UT1 Formal Errors from the BA 50 Balanced Scheduling Strategy INT01 R&Ds

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Abstract The original operational IVS INT01 scheduling strategy (the "standard" strategy or STN) used as few as ∼30 strong but badly distributed sources, resulting in bad source and observation sky coverage at some times of the year. In response, in 2009, we proposed the Maximal Source Strategy (MSS) to maximize sky coverage by using all geodetic sources that are mutually visible at the primary INT01 stations. This yielded an operational INT01 MSS source set that had ∼90 sources but was, on average, weaker than the STN. Increasing sky coverage tends to decrease the UT1 formal error, while decreasing average source strength tends to increase the UT1 formal error by creating longer observations and scheduling fewer observations. To resolve this conflict, we investigated using *Sked*'s Bestsource command to select balanced source sets of varying sizes between the STN and MSS sizes, trying to select enough sources for good sky coverage but not enough to introduce too much weakness. We wanted to balance sky coverage and source strength to try to minimize the UT1 formal errors, while also considering balancing's effect on two other metrics. Our investigation led to the 50 source, balanced "Balanced 50" (BA 50) strategy. The IVS Observing Program Committee allocated six 2016 and 2017 R&D sessions for us to compare the BA 50 strategy to the MSS strategy, which had become the sole operational INT01 scheduling strategy in mid-2016. This paper reports the R&Ds' first results, focusing on their UT1 formal errors.

Keywords Intensives, UT1, sources, scheduling

NVI, Inc.

1 Introduction

The IVS observes one-hour INT01 sessions that provide rapid UT1-TAI estimates. The initial INT01 scheduling strategy, which we unofficially call the STN strategy, was to observe a strong but small, sparse source set whose size varied as sources were replaced due to flux changes. The STN was unevenly distributed and caused seasonal variations in observation coverage. As reported in [1] and [5], the size of an INT01 session's UT1 formal error is connected to the width of its azimuth observation coverage. The STN had narrow coverage and large UT1 formal errors at some times of the year, especially early October.

In 2009, we suggested improving source coverage by using all geodetic sources that are mutually visible at the two main INT01 stations, Kokee Park, Hawaii, USA and Wettzell, Germany, at some time during the year. We call this the Maximal Source Strategy (MSS). This improved the early October observation coverage and UT1 formal errors but raised the UT1 formal errors at some other times of the year, e.g., early to mid-November, presumably because the MSS had introduced weak sources, which take longer to observe and lead to fewer observations and, in turn, higher UT1 formal errors.

This indicated a need to balance the good strength but bad sky coverage of the, at minimum, ∼30 source STN source sets and the good sky coverage but weakness of the ∼90 source MSS source set that was ultimately used for operational INT01 observing. In 2014 we began to select source sets with varying numbers of sources and to use the balancing algorithm of the Bestsource command in *Sked*, the program that schedules INT01 sessions, to try to balance source strength and sky coverage and minimize the UT1 formal error, while considering two other metrics. This led us to the Balanced 50 (BA 50) source strategy. The IVS Observing Program Committee (OPC) allocated six R&D sessions for us to test the BA 50 against the MSS. This paper reports the UT1 formal errors from these sessions.

Section 2 discusses the original STN strategy and its inadequate sky coverage. Section 3 discusses our first solution (the MSS strategy) and its introduction of weak sources. Section 4 discusses our new solution (the BA 50 strategy) and the six R&D sessions that tested it. Section 5 reports conclusions and a subsequent update.

2 Original STN Strategy

In 2004, Baver et al. [1] noted two INT01 sessions with equal numbers of observations (15) and almost equal session fits (31 ps vs. 32 ps) but very different UT1 formal errors. Figure 1 plots azimuth observation sky coverage at the sessions' stations, Kokee (left side of each plot pair) and Wettzell (right side). The session in Figure 1 (left pair) has good (wide) sky coverage and a good (low) UT1 formal error (13 µs), but the session in Figure 1 (right pair) has bad, narrow sky coverage and a very high UT1 formal error (49 µs). This was part of a pattern that Baver et al. found in two years of INT01 plots. So [1] noted that wide observation sky coverage is generally empirically connected to low UT1 formal errors (i.e., that narrow sky coverage is connected to high UT1 formal errors). Starting in 2012, Uunila et al., e.g. in [5], independently confirmed this connection.

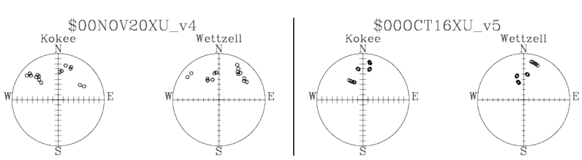

Fig. 1 Two INT01 sessions with similar numbers of observations and session fits but very different azimuth-elevation observation sky coverage and UT1 formal errors. Each plot pair shows Kokee (left) and Wettzell (right). Left pair: wide sky coverage and a low UT1 formal error (13 µs). Right pair: narrow sky coverage and a high UT1 formal error (49 µs). From [1].

