Journal of Geodesy (2022) 96:83
https://doi.org/10.1007/s00190-022-01675-0

ORIGINAL ARTICLE

Potential of UT1–UTC transfer to the Galileo constellation using onboard VLBI transmitters

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Received: 2 March 2022 / Accepted: 7 October 2022 / Published online: 19 October 2022

Abstract
UT1–UTC is one of the Earth orientation parameters (EOP) that can only be determined by very long baseline interferometry (VLBI), observing distant celestial sources to measure the Earth rotation angle. Earth orbiting satellites tracked from Earth are insensitive to this angle, and the orbit determination and time synchronization (ODTS) procedure for GNSS satellites hence requires the UT1–UTC as an input. Today, UT1–UTC is provided by the International Earth Rotation and Reference Systems Service (IERS). A VLBI transmitter (VT) onboard GNSS satellites would, as an alternative way, allow the direct transfer of this information as an integrated step to the ODTS process thanks to the space-tie established between the VLBI and GNSS techniques. Here, we investigate the transfer quality of the UT1–UTC in such a concept by considering different VLBI baselines. In the simulations, we assume observations from a VT onboard a Galileo satellite together with quasar observations acquired with the same VLBI ground stations during a session and therewith allowing to directly transfer UT1–UTC to the GNSS constellation. The geometrical setting of the Galileo satellite with respect to the ground stations is quantified by the UT1–UTC dilution of precision (UDOP). Our simulations show that it is feasible to transfer UT1–UTC with a precision of about 30 μs for a long VLBI baseline where the UT1–UTC precision estimated from quasar observations is 20 μs. Using VLBI networks instead of a single baseline can improve the transfer precision further by more than 20 % depending on the baseline selection.

Keywords Galileo · VLBI · UT1–UTC

1 Introduction

Possibility of tracking GNSS (Global Navigation Satellite System) satellites with VLBI (very long baseline interferometry) has been discussed (Hase 1999; Petrachenko et al. 2004; Dickey 2010; Tornatore et al. 2010) and demonstrated (Haas et al. 2014; Tornatore et al. 2014; Hellerschmied et al. 2016; Plank et al. 2017). Extended simulations were conducted (Plank et al. 2014; Hellerschmied et al. 2015; Plank et al. 2015; Bruni et al. 2017; Anderson et al. 2018; Klopotek et al. 2020) to assess the benefit of VLBI observations of GNSS satellites. The co-location of these geodetic techniques at the observation level can be extended to space with a VLBI transmitters (VT) and GNSS placed on the same satellite. Geodetic space-ties between these techniques are expected to improve the consistency of the combination supporting the realization of the International Terrestrial Reference Frame (ITRF, Plag and Pearlman (2007)). Dedicated space missions were proposed for a geodetic satellite providing space-ties (Bar-Sever et al. 2009; Nerem et al. 2011; Biancale et al. 2017). A recent study has also assessed the feasibility of placing VLBI transmitters (VT) on Galileo satellites (Jaradat et al. 2021).

While VT onboard GNSS satellites are of high interest for consistent combination of GNSS and VLBI, to be able to improve the ITRF and satellite orbits, VT observations also offer the unique opportunity to directly transfer absolute orientation with respect to the International Celestial Reference Frame (ICRF) to the satellite constellation exploiting the space-tie between the two techniques. Of particular interest is the transfer of absolute orientation in space around the polar axis, i.e., UT1–UTC, to GNSS orbits as part of the near-real time orbit determination and time synchronization (ODTS)

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procedure performed by the system operator as alternative to the conventional procedure.

UT1–UTC is one of the five Earth orientation parameters (EOPs) that can only be accessed by VLBI and is determined by the International VLBI Service for Geodesy and Astrometry (IVS) (Nothnagel et al. 2016). EOPs are today published as the low-latency Bulletin A weekly and as the long-term EOP time series IERS 14 C04 two times per week by the Earth Orientation Centre of the International Earth Rotation and Reference Systems Service (IERS) (Vondrák and Richter 2004). In particular, UT1–UTC requires daily monitoring due to variations that are hard to predict, caused by mass motions in the Earth system. UT1–UTC values are provided by IVS from weekly R1 and R4 sessions within 2–3 μs (microsecond) and daily one-hour Intensive sessions with uncertainties within $\sim$ 20 μs based on long east–west baselines (Malkin 2020). Although results have not been submitted to the IERS Rapid Service/Prediction Center (RS/PC), Haas et al. (2010) demonstrated that the determination of UT1–UTC is possible in less than five minutes just after the end of the observations.

In practice, GNSS observations have a low sensitivity to UT1–UTC: Orbit determination of GNSS satellites provides the correct orientation of the orbits with respect to the ground station network while the absolute orientation of the constellation in space is basically undetermined. Navigation messages of the GNSS such as Galileo, provide the users with broadcast ephemerides that refer to the terrestrial reference frame, allowing the users to obtain positioning results directly in the rotating frame. Nevertheless, the ODTS process performed in the ground segment to prepare the broadcast information requires proper absolute orientation of the satellite orbits in inertial space to properly account for inertial accelerations and gravitational perturbations by Earth and celestial bodies. Today, that information is being provided by IERS as derived from IVS VLBI sessions.

Instead of two independent operations for GNSS and VLBI, a VT onboard GNSS satellite can integrate VLBI observations and transfer UT1–UTC information directly into the ODTS procedure by using simultaneous quasar and VT observations. The concept allows a direct and rapid transfer of the Earth rotation state to the Galileo satellite via VT observations. Using GNSS observations, the information is further transferred to the ground tracking network and to the satellite constellation as a whole. This transfer from VLBI to GNSS through quasar, VT, and GNSS observations is equivalent to providing the absolute orientation around the polar axis to the GNSS constellation and tracking network (given nutation and polar motion). The concept can be beneficial for integrated and automated ODTS procedures where UT1–UTC does not necessarily need to be estimated explicitly. In addition, it also indicates the feasibility of passing one method-specific information to another technique through a space-tie. However, the quality of this transfer remains to be quantified.

We thus simulate here the use of the absolute orientation of the VLBI stations—obtained from quasar observations in IVS Intensive sessions—and its transfer to the Galileo satellite constellation and tracking network through observations of a VT onboard Galileo satellites with VLBI telescopes and assess the achievable transfer performance. In the following sections, first the sensitivity of UT1–UTC for the orbit and observation geometry is evaluated before running the main simulations for UT1–UTC transfer. The simulation procedure is explained in Sect. 3, and the precision of the UT1–UTC transfer is simulated for different baselines in Sect. 4.

2 Sensitivity analysis

Before running the VT UT1–UTC transfer simulations, a sensitivity analysis is carried out to evaluate the effect of UT1–UTC uncertainty on the orbit determination as well as the influence of observation geometry on UT1–UTC transfer. The sensitivity of the orbit determination is evaluated by running a standard orbit determination process with simulated GNSS observations as shown in Sect. 2.1. The effects of visibility of Galileo satellites by VLBI stations/baselines are evaluated by introducing the '*UT1–UTC dilution of precision*(UDOP)' concept, which provides a preliminary assessment of the UT1–UTC transfer precision (see Sect. 4) which depends strictly on the observation geometry among other parameters.

2.1 Sensitivity of orbit to UT1–UTC

In order to quantify the importance of precise knowledge of UT1–UTC for precise orbit determination of GNSS satellites, a simple sensitivity analysis was performed using the Bernese GNSS Software V5.2 (BSW52, Dach et al. (2015)). Based on a typical network of 12 monitoring stations (see Fig. 3), simulated code and phase observations (see Sect. 3) are used for the determination of one-day Galileo orbit arcs (1) using UT1–UTC from IERS EOP data and, (2) using a biased UT1–UTC value.

