On the Impact of Inhomogeneities in Meteorological Data on VLBI Data Analysis

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Abstract In this study, we address the issue of the quality of meteorological data employed for VLBI data analysis. We use data from six numerical weather models (NWMs) to form references on which the homogenization process is based. We explore the impact of the choice of NWM as well as the way to extract data from it. Among our findings is that data from the surface fields of NWMs are not suitable for either geodetic analysis or homogenization efforts, whether they are in their original form or after they have been compensated for the height difference between the orography of the NWM and the actual elevation. The reason lies in the fact that for 77% of the VLBI stations a height bias larger than 2.5 mm appears, as well as an average bias in the zenith wet delay estimates of 12.2 mm. Should the proposed extraction approach be followed, the difference between operational and reanalysis NWMs is not significant for such an application. Our conclusions are based on the analysis of VLBI data over 13 years.

Keywords VLBI, numerical weather models, homogenization, Earth orientation parameters, reference frames

1 Introduction

Due to the highly volatile character of the neutral atmosphere, the modeling of the related propagation delay is challenging. This poses the most prominent limitation in the precision and accuracy of the parameters estimated by microwave-based space geodetic techniques.

The work presented in this paper is restricted to the potential accuracy limitation that the mismodeling of the nuisance effects of *neutral atmospheric propagation delay* and the *thermal deformation of antennas* poses to the Very Long Baseline Interferometry (VLBI) technique due to erroneous meteorological records employed to mitigate them. As both effects are considered at the observation level, any errors not described in the observation covariance matrix will propagate in the estimated parameters and their accuracies. Being a function of surface pressure, the zenith hydrostatic delay (ZHD) is subject to inhomogeneities in the related observations, which could result in spurious trends in the zenith wet delays (ZWDs) and consequently render the physical interpretation of trends in integrated water vapor (IWV) uncertain. Moreover, they can bias the height time series and thus finally distort the scale of the estimated terrestrial reference frame (TRF) (Heinkelmann et al., 2009). As far as the thermal deformation is concerned, inaccurate temperature values allow site motions closely following the temperature anomalies, whereas an artificial offset in the temperature induces a virtual height displacement (Nothnagel, 2008).

The other microwave-based space geodetic techniques currently contributing to the ITRF customarily acquire the necessary meteorological data by either empirical or numerical weather models (NWMs). Conversely, VLBI analysis enjoys the advantage that the aforementioned nuisance effects can be potentially eliminated more effectively by employing in situ observations, because in principle all VLBI stations are equipped with meteorological sensors. Nevertheless, there are cases where erroneous meteorological records

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yield unacceptable results which have a dubious traceability at the parameter level.

In this work, we homogenize the meteorological observations recorded in the vicinity of VLBI stations. In order to meet this objective, reference series which experience all broad climatic influences of the candidate sites but none of their artificial biases, trends, or drifts are required. We resort to NWMs to obtain such series, following the procedure outlined in Section 2. For our investigations we test the following NWMs:

1. ECMWF's atmospheric operational analyses,
2. ECMWF's ERA-Interim (Dee et al., 2011),
3. NOAA/OAR/ESRL PSD's NCEP-DOE AMIP-II reanalysis (Kanamitsu et al., 2002),
4. NASA's MERRA-1 (Rienecker et al., 2011),
5. NASA's MERRA-2, and
6. JMA's JRA-55 reanalysis[1].

We performed a *penalized maximal t test* (e.g. Wang et al., 2007) on the formed pressure and temperature difference time series to detect abrupt shifts in the recursive average. Afterwards, we investigated the effect on time series of the station positions, Earth orientation parameters (EOP), and ZWDs from a reprocessing of 13 years of VLBI data while applying the different meteorological data sets.

2 Extracting Data from Numerical Weather Models

As proven in Heinkelmann et al. (2016), performing the hypsometric adjustment on values extracted from surface fields yields unacceptable results, specifically in regions with steep topographic gradients.

