In-depth analysis of schedules optimized for certain VLBI experiments using VieSched++

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Abstract Scheduling is an integral part of every VLBI experiment and, at this stage, already determines the geometric stability of the final solution. To increase the quality of the schedule, the TU Wien scheduling concept consists of two steps. The newly developed VLBI scheduling software VieSched++ offers the possibility to generate hundreds of different schedules for a single experiment automatically. Each of these schedules is then simulated hundreds of times using the VieVS VLBI module ending up with hundred thousands of simulations for a single experiment. The results are used to investigate the connection between scheduling optimization criteria and scheduling parameters with geodetic results gained during the analysis of simulations for the selection of the best suited schedule for the session at hand. In this work, we are providing an in-depth analysis of these correlations for the schedule of the T2129 session. We will show the importance of OHIGGINS for this network and highlight which optimization criteria play the biggest role in this session.

Keywords Scheduling VieVS VieSched++

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1 Introduction

The generation of a VLBI observing plan, the so-called schedule can be seen as an advanced optimization problem. So far, brute force algorithms are used to generate schedules on a scan by scan basis (Gipson, 2010; Sun, 2013; Schartner and Böhm, 2019). At each step, all possible next scans are calculated, evaluated and compared to select the best one based on optimization criteria. Unfortunately, developing these optimization criteria is a serious challenge and some of the criteria are competing against each other like the need for a good sky-coverage and the need to maximize the number of observations as discussed in Gipson (2010) and Schartner and Böhm (2019). Therefore, understanding VLBI scheduling is critical for improving VLBI in general, since the schedule directly determines which observations are available during the analysis of the session.

During the analysis, typically the least squares method is used where the correlations between estimated parameters can be derived directly (Nothnagel et al., 2002). With the recent development of a new VLBI scheduling software called VieSched++ (Schartner and Böhm, 2019) and further developments in the Vienna VLBI and Satellite Software (Böhm et al., 2018) it is now possible to look at correlations between scheduling parameters and estimated geodetic parameters using Monte-Carlo simulations.

VieSched++ comes with a so-called multi-scheduling feature (Schartner and Böhm, 2018, 2019), where multiple schedules for one VLBI session can be generated automatically. By simulating these sessions multiple times, the scheduling statistics are compared with repeatability values of estimated geodetic parameters as well as their formal errors.

This is demonstrated for a schedule of the official International VLBI Service for Geodesy and Astrometry (IVS) (Nothnagel et al., 2017), namely session T2129.

The goal of session T2129 is to provide high-quality station coordinates which can be used to derive terrestrial reference frames. In total, 15 VLBI stations are participating in this session. From a scheduling point of view, this session is especially interesting, since it has many challenges: The network geometry is far from optimal, with only two stations in the southern hemisphere, namely HART15M and OHIGGINS. Additionally, the sampling rate is very low with only 128 Mbit/s which is very problematic, since some antennas have poor sensitivity such as OHIGGINS with system equivalent flux densities (SEFD) of 10.000 Jansky (Jy) in X- and 18.000 Jy in S-band and VERAMZSW with an SEFD of 13.160 Jy in S-band. Together with the remote location of OHIGGINS in Antarctica, generating an optimal schedule, where OHIGGINS is properly included, is a serious challenge. This makes it a perfect candidate to investigate the correlations between scheduling statistics and estimated geodetic parameters to understand how this challenging session can be optimized from a scheduling point of view.

2 Method

Using the VieSched++ multi-scheduling feature, 500 schedules of session T2129 are generated. Each of these schedules follows a different scheduling logic specified through their weight factors and through allowing subnetting or not (Schartner and Böhm, 2019). The weight factors directly determine the source selection and are therefore the most important factor one can vary in order to optimize the schedule (Schartner et al., 2017; Schartner and Böhm, 2018, 2019). These sessions are then simulated 500 times each using VieVS. Together, this leads to a total of 250.000 simulations which can be analyzed. By combining the results of the 500 simulations per schedule, repeatability values can be calculated as well as mean formal errors. Therefore, a series of scheduling values such as number of observations, as well as a series of repeatability and mean formal error values are available and correlations can be calculated between those.

The simulation is calculated including tropospheric turbulences, clock drifts, and white noise (Pany et al., 2011), where the same simulation parameters are used for all stations. The troposphere is simulated using a turbulence simulator with C_n values of $1.8 \cdot 10^{-7}$ $m^{-1/3}$ (Nilsson et al., 2007) and scale height of 2 km, the clock is simulated using random walk and integrated random walk with an Allan standard deviation of $1 \cdot 10^{-14}$ after 50 minutes (Herring et al., 1990), and additionally 30 ps white noise is added to the observations.