Figure 1 shows the 3D RMS of the differences between the two estimated daily orbits. The box-plot shows the median, quartiles and extremes for all RMS values per orbit, computed over all satellites and 30 days as a function of the imposed UT1–UTC bias. The figure shows that an incorrect UT1–UTC value leads to a degraded orbit quality. However, as the GNSS orbits are given in the Earth-fixed frame, i.e., the same frame in which the coordinates of the observing stations are given, an orientation offset of the Earth in the inertial frame due to incorrect UT1–UTC can to a large

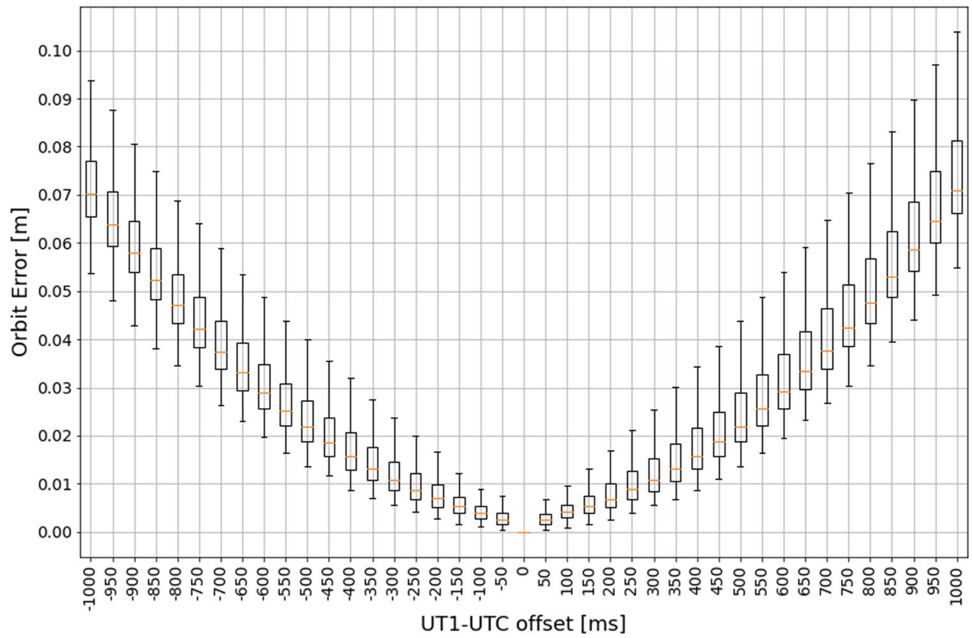

Fig. 1 Effect of UT1–UTC offsets on estimated satellite orbits. Orange lines, boxes, and whiskers correspond to the median, quartile, and extremal values, respectively, of the 3D orbit error rms values for estimated daily orbits computed for all Galileo satellites and a total of 30 days

extent be compensated by a corresponding misorientation of the satellite orbits in the inertial frame, thus not causing a biased orientation of the satellite orbits in the Earth fixed frame. The orbit degradation with shifted UT1–UTC is thus mainly caused by the incorrectly applied third body perturbations from Sun and Moon on the satellite orbits that are not correctly oriented in the inertial frame. Consequently, an impact at the few centimeter level has to be expected if incorrect UT1–UTC values are used in the orbit determination process. Accurate UT1–UTC information is thus required in order to reach centimeter level orbit accuracies which is, e.g., particularly relevant when precise inter-satellite range measurements are used for high-precision operational orbit determination for the future second generation Galileo satellites. Precise absolute orientation of GNSS orbits is required, e.g., for precise orbit determination of low Earth satellites equipped with GNSS receivers as well as for the extension of the GNSS Space Service Volume to higher orbits and up to the Moon (Enderle et al. 2018).

2.2 Sensitivity of VT observation to UT1–UTC

For successfully acquiring VLBI observations of an Earth orbiting satellite, the satellite needs to be visible by two VLBI stations and the geometric configuration of the satellite with respect to the stations has to be favorable to achieve a high sensitivity for the estimated parameters. In order to assess the sensitivity of a VT observation to UT1–UTC as a function of the relative location of the Galileo satellite with respect to the two observing VLBI stations, a quantity may be introduced that can be called UT1–UTC dilution of precision (UDOP, Belli (2020)) in analogy to the position dilution of precision (PDOP), which is well established for GNSS positioning applications (Swanson 1978). Considering UT1–UTC as the only parameter, the UDOP may be defined as the square root of the inverted 1x1-normal matrix, the cofactor matrix, i.e., as the square root of the reciprocal sum of the squared derivatives of the VT observations with respect to the Earth rotation angle. For a single VT observation, this reads

$$UDOP \equiv \left\| \boldsymbol{e_3} \cdot \left(\frac{\boldsymbol{y}}{R} \times \left(\frac{\boldsymbol{R_1}}{\rho_1} - \frac{\boldsymbol{R_2}}{\rho_2} \right) \right) \right\|^{-1} \quad (1)$$

where $\boldsymbol{y}$ is the satellite position vector and $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$ are the station position vectors, all in the Earth-fixed frame, ρ_1 and ρ_2 are the ranges between the satellite and the stations, R is the radius of the Earth, and $\mathbf{e}_3$ is the unit vector along the polar axis. A small value of UDOP indicates a high sensitivity of the observation to UT1–UTC, while a large value indicates a low contribution of the corresponding observation to the estimation of UT1–UTC. Multiplying this geometric UDOP value with the VT observation uncertainty provides the contribution of the measurement uncertainty to the uncertainty of the estimated UT1–UTC parameter. Equation (1) provides the UDOP value as unitless quantity. Multiplying with the VT measurement precision in unit of length provides the corresponding uncertainty in the UT1–UTC angle also in units of length, measured along the Earth equator. Multiplying the UDOP by 2.15 converts the units to µs/mm, i.e., a UDOP value of 1 corresponds to a formal UT1–UTC parameter uncertainty of about 20 µs for a typical VLBI measurement error of 9 mm (Schuh and Behrend 2012).

As an example, Fig. 2 shows the UDOP values as a function of geographical location of Galileo satellites for

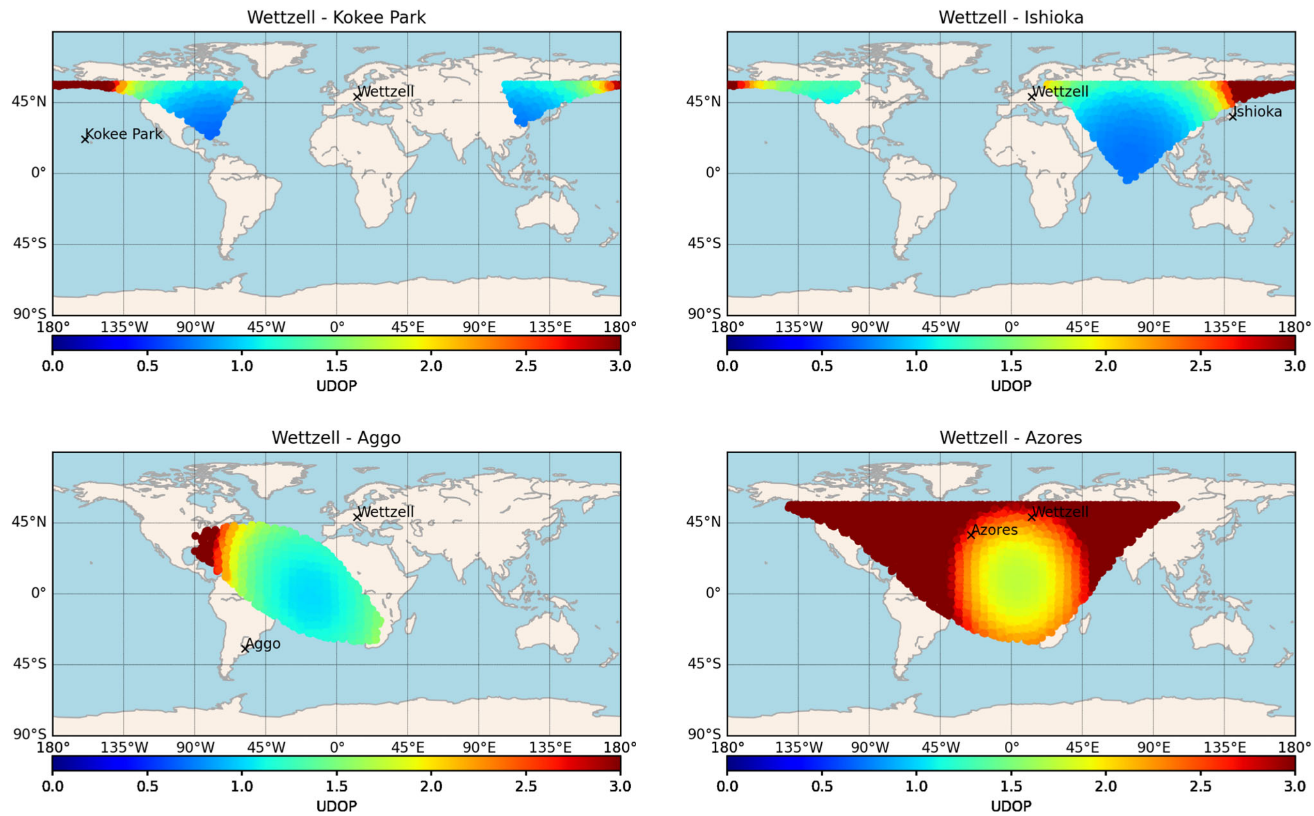

Fig. 2 Common visibility and UDOP values for Galileo satellite positions observable for the baselines Wettzell–Kokee Park (top left), Wettzell–Ishioka (top right), Wettzell-AGGO (bottom left), Wettzell–Azores (bottom right)

