

# Results with the scheduling software VieSched++

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**Abstract** The Department of Geodesy and Geoinformation at Technische Universität Wien has recently developed a new scheduling software called VieSched++ as part of the Vienna VLBI and Satellite Software (VieVS). VieSched++ is written in C++, it features an elaborate backward fill-in mode for minimizing station idle time and runs multiple versions of the same schedule in a fast batch mode using different optimization criteria and parameters. Large scale Monte-Carlo simulations with VieVS can then be used for selecting the best schedule for the purpose of the session within this sample. In particular, the schedules can be optimized for the given network, source list, observing mode and scientific goal. VieSched++ has already been successfully used for scheduling multiple official IVS sessions.

**Keywords** scheduling VieVS VieSched++ software

## 1 Introduction

The first step of every VLBI experiment is the creation of an observing plan, the so-called schedule, which is then distributed to the participating stations. The schedule makes sure that the observations are synchronized between the stations and at least two stations observe the same source simultaneously. Therefore, the schedule determines which sources are observed in which sequence and also which and how many observations are later available for the analysis.

While several software packages exist for analyzing geodetic or astrometric VLBI sessions, like Calc/Solve (Bolotin et al., 2014), the Vienna VLBI and Satellite Software (VieVS) (Böhm et al., 2018), OCCAM (Titov et al., 2004), c5++ (Hobiger et al., 2010), Where (Hjelle et al., 2017) or GINS (Bourda et al., 2007), this is not the case for scheduling. In the past, almost all geodetic sessions were scheduled with a software called sked (Vandenberg, 1999) while astronomic sessions are scheduled using Sched (Walker, 2018). For geodesy and astrometry, the only notable exception were AUSTRAL sessions (Plank et al., 2017) which were, in the past, scheduled using a Matlab based scheduler (Sun, 2013) which is part of VieVS. However, starting in 2018 several observing programs are now scheduled using a new modern scheduling software called VieSched++ (Schartner and Böhm, 2019) which is also part of VieVS. The following lists shows some of the official International VLBI Service for Geodesy and Astrometry (IVS) (Nothnagel et al., 2017) schedules, generated with VieSched++:

- AUA (035, 037, 040, 041, 044, 047)
- AUM (001 - 010)
- T2 (129, 130, 131, 132)
- EURR&D (09, 10)
- EUR (149)
- OHG (171, 118, 119)
- CRF (110)
- CRDS (102, 103)
- INT3 (021, 028, 035, 042, 049, 056, 063... 182)

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## 2 Method

VieSched++ is written in C++ and uses a brute force approach to generate schedules, similar to sked (Gipson, 2010). However, all algorithms are newly developed to be able to generate high-quality schedules. For example, VieSched++ uses a recursive scan selection to minimize station idle time (Schartner and Böhm, 2018, 2019). It provides an automated iterative source selection and great care was taken to fine-tune the optimization parameters to implement a good scan selection. Since the complexity of optimizing a schedule is very high, VieSched++ comes along with a multi-scheduling feature which is able to not only generate one single schedule but multiple ones simultaneously. These schedules can then be used in the VieVS VLBI software directly for simulations and based on those simulations the best schedule can be selected.

More information about the features and algorithms used in VieSched++ can be found in Schartner and Böhm (2019).

The schedules further discussed in section 3 are created using the multi-scheduling feature. On average, 500 schedules are generated per session varying the weight factors, as they have the biggest impact on the scan selection logic, see Schartner et al. (2017) or Schartner and Böhm (2018, 2019). Each of these schedules is simulated 500 times using the VieVS VLBI software. The simulation includes tropospheric turbulences, clock drifts, and white noise (Pany et al., 2011). The same simulation parameters are used for all sessions and all stations. The troposphere is simulated using a turbulence simulator with  $C_n$  values of  $1.8 \cdot 10^{-7} \text{ m}^{-1/3}$  and a scale height of 2 km (Nilsson et al., 2007). The clock is simulated using random walk and integrated random walk corresponding to  $10^{-14}$  at 50 minutes (Herring et al., 1990). Additionally, 30 ps white noise is added to the observations.

## 3 Results

In the following subsections, results gained for the T2, EURR&D and INT3 observing programs are further discussed and compared with previously submitted schedules generated with sked. The schedules generated with VieSched++ are highlighted in blue in Table

1 and 2. The fact that the sked schedules are performing that poorly compared to the VieSched++ schedules is not necessarily due to limitations in the sked scheduling software but also due to the fact that these schedules were created using bad scheduling parameters. By using different scheduling parameters, the sked solution could be improved as well (John Gipson, personal communication 2019). However, optimizing scheduling parameters is not that easy in sked and these schedules were submitted and observed with this unoptimized schedules.

