Monitoring Source Flux Density and Antenna Sensitivity with Improved Feedback for the AUSTRAL VLBI Sessions

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Abstract Very Long Baseline Interferometry (VLBI) is a unique technique for measuring the Earth's orientation for deriving precise reference frames that allow accurate positioning of objects on the Earth and in the sky. Although it has a long history, VLBI in the Southern Hemisphere is not as old as in the Northern Hemisphere, with significantly fewer telescopes and observations. Therefore, VLBI observations and results from the Southern Hemisphere are crucial to the global community to prevent inaccuracies in the derived global reference frames. As one of the main contributors from the south, the Australian AuScope VLBI array strives to achieve better results through improved source flux density and antenna sensitivity monitoring with more automation. We investigated an improved approach to monitoring the performance of VLBI sessions and are implementing it in the Australian mixed-mode sessions using the dynamic observing program (Dynob). This work is an overview of the implementation of Dynob with emphasis on automated feedback, which allows quick and continuous session improvements.

Keywords VLBI, Dynamic observing, Dynamic feedback

1 Introduction

The VLBI telescopes at Hobart, Katherine, and Yarragadee, which are owned by the University of Tasmania (UTAS) in Australia, have been dedicated to VLBI observations globally and locally since 2011. A VLBI observation is the recording of radio signals of specific frequency ranges from distant quasars using two or more radio telescopes. As we now prepare to enter the next generation of VLBI observing, known as the VLBI Global Observing System [VGOS, 5], UTAS has explored the possibility of a more efficient and improved way of observing. For operational efficiency, UTAS has initiated the 'dynamic observing' research aiming to reduce the labor and cost for continuous observing [4]. This original study focused on short-notice automated scheduling, which is beneficial for utilizing antennas and potentially improving a schedule when some antennas fail to participate in the observation [3]. While inheriting the original goals, the research on dynamic observing, now called Dynob, has been extended to improve the observing efficiency and results of the VLBI mixed-mode observing using automated feedback.

On the global scale, the observing efficiency is only about 80% in terms of the used-to-scheduled ratio, averaged from the analysis reports of the first half-year of 2021 for the participating stations. There can be various reasons that reduce the efficiency, and one of those is the mismatch of the predicted and actual source flux density and antenna sensitivity. The a priori source flux density and antenna sensitivity are essential parameters in VLBI scheduling to calculate the integration time for observations based on a minimum target signal-to-noise ratio (SNR). Conventionally, the antenna sensitivity is characterized by the system equivalent flux density (SEFD), a measurement of the combined system temperature proportional to the total power received at the receiver (Tsys). The antenna SEFD is usually measured once after each major upgrade, such as a receiver change. The SEFD value, in theory, should not vary significantly at daily intervals due to a cooling

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or ambient temperature control mechanism at the telescopes. However, the telescope sensitivity may fluctuate in reality, due to recording backend and hardware issues that are not immediately obvious, in the form of temperature, which especially has a detrimental effect on the AuScope VGOS stations.

The source flux density used for planning the geodetic VLBI observations is estimated after every 24-hour session based on the global average. This procedure has been sufficient for the legacy S/X sessions with a 100% error factor for the target SNR used at the planning stage. Although adequate, this approach is not ideal as it compromises the possibility for more observations within the 24-hour session window and does not reliably solve the observing efficiency issue. Here is where Dynob comes into play, by continuously monitoring antenna sensitivity and source flux density based on a scan-by-scan technique, wherein a ‘scan’ is when two or more telescopes observe the same source simultaneously. The details for the scan-by-scan performance monitoring approach can be found in [2]. We demonstrate this approach using the AUSTRAL VLBI sessions observed by the Australian network with contributions from Warkworth and Hartebeesthoek, utilizing better feedback from the Dynob program.

