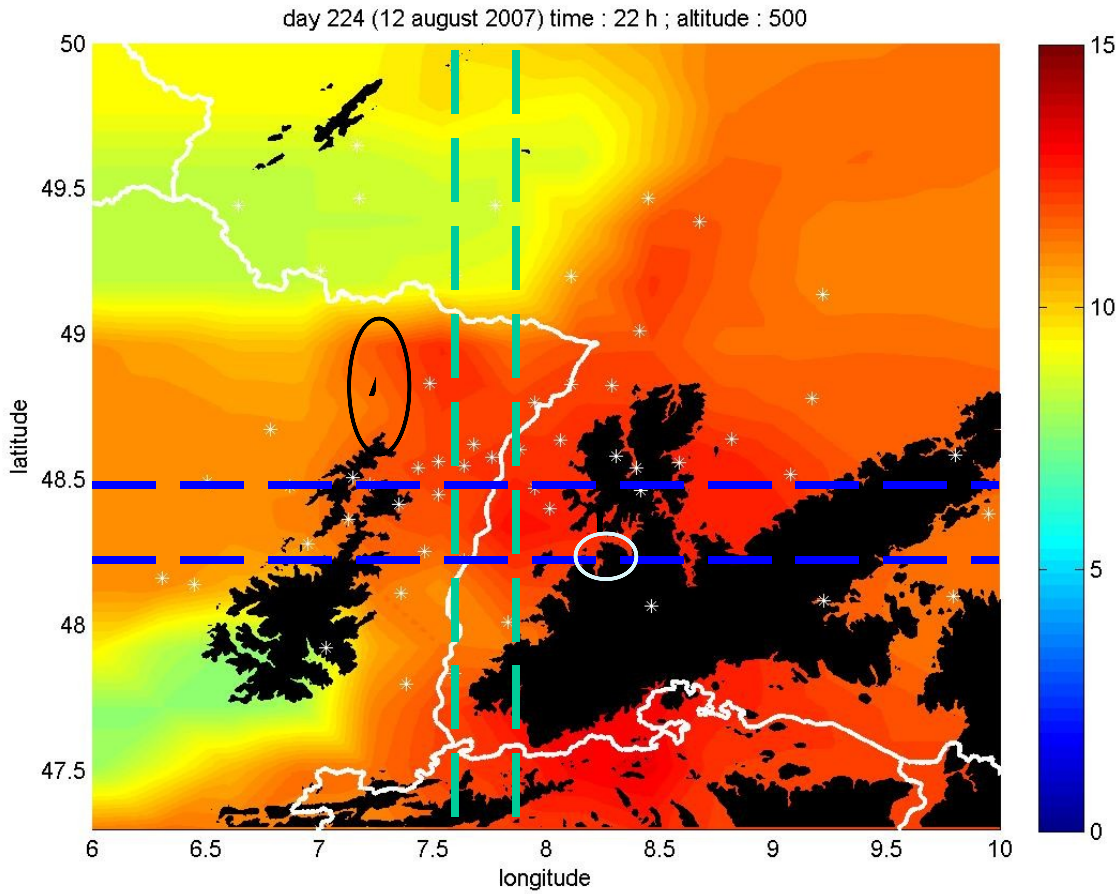
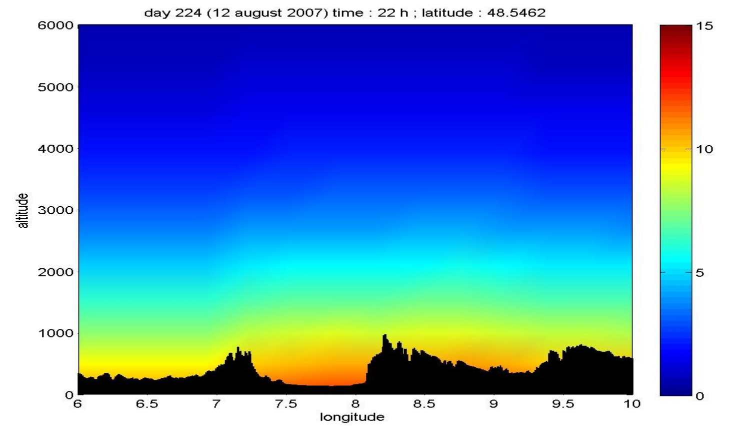
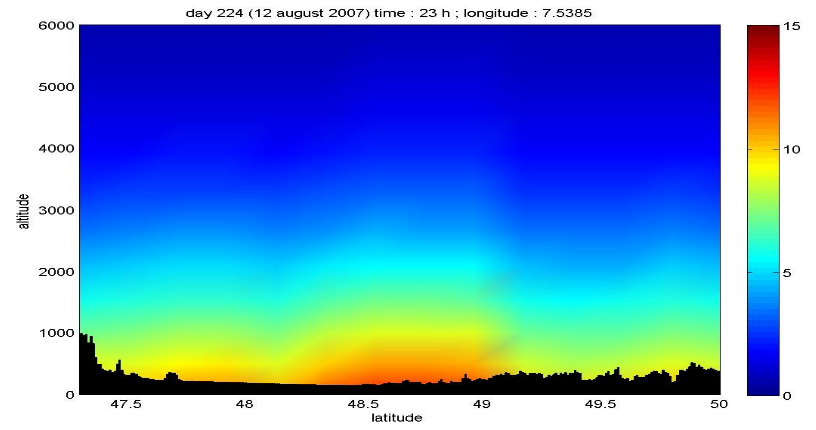
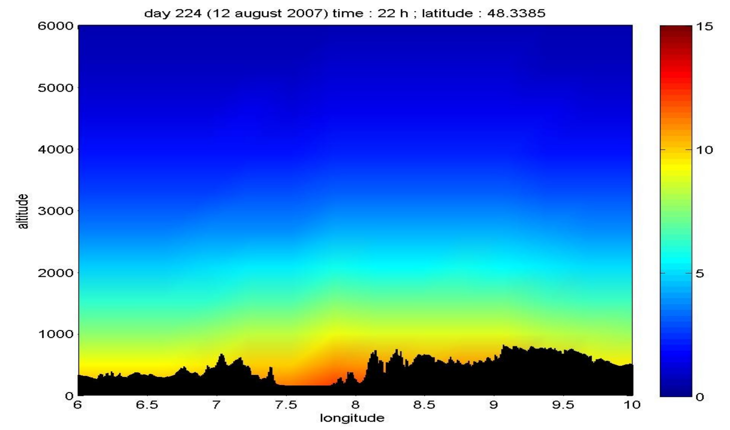