four VLBI station baselines. We selected the two long East–West baselines Wettzell–Kokee Park (WzKk) and Wettzell–Ishioka (WzIs) that are routinely used in IVS Intensive sessions. In addition, we considered the long baseline Wettzell-AGGO (Argentinian German Geodetic Observatory) (WzAg) with stations on both hemispheres offering improved visibility above the equatorial region, as well as the baseline Wettzell-Sta.Maria on the Azores Islands (WzAz) as a European baseline for a European satellite system.

It can be seen that the sensitivity increases for satellite positions closer to the equatorial plane. Table 1 shows the best achievable UDOP for the four considered baselines using an elevation cutoff angle of 3 degrees. After running the sensitivity analysis, the simulation procedure assessing the UT1–UTC transfer uncertainty by using VT which is the main framework of the study is explained in the following section.

3 Simulation procedure for UT1–UTC transfer

In order to assess the achievable precision of UT1–UTC transferred from VLBI to GNSS through VT observations of Galileo satellites, a simulation study was performed using the BSW52. The simulation is based on three solutions that are described in detail in the following:

Table 1 Best possible UDOP values for different baselines for VT on Galileo satellites

Baseline	Best UDOP
Wettzell–Ishioka	0.713
Wettzell–Kokee Park	0.668
Wettzell-AGGO	1.015
Wettzell–Azores	1.696

– GNSS solution: Galileo code and phase observations of a tracking network are simulated and processed using a standard ODTS procedure. This solution is insensitive to UT1–UTC, i.e., the UT1–UTC parameter setup for estimation is singular.
– VT solution: VLBI observations of a VT onboard Galileo satellites are simulated for different baselines of VLBI stations and processed for various geometrical configurations. Into this solution the UT1–UTC value to be transferred is introduced as well as its uncertainty as expected from a IVS Intensive session.

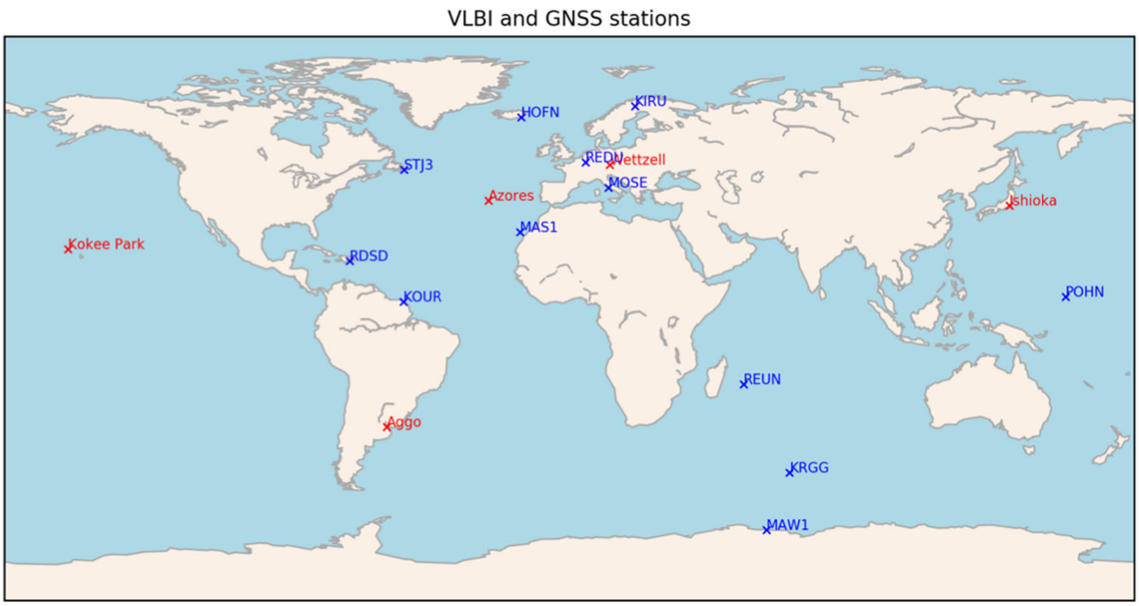

Fig. 3 Selected GNSS (blue) and VLBI (red) stations for simulations

– Combined solution: The GNSS and the VT solutions are combined at the normal equation level to assess the UT1–UTC transfer performance. In this solution, the formal error of the estimated UT1–UTC value indicates how well the VT concept can transfer the VLBI-derived UT1–UTC to the GNSS tracking station network.

Computing GNSS solutions for Galileo satellites using code and phase tracking data is standard for BSW52. Nevertheless, some adaptations in the BSW52 input files are necessary to be able to process Galileo observations. Considering a Galileo constellation ground track repeat cycle of ten days, dual-frequency Galileo code and phase observations for twelve Galileo sensor stations (GSS) covering Day of Year (DoY) 181 (30th of June) to DoY 190 (7th of July) in 2019 were simulated (see Fig. 3). A measurement noise of 1 mm and 10 cm are considered for phase and code observations, respectively, generated with a sampling rate of 30 seconds.

A standard ODTS solution using code and phase undifferenced observations in ionosphere-free linear combination is computed with station coordinates fixed on ITRF values. The estimated parameters are orbit parameters for 1-day arcs (state vectors and radiation pressure parameters of the empirical ECOM Model (Beutler et al. 1994)), epoch-wise clock corrections for stations and satellites, phase ambiguity parameters, and station-specific troposphere zenith delay parameters. In addition a UT1–UTC parameter is setup for estimation but constrained as GNSS observations have a low sensitivity to absolute orientation in space. Results are stored as unconstrained normal equation files.

Determining VLBI solutions is more challenging since BSW52 does not support the analysis of VLBI observations and hence VT observations need to be properly emulated given the available software capabilities. In fact, VLBI group delay observations are very similar to GNSS single difference code observations. The main difference is the measurement precision, which is of the order of 9 mm (30 picoseconds) for VLBI observations (Niell et al. 2018). Another aspect that is not supported by the software is to guarantee simultaneous observations of a VT by the two stations in a baseline. This condition is assured by proper scheduling of the simulation epochs using visibility conditions.

In order to emulate VT observations between two stations, simultaneous code observations are simulated for the two stations to the same Galileo satellite. These observations are then processed in BSW52 as undifferenced observations with epoch-wise estimation of satellite clock corrections. Since the stations are observing the same satellite simultaneously, the satellite clock parameter is the same for the baseline stations. Therefore, processing observations for both stations and additionally estimating a satellite clock parameter is mathematically equivalent to processing the difference of the two observations, which eliminates the clock parameter leaving the degree of freedom the same.

The noise added to the simulated observations is the typical VLBI measurement noise of 9 mm; however, divided by $\sqrt{2}$ as the formation of the single differences or, equivalently, the estimation of the satellite clock correction increases the noise by this factor again. Therefore, the noise for the simulated code observations that emulate VLBI measurements is selected as 6 mm.

As quasar observations cannot be processed with BSW52, the uncertainties expected for the parameters estimated from quasar observations, e.g., in an IVS Intensive session, have to be inserted to the VT processing as a priori information. This is accomplished by setting up UT1–UTC parameters for estimation but constrained with typical a priori standard deviations obtained from IVS sessions to an a priori value. These UT1–UTC parameters are then pre-eliminated before writing the normal equation. In this way, the UT1–UTC uncertainty obtained from the IVS session is implicitly and unremovably included in the stored normal equation. The resulting normal equation thus only contains the orbital elements of the observed Galileo satellite. The right-ascension of the ascending node of the orbit carries the information about the value and uncertainty of the introduced UT1–UTC information.

