Precise Orbit Determination of GIOVE–B Based on the CONGO Network

P. Steigenberger · **U. Hugentobler** · **O. Montenbruck** · **A. Hauschild**

Abstract GIOVE–B is one of two test satellites for the future European Global Navigation Satellite System Galileo. The Cooperative Network for GIOVE Observation (CONGO) is a global tracking network of GIOVE–capable receivers established by Deutsches Zentrum für Luft– und Raumfahrt (DLR) and Bundesamt für Kartographie und Geodäsie (BKG). This network provides the basis for the precise orbit determination of the GIOVE–B satellite for the time period 29 June till 27 October 2009 with a modified version of the Bernese GPS Software. Different arc lengths and sets of orbit parameters were tested. These tests showed that the full set of nine radiation pressure parameters resulted in a better performance than the reduced set of five parameters. An internal precision of about one to two decimeters could be demonstrated for the central day of 5-day solutions. The orbit predictions have a precision of about one meter for a prediction period of 24 h. External validations with Satellite Laser Ranging (SLR) show residuals on the level of 12 cm. The accuracy of the final orbits is expected to be on the few decimeter level.

Keywords Satellite orbits · Global Navigation Satellite System (GNSS) · Galileo · CONGO · POD

1 Introduction

The European Global Navigation Satellite System Galileo is being developed by the European Space Agency (ESA). Two test satellites (GIOVE–A and GIOVE–B, see Fig. 1) were launched as part of the Galileo in Orbit Validation Element (GIOVE, Benedicto et al 2006; Malik et al 2009). To gain experience with the signals transmitted by these satellites (see Tab. 1) and to estimate satellite orbit and clock parameters, a global network of GIOVE–capable receivers was established. This Cooperative Network for GIOVE Observation (CONGO) is operated by Deutsches Zentrum für Luft- und Raumfahrt (DLR, Oberpfaffenhofen, Germany) and Bundesamt für Kartographie und Geodäsie (BKG, Frankfurt am Main, Germany) in cooperation with local station hosts at the University of New Brunswick (UNB, Canada), the University of New South Wales (UNSW, Sydney, Australia), the Hartebeesthoek Radio Astronomy Observatory (HartRAO, South Africa), the Nanyang Technological University (NTU, Singapore), the Japanese Space Exploration Agency (JAXA, Chofu, Japan), and the Institute for Astronomy, University of Hawaii. The data archiving and the orbit determination are performed at Technische Universität München (TUM, Germany). For further details and initial results of the orbit determination, see Montenbruck et al (2009).

Altogether nine receivers are operated at eight stations, see Fig. 2 and Tab. 2. Three sites are equipped with Septentrio GeNeRx receivers (Simsky et al 2007), the other sites with Javad TRE_G2T or TRE_G3T receivers (GPS World 2008). All stations provide dual-frequency observations of the GIOVE satellites in the E1 and E5a bands in addition to tracking of legacy L1 and L2 GPS signals. Individual stations furthermore support modernized GPS L2C and L5 signals, SBAS and GLONASS tracking or GIOVE E5b, E5 AltBOC (a wide band signal covering the combined E5a and E5b frequency band), and E6 tracking. The GIOVE satellites are only capable of transmitting two frequencies at the same time. The choice which frequency pair is transmitted (E1 and E5a/E5b or E1 and E6) is changed from time to time by ESA.

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Fig. 1: Artist view of the GIOVE-B satellite (Image: ESA – P. Carril).

Table 1: Frequencies of the four Galileo bands.

