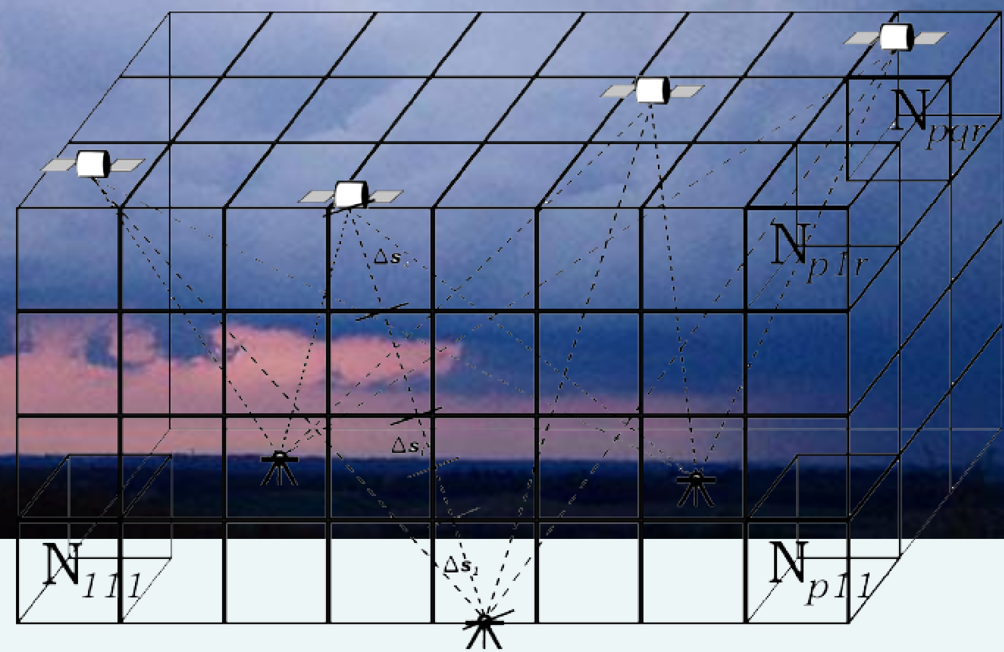
Implementations of GNSS tomography based on BIRA model



Workshop on GNSS tomography and meteorology,
Institute of Geodesy ad Geoinformatics
Wroclaw University of Environmental and Life Sciences,
December, 8, 2014

Hugues Brenot

Belgium Institute for Space Aeronomy

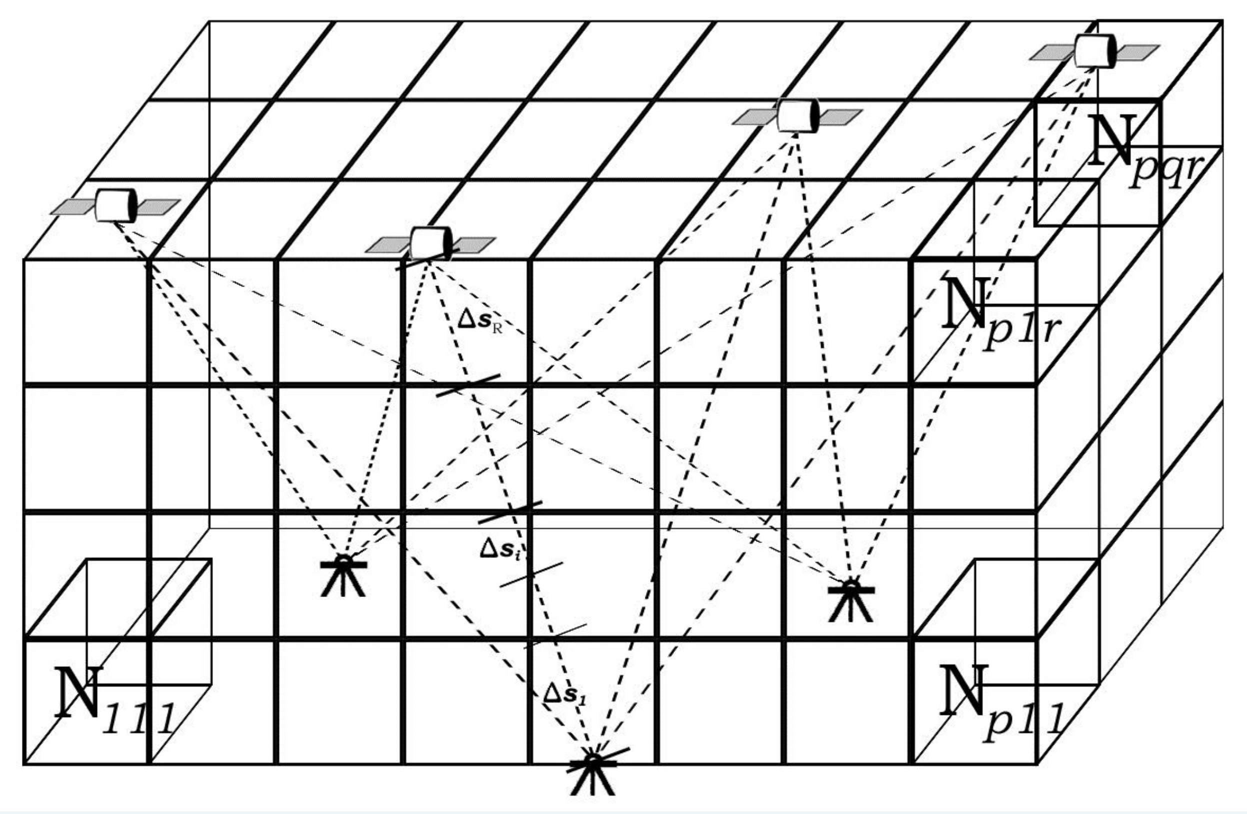
Lecture content

- Presentation of GNSS tomography at BIRA
  - Setting of the tomographic grid
  - Choice of the type of retrievals
  - Choice of the *a priori* conditions
  - Creation of the geometric matrix G
  - Implementations of inversion
  - Characterisation of covariance operator
- Example of applications in meteorology
- Future development

GNSS tomography:
implementations of BIRA model

Setting of the tomographic grid:

- definition of lan X lon X alt grid
  - ➔ param_grid files



Troposphere grids/voxels

GNSS tomography:
implementations of BIRA model

Setting of the tomographic grid:

- definition of lan X lon X alt grid
  - ➔ param files

```
# parameters files for the grid creation
# Longitude
xLON_min 2.
xLON_max 7.
nLON     10
xlondecal 30
# Latitude
xLAT_min 49
xLAT_max 52
nLAT     12
xlatdecal 20
# vertical
regulier reg
xalt_min 0
xalt_pas 500
nalt     20
h_double 5000
xalt_max 10000
alt_ref  asl
xalt_lim 10000
```

```
# specific parameters of embedded Grid
subgrid no
# Longitude
xlon_min 4.00
xlon_max 5.00
nlon     20
# Latitude
xlat_min 50.00
xlat_max 51.00
nlat     20
subgrid_z no
# output options
save_option 1
file_name grid_TEST.dat
```

