Quality Assessment of UT1-UTC (dUT1) Estimates Using VGOS Observations

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Abstract Currently a network of up to nine next-generation VLBI, or VGOS, stations observes 24-hour-long sessions once every two weeks, and two VGOS stations in Hawaii and Germany observe one-hour-long sessions, known as Intensives, five days a week. Similar sessions are conducted with the predecessor S/X legacy system, with a network of up to 15 stations observing 24-hour sessions twice a week and the same pair of stations as for VGOS observing one-hour Intensives every day. The goal of the Intensives is to measure dUT1 precisely in a more timely manner than possible for the 24-hour sessions, which have broader scientific goals. Individual VGOS observations are more precise than S/X observations (Niell et al., 2018). Therefore, the precision and accuracy of the dUT1 estimates from VGOS have the potential to be better than that from S/X.

In this paper, we investigate the level of agreement of dUT1 measurements obtained from both one-hour- and 24-hour-long VGOS sessions with dUT1 obtained from simultaneous S/X legacy sessions and with external dUT1 series from IERS and USNO. We find that the median formal error of the dUT1 is a factor of two smaller for VGOS Intensives than for the S/X Intensives, but similar for VGOS and S/X 24-hour sessions. The VGOS-derived dUT1 series is in good agreement with the S/X-derived dUT1, which is an indication that VGOS and S/X reference frames are in good agreement. Comparisons with external EOP series show that both VGOS and S/X-derived dUT1 are in good agreement with the USNO series for both 24-hour and one-hour sessions. The scatters of the differences of VGOS-derived dUT1 with S/X-derived dUT1 and other external dUT1 series are not consistent with the estimated VGOS formal errors which suggests that a significant amount of unmodeled noise is present in the VGOS observations.

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Keywords UT1-UTC, dUT1, VGOS, Geodetic VLBI

1 Introduction

The VLBI Global Observing System (VGOS) is a broadband geodetic VLBI system made up of small, fast, sensitive antennas capable of observing radio sources with a faster cadence than the predecessor S/X legacy system. VLBI is the only space-geodetic technique, among four, that observes distant quasars. VLBI is therefore capable of realizing a Celestial Reference Frame (CRF) and solving for all five earth orientation parameters: UT1-UTC, two polar motion parameters, and two nutation parameters. Among the space-geodetic techniques, VLBI is the only one that provides UT1-UTC, the diurnal earth rotation phase, otherwise known as dUT1. A significant portion of this quantity can be modeled and predicted using different geophysical phenomena. However, some variations cannot be modeled and need to be observed with high precision.

At present, the S/X legacy VLBI network is providing dUT1 via the so-called Intensive sessions (INT1), which run every day for 1 hour using a single baseline between Kokee Park, Hawaii, and Wettzell, Germany (Figure 1). This network also observes 24-hour sessions (R1/R4) twice a week with 7–14 stations. The newer VGOS network of nine stations has demon-

