Evaluation of KOKEE12M-WETTZ13S VGOS Intensives

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Abstract The KOKEE12M-WETTZ13S (K2-Ws) VGOS Intensive series began on January 4, 2021. This series observed simultaneously with the INT01 S/X Intensives involving KOKEE-WETTZELL (Kk-Wz). Initially, the K2-Ws sessions ran roughly once a week. By the end of 2021 the cadence increased to 5/week. On January 31, 2022, the scheduling parameters were changed to increase the number of scans. Hence we divide the K2-Ws series into 'Old' and 'New.' In this note we evaluate the performance of these sessions using the Calc/Solve analysis software. We compare the UT1 estimates from the K2-Ws VGOS Intensives with several other UT1 series: 1) The simultaneous Ks-Wz INT01 S/X Intensives; 2) The R1 and R4 series; 3) An EOP series produced by JPL. We demonstrate that both VGOS Intensive series are better than the S/X series, and that 'New' is better than 'Old.' For example, if we take the difference of the UT1 estimates from the R1 and R4 and the Intensives and compute the RMS, we find 25.3 µs (S/X) and 22.8 µs (Old) and 16.7 µs (New). The RMS is higher than that predicted based on the formal errors of the estimates, which indicates there is unmodeled error.

Keywords UT1-UTC, dUT1, VGOS, Geodetic VLBI

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1 Introduction and History

In 2020 our institutions coordinated a series of Intensive VGOS sessions using different stations including various combinations of KOKEE12M, MACGO12M, GGAO12M, WESTFORD, and WETTZ13S. This was done to demonstrate the feasibility of these sessions and to gain experience in all aspects of the data flow. These initial sessions were scheduled at Goddard, correlated at Haystack, and analyzed at Goddard.

Based on the success of these sessions, we proposed a regular series of VGOS Intensives using the KOKEE12M-WETTZ13S (K2-Ws) baseline to run simultaneously with the KOKEE-WETTZELL INT01 sessions. The ultimate goal was to include the estimated UT1 from the VGOS Intensives in operational IVS products. These sessions began on January 4, 2021. Initially, these sessions ran roughly once a week but as we gained experience the cadence was increased to 5/week by the end of 2021. The schedules continued to be made and analyzed by Goddard. However, the responsibility for correlation was taken over by the Washington Correlator.

This data set is particularly interesting, because the standard INT01 series uses the co-located KOKEE-WETTZELL baseline (Kk-Wz). This allows us to directly compare the UT1 estimates from the two sets of Intensives. Initially these VGOS Intensives were scheduled similarly with the same limits on scan length as the Kk-Wz scheduled by USNO, with a minimum and maximum scan length of 40 s and 200 s. The SNR target per band was 20, somewhat higher than USNO targets of 20 and 15 for X- and S-band. In part this was done to be conservative, since we had no experience with how these sessions would perform. The K2-Ws Intensives differed from the Kk-Wz Intensives in that we inserted three 120-s calibrator scans. Subsequently the scan length parameters were changed to 20 s and 60 s, and the SNR target reduced to 15. This was based on simulation studies which showed that this would result in an increased number of observations and better formal errors with no adverse effects. Because of the change in scheduling parameters, we divide these into two sets: K2-Ws Old and K2-Ws New.

Some considerations that went into changing the parameters is given by Baver et al. [1]. The new scheduling parameters were first used on January 31, 2022 and have been used in the subsequent K2-Ws Intensives.

In this brief note we evaluate the performance of the K2-Ws VGOS Intensives using Calc/Solve. For a related analysis using *VieVs*, see Mondal et al. [2].

We make the following comparisons which are described in more detail in the appropriate sections:

1. We compare the UT1 estimates from the simultaneous S/X and VGOS Intensive sessions. This gives us a measure of the consistency of the sessions.
2. We compare the UT1 estimates from S/X Intensives and the two VGOS series with UT1 estimates from the R1 and R4 series. This allows us to evaluate the performance of the different Intensive series.
3. We compare the UT1 estimates from S/X Intensives and the two VGOS series with an EOP series produced by JPL.

In these comparisons we take the difference in UT1 estimates and calculate the RMS as a proxy for precision. We also compare the measured RMS with the predicted values based on the formal errors. We demonstrate that there is still substantial unmodeled error.

All the VGOS Intensives were scheduled by Karen Baver of NVI using the *sked* scheduling software. Karen Baver and Sergei Bolotin were responsible for the initial analysis of the VGOS and S/X Intensives, as well as the R1 and R4 sessions, using *nuSolve*. Station support at Kokee Park for both the S/X and VGOS Intensives was provided Chris Coughlin of Peraton. Institutional and station support at Wettzell was provided by Christian Plötz and Torben Schüler of BKG and Alexander Neidhardt of TU Munich. Andrew Sargent and Phillip Haftings of USNO correlated the sessions. Pedro Elosegui, Chester Ruszczyk, and Dhiman Mondal of MIT Haystack Observatory provided technical assistance. John Gipson is responsible for the analysis in this paper.

