GLONASS Satellites Simultaneously Observed by VLBI, GNSS and SLR

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Abstract In recent years, the tracking of GNSS satellites by radio telescopes has become possible for a number of VLBI stations. Due to hardware limitations these measurements will usually be limited to one frequency, and ionospheric delay corrections have to be taken into account. Beyond the possibility of using ionospheric models, we present a method to correct these ionospheric delays by using observations from co-located GNSS receivers. The VLBI observations of quasars and simultaneous GNSS observations with comparable azimuth and elevation from different sessions in 2013 were used for validation. Station coordinates are a major result from simultaneous tracking of satellites using different space techniques. By combining real GNSS and SLR observations with simulated SLR and VLBI data for a number of European stations, the accuracy of station positions is assessed.

Keywords VLBI, SLR, ionosphere, GNSS

1 Introduction

The co-location of geodetic space techniques allows the investigation of technique-specific error sources and errors related to the links between them, by providing an alternative possibility of combining these techniques using on-board satellite offsets (space ties). Using present co-locations between GNSS, SLR, DORIS, on-board low Earth orbiters, and GNSS satellites, very promising results were presented in recent years (e.g., [1, 2]). Unfortunately, VLBI could not be considered for co-location in space due to the impossibility of tracking near-Earth satellites by radio telescopes and bandwidth limitations of the receiver chain. Thanks to recent hardware developments at some stations, tracking of GLONASS satellites will become the first possibility of combining VLBI with other space techniques in space. The first GLONASS tracking sessions were already carried out for the baselines Medicina–Onsala and Wettzell–Onsala, see [3], [4], and [5]. As usual L_1 GNSS signals are tracked, this kind of observations will not be possible for all VLBI stations and, depending on hardware characteristics, may consist of only one frequency. Therefore, our first goal was to analyze possibilities for correcting the remaining ionospheric delays. In a second stage, prospective accuracies for station coordinates were estimated from real and simulated GNSS, SLR, and VLBI data.

2 Real Observations and Simulation Method

We used real VLBI and GNSS data collected at the European stations Matera, Onsala, and Wettzell in 2013 to investigate ionospheric corrections. For accuracy studies, GNSS and SLR data of GPS week 1774 (5–11 January 2014) were used, together with simulated SLR and VLBI observations of GLONASS satellites for the same time span. Table 1 gives an overview of all observations and synthetic data. The simulation of VLBI data included a turbulence model for wet troposphere delays and receiver clock behavior following [6]. White noise of 2 cm and 67 ps for SLR and VLBI were added to the computed distances. These simula-

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tions were repeated 26 times to allow statistical interpretation (based on [7]). To obtain a realistic scenario, measurements of three GLONASS satellites within one hour per day by n stations were simulated using an observation interval of 60 s. The SLR simulation was only performed for one laser station at Wettzell, and VLBI was simulated both for a single baseline and for a small European network. For both simulation and processing, a modified version of the Bernese GNSS Software V5.2 was used.

3 Ionospheric Delay Correction

3.1 GNSS-based Ionospheric Models

A well-investigated method for correcting single-frequency VLBI observations for ionospheric delays is the usage of a GNSS-based ionospheric model (e.g., [8, 9]). To check the quality of different models, data from VLBI session R1615 were used (see Table 1). Figure 1 shows the impact of applying such models for three European baselines. The differences of the baseline lengths w.r.t. ITRF2008 positions caused by applying or ignoring the ionospheric corrections from NGS Card files are shown in black (1st bar) and red (2nd). The green (3rd) and blue bars (4th) represent the differences for a global ionosphere model provided by the Center for Orbit Determination in Europe (CODE) and for a regional model based on smoothed, undifferenced GPS code observations of eight well-distributed European IGS stations. The regional model could not fully compensate for the ionospheric delay, resulting in an elongation of the baselines. As a global model cannot represent local structures, the results are not satisfactory either. It has to be mentioned that ionospheric delays might also be compensated by other parameters such as wet tropospheric delays and receiver clock offsets. Here, depending on the solution type, differences of up to ±5 cm for tropospheric wet delays and changes in receiver clock offsets of up to ±0.1 ns could be detected. In general, GNSS-based ionospheric models are a possibility for correcting VLBI observations for ionospheric delays. However, if GNSS satellites are observed, it might be worth trying to derive ionospheric delay corrections from co-located GNSS observations.

