The southern hemisphere AUSTRAL program: A pathway to VGOS

J. Lovell, J. McCallum, L. Plank, E. Rastorgueva-Foi, S. Shabala, D. Mayer, J. Böhm, O. Titov, J. Quick, S. Weston, S. Gulyaev, T. Natusch, C. Reynolds, H. Bignall, J. Sun, A. Neidhardt

Abstract The AuScope VLBI array participated in 210 IVS sessions in the 12 months from July 2014. More than half of these were dedicated to the southern hemisphere AUSTRAL program together with antennas at Hartebeesthoek (South Africa) and Warkworth (New Zealand). AUSTRAL has three main streams: astrometry to monitor and enhance the southern hemisphere celestial reference frame; geodesy to improve the southern hemisphere terrestrial reference frame and the baseline time series; and15-day CONT-like sessions to densify the time series and investigate a range of observing strategies. The high observing rate is providing new insight into some of the challenges of a 24/7 VGOS observing program and is allowing us to trial new scheduling and observing strategies such as Dynamic Observing. All AUSTRAL sessions are being scheduled with VieVS, observations are carried out remotely using the eRemoteCtrl software, data are processed at the Curtin University AuScope correlator and analysis is carried out in Hobart and at Geoscience Australia. We present some results from the AUSTRAL program and describe the steps we have taken and have planned to approach VGOS-like operations.

Jim Lovell, Jamie McCallum, Lucia Plank, Elizaveta Rastorgueva-Foi, Stas Shabala
University of Tasmania, Private Bag 37, 7001 Hobart, Australia
David Mayer and Johannes Böhm
Technische Universität Wien, Gußhausstraße 27-29, 1040 Vienna, Austria
Oleg Titov
Geoscience Australia, P.O. Box 378, Canberra, ACT 2601, Australia
Jonathan Quick
Hartebeesthoek Radio Astronomy Observatory (HartRAO), P.O.Box 443, Krugersdorp 1740, South Africa
Stuart Weston, Sergei Gulyaev, Tim Natusch
Institute for Radio Astronomy and Space Research, School of Computing and Mathematical Sciences, Auckland University of Technology, Private Bag 92006, Auckland 1142, New Zealand
Cormac Reynolds and Hayley Bignall
International Centre for Radio Astronomy Research, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
Jing Sun
Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road Shanghai 200030, China
Alexander Neidhardt
Technische Universität München, Forschungseinrichtung Satellitengeodäsie, Geodetic Observatory Wettzell, Sackenrieder Str. 25, D-93444 Bad Kötzting, Germany

Keywords Geodesy, Astrometry, VLBI, VGOS

1 Introduction: The Challenges of VGOS

The move toward the VLBI Global Observing System (VGOS) presents some significant technical and organisational challenges to the geodetic VLBI community. Operations will move from approximately 150 24-hour sessions per year to continuous observations. Broader bandwidths, higher data recording rates and the need for fast turnaround of products will stress data network and storage resources. It is likely that economies will have to be found to keep the cost of operations down and this may require centralised, remote operations centres and more automation. Streamlining the connections between scheduling, observing, data processing and analysis will be required and real-time adaption of schedules during an observation to react to unforeseen events will also improve data quality. Further, the improved accuracy and precision of solutions in the

VGOS era will only be possible if sources of error that are currently insignificant, such as quasar structure, are mitigated against. There is also the prospect of developing new observing modes involving twin and sibling telescopes.

In this paper we describe the work that has been undertaken in the southern hemisphere in recent years to address some of these challenges. In Section 2 we briefly describe the AuScope VLBI array and how it functions as a VGOS pathfinder. In Section 3 we outline the southern hemisphere focused AUSTRAL observing program and in Section 4 we show how it is helping to address some of the VGOS challenges. Lastly, in Section 5 we describe our plans to upgrade the AuScope network to full VGOS compatibility.

2 The AuScope VLBI Array

In 2007 the Australian Federal Government through the National Collaborative Research Infrastructure Strategy (NCRIS) funded Capability 5.13: "Structure and Evolution of the Australian Continent" from which AuScope was established (www.auscope.org.au). Part of the AuScope initiative was to upgrade Australian geospatial infrastructure, including VLBI. This involved the construction of three new 12 m diameter radio telescopes across the continent, in Hobart (Tasmania) co-located with the existing 26 m telescope and HOB2 GNSS antenna, at Yarragadee (Western Australia) co-located with the MOBLAS-5 SLR station, GNSS and DORIS facilities, and a new site in Katherine (Northern Territory) where a GNSS facility has also been established. The Hobart antenna (Hb) commenced operations in 2010 with the Katherine (Ke) and Yarragdee (Yg) sites following in 2011. The telescopes were built to match the VGOS requirements as closely as possible or to allow for future upgrades to VGOS compatibility where it was not possible to do so at the time. At present, all three telescopes operate with room-temperature S/X systems although an upgrade to cooled, broadband systems is now funded.