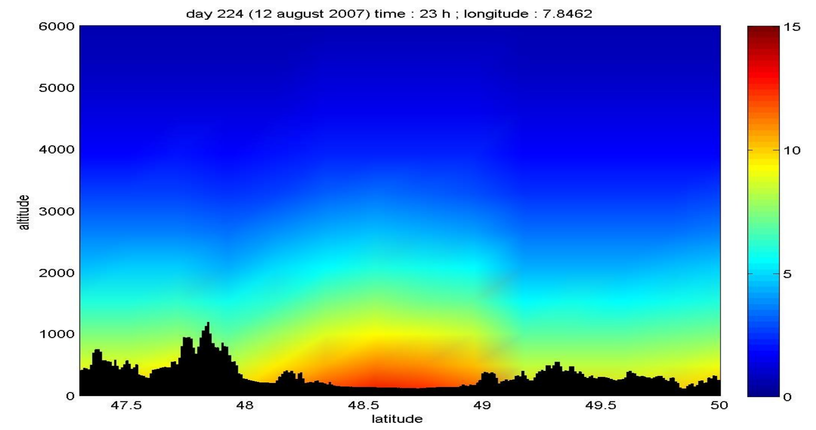


Vertical cuts









Concluding remarks

- GPS stations provide IWV estimates with good accuracy (about 1mm PWV)
- GPS tomography retrieves 3-D water vapor density field (accuracy better than 1 g/kg in sensitivity tests) for detailed case studies
- Tomography important points:
  - Need for homogeneous network
  - Horizontal resolution linked to station spacing
  - Vertical resolution linked to topography and station spacing
  - Empirical α values (matrix)
- Tomography offers good operational prospects anywhere where a sizeable network is available (variable mesh?)
- Is this a product for assimilation or for verification ?


Network Status@Tue Nov 4 06:01:44 UTC 2008

Thank You for your Attention !

And now to the LUAMI project …