Table 1 Data used for investigations: I_1 = ionosphere model; I_2 = ionosphere from GNSS observations; I_3 = accuracy investigation; Ma = Matera, On = Onsala60, Wz = Wettzell, Mc = Medicina, Ys = Yebes40m, [1]IGS station name [2]ILRS station name.

session	I_1	I_2	I_3	stations	date (year, doy)
R1615	x			Ma, On, Wz	2013, 343/344
R1566		x		Ma, On, Wz	2013, 002/003
R1567		x		Ma, On, Wz	2013, 007/008
R1569		x		On, Wz	2013, 022/023
R1570		x		Ma, On, Wz	2013, 028/029
R1578		x		Ma, On, Wz	2013, 084/085
R1580		x		On, Wz	2013, 098/099
EUR123		x		Ma, On, Wz	2013, 126/127
R1585		x		On, Wz	2013, 133/134
R1591		x		On, Wz	2013, 175/176
EUR124		x		On, Wz	2013, 185/186
R1606		x		Ma, Wz	2013, 280/281
R1615		x		Ma, On, Wz	2013, 343/344
R1616		x		Ma, On, Wz	2013, 350/351
GNSS (*real*)			x	GOPE[1],ONSA[1] POTS[1],WTZR[1]	2014, 005-011
SLR (*real/sim*)			x	WLRS[2]	2014, 005-011
VLBI_1 (*sim*)			x	On, Wz	2014, 005-011
VLBI_2 (*sim*)			x	Mc, On, Wz, Ys	2014, 005-011

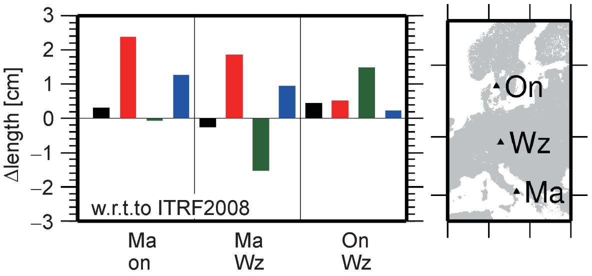

Fig. 1 Changes of the baseline length w.r.t. ITRF2008 for different options for correcting ionospheric delays: standard processing (*1st bar*), without ionospheric correction (*2nd*), CODE model (*3rd*), regional model (*4th*).

3.2 Ionospheric Delays from GNSS L_4 Residuals

When combining GNSS L_1 and L_2 phase observations using the geometry-free linear combination L_4,

$$L_4 = L_1 - L_2 = \lambda_1 N_1 - \lambda_2 N_2 + \left(1 - \frac{f_1^2}{f_2^2}\right) \delta ion_1 \quad (1)$$

only phase ambiguities and ionospheric delays remain in the observable. After fixing the ambiguities, the remaining residuals resulting from a least-squares adjustment contain the ionospheric delay. As it is necessary to form double differences between two stations and two satellites for ambiguity fixing, these residuals have to be split up into two satellite components $R^B_{S1,2}$ for each individual baseline B. Because there are only $n-1$ linearly independent double differences for n single baselines, an additional and independent constraint has to be introduced ([10]). This regularization step can be performed by fixing one satellite S or by introducing a zero-mean condition over a certain period of time. For the following investigations, an epoch-wise zero-mean condition was used. As the resulting residuals R^B_S only provide relative information, a bias parameter has to be added to get absolute values. An epoch-wise mean slant delay correction $\bar{I}_{model}$ based on a CODE ionosphere model is able to provide this absolute information. The ionospheric delay correction I^B_S can be written as

$$I^B_S = R^B_S + \bar{I}_{model}, \quad (2)$$

i. e., the estimated values will be model-mean values instead of zero-mean values. In principle, this method could be applied to all baseline lengths as visibility conditions are nearly identical for co-located VLBI and GNSS stations. Unfortunately, fixing ambiguities for GLONASS observations might be difficult for very long baselines using the Bernese GNSS Software ([11]). As a solution, the regularization step described above could be repeated to obtain undifferenced residuals. Then, ambiguity fixing could be done using shorter baselines w.r.t. additional GNSS stations.

