Investigating the Relationship between Simulated and Observed Geodetic Schedules

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Abstract Simulations are increasingly used to predict the quality of geodetic VLBI schedules prior to observation within the IVS community. These simulations attempt to predict the error of a given observing network. While this exercise proves to be a valuable tool for the geodetic VLBI community, we seek to expand upon previous work to establish the relationship between errors calculated from observed VLBI schedules and simulated errors produced by the scheduling software VieSched++. Using schedules that have previously been observed, we are able to compare formal errors measured from Earth Orientation Parameter (EOP) observations to those calculated from simulations. Several VLBI session types are examined and compared in an attempt to better tie simulations to EOP characteristics.

Keywords VLBI, EOPs, geodesy, simulation, scheduling

1 Introduction

Very Long Baseline Interferometry (VLBI) is the only geodetic technique that is capable of measuring all five Earth Orientation Parameters (EOPs): UT1–UTC, polar motion (x, y), and nutation (x, y). To measure all five EOPs, the IVS observes two weekly 24-hour legacy sessions (IVS-R1, IVS-R4) and three monthly 24-hour VGOS sessions (VGOS-OPS). Additionally, the IVS maintains several one-hour sessions to exclusively measure UT1–UTC. These include the legacy IVS-INT1 and VGOS VGOS-INT-A sessions, which are observed Monday–Friday. In 2023–2024, the 24-hour sessions averaged ten stations per session, out of a potential pool of 23 legacy stations (including five VGOS stations operating in mixed mode) and 16 VGOS stations. The one-hour IVS-INT1 and VGOS-INT-A sessions each use two to three stations, which also participate in 24-hour sessions.

Given that each of these sessions has approximately ten stations globally, observing up to two quasars per minute for 24 hours, it quickly becomes apparent that producing optimal session schedules is vital to increasing the precision of geodetic measurements. Simulating VLBI schedules for geodetic observations is becoming an increasingly popular method of optimizing a complex network of antennas with varying capabilities, characteristics, and mutual sky.

The VLBI scheduling software VieSched++ [1] uses a technique called "multischeduling" to generate many different schedules for the same session. These schedules are simulated and then evaluated to determine which one minimizes EOP formal errors, increases repeatability, or optimizes a number of other parameters. VieSched++ is already being used operationally in IVS sessions such as the VGOS-RD, VGOS-INT-B, VGOS-INT-C, IVS-CRF, and IVS-CRF-DS.

Simulations are also being used to explore scheduling strategies. VieSched++ has been used to determine optimal VGOS sites [2], baseline geometry and its impact on UT1–UTC measurements [3, 4], and UT1–UTC sensitivity to station and pole coordinates [5]. The IVS Coordinating Center uses simulations generated with SimpleSimul. These simulations are used to determine the optimal networks for IVS-R1 and IVS-R4 sessions [6, 7].