2 Dynamic Observing

The AuScope dynamic observing has evolved from an automated scheduling and observing technique [4] to the core of the feedback system in the new mixed-mode observing at the University of Tasmania (UTAS) [1]. The development of Dynob extends the original concept of the AuScope dynamic observing into automating the entire VLBI operation from scheduling to correlation, with an additional mechanism to monitor the performance of telescopes in near real-time, providing constant feedback for improvement. Dynob is also the tool that centralizes and controls all the VLBI operational procedures optimized for the practices at UTAS. The first application of the expanded Dynob project was the establishment of a one scan per week, less-than-60-second per scan ‘fringe check’ series for the diagnosis of the program while providing quick feedback on the antenna performance. Although fringe checking usually involves only one scan, the entire observing and processing process still applies. The Dynob program has now replaced the manual operation procedure at UTAS, allowing the operator and observers to perform a fringe check with multiple AuScope VLBI telescopes by clicking a button. About 90 fringe check sessions have been run using Dynob in parallel with its development, observing various sources.

The general Dynob process is illustrated in Figure 1, with more information given in [1]. The Dynob process starts by creating the schedule files and passing them to the observing computer, and then it triggers the loading of the schedule and the start of observing according to the scheduled time. It can automatically proceed with the data transfer and correlation when the observation ends before finally generating a visible plot showing the scan quality. Each component can be manually started or interrupted and resumed again with the automation. The complete automation of this process applies to the fringe check sessions because they involve only the AuScope telescopes, and the size of data is relatively small so that transferring over the Internet is feasible. For the 24-hour sessions, each station would need a super-fast connection to the correlator and the data recorded on the FlexBuff system to achieve the same. A few near real-time fringe checking tests for 24-hour sessions were conducted with collaboration from Hartebeesthoek to stream the data to Hobart after every scan. The automation works for the weekly fringe check sessions, but real-time transferring of the S/X data recorded in the AUSTRAL mode [6] takes about seven hours for every six hours of observations from Hartebeesthoek. For the data recorded using Mark5B at Yarragadee, Dynob automatically extracts about 12

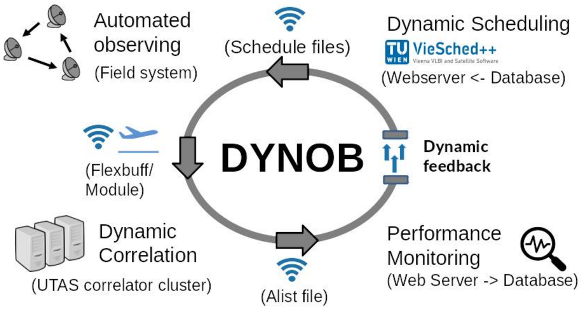

Fig. 1 Dynob is the tool that automates and connects each component of the VLBI operation. Near real-time performance is feedback to improve the schedule quality.

seconds of the data at the interval between each scan before sending it to avoid interruption of recordings. By default, the near real-time fringe checks run once every three hours on bright sources only with source flux densities above 2 Jy.

The evolution of the dynamic observing concept into Dynob was driven by the need for a stable telescope calibration with a better, faster, and continuous approximation of the antenna SEFDs and source flux densities to achieve good observed-to-expected SNRs, i.e., closer to 1. This improvement can allow the SNR error factor placed during the scheduling process to be reduced from more than 100% to a lower value to yield more observations and better station coordinate repeatabilities. The minimum SNR needed for the post-processing is 7, but the usual target SNR used is 20, whereas [2] shows that the optimum range is around 10 — 13. The error factor is in place for many reasons, but all serve the purpose of reducing the number of observations lost due to a low SNR. The automated feedback system of Dynob consistently monitors the source flux density and antenna sensitivity and improves the schedule so that the predicted SNRs are much closer to those observed.

3 Improved Feedback

The modern scheduling technique of a VLBI session typically involves telling the software scheduler how sensitive the telescopes are and how bright the sources are. The scheduler then recursively calculates and assigns an integration time to a scan to achieve the target SNR based on these inputs until the individual scans make up the typical 24-hour session. To attain a good observed-to-expected SNR agreement at all baselines, the predicted sensitivity of all stations should be as accurate as possible, given that the source flux density prediction is precise. The SNR performance of a 24-hour session is seen clearly through the feedback of Dynob, as illustrated in Figure 2 using two radio sources visible to the AUSTRAL network at the opposite time.