GNSS tomography:
implementations of BIRA model

Maximum dimensions of BIRA tomography model: dimpar.h file

maximum size of the tomographic grid
```
      INTEGER ngril
      PARAMETER (ngril=6600)
```

maximum number of rays
```
      INTEGER nmaxray
      PARAMETER (nmaxray=6600)
```

epsilon (criterion of equality)
```
      REAL*8 eps
      PARAMETER (eps=1D-10)
```

maximum size of the horizontal tomographic grid
```
      INTEGER ngril1d
      PARAMETER (ngril1D=2000)
```

maximum number of GNSS stations
```
      INTEGER max_stat
      PARAMETER (max_stat=120)
```

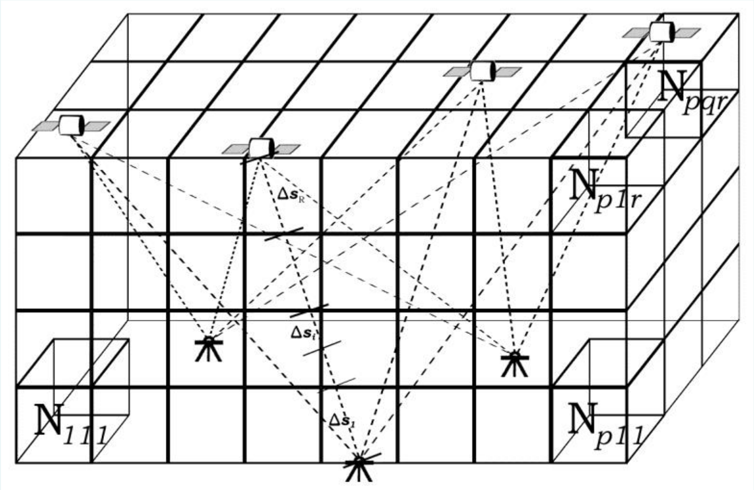
GNSS tomography:
implementations of BIRA model

<u>Choice of the type of retrievals:</u>

- **3D field of wet refractivity (N_w)**

WET DELAY ➔ WET REFRACTIVITY

$$SWD = 10^{-6} \int N_{wet}\, ds = 10^{-6} \sum N_{wet}\, \Delta s$$



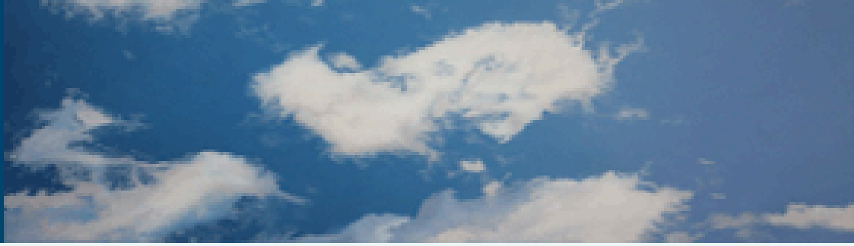
Troposphere grids/voxels

- **3D field of water vapour density (ρ_{wv})**

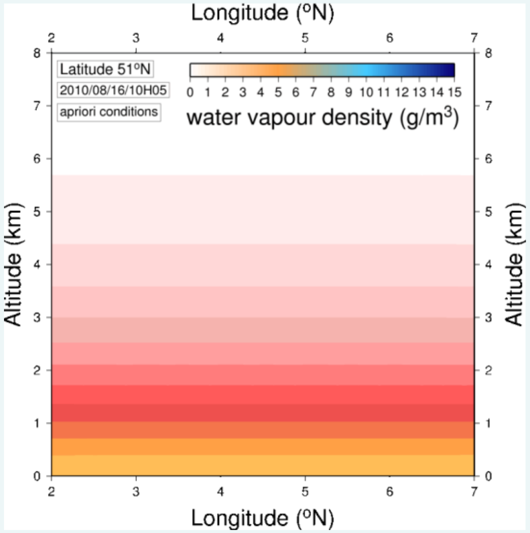
WATER VAPOUR CONTENT ➔ WATER VAPOUR DENSITY

$$SIWV = 10^{-6} \int \rho_{wv}\, ds = 10^{-6} \sum \rho_{wv}\, \Delta s$$

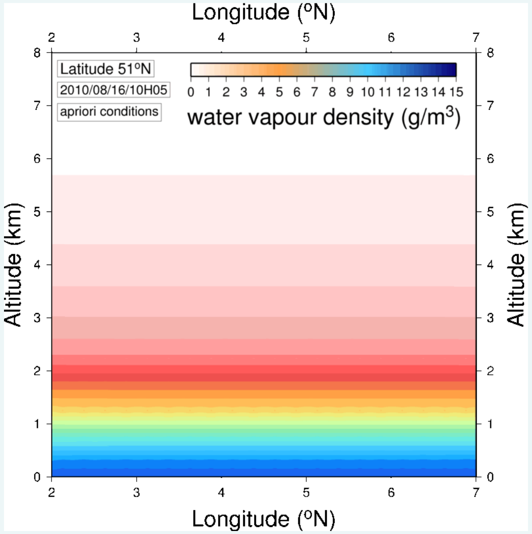
GNSS tomography:
implementations of BIRA model