All three telescopes are controlled and monitored remotely from the operations centre at the University of Tasmania. Observations are coordinated through the IVS with most experiments correlated at Bonn, Washington, or the AuScope correlation facility at Curtin University in Western Australia. A detailed description of the AuScope VLBI infrastructure and characteristics of the array has been presented by Lovell et al. (2013).

3 The AUSTRAL Observing Program

The AUSTRAL observing program is a series of sessions additional to the usual IVS program, dedicated to observations with the AuScope array, Hartebeesthoek and Warkworth (Figure 1) and focused on specific areas of priority in the southern hemisphere:

1. One session per month of astrometry to monitor and enhance the southern hemisphere reference frame. Some of these sessions have also included the Parkes 64 m antenna to improve sensitivity to weak sources,
2. About two 15-day CONT-like sessions per year to densify the geodetic time series and trial and evaluate a range of different observing strategies
3. The remainder (and vast majority) of sessions were geodetic and aimed at improving the terrestrial reference frame and baseline time series in the southern hemisphere

In the 12 months commencing 2014 July 1, the AuScope array was the busiest geodetic VLBI facility in the world, participating in 210 days of observations. Of these, 118 days were dedicated to the AUSTRAL program. The AuScope telescopes participated in all sessions while the Hartebeesthoek 15 m and Warkworth 12 m contributed to ~ 50% of the AUSTRAL days.

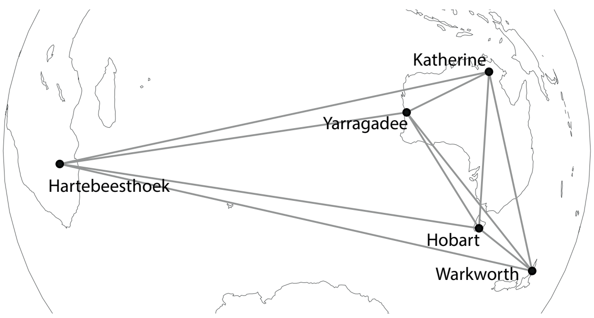

Fig. 1 The AUSTRAL network.

Scheduling for the AUSTRAL sessions is carried out in VieVS (Böhm et al., 2012), observations are made at 1 Gbps recording rates (16×16 MHz IFs and 2-bit digitisation), data correlated at Curtin University and data analysis carried out at the University of Tasmania and Geoscience Australia.

4 Addressing VGOS Challenges with the AUSTRAL Program

The southern hemisphere network involved in the AUSTRAL program is not fully compliant with VGOS because it does not yet have broadband systems, fast internet connections to all sites or enough operational funding to support continuous observations. However, the array is capable of addressing some of the challenges of VGOS. We have small, fast slewing antennas and a higher than standard data recording rate which allows us to trial and investigate VGOS scheduling strategies that involve many more scans per day than typical IVS Rapid observations. Our ability to observe for 210 days over 12 months from a central operations centre also allows us to work on improving and streamlining operational procedures

4.1 Continuous Remote Operations

At its inception the model for operation of the AuScope array was to make it as automated as possible and remote controllable. To do this, we used our experience in remotely operating the University of Tasmania Ceduna 30 m antenna (in South Australia), adopted software that allows for remote operation and monitoring such as eRemoteCtrl (Ett et al., 2012) and MONICA (Brodrick, 2015) and also developed our own interfaces. The observatories are equipped with cameras to provide real-time visual monitoring of equipment, back-up power generators and internet connections, internet power switches and environmental monitors. In this way it is possible to operate the sites entirely remotely for long periods of time with the only required local support being management of recording media. Our experience with this mode of operations has provided feedback to the eRemoterCtrl software developers and has lead to several improvements. At the Hobart observatory we operate a small PC cluster running the DiFX software correlator (Deller et al., 2007) and this is used regularly to run brief automated fringe checks on the AuScope baselines.

The high observing cadence in 2014/2015 combined with four non-stop 15-day CONT-like sessions between December 2013 and the end of June 2015 allowed us to experience VGOS-like operations and develop methods to handle a continuous stream of data.

In Figure 2 we show the baseline time series for Katherine-Yarragadee which demonstrates the benefits of a higher sampling rate since July 2013. Systematic effects become much more apparent as do the true uncertainties in the data.

