Balancing Sky Coverage and Source Strength in the Improvement of the IVS-INT01 Sessions

Karen Baver, John Gipson

Abstract The USNO NEOS Operation Center uses two alternating strategies to schedule IVS-INT01 sessions—the original "STN", which uses a relatively small set of strong geodetic sources, and the USS, which uses all sources from the 10AUG23 geodetic source catalog that are mutually visible at the main IVS-INT01 stations. The USS' larger number of sources is meant to maximize sky coverage but also results in a set of sources that is weaker, on average. Improved sky coverage should lower the UT1 formal error, but weaker sources should raise it. We have seen that where the STN already provides good sky coverage, adding weaker sources through the USS can degrade performance, indicating that the USS may be adding too many sources. Here we give a preliminary report on trying intermediate numbers of sources in an effort to find a better balance of average source strength and sky coverage and improve performance against metrics such as the UT1 formal error. We identify a promising source set.

Keywords Intensive, scheduling, UT1

1 Development of Alternative Source Sets and Schedules

USNO schedules the INT01 sessions, using the Sked program [1]. USNO uses two infrequently updated source sets based on contrasting strategies of source strength and sky coverage to schedule the sessions. The original set ("STN") is a relatively small set of (currently 32) strong geodetic sources. (The STN also has 19 sources that are not mutually visible at Kokee and Wettzell, the two stations that mainly observe in the INT01 sessions.) The USS set is all sources (currently 91) from the 10AUG23 geodetic catalog that are mutually visible at Kokee and Wettzell sometime during the year. The USS' larger number of sources is meant to maximize sky coverage but also results in a set of sources that is, on average, weaker. Improved sky coverage should lower the UT1 formal error, but weaker sources should raise it, resulting in a trade-off. We have seen that where the STN already provides good sky coverage, adding weaker sources through the USS can degrade performance, indicating that the USS may be adding too many sources. Here we try intermediate numbers of sources in an effort to find a better balance of average source strength and sky coverage. We create two series of source sets with varying numbers of sources using two selection strategies through Sked's *BestSource* command. Then we create schedules from the source sets and test them against three metrics.

The *BestSource* command selects a list of "good" sources from an initial catalog for a given network and observing span, based on source strength, mutual visibility, and sky coverage. The command takes three arguments. Argument 1 (*N*) is the desired number of sources. Argument 2 (*Mode*) takes values of 1, 2, and 3 and determines how the sources are initially ranked. Argument 3 (*NumCov*) determines how many sources to consider at a time when considering sky coverage. The algorithm works as follows. The first step gives all sources in the starting catalog an overall score which depends on the *Mode*. It does so by scheduling a series of hypothetical scans for each source at 10-minute intervals over the du-

NVI, Inc.

ration of the schedule. For each scan, the source is given a sub-score, and the total score is the sum over all scans. For *Mode=1,2,3* the sub-score is, respectively, 1) the number of observations in the scan; 2) 1/(scan_duration)—a measure of the source's strength, and 3) (number_of_observations)/(scan_duration). Sked then builds an output source list iteratively, starting with the highest ranked source. Sked considers the improvement in sky coverage that would result by adding, individually, each of the remaining sources to the output list. From among the top *NumCov* sources, it picks the source that has the highest *Mode* ranking. This process repeats until Sked has selected *N* sources or there are no more sources left in the input list. (The latter happens if the number of observable sources is < N.) In this study we always used *Mode=2*—that is, sources were ranked by 1/(scan_duration), i.e., source strength—and *NumCov=3*, which meant that coverage played an important but not overwhelming role.

We used *BestSource* to make two series of six source sets apiece with varying numbers of sources, to be used to schedule 26 test Intensives apiece. The basis for both series was the current (13SEP23) geodetic source catalog, a set of sources used for generating geodetic schedules. In series 1, for each source set, our strategy was to choose one group of sources that would be visible at any time at Kokee and Wettzell, so that the source set could be used for all schedules regardless of their observing times. The number of sources in the six source sets ranged from 40 to 90 in increments of 10. We call these source sets BA_x, where x is the number of sources in the set and *BA* stands for "Best-All" because the same source set is used for all schedules. (We call the source set with the most sources BA_{90} although the *BestSource* command found only 89 sources.) In series 2, for each of the six source sets, we chose 26 independent groups of sources, one per proposed, individual schedule, from the sources that could be observed during the corresponding schedule. The number of sources in each group in a source set was the same. This number ranged from nine to 24 in increments of three. We call the source sets composed of these groups BI_x for "Best-Individual".

