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# Atmospheric Loading Coefficients Determined from Homogeneously Reprocessed GPS and VLBI Height Time Series

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**Abstract.** This investigation compares homogeneously reprocessed VLBI (OCCAM6.1e at DGFI) and GPS (Bernese5.1 at GFZ and TUM) long-term height series. Furthermore, atmospheric loading coefficients are estimated from these series using local ECMWF pressure and simple linear regression. The VLBI and GPS data analysis used fully homogenized models in both software packages and the solutions were run twice, once with simple tropospheric modeling (NMF and constant a priori zenith delay) and once with state-of-the-art models (VMF1 and a priori zenith delay from ECMWF). The results indicate that the similarity between both techniques is better using the state-of-the-art models. However, a comparison of the loading signals derived from the VLBI- and GPS-estimated coefficients with time series of modeled atmospheric loading crustal displacements shows good agreement only for a few sites.

## 1. Introduction

This paper investigates two issues.

- "Can position time series be improved using state-of-the-art models?"

  by applying several criteria to the similarity of homogeneously reprocessed VLBI and GPS height series at colocations (e.g. estimated harmonic annual signals and atmospheric loading regression coefficients).

- "Can a simple regression approach describe the atmospheric loading signal compared to corrections computed from global approaches?"

  where regression-derived height corrections are compared to corrections described by [5].

## 2. Data

The VLBI and GPS height time series used in this investigation were completely reprocessed with data 1994 – 2005 (VLBI at DGFI with OCCAM 6.1, LSM [6], GPS at GFZ and TUM with Bernese 5.1 [3], for details on the reprocessing see [8]). They were computed twice with all models carefully adapted:

- **iteration 1:** using "old" models, e.g. NMF (Niell Mapping Function), constant a priori zenith delay (ZD),
- **iteration 2:** using "state-of-the-art" models, e.g. VMF1 (Vienna Mapping Function 1 [1]), a priori ZD computed from ECMWF [7] and thermal deformation correction for VLBI [6].

ECMWF pressure was used to estimate the atmospheric loading regression coefficients ($\Delta h = coef \cdot \Delta p$) from the height time series. The atmospheric loading crustal deformations to evaluate the regression approach are by [5].

## 3. Results I: Homogeneously Reprocessed VLBI and GPS Height Time Series

It is quite difficult to assess the similarity of daily VLBI and GPS height time series with objective criteria, as:

- if the a priori modeling is state-of-the-art, the expected signals usually are quite small compared to the noise floor of daily height estimates,
- there are not many VLBI- and GPS-colocation sites with a high number of overlapping observation days (we use 17 sites),
- the "daily" estimates for VLBI and GPS do usually not represent the same 24 h interval,
- the approach to compare time series must account for inhomogeneous formal errors of the estimated heights (especially for the VLBI data),
- some approaches to evaluate similarity of time series only account for linear dependency, like correlation coefficients, which will e.g. ignore differences in amplitudes of harmonic signals.

A discussion of this problem is given in [2], where a Kalman filter is applied.

### 3.1. Height Time Series

In a first step, the height time series of both iterations were compared after smoothing them by a weighted mean (±35 day windows each 7 days). Many of these VLBI- and GPS-series show a large number of episodic and annually recurrent common patterns, like the sites Wettzell (Germany, Fig. 1, left) and Ny-Ålesund (Spitsbergen, Norway, Fig. 1, right). [2] reveals comparable results using the ITRF2005 data. Nevertheless, not all sites show such a good similarity of VLBI and GPS, and for some of them, the VLBI sites do not have dense enough data to compare the data adequately.

Without sophisticated analysis, it is difficult to judge for which iteration the VLBI and GPS series are more similar (with exceptions like Ny-Ålesund). However, at some sites, one can see several patterns change from iteration 1 to 2, with the tendency to smoother behaviour for iteration 2 (see Fig. 1).