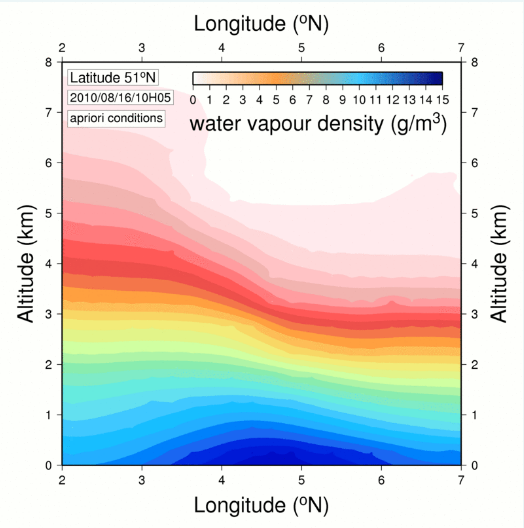
Choice of the *apriori* conditions



from standard atmosphere
modSTAN



from radiosondes
modRS

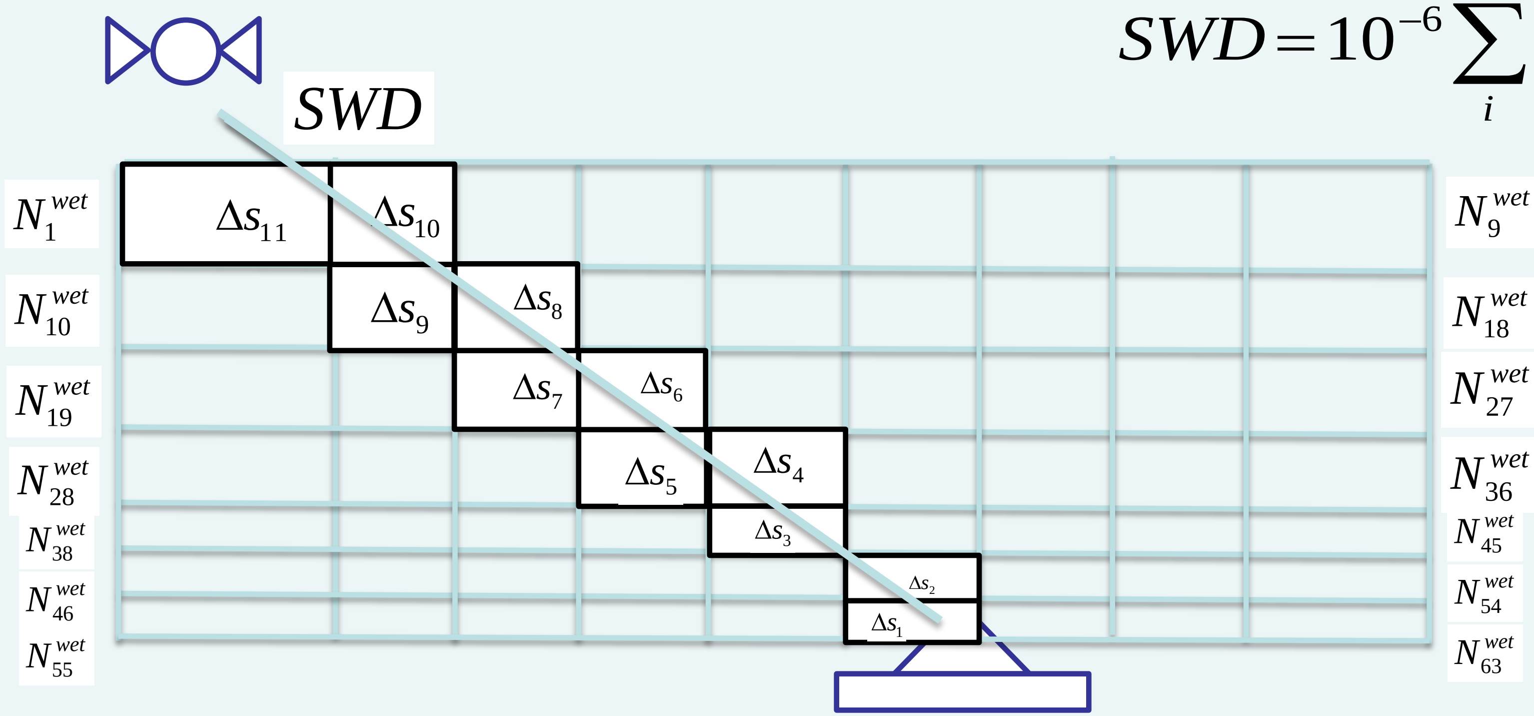


from NWP model
modWRF

GNSS tomography:
implementations of BIRA model

Creation of the geometric matrix

$$SWD = 10^{-6} \sum_i N_i^{wet} \; \Delta s_i$$



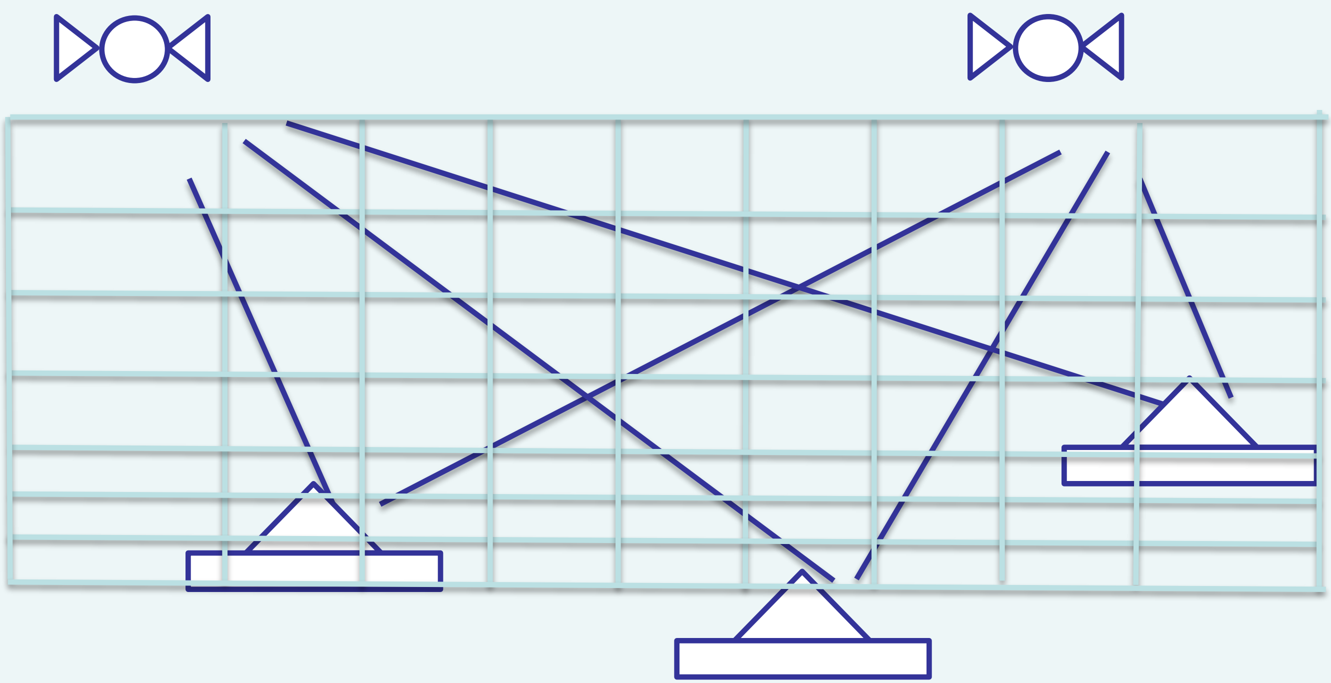
$$SWD = 10^{-6} \cdot (N_{60}^{wet} \cdot \Delta s_1 + N_{51}^{wet} \cdot \Delta s_2 + N_{41}^{wet} \cdot \Delta s_3 + N_{32}^{wet} \cdot \Delta s_4 + N_{31}^{wet} \cdot \Delta s_5 + N_{22}^{wet} \cdot \Delta s_6 + \ldots.$$

$$\ldots. + N_{21}^{wet} \cdot \Delta s_7 + N_{12}^{wet} \cdot \Delta s_8 + N_{11}^{wet} \cdot \Delta s_9 + N_2^{wet} \cdot \Delta s_{10} + N_1^{wet} \cdot \Delta s_{11})$$