Band	Frequency [MHz]	Comment
E1	1575.420	same as GPS L1
E5a	1176.450	same as GPS L5
E5b	1207.140	
E6	1278.750	

As only three E6–capable receivers are available in the CONGO network, transmission periods with E1/E6 are not considered. The Javad TRE_G3T receiver is also capable of tracking GLONASS but this GNSS is not considered in this paper. Three different antenna types are used within the CONGO network: Leica surveying antennas (`LEIAX1203+GNSS`), a Leica choke ring antenna (`LEIAR25.R3`), and the Trimble Zephyr Geodetic 2 antenna. The deployment of the CONGO network started in 2007 and reached the number of 8 stations on 29 July 2009. More details on the characteristics of the CONGO tracking stations are given in Montenbruck et al (2010). Due to frequent outages of the GIOVE–A satellite (mainly due to an orbit raising maneuver) during the time period considered, this paper is limited to GIOVE–B.

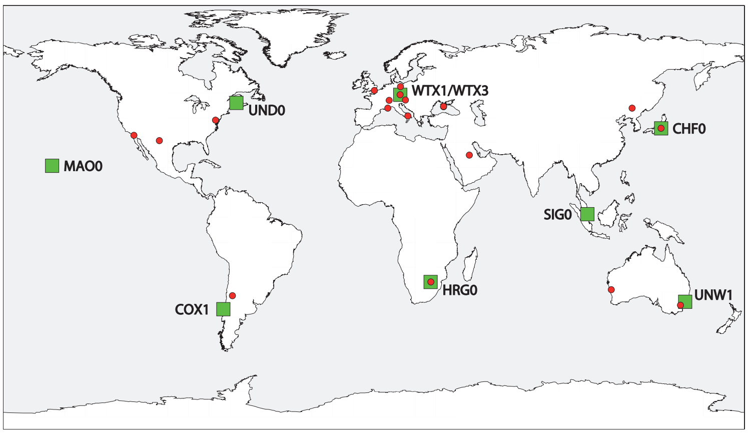


Fig. 2: GNSS stations of the CONGO network (squares) and SLR stations tracking the GIOVE satellites (circles).

All publications on GIOVE orbit determination up to now are based on ESA's GESS (Galileo Experimental Sensor Station, Giraud et al 2009) network: Schönemann et al (2007) and García et al (2009) achieved an orbit accuracy of about 20 cm for GIOVE–A whereas Kirchner et al (2009) report the same value for both GIOVE satellites. Falcone et al (2006) achieved this accuracy level only by including Satellite Laser Ranging (SLR) observations in addition to the microwave observations. Urschl et al (2008) determined the GIOVE–A orbit solely based on SLR observations with an accuracy of about one meter.

Table 2: GNSS tracking stations of the CONGO network.

Abb.	Location	Country	Receiver	Antenna	Radome
CHF0	Chofu	Japan	JAVAD TRE_G2T DELTA	TRM57971.00	NONE
COX1	Concepcion	Chile	SEPT GENERX	LEIAX1203+GNSS	NONE
HRG0	Hartebeesthoek	South Africa	JAVAD TRE_G2T DELTA	LEIAX1203+GNSS	NONE
MAO0	Maui	Hawaii, USA	JAVAD TRE_G3T DELTA	LEIAX1203+GNSS	NONE
SIG0	Singapore	Republic of Singapore	JAVAD TRE_G2T DELTA	LEIAX1203+GNSS	NONE
UND0	New Brunswick	Canada	JAVAD TRE_G2T DELTA	TRM55971.00	NONE
UNW1	Sydney	Australia	SEPT GENERX	LEIAX1203+GNSS	NONE
WTX1	Wettzell	Germany	SEPT GENERX	LEIAX1203+GNSS	NONE[a]
WTX3	Wettzell	Germany	JAVAD TRE_G2T DELTA	LEIAX1203+GNSS	NONE[a]

[a] WTX1 and WTX3 are operated at the same antenna with an antenna splitter. This antenna was replaced by a modified LEIAR25 without radome (LEIAR25.R3 NONE) on 7 August 2009.