Starting from the X-band, the first information, marked as ‘1’, shows that the SNR ratio for source 1741-038 was generally around 1 for the Hb-Yg baseline, whereas the source 0454-234 had higher than predicted flux density. The digital sampler at Katherine was unstable during the session. As a result, the sensitivity of the station dropped, as marked by the box with the number ‘2’, compared to the first box. This effect caused the SNR ratio of all its baselines to degrade by about 50%. A reconfiguration of the digital sampler at time ‘3’ solved the problem. As shown in the S-band, there was basically non-detection for source 1741-038 before the reconfiguration, which was the larger part of the session. One more thing to note is that the sensitivity of Ke at the S-band was significantly lower than predicted for this session. With the feedback loop, we can quickly alert the operator to check the system and fix any issues or schedule the next session with an SEFD value closer to reality. Figure 3 shows the more desired performance feedback in AUM045, conducted in January 2022.

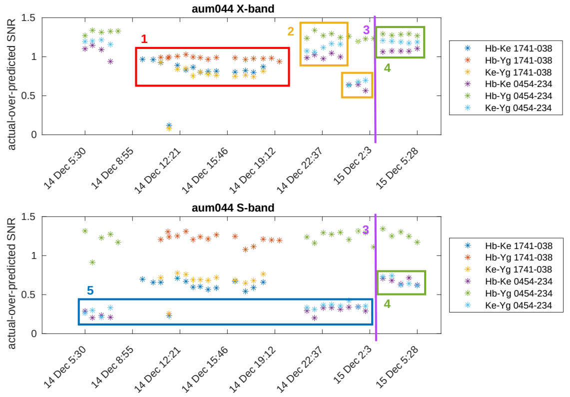

Fig. 2 Illustration of the performance feedback for AUM044 conducted on 14 December 2021. Only the 12-meter Australian telescopes at Hobart (Hb), Katherine (Ke), and Yarragadee (Yg) are shown.

This session used the source flux densities monitored by the AUSTRAL session three months before the session and the same antenna SEFDs as AUM044. As we see in the X-band, the SNR ratio for all baselines converged around 1, which means that the predictions of the source flux densities for the two sources and the sensitivities for all telescopes were accurate. In contrast with the existing approach to monitoring the antenna SEFD and the source flux density, which is based on the session’s average (session-wise), we use a “selective scans” (scan-wise) method [2]. The reason for a new approach is that the session-wise re-estimation cannot reliably indicate the source flux density and the antenna sensitivity. As seen from Figure 2, the poorly performed observations can make up most of a session

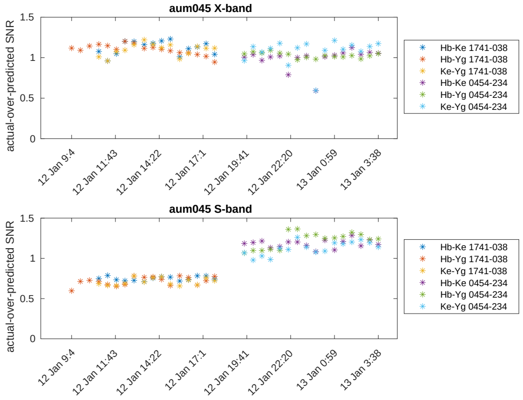

Fig. 3 Illustration of the performance feedback for AUM045 conducted on 12 January 2022. Only the 12-meter Australian telescopes at Hobart (Hb), Katherine (Ke), and Yarragadee (Yg) are shown.

and should be removed during the re-estimation process.

An important aspect of the scan-wise method is selecting only the well-observed radio sources with stable flux densities as the reference, which we can determine via the Dynob feedback mechanism through constant monitoring. Figure 4 shows a source used as the reference in [2]: 0454-234, versus a more stable source: 0458-020, relative to the Australian network within the last half of the year 2021.

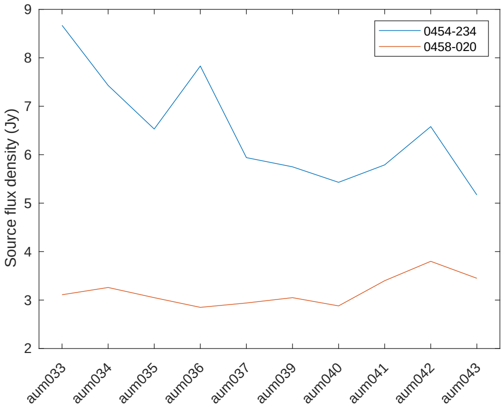

Fig. 4 Comparison of source flux density for sources 0454-234 and 0458-020 monitored by the AUSTRAL station network. The latter source appears to be more stable and could be a better candidate as a reference source.