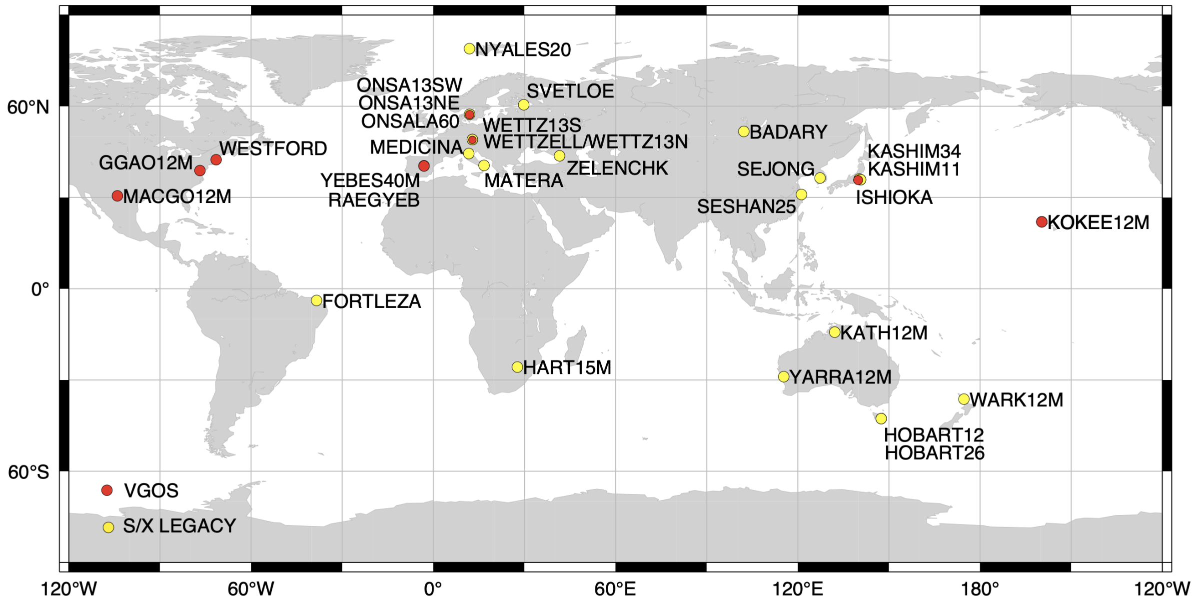

Fig. 1 Location of VGOS (red circles) and S/X legacy (yellow circles) VLBI stations.

strated theoretical observation uncertainties that are a factor of ten smaller than from S/X legacy systems (Niell et al., 2018). Therefore, the dUT1 parameters from VGOS observations could be more accurate and precise than that from S/X legacy.

High precision UT1-UTC is critical for many applications, such as satellite orbit determination, spacecraft navigation, astronomical observations, and other geophysical studies. In this paper, we explore the quality of dUT1 measurements obtained from VGOS observations and compare them with dUT1 measurements obtained from S/X legacy observations, as well as with external dUT1 from IERS and USNO.

2 Data

We utilized both one-hour-long Intensive and 24-hour-long VGOS and S/X legacy sessions observed between 2019 and 2021. The Intensive sessions, both VGOS and S/X, have the observations from only two stations and thus from a single baseline. The regular 24-hour sessions contain multiple baselines among the stations observing a source simultaneously. S/X legacy stations observed both one-hour Intensive and 24-hour regular sessions more frequently than the VGOS network. Therefore, we used only the S/X sessions that overlapped the day of a VGOS session and estimated the dUT1 parameter at the common integer day boundary. In total, we have used the Intensive sessions for 85 days and the 24-hour regular sessions for 65 days. All VGOS and S/X sessions are publicly available on the CDDIS server (https://cddis.nasa.gov/archive/vlbi/ivsdata/).

3 Analysis

We processed the VLBI observables from all sessions using the VieVS geodetic software package (Böhm et al., 2009) to obtain dUT1 estimates, along with other parameters of geodetic interest, as described next. Given that the Intensive and regular VLBI sessions have different observing lengths and station network configurations, the analysis strategies are different. The 24-hour sessions were observed with seven or more stations; therefore, site positions, source positions, clocks parameters, atmospheric parameters, and EOPs can all be estimated. In contrast, the one-hour Intensive sessions do not contain enough

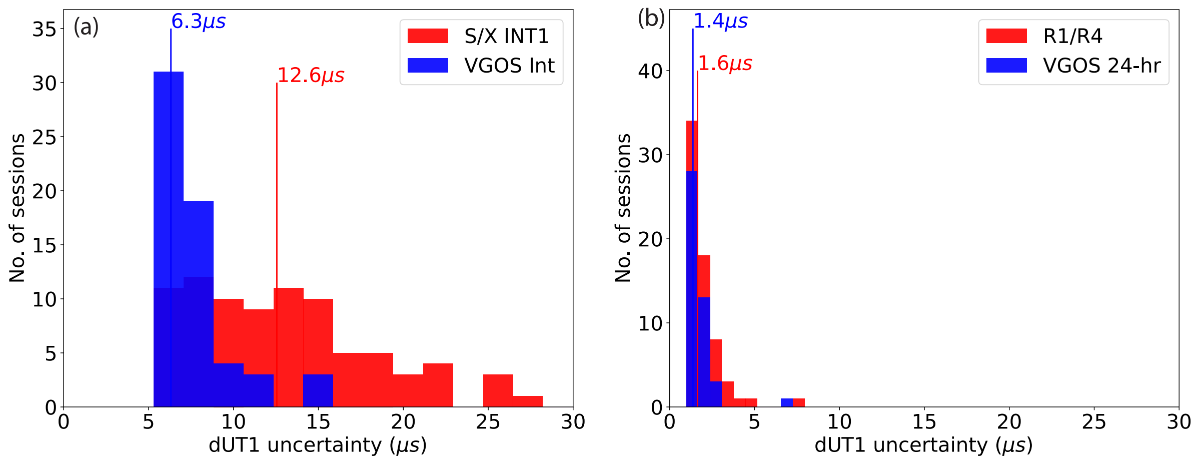

Fig. 2 Histogram of the dUT1 uncertainties (formal errors) estimated for (a) one-hour Intensive sessions and (b) 24-hour-long sessions from VGOS and S/X legacy observations. The vertical lines and the numbers represent the median of the formal error from all sessions.