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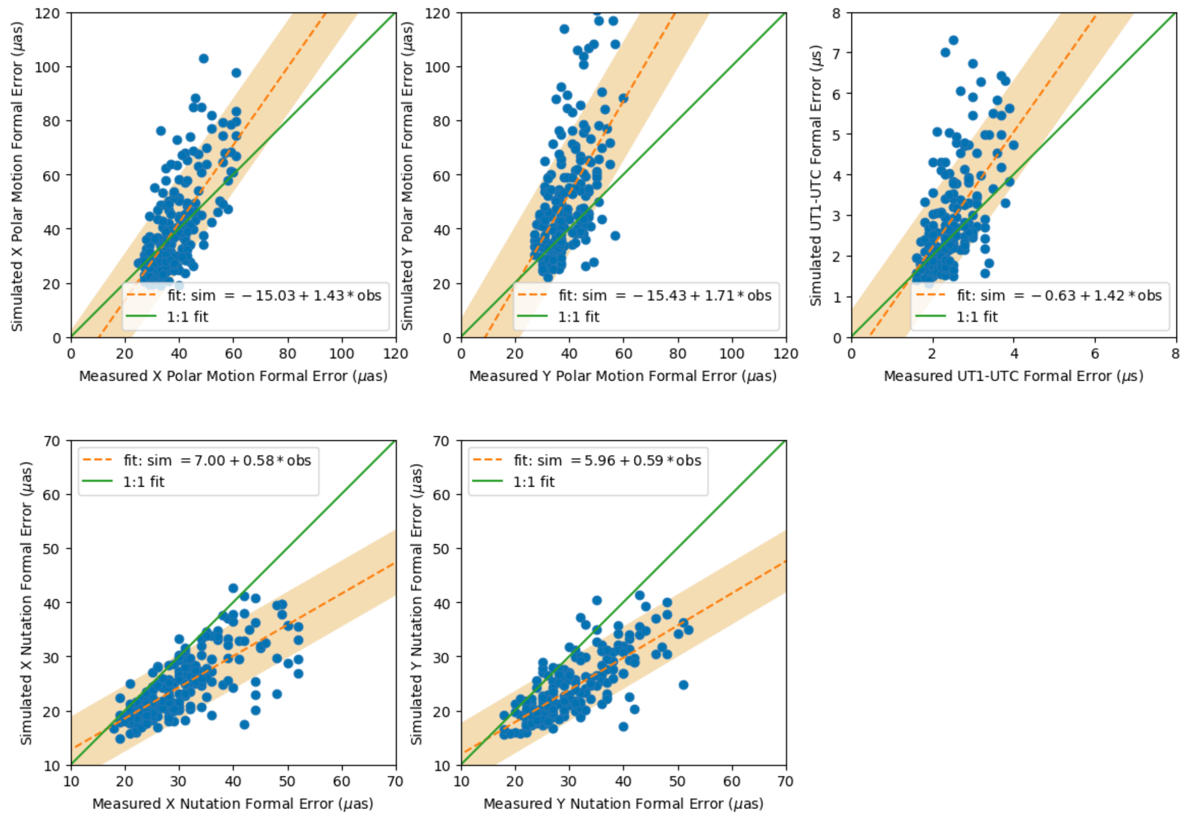

Fig. 1 IVS-R1 simulated versus measured EOP formal errors. The orange dashed line is the line of best fit, and the orange shading is the one sigma standard deviation. The green line, or the "1:1 line", shows what values simulations would need in order to be equal to the measured formal errors.

This investigation seeks to expand on the previous study by Hardin 2022 [8]. The original results were inconclusive, largely due to the simulated schedules not reflecting how the schedules were actually observed. This new study seeks to improve upon the previous results by modifying the simulated schedules to reflect the usable observations made by participating stations.

2 Methodology

All sessions analyzed are from 2017–2024 operational IVS geodetic series: IVS-R1 ("R1"), IVS-R4 ("R4"), IVS-INT1 ("INT1"), VGOS-OPS ("VO"), and VGOS-INT-A ("V2"). SKED, vgosDb, and EOP files are taken from the Crustal Dynamics Data Information System (CDDIS) [9].

In these sessions it is common for stations to either miss observations or drop out entirely due to issues at the station. The successful observations are recorded by correlators and analysts in the vgosDb for the given session. Conversely, failed observations can be determined by comparing the original schedule to the observations listed in the vgosDb. Prior to simulating the schedules, failed observations are removed from the original schedules to more closely reflect the data captured by the actual observed schedule; we refer to this process as "pruning."

VieSched++ is used to simulate schedules before and after pruning. These simulations predict the EOP formal errors for each session, which are then compared to the corresponding formal errors calculated by NASA's GSFC IVS Analysis Center. Simulations and measurements are grouped by series (e.g., "R1", "R4") to allow for different behavior between series.

