GPS Tomography: Validation of the Reconstructed Humidity Fields

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Introduction

Vertical profiles of atmospheric properties are almost exclusively available from radiosonde soundings. 14 German radiosonde stations provide 2 or 4 profiles per day corresponding to a temporal resolution between 6 h and 12 h and a horizontal resolution of ~200 km. In parallel there exists a dense network of ~265 German GPS stations which provide (near) real-time data for the GPS atmosphere processing at the GFZ. Several atmosphereic products such as slant total delays (STD), zenith total delays (ZTD) and integrated water wapour (IWV) are operationally avaiable with a temporal resolution of 2.5 minutes (STD) or 15 minutes (ZTD, IWV).

Especially the STDs , i. e. the signal delays due to the neutral atmosphere, contain spatially resolved information about the atmospheric state. 3D humidity fields can be reconstructed from large numbers of STDs by means of tomographic techniques. Radiosonde profiles and GPS tomography could be combined and provide vertical atmospheric structures with a much higher temporal and spatial resolution than today. Therefore, radiosonde profiles and tomographically reconstructed fields for one year (2007) were compared in order to estimate the quality of the tomographic reconstructions.

The STD is related to the atmospheric pressure, temperature and humidity fields. After separating the wet fraction from the STD the wet part of the atmospheric refractivity N_{WET} can be obtained by means of inverse reconstruction techniques:

$$\Delta L_{wet} = 10^{-6} \int_S N_{wet}(s)\, ds$$

The wet refractivity is correlated to the partial pressure of water vapour *e* by

$$N_{wet} = k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

and the field of the absolute humidity *a* can be obtained if additional temperature data are available:

$$a = \frac{e}{R_v T}$$

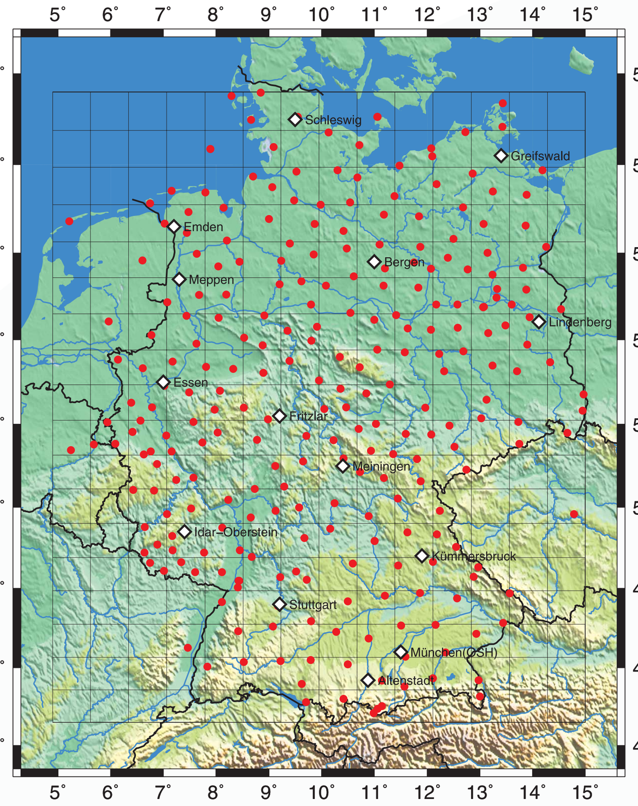


Fig. 1: Locations of the 272 GPS stations (•) inside the tomography grid (black) and the 14 German radiosonde stations (◇). A 14x18x24 cell grid with 6048 cells was chosen for the reconstruction.

Tomography

The integral observations ΔL_{wet} can be combined to a spatially resolved field of the wet refractivity by means of tomographic reconstruction techniques. A large number of observations has to be processed which requires computationally efficient algorithms. The Algebraic Reconstruction Techniques (ART) can be used to solve the basic equation iteratively:

$$\mathbf{Ax} = \mathbf{m}$$

The vector of observations **m** and the kernel matrix **A** are defined by the observed delays and the subpaths of the slants in each voxel. The unknown state vector **x** represents the refractivity inside each voxel.This defines an ill-posed inverse problem with incomplete data and special techniques are required to obtain stable and reliable results. The results shown here have been reconstructed using the Multiplicative Algebraic Reconstruction Technique (MART):

