Orbit determination for GIOVE-A using SLR tracking data

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Abstract

The first European navigation test bed satellite GIOVE-A was launched on 28 December 2005. SLR observations of GIOVE-A, collected from the ILRS tracking network, are available since 21 May 2006. SLR data are primarily needed for the validation of the microwave-based orbit. As no microwave tracking data are available until now, the orbit determination based on SLR data is of high interest. We present GIOVE-A orbit determination results based on SLR-only data. In addition, the contribution of SLR data to the microwave-based orbit determination is demonstrated.

For the SLR-based orbit determination of GIOVE-A SLR data of the first GIOVE-A SLR tracking campaign were used. Orbits with different arc lengths were determined, as well as orbit predictions. Orbit overlaps were derived to assess the orbit quality. SLR-based orbits of 9-days arc length were determined with an accuracy of about 10 cm in radial orbit component, and about 0.5 m and 1 m in along-track and out-of-plane components.

The microwave-based GIOVE-A orbits as well as the first Galileo orbits in the In Orbit Validation (IOV) phase will rely on microwave tracking data of a very limited number of stations. Therefore, SLR would give an important contribution to the orbit determination through a combined analysis of microwave and SLR data. The possible improvement of the orbit accuracy including SLR observations is demonstrated on the basis of an a priori variance-covariance analysis. For this purpose SLR range measurements and simulated microwave data of GIOVE-A are used.

1. Introduction

Galileo, the European global navigation satellite system (GNSS), is presently being developed. The first of two “Galileo In-Orbit Validation Element” test satellites, GIOVE-A (GSTB/V2A), was successfully launched on 28 December 2005. It carries a retroreflector array and can thus be observed by Satellite Laser Ranging (SLR). For evaluating the characterization of the on-board atomic clocks a first SLR tracking campaign on GIOVE-A was initiated. Between 22 May and 24 July 2006, 14 globally distributed SLR stations participated in the campaign.

As no microwave tracking data are available for scientific use, the orbit determination based on SLR is of high interest. In Section 2, we present first results of the GIOVE-A orbit determination using SLR data of the tracking campaign. Different orbit solutions with varying arc-length were determined. In order to assess the orbit quality, orbit overlaps were computed and compared with each other. In addition, orbit predictions were generated and evaluated by comparing the predicted orbits with the orbits derived from real tracking data.

Orbit determination of GIOVE-A (and the first Galileo satellites as well) based on microwave observations will rely on data of a very limited number of microwave tracking receivers in the beginning. In view of this situation, SLR data would give an important contribution for precise orbit determination. SLR data may significantly improve the orbit estimates used in addition to the microwave data in a combined analysis. Section 3 shows results of an a priori variance-covariance analysis, demonstrating the possible positive impact of additional SLR data on GIOVE-A orbit determination. For this purpose, simulated microwave data and real SLR data from the tracking campaign were used.

2. GIOVE-A orbit determination using SLR observations

In this Section, we present first GIOVE-A orbit determination results based on SLR data only. SLR data collected during the first GIOVE-A SLR tracking campaign lasting nine weeks (May 22 – July 24, 2006) were used. The SLR data are provided by the International Laser Ranging Service (ILRS) (Pearlman et al., 2002). The triangles in Figure 1 indicate the geographical location of the 11 SLR sites that were included in our analysis. Note that we did not use SLR measurements of San Juan (located in South America), as no official terrestrial reference frame coordinates have been available at the time of analysis.

The temporal distribution of the SLR tracking data is shown in Figure 2. Each line represents 24 hours of a particular day. SLR observation epochs are indicated with a bar. The varying data coverage is clearly visible. Thus, the quality of the orbits derived from these data will vary, depending on the available SLR data.