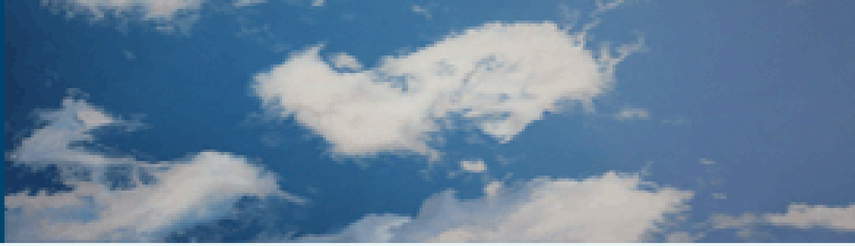
GNSS tomography:
implementations of BIRA model

Observations	Tomography model structure	Unknowns	Noise
data	geometrical matrix	model solution	errors

$$\boldsymbol{d} = \boldsymbol{G} \cdot \boldsymbol{m} + \boldsymbol{C_D}$$



GNSS tomography:
implementations of BIRA model



Implementation of inversion:

Linear inverse problem:
model solution retrieved by
weighted, damped least-squares adjustment

$$d = Gm + C_D$$

$$m = m_0 + \underbrace{(G^T C_D^{-1} G + C_M^{-1})}_{A}{}^{-1} G^T C_D^{-1} (d - Gm_0)$$

- $\boldsymbol{d}$ data
- $\boldsymbol{G}$ geometrical matrix
- $\boldsymbol{m}$ model solution
- $\boldsymbol{C_D}$ covariance operator data
- $\boldsymbol{m_0}$ apriori model
- $\boldsymbol{C_M}$ covariance operator apriori model

Singular Value Decomposition (SVD)

$$A = U \Lambda V^T$$

$\boldsymbol{A}$	geometrical matrix	p x q
$\boldsymbol{U}$	orthonormal matrix of eigenvectors (data space)	p x p
Λ	diagonal eigenvalues matrix	p x q
$\boldsymbol{V}$	orthonormal matrix of eigenvectors (model parameter space)	q x q

→ $$A^{-g} = V \Lambda^{-1} U^T$$

GNSS tomography:
implementations of BIRA model

Maximum dimensions of BIRA tomography model: dimpar.h file

Linear inverse problem:
model solution retrieved by
weighted, damped least-squares adjustment

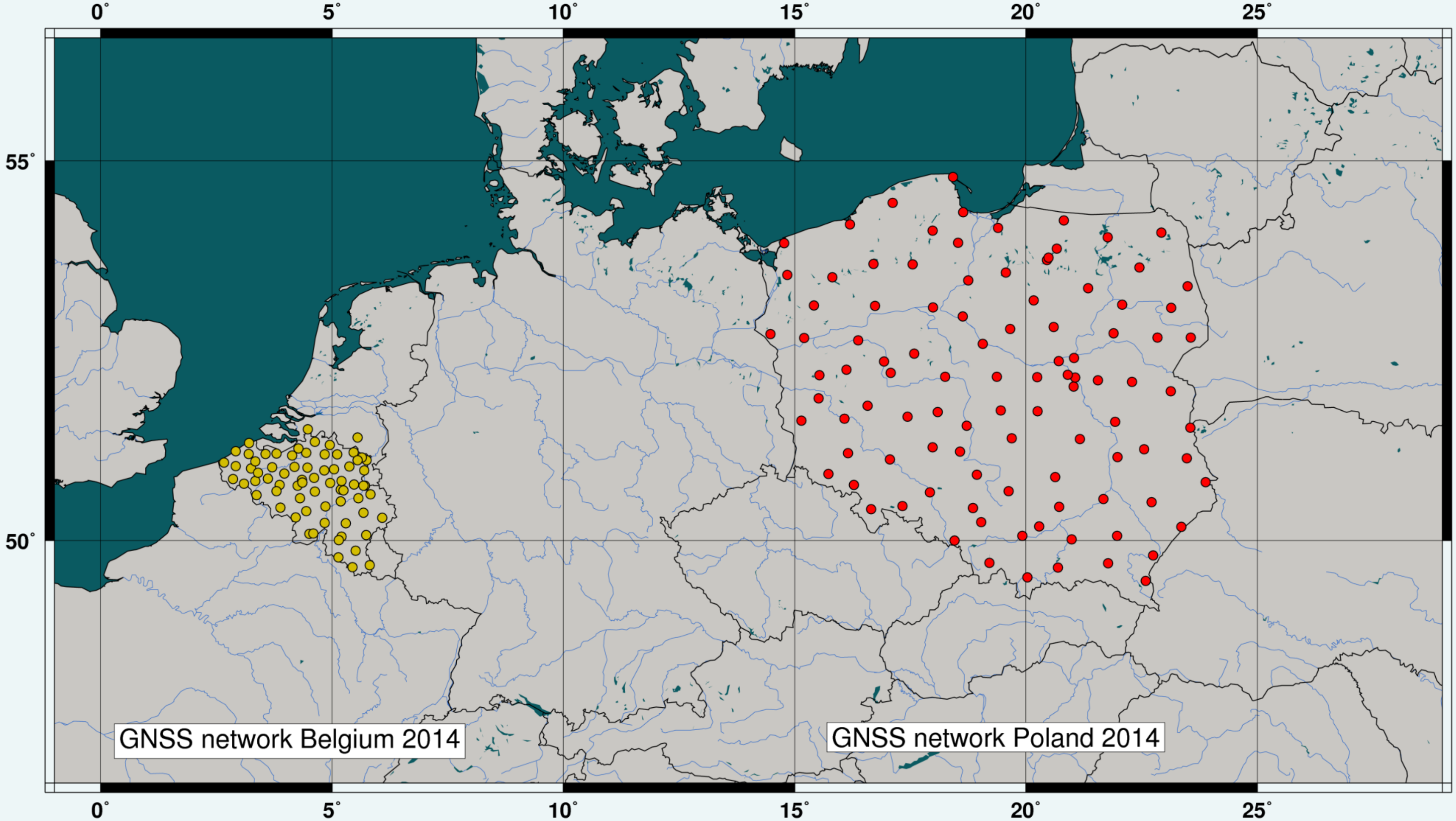
$$d = Gm + C_D$$

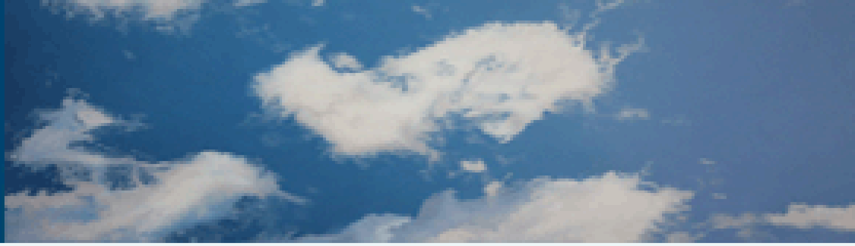
$$m = m_0 + \underbrace{(G^T C_D^{-1} G + C_M^{-1})}_{A}{}^{-1} G^T C_D^{-1} (d - Gm_0)$$