### 3.1 T2

The aim of the T2 schedules is to provide accurate station coordinates for estimating terrestrial reference frames. These sessions consist of the biggest station networks of all official IVS sessions with 15 to 22 participating stations. However, the network geometry is far from optimal. Since most of the stations are in the northern hemisphere (Plank et al., 2015) this situation is also reflected in the T2 network geometry. For example, 15 stations are participating in session T2129 but only two of those are in the southern hemisphere, namely HartRAO and O'Higgins.

The observations are recorded using a low sampling rate of 128 Mbit/s which is problematic since some of the stations have very low sensitivity with a system equivalent flux density (SEFD) of more than 10.000. The suboptimal geometry of the network, together with the low recording rate makes it especially hard to include O'Higgins into the schedule. O'Higgins has very high SEFD values of 10.000 in X-Band and 18.000 in S-Band and is located in Antarctica.

Table 1 compares statistics of schedules generated with sked and VieSched++.

In the previously submitted schedules generated with sked, the number of observations with O'Higgins is always below 100 after 24 hours. One of the goals of the new schedules is to include O'Higgins better into the session. By using VieSched++ it is possible to increase the number of observations with O'Higgins by a factor of four as can be seen in Table 1.

In general, the number of observations with VieSched++ is about twice the number of observations with sked, sometimes even three times, while the number of scans roughly stays the same or is even lower.

**Table 1** comparison of statistics between schedules created with sked (top) and VieSched++ (bottom, blue) for T2 sessions

	#sta	#scans	#obs	%idle	%obs	#obs Oh
T2123	19	617	6773	30.98	50.46	79
T2124	17	733	7175	28.10	44.54	22
T2125	17	1064	5528	22.94	53.70	48
T2126	17	1075	6081	24.55	49.66	98
T2127	19	627	6304	34.30	45.22	73
T2128	18	803	5983	26.24	44.90	97
<b>T2129</b>	15	526	12713	8.20	66.90	400
<b>T2130</b>	22	626	16730	10.45	69.24	451
<b>T2131</b>	19	771	15714	4.33	73.68	267
<b>T2132</b>	18	631	10219	6.04	73.37	406

This means that on average scans with more participating stations are scheduled. Additionally, it is possible to reduce the idle time of the stations by a factor of two to three and increase the observing time by almost 50%.

### 3.2 EURR&D

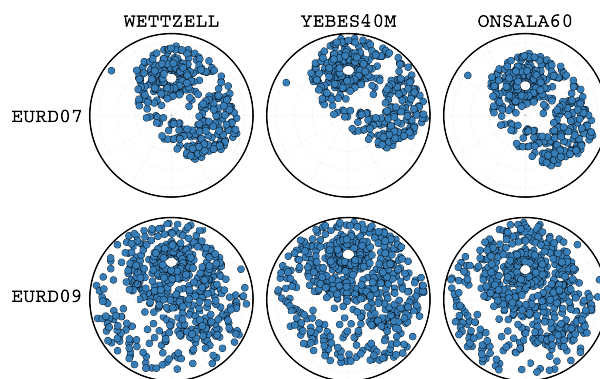
Similar to the T2 session, the aim of the EURR&D sessions is to provide high accuracy station coordinates for terrestrial reference frames. The network consists of mostly European stations and the observing rate is 512 Mbit/s, which makes it easier to generate a good schedule.

Table 2 compares statistics of schedules generated with sked and VieSched++.

**Table 2** Comparison of statistics between schedules created with sked (top) and VieSched++ (bottom, blue) for EURR&D sessions

	#sta	#scans	#obs	%idle	%obs
EURD05	8	374	10134	25.00	39.97
EURD06	6	538	8061	21.63	30.87
EURD07	8	344	9437	36.42	29.40
EURD08	7	361	7215	25.78	33.08
<b>EURD09</b>	8	665	11565	5.78	39.03
<b>EURD10</b>	8	669	13480	3.08	42.70

Compared to the results from T2 listed in Table 1 the improvement regarding scheduling statistics seems lower based on the statistical values. However, VieSched++ is able to generate schedules with a higher number of observations but this time the number of scans also increases. The main difference between the

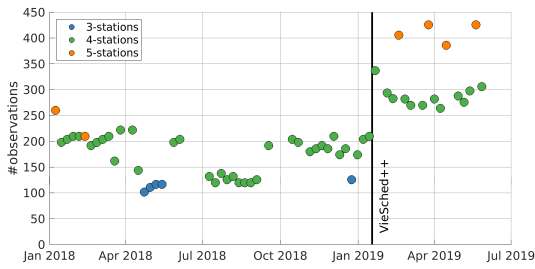
**Fig. 1** Sky coverage of stations scheduled with sked (top) and VieSched++ (bottom).

sked schedules and the VieSched++ schedules is the sky coverage of the stations as shown in Figure 1. Since sked only schedules scans with the full network it focuses mainly on one small part of the sky. This results in low slew times and thus many observations but also in a very poor sky coverage as shown in Figure 1 for EURD07. In contrast VieSched++ decides to split the network more often resulting in a way better sky coverage as shown in Figure 1 for EURD09. A good sky coverage helps to estimate tropospheric time delays which are one of the major error sources in geodetic VLBI (Schuh and Böhm, 2013). Especially observations at different elevations are necessary to distinguish tropospheric delays, clocks and station heights which are highly correlated (Nothnagel et al., 2002).