This paper discusses the GIOVE orbit processing based on the CONGO network as implemented at TUM and evaluates the quality of different orbit products. It provides the first independent analysis of GIOVE precise orbit determination using a newly established network of GNSS monitoring stations with different types of receivers and antennas. The experience gained in this study may contribute to the build-up of dedicated Galileo processing capabilities within the International GNSS Service (IGS, Dow et al 2009). Section 2 describes the options and strategies for processing the observations of the CONGO network. The quality of the orbits as well as orbit predictions computed with different strategies is assessed by comparisons, orbit fits, and SLR residuals in Sec. 3.

2 GNSS Processing

All CONGO stations transmit their data in real–time via the Ntrip protocol (Weber et al 2005). The real–time streams are recorded, monitored, converted to RINEX 3.00 (Gurtner and Estey 2007) data, and archived at TUM. The RINEX data of the CONGO network are processed with a modified version of the Bernese GPS Software (Dach et al 2007; Svehla et al 2008). This version allows to process a predefined selection of two frequencies, e.g. E1 and E5a. The preprocessing (detection of outliers and cycle–slips) is based on smoothed code observations, but the raw (unsmoothed but preprocessed) code observations are used for the further processing. After synchronizing the receiver clocks with the GPS observations, a GPS–only precise point positioning (PPP) solution is computed where the CODE (Center for Orbit Determination in Europe, one of the IGS analysis centers) final or rapid satellite orbits and clocks (Bock et al 2009) are fixed. Daily station coordinates, epoch–wise receiver clock parameters, troposphere zenith delay parameters with 2 h parameter spacing and troposphere gradients with 24 h parameter spacing are estimated from the ionosphere–free linear combination (LC) of L1 and L2 phase and code observations. A cutoff angle of 10° and elevation–dependent weighting with $w = \cos^2(90^\circ - \epsilon)$ are applied. Outliers are detected and rejected in an iterative procedure. Typical values for the repeatabilities of the station coordinates are $2-5$ mm for the horizontal components and $5-10$ mm for the vertical component.

The station positions, troposphere zenith delays and gradients as well as the receiver clock parameters obtained in this GPS–only solution are introduced as known parameters in the GIOVE orbit and clock determination step. The ionosphere–free linear combination of E1 and E5a is processed with a sampling rate of 30 s. Only the orbital parameters of the GIOVE satellites, their satellite clocks, float ambiguities, and one combined inter–system/inter–-frequency bias for each receiver but one are estimated. These biases originate from receiver–specific code biases for GPS and GIOVE signals and signals on different frequencies (L1/L2 for GPS and E1/E5a for GIOVE). The orbital parameters consist of the six Keplerian elements and up to nine radiation pressure (RPR) parameters of the model of Beutler et al (1994): three constant terms and six periodic terms. These RPR parameters are given in a Sun–oriented coordinate system with one axis pointing from the satellite to the Sun (D), the second axis parallel to the satellite's solar panel axis (Y), and the third axis (X) completing a right–handed system. No a priori RPR model is used. The estimated constant term in D–direction is typically $-1.5 \cdot 10^{-7}$ ms^{-2} whereas the other terms are about two orders of magnitude smaller. The a priori orbit information originates from predictions for SLR tracking of the GIOVE satellites provided through the International Laser Ranging Service (ILRS, Pearlman et al 2002).

The satellite antenna offsets w.r.t. the center of mass for the ionosphere–free linear combination of E1 and E5a computed from the offsets of the basic frequencies given in Zandbergen and Navarro (2009) are listed in Tab. 3. In contrast to Zandbergen and Navarro (2009), the coordinate system definition of Tab. 3 is consistent with that of the Block IIA GPS satellites (X–axis positive to hemisphere containing the Sun, Y–axis along solar panel, Z–axis towards nadir). As no E1 and E5a calibrations for the receiver antennas were available, the GPS L1 and L2 offsets from igs05.atx (Schmid et al 2007) were used for E1 and E5a, respectively. Becker et al (2010) showed that the L2

Table 3: GIOVE microwave (MW) transmitter and SLR retroreflector offsets w.r.t. the center of mass. The MW offsets refer to the ionosphere–free linear combination of E1 and E5a.