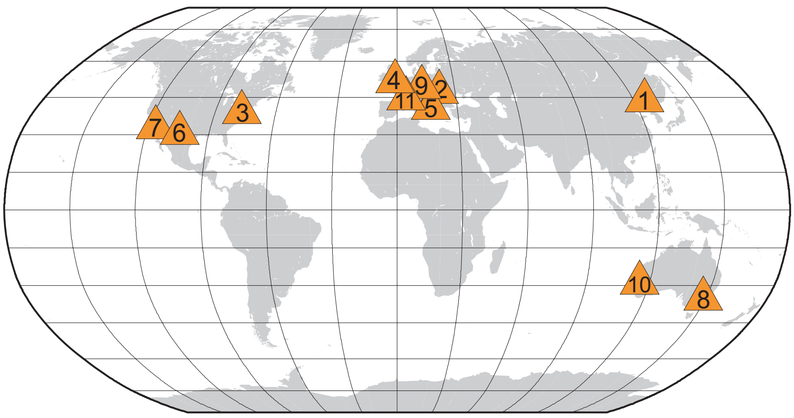

Figure 1. *Geographical location of the 11 SLR sites used for orbit determination*

In each orbit determination process six osculating elements and nine dynamical orbit parameters were estimated. The dynamical parameters represent solar radiation pressure (SRP) parameters defined in the SRP frame (D,Y,X). The SRP frame origin corresponds to the satellite's center of mass. The D-axis points towards the Sun, the Y-axis points along the solar panel axis, and the X-axis completes the right-handed system. The nine estimated SRP parameters are three constant acceleration (in D,Y, and, X direction) as well as six once per orbit revolution sinusoidal accelerations (sine and cosine in D, Y, and X direction).

Different orbits solutions were prepared using arc-lengths of n-days (n = 5, 7, 9, 11, 14) in order to estimate the arc-length that leads to the best possible orbit quality. The Bernese GPS Software Version 5.0 (Hugentobler et al., 2005) was used for the parameter estimation.

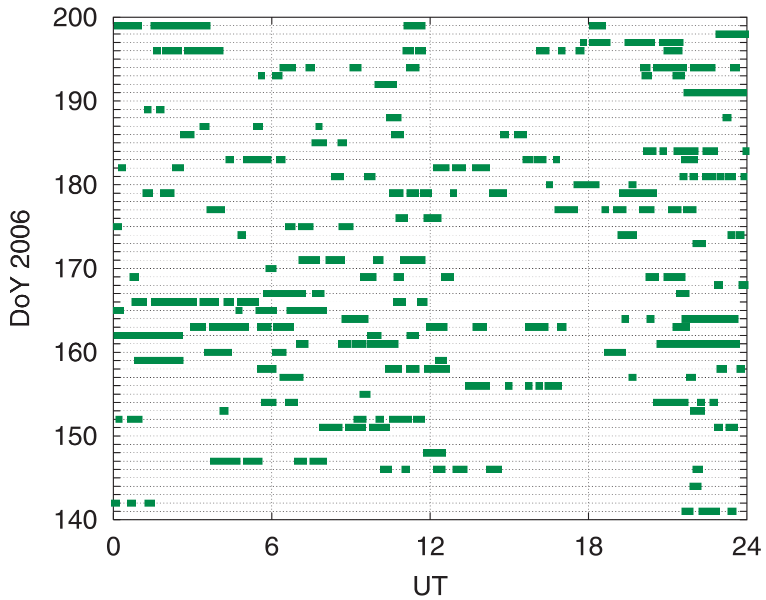

Figure 2. *SLR data coverage of the GIOVE-A SLR tracking campaign*

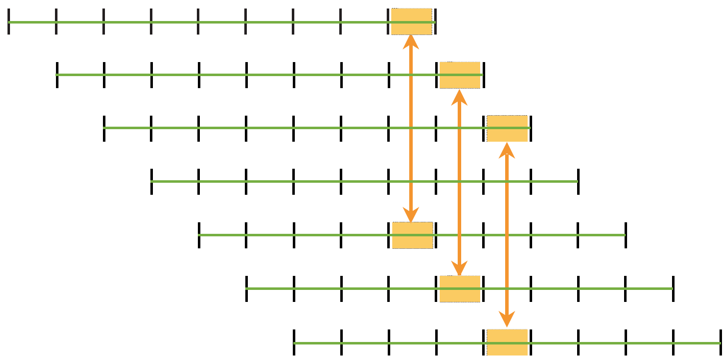

Figure 3. *Sketch illustrating the generation of orbit overlaps for 9-day arcs; orbit overlap is the orbit difference between last and central day*