3 Results

Figure 1 shows the correlation matrix between the scheduling parameters gained from 500 different schedules generated for session T2129. The first six rows and columns list general scheduling statistics, like the number of scans, the number of observations and the number of observed sources. The number of scans is further divided into scans scheduled with (“subnetting scans”) and without (“single source scans”) subnetting and scans scheduled during fillin-mode. Subnetting is a technique, where the software decides to split the network into two pieces and therefore is considering two scans simultaneously during the scheduling algorithm (Petrov et al., 2009). Fillin-mode is a concept which is used to reduce station idle time. During the wait time for slower slewing antennas, it is often possible to squeeze in another scan using a reduced antenna network, which is called fillin-mode (Gipson, 2010). VieSched++ uses a recursive scan selection to implement fillin-mode scans, see Schartner and Böhm (2018, 2019).

Followed by the general scheduling statistics, the number of scans and observations are listed for each station. The last five rows and columns are the multi-scheduling parameters, which were varied to create the schedules. Among those are four weight factors and a boolean type parameter which shows whether subnetting was allowed during the creation of the schedule or not.

By focusing on the top left corner in Figure 1 where the correlations between the general scheduling statistics are visualized one can see that there is obviously a strong negative correlation between the number of scans scheduled with and without subnetting but also a negative correlation between the number of fillin-

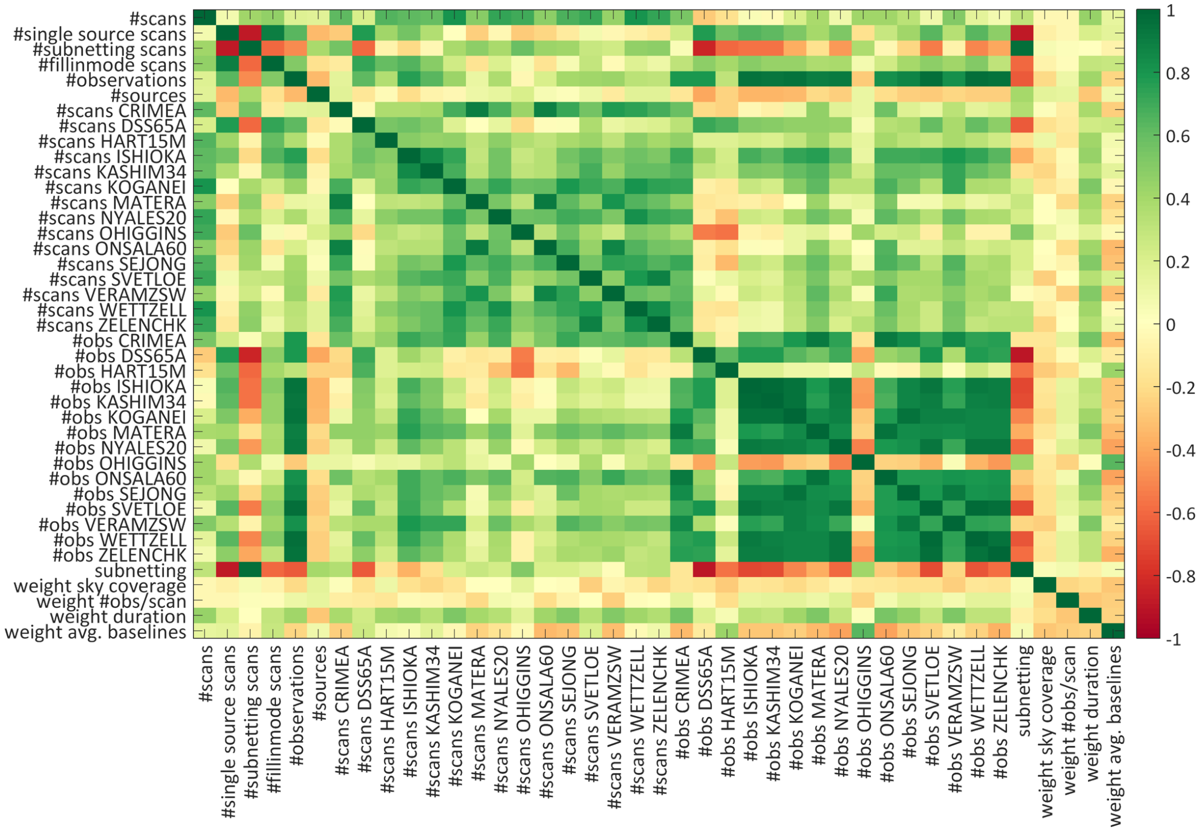

Fig. 1 Correlations between scheduling statistics.