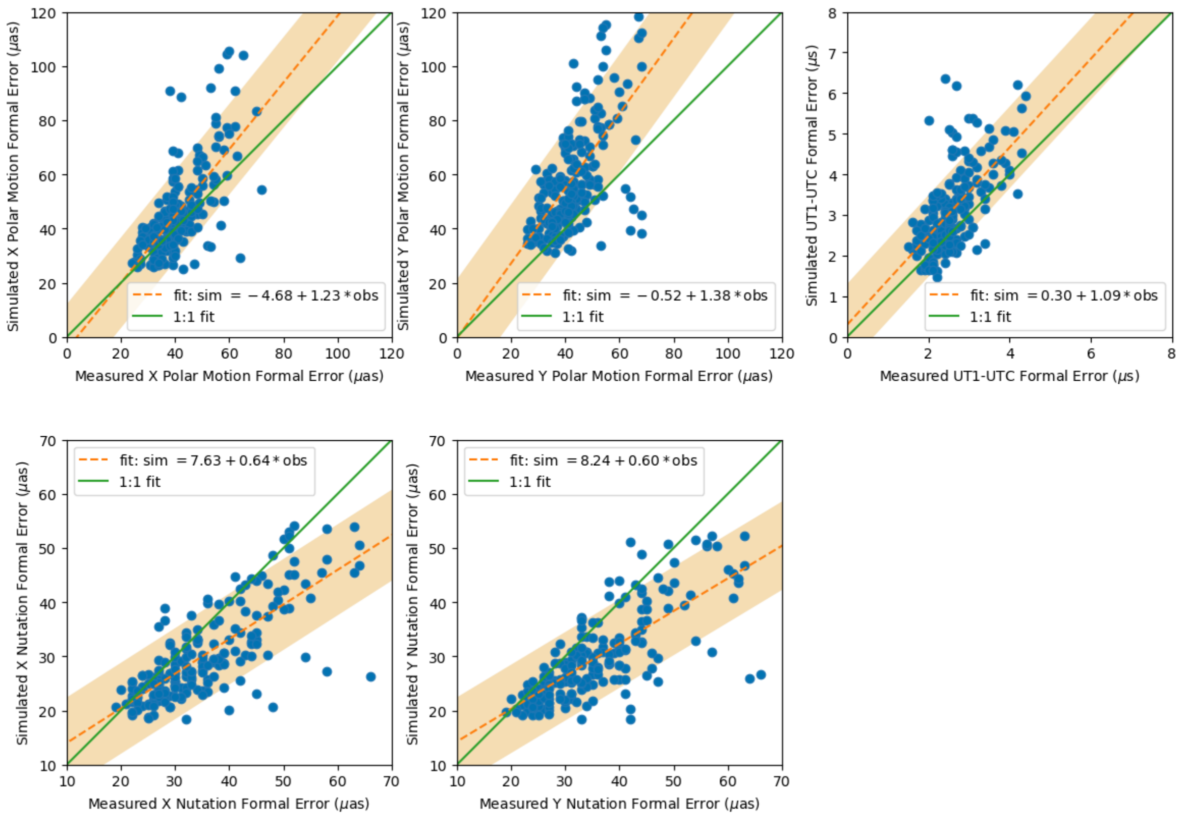

Fig. 2 IVS-R4 simulated versus measured EOP formal errors. The orange dashed line is the line of best fit, and the orange shading is the one sigma standard deviation. The green line is the 1:1 line.

3 Results

Simulated IVS-R1 formal errors are linearly correlated with measured formal errors for all five EOPs (see Figure 1). In this case, the simulations predict higher formal errors for UT1–UTC and polar motion, while they underestimate the measured errors for nutation. This is a recurring relationship for 24-hour sessions, and it is discussed in more detail in Section 4. Furthermore, while the simulations do not perfectly predict measured formal error, they do provide a clear linear relationship that can be used to more accurately predict measured formal error. The normalized residuals for each linear fit can be found in Table 1.

IVS-R4 sessions behave similarly to the IVS-R1s and have a linear relationship between measured and simulated values (Figure 2). As with the R1s, IVS-R4 simulations predict larger UT1–UTC and polar motion formal errors than are actually measured and underestimate nutation formal errors. Given the similarities between the IVS-R1 and IVS-R4 simulated:measured relationships, it may be possible to combine the results of the two sessions and simply use a single relationship for all IVS legacy rapids.

Table 1 Normalized RMS of simulated versus measured formal errors for each session type. Values closer to 0 indicate a better fit.