Therefore, we choose to work with model level (σ-pressure coordinate system) data. An alternative would be to employ pressure level data. The reason for choosing the model level lies mainly in the fact that most NWMs (e.g., ECMWF's products) are generated on model levels and at the surface; the transformation to pressure levels introduces a deterioration in the vertical resolution.

A potential source of bias in the pressure time series is that in the transformation from ellipsoidal heights to dynamic heights, the geoid undulation N, is currently not considered. This results inescapably in a logarithmical bias proportional to N as large as 5 hPa w.r.t. reliable in situ pressure records. For our investigations, we extract N from EIGEN---6C4 (Förste et al., 2014) using full-degree spherical harmonic synthesis.

Utilizing the 3D temperature and specific humidity fields as well as the pressure and geopotential number surface fields, we calculate the pressure and temperature at the points of interest following the procedure oulined here, which largely follows ECMWF (2015). Initially, the 3D pressure field is calculated:

$$\begin{aligned} p_k &= \frac{1}{2}\left(p_{k-\frac{1}{2}} + p_{k+\frac{1}{2}}\right), \quad && \text{for } 1 \leqslant k \leqslant k_{max} \\ p_{k+\frac{1}{2}} &= A_{k+\frac{1}{2}} + B_{k+\frac{1}{2}} p_s, && \text{for } 0 \leqslant k \leqslant k_{max} \end{aligned} \tag{1}$$

where k is the generalized vertical index, k_{max} is the number of vertical levels, p_s is the surface pressure, p_k is the full-level pressure, $p_{k\pm\frac{1}{2}}$ is the pressure at the interfaces, and $A_{k+\frac{1}{2}}$ and $B_{k+\frac{1}{2}}$ are constants. The next step includes the calculation of full-level values of the geopotential in a finite difference form:

$$\begin{aligned} \phi_k &= \phi_s + \sum_{j=k+1}^{k_{max}} R_{dry}(T_v)_j \ln\left(\frac{p_{j+\frac{1}{2}}}{p_{j-\frac{1}{2}}}\right) + \alpha_k R_{dry}(T_v)_k \\ \alpha_k &= \begin{cases} \ln 2, & \text{for } k = 1 \\ 1 - \frac{p_{k-\frac{1}{2}}}{p_{k-\frac{1}{2}} + p_{k+\frac{1}{2}}} \ln\left(\frac{p_{k+\frac{1}{2}}}{p_{k-\frac{1}{2}}}\right), & \text{for } k > 1 \end{cases} \end{aligned} \tag{2}$$

where ϕ_s denotes the geopotential at the orography and $(T_v)_k$ stands for the virtual temperature on level k (to account for moisture fluctuations):

$$T_v = T\left(1 + \left(\frac{R_{vap}}{R_{dry}} - 1\right) q\right), \tag{3}$$

q is the specific humidity, T is the temperature, and R_{vap} and R_{dry} denote the gas constant for water vapor and dry air, respectively. Following this robust extraction approach the bias between different models almost vanishes (Figure 1 and Figure 2).

As far as the temperature is concerned, the reference temperature of each VLBI site is of crucial importance for the thermal deformation correction. Currently these values are extracted from GPT (Boehm et al., 2007), the finite resolution of which introduces a bias in some cases (Figure 3).

[1] jra.kishou.go.jp/JRA-55/index_en.html

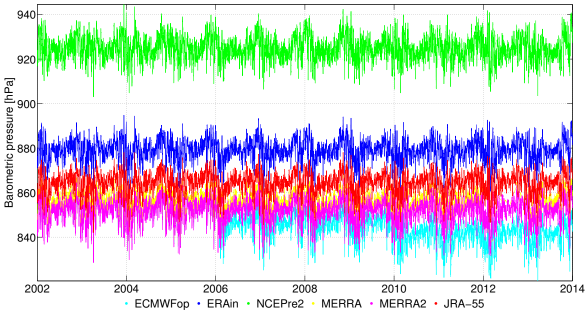

Fig. 1: Surface pressure time series at Zelenchukskaya, Russia, from ECMWF's operational model, ERA-Interim, NCEP-DOE_AMIP-re2, MERRA, MERRA2, and JRA-55.