The purpose of varying the number of sources in each series was to compare the strategies of maximizing source strength (as in the STN), maximizing sky coverage (as in the USS), and using a balance of these two characteristics (new cases). We chose 40 sources as the *BA* series' lower limit because the STN catalog has had ∼40 to 50 sources in recent years. (We did not realize that not all of the STN's sources are usable. In retrospect, the *BA* lower limit should have been lower.) We chose 90 sources as the upper limit because the USS currently has ∼90 sources. We chose nine sources as the lower *BI* limit because operational STN schedules tend to have nine or fewer sources, and USS schedules tend to have 10 or more sources. We chose 24 as the upper limit because operational experience suggested that this is probably the maximum number of sources that can be currently scheduled in USS schedules.

Our main interest is the varying number of sources in the *BA* and *BI*, but we also compare the two series.

We included the operational STN and USS source sets from the start of 2014 in order to use them to evaluate the test source sets as potential alternative operational source sets. But for consistency with the test sets, we used the current (14FEB06) flux models. We call the resulting sets STN_{rf} and USS_{rf}, where "rf" means reselected fluxes.

We used Sked to generate schedules for 26 days of the year spaced two weeks apart, starting at 18:30 UT. Because the schedules started at the same time, they differed in the part of the sky that was visible. The visible sky at session start time can be identified by GST. In comparing scheduling strategies, it is important to compare them at the same GST and also to evaluate them at many GSTs, because, depending on the GST, one strategy may be superior. For all 26 GSTs, we created schedules using the six *BI* sets, the six *BA* sets, STN_{rf}, and USS_{rf}. To improve statistical significance, we created multiple schedules per combination of GST and source set by 1) creating a schedule template and determining the initially available sources and 2) creating one schedule per initial source by selecting each source in turn, then running Sked's autosked mode to complete the schedule. If a schedule's final observation began fewer than 55 minutes into the schedule, we discarded the schedule as too short.

Due to space limitations, this paper only considers each source set's data averaged over all 26 GSTs. Also, please note that we have not yet calculated the statistical significance of any result.

2 Comparison of Source Sets

In comparing source sets, it is useful to consider all 26 BI_x source groups for a given x together. We call this set BIU_x where U means "union". Figure 1 plots the STN_{rf} and USS_{rf} sets by right ascension and declination, along with the sets at each end of the two series—BIU_9 and BA_{40} and BIU_{24} and BA_{90}. Venn diagrams show the number of sources shared by adjacent sets.

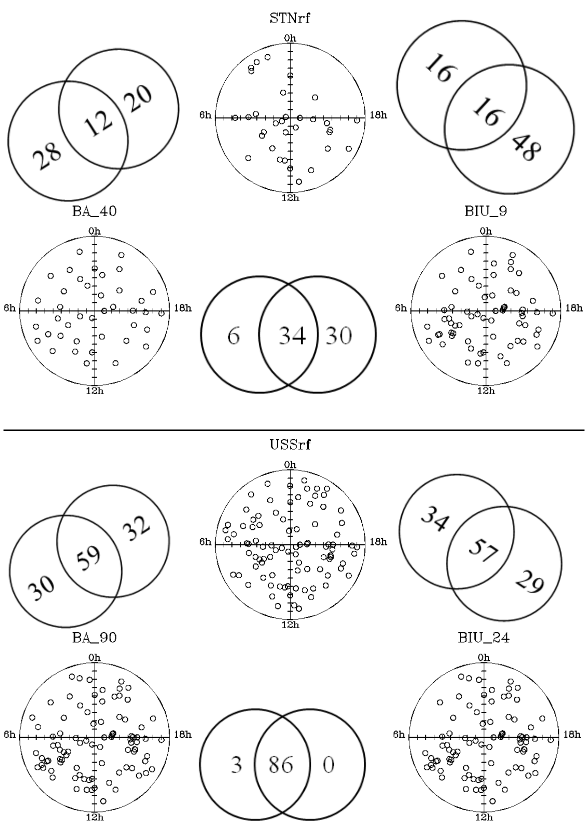

Fig. 1 Source distributions in the three source sets at the lower limits (top two rows) and upper limits (bottom two rows) of the BIU, BA, and STN_{rf}/USS_{rf} series. The Venn diagrams show the number of sources in the adjacent source sets.

