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Strategies to mitigate aliasing of loading signals while estimating GPS frame parameters

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Abstract Although GNSS techniques are theoretically sensitive to the Earth center of mass, it is often preferable to remove intrinsic origin and scale information since they are known to be affected by systematic errors. This is usually done by estimating the parameters of a linearized similarity transformation which relates the quasi-instantaneous frames to a secular frame such as the International Terrestrial Reference Frame (ITRF). It is well known that non-linear station motions, not-accounted for in the secular ITRF, can partially alias into these parameters. We discuss in this paper some procedures that may allow reducing these aliasing effects in the case of the GNSS techniques, mainly GPS. The options include the use of well distributed sub-networks for the frame transformation estimation, the use of site loading corrections, a modification of the stochastic model by down-weighting heights, or the joint estimation of the low degrees of the deformation field. We confirm that the standard approach consisting of estimating the transformation over the whole network is particularly harmful for the loading signals if the network is not well distributed. Down-weighting the height component, using a uniform sub-network, or estimating the deformation field perform similarly in drastically reducing the aliasing effect amplitude. The application of these methods to reprocessed GPS terrestrial frames permits an assessment of the level of agreement between GPS and our loading model, which is found to be about 1.5 mm in height and 0.8 mm WRMS in the horizontal at the annual frequency. Aliased loading signals are not the main source of discrepancies between loading displacement models and GPS position time series.

Keywords Loading effects · Terrestrial Reference Frame · GNSS

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1 Introduction

Global Navigation Satellite System (GNSS) techniques are used to accurately monitor ground deformations, from a few minutes to decades. The most accurate processing strategies consist in processing GNSS data received at a wide set of global stations simultaneously using the most current and consistent models. All the phenomena that affect the GNSS observables need to be modeled, especially if their time scales of variation are shorter than the sampling rate of the estimated parameters. This is the case for solid Earth tides, pole tides, and ocean tidal loading effects which are well modeled (McCarthy and Petit, 2004). Non-tidal loading effects, which include the effect of the atmosphere, ocean circulation, and hydrological loading are still under investigation. Correlations have been noted with space geodetic results, either from GNSS (van Dam et al, 1994, 2001), Very Long Baseline Interferometry (VLBI) (van Dam and Herring, 1994; Petrov and Boy, 2004), Satellite Laser Ranging (SLR) and Doppler Orbitography Integrated on Satellites (DORIS) (Mangiarotti et al, 2001), but non-tidal loading effects are not yet recommended for operational GNSS data processing (Ray et al., 2007; see `http://www.bipm.org/utils/en/events/iers/Conv_PP1.txt`). Comparisons with space geodetic results are still needed to validate the models and to develop optimal strategies to attenuate systematic loading effects without introducing excessive modelling errors.

GPS, SLR, VLBI and DORIS position time series are expected to show similar variations if position time series are computed in the same reference frame and if the loading signatures are significant compared to measurement errors. However, technique-specific systematic errors limit the empirical correlations so far. For example, GPS apparent geocenter motion is not in agreement with expected values (Lavallée et al, 2006). A simple frame transformation is commonly used to remove global biases that affect all the station positions. A tridimensional similarity expresses station positions with respect to an external reference frame, usually the International Terrestrial Reference Frame (ITRF) or a related frame, by (where negligibly small non-linear terms have been dropped):

$$X^i(t) = T(t) + (1+\lambda(t)) \cdot [X^i_r(t_0) + \dot{X}^i_r \cdot (t-t_0)] + R(t) \cdot [X^i_r(t_0) + \dot{X}^i_r \cdot (t-t_0)] + \delta^i_{stat} \quad (1)$$

where X^i is the estimated position of station i at the epoch t, X^i_r and $\dot{X}^i_r$ are its position and velocity in the reference frame expressed at the epoch t_0, δ^i_{stat} is the noise term and T, R and λ are the transformation parameters, respectively, the translation vector, the antisymmetric rotation matrix and the scale factor at the epoch t. This transformation is also the basis for the minimum constraint equations that are sometimes used to regularize, with minimum information, station coordinates estimated with space geodetic techniques. Indeed, orientation should normally be constrained for all techniques, as well as the origin for VLBI.

It is known that applying such a transformation affects non-linear variations of the estimated time series of GPS station coordinates (Blewitt and Lavallée, 2000; Tregoning and van Dam, 2005; Collilieux et al, 2009). Indeed, as the ITRF is a secular frame (Altamimi et al, 2007), the station position seasonal variations can partly alias into the transformation parameters. This effect is not desired and can be problematic for many applications: comparison with loading models, inversion to estimate loading mass density distributions, or comparison of space geodetic results from different techniques. The aim of this paper is to quantitatively describe this aliasing effect and to review and evaluate procedures that could be used to reduce it. Section two describes the synthetic data that are constructed to evaluate various suggested procedures. Section three assesses the results of the tests carried out on the synthetic data to show the performances of the methods. And finally section four applies the procedures to real GPS solutions in order to compare GPS displacements with loading models.

2 Strategy

2.1 Method to compute position time series

This section recalls the most general method that can be used to compute position time series in an homogeneous reference frame from a set of daily/weekly solutions.

Firstly, a secular reference frame is needed. It is recommended to recompute secular positions and velocities for every station or for a subset of reliable stations from its own set of solutions. At this step, discontinuities should be identified in the position time series and modeled in the estimated secular frame $X_{ref}(t)$. The estimated long term coordinates should be referred to the adopted secular reference frame, for example, the ITRF, using stations showing the same discontinuity list. This step is necessary to avoid possible errors in the adopted secular frame or inconsistencies with the input dataset which may affect transformed position time series. Secondly, the transformation parameters should be estimated between each daily/weekly solution and the estimated secular coordinates of the epoch using equation (1). The next section will discuss different strategies for this purpose. Finally, detrended residuals $dX^i(t)$ can be computed as follow:

$$dX^i(t) = X^i(t) - X^i_{ref}(t) - [\hat{T}(t) + (\hat{R}(t) + \hat{\lambda}(t) \cdot I_3) \cdot X^i_0(t)] \quad (2)$$

where $X^i_0(t)$ are approximated coordinates of station i whereas trended residuals $tX^i(t)$ can be computed as follow:

$$tX^i(t) = X^i(t) - [\hat{T}(t) + (\hat{R}(t) + \hat{\lambda}(t) \cdot I_3) \cdot X^i_0(t)] \quad (3)$$

The first two steps can be merged into one single step as done in the CATREF software (Altamimi et al, 2007). However, less flexibility is allowed for the estimation of the transformation parameters. We will specifically discuss here the second step which consists in estimating transformation parameters. The differences between the various methods will be highlighted using synthetic data.