Meanwhile, we had noticed a seasonal aspect to the varying observation coverage and in 2006 identified the cause: the strategy being used to observe sources in the INT01 sessions, the STN. The STN strategy consisted of observing strong but small sets of sources that contained, at minimum, ~30 sources. The STN source sets were sparse and uneven, with large gaps, as shown in a right ascension and declination plot of a 27-source version from INT01 session i14315 (Figure 2 (left)). Because the Kokee–Wettzell baseline is long and INT01 sessions observe for only an hour, they observe a small, quasi-oval sky slice that moves during the year, sampling varying numbers and sets of sources. Figure 2 (center) and Figure 2 (right) show the areas of the sky observed at two times of the year, with dark circles showing mutually visible sources. Figure 2 (right), which represents mid-November, has wide source coverage, which enables wide observation coverage and promotes low UT1 formal errors. But Figure 2 (center), which represents early October, has narrow source coverage, which restricts the observations to a narrow part of the sky and leads to high UT1 formal errors. These cases represent the two extremes of the year, and the early October case illustrates the need to find additional sources for some times of the year.

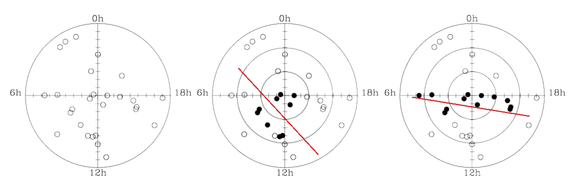

Fig. 2 Right ascension/declination plots of the i14315 STN source set. Left: source positions. Center: Mutual visibility (dark circles) on October 1 (18:30 UT) (narrow source coverage). Right: Mutual visibility on November 15 (18:30 UT) (wide source coverage). Plot edges are at 0°N, concentric circles mark 30°N and 60°N, and centers are at 90°N. The lines show the approximate width and orientation of the mutual visibility "ovals".

3 MSS Strategy

In 2009, we suggested the MSS strategy: improving source coverage in early October, and all year, by using all geodetic sources that are mutually visible at Wettzell and Kokee at some time during the year. We tested the MSS in nine 2009/2010 IVS R&D sessions. Then the IVS USNO NEOS Operation Center (USNO) began using the MSS strategy in operational INT01s in mid-2010, alternating it with the STN every other day. In mid-2016 USNO began using only the MSS.

The pairs of right ascension and declination plots in Figure 3 show the i14315 STN (left side of each pair) and the i14316 MSS (right side) source sets. The MSS set is more extensive, with much smaller gaps. The left and right pairs of plots show mutually visible sources (dark circles) at 18:30 UT on October 1 and November 15, respectively. The October MSS mutual visibility (left pair, right side) is much wider than that of the October STN (left pair, left side), with sources added on each side of the STN mutual visibility area. But the STN November (right pair, left side) and MSS November (right pair, right side) mutual visibility areas are similar in width, indicating that the mid-November sky coverage did not need to be widened. Instead, using the MSS at that time mainly added redundancy by filling in gaps without widening coverage.

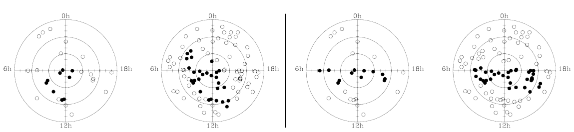

Fig. 3 i14315 STN and i14316 MSS mutual visibility (dark circles). Left pair: STN (left) and MSS (right) (October 1, 18:30 UT). Right pair: STN (left) and MSS (right) (November 15, 18:30 UT).

Figure 4 shows that the MSS solved the early October UT1 formal error problem. Figure 4 (left) plots the 2011 and 2012 STN UT1 formal errors, and two spikes show the very high early October UT1 formal errors. These spikes are absent in the MSS UT1 formal errors in Figure 4 (right). Also when the observed UT1 formal errors for the first half of October in both years are averaged, the MSS average (15.1 μs) is less than half that of the STN average (32.0 μs) [3].

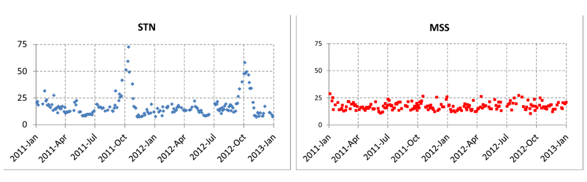

Fig. 4 UT1 formal errors from alternating 2011–2012 STN (left) and MSS (right) sessions. From [3].