The GNSS and the VT solutions are finally combined at normal equation level. The combination of the two normal equations transfers the UT1–UTC uncertainty from IVS that is implicitly included in the VT normal equation to the combined solution. The UT1–UTC parameter that is setup in the GNSS normal equation can thus be estimated and its formal uncertainty assessed. Note that this corresponds to a sensitivity analysis, i.e., systematic errors are not considered. The formal uncertainty of the UT1–UTC parameter estimated in the combined solution is governed (1) by the original uncertainty inserted from the IVS session, inflated (2) by the observation noise of the VT and (3) by the uncertainty given by the GNSS observations for the given observation geometry. It will thus always be larger than the uncertainty of the original UT1–UTC parameter estimated with VLBI using quasar observations. In the following we denote the UT1–UTC obtained from IVS Intensive sessions as ‘input UT1–UTC’ and the UT1–UTC obtained by the simulation described above as ‘transferred UT1–UTC.’

4 Results

4.1 Single satellite VT observations

Using the combination procedure described above the formal uncertainty of the transferred UT1–UTC parameter is determined for the four selected baselines and a single VT observation. Figure 4a shows the uncertainty of the transferred UT1–UTC parameter as a function of the precision of the input UT1–UTC obtained from IVS. A large uncertainty of the input value is directly reflected in the uncertainty of the transferred parameter, leading to a linear increase that is essentially independent on the baseline. For a high precision of the input UT1–UTC, the estimated uncertainty levels are at values which are specific for the different baselines, with the smallest value for the long baseline WzIs (21 µs) and the largest for the shortest baseline WzAz (36 µs). These best case values are, on the one hand, given by the corresponding UDOP value associated with the geometric configuration of the VT observations (14 µs and 34 µs for 9 mm VT measurement noise, see Table 1) and, on the other hand, by the GNSS observation geometry and measurement noise. The dashed vertical line corresponds to the typical UT1–UTC uncertainty obtained from IVS Intensive sessions for long baselines.

Figure 4b shows the variation of the formal uncertainty of the transferred UT1–UTC value as a function of the synchronization uncertainty of the clocks of the two observing VLBI stations, which is given by the VLBI session based on the quasar observations. The input UT1–UTC uncertainty is fixed to the nominal 20 µs for all baselines. We observe a slow degradation of the quality of the transferred UT1–UTC value for increasing clock synchronization uncertainty above about 20 ps except for the shortest baseline which shows a faster degradation. For the following simulations, it is assumed that the clock synchronization error is contained in the VT measurement error of 9 mm. In addition, the effect of the uncertainty of the tropospheric zenith delay estimated in the IVS session is investigated. No significant impact on the transferred UT1–UTC value is, however, observed for typical troposphere delay uncertainties at the millimeter level.

As the precision of UT1–UTC provided by IVS Intensive sessions depends on the baseline length and degrades with shorter baselines, we will in the following simulations use a typical input UT1–UTC precision of 20 µs for the long baselines WzKk and WzIs while for the shorter baselines WzAg and WzAz a precision of 40µs is considered (see Table 2). The contribution of the uncertainties in the estimated station clocks and zenith delay parameters in the precision of the UT1–UTC estimated in the combined solution is not considered but could be included in the analysis by increasing the VT measurement precision accordingly.

In the following figures, results from the combined VT and GNSS solutions are presented. For ten successive days, a sampling of 15 min and an elevation cutoff angle of 3 degrees, all possible VT observations of Galileo satellites were determined and for each of them a combined daily solution was computed and the resulting precision of the transferred UT1–UTC parameter determined. With this, a total of 12,156 combined solutions with single VT observations were obtained.

Figure 5 shows the total visibility time of all Galileo satellites during a full Galileo repeat cycle of 10 days. As expected, we find longer common visibility for the short baselines. For the shortest baseline WzAz, we observe a mean daily visibility of around 6 h per day per satellite (with the exception of $E14$ and $E18$ that were deployed on eccentric orbits). Interestingly, we also find reasonably good visibility for the long baseline WzIs of about 3 h per day per satellite, while WzAg offers only around 1.5 h of common visibil-

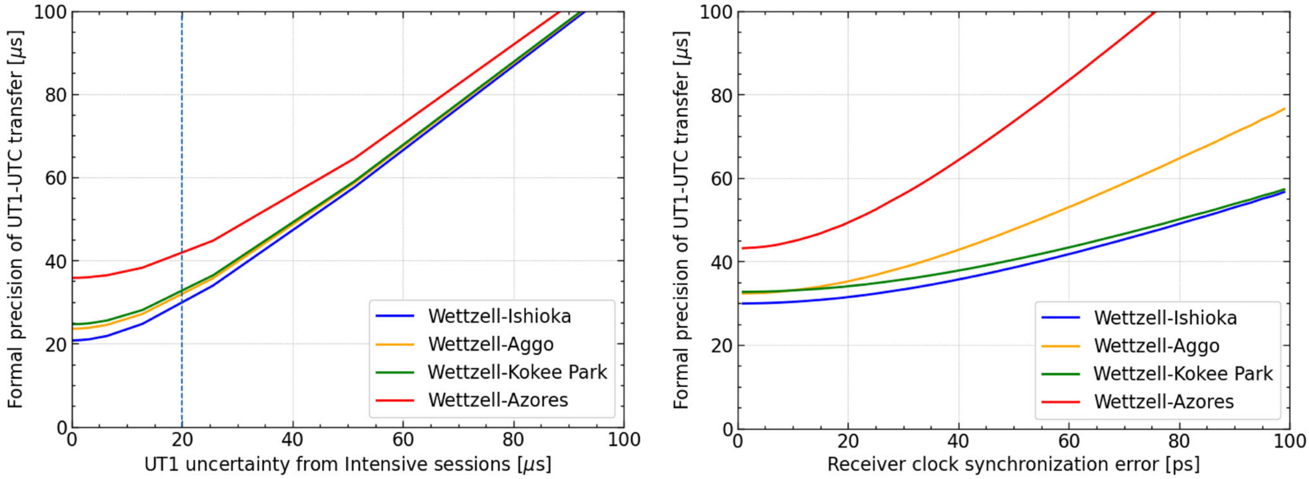

Fig. 4 (Left) Effect of the input UT1–UTC precision from quasar observations on the uncertainty of the transferred UT1–UTC value for four baselines. The dashed vertical line corresponds to 20µs. (Right) Effect of the synchronization precision of VLBI station clocks on the formal error of the transferred UT1–UTC value