2 Intensive Data Sets

We considered three different Intensive data sets from 2021 through 2022-6-30:

1. S/X Standard: Kk-Wz S/X Intensives scheduled by USNO. For the sake of uniformity, we exclude S/X Intensives with more than two stations, or Intensives that use other stations.
2. K2-Ws Old: Scheduled using old scheduling parameters. MinScan 40, MaxScan 200, and SNR 20.
3. K2-Ws New: Scheduled using new scheduling parameters. Minscan 20, MaxScan 60, and SNR 15.

We used the standard Goddard processing methodology for Intensives on all of three series. *nuSolve* was used to do initial data editing and ambiguity resolution. In the final analysis, where we estimate UT1 using *Solve*, the reference frame was fixed to a TRF and CRF derived from all available 24-hour S/X and VGOS sessions through 2021-12-31; the USNO finals was used for the a priori EOP; we used VMF3 for the a priori atmosphere and mapping functions, and modeled atmosphere loading. In addition to estimating a UT1 offset, we estimated wet zenith delay offsets at the Kokee and Wettzell antennas and a second order clock at Wettzell. The zenith delay offsets were constant for each session. We did not estimate gradients. The data was reweighted on a session-by-session basis by adding in a constant amount of noise to each observation in an Root Sum Square sense until $\chi^2 \sim 1$.

Figures 1 and 2 display the number of observations and the Formal Error (FE) session-by-session.

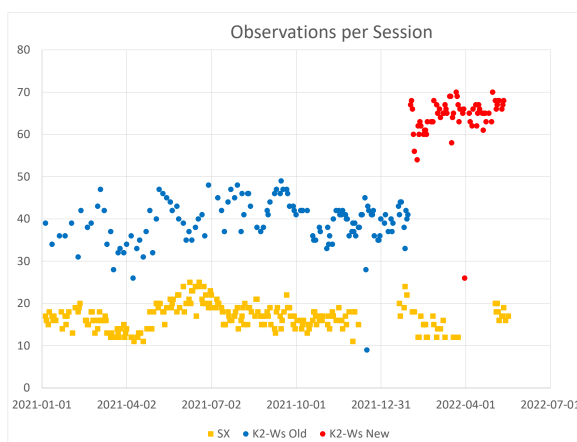

Fig. 1 Observations per session.

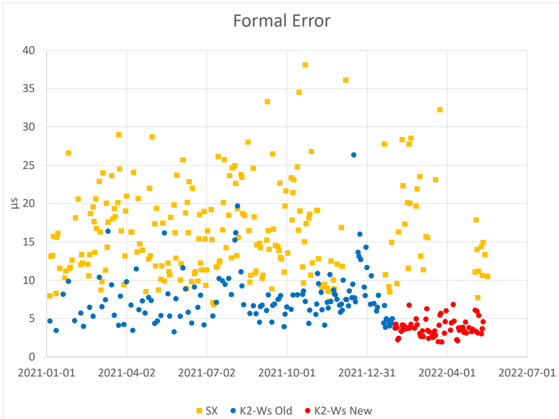

Fig. 2 Formal Errors of S/X and VGOS Intensives. Note the clear reduction in formal error with the K2-Ws New VGOS.

Table 1 summarizes some statistical characteristics of these series. In this and subsequent tables, to minimize the effect of bad data in calculating numerical results, we exclude sessions with fewer than ten observations, or a formal error greater than 40 µs. These sessions would probably not be used in operational analysis. The K2-Ws Old sessions have more than twice the number of observations as the S/X sessions, and the formal error (FE) is roughly half that of the S/X sessions. The reduction in FE is due to two factors: an increase in the number of observations, and a reduction in the uncertainty of each observation. The K2-Ws New series has roughly 60% more observations than K2-Ws Old, and the median formal errors are 33% smaller. Based on these results we would expect the K2-Ws Old series to be better than the S/X series, and the K2-Ws New series to better yet.

Table 1 Characteristics of Data Sets.

Data Set	Span	# Sess	Med # Obs	Med FE (µs)
S/X Standard	2021-01-04 to 2022-06-30	207	18	18.3
K2-Ws Old	2021-01-04 to 2022-01-28	120	40	9.5
K2-Ws New	2021-01-31 to 2022-06-30	74	65	6.4

3 Consistency between S/X and VGOS Intensives

In this section we study the consistency of the S/X and VGOS Intensives. For each day that we have both an S/X and VGOS Intensives we compute the difference between the S/X and VGOS estimates of UT1. As mentioned previously, for the S/X Intensives we only use the two station Kk-Wz Intensives. This comparison is particularly clean because of the following:

1. Since the S/X and VGOS antennas co-located, geophysical effects will be common and hence will disappear when we compute the difference.
2. Because the sessions are scheduled to run simultaneously with the same duration, there is no need to extrapolate the UT1 estimates.

