Abstract. The parameter space that can be covered by GPS, VLBI and SLR is very broad, and many overlaps exist between the techniques. Up to now, this is not yet fully exploited in inter-technique comparisons and combinations as in most cases only station positions and Earth orientation parameters (EOP) are considered. In this contribution we include the troposphere parameters additionally, and it is demonstrated that a combined terrestrial reference frame (TRF) improves the agreement of the GPS- and VLBI-derived troposphere zenith delays (ZD). The benefit of a combination is shown for the EOP as well, although non-continuous VLBI observations complicate the situation for Universal Time (UT). Finally, the potential of connecting GPS and SLR by estimating degree one spherical harmonic coefficients of the Earth’s gravity field is analyzed.

Keywords: EOP, troposphere parameters, low-degree spherical harmonics, rigorous combination

1 Introduction

Many solutions from the space-geodetic techniques are available through the International Earth Rotation and Reference Systems Service (IERS) and its technique-specific services. However, in most cases the provided time series show systematic biases and reveal differences that result from the application of different models during the analyses of the observations. In order to give one example, Schmid et al. (2005) demonstrated that the usage of phase centre models for GPS antennas that were calibrated relatively to one reference antenna instead of absolutely calibrated models causes significant biases in the ZD of several millimetres. All differences in the a priori models that were used to generate solutions show up as discrepancies in the estimated parameters. In order to overcome this problem, GeoForschungsZentrum Potsdam, Deutsches Geodätisches Forschungsinstitut, Institute for Geodesy and Geoinformation of the University of Bonn and Bundesamt für Kartographie und Geodäsie joined forces. Within this group, a broad variety of expertise concerning the analysis of GPS, VLBI and SLR is available so that high-quality solutions for all of these techniques could be generated. The alignment of the analysis standards within the group goes considerably beyond the IERS Conventions 2003 (McCarthy and Petit 2004) and their updates, as detailed agreements were made concerning the models used for, e.g., pole tide, ocean loading, a priori ZD delay, mapping function for the troposphere delay, a priori nutation, or the method of interpolating the a priori EOP to the epochs of observation.

2 Analysis strategy

2.1 Processing procedure

The analysis can be divided into four major steps:

- analysis of the observations for the year 2004 using the pre-defined common standards to get single-technique normal equations (NEQs),
- generation of yearly single-technique solutions,
- generation of weekly combined NEQs,
- generation of a yearly solution based on the weekly combined NEQs of the preceding step.

The full reprocessing of all observations (step 1) delivers homogeneous time series for each technique. The GPS analysis was done with the Bernese GPS Software 5.0 (Dach et al. 2007), EPOS at GFZ was used for the SLR analysis, and two VLBI solutions computed with CalcSolve (Petrov 2002) and Occam (Titov et al. 2004) have been combined to an intra-technique VLBI solution according to Vennebusch et al. (2007). It must be emphasized that the application of common analysis standards in all these software packages guarantees a high level of homogeneity.
between the techniques, although the homogenization can still be improved. Another important advantage of our studies is the extended parameter space. Normally, just station coordinates and EOP are provided in the solutions available via the IERS. We included additionally station-specific troposphere parameters (2D and horizontal gradients) for GPS and VLBI, geocentre coordinates for GPS, and spherical harmonic coefficients (SH) of the Earth’s gravity field for SLR (degree 1-2). Amongst others, Pavlis (2004) showed that the estimation of low-degree SH from SLR observations is reasonable. The datum-free NEQs resulting from step 1 cover one week in the case of GPS and SLR, and 24 hours in the case of VLBI, where 129 global and eight regional sessions were selected. The regional sessions do not allow a reasonable estimation of EOP, but they deliver a valuable densification for the TRF.