$\boldsymbol{C_D}$ covariance operator data ➞ in [0,1]

$\boldsymbol{m_0}$ apriori model
$\boldsymbol{C_M}$ covariance operator apriori model ➞ in [0,1]

Applications in meteorology

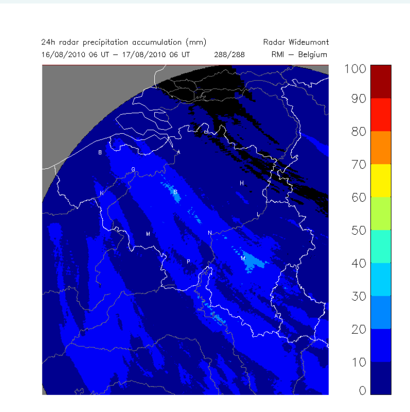


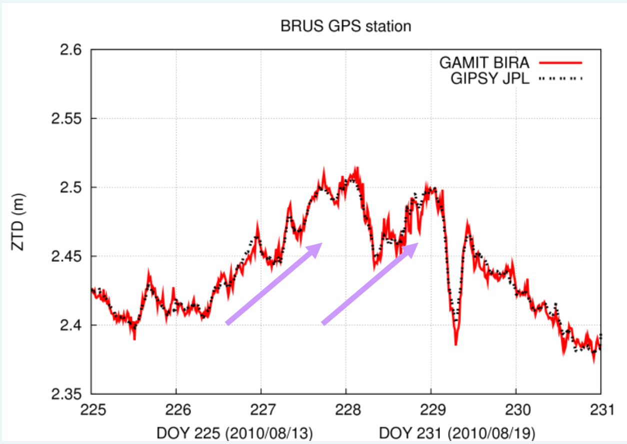


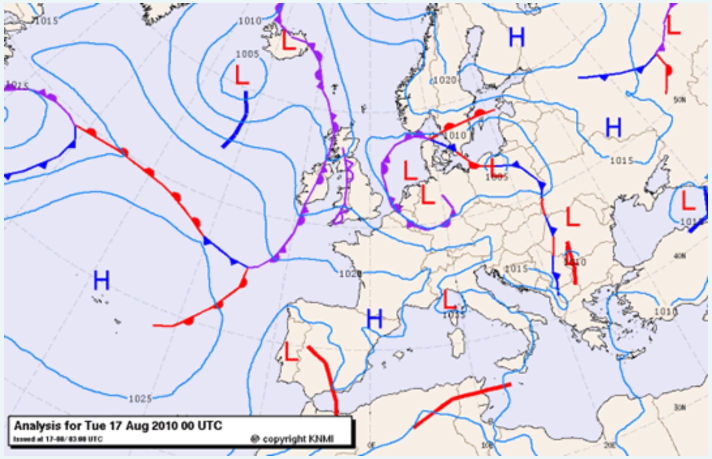
Applications in meteorology

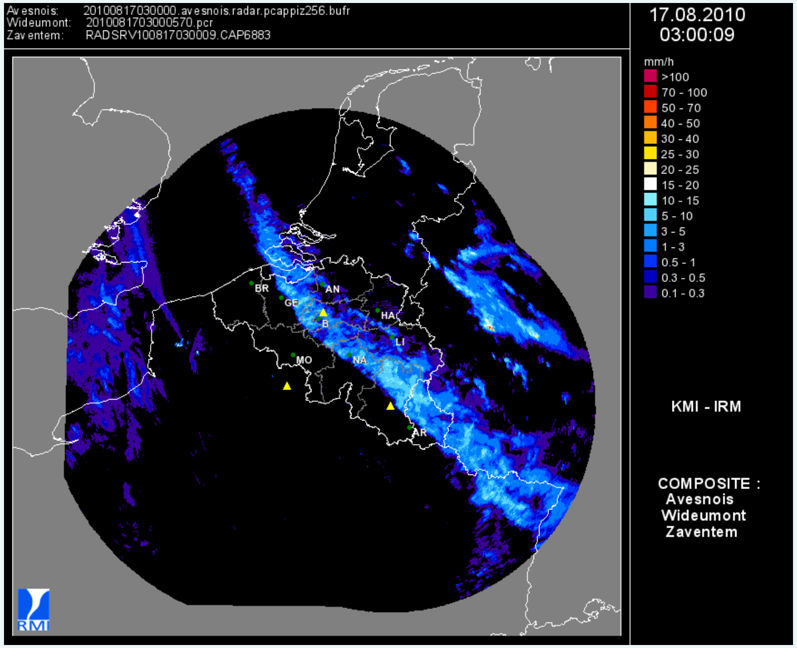
Pouring rain of the 15th-17th August 2010

→ Depression so-called *"Yvette"* coming from Germany









(*Brenot et al.*, 2012,
oral presentation EGU)

Applications in meteorology

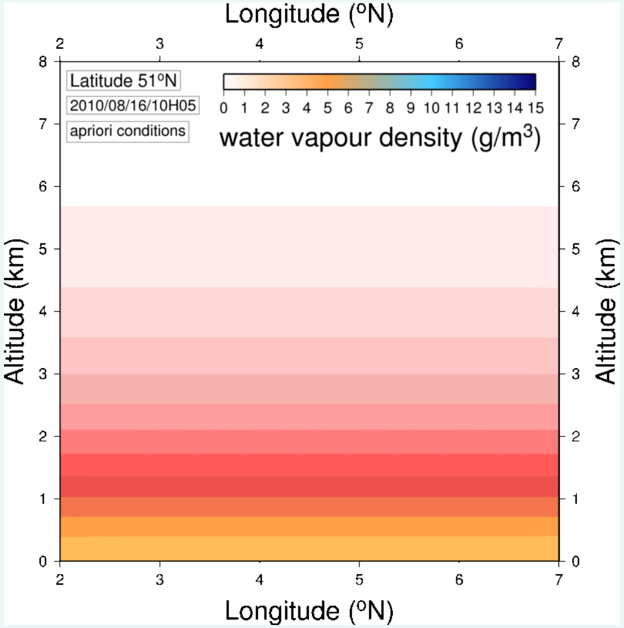
<u>Cell dimensions</u>:

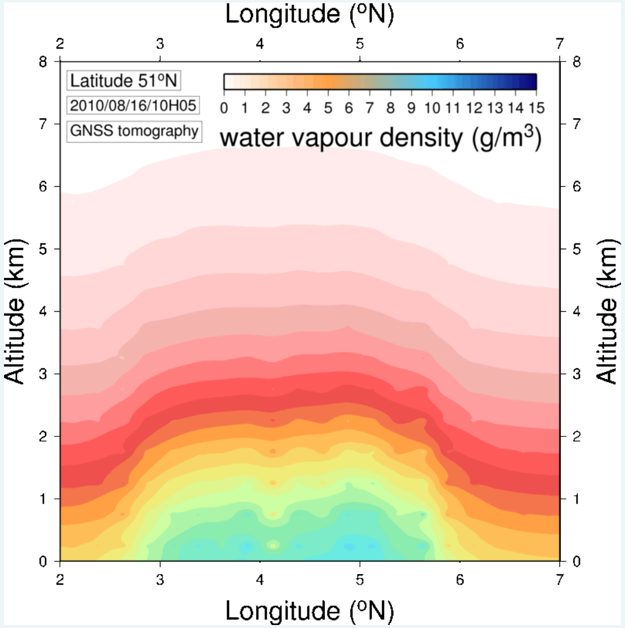
-> Horizontal: 0.1 ° width (~ 10 km)

-> Vertical resolution: 500 m
from 0 to 10000 m

-> C_D = 10% C_M = 90%

<u>Test of initial conditions:</u> standard atmosphere





(***Brenot et al.***, 2012,
oral presentation EGU)

Applications in meteorology

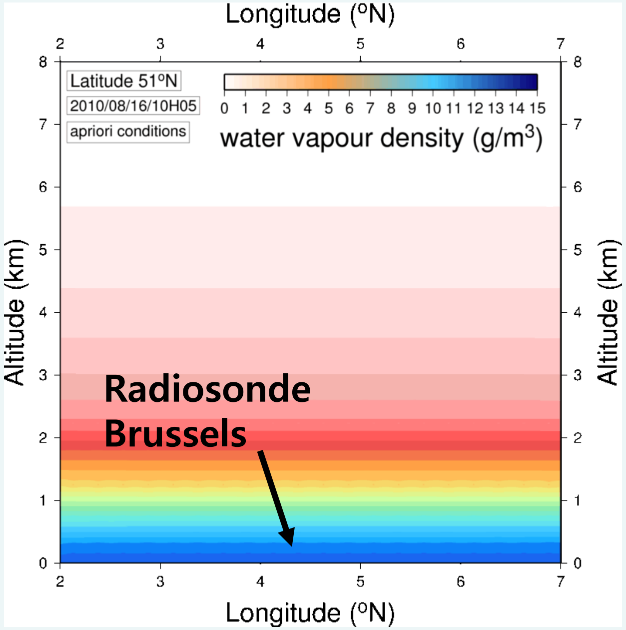
Cell dimensions:

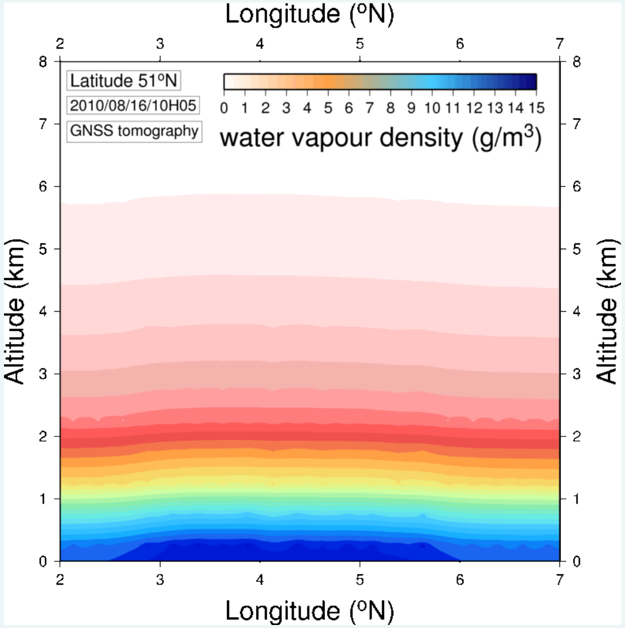
-> Horizontal: 0.1 ° width (~ 10 km)

-> Vertical resolution: 500 m
from 0 to 10000 m

-> C_D = 10% C_M = 90%

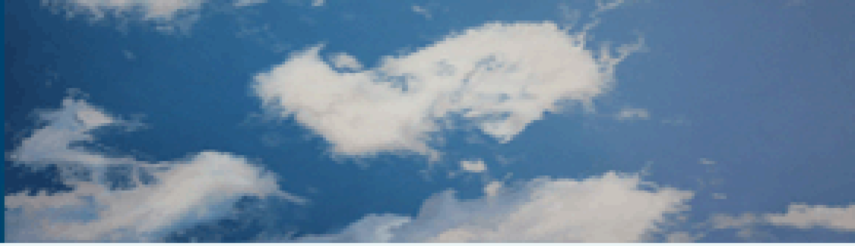
Test of initial conditions: **standard atmosphere based on radiosonde**





***Brenot et al.*, 2012,**
oral presentation EGU)

Applications in meteorology



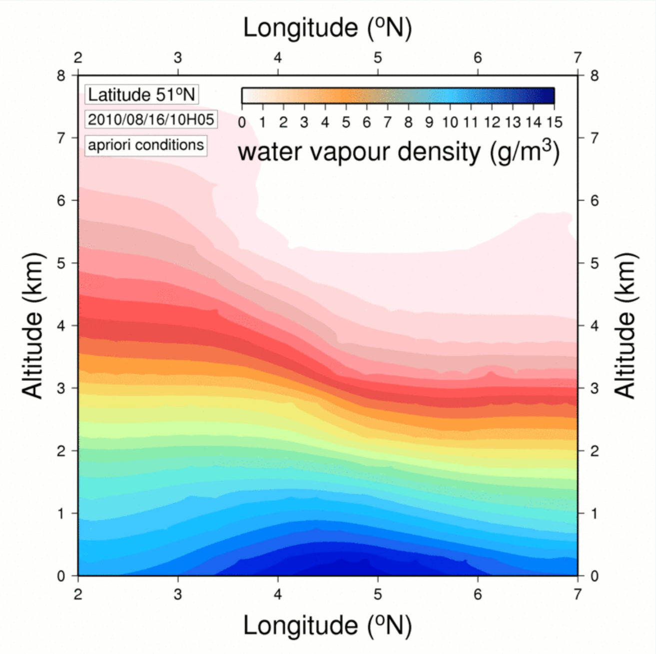
Cell dimensions:

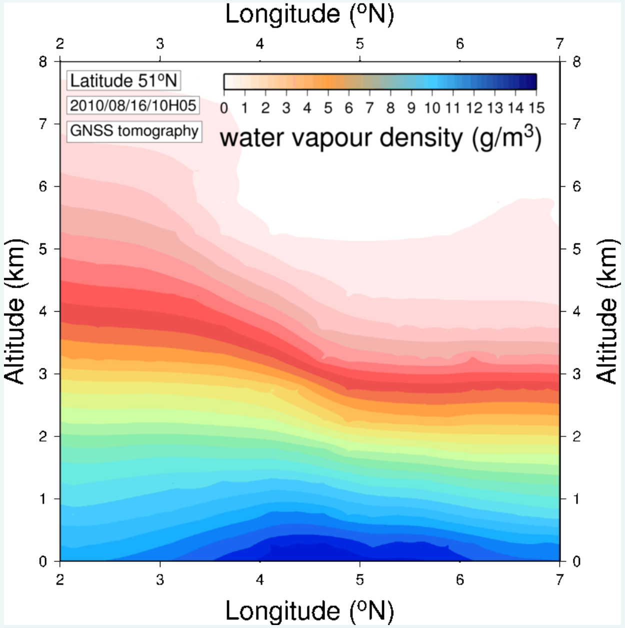
-> Horizontal: 0.1 ° width (~ 10 km)

-> Vertical resolution: 500 m
from 0 to 10000 m

-> C_D = 10% C_M = 90%

Test of initial conditions: atmosphere based on ALARO model (4 km resolution)

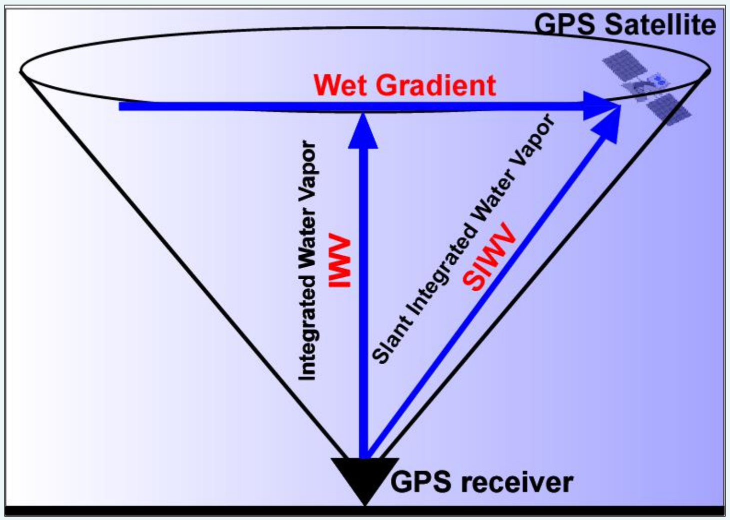




(*Brenot et al.*, 2012,
oral presentation EGU)

3D field of water vapour density GNSS by tomography

Retrievals of Slant IWV



SIWV = IWV *mf + Wet Gradients * ∏

With a use of a mapping function (mf) and a gradient mapping function ∏

-> input data for the GNSS tomography

- Linear inverse problem

d data
G geometrical matrix
m model solution
$\mathbf{C_D}$ covariance operator data

$$d = Gm + C_D$$

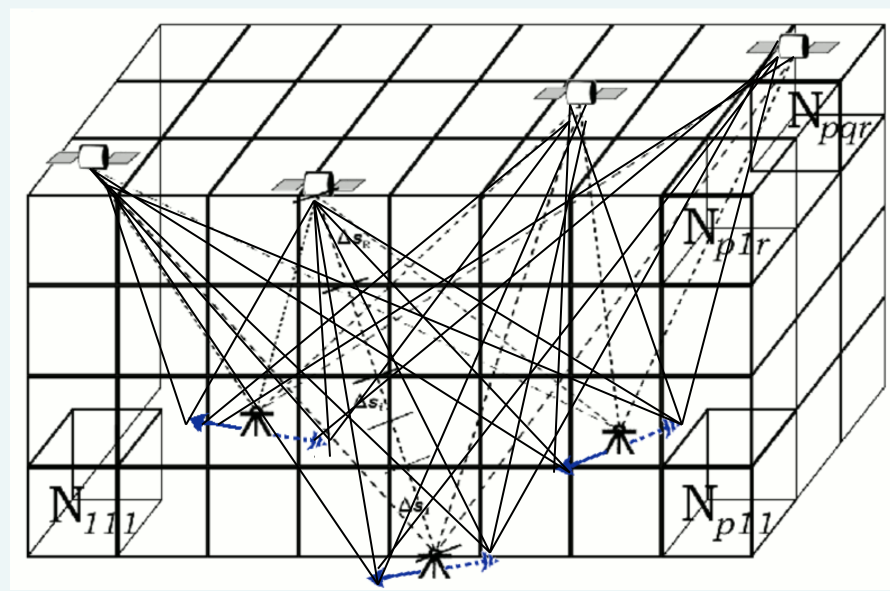
- Mixed invert problem (under- and over-determined)

$$m = G^{-1}d + C_D'$$

➔ $$m = m_0 + \left(G^t C_D^{-1} G + C_M^{-1}\right)^{-1} G^t C_D^{-1} (d - Gm_0)$$

$\mathbf{m_0}$ apriori model
$\mathbf{C_M}$ covariance operator apriori model

➔ Use of gradients to improve to geometrical resolution of our tomographic software



(*Brenot et al.*, 2012, oral presentation EGU)

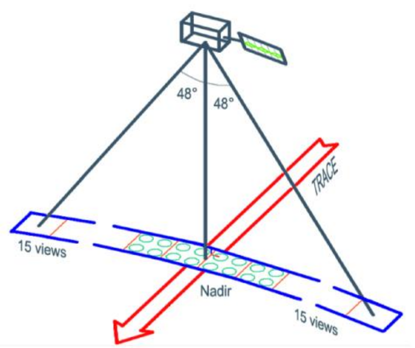
Applications in meteorology

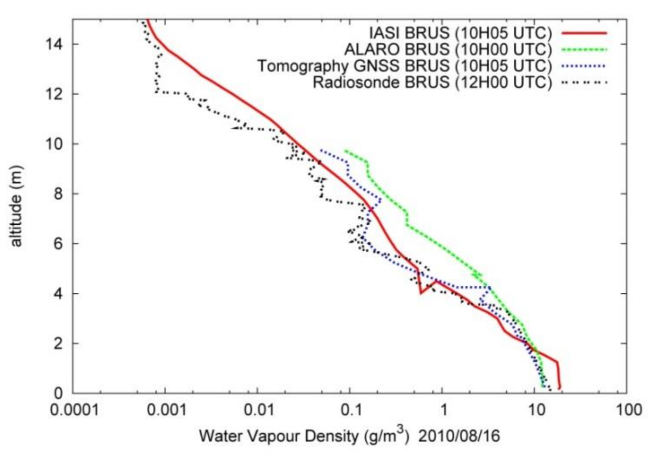
Cell dimensions:
-> Horizontal: 0.1 ° width (~ 10 km)