Type	X [mm]	Y [mm]	Z [mm]
MW GIOVE–A	−4.0	1.0	819.2
MW GIOVE–B	−3.2	3.4	1352.4
SLR GIOVE–A	828.0	655.0	688.0
SLR GIOVE–B	804.3	−294.1	1330.1

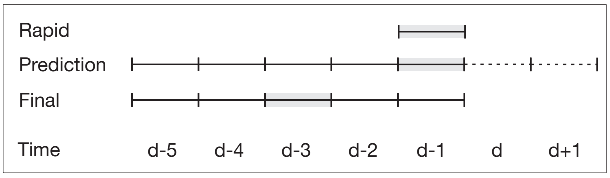


Fig. 3: CONGO rapid and final processing. For the current day *d* the rapid solution covers the previous day *d–1*. Five consecutive NEQs from *d–5* till *d–1* are combined to get an orbit prediction for the current and the next day. The final solution is computed with a delay of 3 days as the middle day of a 5–day arc is used.

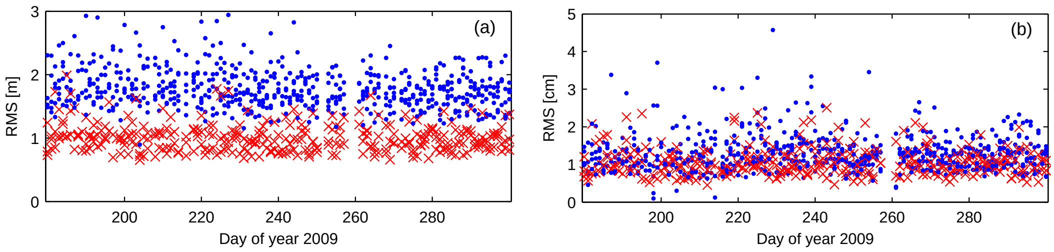


Fig. 4: Daily RMS values of the (a) code and (b) phase residuals of the 1–day rapid orbit solutions. Sites equipped with GeNeRx receivers are indicated by *red crosses*, sites with Javad receivers by *blue dots*. The gap at the days 258 – 260 is related to a GIOVE–B transmission outage.

and E5a values obtained from anechoic chamber calibrations agree within 1 – 2 mm. Satellite and receiver antenna phase center variations were neglected for the GIOVE observations as they are unknown for all frequencies of the transmitting antennas and the GIOVE-specific frequencies of the receiving antennas. Solid Earth tides and pole tides were modeled according to the IERS Conventions 2003 (McCarthy and Petit 2004), ocean loading corrections were provided by Scherneck (1991)[1] computed from FES2004 (Lyard et al 2006).

Two different product lines are generated in the operational CONGO processing running once per day: a rapid solution including an orbit prediction and a final solution to get the best quality orbits but with a higher latency, see Fig. 3. The rapid solution is computed as soon as the CODE rapid orbit and clock products for the GPS–only PPP solution are available. It consists of a basic 1–day solution to generate normal equations (NEQs) including all parameters mentioned above. For comparison purposes two different solutions are computed: a combined code + phase solution and a phase–only solution. Significant differences between both solutions are an indicator of changes in the inter–frequency/inter–system biases, e.g., due to firmware updates or hardware changes.

The rapid 5–day solution as well as the final solutions are computed from the 1–day NEQs. The orbital elements and RPR parameters are stacked resulting in one set of parameters for the multi-day arc (Beutler et al 1996). Based on the NEQs of the 5 previous days, an orbit prediction for the current and the next day are generated. For the final orbits, the middle day of a 5–day arc is used. This orbit is kept fixed to compute the final clock solution for the corresponding day. For the 1–day rapid orbits, only five RPR parameters are estimated (three direct parameters and two periodic parameters in X–direction). Based on the results of Sec. 3, the full set of nine RPR parameters is used for the 5–day solutions (orbit prediction as well as final solution).