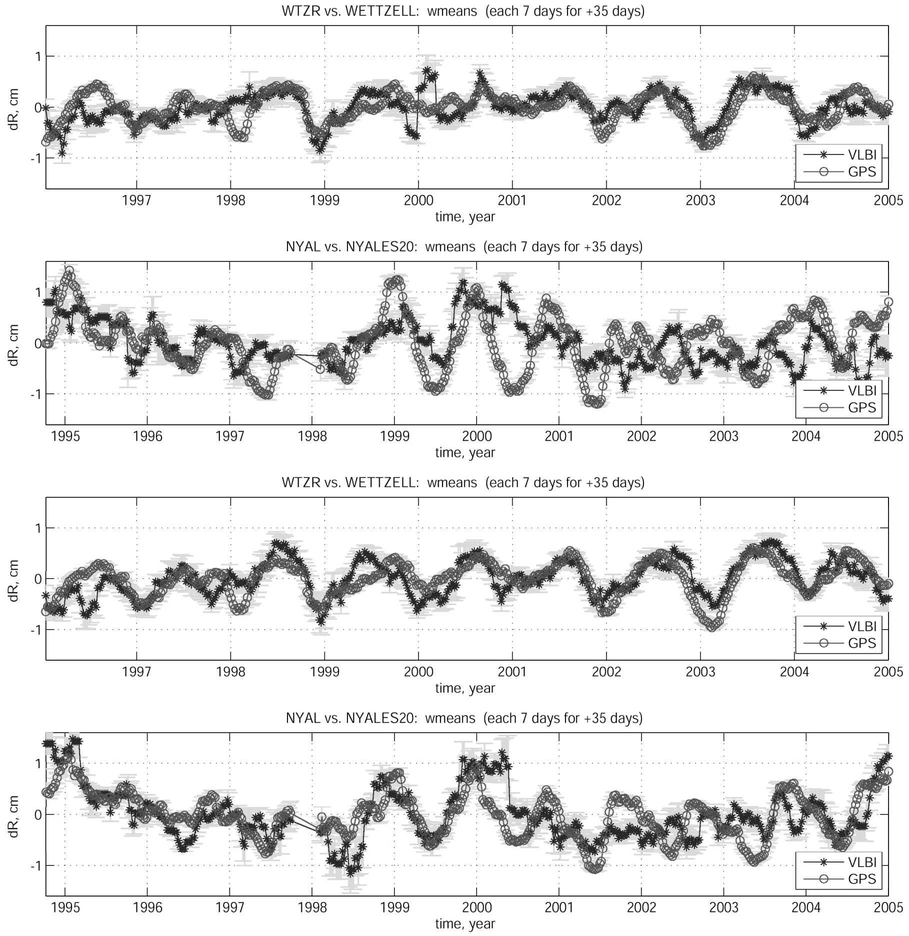

Figure 1. VLBI and GPS height series of the sites Wettzell (Germany, left) and Ny-Ålesund (Spitsbergen, Norway, right). The upper row illustrates the smoothed (70 day weighted mean) series of iteration 1, the lower row the ones of iteration 2

## 3.2. Annual Signals in Height Time Series

In order to get an impression of the improvement of the similarity between homogeneous VLBI and GPS height time series, it seems to be appropriate to have a closer look at the annual behaviour of the series. One possiblilty is to simply estimate harmonic annual signals from the VLBI and GPS series of both iterations and compute WRMS values for the VLBI-GPS differences of the amplitudes and phases (comparable studies have also been made by [2]).

If one of the compared series is not very dense or unevenly distributed, such a criterion should generally be more robust than comparing the time series directly, as the information extracted from the data is more compact than the time series themselves (although it might not be very robust in all cases).

For the 17 colocated sites, the VLBI-GPS differences of the amplitudes and phases of iteration 1 have a WRMS of 2.2 mm and 44° and 1.8 mm and 43° for iteration 2. As the series of iteration 2 is available beyond the year 2005 into 2007, this can additionally stabilize the similarity of the annual signals (the WRMS for all the data 1994 – 2007 of iteration 2 is 1.7 mm and 38°).

## 4. Results II: VLBI and GPS Estimated Atmospheric Loading Coefficients

In this section, we estimate atmospheric loading regression coefficients ($\Delta h = coef \cdot \Delta p$) from the VLBI and GPS time series, using "local" pressure interpolated from ECMWF. This approach has been applied several times, [4] gives an overview and compares the estimated coefficients of related publications. Theoretically, iteration 2 can better display the atmospheric loading deformation, as shortcomings of both, the mapping function and the constant a priori ZD of iteration 1 unintendedly absorb parts of this signal.