For each solution we generated between 32 and 50 n-day arcs within the 60 days interval of the SLR tracking campaign of GIOVE-A. Consecutive n-day arcs are shifted by one day each. Thus, overlapping orbits can be generated. The resulting orbit differences (referred to as orbit overlaps in the following) indicate the orbit quality. Small overlaps indicate a good quality, whereas large overlaps indicate a bad quality of the determined orbit. We assume that the central part of an arc is best defined and that the boundary parts of an arc are worst defined. The overlap analysis concept is to compare the last day of an arc with the corresponding central day of another arc of the same arc-length, as illustrated in Figure 3. In the sketch each line represents a 9-day arc, day boundaries are indicated. The arrows show the orbital parts that are compared with each other.

Figure 4 shows the orbit overlaps of the GIOVE-A 9-day arcs. This arc length of 9 days has proved to be the best one, as the overlaps of the other orbit solutions with arc lengths of 5, 7, 11, or 14 days are larger. The orbit overlaps vary significantly, as the orbit quality is highly correlated with the number and temporal distribution of the SLR observations. Arcs with less or badly distributed observations are determined worse. Satellite maneuvers might also cause problems, if they are not considered in the orbit model. The radial orbit overlaps (top chart in Figure 4) show values of up to 10 cm. The radial component is best defined, as the SLR ranges represent observations mainly in radial direction. Orbit overlaps in along-track and out-of-plane components vary up to

1 m and 2 m, respectively. For arcs with a good temporal distribution of SLR data the orbit overlaps are smaller with values up to 0.5 m in along-track and 1 m in out-of-plane component. The formal errors of the satellite positions in the orbit system (radial, along-track, out-of-plane) show corresponding magnitudes similar to the overlap values.

Figure 5 displays the range residuals derived from the 9-day arc solution. The standard deviation of the residuals is about 2 cm, which is within the range of the accuracy of the SLR observations. SLR observations are assumed to be accurate at the 1-2 cm level.

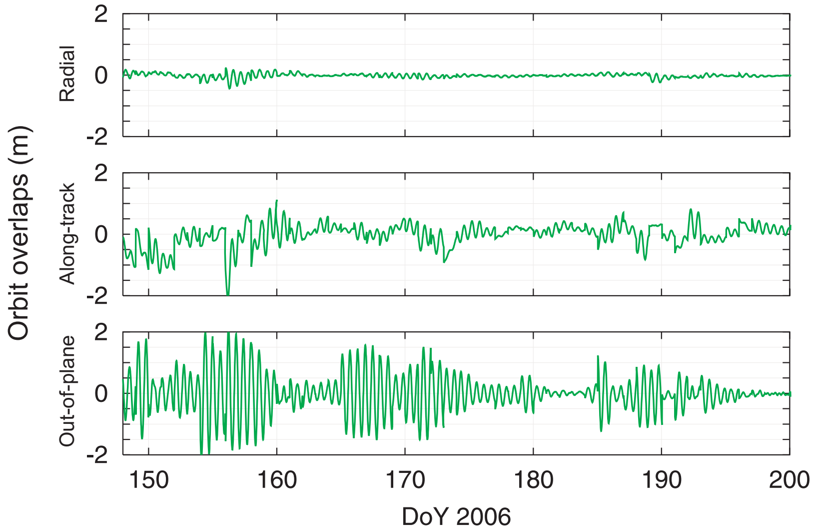

Figure 4. *Orbit overlaps of SLR-based 9-day arcs of GIOVE-A; orbit overlaps are the orbit differences between the central days and the last days of the corresponding 9-day arcs*