Compared to the sked solutions it is possible to reduce the idle time by a factor of four to five as shown in Table 1. The time gained is used mostly for slewing purposes to achieve better sky coverage.

### 3.3 INT3

The purpose of the INT3 sessions is to provide dUT1 values. The network consist of four to five stations, the observing rate is 1024 Mbit/s and the session duration is only one hour. Since the complexity of intensive schedules is relatively simple due to the low number of stations and short session duration, scheduling of intensive sessions is rather easy compared to global 24-hour sessions. Therefore, it was not expected to gain significant improvement when changing from sked to VieSched++. However, Figure 2 shows that even for



**Fig. 2** Number of observations in INT3 sessions color-coded by number of participating stations.

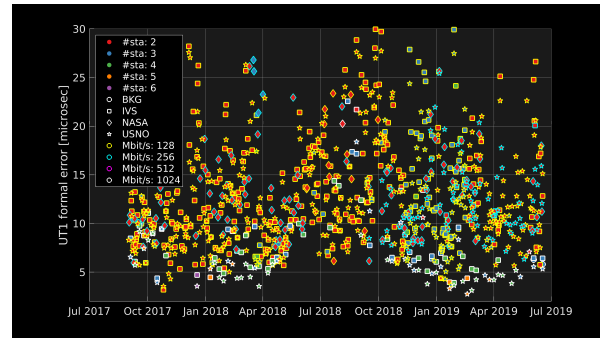
intensive sessions the number of observations can be improved.

Figure 3 shows the dUT1 estimates gained from intensive sessions as they are listed in the analysis reports. The values are color-coded by the number of participating stations, the analysis center which delivered the analysis report and by the observing rate. Figure 4 shows the same values, but this time only the INT3 sessions are colored. Starting with 21st of January 2019, VieSched++ is used to generate these schedules. It can be seen that the INT3 sessions provide the most accurate dUT1 estimates, due to the higher number of stations and the higher observing rate. While Figure 2 shows the number of scheduled stations, Figures 3 and 4 shows the number of stations which were actually observing the session, since it can happen that one station drops out.

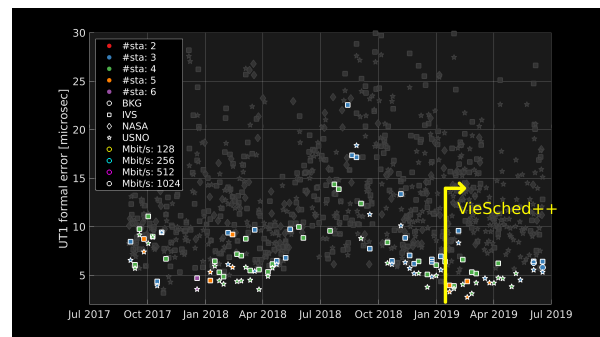
Figure 4 shows, that by changing the scheduling software to VieSched++ the formal errors of the dUT1 values is improved to solutions from the previous half year. At the beginning of 2018, the accuracy was roughly at the same level, while after April 2018 the results got significantly worse. It is unclear why this happened, however, it corresponds with a time period where the number of observations was also very low as seen in Figure 2.

## 4 Conclusions and outlook

VieSched++ is a new, modern VLBI scheduling software written in C++. It uses many new features and algorithms to generate high-quality schedules. While generating optimized schedules for VLBI experiments should be the norm, unfortunately, this is not the case.



**Fig. 3** dUT1 formal errors from intensive sessions listed in analysis reports, color-coded by number of stations, analysis center and sampling rate.



**Fig. 4** dUT1 formal errors from INT3 sessions listed in analysis reports.

This work shows, that it is possible to achieve twice the number of observations compared to previously uploaded results. Based on the newly created optimized schedules, improvements can also be expected during analysis for these sessions. Unfortunately, so far this could only be verified for INT3 sessions since most other sessions are not yet correlated and no VgosDB database are available for analysis at the moment.

While VieSched++ is already stable and freely available through our GitHub page <https://github.com/TUW-VieVS>, development continues to improve the quality of the generated schedules even further. Additionally, a YouTube channel called “VieVS” is available, where the usage of VieSched++ is explained.

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