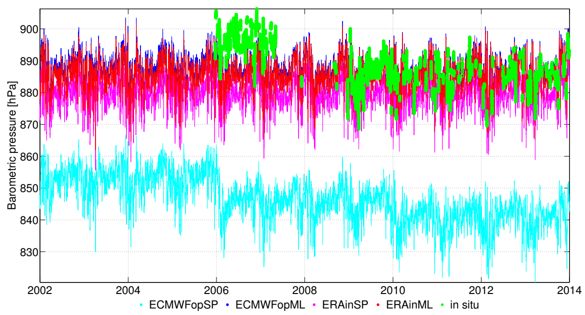

Fig. 2: Pressure time series at Zelenchukskaya, Russia. The suffix "SP" describes data extracted from the surface pressure fields and the suffix "ML" describes data from model levels. Data labeled "in situ" were retrieved from the pressure sensor mounted in the vicinity of the VLBI station.

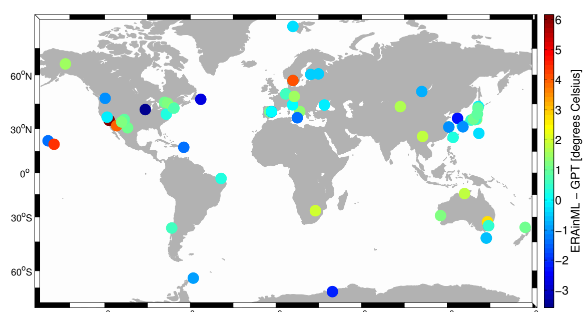

Fig. 3: The bias between the reference temperature currently in use for the thermal deformation calculation (GPT) and our estimation from ERAinML data.

3 VLBI Data Analysis and Results

We utilize the Least Squares Adjustment module of the VieVS@GFZ VLBI software (Nilsson et al., 2015) to analyze interferometric group delay data (Nothnagel et al., 2015) from the IVS-R1 and IVS-R4 rapid turnaround VLBI experiments (1,326 24-hour multi-baseline sessions), spanning the period from 2002 until 2015 and featuring in total a global 32 station network. We indicatively produce five solutions, with the meteorological parameters (pressure and temperature) being the only point of difference. These use meteorological data from:

1. in situ, as recorded at the VLBI sites (when unavailable, GPT2 (Lagler et al., 2013) is used),
2. GPT2,
3. hourly MERRA2 surface fields (MERRA2sfc),
4. six-hourly ECMWF's ERA-Interim reanalysis model level data (ERAinML), and
5. homogenized in situ data adjusted for the height difference between the meteorological sensor and the VLBI reference point, with ERAinML serving as a reference.

For the sites where information is available, we compensate for the height difference between the VLBI reference point and the level each meteorological data set refers to. In all solutions, we compensate for deformations induced by non-tidal atmospheric pressure loading (NTAL) and continental water storage loading[2] (CWSL), in addition to the conventional displacement models (Petit and Luzum, 2010), to reduce correlations. Furthermore, we employ the Potsdam mapping functions which utilize the advanced mapping concept and a rigorous ray-tracing approach using ERA-Interim (Balidakis et al., 2016). Station coordinates and EOPs are estimated at daily intervals, whereas ZWDs are estimated at hourly and linear horizontal delay gradients at six-hourly time intervals.

The largest effect of alternating meteorological data sets in VLBI data analysis is expected in the height coordinate component. For solutions 2, 4, and 5, the station heights change by more than 2.5 mm in 22% of the VLBI stations, whereas 77% of the VLBI stations

[2] CWSL series were calculated from the LSDM, forced by the ECMWF operational model (Dill and Dobslaw, 2013). We calculate the NTAL series consistently, utilizing the ECMWF's operational model, assuming a dynamic ocean response to pressure and wind forcing from the barotropic model MOG2D-G.

are biased for the third solution (Figure 4). We find that employing meteorological data homogenized with ERAinML reduces the weighted root mean square of the height time series by 6.2% on average.

