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Precision and accuracy of GPS-derived station displacements

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ABSTRACT

Space geodetic techniques like Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) provide valuable input for, e.g., studies of Global Isostatic Adjustment (GIA). This paper discusses the current precision and accuracy of GPS-derived vertical and horizontal station displacements. The precision is evaluated by repeatabilities and solutions computed from different subintervals of the data available. However, due to systematic effects, the precision is often much better than the accuracy. The accuracy is evaluated by comparisons of the space geodetic techniques amongst each other and comparisons with geophysical models for atmospherical and hydrological loading. Besides the analysis of time series, co-located GNSS, SLR, and VLBI sites allow for a comparison of velocities estimated in Terrestrial Reference Frame (TRF) solutions of the different techniques.

1. Introduction

Deformation processes of the solid Earth can be monitored with the space geodetic techniques, e.g., Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI). For most applications it is important to have an impression of the reliability of the estimated station coordinates and velocities. Precision and accuracy are two widely used terms to quantify the reliability. Accuracy describes the deviation of estimated parameters from the true value. Precision refers to the closeness of agreement (scatter) between individual parameters. Repeatability, on the other hand, quantifies the precision for a limited time interval, e.g., the standard deviation (STD, measure for the dispersion around a mean value) of daily solutions w.r.t. a weekly solution. If the parameters are computed in a least squares adjustment, formal errors can be derived from the covariance matrix. Due to unmodeled correlations of the observations and systematic errors, the formal errors resulting from the adjustment of GNSS observations are usually by far to optimistic. This is in particular true for the station positions and velocities estimated in a Terrestrial Reference Frame (TRF) solution.

Therefore, Williams et al. (2004) used different noise models and a maximum likelihood (ML) approach to get more realistic error estimates. Several authors already assessed the accuracy by comparisons of space geodetic techniques amongst each other. Campbell (2003) compared the station heights of GPS and VLBI sites and found an agreement on the level of 1 mm/y. Kierulf et al. (2009) studied the velocities from two GPS sites, three DORIS sites, and the VLBI telescope located at Ny-Ålesund. Although using outdated models for the GPS processing, they achieved velocity accuracies based on statistical methods of 0.2–0.9 mm/y. Willis and Heflin (2004) found a consistency level between DORIS- and GPS-derived velocities of 2.4–3.3 mm/y.

In contrast to the other space geodetic techniques, GNSS receivers are quite cheap and can thus be used as dense tracking networks. Therefore, primarily GNSS stations are used to study Global Isostatic Adjustment (GIA, e.g., Lidberg et al., 2007; Sella et al., 2007; Árnadóttir et al., 2009; Bradley et al., 2009) and also this paper focusses on the accuracy and precision of one particular GNSS, namely the Global Positioning System (GPS). However, the independent techniques SLR and VLBI are used for the validation of GPS-derived velocities.

Section 2 describes the GPS, SLR and VLBI solutions discussed in this paper. The precision of the GPS solutions is assessed in terms of repeatabilities and comparisons of co-located GPS sites for time series as well as TRF solutions in Section 3. Finally, Section 4 evaluates the accuracy by comparisons of the GPS solutions with SLR and VLBI as well as geophysical series.

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2. Space geodetic solutions

Homogeneously reprocessed coordinate solutions are a prerequisite for a reliable assessment of the precision and accuracy. Therefore, the solution series discussed in this paper are all completely reprocessed starting with the observation data. The first GPS solution is the contribution of the Center for Orbit Determination in Europe (CODE, Dach et al., 2009) analysis center to the IGS (International GNSS Service, Dow et al., 2009) reprocessing (Steigenberger et al., 2008). This solution was computed with the Bernese GPS Software (Dach et al., 2007) and covers the time period January 1994 until December 2008 with a network of 244 sites. Different temporal resolutions (1-day, 3-day, weekly) are available but mainly the weekly solutions are discussed in this paper. Details on previous reprocessed GPS solutions generated with a similar processing scheme can be found in Steigenberger et al. (2006, 2009a).

The second GPS solution as well as the SLR and VLBI solutions (used for the validation of the GPS results of this paper) originate from the GGOS-D project (Rothacher et al., 2010). In this project, much effort was spent on the homogenization of the software packages used for the processing of space geodetic observations as regards modeling and parameterization. Therefore, a maximum level of consistency of the SLR and VLBI solutions used for the comparisons with GPS is guaranteed. The GPS solution was also computed with the Bernese GPS software and covers the time period January 1994 until December 2006. Only daily solutions are available. The SLR solution is a combination of two contributions from Deutsches Geodätisches Forschungsinstitut (DGFI) and Deutsches GeoForschungsZentrum (GFZ). Range measurement to Lageos-1 and -2 were processed for the time interval January 1993 until December 2006. The combined VLBI solution covers the time period January 1984 until December 2006. Two independent software packages were used to compute the contributions to the combination: OCCAM v6.1 (Titov et al., 2004) for the solution of DGFI and the Calc/Solve (Petrov, 2006) for the solution of Institut für Geodäsie und Geoinformation (IGG) of the University of Bonn. More details on the GPS, SLR and VLBI solutions as well as on the combination are given in Steigenberger et al. (2010).