3.3 Validation of Delays Based on GNSS L_4 Residuals

To evaluate this method, real VLBI and GNSS observations were screened to find corresponding observations, i. e. observations in the ”same” direction at the ”same” epoch. As we split the residuals only into single differences, this condition should be fulfilled at both VLBI stations, which hardly occurs. Therefore, thresholds for direction and observation time differences were defined. If deviations in elevation and azimuth are smaller than 2° and 5°, resp., and if the time difference is smaller than 15 min, the GNSS observation was accepted as a so-called associated observation. Besides, only baselines shorter than 1,000 km, namely Onsala–Wettzell and Matera–Wettzell, were analyzed. For a typical 24 h session, we found 15–25 quasar observations associated with 200–300 GNSS observations. In Figure 2, associated observations are shown for session R1615 at Wettzell. To validate the estimated GNSS-based ionospheric delay corrections ($L4R$) available for each associated observation, VLBI-derived ionospheric corrections contained in the X-band NGS Card observation files (NDC) were used. These corrections $\tau'_{X,ion}$ are computed as [12]

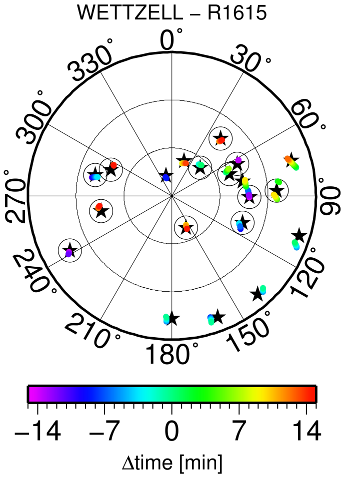

Fig. 2 Associated observations to quasars (asterisks) and GNSS satellites (*colored dots*) for session R1615 at Wettzell, including baselines w.r.t. Matera (*without circle*) and Onsala (*with circle*).

$$\tau'_{X,ion} = \frac{f_S^2}{f_X^2 - f_S^2}\left(\tau_X - \tau_S\right) + \tau_{1,inst} - \tau_{2,inst} \quad (3)$$

with $\tau_{1,inst}$ and $\tau_{2,inst}$ representing the receiver-specific offsets. Hence, the difference $L4R - NDC$ also contains an unknown receiver offset, which can be considered as constant over 24 h [12]. As a consequence, a baseline-specific mean difference can be assumed to represent the receiver offsets of the corresponding VLBI stations. Therefore, the baseline-specific standard deviation of

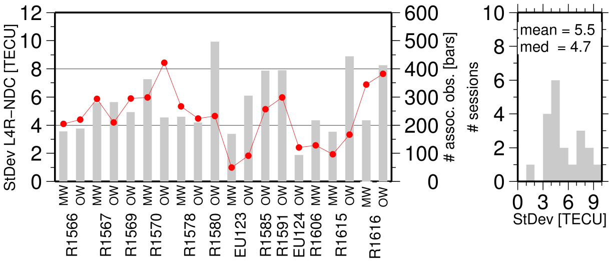

Fig. 3 Validation of ionospheric delay corrections based on GNSS L_4 residuals by means of ionospheric correction values from NGS Card files. *Left:* standard deviation of the mean difference *L4R-NDC* (*dots*) and number of associated observations (*bars*) for different sessions; *right:* histogram of the standard deviations. OW = Onsala–Wettzell, MW = Matera–Wettzell.

the mean difference $L4R-NDC$ is used as a validation criterion. In Figure 3, results from various sessions in 2013 are shown. The standard deviations of the mean differences are between 1 and 10 TECU[1]. Considering all 4,599 associated observations, mean and median values of 5.5 and 4.7 TECU can be found. Differences in the resulting standard deviations arise from remaining unresolved ambiguities in the L4R approach, the distribution of associated observations over each session, and also the ionospheric activity. The impact of the thresholds is below 1 TECU as regards time and elevation (see Figure 4). As the standard deviations increase with increasing azimuth thresholds, azimuth differences of associated observations should be kept small for future validation scenarios. At this point the balance between the number of remaining associated observations and small standard deviations is important. Further validation steps will be based on GNSS observations only, comparing solutions using our approach and results based on the ionosphere-free linear combination L_3, and tests with real VLBI tracking data of GLONASS satellites will be provided.