Session	UT1–UTC	PM-x	PM-y	dX	dY
IVS-R1	0.4	0.3	0.5	0.1	0.1
IVS-R4	0.3	0.3	0.4	0.2	0.2
VGOS-OPS	0.4	0.6	0.6	0.2	0.2
IVS-INT-1	0.2	–	–	–	–
VGOS-INT-A	0.1	–	–	–	–

VGOS-OPS sessions have a shorter history than the R1s and R4s, resulting in fewer data for use in statistics (Figure 3). However, they offer an even more extreme case than the R1s and R4s in that the VOs predict much higher formal errors than are measured for polar motion and UT1–UTC. As is the case with the other

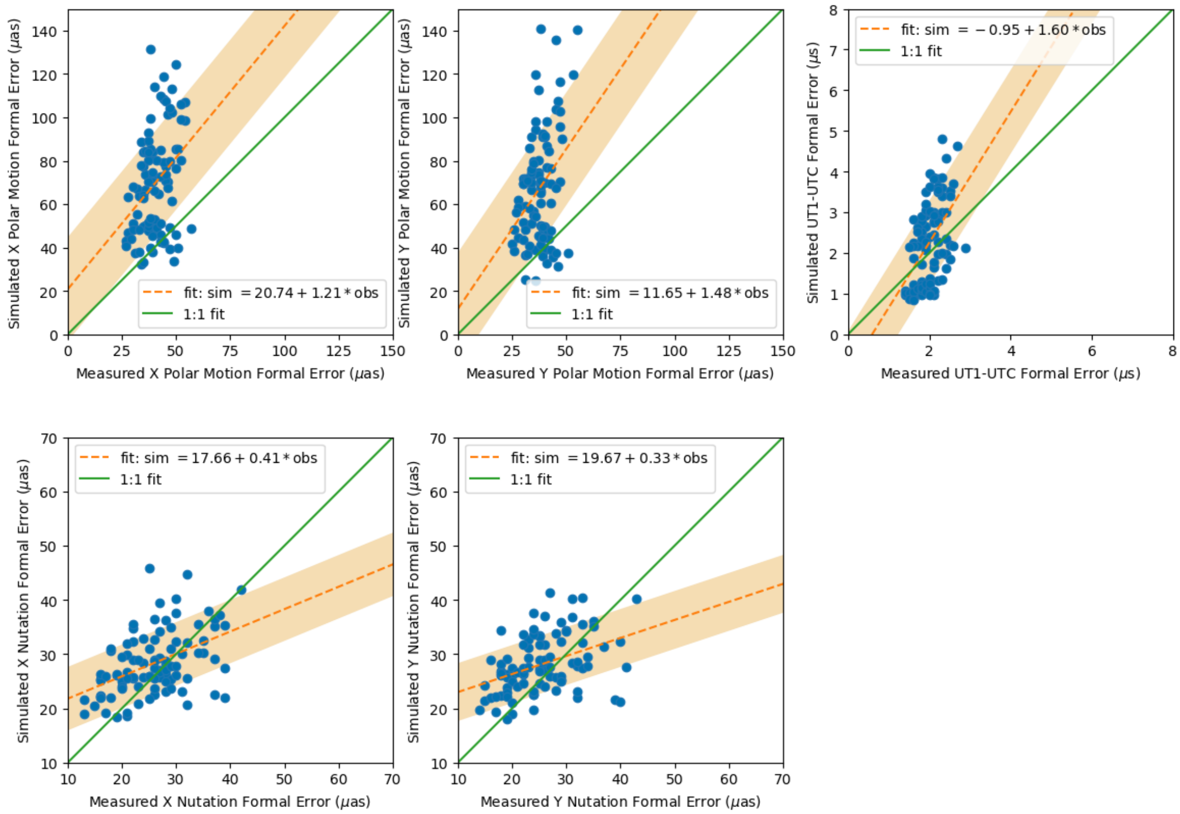

Fig. 3 VGOS-OPS simulated versus measured EOP formal errors. The orange dashed line is the line of best fit, and the orange shading is the one sigma standard deviation. The green line is the 1:1 line.