The data discussed in this paper covers the time period 29 June 2009 (180/2009) until 27 October 2009 (300/2009). The station–specific RMS values of code and phase residuals of the rapid 1–day solution are plotted in Fig. 4 and their mean values are listed in Tab. 4. Whereas the order of magnitude of the phase residuals is

[1] http://www.oso.chalmers.se/~loading/

Table 4: Mean RMS of the residuals of the 1–day CONGO rapid solution. The sites are grouped by receiver type.

Site	Receiver	Code [m]	Phase [cm]
COX1	GeNeRx	0.93	1.04
UNW1		1.01	1.08
WTX1		1.07	1.10
CHF0	Javad	1.97	1.69
HRG0		1.81	1.33
MAO0		1.73	1.98
SIG0		1.92	1.19
UND0		1.68	1.42
WTX3		1.63	1.22

quite similar for both receiver groups, the code residuals of the GeNeRx receivers are smaller by about 44% compared to the Javad receivers. This effect is related to narrower tracking loops of the GeNeRx receivers. Activating the receiver-internal smoothing option of the Javad receivers reduced the code residuals of this receiver type by about two-thirds. Therefore, this option is now used for recording the observation data of the Javad receivers in the CONGO network.

3 Orbit Validation

3.1 Orbit Validation Methods

3.1.1 Internal Consistency

The easiest way to evaluate the internal consistency of satellite orbits is the direct comparison of positions from different orbit solutions of the same type, e.g., the last day of a 3–day arc with the middle day of a 3–day arc centered at the next day. The residuals are usually given in a satellite–centered orbit system in along–track, radial, and out of plane (cross–track) direction. The direct comparison can of course also be used for orbit predictions and allows for an assessment of the prediction accuracy. All direct orbit comparisons discussed in this paper were performed with a tabular spacing of 15 minutes.

The consistency of consecutive orbit solutions can be evaluated by the 3D RMS of multi–day orbit fits w.r.t. the original orbits. E.g., for a 2-day orbit fit, a new orbital arc with a validity of 48 h is determined from two orbits with 24 h validity from consecutive days, see Fig. 5. The two orbits with 24 h validity are completely independent if one uses 1-day arcs but also the middle day of multi–day orbital arc can be used. In the latter case, one has to be aware that the RMS gets smaller with increasing arc length since the orbits are based on overlapping data resulting in a smoothing effect of longer arcs. The RMS of the differences (in our case at 15 minute intervals) between all original 24 h orbits w.r.t. the multi-day arc can then be used as quality indicator for the internal consistency of the orbits.

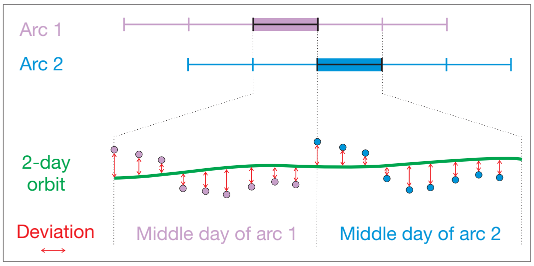


Fig. 5: 2-day orbit fit through middle days of 5-day arcs. The orbit positions of the middle days of arc 1 and arc 2 are used as input for the fit of a 2-day arc. The arrows represent the deviation of the original positions of arc 1 and arc 2 w.r.t. the newly adjusted 2-day orbit. The 3D RMS deviations are used as a measure for the internal consistency of the orbits.

Table 5: SLR residuals and 3D RMS of 2–day orbit fits for different arc lengths and number of RPR parameters.