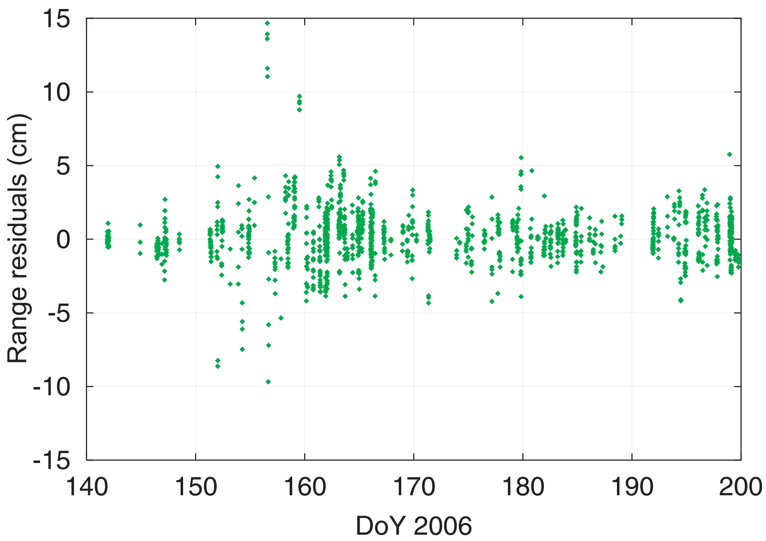

Figure 5. *Range residuals derived from SLR-based 9-day arcs of GIOVE-A*

In addition to the SLR-based 9-day arcs, we computed consecutive 5-day orbit predictions. For the overlap computation, each predicted day is compared with the corresponding central day of the orbit part covered by SLR observations, as illustrated in Figure 6. Thus, for each 9-day arc overlaps of the five prediction days are generated.

Figure 7 shows the orbit overlaps for all prediction days of all orbital arcs. The predictions are getting worse in time due to the accumulated orbit errors. The computed prediction overlaps are dominated by the along-track error of the orbital arc, as this error increases exponential in time. The overlaps indicate a potential orbit accuracy of about 20-30 m after 5 days of prediction.

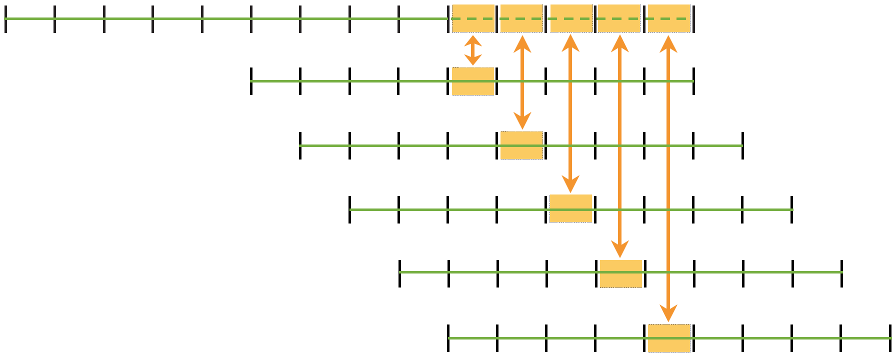

Figure 6. *Sketch illustrating the generation of orbit overlaps for 9-day arcs with 5 day predictions; orbit overlap is the orbit difference between each prediction day and the corresponding central day of the orbit part covered by SLR observations*

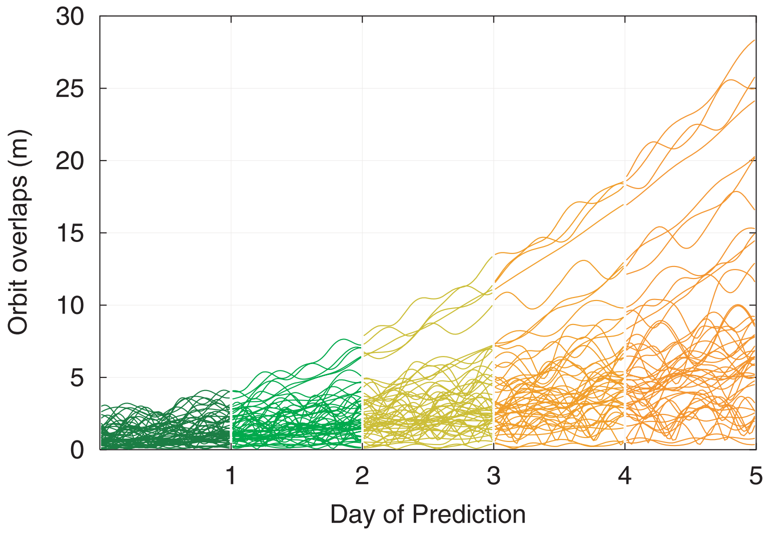

Figure 7. *Orbit overlaps of 5-day predictions based on GIOVE-A 9-day arcs; orbit overlaps are the orbit differences between the prediction days and the central days of the corresponding 9-day arcs*

3. Combined analysis of SLR and microwave observation for GIOVE-A orbit determination

This Section demonstrates the possible contribution of SLR to GIOVE-A orbit determination through a combined analysis of microwave and SLR data. As no microwave tracking data of GIOVE-A were available at the time of our analyses, we performed an a priori variance-covariance analysis. For such an analysis the observations are not needed, rather the number and temporal distribution and the assumed a priori error of the observations. Note that model deficiencies are not considered here.