3. Precision

3.1. Time series

The deviation of individual (e.g., daily) solutions from a combined (e.g., weekly) solution can be used to quantify the precision. These so-called repeatabilities of seven individual coordinate solutions compared to the corresponding weekly solutions are shown in Fig. 1 for the reprocessed CODE series (i.e., one dot per week and coordinate component). The repeatability values improve with time due to the densification of the network resulting in shorter baselines and thus enabling a more successful ambiguity resolution. A further aspect responsible for the larger repeatabilities in the early years is the quality of the measurements provided by the receivers, in particular the bad code quality of old ROGUE receivers (the dominating receiver type in the early years). As high-quality code observations are essential for the Melbourne-Wübbena ambiguity resolution, this solution strategy was skipped for baselines between sites with one or even both receivers belonging to the ROGUE group. With decreasing baseline lengths (due to an increasing number of sites) and the replacement of the ROGUE receivers, the repeatability decreases. The mean repeatabilities for the reprocessed solution are 1.7 mm, 2.3 mm and 4.4 mm for the north, east and up component with median values of 1.4 mm, 1.9 mm and 4.1 mm, respectively. The repeatability nowadays is on the level of about 1 mm for the horizontal and 3 mm for the vertical component.

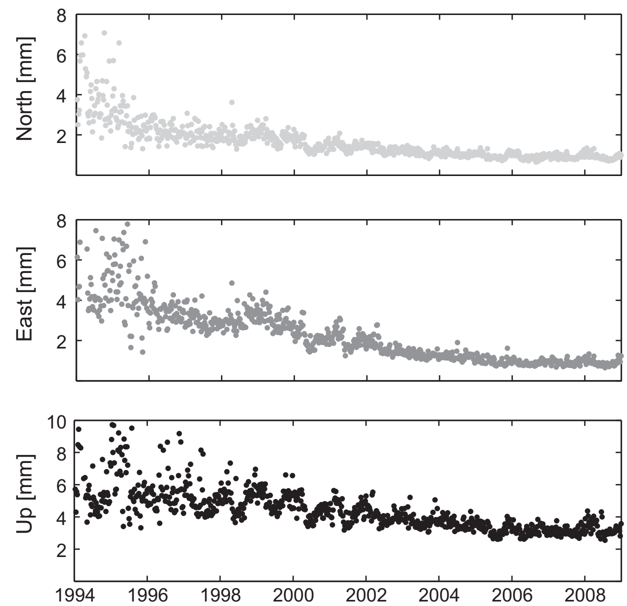

Fig. 1. Daily station coordinate repeatabilities w.r.t. weekly solutions derived from the CODE reprocessing. The mean repeatabilities are $\overline{N} = 1.7$ mm, $\overline{E} = 2.3$ mm, $\overline{U} = 4.4$ mm. Note the different scale of the height component.

Co-located GPS sites (i.e., two or more GPS antennas and receivers operated in parallel at one station) can also be used to assess the precision of GPS-derived station coordinate time series. However, the quality of the time series of one individual site or both sites might be affected by site-specific systematic effects. Table 1 lists STDs of co-located GPS sites of the CODE reprocessing. Only stations with more than 52 common weeks are considered for the comparison. Several of the larger STD values can be explained by systematic effects. The huge STD of the up component of Thule is related to a degraded tracking performance of the THU1 site (observation rate of about 65% only) after an outage in the middle of 2001 resulting in quite noisy coordinate time series. As this problem persists until the end of the operation of THU1 (beginning of 2003) and THU3 tracking only started in September 2001, the whole comparisons of Thule are corrupted by this problem. As the time series of Tromsø is affected by two discontinuities due to antenna changes at the TRO1 site, also subintervals without discontinuities are given. After the antenna change in 2004, the STD values are significantly smaller except for the height component of the last interval. However, the STD values are in general below 2 mm for the horizontal and 4 mm for the vertical component. In addition, one has to keep in mind that the precision of a single station is smaller by a factor of $\sqrt{2}$ as the STD values of the differences of two stations are shown in Table 1.

3.2. Terrestrial reference frame

TRF solutions currently include the estimation of station positions for a reference epoch and linear station velocities. As a number of GPS stations are affected by discontinuities due to equipment changes, new station positions are estimated if a discontinuity has been detected. For the TRF studies described in this section, the GGOS-D data was used. The time spans of 13 years of data allow for stable TRF solution. The general strategy of estimating GPS-only TRFs follows Steigenberger et al. (2009b). The geodetic datum was defined by no-net-rotation (NNR) conditions for