Arc length [days]	# RPR	SLR residuals Mean [cm]	SLR residuals STD [cm]	Orbit fit 3D RMS [cm]
3	5	4.61	13.29	9.48
	9	20.13	20.87	7.74
5	5	4.84	11.89	7.37
	9	11.85	14.44	4.77
7	5	4.41	10.32	5.43
	9	8.28	11.58	2.78
9	5	5.10	11.08	4.64
	9	6.39	11.05	1.75

3.1.2 Satellite Laser Ranging

Satellite Laser Ranging observations allow for an independent validation of GNSS orbits determined from microwave observations. The GIOVE satellites are observed on a regular basis by the SLR tracking stations of the ILRS. Although they have a quite low tracking priority among all satellites tracked by the ILRS[2], altogether 1614 normal points (NPs) are available for GIOVE–B in the time period 180 – 300/2009. Most NPs are obtained during nighttime due to the large distance of the GIOVE satellites resulting in difficult tracking conditions. However, the station distribution of the NPs is quite inhomogeneous: more than one third of the NPs are provided by the Zimmerwald station (Switzerland), 9 stations provide more than 50 NPs and only 5 stations more than 100 NPs. The Simeiz station (Ukraine) was excluded due to residuals in the range of several tens of meters. For the SLR validation of the GIOVE orbits based on microwave observations, the coordinates of the altogether 18 SLR stations shown in Fig. 2 were fixed to SLRF2005 (Luceri and Bianco 2007). Two of these SLR stations are co-located with CONGO GNSS stations, namely Wettzell and Hartebeesthoek. Meteorological observations at the stations were used to model the tropospheric delay according to Marini (1972). The other models are completely identical to the microwave analysis to guarantee full consistency.

Besides the analysis of SLR residuals, a direct comparison of orbits determined from SLR and microwave observations can also be performed. SLR-based orbit solutions for such a comparison were computed by DLR using the SLRORB software (Kraft 2009). In view of the sparseness of the GIOVE-B SLR observations (on average 10 – 15 normal points per day) 7–day solutions were computed employing a 9 parameter RPR model. The central day of each sliding 7–day arc was then used for comparison with the GNSS-based orbits. Position differences were evaluated at 15 minute intervals and the 3D RMS position error was computed on a daily basis for the performance comparison. No SLR orbits are available during the eclipse phase, where a proper fit of the SLR measurements over one week arcs could not be achieved with the employed dynamic force model.

3.2 Orbit Validation Results

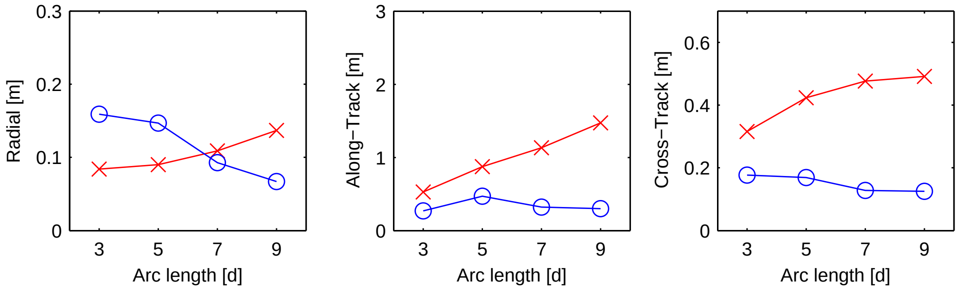
To find the optimal orbit parameterization for GIOVE–B, orbits of different arc length (3, 5, 7, and 9 days) and with a different number of RPR parameters were computed. Two different parameterizations for the radiation pressure were used:

- 5 RPR parameters: three linear terms and two periodic terms in X–direction
- 9 RPR parameters: three linear terms and the full set of six periodic terms.