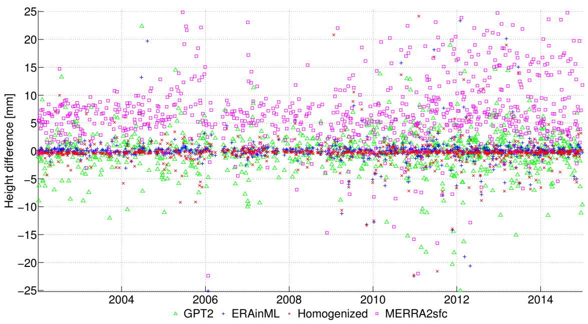

Fig. 4: Differences between the residual height estimates at Ny-Ålesund, Svalbard w. r. t. the first solution.

Mismodeling the ZHD is partly compensated by the ZWD estimates. For instance, if the recorded pressure series at a certain site has a significant[3] positive bias w. r. t. the actual one, the sign of the estimated ZWDs could be negative, indicating the modeling error. In such a case (e.g., Sejong, South Korea), the impact of the blunder is partly mitigated in all other parameters, but the inference of long term trends of IWV is not reliable. Here, a bias is found in the ZWD series of 5.4 mm, 12.2 mm, and 4.0 mm for solutions 2, 3, and 4 (over all stations) w. r. t. the first. When we employ the homogenized data set, the average bias is only 1.7 mm (Figure 5).

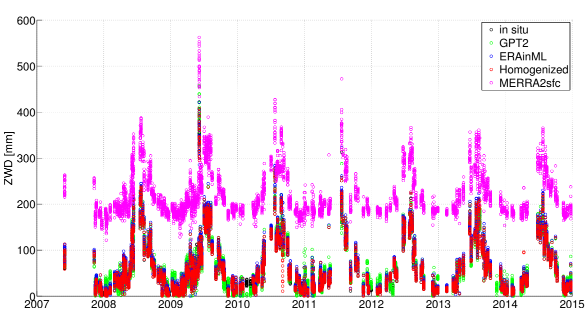

Fig. 5: Zenith wet delays at Badary, Russia.

[3] This is not a constant either over the VLBI sites or over time; e.g., for Wettzell, an artefact pressure increment larger than 30 hPa during summer will result in negative ZWDs.

We perform the seven-parameter Helmert transformation between the first solution and all others, in a session-wise manner. As illustrated in Figure 6, the scale factor is considerably distorted, when either GPT2 or MERRA2sfc are employed, as in addition to the scatter increase (2.5 mm, 7 mm) a bias is introduced (1 mm, 4 mm). On the contrary, respectively the impact of ERAinML is at the sub-millimeter level. The EOPs are not largely affected except for the MERRA2sfc solution where an increase in the WRMS of all series is observed, as well as a bias of 0.2 mas and -0.1 mas in the x and y terrestrial pole coordinates.

4 Conclusions

In this study, we address the inhomogeneities in the raw meteorological data available in the VLBI archive that are employed for VLBI data analysis, i.e. pressure and temperature. Five VLBI solutions were generated and the estimates intercompared. Data either from empirical models or the surface fields of NWMs bias the heights and consequently distort the scale of the resulting TRF. We recommend the use of a data set homogenized in a manner similar to the one presented here (ideally) or data extracted from the model levels of spatio-temporally dense (meso-beta scale) NWMs.

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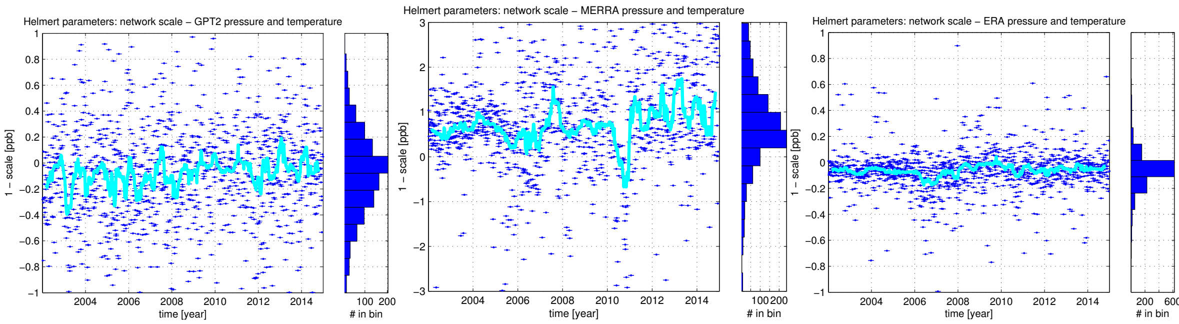
References