2.2 Synthetic data and tests

We have simulated GPS weekly station position sets as follows

$$X^i(t) = X^i_{itrf2008}(t) + (t - t_0) \cdot \dot{X}^i_{itrf2008} + \Delta^i_{load}(t) + \delta^i(t) \quad (4)$$

where $X^i(t)$ is the position vector of the station i at epoch t, $\Delta^i_{load}(t)$ is the loading displacement in the Center of Figure (CF) frame and $\delta^i(t)$ is a spatially correlated noise term. Station positions have been generated from 1998.0 to 2008.0, comprising 512 weeks. The real GPS network of the Massachusetts Institute of Technology (MIT) analysis center (MI1 reprocessed solution), which is the most inclusive of all the reprocessed GPS solutions, has been adopted and station positions have been simulated only when station parameters were available in their SINEX files. The full network is composed of 748 stations with many stations concentrated in North America and Europe. The vector of spatially correlated noise $\delta(t)$ has been simulated from the full covariance matrices of the MI1 solutions. The loading displacement model $\Delta^i_{load}(t)$ has been computed as the sum of three loading displacement models. The first includes the effect of the atmosphere at a 6-hour sampling rate according to the model of the National Center for Environmental Prediction surface pressure. The second is derived from the ECCO Ocean Bottom Pressure model at a sampling rate of 12 hours (JPL, 2008). The third predicts the hydrological effect at monthly intervals (Rodell et al, 2004). These models have been averaged or interpolated to weekly spacing before being merged. They specifically show power at the seasonal frequencies and especially the annual (Ray et al, 2008).

2.3 Description of tests

Synthetic data sets computed from equation 4 have been analyzed as if they were real data. We estimate the transformation parameters between the position set of week t and a secular reference frame expressed with respect to ITRF2008 preliminary solution (Altamimi, Z. and Collilieux, X. and Métivier, L., 2010). With real data, estimated transformation parameters are non-zero due to apparent geocenter motion (combination of Center of Mass (CM) displacement with respect to CF due to loads and systematic errors), conventional orientation of the weekly frame, GPS scale dependency with the satellite and ground antenna phase center offsets and variations, noise, and aliasing effects related to loading. No frame error has been introduced in equation 4 to construct the synthetic data, which means that estimated translation, rotation, and scale parameters from synthetic solutions only reflect noise and aliasing terms. Figure 1 shows the transformation parameters estimated from the synthetic data in the hereafter called *standard* approach: all the transformation parameters are estimated with all available stations. Significant aliased annual signals can be seen, especially in the X and Z translation components, in the scale factor, and also in the rotations. The extra noise variations in 2006 is related to the large variations of the variances of some point positions at the time of an Earthquake; Station SAMP (Indonesia) is the most affected. We have checked that this extra-noise does not change the conclusions shown here.

The columns of Table 1 enumerate the strategies that are tested here to reduce the aliasing error. Instead of using the whole set of available stations to estimate the transformation parameters, strategy *subnet* consists in using a well distributed subset of stations to compute the transformation parameters. Indeed, loading effects are spatially correlated and extracting a subset of stations is useful to avoid over-weighting those areas with a high station density, which accentuates the aliasing effect. Stations of the sub-network are chosen to have at least 80% of the full 11-year period covered by data and a limited set of discontinuities with segments longer than 20%. We followed the approach suggested by Collilieux et al (2007) to remove stations in dense areas and ensure a globally uniform distribution. However, we had to preserve some stations in poorly covered areas that did not exactly match the above criteria, specifically in the southern hemisphere.

It is also worth noting that the loading signals have larger amplitude in the height than in the horizontal components (Farrell, 1972). With respect to the 7-parameter transformation, loading effects can be considered as biases since they are not modeled, and this bias is more important in the vertical. As a consequence, down-weighting the height measurements has been suggested to reduce the aliasing effect (T. Herring, personal communication, 2009). This approach is already implemented in the Globk software (Herring, 2004). There are several ways to implement this down-weighting. We tested two approaches. First, we chose to use the inverse of the diagonal covariance matrix of the solution to weight the transformation but we modified the height formal error by a scaling factor. This approach is named hereafter *downdiag*. However, the off diagonal terms of the covariance matrices contain significant statistical information, which is important to preserve. So we also implemented the down-weighting of heights while preserving the correlation terms of the covariance matrices following Guo et al (2010), called *downfull*.

Another way to handle this problem is to change the frame transformation model to include information about the loading displacements:

$$X^i(t) = T(t) + (1 + \lambda(t)) \cdot [X_r^i(t) + \Delta_{load}^i(t)] \\ + R(t) \cdot [X_r^i(t) + \Delta_{load}^i(t)] + \delta_{stat}^i \quad (5)$$

It allows accounting for the non-linear variations of the reference frame. This approach is hereafter named *loadmod*. It has been shown to be equivalent to correcting daily/weekly station positions by the model prior to estimating the transformation parameters (Collilieux et al, 2010a).

Finally, we test the degree-1 deformation approach suggested by Lavallée et al (2006), equation (A6-A7), which consists in estimating the low degree spherical harmonics of the load mass density that generates the deformation field simultaneously with the transformation parameters, hereafter called *loadest*. Those authors were however interested in the degree 1 terms of the load surface density whereas we focus here on the transformation parameters. Please note that there is an error in equation (A7): $(\frac{3}{h+2l} - 1)$ should be replaced with $1/(\frac{h+2l}{3} - 1)$.

It is worth noting that in all these methods, the frame scale factor, λ, in equation 1 can be estimated or not.

2.4 Evaluation of the alias error

The outputs of all the processing methods described above are the transformation parameters. Once they are computed, they can be incorporated into equation (2) or (3) to compute the residuals of the station positions for every station. When synthetic data are processed, it is possible to quantify the effectiveness of all the methods by checking how close the estimated transformation parameters are to zero. As their effect on station positions is different from one site to another, we also compare the station position residuals to the loading displacements that have been used to create the synthetic data.

Note that the Weighted Root Mean Squares (WRMS) of the differences for station positions are dominated by noise. As a consequence, these statistics are not interesting to evaluate the aliasing effects. As the loading effects have a large signal at the annual frequency (see Figure 1), we choose to evaluate each method on its ability to properly recover the loading signal at the annual frequency in the station position time series.