Yearly single-technique solutions were generated in the second step. This step is necessary to get an idea about the potential of each technique and, thus, to realistically assess the quality that can be expected for the combined solution. An internal measure for the quality of the solutions is the repeatability of station coordinates (Table 1). The quite dense network of almost 200 GPS sites reveals the best stability with a weekly repeatability of about 2 mm for the horizontal components and a factor three worse for the height. Correlations of the height with the troposphere delay and the clocks are responsible for the worse stability compared to the horizontal components. This behaviour is visible for the VLBI solution as well, but its repeatability is worse by a factor of about two compared to GPS. However, it must be kept in mind that the VLBI network is less dense and determined with 24-hour sessions. SLR, with the same amount of stations but weekly solutions, is less precise than VLBI. Considering that we have a single SLR solution and that all sites contribute to the repeatabilities, the order of magnitude agrees well within that shown by Bianco et al. (2006). Comparing with other analysis (e.g. Altamimi et al. 2007), it must be emphasized that we use an RMS instead of WRMS, and internal comparisons showed that this difference is especially important for VLBI and SLR where the formal errors are strongly varying. The 3D repeatabilities were used for a relative weighting of the technique-specific NEQs in the combination.

Finally, a yearly solution based on the previously generated weekly combined NEQ was computed in order to have a homogeneous TRF as basis for the time series of EOP and troposphere parameters. The TRF datum has been defined by a sub-set of good GPS sites using a no-net-rotation and no-net-translation condition w.r.t. ITRF2000 (Altamimi et al. 2002). As we estimate the SH of degree one from SLR data, SLR itself cannot contribute to the translational datum. The SH of degree one and the geocentre coordinates from SLR and GPS, respectively, are not combined as we first want to analyze the estimates regarding any systematic differences.

The connection between the three techniques’ networks was realized by the application of local ties (LT) at co-located sites. An overview of the co-locations available for our analysis is given in Fig. 1 (at the end). Altogether there are 30 VLBI-GPS co-locations, 23 SLR-GPS co-locations and therein six stations where all three techniques are assembled. Unfortunately, no further VLBI-SLR co-locations are available so that these networks are connected mainly indirectly via GPS. After a careful selection, we applied LT for 23 VLBI-GPS and 21 SLR-GPS co-locations.

### Table 1: Repeatability of station coordinates for the single-technique solutions in [mm].

<table>
<thead>
<tr>
<th>Solution</th>
<th>#Stations</th>
<th>North</th>
<th>East</th>
<th>Up</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS (week)</td>
<td>185</td>
<td>1.91</td>
<td>1.80</td>
<td>5.66</td>
<td>3.60</td>
</tr>
<tr>
<td>VLBI (day)</td>
<td>33</td>
<td>4.65</td>
<td>4.00</td>
<td>11.09</td>
<td>7.32</td>
</tr>
<tr>
<td>SLR (week)</td>
<td>32</td>
<td>15.61</td>
<td>17.16</td>
<td>17.13</td>
<td>16.65</td>
</tr>
</tbody>
</table>

### 2.2 Combination strategy for EOP

It is essential to say some words about the parameterization and the combination strategy for EOP to understand and interpret the results. Figure 2 visualizes the basic principle. The difficulty in combining daily EOP from satellite techniques and VLBI is due to the data coverage: GPS and SLR observe continuously whereas gaps occur between two consecutive 24 h VLBI sessions so that a continuous time series at daily intervals cannot be derived. An additional problem arises because VLBI sessions typically start at 17 or 18 UTC. Thus, the balance point of all observations, where offset and drift parameters are estimated best, differs from 12 UTC. We deal with this situation in such a way that we change the parameterization in the NEQs from offset/drift per session into a linear function with two values at 0 and 24 UTC (“polygon 0h-0h”) which can then be stacked with the appropriate midnight epochs of the piece-wise linear parameterization used for the continuous time series (“continuous polygon”) derived from GPS and SLR. It is clear that a VLBI-only time series consisting of offsets given at the mid-epochs of the sessions is more stable than a time series of estimates at 0 h. Thus, if the best VLBI-only estimates are of interest, the EOP offsets at the mid-epochs of the sessions should be considered. However, if we