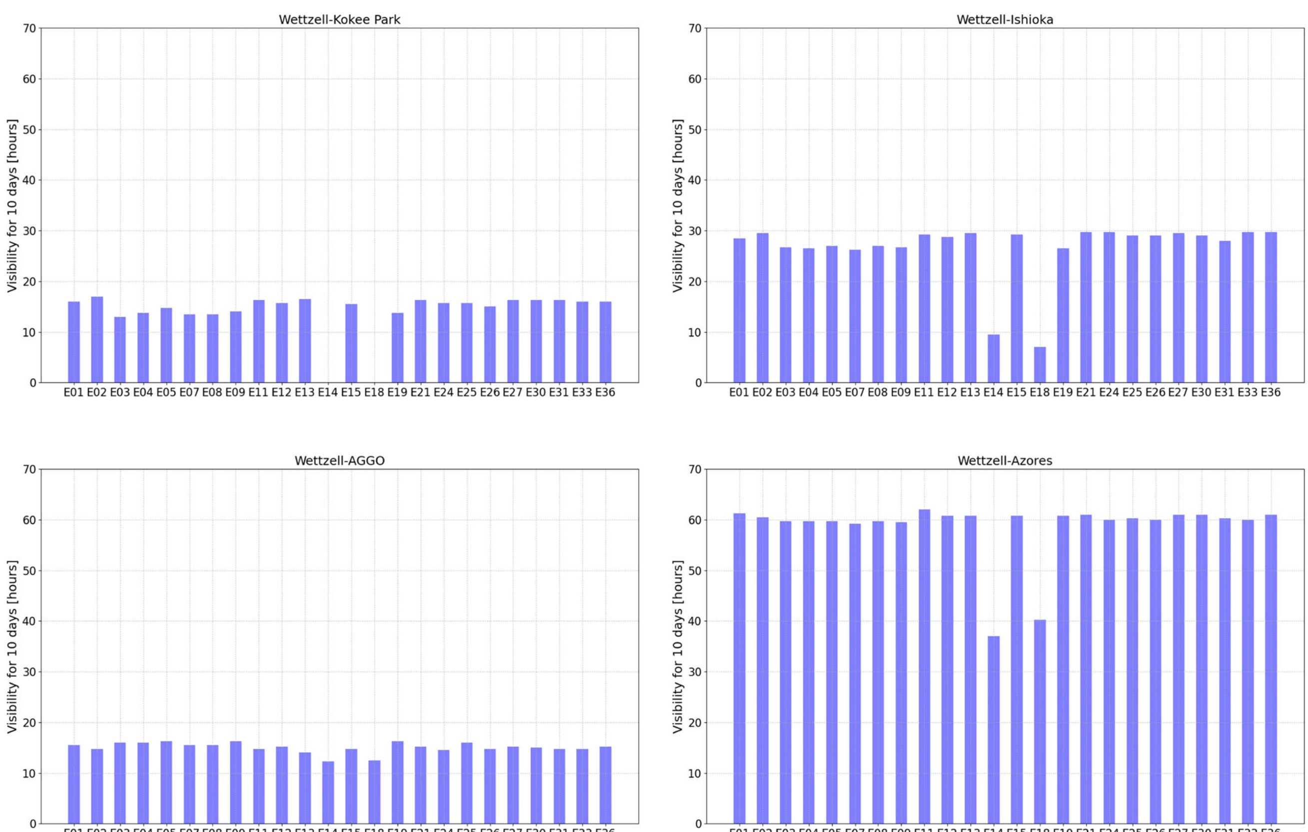

Fig. 5 Cumulative visibility time interval per 10 days for each Galileo satellite and the baselines Wettzell–Kokee Park (top left), Wettzell–Ishioka (top right), Wettzell-AGGO (bottom left), Wettzell–Azores (bottom right)

ity per satellite and day, which is similar as for the long baseline WzKk. The large difference in the common visibility of WzIs and WzAg is due to the section of the ground track that is visible (see Fig. 2). While for baseline WzAg the satellites are visible close to the equator where they rapidly move along meridian circles, the baseline WzIs has common visibility of the ground track section around latitude of 55 degree where the satellites change direction of motion

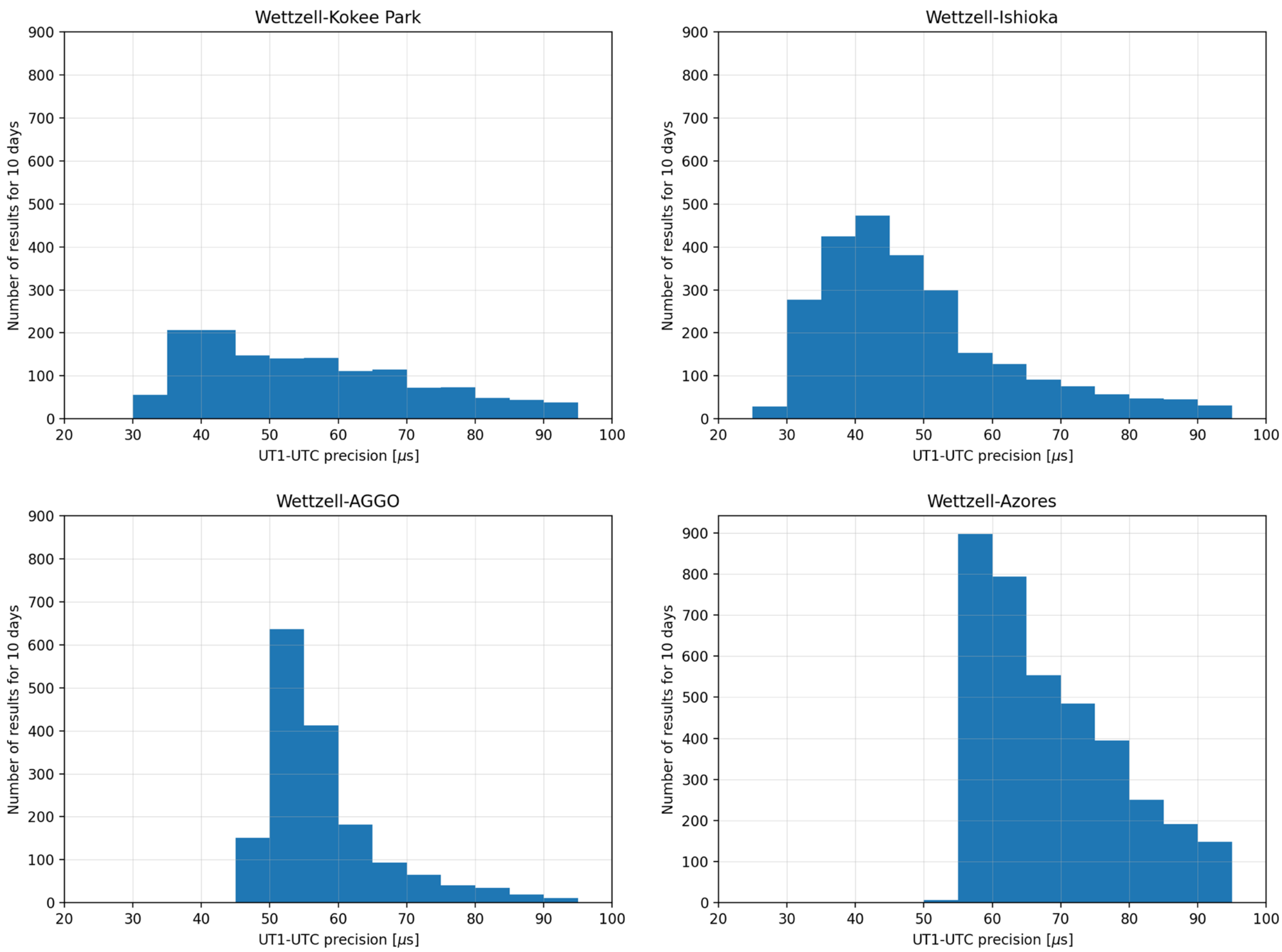

Fig. 6 Histogram of estimated UT1–UTC transfer precisions for all possible visibilities of Galileo satellites and four baselines. Wettzell–Kokee Park (top left), Wettzell–Ishioka (top right), Wettzell-AGGO (bottom left), Wettzell–Azores (bottom right)

in North-South direction. The figure, however, only presents the possible VT observation occasions, which are directly depending on the common visibility of the stations; it does not indicate the contribution of these observations to the transfer precision of UT1–UTC.

The histogram of the number of the transferred UT1–UTC parameters for a given precision estimated in the combined solution computed over all VT observations of Galileo satellites is displayed in Fig. 6. The precision of the transferred UT1–UTC reflects the strength of the observation geometry (UDOP) and the precision of the input UT1–UTC from the IVS session. The best results with a UT1–UTC precision around 30μs are obtained for baselines WzIs and WzKk. However, WzIs surpasses WzKk in terms of the number of results due to the better visibility and observation geometry. Among all considered baselines, WzIs thus provides the largest number of high precision UT1–UTC values. The best 10% of all baseline solutions (in total there are 1597, 2853, 1723, 5988 solutions with 15 min sampling in 10 days for WzKk, WzIs, WzAg, WzAz, respectively) provide a precision of the transferred UT1–UTC of better than 38μs for WzKk, 35μs for WzIs, 50μs for WzAg, and 58μs for WzAz (see Table 2).

Complementing the histograms in Figs. 5, 6 and 7 shows the distribution of the visibility time intervals for all satellites as a function of time for 10 days as well as the temporal distribution of the achievable precision of the estimated UT1–UTC parameter for each Galileo satellite for the four baselines. We again observe a large number of visibility intervals providing, however, relatively low UT1–UTC precision for the shortest baseline WzAz, while, for the longest baseline WzKk, the visibility intervals are relatively sparse and scattered in the achievable precision of the transferred UT1–UTC.