-> Vertical resolution: 500 m
from 0 to 10000 m

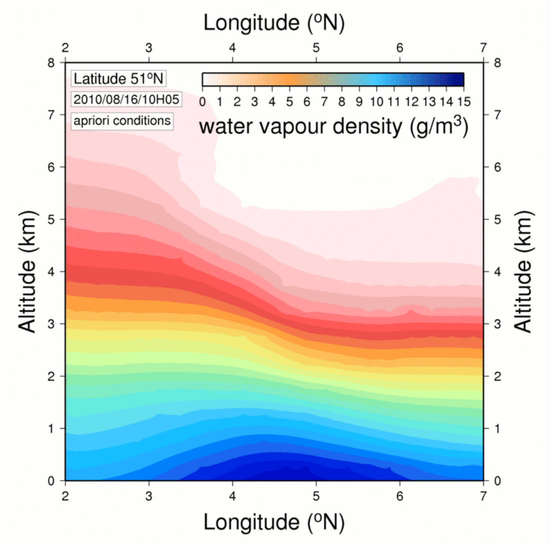
Covariance operator: -> data C_D = 10%
-> model C_M = 90%

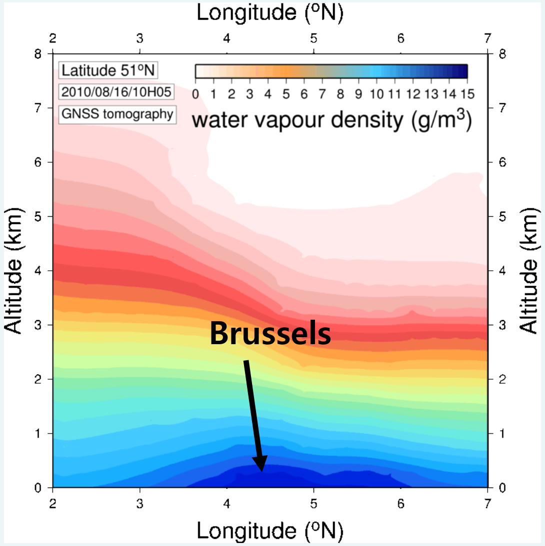
IASI Pixel diameter of about 12 km





Initial conditions: atmosphere based on ALARO model





(*Brenot et al.*, 2012,
oral presentation EGU)

GNSS tomography with gradient improvement

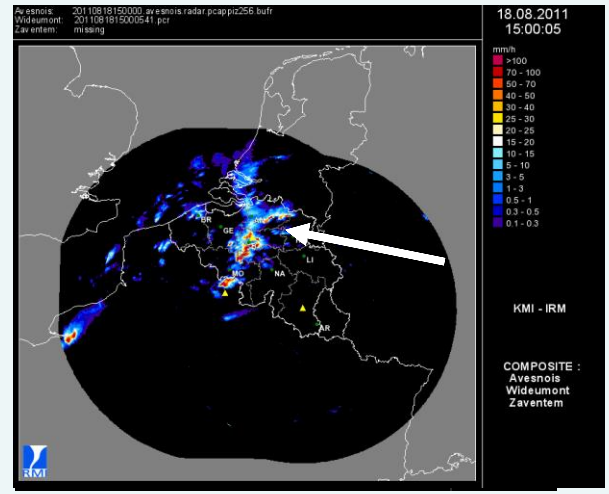
Applications in meteorology

3D field of water vapour density GNSS by tomography

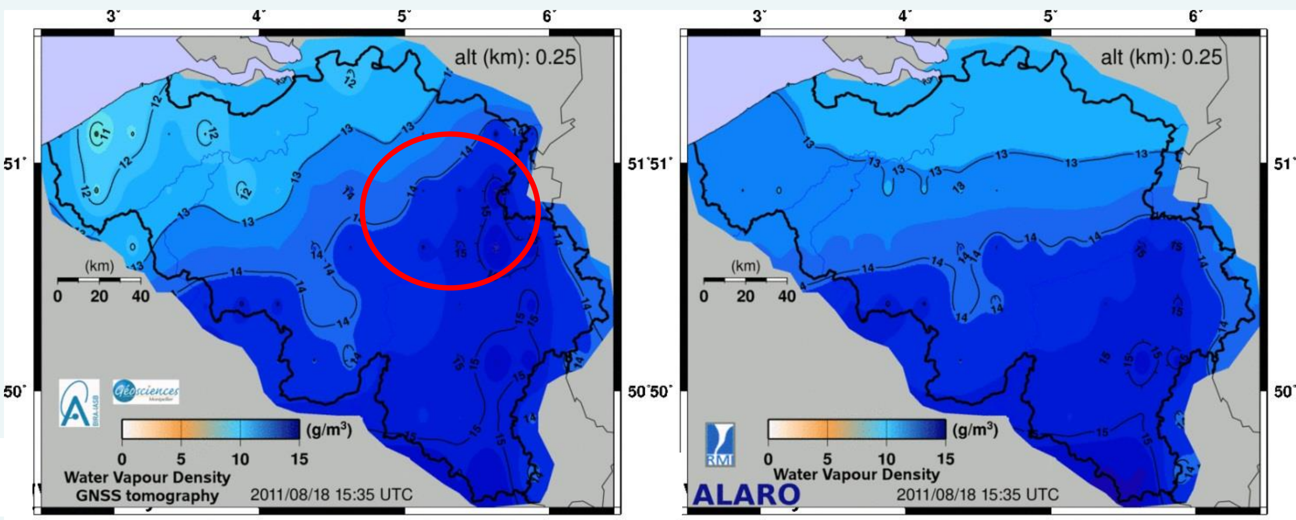
Storm of the 18th August 2011

→Flood event in Brussels

→Storm at Belgium's Pukkelpop music festival kills five after stage collapses



Interest for nowcasting



(*Brenot et al.*, 2012, oral presentation EGU)

Future development

- Useful GNSS tomography for monitoring of extreme weather

  - improvement of the geometry with gradients
  - Kalman filter
  - faisability of stacking data
  - NRT products

- Assimilation of tomographic profiles in ALARO

- Intercomparison and sensitivity test of tomography (IAG workgroup)

- Radio occultation and tomography

Thank you!

Potential of GNSS products for meteorology/nowcasting

GNSS obs. 2D images

Belgium dense network

Baselines

5 km to 30 km