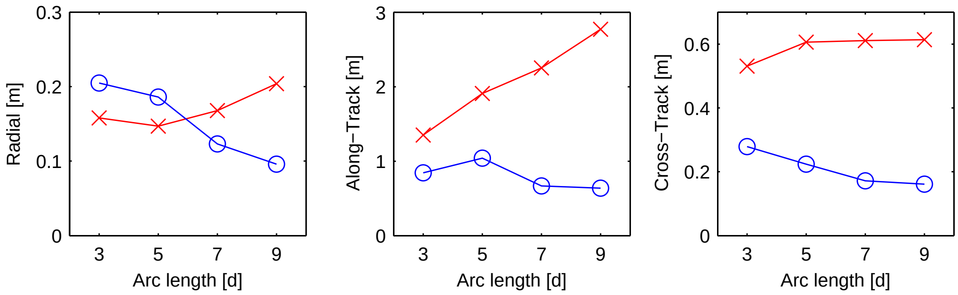
To evaluate the impact of the different number of RPR parameters, the last observed day and the first predicted day of final solutions with different arc lengths are compared with the middle day of the corresponding solutions. The mean RMS values in radial, along–track, and cross–track direction are shown in Fig. 6. The largest RMS values occur for the along–track direction: an almost linear increase of the RMS with increasing arc length for the solutions with 5 RPR parameters is obvious. For the solutions with 9 RPR parameters, almost no dependency on the arc length is visible. The radial RMS values are the smallest for both solution types but the 9 RPR parameter solutions show a decrease with increasing arc length whereas the 5 RPR parameter solutions show an increase.

The STDs and offsets of SLR residuals for orbits with different arc lengths and number of RPR parameters are given in Tab. 5. The microwave-based orbits are kept fixed and residuals are computed from the SLR observations

[2] http://ilrs.gsfc.nasa.gov/satellite_missions/priorities/index.html



(a) Comparison of the middle day with the last day.



(b) Comparison of the middle day with the first predicted day.

Fig. 6: Mean RMS values for orbit comparisons of solutions with different arc length as well as 5 RPR parameters (*red crosses*) and 9 RPR parameters (*blue circles*).

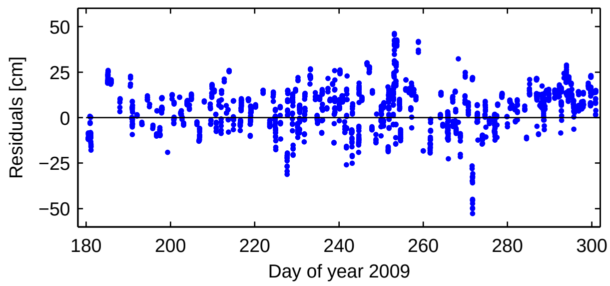


Fig. 7: SLR residual time series of the CONGO orbits (central day of a 5-day orbit arc with 5 RPR parameters).

as external validation of mainly the radial component. Outliers in the SLR residuals larger than 50 cm have been excluded. For 9 RPR parameters, a quite large offset of 20 cm as well as a STD of 21 cm are visible for the 3–day arcs. Offset and STD decrease with increasing arc length. This result is in agreement with the RMS of the radial component of the orbit comparisons discussed above. For the solution with 5 RPR parameters, no significant dependence of offset and STD on the arc length are present. As an example, the time series of SLR residuals for the 5–day orbits with 5 RPR parameters is shown in Fig. 7. No significant elevation dependence of the SLR residuals is present (not shown here).

As internal validation, 3D RMS values are given in the last column of Tab. 5. These RMS values were obtained from 2–day orbit fits through middle days of consecutive multi-day arcs as shown in Fig. 5. It is clear that the RMS of the orbit fits decreases with increasing arc length due to the smoothing effect of the longer arcs. Therefore, the orbit fits can only be used for a comparison of the different number of RPR parameters. For all arc lengths, the solutions with 9 RPR parameters show smaller orbit fit RMS values due to the better fitting related to the higher number of parameters. Based on the results discussed above, a 9–day arc with 9 RPR parameters provides the best performance for orbit determination and prediction. However, due to practical reasons (initialization after outages), 5–day arcs are used for the operational CONGO processing.