Figure 8 shows the distribution of the geographical locations of Galileo satellites for which VT observations are performed together with the corresponding precision of UT1–UTC transferred from the IVS UT1–UTC precision to the GNSS solutions, separately for the four baselines considered. We note a spatial pattern which is very similar to that shown in Fig. 2 for the UDOP, clearly indicating the

Table 2 UT1–UTC transfer simulation inputs for the measurement precisions and UT1–UTC uncertainties from intensive session and results of transfer precisions of the top 10% of all solutions for different baselines

Baseline	Measurement precision (mm)	UT1–UTC input (μs)	Total Number of solutions	Precision of the best 10% of total solutions (μs)
WzKk	9	20	1597	≤ 38
WzIs	9	20	2853	≤ 35
WzAg	9	40	1723	≤ 50
WzAz	9	40	5988	≤ 58

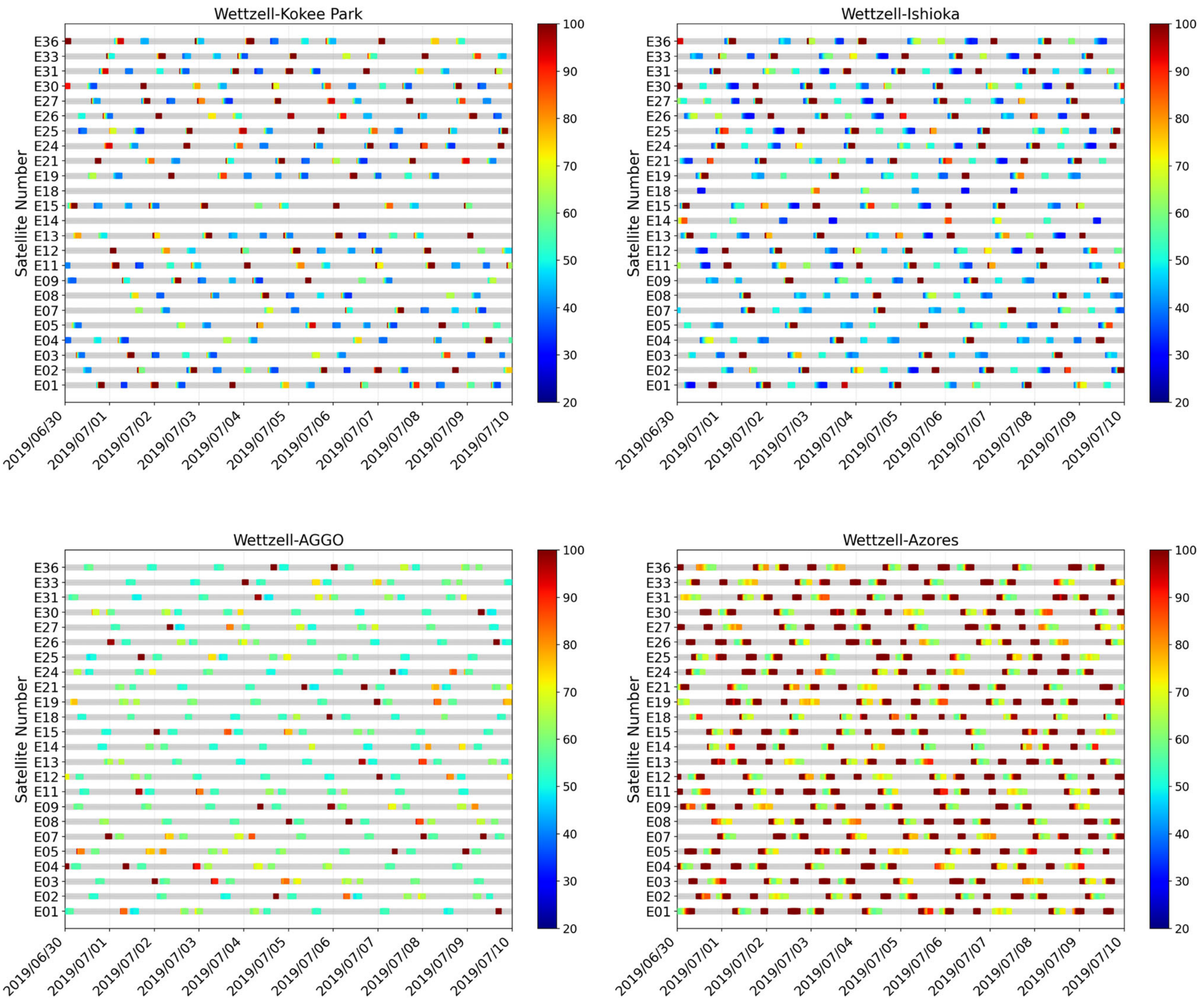

Fig. 7 Visibility intervals and obtained UT1–UTC transfer precisions [μs] for each Galileo satellite for 10 days for the baselines Wettzell–Kokee Park (top left), Wettzell–Ishioka (top right), Wettzell-AGGO (bottom left), Wettzell–Azores (bottom right)

importance of the geometrical configuration of the observed Galileo satellite and the two observing VLBI stations. The difference in the magnitude of the uncertainties displayed in the two figures results from the additional uncertainties contributed by the input UT1–UTC value and the GNSS observations as discussed in Sect. 3.

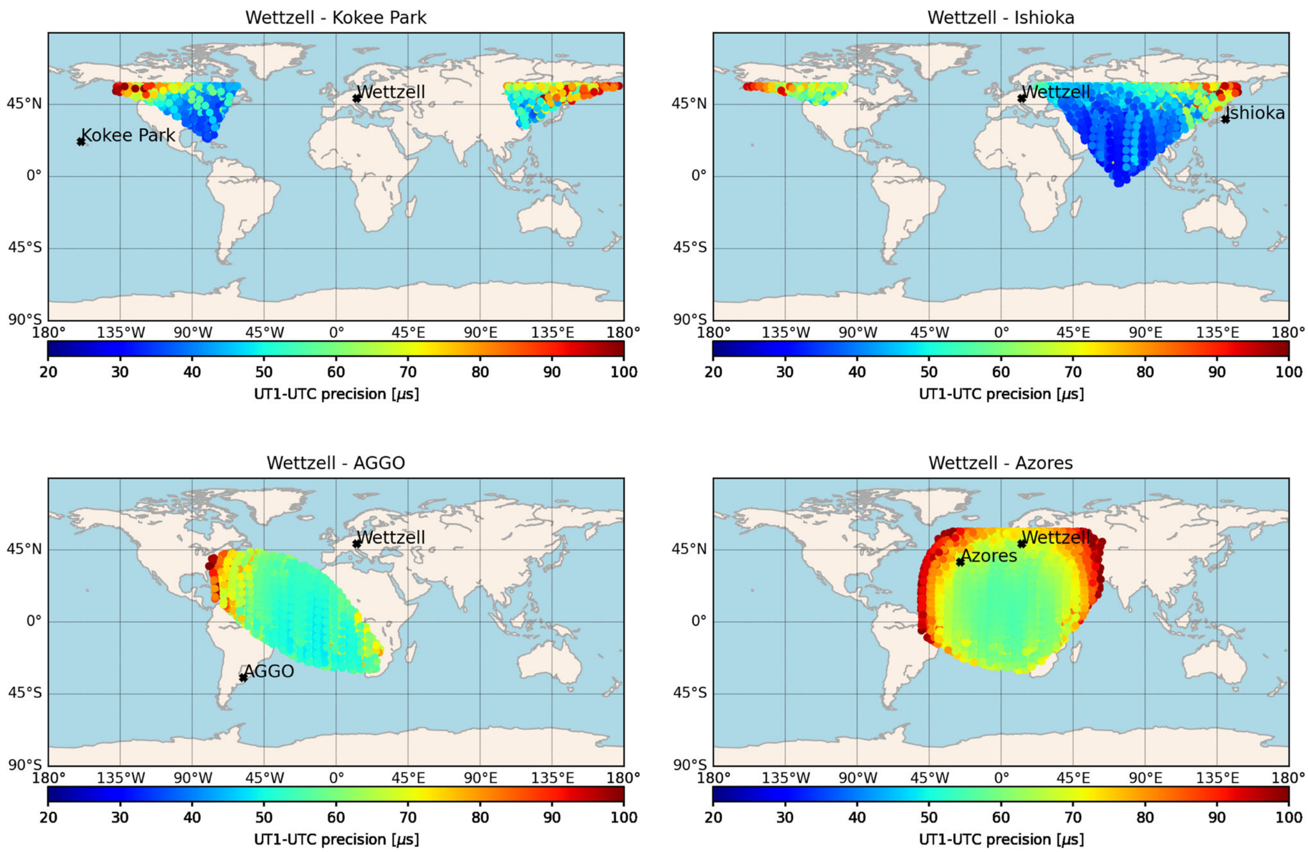

Fig. 8 UT1–UTC transfer precisions for different baselines including all Galileo satellites as a function of geographical location. Wettzell–Kokee Park (top left), Wettzell–Ishioka (top right), Wettzell-AGGO (bottom left), Wettzell–Azores (bottom right)