### 4.1. Atmospheric Loading Coefficients

Although computing atmospheric loading corrections by a linear regression coefficient multiplied with local pressure is a very basic approach to model crustal deformation, such coefficients have much more direct physical meaning than a harmonic annual signal. Like this, we hope to conclude that the iteration with smaller VLBI-GPS differences of the regression coefficients produces the more "physical" height series, as they represent more clearly "real" height motion rather than apparent motion, e.g. from tropospheric mismodeling.

Fig. 2 indicates that iteration 2 yields better results: firstly, the similarity of VLBI and GPS coefficients is much better for iteration 2 than 1 (the WRMS of the differences is 0.134/0.083 for iterations 1 and 2 in mm/mbar). This is quite robust, as using the full time series of station positions of iteration 2 up to 2007 only improves the WRMS slightly to 0.080 mm/mbar. Secondly, the similarity of these coefficients to those of the GGFC (Global Geophysical Fluids Center [11]) also improves much: the WRMS of the VLBI-GGFC differences is 0.301/0.154, of the GPS-GGFC differences 0.232/0.161 mm/mbar (iteration 1/2). The GGFC regression coefficients were fitted to NCEP pressure data 1980 – 1997 vs. modeled crustal displacements (by convolving Green's functions with inverse barometric ocean, see [10]).

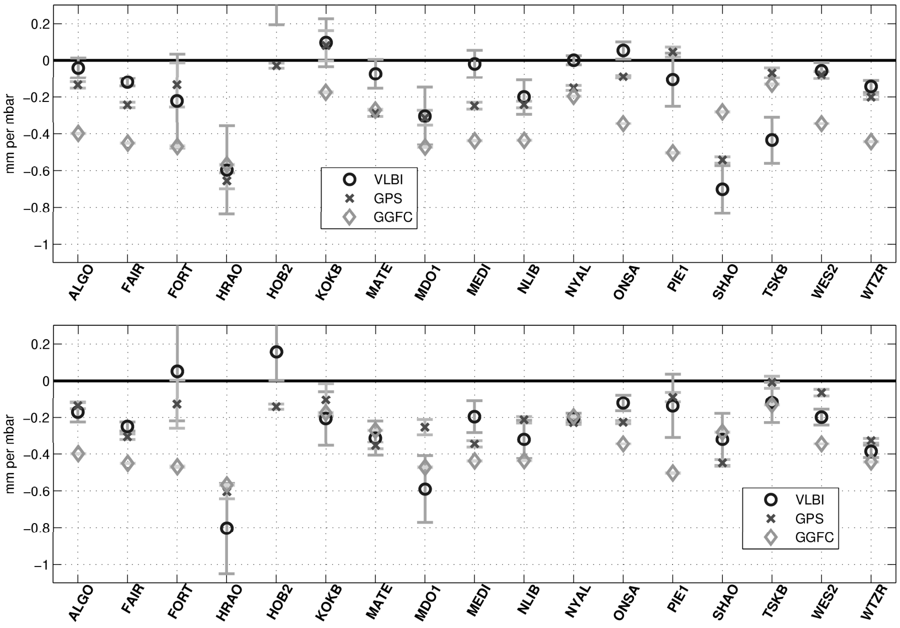

Figure 2. Atmospheric loading regression coefficients and their formal errors, determined from VLBI- (circles) and GPS- (crosses) height series (left/right: iteration 1/2), and coefficients provided by the GGFC (diamonds)

## 4.2. Comparing Pressure-Times-Coefficient Series to Modeled Crustal Displacements

To assess the “physical interpretability” of the estimated coefficients, we compared the correction series computed with the VLBI-derived coefficients and the local pressure to the modeled crustal displacements according to [5].

Fig. 3 is an example for good agreement. But zooming into the series (only 2005, on the right), it is very obvious that the corrections computed from the raw pressure (in black) have much more energy in the high frequency domain than the modeled crustal displacements (in grey).