Figure 3 displays the difference in UT1 estimates between the S/X and VGOS Intensives. Large gaps in the plot are due to instrumental problems at one of the stations. Since the S/X and VGOS sessions are assumed independent, the error in the estimated UT1 is uncorrelated, and hence the error in the UT1 difference is the RSS of the FE errors of each estimate. Visually there is a clear reduction in scatter for the New strategy: the agreement between S/X and VGOS is improved. Since there is no systematic change in the S/X observing, this implies that the New strategy with more observations is more accurate.

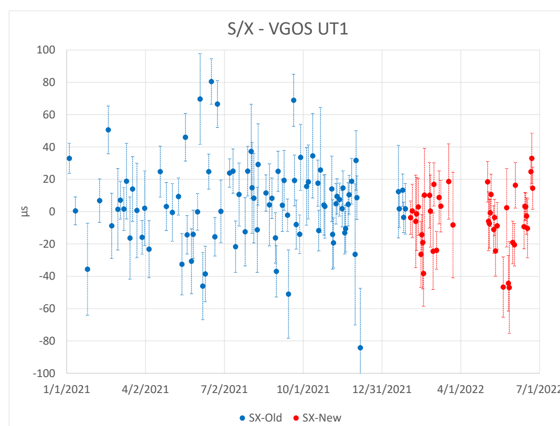

Fig. 3 Difference between S/X and VGOS UT1 estimates.

Table 2 presents the same results in tabular form. The third column computes the average difference between the two series, the fourth the RMS of the difference. The last column gives median formal error of the difference. The K2-Ws New series agrees more closely with the S/X than the K2-Ws Old series. The difference between the RMS and the median FE is a measure of the unmodeled error. For the K2-Ws Old series the difference is much larger than for K2-Ws New.

Table 2 Difference (µs) between S/X and VGOS estimates.

Data Set	# Session	Avg. Dif.	RMS	Median FE
K2-Ws Old	108	+3.4	25.0	19.4
K2-Ws New	43	−5.3	18.7	18.2

4 Comparison with R1 and R4 Sessions

In this section we compare the UT1 estimates from the Intensives with R1 and R4 (‘Rapid’) sessions. The Rapid sessions observe for 24 hours, use a large network (typically 10–14 stations), and have on the order of 10,000 observations instead of the 20–60 in the Intensives. Because of this, the formal error for UT1 is much less than for the Intensives, typically ~ 2 µs. We also expect a reduction in systematic errors since some station-dependent errors will average out. Although there is some variation because of holidays and maintenance schedules, the Rapids typically start on Monday (R1) and Thursday (R4). The INT01 series observe every week day. Figure 4 displays the temporal relationship between the Intensive and Rapid schedules for the first week of 2021. The start and end of each session is indicated on the horizontal axis. The vertical axis has no meaning, and the different heights are used to distinguish the Intensive from the Rapid sessions.

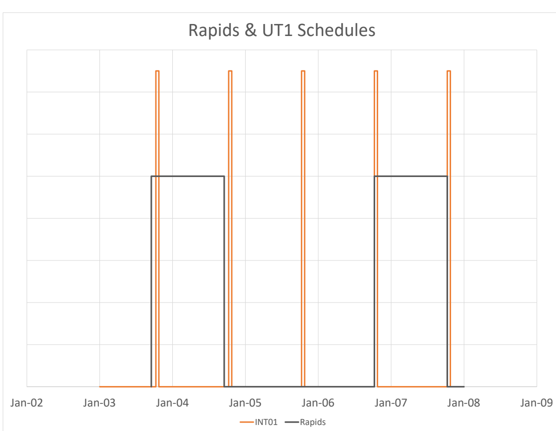

Fig. 4 Rapids and INT01 during the first week of 2021.

The comparison of the UT1 estimates is complicated by the following:

1. The Rapid networks vary from session to session.
2. The time span is different.
3. The epoch of UT1 estimate is different.

The last problem can be addressed, because, in contrast with the Intensives, the Rapids estimate both a UT1 offset and a rate. This allows us to extrapolate the UT1 estimate to the epoch of the Intensives. This extrapolation introduces additional error, both because of the uncertainty in the estimates of the offset and rate, and also because of the stochastic nature of UT1. Assuming we knew the offset and rate perfectly, the expected error in extrapolation grows like 35 µs $T^{3/2}$, where T is measured in days. To limit extrapolation error, we only consider Rapids which are within $\sim$0.5 days of the Intensive, which leads to an extrapolation error of $\sim$10 µs. As illustrated in Figure 4, this accounts for 80% of the Intensives.