3 Evaluation of the methods

3.1 Scale

Not estimating the scale in the frame transformation has been recommended by several authors (Tregoning and van Dam, 2005; Lavallée et al, 2006). Indeed, as can been noted in Figure 1, a large annual signal is observed in the scale when it is estimated in the *standard* approach. Figure 2a) shows, for every stations with sufficient data (more than three years), the comparison between the in phase and out of phase terms of the annual signals estimated in the station position time series residuals (computed by applying velocities and transformation parameters only) and the annual signals estimated in the loading models used to generate the data. The more closely the points are located on the diagonal, the more satisfactory the transformation is. It is interesting to note the systematic behavior of the annual signal. Most of the terms are over-estimated using the *standard* method, except the East component. As could be expected the height component is the most affected, especially the out of phase term which is biased by about 1 mm. If the scale is not estimated, see Figure 2b), the picture is almost unchanged for the horizontal components but the height annual signals are obviously better recovered. Figure 3a-b) shows the aliased loading signal in the translations and scale factors for these two cases. The translation parameters are almost unchanged when the scale factor is not estimated since the GPS network covers almost the whole globe.

Collilieux et al (2010b) showed that the annual variations observed in the newly reprocessed GPS scale factor can be partly explained by our loading model but not completely. However, the scale behavior is quite stable in time so that it is reasonable to estimate one constant scale factor for the whole period of time. This can be done in a one-step run if all the transformation parameter time series are estimated simultaneously or in a two-step approach by applying in a second step the mean scale factor to the reference solution. A 6-parameter transformation (no scale) can then be estimated. Unfortunately, most of the methods presented above cannot fully fix the problem of aliasing in the scale factor. The method consisting in incorporating the loading model in the transformation (*loadmod*) performs nicely, see Figure 2c) and Figure 3c), but only if the loading perfectly fits the GPS data (see section 4 for discussion). It is possible to reduce the annual signal in the scale when using a well distributed network of stations for the frame transformation, as discussed by Collilieux et al (2007). However, the performance of the method is variable and depends strongly on the sub-network. Indeed, we did not notice a reduction in the annual scale amplitude when studying our MIT well distributed sub-network either with synthetic or real data. Only the estimation of the deformation field, as already discussed by Lavallée et al (2006), seems to decrease significantly the scale factor annual signal (see section 3.4) but does not nullify it.

As a consequence, we will discuss the following results in the case of a 6-parameter frame transformation. The scale issue will be discussed further for strategy *loadest* only.

3.2 Down-weighting height

Transformation parameters obtained with the *standard* approach have been computed using the full covariance matrix of the solutions. It is worth noting that GPS height determinations are about 3 times less precise than the horizontals, which means that the height component is naturally down-weighted in the *standard* approach ($\sigma_{up} \approx 3 \cdot \sigma_{north}$).

Figure 2d-f) shows the results obtained when the whole network of stations is used to compute the transformation parameters while applying down-weighting of the heights (no scale estimated here). The only difference with 2b) is the weighting. Three different down-weighting strategies are shown. Height uncertainties were multiplied by 1.5 ($\sigma_{up} \approx 5 \cdot \sigma_{north}$) or by 3.0 ($\sigma_{up} \approx 10 \cdot \sigma_{north}$) but the correlations were preserved, Figure 2d-e). Correlations were cancelled in Figure 2f) ($\sigma_{up} \approx 10 \cdot \sigma_{north}$). It can be clearly noticed that down-weighting height has a positive effect for the horizontal components. When the height weight is slightly decreased, the pattern of the annual is closed to the *standard* case but the error has been significantly mitigated. Even the height agreement is improved with estimated correlations larger than 99% and mean deviations smaller than 0.3 mm for the in phase and out of phase terms. When the height weight decreases again (Figure 2e)), the agreement gets better. Indeed, the translation parameter along the x and y axes become smaller, see Figure 3d-e). However, there is a difference depending on whether the correlations are used or not in the weighting. The recovered annual term in the North component is different, compare Figure 2e) and Figure 2f), which is related to the differences in the x- and z-translations, see Figure 3e) and Figure 3f). The out of phase term is generally under-estimated in the full-weighting case whereas the in phase term is slightly over-estimated. However, the error is reasonable for both methods when synthetic data are studied. We also tried to decrease the height weight even more but the general level of agreement between the residuals and the true values did not improve significantly.

3.3 Using a sub-network

Restricting the transformation to a subset of stations is the most natural way to proceed. This is what is commonly done when some station coordinates that are weakly determined are rejected from the transformation estimation (with a simple outlier rejection test). Additionally, using a well distributed sub-network significantly reduces the transformation parameter biases. Our network is composed by 77 stations, selected following the criteria defined above. Figures 2g) and 3g) show the performance of the method. The biggest bias in the residual position time series is observed in the in phase annual term of the north component and in the out of phase term of the east component. The average error at the annual frequency is within 0.2 mm WRMS for this term which shows that the approach is reliable to mitigate aliasing effects. Aliased annual signals are reasonably small in the translation parameters although signal along the z axis is still visible. When the height was down-weighted conjointly by 1.5, the aliasing errors have slightly decreased but only by 0.1 mm annual WRMS in the in phase terms of the annual signal for the north and height components. For this particular weighting, it performs better to use a subset of stations than the full network. When the height uncertainty is multiplied by 3.0, the effect of the down-weighting tends to dominate which means that using either the sub-network or the full network give similar results.

3.4 Estimating the deformation field

We have seen above that using a loading model in the transformation is effective. The main limitation is the loading model accuracy and possible GPS systematic errors but another limitation is the availability of the loading model itself. Estimating the displacements caused by the loading of the Earth's crust is an alternative. However, due to the spatial distribution of GPS sites, it is only possible for the longest wavelengths of the deformation field. Following Wu et al (2003), we only estimated the load surface density coefficients up to the degree five. We also paid attention to model the deformation field in the CF frame, by adopting degree 1 load Love numbers in the CF (Blewitt, 2003), in order to estimate a translation which relates ITRF origin to GPS frame origin. Indeed, modeling the deformation field in the Center of Network frame (Wu et al, 2002) would have had no effect to reduce aliasing and modeling the deformation field in he CM would have removed the geocenter motion contribution from the estimated translation, which is not desired.