The BIU and BA series have good sky coverage throughout. Their most notable difference is that the first BA source set, BA_{40}, is fairly uniform, but the first BIU source set, BIU_9, has redundant sources—sources that are close together and provide little improvement in sky coverage. But BA_{40} has 24 fewer sources than BIU_9, and this might play a role in its lack of redundancy. The BA series shows redundancy by its final source set, BA_{90}. The final BIU source set, BIU_{24} has similar redundancy, and in fact, BIU_{24} is a subset of BA_{90} with three fewer sources, indicating that the BI and BA strategies converge as sources are added. The differences between the STN_{rf} source set and the BIU_9 and BA_{40} source sets are striking. STN_{rf} has large gaps in its sky coverage, even though it has only eight fewer sources than BA_{40}. This is not surprising, because the STN sources were picked largely for strength. USS_{rf} has a similar number of sources to BIU_{24} and BA_{90}, but it shares only ~2/3 of its sources with those sets, because it came from a different source catalog. But it has a similar degree of sky coverage to the other two sets, as well as some redundancy.

Table 1 compares the 14 source sets and the schedules made from them. Averages are taken over all 26 GSTs in a source set.

The total source count applies to the BA and BIU sets. The mid-session count is the number of sources available for scheduling at mid-session in a representative schedule from each GST. Of the two counts, the mid-session count has the more direct effect on scheduling, and it strictly increases in each series as sources are added to the source sets. In general, more sources are available in the BA series than in the BI (11.4–23.5 vs. 7.8–19.6), an important advantage for scheduling. The BI_{12}/BA_{70} and the BI_{21}/BA_{80} pairs have comparable total numbers of sources, permitting reasonably direct comparisons. These pairs also indicate that the BA series provides more sources for scheduling. Every set but BI_9 provides more sources at mid-session than STN_{rf}, and five sets (BI_{21}, BI_{24}, BA_{70}, BA_{80}, and BA_{90}) provide more sources than USS_{rf}.

The schedules are compared by the average number of scheduled sources, sky coverage (measured by sky gap, as discussed below), and source strength (measured by scan length). In each series, more sources were scheduled as more sources were added to the source sets. More sources were scheduled for the BA than the BI series (13.1–17.1 vs. 8.9–16.3). For source sets with fewer than 15 sources at mid-session, more sources were scheduled than were available at mid-session, indicating that the schedules took advantage of sources that rose or set during the schedule. For source sets with more than 15 sources at mid-session, fewer sources were scheduled than were available at mid-session, indicating that the larger source sets provided more sources than were needed for scheduling. Every set but BI_9 scheduled more sources than the STN_{rf}. Seven sets (BI_{21}, BI_{24}, BA_{50}, BA_{60}, BA_{70}, BA_{80}, and BA_{90}) scheduled more sources than the USS_{rf}.

Sky gap is the average distance of a point in the sky to the nearest observation. It is an inverse measure of

Table 1 Characteristics of the source sets (top section) and the schedules generated from them (bottom section).

averages are over all GSTs in a set	STN_{rf}	BI_9	BI_{12}	BI_{15}	BI_{18}	BI_{21}	BI_{24}	BA_{40}	BA_{50}	BA_{60}	BA_{70}	BA_{80}	BA_{90}	USS_{rf}
#sources: total	32	64	69	72	75	79	86	40	50	60	70	80	89	91
mid-session (avg)	8.1	7.8	10.3	12.8	15.2	17.6	19.6	11.4	14.6	16.4	18.5	21	23.5	17
Avg number of scheduled sources	9.6	8.9	11.6	13.7	15.0	16.1	16.3	13.1	15.4	16.3	16.7	17.0	17.1	15.3
Avg sky gap	12.6	11	9.9	9.5	9.4	9.2	9.1	9.5	9.1	9.0	8.9	8.9	9.0	9.5
Avg scan length (seconds)	126.5	130.3	135.1	137.5	139.9	140.9	141.5	132.8	137.7	142.7	144.0	143.1	143.2	145.7