24-hour sessions, the simulated formal errors for nutation slightly underpredict measured formal errors. Although the VGOS-OPS simulated:measured relationships are somewhat different than the legacy sessions, they remain linearly correlated, and thus the simulations can be used to improve the accuracy of predicted formal errors.

IVS-INT-1 sessions have similar predicted and measured UT1–UTC formal errors, although there is some scatter around the 1:1 line (Figure 4). However, the IVS-INT-1 simulations are generally a good representation of the corresponding measured formal errors.

VGOS-INT-A simulations strongly underestimate UT1–UTC formal errors (Figure 5). However, this is due to the VGOS-INT-A measured formal errors being rescaled by the analysis center before being published [10]. This means that the errors simulated by VieSched++ are essentially being compared to the errors

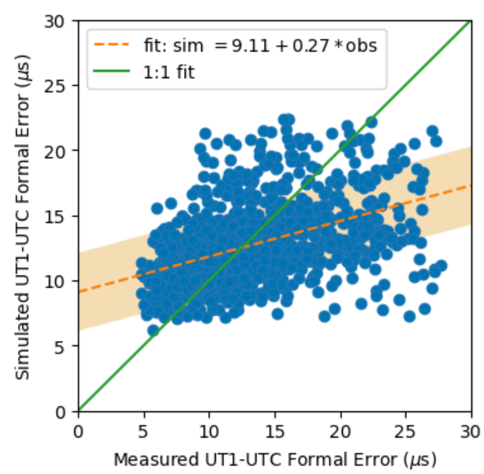

Fig. 4 IVS-INT-1 simulated versus measured UT1–UTC formal errors. The orange dashed line is the line of best fit, and the orange shading is the one sigma standard deviation. The green line is the 1:1 line.

simulated by SimpleSimul. Despite the differences in values, the two simulations are strongly correlated.

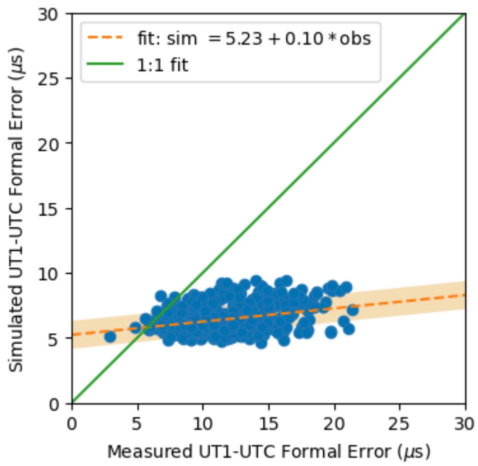

Fig. 5 VGOS-INT-A simulated versus measured UT1–UTC formal errors. The orange dashed line is the line of best fit, and the orange shading is the one sigma standard deviation. The green line is the 1:1 line.

4 Conclusions

This study demonstrates that VieSched++ can produce simulations that can be used as a predictor for measured EOP formal error for all session types discussed here. We find that simulations are much more effective predictors when they are used with schedules that accurately represent what was observed as opposed to the (idealized) initial schedule. Additionally, we found that while the 24-hour VGOS session (VGOS-OPS) simulations are correlated with the observed errors, the relationship is less reliable. This could be due to the shortened time series compared to the IVS-R1s and IVS-R4s, implying that this relationship could change as more data are collected.

It is of note that the simulations predict larger formal errors for UT1–UTC and polar motion than is measured for all 24-hour session types. This study alone cannot determine whether these simulations overestimate formal errors or whether the measurements underestimate them. However, Davis and Byram [11] compare measured VLBI EOP formal errors to residuals (where residuals are calculated as the observation with respect to the IERS Rapid Service / Prediction Center Finals EOP product), and they find that formal errors are frequently underestimated.

Finally, a correction can be derived for each session type based on the relationship between simulations and measurements; this correction can then be applied to the simulated results to better represent observational results. These corrections are typically unique per session type, but some session types may be able to share corrections (such as IVS-R1s and IVS-R4s).

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