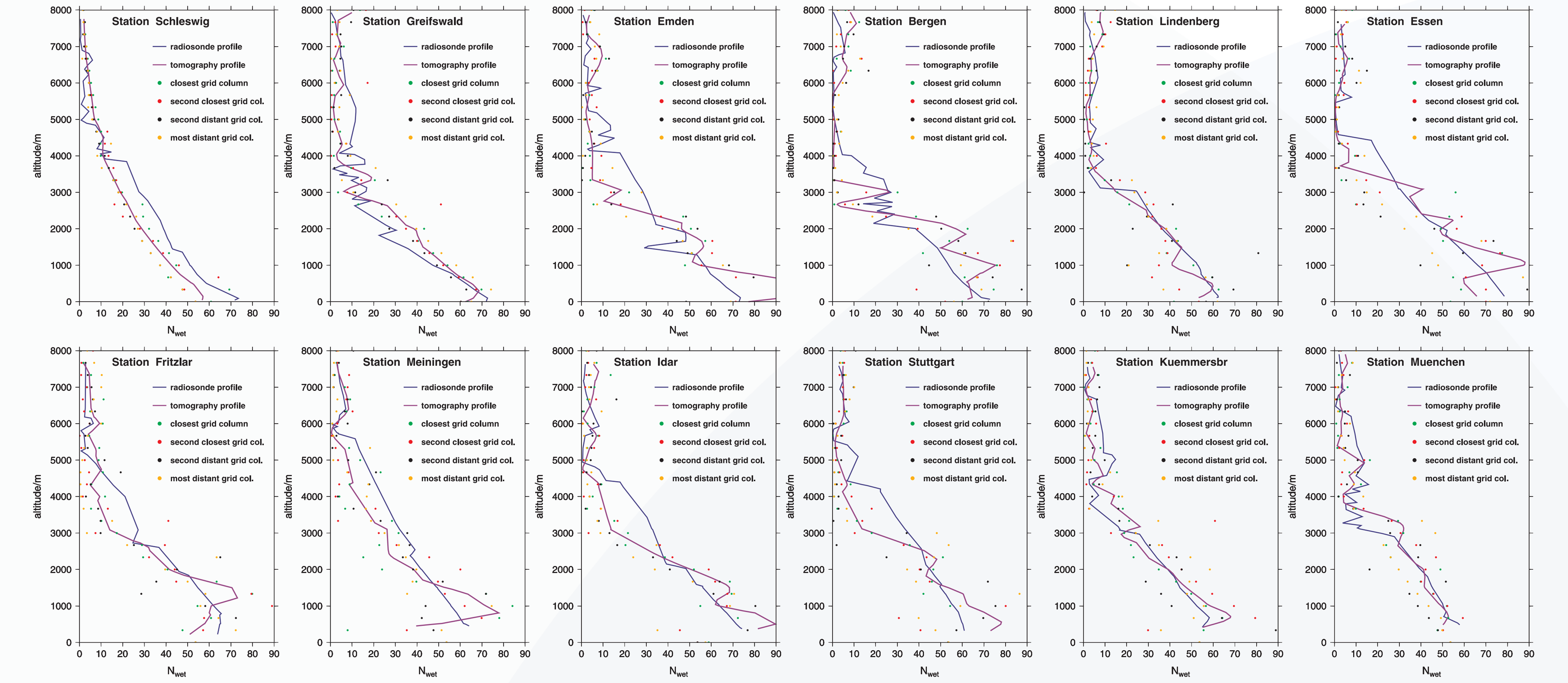
$$x_j^{k+1} = x_j^k \cdot \left(\frac{m_i}{\langle \boldsymbol{A}^i, \boldsymbol{x}^k \rangle} \right)^{\frac{\lambda_k A_j^i}{\sqrt{\langle \boldsymbol{A}^i, \boldsymbol{A}^i \rangle}}}$$

Using a relaxation parameter λ=0.2 and an initialisation with a constant vertical profile reliable reconstructions could be obtained.The tomographic reconstruction is based on a geospacial grid. The data presented here have been reconstructed using a grid (fig. 1) with a horizontal spacing of ~50 km and a vertical spacing of ~330 m. With a temporal resolution of 30 minutes between 18000 and 32000 STDs are available for each reconstruction leading to 6048x32000 ~190·10⁶ matrix elements a_{ij}.