sky coverage. Adding sources reduces the sky gap in the *BI* schedules, but the *BA* schedules have little difference in sky gap after BA_{40}. The *BA* schedules provide lower sky gap values (better sky coverage) than the *BI* schedules. It takes the 72-source BI_{15} set to produce schedules with as low a sky gap (9.5) as those produced from the 40-source BA_{40} set. In addition, the BA_{70} and BA_{80} schedules have lower sky gap values than the corresponding BI_{12} and BI_{21} schedules. The STN_{rf} schedules have the largest average sky gap of any set (12.6), which is not surprising given its sparse source distribution. The USS_{rf} value, 9.5, is smaller than the STN_{rf} value but larger than most of the sky gap values, including the analogous BI_{24} and BA_{90} sets.

Source strength is inversely proportional to average scan length; it takes longer to observe weaker sources. In the *BI* schedules, adding new sources always increases the scan length, implying that weaker sources are being scheduled. In the *BA* schedules, adding new sources increases the scan length through BA_{70}, then decreases it. The *BI* scan lengths are less than the *BA* lengths (130.3–141.5 vs. 132.8–143.2 seconds), indicating that the *BI* selects stronger sources. The BI_{12}/BA_{70} and BI_{21}/BA_{80} pairs support this. As expected, the average scan length is shortest for the STN_{rf} schedules. It is longest for the USS_{rf} schedules.

The schedule characteristics generally show the expected trade-offs. Adding sources within a series generally increases sky coverage but weakens source strength. But changes in the characteristics generally slow down or reverse towards the end of each series. So adding sources eventually becomes useless or counterproductive. The *BI* schedules have greater source strength but worse sky coverage than the *BA* schedules. The STN_{rf} is similar to the *BI* series but has even greater source strength and even worse sky coverage. The USS_{rf} is the exception to the trade-offs. It has the weakest source strength but does not compensate with the greatest sky coverage. Instead it is inferior in all three schedule characteristics to BI_{21} through BI_{24} and BA_{50} through BA_{90}.

3 Simulation Results

We evaluated the 26 schedule sets made from each of the 14 source sets using the following three metrics.

Unscaled UT1 Formal Error. We used the simulation capability of Solve to determine the unscaled formal error of the UT1 estimate from each Intensive schedule. The unscaled formal errors depend only on the observations used and the errors in the observations. By assumption, there are no modeling errors, so the formal errors give lower limits on the real errors. All things being equal, lower formal errors are better.

Atmospheric Turbulence. A session is robust if its UT1 estimate does not change much with random noise such as atmospheric turbulence. We used the metric 1 Solve configuration but added random noise that simulated atmospheric turbulence to each schedule's simulated observations. We did this 300 times per schedule and then calculated each schedule's RMS of the UT1 estimates about the mean. We then averaged the RMS values for each source set. A lower average RMS indicates that the schedules generated from a source set are less vulnerable to atmospheric turbulence.

Source Loss. A session is robust if its UT1 estimate does not change much when it fails to observe one of its scheduled sources. We ran a set of Solve solutions for each schedule in which we suppressed the schedule's sources, one at a time. We then calculated the RMS of each schedule's UT1 estimates about the mean, and we averaged the RMS values for all schedules from a given source set. A lower average RMS indicates that the schedules generated from a source set are less vulnerable to source loss.

Table 2 summarizes the performance of the source sets' schedules against the metrics.

Unscaled UT1 Formal Error. In each series, the UT1 formal error generally increases as the number of sources increases. Source redundancy is probably a factor; as new (and weaker) sources are added to the source sets, some are close to previous sources, and if

Table 2 Performance under the metrics: unscaled UT1 formal error and vulnerability to atmospheric turbulence and source loss (UT1 estimate RMSs), averaged over all GSTs in each source set. The units are μs. The best values in each series are in bold type.