Microwave phase observations were simulated for 13 GIOVE-A tracking sites, which are chosen similar to the proposed sites of the first Galileo tracking network. Their global distribution is indicated with circles in Figure 8. In addition we used the SLR true observations of the SLR sites represented with triangles.

The microwave phase observations are sampled with 30 s and have an accuracy of 1 mm. Observation equations were set up for microwave phase zero difference observations and SLR normal points. Satellite clocks, ambiguities, and orbit parameters were included in the parameter estimation. Other parameters, as station coordinates, receiver clocks, tropospheric zenith path delays, and Earth orientation parameters are assumed to be known accurately, as for example from a global analysis of GPS and GLONASS data.

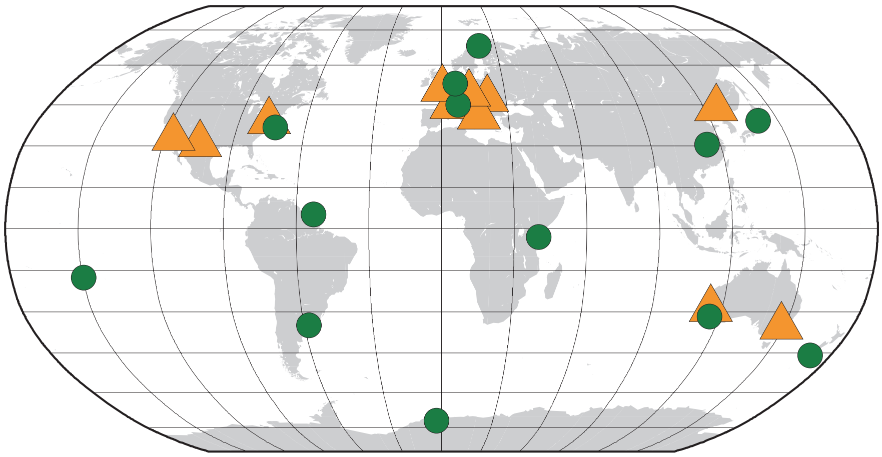

Figure 8. *GIOVE-A tracking sites (circles) and SLR tracking sites (triangles)*

The *a priori* variance-covariance matrix is derived from the obtained normal equation system. The *a priori* formal errors of the orbit parameters are then computed from the variance-covariance matrix. We used the same orbit parameters as in Section 2, i.e. six osculating elements and nine solar radiation pressure parameters in D,Y,X- direction. In summary 57 orbital arcs of 3 days length were determined, shifted by one day each.

To assess the impact of additional SLR observation on GIOVE-A orbit determination, we performed three different analysis with different SLR observation weight scenarios. The first solution corresponds to a pure microwave solution. The SLR observation weight is set to zero by setting the a priori sigma σ_{SLR} to infinity. In the second case, σ_{SLR} is set to 1cm. In the third case, the SLR observation weight is increased (with σ_{SLR} = 1 mm), and corresponds to the microwave observation weight.

We calculate the a priori formal errors of the satellite position in the inertial system from the *a priori* formal orbit errors by applying the law of error propagation. Figure 9 shows the *a priori* formal errors of the satellite position in radial, along-track, and out-of plane component for the three different solutions of a GIOVE-A 3-day arc. The absolute error values must be considered to be much too optimistic, as the error scales with the number of observations. We used 30 s sampled microwave data, but did neglect any temporal correlations between consecutive observations. A sampling rate of 180 s should rather be used for further studies.