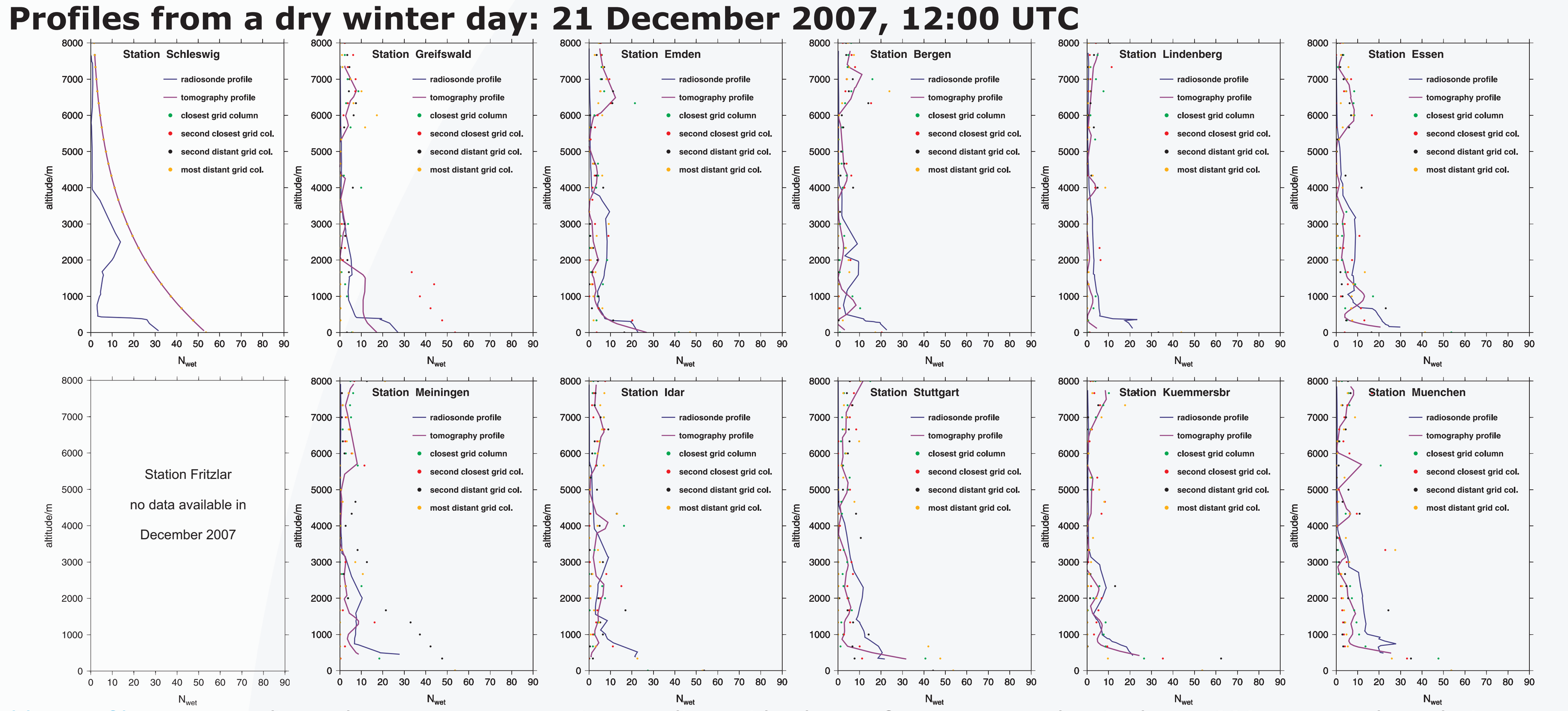
Comparison of radiosonde and tomography profiles

Radiosonde data from 2007 as provided by the German Meteorological Service (DWD) were compared to tomographically reconstructed N_{wet} fields. Radiosondes are launched twice a day from 14 German stations at 0:00 UTC and 12:00 UTC and provide vertical samples every 20 - 500 m depending on the rate of ascent. Each profile consists of 20 - 60 observations below 10 km. The GPS tomography was started for all launch times in 2007 resulting in ~730 N_{wet} fields for Germany. 30 minutes of STD data between 23:45 and 0:15 UTC and 11:45 and 12:15 UTC were used by the tomography. All reconstructions were initialised with the same N_{wet} profile and 100 iterations of the MART algorithm were carried out. To compare radiosonde and tomography profiles the 24 vertical layers from the reconstructed fields were interpolated on the radiosonde positions assuming a vertical ascent without any horizontal drift. In total, more than 20000 profiles were compared.