But the UT1 formal errors at other times of the year increase with the MSS. In the first half of November, the MSS UT1 formal error average (12.0 μs) is 20% higher than the STN average (10.0 μs) [3]. This is a small trade-off for the large improvement in early October, but ideally the INT01 source strategy should provide as low UT1 formal errors as possible all year.

Our explanation in 2013 for the MSS' effect on the INT01 UT1 formal errors was as follows. Adding sources has two competing effects. First, at times of the year with narrow source coverage, adding sources at first widens the sky coverage and decreases the UT1 formal errors. But, when enough sources have been added to achieve wide enough coverage, adding more sources becomes redundant, and the UT1 formal errors are no longer improved. Meanwhile the additional sources are weaker and take longer to observe, leading to fewer observations and, in turn, higher UT1 formal errors. So at times of the year such as early October, adding sources should first lower the UT1 formal errors, then raise them. Meanwhile at times such as mid-November that already have wide enough source coverage with strong sources, any sources added will be redundant and weaker, so that adding sources will increase the UT1 formal errors from the start. In general, we expected that adding sources might lower, then raise the average UT1 formal error, and that there should be a balancing point where using the right number of sources would yield a minimum average UT1 formal error.

4 BA 50 Strategy

In 2014 we began to generate and evaluate source sets for a balance of sky coverage and strength through a) varying the number of sources and b) using the *Sked* Bestsource command, whose algorithm selects source sets balanced by sky coverage and strength. Ultimately we evaluated source sets with 30 to 90 sources, in increments of ten, to match the sizes of the minimal STN and the MSS source sets. The range was inclusive, because the Bestsource algorithm provided balance not found in the STN or MSS sets. In 2016, after considering the source sets' effects on the UT1 formal error and two other metrics, we selected 50 as the best number of sources. We call the new strategy the BA 50 (originally for "Best All 50" [2] but now for "BAlanced 50").

Figure 5 plots the INT01 i14315 STN source set (left), the BA 50 source set from R&D RD1608 (center), and the i14316 MSS source set (right). The BA 50 set has extensive and fairly even sky coverage. Gaps exist but are much smaller than the STN gaps, and although the BA 50 is not as well filled at places as the MSS, it avoids the redundancy of the MSS, shown by overlapping sources. So the BA 50 offers the best compromise in sky coverage. Also, in the 2011 and 2012 operational INT01s, the average scheduled STN SNR was 130% that of the MSS, while in the 2016 and 2017 R&D schedules described in this paper, the average scheduled BA 50 SNR was 115% that of the MSS. This suggests that the strength of the tested BA 50 source sets falls between the strength of the tested STN and MSS source sets. So there is evidence that the BA 50 strategy balances sky coverage and source strength. Figure 6 verifies that the BA 50 provides as wide source coverage as the MSS in early October and mid-November and only removes redundant sources.

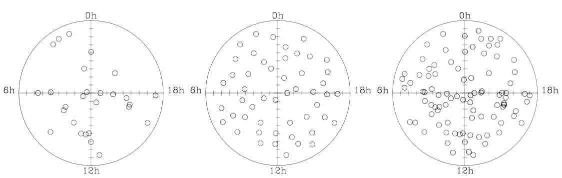

Fig. 5 Right ascension and declination source positions. Left: i14315 STN, center: RD1608 BA 50, and right: i14316 MSS.

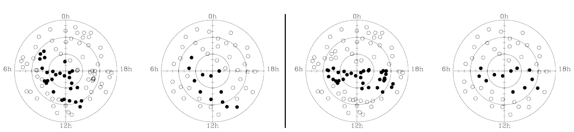

Fig. 6 i14316 MSS and RD1608 BA 50 mutual visibility. Left pair: MSS (left) and BA 50 (right) on October 1 (18:30 UT). Right pair: MSS (left) and BA 50 (right) on November 15 (18:30 UT).

We tested the BA 50 strategy in six 2016/2017 IVS R&D sessions, in which Wettzell and Kokee observed 24 one-hour pseudo-Intensives per R&D. The other stations, which varied, observed one 24-hour session that provided a single UT1 estimate and rate to use for an independent check of the pseudo-Intensives' UT1 estimates. We selected a different BA 50 source set for each R&D, using the most up-to-date source fluxes, and used it for every pseudo-Intensive in that R&D.

Table 1 shows the organization of the R&D pseudo-Intensives. The BA 50 alternates with the MSS in each R&D session, giving 72 MSS and 72 BA 50 pseudo-Intensives over which results can be averaged. The STN was no longer observed by the time of the R&D sessions and was excluded. We also needed to test the BA 50 and the MSS on sky areas observed by the INT01 sessions at different times of the year, especially early October and early and mid-November. The GST at which an INT01 session starts determines the area of the sky observed. So in each R&D, we started each pseudo-Intensive at one of 24 evenly spaced GSTs (00:00, 01:00, through 23:00). Within each GST's six pseudo-Intensives, we alternated the MSS and BA 50 strategies, giving three MSS and three BA 50 pseudo-Intensives per GST. GSTs 19, 21, and 22 approximated early October and early and mid-November observing, respectively.