observations to estimate all the parameters. Therefore, only one clock offset at one station, atmospheric wet delay at both stations, and one dUT1 parameter are estimated. The site positions, source positions, polar motion, and nutation parameters remained fixed in the solution. We have used ITRF2014-equivalent site positions of the VLBI stations. For the 24-hour sessions, we first generated the normal equations and then stacked the normal equations to solve for the EOPs using a common set of stations as a reference frame datum. For the one-hour Intensive sessions, we compared the dUT1 values estimated independently for each session. Comparisons were made among the dUT1 series from four sources: values obtained from VGOS observations, values obtained from S/X legacy observations, and external EOP series from the IERS 14C04 and USNO Final series. We used the weighted mean (bias) and weighted standard deviations (scatter) as the metrics to describe the agreement and scatter between two series.

4 Comparison of Formal Error

We compared the formal errors estimated from the VGOS and S/X 24-hour and one-hour sessions. The formal error is the uncertainty of the dUT1 parameter estimated from a re-weighted solution in which extra noise was added in quadrature to each observation to account for mismodeling and to make the chi-square per degree of freedom, χ^2/dof, equal to one (Equation 1).

$$\sigma_j^2 = \sigma_{j,meas}^2 + \sigma_{j,noise}^2 \quad (1)$$

Here, $\sigma_{j,meas}^2$ is the group delay variance for each observation and $\sigma_{j,noise}^2$ is the constant additive noise variance.

The median formal error of 6.3 μs for the VGOS Intensives is a factor of two smaller than the median error of 12.6 μs for the S/X legacy Intensives (Figure 2a). The smaller error for VGOS dUT1 is due mainly to the lower group delay uncertainties and increased number of observations in VGOS sessions, given that the baseline geometry is identical for both S/X and VGOS Intensives. The mean number of observations in a VGOS Intensive is typically twice the mean number in an S/X Intensive. The group delay uncertainties for VGOS are also approximately ten times smaller than for S/X; for example, the median group delay uncertainties in VGOS and S/X legacy sessions observed on 19 October 2021 were 1.3 ps and 11.1 ps, respectively.

In the 24-hour regular sessions, the median formal errors from VGOS and S/X are comparable (Figure 2b), 1.4 and 1.6 μs, respectively. The similarity in the formal errors likely reflects differences in the geographical distributions of the networks. If the networks were similar, one would expect the dUT1 for-