Profiles from a humid summer day: 13 July 2007, 0:00 UTC



Profiles from a dry winter day: 21 December 2007, 12:00 UTC



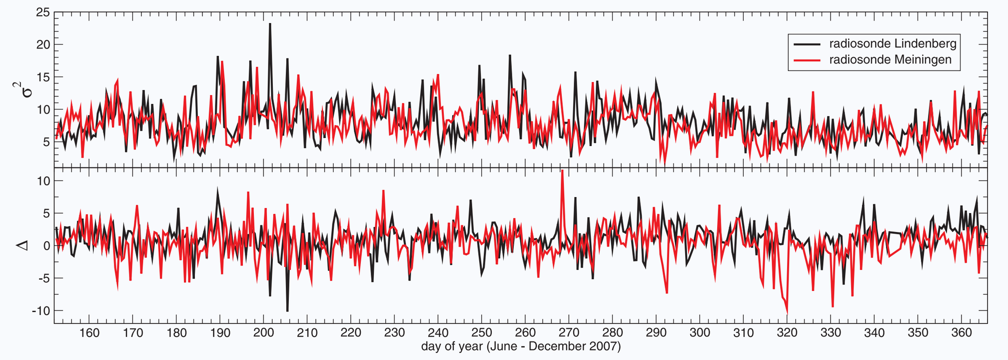
blue profiles - radiosonde
purple profiles - tomography, interpolated

Surrounding grid columns from tomography, 24 layer, 330 m vertical resolution: closest, second closest, second distant and most distant column

Statistics

In order to quantify the quality of the reconstructed fields the differences between the observed N_{wet} data and the reconstructed data interpolated on the radiosonde profiles were investigated: $\Delta = N_{RS} - N_{tomo}$
The mean difference $\overline{\Delta}$, the standard deviation σ, and the variance σ^2 were computed for each profile, all profiles of one station and for all observations. The results for June and December 2007 are given below.

	June 2007			December 2007		
Station	$\overline{\Delta}$	σ	σ^2	$\overline{\Delta}$	σ	σ^2
Schleswig	4.484	8.343	69.610	-9.901	9.185	84.356
Greifswald	0.856	8.399	70.548	0.899	8.057	64.915
Emden-Flugplatz	0.529	9.416	88.663	0.788	8.877	78.799
Bergen	-0.301	11.639	135.468	0.816	9.113	83.056
Lindenberg	1.044	8.129	66.075	0.331	7.422	55.091
Essen	0.498	10.090	101.810	2.112	7.394	54.670
Fritzlar - Kasseler Warte	1.848	8.769	76.890	0.645	9.172	84.119
Meiningen	0.746	8.492	72.117	0.686	7.043	49.608
Idar-Oberstein	1.201	9.585	91.876	0.957	9.095	82.714
Stuttgart	0.547	11.709	137.106	1.046	9.114	83.070
Kümmersbrueck	-0.113	7.790	60.681	0.843	6.350	40.322
München-Oberschleissheim	2.914	10.180	103.636	1.465	6.551	42.910
all data, all stations	1.197	9.631	92.748	0.035	8.833	78.024



While the bias $\overline{\Delta}$ is rather small for all stations (~1 refractivity unit) the standard deviation σ reaches pretty high values. This is mostly due to the fact that all parts of the reconstructed fields contribute to the statistics even if no STD data were available in the region around the radiosonde station. In such cases some or all voxels remain in their initial state which might be far from reality. The outlayers resulting from these parts are mainly responsible for the high variance and should be removed in further analyses. Differences between the stations are dominated by the number and distribution of nearby GPS stations. The changing GPS satellite constellation as seen in the local systems of the GPS stations leads to highly varible observations from different parts of the atmosphere. The STD distribution within the tomography grid is therefore variable and leads to reconstructions of different quality. The bias as well as σ and σ^2 show fast temporal fluctuations which differ considerably between the radiosonde stations. Exsamples for 2 stations and 6 month are shown in the graph on the left side.

Conclusions

Tomography and radiosonde profiles agree in general very well as long as sufficient STD data are available within the given region and period of time. There are considerable temporal and regional variations in the reconstruction quality caused by the highly variable GPS satellite constellation and the inhomogeneous GPS station distribution. In future, regions with insufficient observations should be identified and excluded from the validation. The comparison with radiosonde profiles shows three important features of the reconstructed vertical structures: (1) The lower part of the profiles up to 3-4 km has approximately the same quality as the upper part even though there are very few intersecting slant paths. (2) The quality of the profiles seems not to be correlated with the hight distribution of the surrounding GPS stations, i. e. reliable profiles can be reconstructed in flat terrain with all nearby stations on the same altitude. (3) The reconstruction quality is not correlated with the atmospheric humidity, i. e. very dry and very wet weather situations can be treated equally well.

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