For comparison with the other approaches, we first plotted the results when the scale was fixed to zero. Although only low degrees are estimated, it can be noticed on Figure 2h) and 3h), built with a truncation degree equal to five, that the method is effective to reduce the aliasing effect. It performs better than any other in the horizontal and is as effective in the vertical. And here, the full covariance matrix has been used with no modification of the stochastic model. The full network of stations is also used, except those that have been identified as outliers in the least squares estimation process.

We also estimated the scale factor in the frame transformation as a test. The aliasing effect depends on the truncation degree of the spherical harmonic expansion of the load density. We noticed using the synthetic data that the scale factor annual signal amplitude becomes smaller than 0.2 mm for degree three up to degree six. Figure 3i) shows for example the estimated scale factor for a truncation degree of five. The variations of scale, compared to Figure 3a) are drastically reduced but inter-annual variations are not removed. We noted a larger annual signal in the scale factor estimated from real data with an amplitude of 0.6±0.1 mm for a truncation degree equal to five. This is however much smaller than the amplitude estimated in the standard approach which is 1.6 mm. If the estimation of the scale is needed, this approach is relevant but does not fully solve the aliasing issue, especially at the inter-annual frequencies.

3.5 NNR-condition

We discussed above the 7-parameter transformation which is used to constrain the frame origin, orientation, and scale. However, GPS is theoretically sensitive to the origin and scale of the frame so that only the orientation must be defined in principle. Constraining a normal matrix with the standard minimum constraint approach is equivalent to performing a non-weighted transformation between a conventionally oriented frame and the output frame. As a consequence, this constraint should affect the loading signal as well, but to a lesser extent since only orientation is considered. We performed the same computation as above but estimating only the rotation parameters when using the full network of stations (*standard*) or a well distributed sub-network (*subnet*). Aliased loading effects in the rotation parameters show repeatabilities smaller than 5.6 μas in any cases, which is about 0.15 mm. However, the annual signal amplitude in the X and Y component is divided by about 2 to reach 2.3 and 3.8 μas respectively when a sub-network is used. As a consequence, the impact on the position time series is quite small. The worst determined term is the in phase annual term in the North component for both *standard* and *subnet* strategies. While the correlation and WRMS of the in phase North term with respect to the true values are 86% and 0.2 mm for the standard case, it is however 96% and 0.1 mm when a well distributed sub-network is selected for the NNR condition. As a consequence, a well-distributed network is required for applying the NNR-condition and to recover annual signals in the horizontal at the level of 0.1 mm WRMS.

4 Application to real data

We applied here the approaches described above to real GPS position time series to see if the agreement between the GPS position time series and our loading model is improved compared to the *standard* approach. Figure 4 is similar to Figure 2, except that the annual signal plotted in the y axis comes from the analysis of the MI1 GPS data. The x axis still shows the annual signal estimated in the loading model over the same epochs of observations. Such a plot represents the level of agreement between GPS products and the loading model at the annual frequency, depending on the approach adopted to define the frame origin, orientation and scale. Figure 4a) shows the *standard* approach when the scale is estimated, as a reference. A clear bias can be observed, especially for the out of phase terms in the height, as seen with the synthetic data. As a consequence, for all the results that are shown next, the scale factor is not estimated. We also show on Figure 5a) the translations and scale factor estimated for the *standard* approach. Figure 5b-f) shows the differences between the estimated translations for alternative approaches and the *standard* approach.

Using the loading model in the transformation (*loadmod*), cf. Figure 4b), does not show better agreement between GPS and the loading model than any of the other methods: using a sub-network for the frame transformation (*subnet*), Figure 4c), down-weighting height (*downfull*), Figure 4d-e) or estimating the deformation field (*loadest*), Figure 4f). This shows that discrepancies between GPS displacements and the loading models are not related to the aliasing effects. It can be noticed on Figure 5 that translation differences with the *standard* approach reach about 1 mm at the annual frequency in the x and z axes. As observed with synthetic data, the agreement between the GPS North component annual term and the loading model is better when the aliasing is reduced. The *loadest* approach seems to perform slightly better than any of the other approaches. Indeed, the WRMS of the differences of annual signals (in phase and out of phase terms) and their correlations are smaller in all the components except the out of phase term in the North component. However, the fit with the loading model is satisfactory for the three other approaches although caution should be addressed to interpret the results of the *downfull* strategy. The North annual out of phase terms recovered when the height uncertainty is multiplied by three seem to be under-evaluated compared to any other approaches, which is not the case when the height uncertainty is multiplied by 1.5. This was not so obvious for the synthetic data although visible. We notice that this effect is related to larger difference in the z translation annual signal, see Figure 5e). As a consequence, using an uncertainty scaling factor of 1.5 or using diagonal weight only is preferred. We think it is always better not to affect the stochastic model, which is why we favor using either a well distributed network for the frame transformation or estimating the low degree coefficients of the deformation field simultaneously.

Lavallée et al (2006) suggested two approaches to estimate the low degrees of the load surface density. We adopted here the so-called degree-1 deformation approach since we wanted to remove the absorbed loading signal in the translations while preserving the geocenter motion in these parameters. The CM-approach consists in modelling the deformation field in the CM frame and estimating rotation parameters only since GPS is theoretically sensitive to CM. The two approaches lead to two distinct estimates of the deformation field. As an illustration, Table 2 supplies the annual signals estimated in the geocenter motion time series computed from the degree-1 coefficients. Differences may reach up to 2.2 mm in the amplitudes and may exceed one month in phase. Forward loading model from Collilieux et al (2009) is supplied as a comparison but any of the two estimations really seem to fit better to the loading model. However, the aliasing effect reduction using these two distinct deformation fields is similar which validates the degree-1 deformation field used for the purpose of aliasing mitigation in this study. We also reported in Table 2 the opposite of the translation estimated with degree-1 deformation approach. It can be observed that apparent reprocessed GPS geocenter motion is still not reliable.

Thanks to the different tests we did, we are now able to conclude about the level of agreement between the GPS position time series and the loading model. Indeed, we can reasonably exclude the aliasing effect as being a major source of discrepancies. When looking at figure 4f), the following general comments can be formulated. The agreement of the annual signal in the Height component is good in average since all the points are located along the diagonal. The mean discrepancy is 1.6 *mm* for the in phase term and 1.5 *mm* for the out phase term. In the horizontal, the loading model generally shows a smaller amplitude than the GPS and the agreement for the in phase and out of phase term of the annual signals is less than 0.8 for both components. These results are encouraging but discrepancies are still quite important. The horizontal component signals of the GPS stations should be investigated further in the future studies, especially by comparing GPS results with different loading models and the results of the Gravity Recovery and Climate Experiment (GRACE) to better understand the origin of the discrepancies shown here.