Table 1 Organization of the one-hour R&D pseudo-Intensives.

GST	RD1608	RD1610	RD1701	RD1702	RD1706	RD1707
00:00	MSS	BA 50	MSS	BA 50	MSS	BA 50
01:00	BA 50	MSS	BA 50	MSS	BA 50	MSS
02:00	MSS	BA 50	MSS	BA 50	MSS	BA 50
			......			
23:00	BA 50	MSS	BA 50	MSS	BA 50	MSS

Two types of UT1 formal errors are of interest. The predicted UT1 formal errors from the schedules show the most direct influence of using the two strategies, before unrelated effects, such as observation loss due to equipment failure, occur. The observed UT1 formal errors from the data are subject to the unrelated effects, but these formal errors must still be checked for any systematic BA 50 problems.

Table 2 (top) shows the predicted UT1 formal errors averaged over all MSS and all BA 50 schedules. The BA 50 improves the predicted errors' average by 1.4 µs (18%) and standard deviation by 0.5 µs (33%). Table 2 (bottom) shows the observed, averaged UT1 formal errors. The BA 50 improves the observed errors' average by 2.6 µs (19%) and standard deviation by 1.1 µs (17%). So the BA 50 strategy shows promise for improving the average UT1 formal errors.

With only three MSS and three BA 50 pseudo-Intensives per GST, there is not much data for drawing conclusions about the BA 50's effectiveness at individual GSTs. More data is needed. But Figure 7 (left), which plots the predicted UT1 formal errors for each GST, shows preliminary promise, because the BA 50

Table 2 Predicted and observed UT1 formal errors, in µs, averaged over all MSS and all BA 50 pseudo-Intensives.

A) Predicted	MSS	BA 50	Improvement
Average	7.9	6.5	1.4 (18%)
Standard deviation	1.5	1.0	0.5 (33%)
B) Observed	MSS	BA 50	Improvement
Average	13.4	10.8	2.6 (19%)
Standard deviation	6.3	5.2	1.1 (17%)

UT1 formal error average for a GST is lower than the corresponding MSS average for 21 of the 24 GSTs, and for the other three GSTs, it is either equal or only slightly higher. Without more data, it is hard to draw even a preliminary conclusion about the observed UT1 formal errors when broken down by GST, due to the low number of pseudo-Intensives per GST combined with the vulnerability of the sessions to problems not related to the strategies. So, we only include Figure 7 (right), the plot of the observed UT1 formal errors by GST, for completeness and note that it indicates that the BA 50 UT1 formal error average is lower than the MSS average at 18 of the 24 GSTs.

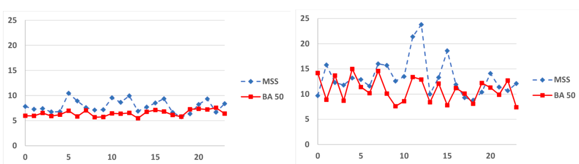

Fig. 7 Predicted (left) and observed (right) MSS (dashed line) and BA 50 (solid line) UT1 formal errors in µs averaged over individual GSTs.

Based on the averaged MSS and BA 50 UT1 formal errors, USNO has begun to schedule alternating MSS and BA 50 operational INT01 sessions on a trial basis.

5 Conclusions, Updates, and Acknowledgments

In 2014 we began to use source set size and a *Sked* algorithm to balance sky coverage and source strength to minimize UT1 formal errors and two other metrics. This led to the 2016 BA 50 strategy, which we tested against the MSS in six 2016 and 2017 R&Ds.

The R&Ds' sets of 72 MSS and 72 BA 50 R&D pseudo-intensives are large enough to conclude that the overall BA 50 UT1 formal errors are promising. The BA 50 improves the predicted and observed UT1 formal error averages and standard deviations by at least 17%. But there is not yet enough test data to draw meaningful conclusions about the BA 50's effect on the UT1 formal errors for individual areas of the sky. Meanwhile, based on the averaged MSS and BA 50 R&D UT1 formal errors, USNO has begun to schedule BA 50 operational INT01 sessions on a trial basis, alternating them with MSS sessions.

In late 2018, while preparing a related paper, we found a forgotten, unresolved 2016 result that contradicted our 2014 initial simulations, which had shown that the UT1 formal error increases with increasing source set size. New work to resolve the discrepancy showed that the 2014 results were atypical and that the UT1 formal error, at most, barely increases with increasing source set size. But balancing itself improves the UT1 formal error relative to both the STN and MSS strategies, and the BA 50 strategy remains useful.

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