The time series of the 2-day orbit fit RMS values is shown in Fig. 8 for the final CONGO orbits. The improvement after day 218 is probably related to the commissioning of the station in Singapore that significantly improved the

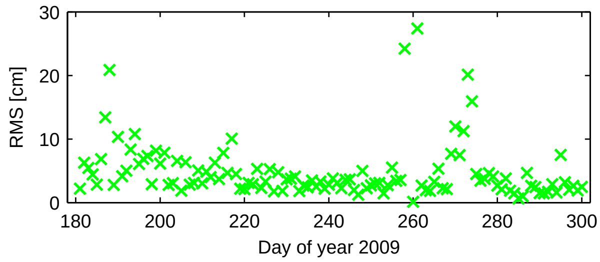


Fig. 8: 2–day orbit fit time series of the CONGO final orbits (central day of a 5-day orbit arc with 9 RPR parameters).

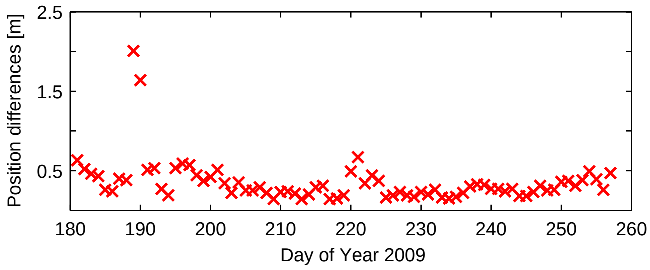


Fig. 9: Daily 3D RMS position differences between GIOVE-B satellite orbits derived from SLR and microwave observations.

global coverage of the CONGO network. The increased values around day 260 are related to the GIOVE transmission outage already mentioned above.

The daily 3D RMS position differences between orbits computed from SLR and microwave observations are plotted in Fig. 9. The comparison is confined to days 180 – 257 since no proper SLR–based orbits could be obtained during the eclipse period of GIOVE–B. The mean RMS position differences exhibit a median value of 27 cm, which is roughly twice the value of the RMS SLR residuals of the microwave orbits discussed above. Due to the distance of the GIOVE–B satellite, the SLR residuals mainly evaluate the radial component of the microwave orbits and are, therefore much smaller than the RMS position difference of the SLR and microwave orbits. Despite the limited SLR tracking coverage, the SLR-only orbit determination can provide a few decimeter accuracy, which is well compatible with the needs of a Standard Positioning Services (SPS). This result is of particular interest for other GNSS satellites such as COMPASS-M1, which are not presently supported by any of the global GNSS tracking networks.

4 Summary

The CONGO network offers the possibility of a continuous tracking of the GIOVE satellites. The orbit determination shows an accuracy that is on the few decimeter level. For orbit arcs longer than three days, the full set of nine RPR parameters shows a better performance than the reduced set of five RPR parameters. Orbit predictions agree with the final orbits on a level of one meter after one day with the largest differences in the along–track direction. The current work provides the first independent validation of results achieved earlier by the ESA project teams with dedicated infrastructure. Overall, a similar accuracy is achieved despite a smaller amount of tracking stations and the use of commercial off-the-shelf receivers and antennas. This is of high relevance for the future scientific exploitation of Galileo which will rely on a global IGS-type infrastructure rather than the mission-specific ground network. The orbit predictions of the operational CONGO processing are used by DLR for the computation of real–time clocks with the Real–Time Clock Estimation (RETICLE) system (Hauschild and Montenbruck 2008) that was enhanced for the capability to process GIOVE data (Cao et al 2010). Recently, three more stations have been added to the CONGO network: O'Higgins in Antarctica, Stanford in the United States, and La Laguna (Tenerife). A further extension of the CONGO network is planned for the near future.

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