5 Conclusion and recommendations

We reviewed the procedures that can be used to modify the origin, orientation, and scale of a time series of GPS frames. We paid attention to discuss the transformations which preserve the loading signals that are inherently contained in the station coordinates. This is especially important in order to interpret correctly the non-linear variations in the station position time series. We showed using synthetic data that the standard approach consisting in using the largest set of stations in the frame transformation is not optimal whether the scale is estimated or not. The scale parameter should be definitively fixed to a constant value over time or its seasonal variations fixed to zero. But a rigorous approach is possible only if all the frame time series are analyzed in one unique estimation process. The benefit of using an alternative approach is especially important for the horizontal component annual signal. Down-weighting height, restricting the station set to a well distributed sub-network, or estimating the low degrees of the load surface density all perform well. The well distributed network approach is the easiest to implement whereas the height down-weighting may seem difficult to comprehend due to the modification of the stochastic model. A slight advantage is given to the third method consisting in estimating the deformation field, which is almost free of any systematic bias according to our simulations. Thanks to this study, we were able to conclude that aliasing effect is not the main source of discrepancy between GPS position time series and the loading models. Annual signals are shown to agree at the 1.5 mm level in the height and the 0.8 mm level in the horizontal. Further studies are needed to understand the sources of the remaining inconsistencies.

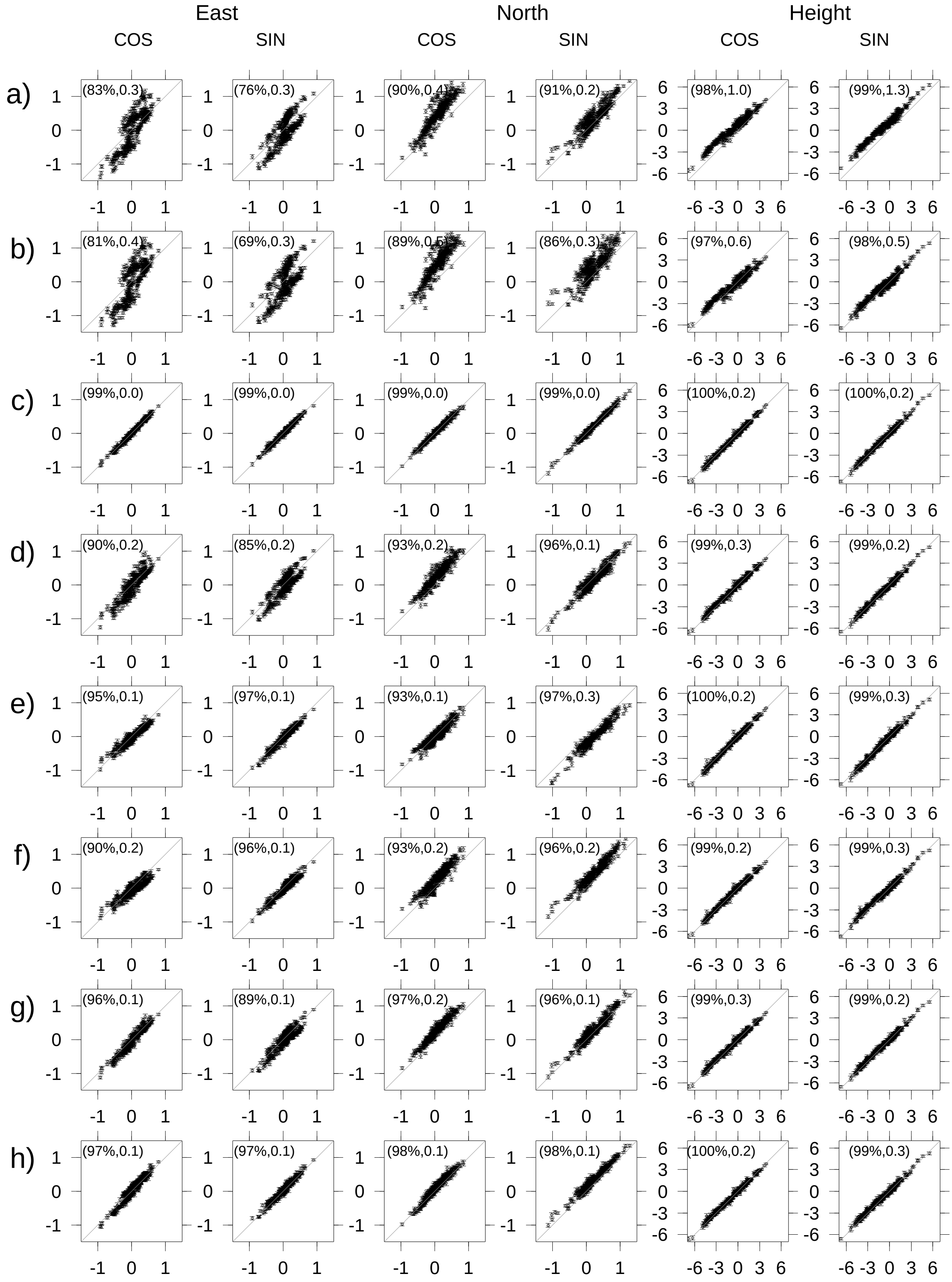

Fig. 2 Comparison of the annual signal estimated in the residuals of the frame transformation as defined in section 2.3 (y axis) applied to synthetic data, and the annual signal estimated in the loading model that has been used to generate the synthetic data (x axis) in millimeters. In phase term (COS) and out of phase term (SIN) are presented for the East, North and Height components from the left to the right for the different strategies presented in section 2.2. a) *standard*, scale estimated; b) *standard*, scale not estimated; c) *loadmod*, scale estimated; d) *downfull* height standard deviations multiplied by 1.5; e) *downfull* height standard deviations multiplied by 3.0; f) *downdiag* height standard deviations multiplied by 3.0; g)*subnet*; h)*loadest*. Scale factors have not been estimated for d) to h). Numbers inside the brackets for each plot are the correlation coefficient and the WRMS of the differences in millimeters.