Balidakis K, Zus F, Douša J, Nilsson T, Glaser S, Soja B, Karbon M, Heinkelmann R, and Schuh H (2016) On the impact of different mapping functions on geodetic and tropospheric products from VLBI data analysis.



(a) GPT2 (b) MERRA2sfc (c) ERAinML

Fig. 6: The scale difference from the epoch-wise Helmert transformation between solutions w. r. t. the 1st.

In: Behrend D, Baver K, Armstrong K (eds), IVS 2016 General Meeting Proceedings, this volume.

Boehm J, Heinkelmann R, Schuh H (2007) Short note: A global model of pressure and temperature for geodetic applications. Journal of Geodesy 81(10):679–683.

Dee DP, with 35 co-authors (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society 137(656):553–597.

Dill R, Dobslaw H (2013) Numerical simulations of global-scale high-resolution hydrological crustal deformations. Journal of Geophysical Research: Solid Earth 118:5008–5017.

ECMWF (2015) Part III: Dynamics and Numerical Procedures, ECMWF. IFS Documentation, operational implementation 12 May 2015.

Förste C, with eight co-authors (2014) EIGEN-6C4 the latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse.

Heinkelmann R, Boehm J, Schuh H, Tesmer V (2009) The effect of meteorological input data on the VLBI reference frames. In: Drewes H (ed) Geodetic Reference Frames: IAG Symposium Munich, Germany, 9-14 October 2006, Springer Berlin Heidelberg, Berlin, Heidelberg, p 245–251.

Heinkelmann R, Balidakis K, Phogat A, Lu C, Mora-Diaz J, Nilsson T, Schuh H (2016) Effects of meteorological input data on the VLBI station coordinates, TRF and EOP. In: Freymueller J (ed) International Association of Geodesy Symposia, Prague 2015, *submitted*.

Kanamitsu M, Ebisuzaki W, Woollen J, Yang SK, J HJ, Fiorino M, L PG (2002) NCEP–DOE AMIP-II Reanalysis (R-2). Bulletin of the American Meteorological Society 83:1631–1643.

Lagler K, Schindelegger M, Böhm J, Krásná H, Nilsson T (2013) GPT2: Empirical slant delay model for radio space geodetic techniques. Geophysical Research Letters 40(6):1069–1073.

Nilsson T, Soja B, Karbon M, Heinkelmann R, Schuh H (2015) Application of Kalman filtering in VLBI data analysis. Earth, Planets and Space 67(1):1–9.

Nothnagel A (2008) Conventions on thermal expansion modelling of radio telescopes for geodetic and astrometric VLBI. Journal of Geodesy 83(8):787–792.

Nothnagel A, International VLBI Service for Geodesy and Astrometry (IVS) et al (2015) The IVS data input to ITRF2014. International VLBI Service for Geodesy and Astrometry, GFZ Data Services.

Petit G, Luzum B (eds) (2010) IERS Conventions (2010), IERS Technical Note, vol 36. Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany.

Rienecker MM, with 28 co–authors (2011) MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. Journal of Climate 24:3624–3648.

Schuh H, Behrend D (2012) VLBI: A fascinating technique for geodesy and astrometry. Journal of Geodynamics 61:68–80.

Wang XL, Wen QH, Wu Y (2007) Penalized maximal t test for detecting undocumented mean change in climate data series. Journal of Applied Meteorology and Climatology 46(6):916–931.