mode scans and subnetting scans. While the first negative correlation can simply be explained by the definition that the sum of the scheduled subnetting scans and the scans scheduled without considering subnetting is the total number of scans. The second negative correlation is due to the better consideration of all stations when using subnetting which results in fewer fillinmode scans. Interestingly, a high number of subnetting scans also results in a lower total number of observations, which also can be explained by the splitting of the full network into two smaller ones during subnetting. Additionally, there is a small negative correlation between the number of scheduled sources and the total number of observations.

When looking at the correlations between the general scheduling statistics and the number of observations per station, some interesting characteristics can be seen: All but two antennas show a strong positive correlation between the total number of observations and the number of observations per antenna. The only exception is HART15M, showing only a low positive correlation and OHIGGINS which is negatively correlated. This means, that a high number of observations with OHIGGINS results in a lower total number of observations in this schedule, which can be explained by the high cost of the inclusion of OHIGGINS into the schedule due to its remote location and very low sensitivity. Additionally, it can be seen that OHIGGINS gets the highest number of observations when subnetting is used extensively which can be explained through its remote location. This can further be confirmed when looking at the cross-correlations between the number of observations of individual stations. While the number of observations of almost all stations is strongly positively correlated, the number of observations of HART15M is almost not correlated with other stations, and the number of observations with OHIGGINS is negatively correlated with the number of observations with all other stations except HART15M.

While the previously discussed characteristics are necessary to understand VLBI scheduling, the most interesting question is how to generate a good sched-