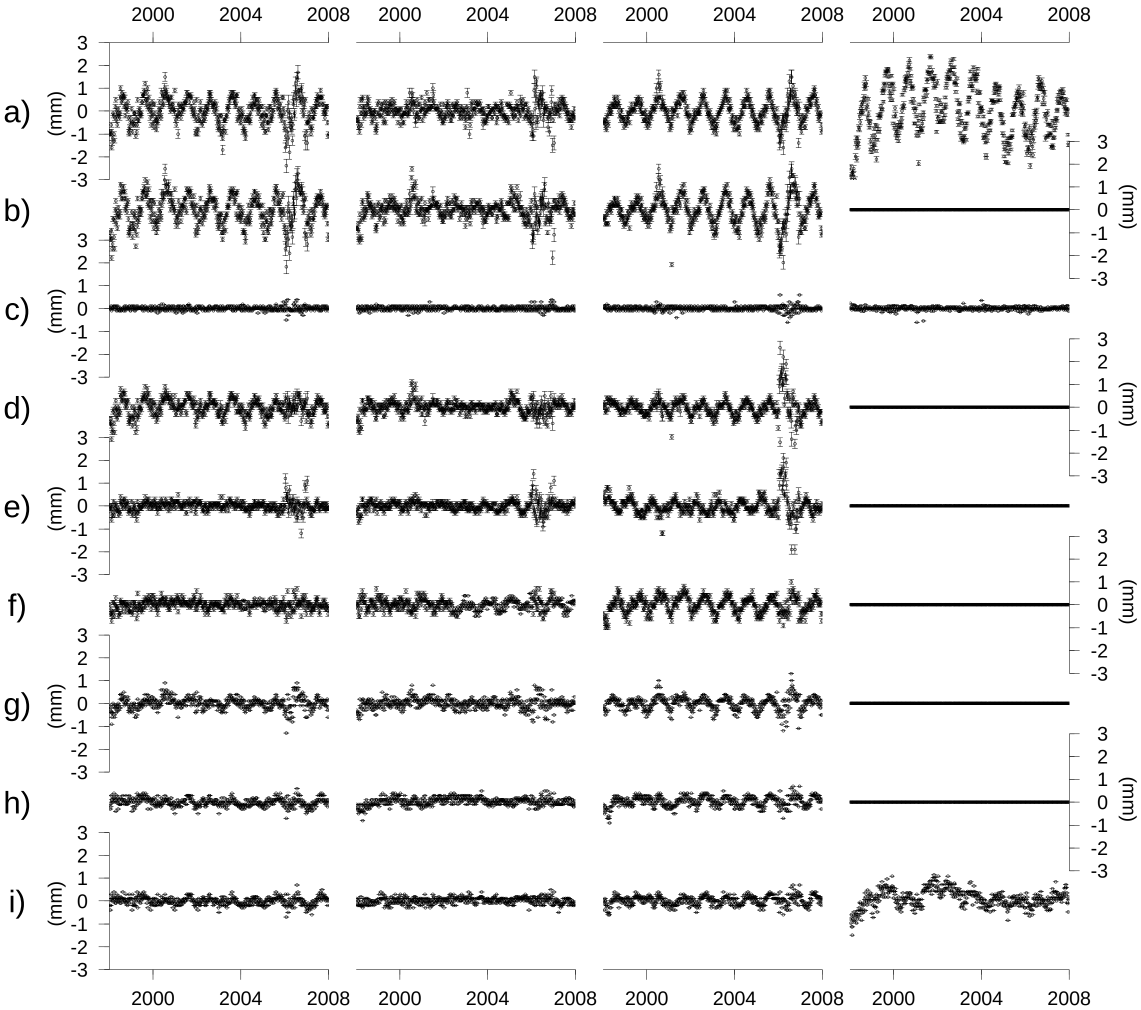

Fig. 3 Translations along the x, y and z axis in millimeters and scale factors in millimeters (ppb value multiplied by 6.4) estimated from synthetic weekly frames and the secular frame. A different strategy has been used for each row. See the legend of Figure 2 for rows a) to h). Strategy used for row i) is identical to row h) except that the scale factor has been also estimated.

Table 1 Strategies used in this study to estimate the transformation between a weekly/daily frame and a secular frame.

Options	*standard*	*subnet*	*downfull*	*downdiag*	*loadmod*	*loadest*
Stations used	All	Well distributed Sub-network	All	All	All	All
Weight matrix	Full	Full	Full, Height down-weighted	Diagonal, Height down-weighted	Full	Full
Loading Corrections	No	No	No	No	Yes	No
load density parameters	No	No	No	No	No	Up to degree 5