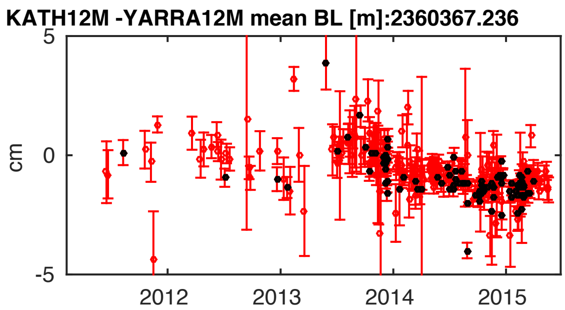

Fig. 2 The baseline time series for Katherine-Yarragdee from mid-2011 until June 2015. AUSTRAL sessions are indicated by the black points. This clearly shows the benefits of a higher sampling rate and its ability to clearly reveal systematic effects.

4.2 Scheduling Strategies

The complete management of the AUSTRAL sessions from scheduling through to analysis is carried out within our collaboration and this allows us to test and improve scheduling strategies (Mayer et al., 2015). In Figure 3 we show baseline length repeatabilities (weighted rms) as a function of baseline length for the AUST sessions. The data are divided into three time periods. The first period, until July 2014 shows the results for observations with the source catalogue comprising all common VLBI sources stronger than 0.5 Jy. The second period covers approximately the next six months after a reduction was made to the list of target sources and shows a significant improvement. Lastly, the third period, from the beginning of 2015 shows a further improvement following a revision of target SEFD levels and an increase in the minimum acceptable source flux density to 0.8 Jy, leading to more scans per day. These continuous improvements over time have lead to almost a factor of two improvement in repeatability over the course of the AUST program.

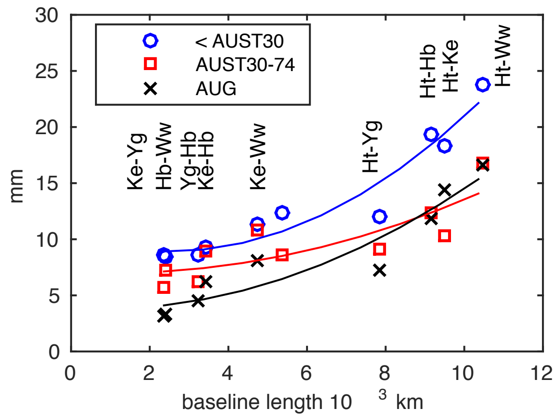

Fig. 3 A factor of ~ 2 improvement in baseline length repeatabilities (wrms) as a result of revision and optimisation of scheduling strategies. The blue circles cover the initial 12 months of the AUSTRAL program, the red squares cover six months following a revision of the source catalogue and the black crosses show results from the first six months of 2015 after SEFD target levels and catalogue flux density limits were revised.

4.3 Feedback and Dynamic Observing

We have commenced work on improving our observing and scheduling strategies though intra-session optimisations, or Dynamic Observing (Lovell et al., 2014). The main concept here is to use monitoring of antenna performance, local conditions (e.g. wind stows) to provide feedback to a central operations centre so that the observing schedule can be modified in real-time to optimise the data quality. Simulations of scenarios such as poorer than expected sensitivity have shown that a vast majority of scans can be recovered to an affected antenna if real-time adaptation is adopted. Further simulations are required and test observations should be planned.

4.4 Variability and Source Structure

While the troposphere is currently the dominant source of error in geodetic VLBI measurements, it is expected that in the VGOS era other effects will also become a significant contributor. One of these is source structure and this has been a significant focus of research at the University of Tasmania in recent years (Shabala et al., 2015). In Figure 4 we show the evolution in total flux density of the quasar 0059+581. There is a strong anticorrelation with group delay. When the quasar undergoes a flare in flux density a new jet component is ejected by the central engine and the source is ’core’ dominated and compact and therefore a good target for geodesy. However, as the new component moves down the jet, the source becomes extended at VLBI resolution, group delay increases and the geodetic solution is degraded.