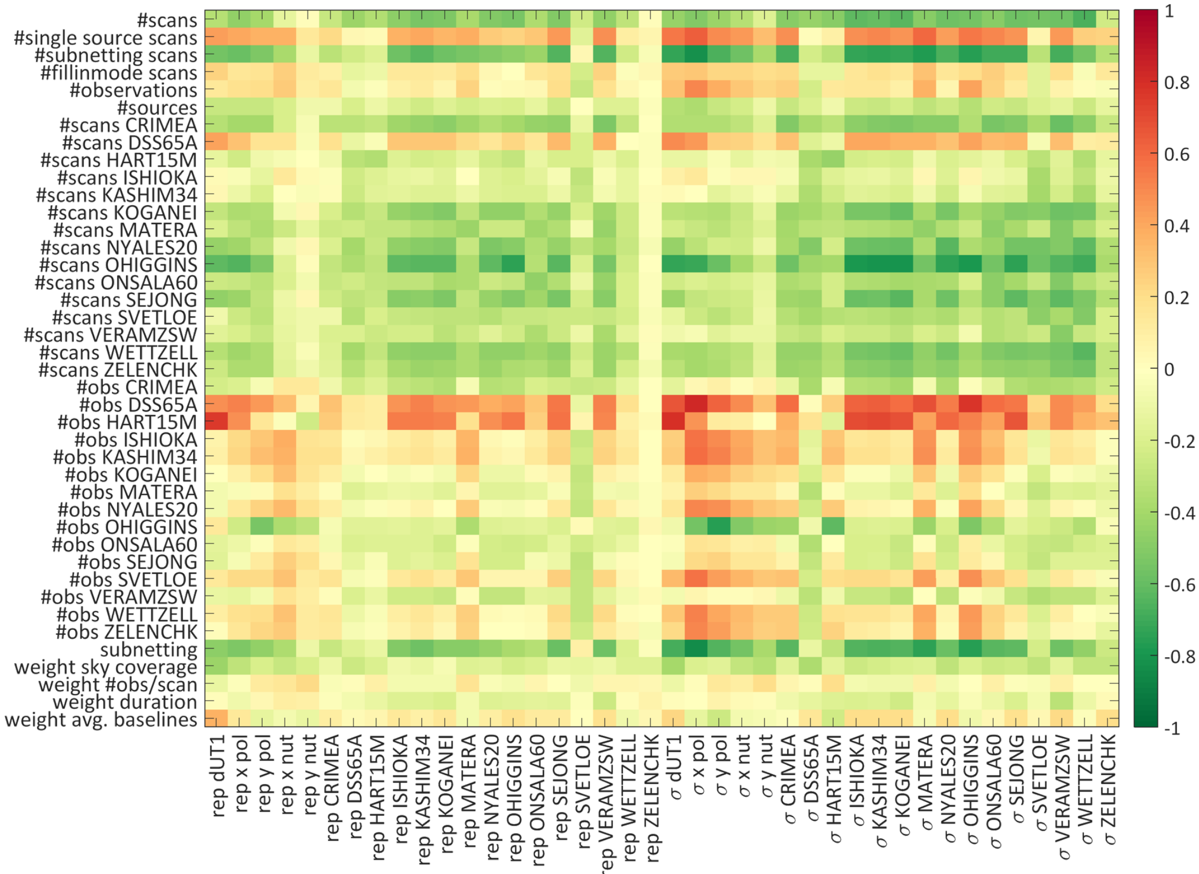

Fig. 2 Correlations between scheduling statistics and accuracies of estimated geodetic parameters.

ule. This can be illustrated when looking at the correlations between the multi-scheduling parameters with the other quantities since the multi-scheduling parameters are the only input parameters which are changed to derive the different schedules. When looking at the multi-scheduling parameters, the enabling of subnetting clearly has the biggest effect on the result. It is strongly negatively correlated with the number of observations of all antennas except for OHIGGINS where it shows a positive correlation. Similar behavior can be seen for the weight factor which aims to average out the number of observations over each baseline ("weight avg. baselines"). This makes sense since OHIGGINS has the lowest number of observations thus leading to baselines with a low number of observations. The baselines then get a high weight during the scheduling logic resulting in an on average higher number of observations with OHIGGINS when the average baseline weight factor is given a high value, see Schartner and Böhm (2019). It can also be verified that giving high weight to optimize the sky coverage, the number of observations is lowered due to the longer slew times. This effect can be countered by increasing the weight of the duration of a scan as well as the number of observations per scan, which results in more scans with more participating stations and, consequently, a higher number of total observations. As already discussed by Gipson (2010) and Schartner and Böhm (2019) finding a sweet-spot between the optimization of the sky-coverage and the number of observations is one of the main challenges in geodetic VLBI scheduling.

Figure 2 depicts the correlation between scheduling statistics and geodetic parameters derived from simulations. The first half of the columns shows repeatability values derived from the 500 simulations per schedule, while the second half shows the mean formal error gained from the least squares adjustment. When looking at the correlations between the general scheduling statistics, in the first few rows with the geodetic parameters, it is evident that many subnetting scans significantly lower the formal errors and the repeatabilities due to their negative correlation resulting in better results. Surprisingly, there is a positive correlation between the total number of observations and especially the formal errors, meaning that a higher number of observations results in poorer geodetic results. While this might seem wrong, it makes perfect sense in this case: First, a high total number of observations results in a poorer sky-coverage since the slew times are kept low and a good sky-coverage is necessary to estimate tropospheric time delays which are among the biggest error sources in geodetic VLBI (Schuh and Böhm, 2013). Additionally, it can be seen that especially observations with OHIGGINS show the biggest positive effect on the geodetic results and as already discussed previously, a high number of observations with OHIGGINS results in a low total number of observations. As already discussed: While a high number of observations is usually desirable, one has to find the sweet-spot between a high number of observations and a good sky-coverage.

Considering the multi-scheduling parameters shown in the last rows, it is evident that especially the allowance of subnetting has the most significant positive effect on the geodetic results, followed by a good sky coverage and a short duration of individual scans.

4 Conclusions and outlook

VieSched++ is using a multi-scheduling feature to create not only a single schedule for a session but multiple ones simultaneously. Based on Monte-Carlo simulations these schedules can be compared based on geodetic results to select the best schedule. As a by-product, correlations between scheduling statistics and estimated geodetic parameter accuracies can be calculated as shown here for session T2129. For these sessions, especially the proper inclusion of OHIGGINS plays an important role to optimize the schedule. The interaction between scheduling optimization criteria like improvement in the sky-coverage and maximizing the number of observations as well as scheduling features like subnetting are discussed.

While these results are only valid for session T2129 with its unique network geometry and challenges, the generation of the schedules and simulations, as well as the calculation of the correlation parameters, are fully automated in VieSched++ and VieVS to be able to replicate this study for all schedules generated with VieSched++.

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