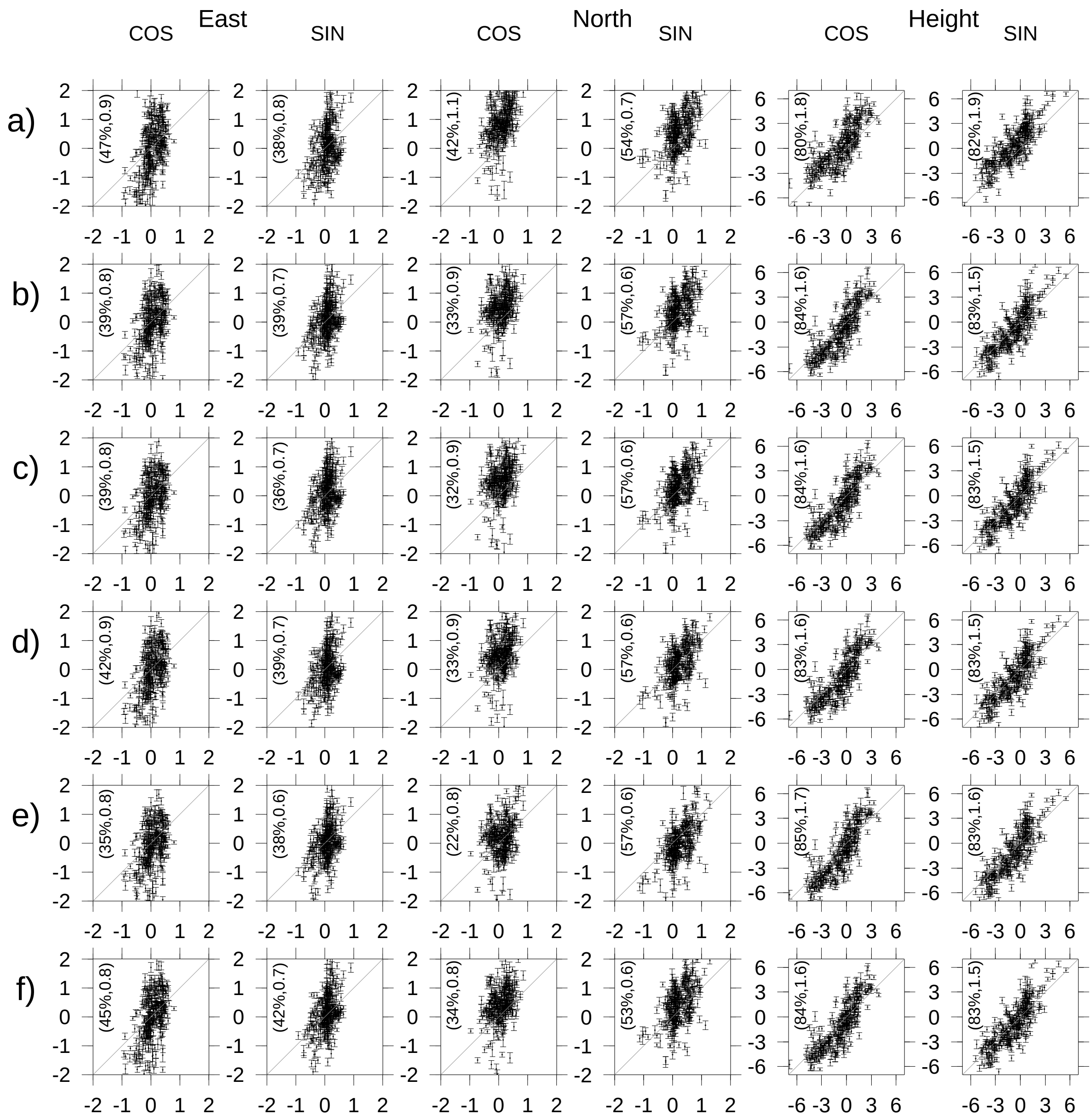

Fig. 4 Comparison of the annual signal estimated in the residuals of the frame transformation as defined in section 2.3 (y axis) applied to real data, and the annual signal estimated in the loading model (x axis) in millimeters. a) *standard*, scale estimated; b) *loadmod*; c) *subnet*; d) *downfull* height standard deviations multiplied by 1.5; e) *downfull* height standard deviations multiplied by 3.0; f) *loadest*. Scale factors have not been estimated for b) to f). Same legend as figure 2.

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References

Altamimi Z, Collilieux X, Legrand J, Garayt B, Boucher C (2007) ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters. J Geophys Res 112(B09401), DOI

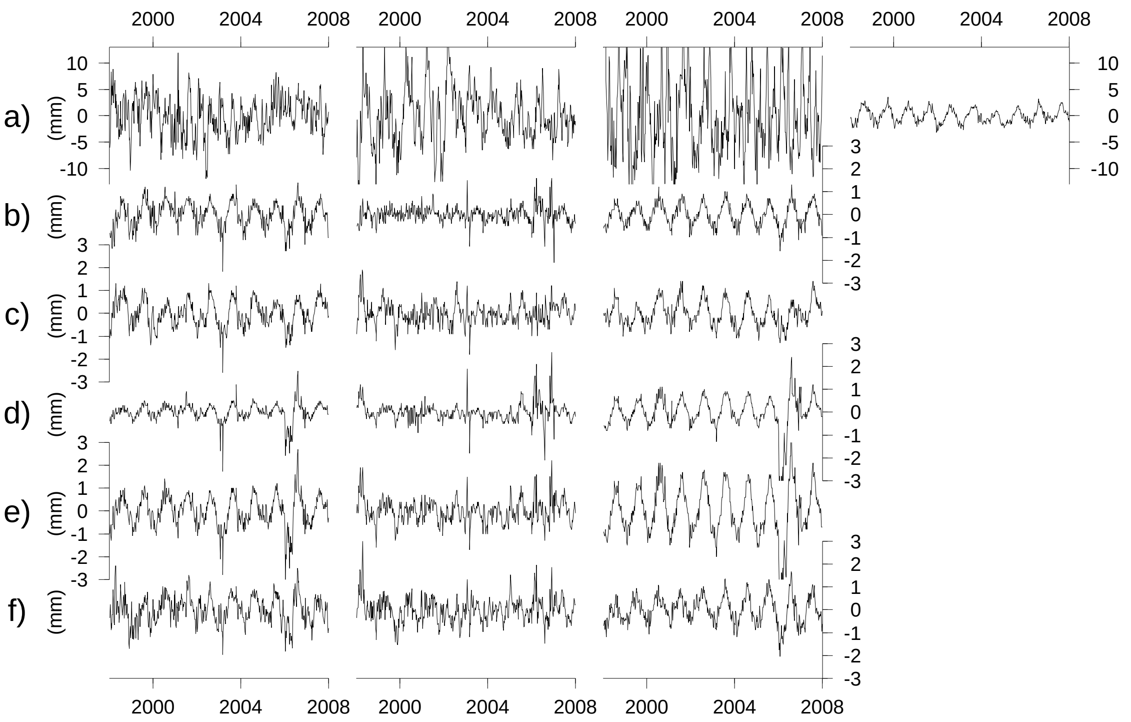

Fig. 5 a) Translations along the x, y and z axis in millimeters and scale factors in millimeters (ppb value multiplied by 6.4) estimated from mi1 weekly frames and the secular frame. b-f) Differences between translation parameters estimated with tested strategies and those derived from the standard method shown in a). See the legend of Figure 4.

Table 2 Estimations of the geocenter motion (CM w.r.t. CF) from GPS mi1 solution with two different strategies. Phase are supplied according to the model $A \cdot \cos(2\pi \cdot (t - 2000.0) - \phi)$ with t in year.