		STN_{rf}	BI_9	BI_{12}	BI_{15}	BI_{18}	BI_{21}	BI_{24}	BA_{40}	BA_{50}	BA_{60}	BA_{70}	BA_{80}	BA_{90}	USS_{rf}
Unscaled UT1	Average	7.9	7.3	**7.2**	7.3	7.6	7.7	7.8	**6.6**	6.9	7.3	7.4	7.5	7.6	8.2
Formal Error	St. dev.	1.4	1.5	**1.4**	1.4	1.3	1.0	1.0	**1.0**	1.1	1.1	1.0	1.0	1.2	1.4
Atmospheric	Average	15.5	**14.1**	14.5	14.8	15.6	15.9	16.2	**14.3**	15.3	16.1	16.4	16.8	16.9	17.1
Turbulence	St. dev.	4.6	**2.8**	2.9	2.7	2.5	2.2	2.4	**2.3**	2.3	2.0	2.0	2.2	2.1	3.2
Source	Average	21.1	18.3	14.6	12.6	12.5	**11.5**	11.9	12.6	11.8	11.5	11.6	**11.4**	11.5	13.0
Loss	St. dev.	8.2	3.9	3.0	2.8	3.0	**2.8**	2.7	2.8	2.3	2.4	2.4	**2.2**	2.2	2.6

scheduled, they can add little sky coverage improvement to offset the loss of source strength. The *BA* series yields a better (lower) range of UT1 formal errors than the *BI* series (6.6–7.6 vs. 7.2–7.8 μs). The improved performance is due to BA_{40} and BA_{50}; the range of formal errors for the other *BA* sets is comparable to the *BI*. Again, the lower source redundancy of BA_{40} and BA_{50} may be a factor. Overall, BA_{40} is the best choice for this metric, giving the lowest UT1 formal error (6.6 μs). The STN_{rf} and the USS_{rf} have the highest values (7.9 and 8.2 μs, respectively) and are the worst choices for this metric.

Atmospheric Turbulence. In each series, vulnerability to atmospheric turbulence increases as the number of sources increases. The *BI* is less vulnerable to atmospheric turbulence than the *BA* is, with lower RMS values (14.1–16.2 vs. 14.3–16.9 μs). BI_{12} and BI_{21} also provide lower RMS values than BA_{70} and BA_{80}. Overall, BI_9 is the best choice for this metric, with an RMS of 14.1 μs, followed closely by BA_{40} (14.3 μs). Five choices are better than the STN_{rf}, and every choice is better than the USS_{rf}.

Source Loss. Previously, we assumed that increasing the number of scheduled sources strictly decreases vulnerability to source loss. However, although the number of scheduled sources strictly increases in each series, the *BI* RMS increases after BI_{21}, and the *BA* RMS fluctuates within 0.2 μs starting with BA_{60}. This suggests that adding sources might only be helpful up to a point, perhaps $\sim$16 sources. The *BA* series is less vulnerable to source loss than the *BI* is, with lower RMS values (12.6 to 11.4 vs. 18.3 to 11.5 μs). This is supported by the superiority of BA_{70} over BI_{12} (11.6 vs. 14.6 μs), although BA_{80} and BI_{21} are comparable. BI_{21} and BA_{80} provide the lowest RMS averages. But BI_{15} through BI_{24} and all *BA* schedules are better than the USS_{rf}, making them reasonable choices. The worst choice is the STN_{rf}.

Overall, no number of sources and neither selection strategy is superior for all three metrics, so tradeoffs must be considered. But the STN_{rf} and the USS_{rf} were each the worst or second worst choice for two metrics, so the STN and USS should be replaced. The BA_{40} source set provided the best UT1 formal error, the second lowest vulnerability to atmospheric turbulence, and vulnerability to source loss that is better than the STN_{rf}'s and USS_{rf}'s. This source set should be evaluated for short-term replacement of the STN and USS, and the selection of 40 sources under the *BA* strategy from any starting source catalog should be evaluated as a general method of INT01 source selection.

4 Conclusions

We selected varying numbers of the best overall sources (*BA*) and the best sources for individual schedules (*BI*) from the current geodetic source catalog. Within both strategies, adding sources yielded schedules with better sky coverage and more, but weaker, sources. The additions worsened the schedules' UT1 formal errors and vulnerability to atmospheric turbulence, but reduced their vulnerability to source loss, up to a point. *BA* gave schedules with better sky coverage and more, but weaker, sources than *BI*. The *BA* schedules had better UT1 formal errors and less vulnerability to source loss, but more vulnerability to atmospheric turbulence. The BA_{40} source set performed the best overall. This set and the strategy that produced it should be investigated for operational use.

References

1. http://lupus.gsfc.nasa.gov/files_user_manuals/sked/sked.pdf J. Gipson, Sked User Manual, 2012.