Table 3 summarizes the results. The last column gives the expected FE of the difference and includes the effect of extrapolation error. Both of the VGOS series agree more closely with the Rapid series than does the S/X, and the New agrees more closely than the Old. Figure 5 presents the same data in graphical form. For clarity we offset the S/X results by 100 µs.

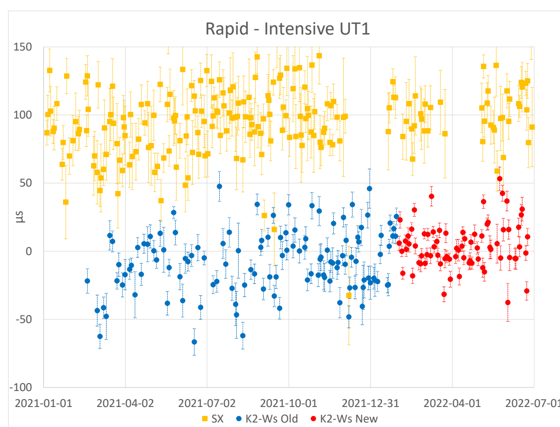

Fig. 5 Difference between Rapid and Intensive estimates of UT1. S/X results offset by 100 µs.

Table 3 Difference (µs) between Rapid and Intensive UT1.

Data Set	# Session	Avg. Dif.	RMS	Median FE
S/X	207	−4.6	25.3	22.4
K2-Ws Old	120	−7.6	22.8	15.3
K2-Ws New	74	+4.1	16.7	14.2

5 Comparison with JPL EOP series

In this section we compare the S/X and VGOS Intensives with a JPL EOP series. This is an external series that combines EOP from VLBI and GNSS, and other information such as atmospheric angular momentum. Because UT1 estimates from S/X VLBI data are one of the inputs, the JPL series is not totally independent of S/X VLBI data. It is independent of VGOS UT1 estimates. We use linear extrapolation of the JPL series to get the UT1 at the epoch of the Intensives. Since we are uncertain of how to handle the errors in the extrapolation, we do not calculate the expected formal error.

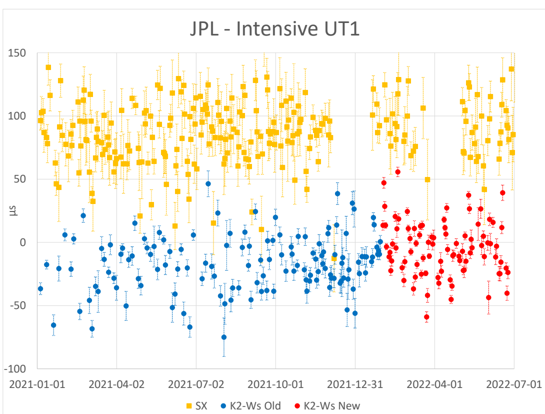

Fig. 6 Difference between JPL and Intensive estimates of UT1. S/X results offset by 100 µs

Table 4 Difference (µs) between JPL EOP and Intensive UT1.

Data Set	# Session	Avg. Dif.	RMS
S/X	248	−12.9	26.6
K2-Ws Old	134	−16.6	22.1
K2-Ws New	87	−4.5	21.6

The pattern is similar to what we have seen before. The VGOS scatter is less than the S/X scatter, and the scatter of K2-Ws New is smaller than K2-Ws Old. However the difference between the New and the Old case is not as large as previously. We attribute this to noise in the JPL time series.

6 Conclusions

In this note we have studied UT1 estimates from three different Intensive series: the standard S/X series using Kk-Wz and two VGOS series using K2-Ws. We have shown that the S/X and VGOS UT1 estimates are consistent and that the K2-Ws New agrees more closely with the S/X then the K2-Ws Old, 18.7 µs vs 25.0 µs. We see similar results when we compare the UT1 estimates from the Intensives with those from the Rapid sessions. The RMS of the differences are: S/X (25.3 µs), K2-Ws Old (22.8 µs), and K2-Ws New (16.7 µs). We also compared the S/X and VGOS estimates of UT1 with the JPL time series. The conclusions are similar to above, although the difference between the Old and New schedules is not as pronounced.

Our overall conclusion is that the K2-Ws VGOS Intensive UT1 estimates are better than the Kk-Ws S/X Intensive estimates and that the K2-Ws New series, with more scans, is substantially better. The UT1 estimates from the VGOS estimates are ready to be used in operational IVS products.

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