	X amplitude mm	X phase degrees	Y amplitude mm	Y phase degrees	Z amplitude mm	Z phase degrees
degree-1 deformation approach	3.8±0.3	48±4	2.0±0.2	3±5	7.9±0.5	38±3
CM-approach	1.0±0.2	71±9	2.4±0.2	310±5	4.5±0.3	51±4
opposite of the Translation from degree-1 deformation approach	0.4±0.2	165±0	3.6±0.3	302± 5	4.4±0.5	125±7
Loading model (Collilieux et al, 2009)	2.1±0.1	28 ±2	2.1±0.1	338 ± 2	2.7±0.1	48 ± 2

10.1029/2007JB004949

Altamimi, Z and Collilieux, X and Métivier, L (2010) ITRF2008: an improved solution of the International Terrestrial Reference Frame. Journal of Geodesy in-press, DOI 10.1007/s00190-011-0444-4

Blewitt G (2003) Self-consistency in reference frames, geocenter definition, and surface loading of the solid Earth. J Geophys Res 108

Blewitt G, Lavallée D (2000) Effect of annually repeating signals on geodetic velocity estimates. Tenth General Assembly of the WEGENER Project (WEGENER 2000), San Fernando, Spain, Septembre 18-20

Collilieux X, Altamimi Z, Coulot D, Ray J, Sillard P (2007) Comparison of very long baseline interferometry, GPS, and satellite laser ranging height residuals from ITRF2005 using spectral and correlation methods. J Geophys Res 112(B12403), DOI 10.1029/2007JB004933

Collilieux X, Altamimi Z, Ray J, van Dam T, Wu X (2009) Effect of the satellite laser ranging network distribution on geocenter motion estimation. J Geophys Res 114:4402–+, DOI 10.1029/2008JB005727

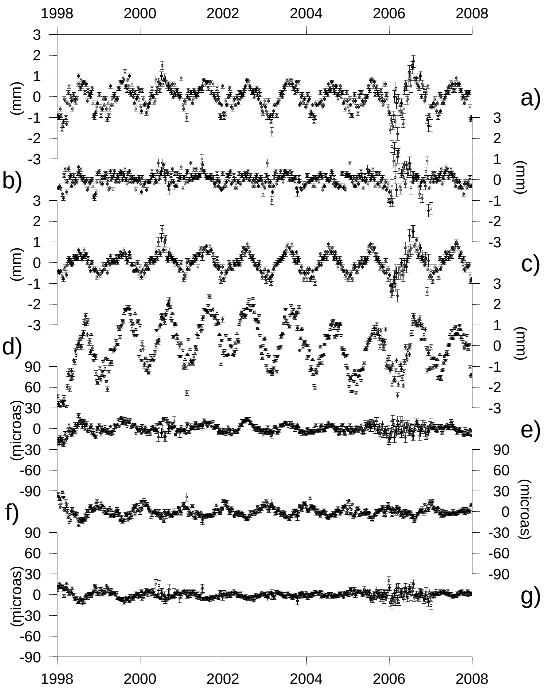

Fig. 1 Transformation parameters estimated from synthetic data computed with the whole network of stations (*standard*). a) x-translation b) y-translation c) z-translation d) scale factor in millimeter (value in ppb scaled by 6.4) x-rotation f) y-rotation g) z-rotation.

Collilieux X, Altamimi Z, Coulot D, van Dam T, Ray J (2010a) Impact of loading effects on determination of the International Terrestrial Reference Frame. Adv Space Res 45:144–154, DOI 10.1016/j.asr.2009.08.024

Collilieux X, Métivier L, Altamimi Z, van Dam T, Ray J (2010b) Quality assessment of GPS reprocessed Terrestrial Reference Frame. GPS Solutions inpress, DOI 10.1007/s10291-010-0184-6

Farrell WE (1972) Deformation of the Earth by Surface Loads. Reviews of Geophysics and Space Physics 10:761–+

Guo J, Ou J, Wang H (2010) Robust estimation for correlated observations: two local sensitivity-based downweighting strategies . J Geodesy 84(4):243–250, DOI 0.1007/s00190-009-0361-y

Herring T (2004) GLOBK: Global Kalman filter VLBI and GPS analysis program version 4.1. Tech. rep., Mass. Inst. of Technol., Cambridge

JPL (2008) Ecco ocean data assimilation. http://eccojplnasagov/

Lavallée DA, van Dam TM, Blewitt G, Clarke PJ (2006) Geocenter motions from GPS: A unified observation model. J Geophys Res 111:5405, DOI 10.1029/2005JB003784

Mangiarotti S, Cazenave A, Soudarin L, Crétaux JF (2001) Annual vertical crustal motions predicted from surface mass redistribution and observed by space geodesy. J Geophys Res 106:4277–4292, DOI 10.1029/2000JB900347

McCarthy D, Petit G (2004) IERS Technical Note 32 - IERS Conventions (2003). Tech. rep., Verlag des Bundesamts fur Kartographie und Geodasie, Frankfurt am Main, Germany, also available at http://maia.usno.navy.mil/conv2003.html

Petrov L, Boy J (2004) Study of the atmospheric pressure loading signal in very long baseline interferometry observations. J Geophys Res p 3405, DOI 10.1029/2003JB002500

Ray J, Altamimi Z, Collilieux X, van Dam TM (2008) Anomalous harmonics in the spectra of gps position estimates. GPS solution pp 55–64, DOI 10.1007/s10291-007-0067-7

Rodell M, Houser PR, Jambor U, Gottschalck J, Mitchell K, Meng CJ, Arsenault K, Cosgrove B, Radakovich J, Bosilovich M, Entin JK, Walker JP, Lohmann D, Toll D (2004) The Global Land Data Assimilation System. Bull Amer Meteor Soc 85(3):381–394

Tregoning P, van Dam TM (2005) Effects of atmospheric pressure loading and seven-parameter transformations on estimates of geocenter motion and station heights from space geodetic observations. J Geophys Res 110:3408, DOI 10.1029/2004JB003334

van Dam TM, Herring TA (1994) Detection of atmospheric pressure loading using very long baseline interferometry measurements. J Geophys Res 99:4505–5417

van Dam TM, Blewitt G, Heflin MB (1994) Atmospheric pressure loading effects on Global Positioning System coordinate determinations. J Geophys Res 99:23,939–23,950, DOI 10.1029/94JB02122

van Dam TM, Wahr J, Milly PCD, Shmakin AB, Blewitt G, Lavallée D, Larson KM (2001) Crustal displacements due to continental water loading. Geophys Res Lett 28:651–654, DOI 10.1029/2000GL012120

Wessel P, Smith WHF (1991) Free software helps map and display data. EOS Transactions 72:441–441, DOI 10.1029/90EO00319

Wu X, Argus DF, Heflin MB, Ivins ER, Webb FH (2002) Site distribution and aliasing effects in the inversion for load coefficients and geocenter motion from GPS data. Geophys Res Lett 29:63–1, DOI

10.1029/2002GL016324
Wu X, Heflin MB, Ivins ER, Argus DF, Webb FH (2003) Large-scale global surface mass variations inferred from GPS measurements of load-induced deformation. Geophys Res Lett 30:5–1, DOI doi:10.1029/2003GL017546