4.2 Multiple VT observations and network solutions

After considering solutions involving single satellite VT observations, let us address, as a case study, the precision of the transferred UT1–UTC determined with solutions involving several observations of the same satellite during a simultaneous pass. Figure 9 shows four arbitrary examples of the formal precision of the transferred UT1–UTC parameter for a series of VT observations for baseline WzKk. The dots in the figure corresponds to UT1–UTC transfer precisions obtained for single VT observations at the indicated epoch while the curves represent the formal error from a cumulative solution with adding more and more observations with a sampling of 30 s. In three of the examples, the UT1–UTC precision of the solutions based on a single VT observation improves because the satellite is moving toward a region on the sky promising a better observation geometry, i.e., a smaller UDOP, while, for one of the examples, the single VT solution degrades with time. The formal precision of the cumulative solution of course gradually improves when more VT observations are added and reaches a precision that is slightly better than the best single VT solution. However, as this difference is small, the most efficient way to achieve a high UT1–UTC transfer precision is to acquire a single VT observation at a satellite location offering highest sensitivity.

Finally, let us assess, based on a few examples, the improvement of the transferred UT1–UTC value when considering VT observations from more than a single baseline. Table 3 shows the precision of UT1–UTC transfer for one VT observation for different single baselines as well as for VT observations of two different Galileo satellites acquired by two different baselines. The results show a significant improvement also when considering a longer baseline than considering a shorter one or when combining two short baselines. In the considered examples, except for the last one, the VT observations are acquired at different epochs. Similar examples with VT observations from different satellites and acquired from different baselines within the same hour can be scheduled, which would, e.g., fit into an IVS Intensive session.

5 Conclusion

The feasibility of the transfer of the UT1–UTC obtained from VLBI quasar observations to the Galileo constellation

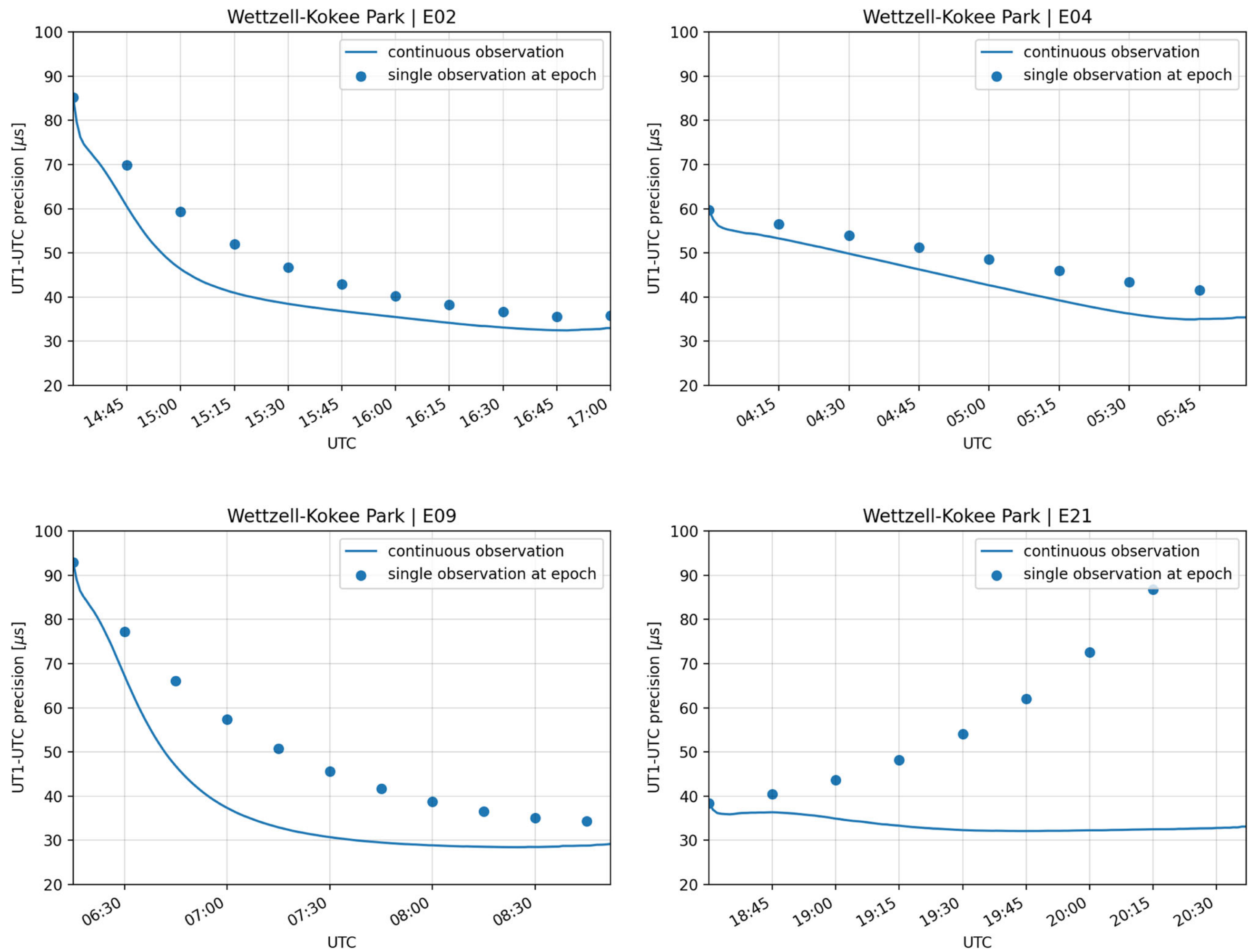

Fig. 9 Four examples indicating UT1–UTC transfer precision for single observations at different epochs (dots) and continuous observations over 2.5 h for baseline Wettzell–Kokee Park

Table 3 Examples of UT1–UTC transfer precision achieved with observations from one and from two baselines

Baseline	Satellite	Epoch	UT1–UTC precision (μs)
WzIs	E33	15:30:00	29.63
WzIs	E27	07:30:00	70.72
WzKk	E31	07:30:00	32.41
WzAg	E31	13:30:00	48.17
WzAz	E33	09:45:00	55.94
IsWzKk	E33+E31	07:30:00 & 15:30:00	22.49
AgWzKk	E31+E31	07:30:00 & 13:30:00	27.80
AgWzIs	E31+E33	13:30:00 & 15:30:00	25.22
AgWzAz	E31+E33	09:45:00 & 13:30:00	36.49
IsWzKk	E27+E31	07:30:00	22.15

through onboard VLBI transmitters is investigated using simulated observations for four baselines. The idea is to directly transfer the UT1–UTC value estimated in VLBI sessions, i.e., the information about the variations in the Earth rotation, to the Galileo constellation using the space tie realized by the VT.

The results of the simulations performed show that the transfer of UT1–UTC information via VLBI transmitters on the Galileo satellites is feasible for single observations with a precision level around 30 μs for the long baselines WzIs and WzKk. The short baselines WzAg and WzAz provide a precision around 50 μs and 55 μs also due to the fact that IVS Intensive sessions based on such short baselines would provide UT1–UTC with a lower precision. Although the precision of UT1–UTC achievable with VT observations on the long baselines WzKk and WzIs are similar, the baseline WzIs offers nearly two times more VT observations than the baseline WzKk because of more favorable visibility conditions for Galileo satellites.

The estimated precision of the transferred UT1–UTC is mainly driven by two factors: the geometrical setting of the Galileo satellite with respect to the two stations of the baseline that may be quantified by the UT1–UTC dilution of precision (UDOP) and the UT1–UTC precision obtained from quasar observations in an IVS session. While the UDOP indicates the sensitivity of a VT observation on UT1–UTC for a given baseline, the UT1–UTC input from the IVS session inflates the uncertainty achievable for the UT1–UTC transfer to the Galileo constellation. Neglecting this contribution to the uncertainty, the limiting UT1–UTC transfer precisions are around 20 μs for WzIs, 25 μs for WzKk and WzAz, and 35 μs for WzAz.