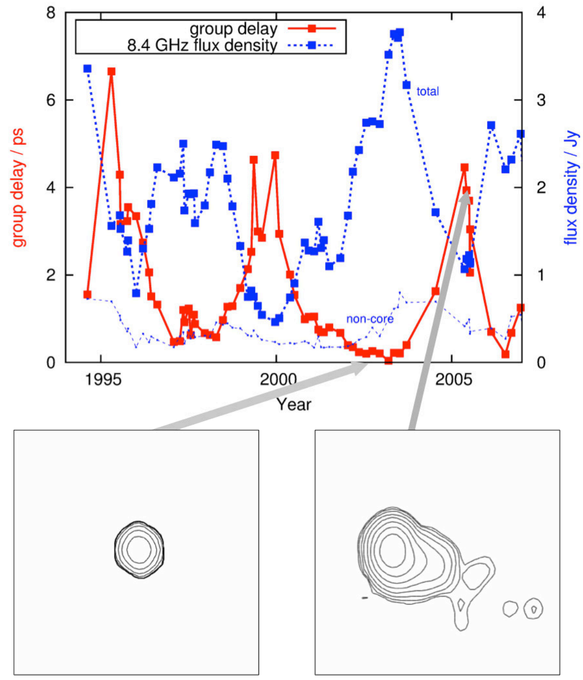

Fig. 4 Top panel: variability in total flux density in the quasar 0059+581 (blue) and a corresponding anti-correlation with group delay (red). Lower panel: VLBI images of the source during and after a flare (left and right respectively). The source is a good target for geodetic observations when it is bright and compact after a new jet component has just been emitted, but its usefulness for geodesy is degraded once the component propagates along the jet.

This work clearly demonstrates that an understanding of the parsec-scale astrophysics of AGN is important in mitigating against source structure effects. In the VGOS era it will be important to monitor the total flux density of the target sources and regularly update catalogues so that sources are scheduled only when they are predicted to be dominated by an unresolved component near the nucleus.

4.5 Twins and Siblings

At Hobart and Hartebeesthoek, we can work on understanding and developing the twin telescope concept by co-observing with the legacy 26 m telescopes. This is discussed in detail elsewhere by Plank et al (these proceedings). New Zealand's 12 m and 30 m telescopes at Warkworth can potentially be used for this program as well (Woodburn et al., 2015).

5 Next Steps

Our priorities during the ramp-up to VGOS operations are to upgrade the AuScope network to broadband receivers and recorders covering 3–14 GHz by the end of 2016. We will also continue to develop and trial some dynamic observing and source structure mitigation techniques, further develop observing software to improve reliability and automation, and use the Hobart 12 m and 26 m telescopes to investigate and assess various sibling/twin telescope observing strategies.

6 Acknowledgments

This work was supported by the AuScope Initiative, funded under the National Collaborative Research Infrastructure Strategy (NCRIS), an Australian Commonwealth Government Programme. The authors are grateful to the Australian Research Council for Fellowships FS1000100037 and FS110200045 and to the Austrian Science Fund (FWF) for Fellowship J3699-N29.

References

Böhm J, Böhm S, Nilsson T, Pany A, Plank L, Spicakova H, Teke K, Schuh H (2012) The new Vienna VLBI software. In: S. Kenyon, M. C. Pacino, U. Marti (eds.), *Proc. IAG Scientific Assembly 2009*, IAG Symposia Series 136, 1007–1011, doi: 10.1007/978-3-642-20338-1_126.

Brodrick D (2015) MoniCA Monitoring Software. Web document `https://www.narrabri.atnf.csiro.au/monitor/monica/`

Deller A T, Tingay S J, Bailes M, West C (2007) DiFX: A Software Correlator for Very Long Baseline Interferometry Using Multiprocessor Computing Environments. *Publ Astron Soc Pac*, 119, 318–336.

Ettl M, Neidhardt A, Schönberger M, Alef W, Himwich E, Beaudoin C, Plötz C, Lovell J, Hase H (2012) e-RemoteCtrl: Concepts for VLBI Station Control as Part of NEXPReS. In: D. Behrend, K. D. Baver (eds.), *IVS 2012 General Meeting Proc.*, NASA/CP-2012-217504, 128–132.

Lovell J E J, McCallum J N, Reid P B, McCulloch P M, Baynes B E, Dickey J M, Shabala S S, Watson C S, Titov O, Ruddick R, Twilley R, Reynolds C, Tingay S J, Shield P, Adada R, Ellingsen SP, Morgan JS, Bignall HE (2013) The AuScope geodetic VLBI array. *J Geod*, 87, 527–538.

Lovell J, McCallum J, Shabala S, Plank L, Böhm J, Mayer D, Sun J (2014) Dynamic Observing in the VGOS Era. In: D. Behrend, K. D. Baver, K. L. Armstrong (eds.), *IVS 2014 General Meeting Proc.*, ISBN 978-7-03-042974-2,

Mayer D, Böhm J, Lovell J, Plank L, Sun J, Titov O (2015) Scheduling Strategies for the AuScope VLBI network. *Vermessung & Geoinformation*, 2+3/2015, 162–168, `http://www.ovg.at/fileadmin/download/vgi2015\_0203/Mayer.pdf`.

Shabala S, McCallum J, Plank L, Böhm J (2015) Simulating the effect of quasar structure on parameters from geodetic VLBI. *J Geod*, 98(9), 873–886.

Woodburn L, Natusch T, Weston S, Thomasson P, Godwin M, Granet C, Gulyaev S (2015) Conversion of a New Zealand 30-Metre Telecommunications Antenna into a Radio Telescope. *Publ Astron Soc Aust*, 32, 14.