The introduced parameters (e.g., station coordinates, troposphere parameters), which are assumed to be known from the GPS/GLONASS analysis, are not error free. Neglecting the formal errors of the introduced parameters, and of temporal correlations between observations causes too optimistic formal errors. However, in this analysis we are not interested in the absolute values of the formal orbit errors, but rather in the relative difference of the formal orbit errors between the three solutions. We may from this assess the impact of additional SLR observations on GIOVE-A (or Galileo) orbit determination in terms of orbit improvement.

The major impact of additional SLR data on the resulting orbit accuracy is given in the radial orbit component. A possible improvement of the radial orbit accuracy of about 60-80% may be feasible, depending on the SLR weight and the number and distribution of SLR observations. The formal orbit error in along-track and out-of-plane components decreases with strong SLR weights, only. A good temporal distribution of the SLR observations over the entire arc is always necessary. Otherwise, if e.g. SLR observations are only available at the beginning of an orbital arc, the orbital errors as well as the orbit positions will show periodic variations.

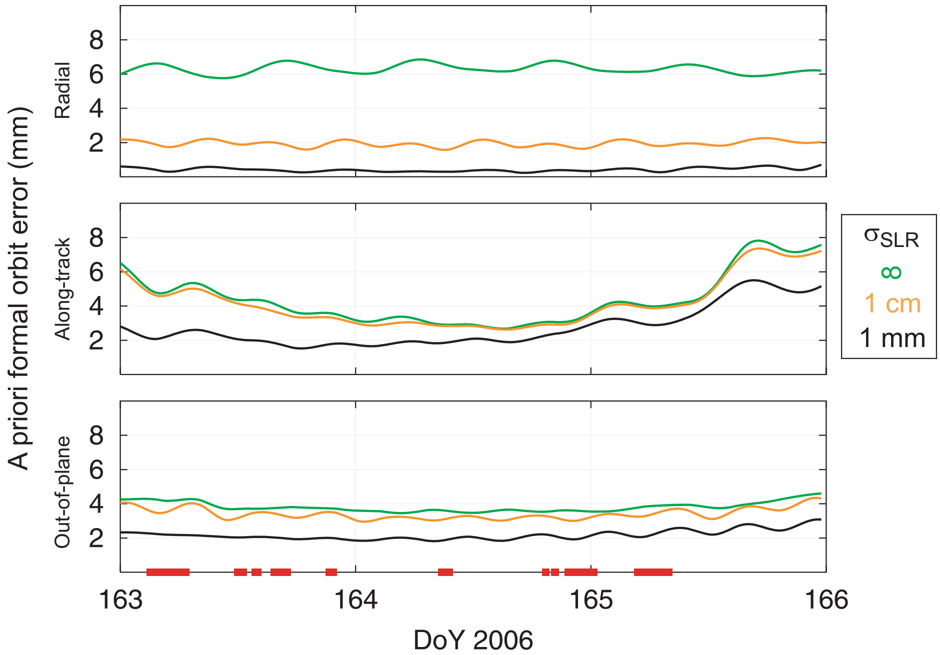

Figure 9. *A priori formal orbit errors in the inertial system; the three lines indicate the different orbit solutions using different a priori sigmas σ_{SLR} for the SLR observations; the bars on the horizontal axis indicate the SLR observation epochs*

4. Summary

We presented GIOVE-A orbit determination results based on SLR observations of the first GIOVE-A SLR tracking campaign. Orbits of several arc-length were determined and compared with each other. Nine-day arcs proofed to provide the best possible orbits with the used orbit model. No a priori solar radiation pressure model was introduced in the orbit determination, but constant accelerations and once-per orbit revolution accelerations were estimated. The orbit accuracy of a 9-day arc is about 10 cm, 0.5 m, and 1 m in radial, along-track, and out-of-plane component, unless the observation coverage of the orbit is poor. If SLR observations are very sparse and not well distributed over the entire arc, the orbit quality decreases. Orbit predictions are at the 20-30 m accuracy level after five days.

The impact of SLR observations used in addition to microwave observations for precise orbit determination of GIOVE-A was demonstrated. An a priori variance-covariance analysis shows a significant orbit improvement mainly in radial direction of about 60%, if additional and well distributed SLR observations are used. This can be addressed to the very low number of microwave tracking sites for the upcoming Galileo system in the very beginning of the system implementation.

References

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