This is why efforts were made to smooth the pressure-times-coefficient series with moving medians, computed for each data point (each 6 hours). Finally, a smoothing interval of 92 days was chosen, as the minima and maxima of the pressure-times-coefficient series for most of the stations then have the same order of magnitude as the modeled crustal displacements.

Gilmore Creek, Alaska (USA) and Hartebeesthoek (South Africa) in the upper row of Fig. 4 (with the smoothed pressure series), are examples for good accordance in the annual domain. However, for some stations variations on shorter time scales do not agree as indicated in the right graph of Fig. 3.

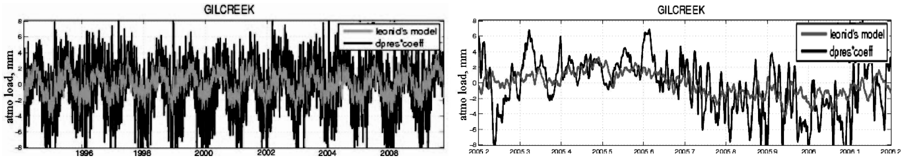

Figure 3. Comparison of corrections "raw-pressure-times-coefficient" (black) and modeled crustal displacements (grey) for Gilcreek. The right graph is the year 2005 zoomed

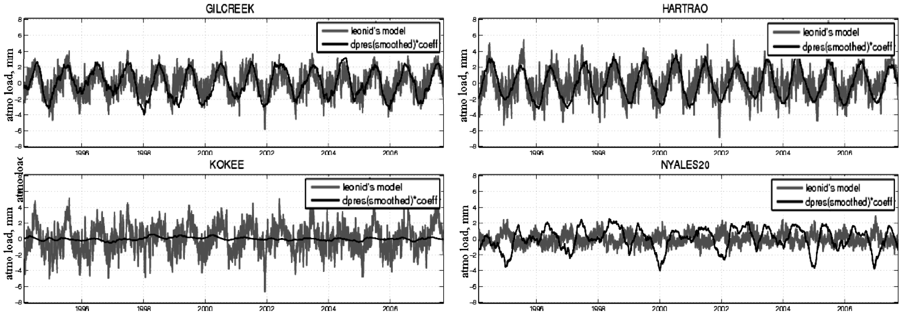

Figure 4. Comparison of "92-days-smoothed-pressure-times-coefficient" (black) and modeled crustal displacement series (grey) for the stations Gilcreek, Hartrao, Kokee and Nyales20

The lower row shows Kokee, Hawaii (USA) and Ny-Ålesund, examples for a bad agreement. Kokee has only 2 mbar RMS of pressure variations during 1994 – 2008 (the 17 sites have between 2 and 12 mbar RMS), and very small VLBI-, GPS- and GGFC-estimated coefficients (Fig. 2, right graph). Thus, almost no signal in the pressure-times-coefficient series are found. In contrary, the modeled crustal displacements clearly vary annually with ±3 mm, which is unexpected, as the deformations for the island Hawaii should be "damped" by the inverse barometric handling of the ocean. The two series for Ny-Ålesund even seem to show a different sign for many of the bump-like features. As for Kokee, the VLBI-, GPS- and GGFC-estimated coefficients for Ny-Ålesund agree well (Fig. 2, right graph). Possible reasons for the disagreements are:

- a linear regression model with local pressure is physically too simple,
- VLBI- and GPS-estimated coefficients are "polluted" by mismodeling,
- the modeled crustal displacements are not good enough in some areas.

## 5. Summary

- "Can position time series be improved using state-of-the-art models?"

  Using the iteration 2 data, the similarity of harmonic annual signals of homogeneous VLBI and GPS height series improves. This is particularly significant for the estimated atmospheric loading coefficients.

- "Can a simple regression approach describe the atmospheric loading signal compared to corrections computed from global approaches?"

> This needs further research: Comparing corrections computed by multiplying the VLBI-derived coefficients with local pressure with the modeled crustal displacements according to [5] makes clear, that sub-annual patterns in both series do not agree. The annual signal is in good accordance for some sites, for others not at all.

Next steps will be to investigate which approach improves geodetic results more (such as station position repeatability, similarity of EOP of the simultaneous CORE-A and NEOS-A VLBI sessions, etc).

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