Increasing the observation number of VT results in a slightly improved UT1–UTC transfer. However, the UT1–UTC precision is essentially given by the observation that provides the highest sensitivity to UT1–UTC, while additional observations of the same satellite pass lead only to a modest further improvement. For UT1–UTC transfer to the satellite constellation, it is thus important to properly schedule a few VT observations with high sensitivity. Adding VT observations acquired by different baselines, on the other hand, significantly improves the UT1–UTC transfer precision. It is, however, not straightforward to schedule regular 1 h IVS Intensive sessions that include several Galileo VT observations. Alternative observation concepts may thus be envisaged that complement long baselines of IVS Intensive sessions with few observations from additional baselines that optimize VT visibility. In this way the higher precision of UT1–UTC estimated on long baselines using quasar observations and optimized VT sensitivity for UT1–UTC can be exploited for UT1–UTC transfer to the Galileo constellation.

Acknowledgements This work was partially supported by ESA through the Project on VLBI transmitter for G2G (Galileo 2nd Generation, Contract No. 40000129356/19/NL/AS), with Antwerp Space as Prime Contractor. Funded by EU; ESA has received funds in its quality as funding body under the European Union's Horizon 2020 research and innovation programme. This work has also received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreements Nos. 670874 and 855677).

Author Contributions UH and OK defined the research topic, HS ran the simulations with the support from UH, and all authors contributed to the writing of the manuscript.

Data availability The multi-GNSS datasets used during the current study are available from: http://ftp.aiub.unibe.ch/CODE_MGEX/. Calculations are based on Bernese GNSS Software Version 5.2 licensed from University of Bern.

References

Anderson JM, Beyerle G, Glaser S, Liu L, Männel B, Nilsson T, Heinkelmann R, Schuh H (2018) Simulations of VLBI observations of a geodetic satellite providing co-location in space. J Geod 92(9):1023–1046. https://doi.org/10.1007/s00190-018-1115-5
Bar-Sever Y, Haines B, Wu S (2009) The geodetic reference antenna in space (GRASP) mission concept. In: EGU general assembly conference abstracts, p 1645
Belli F (2020) Transfer of absolute orientation to Galileo orbits with VLBI. PhD thesis, Master thesis, Technical University of Munich
Beutler G, Brockmann E, Gurtner W, Hugentobler U, Mervart L, Rothacher M, Verdun A (1994) Extended orbit modeling techniques at the CODE processing center of the international GPS service for geodynamics (IGS): theory and initial results. Manuscr Geod 19(6):367–386
Biancale R, Pollet A, Coulot D, Mandea M (2017) E-GRASP/Eratosthenes: a mission proposal for millimetric TRF realization. In: EGU general assembly conference abstracts, p 8752
Bruni S, Rebischung P, Zerbini S, Altamimi Z, Errico M, Santi E (2017) Assessment of the possible contribution of space ties on-board GNSS satellites to the terrestrial reference frame. J Geod 92(4):383–399. https://doi.org/10.1007/s00190-017-1069-z
Dach R, Andritsch F, Arnold D, Bertone S, Fridez P, Jäggi A, Jean Y, Maier A, Mervart L, Meyer U, Orliac E, Geist E, Prange L, Scaramuzza S, Schaer S, Sidorov D, Susnik A, Villiger A, Walser P, Thaller D (2015) Bernese GNSS software version 5.2. https://doi.org/10.7892/boris.72297
Dickey JM (2010) How and Why to do VLBI on GPS. arXiv:1008.4642
Enderle W, Gini F, Boomkamp H, Parker JJ, Ashman BW, Welch BW, Koch M, Sands OS (2018) Space user visibility benefits of the multi-gnss space service volume: an internationally-coordinated, global and mission-specific analysis. In: Proceedings of the 31st international technical meeting of the satellite division of the institute of navigation (ION GNSS+ 2018), pp 1191–1207
Haas R, Sekido M, Hobiger T, Kondo T, Kurihara S, Tanimoto D, Kokado K, Wagner J, Ritakari J, Mujunen A (2010) Ultra-rapid DUT1-observations with e-VLBI. Artif Satell. https://doi.org/10.2478/v10018-010-0007-6
Haas R, Neidhardt A, Kodet J, Plötz C, Schreiber U, Kronschnabl G, Pogrebenko S, Duev D, Casey S, Marti-Vidal I et al (2014) The Wettzell-Onsala G130128 experiment—VLBI-observations of a GLONASS satellite. In: Behrend D, Baver KD, Armstrong KL (eds) IVS 2014 general meeting proceedings" VGOS: the new VLBI network. Science Press, Beijing, pp 451–455
Hase H (1999) Phase centre determinations at GPS-satellites with VLBI. Eur VLBI Geod Astrom 13:273–277
Hellerschmied A, Böhm J, Kwak Y, McCallum J, Plank L (2016) VLBI observations of GNSS satellites on the baseline Hobart-Ceduna. In: EGU General assembly conference abstracts, EGU general assembly conference abstracts, pp EPSC2016–8895
Hellerschmied A, Böhm J, Neidhardt A, Kodet J, Haas R, Plank L (2015) Scheduling VLBI observations to satellites with VieVS. https://doi.org/10.1007/1345_2015_183

Jaradat A, Jaron F, Gruber J, Nothnagel A (2021) Considerations of VLBI transmitters on Galileo satellites. Adv Space Res. https://doi.org/10.1016/j.asr.2021.04.048

Klopotek G, Hobiger T, Haas R, Otsubo T (2020) Geodetic VLBI for precise orbit determination of earth satellites: a simulation study. J Geod. https://doi.org/10.1007/s00190-020-01381-9

Malkin ZM (2020) Statistical analysis of the results of 20 years of activity of the international VLBI service for geodesy and astrometry. Astron Rep 64(2):168–188. https://doi.org/10.1134/s1063772920020043

Nerem R, Bar-Sever YE, Grasp Team (2011) The geodetic reference antenna in space (GRASP)—a mission to enhance the terrestrial reference frame. In: AGU fall meeting abstracts, vol 2011, pp G51B–04

Niell A, Barrett J, Burns A, Cappallo R, Corey B, Derome M, Eckert C, Elosegui P, McWhirter R, Poirier M et al (2018) Demonstration of a broadband very long baseline interferometer system: a new instrument for high-precision space geodesy. Radio Sci 53(10):1269–1291

Nothnagel A, Artz T, Behrend D, Malkin Z (2016) International VLBI service for geodesy and astrometry. J Geod 91(7):711–721. https://doi.org/10.1007/s00190-016-0950-5

Petrachenko B, Corey B, Himwich E, Ma C, Malkin Z, Niell A, Shaffer D, Vandenberg N (2004) Vlbi2010: networks and observing strategies. In: International VLBI service for geodesy and astrometry 2004 general meeting proceedings

Plag HP, Pearlman M (2007) The global geodetic observing system: meeting the requirements of a global society on a changing planet in 2020 the reference document. Int Assoc Geod

Plank L, Böhm J, Schuh H (2014) Precise station positions from VLBI observations to satellites: a simulation study. J Geod 88(7):659–673

Plank L, Hellerschmied A, McCallum J, Böhm J, Lovell J (2017) VLBI observations of GNSS-satellites: from scheduling to analysis. J Geod 91(7):867–880. https://doi.org/10.1007/s00190-016-0992-8

Plank L, Böhm J, Schuh H (2015) Simulated VLBI satellite tracking of the GNSS constellation: observing strategies. In: International association of geodesy symposia, Springer, pp 85–90. https://doi.org/10.1007/1345_2015_87

Schuh H, Behrend D (2012) VLBI: a fascinating technique for geodesy and astrometry. J Geodyn 61:68–80

Swanson E (1978) Geometric dilution of precision, Navigation. J Inst Navig 25(4):425–429

Tornatore V, Haas R, Casey S, Duev D, Pogrebenko S, Calvés GM (2014) Direct VLBI observations of global navigation satellite system signals. In: Earth on the edge: science for a sustainable planet, Springer, pp 247–252

Tornatore V, Haas R, Molera G, Pogrebenko S (2010) Planning of an experiment for VLBI tracking of GNSS satellites. In: Proceedings of the 6th IVS general meeting, pp 70–74

Vondrák J, Richter B (2004) International earth rotation and reference systems service (IERS) web: www.iers.org. J Geod 77(10-11):585–678, https://doi.org/10.1007/s00190-003-0370-1