The variability of the source flux density is often inconsistent, which means a regular update of the reference source is also needed. An arbitrary half-a-year window might be sufficient to determine the rate and degree of changes. This process of monitoring the antenna SEFD and the source flux density and updating reference sources can be more efficient through automated feedback. Using a set of more stable reference sources could potentially solve the less accurately predicted source flux densities, such as in the S-band for the source 1741-038 in Figure 3.

The processing time of a 24-hour AUSTRAL session from observing to analysis takes about three months without Dynob, including the data transfer from other stations to Hobart. Even the highest priority sessions within the International VLBI Service for Geodesy and Astrometry (IVS) would take three to four weeks. In the continuous observing era where data start to accumulate, Dynob will play a critical role in monitoring the source flux density and antenna sensitivity, keeping these pieces of information the most up-to-date, thereby maintaining the quality and efficiency of observations.

4 Results

This section compares the median SNR performance for 12 AUA sessions (once a month) and 18 AUM sessions (once or twice a month) in 2021. The AUM series has a better observed-to-predicted SNR ratio in the X-band than the AUA series and about the same performance in the S-band (Figure 5). All AUM sessions used the Dynob-monitored antenna SEFDs for the scheduling, but the source flux densities were from the general catalog of SKED. The reason was due to the modelling approach and feedback mechanism for the source flux density still under research and development.

From Figure 5, we see that the issues with the telescopes around 11 April and 22 September are more apparent for the AUM as the SNR ratio became unusually low, although it impacted both the AUA and AUM sessions. A plunge in the actual-to-predicted SNR ratio for the AUA and AUM is usually a DBBC3 (digital sampler) issue, as the DBBC3s at Katherine and Hobart were still in the commissioning phase. Nevertheless, the median ratios for the AUA data points are 0.7 and 0.9 in the X- and S-band, respectively, compared to 1.0 and 1.1 for the AUM.

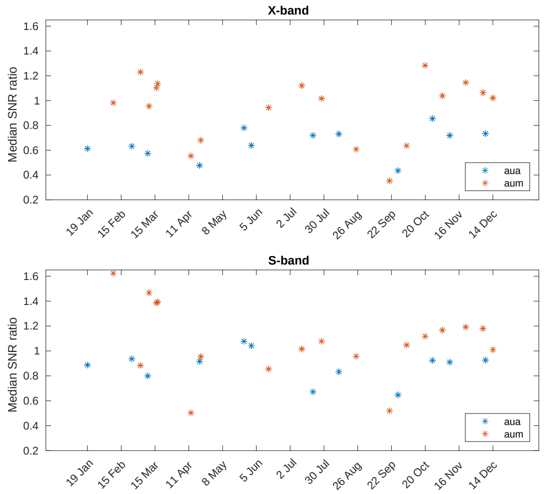

Fig. 5 Median SNR for 12 AUA and 18 AUM sessions in 2021. The AUM performed significantly better than the AUA in the X-band while having a similar performance in the S-band.

5 Future Work

The Dynob program is functioning as intended, and all AUM sessions in 2022 have implemented it from scheduling until performance monitoring. Automation for the reference source list updates will be a future functionality for Dynob. Using Dynob on a larger station network and its application at other operating centers will need further research. The current work is a fully functioning prototype optimized for the AUSTRAL sessions, which serves as the proof of concept for dynamic observing in a continuous observing era.

6 Conclusion

The AuScope dynamic observing program (Dynob) is a tool that automates the entire VLBI observation procedure from scheduling to correlation, with a feedback mechanism to monitor the SNR performance of the session. Dynob implements the new scan-wise monitoring approach, which allows the continuous monitoring of the antenna SEFD and source flux density through its dynamic feedback to improve the prediction of SNR for subsequent schedules. Results show an improvement of the actual-to-predicted SNR ratio in the X-band for the 2021 AUM sessions, which used the antenna SEFD monitored by Dynob, compared to the conventionally scheduled AUA sessions. Dynob's feedback mechanism can detect stable radio sources through the time series resulting from consistent monitoring, which will be the candidates for the reference sources for future performance monitoring.

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