4 Simultaneous Observation Time Series

Real and simulated tracking data of GLONASS satellites by GNSS, SLR, and VLBI (see Section 2) are used to derive station coordinates. As input files, GNSS orbits and clocks as well as ERP final products from CODE were used. Coordinates, troposphere (GNSS and VLBI), and receiver clock offsets (VLBI) were set up in the data processing. For GNSS and VLBI, an NNR and NNT condition was applied, whereas single SLR station coordinates are estimated w.r.t. the GNSS orbits. Table 2 shows the number of observations, the formal errors and the repeatability of the station coordinates for real and simulated data. Comparing real and simulated SLR data reveals a higher number of simulated observations, as we do not take weather and clear sky conditions into account. Therefore, smaller formal errors are reasonable. Using the simulated VLBI data for the baseline Onsala–Wettzell, formal errors of 1.2 cm for the north and up components can be found. The significantly smaller value for the east component might be a result of the orientation of the baseline. This effect also shows up in the repeatability values, where the north component is around 1.5 cm and the other values are below 1 cm. If a small network is used, the results get worse. Only the formal errors for the up component are improved, perhaps due to the higher number of observations. The degradation of the other components might be associated with sky coverage and observation scheduling, as the simulated satellites were chosen randomly from different orbit planes.

5 Conclusions and Outlook

The presented method based on GNSS L_4 residuals for the estimation of ionospheric delay corrections will be applied and further validated by using real VLBI satellite tracking data. Referring to standard deviations of 5 TECU (80 cm for GNSS L_1) for the presented validation approach, the method will be more accurate for real tracking data as a consequence of using the same signal from the same source. Further investigations related to the influence of the ambiguity resolution quality on the ionospheric corrections should be done in terms of satellite tracking observations based on longer baselines. According to simulations, a station coordinate repeatability of 1–2 cm can be expected for a baseline such as Onsala–Wettzell when observing different GLONASS satellites under good sky coverage. Analyses of different scenarios (e.g., single-pass tracking and shorter observation intervals per satellite including careful scheduling) and assessment of their prospective benefits will be the subject of further research.

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[1] 1 TECU corr. to 0.6 cm (X-band) and 80 cm (GNSS L_1)

Table 2 Results from real and simulated tracking data (GNSS also includes IGS stations GOPE and POTS; VLBI$_1$ = baseline Onsala–Wettzell; VLBI$_2$ = European network; number of observations per station for SLR and within the network for GNSS and VLBI).

		real			**simulated**						
		GNSS		**SLR**	**SLR**	**VLBI$_1$**		**VLBI$_2$**			
stations		ONSA	WTZR	WLRS	WLRS	On	Wz	Mc	On	Wz	Ys
observations		250,000 each		216	378	377		957			
formal error [cm]	N	0.012	0.012	0.39	0.19	1.26	1.16	2.10	1.68	1.48	1.50
	E	0.012	0.012	0.76	0.28	0.74	0.72	1.70	0.97	1.42	1.57
	U	0.003	0.004	0.70	0.14	1.22	1.33	0.76	0.36	1.15	0.33
repeatability [cm]	N	-	-	-	0.13	1.58	1.49	2.00	1.51	1.88	2.39
	E	-	-	-	0.20	0.65	0.65	2.22	1.58	2.71	2.29
	U	-	-	-	0.32	0.76	0.93	0.38	1.62	1.08	0.52

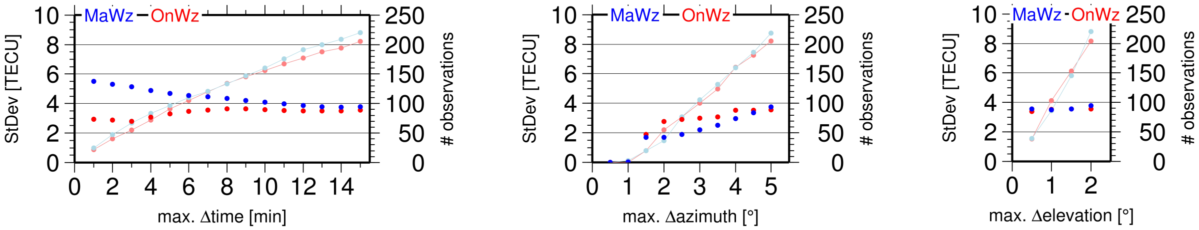

Fig. 4 Impact of different thresholds for differences in time, azimuth, and elevation on the standard deviation (session R1566).

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