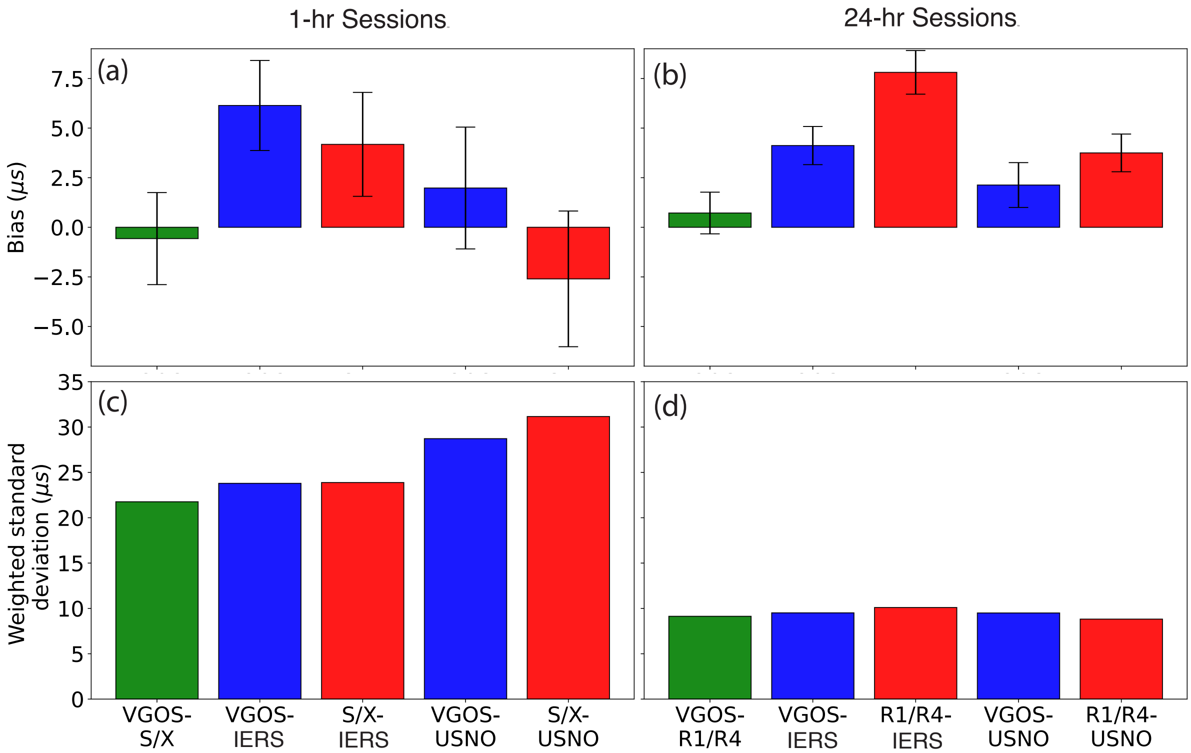

Fig. 3 Weighted mean bias (a and b) and weighted standard deviation (c and d) of the difference of VGOS and S/X dUT1 with respect to each other and with respect to other external EOP series for one-hour Intensive (left column) and 24-hour (right column) sessions.

mal errors to be significantly smaller for VGOS than for S/X, as was observed for the one-baseline Intensives. The VGOS network has 7–9 stations mostly distributed over the northern hemisphere, whereas the S/X legacy network has more than nine stations distributed over both hemispheres. Thus, the S/X legacy network may have provided better geometric strength for measuring dUT1 than the VGOS network.

The formal errors for the Intensive sessions are larger than for the 24-hour sessions for both VGOS and S/X legacy networks, primarily because of the smaller number of observations in Intensive sessions. This difference in the number of observations is due both to the difference in session duration and to the greater number of baselines in 24-hour sessions.

5 VGOS Comparison with Other EOP Series

We have compared the bias and scatter of the differences of dUT1 values estimated from VGOS observations with dUT1 values estimated from S/X observations, and with the dUT1 values from other Combination Centers. The Combination-Center dUT1 series include the solutions from S/X observations but not from VGOS observations; therefore, the VGOS-derived dUT1 values are independent of all of the other dUT1 series.

For the Intensive observations, the VGOS-derived dUT1 series is in the best agreement with S/X-derived dUT1; the bias of the difference between two series is -0.6 ± 2.3 μs (Figure 3a). Both VGOS and S/X have negligible bias to the USNO series. Both series agree better with USNO than with IERS dUT1. The scatter of the VGOS series is smaller when compared with S/X than with IERS and USNO (Figure 3c).

For the 24-hour-long sessions, the VGOS-derived dUT1 series is also in good agreement with S/X derived dUT1 series (Figure 3b). The bias between two series is 0.7 ± 1.0 µs. In general, the VGOS-derived dUT1 agrees better with IERS and USNO dUT1 series than does S/X. The scatters of the VGOS-derived dUT1 series with S/X and other external EOP series are similar (Figure 3d).

The scatter (standard deviation) of the Intensive-derived dUT1 is larger than the dUT1 estimated from the 24-hour sessions. This is partly because the dUT1 derived from the Intensive sessions absorbs the error from the parameters that remained fixed in the solution, such as the terrestrial and celestial reference frames, polar motion, and nutation. It is possible to estimate these additional parameters in the analysis of the 24-hour-long sessions because of the availability of more observations. However, the primary reason the 24-hour sessions have smaller dUT1 uncertainties, and thus scatter, is because those sessions have a larger number of antennas and a better network geometry, as well as many more observations.

6 Conclusions

Our comparison shows that the formal errors of the dUT1 estimates are a factor of two smaller for the VGOS Intensives than for the S/X Intensives, but is similar for the VGOS and S/X 24-hour sessions. VGOS-derived dUT1 estimates, from both 24-hour and one-hour Intensive, agree better with USNO Final EOP series than with IERS. The best agreement is seen with the simultaneous S/X sessions. The small bias between the VGOS and S/X dUT1 estimates suggests that the reference frames for the two networks are in good agreement.

The VGOS dUT1 scatters relative to IERS, USNO Final, and S/X series are similar, though larger for Intensives than for the 24-hour sessions, as one would expect. The large scatter is not consistent with the smaller formal error for both the VGOS and S/X dUT1 results, which suggests that there is significant unmodeled noise present in the solutions. For example, the observed scatter of the dUT1 differences between VGOS and S/X Intensives is about 21.7 µs; however, one would expect the scatter to be about 14.0 µs, given that the median formal errors of VGOS and S/X Intensives are 6.3 and 12.6 µs, respectively. Therefore, about 16.5 µs of additional noise is present. Similarly, the VGOS minus S/X 24-hr series contains about 8.8 µs of unmodeled noise.

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