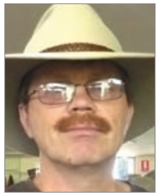
Vermessung & Geoinformation 2+3/2015, P. 162 – 168, 7 Figs.

# Scheduling Strategies for the AuScope VLBI network





*David Mayer, Johannes Böhm, Wien; James Lovell, Lucia Plank, Hobart; Jing Sun, Bejing; Oleg Titov, Canberra*

**Abstract**

In recent years Australia established the AuScope VLBI array which consists of three new 12-m radio telescopes across the continent (Hobart, Katherine and Yarragadee). With this network, the independent AUSTRAL observing program is carried out, regularly adding two more telescopes, the 12-m telescope in New Zealand and the 15-m telescope in South Africa. The observing plans (schedules) are created in Vienna, Austria and the correlation is done in Perth, Australia. The network engages in different AUSTRAL experiments (astrometric and geodetic) with contradictory aims, therefore scheduling approaches have to be adjusted to fit the required needs. We discuss the different techniques used to create these schedules, and provide first results, suggesting that solutions from the AuScope VLBI network are on a similar level of accuracy as standard global VLBI sessions performed by the International VLBI Service for Geodesy and Astrometry (IVS).

**Keywords:** VLBI, AuScope, Scheduling, Geodesy, Astrometry

**Kurzfassung**

In den letzten Jahren wurde in Australien das AuScope VLBI-Netzwerk errichtet. Es handelt sich um drei neue VLBI-Teleskope (Hobart, Katherine und Yarragadee), welche über den Kontinent verteilt wurden. Mit diesen drei Teleskopen, und gelegentlich zwei weiteren, dem 12-m-Teleskop in Neuseeland und dem 15-m-Telescop in Südafrika, wird das AUSTRAL Beoabachtungsprogramm durchgeführt. Die Beobachtungspläne (sogenannte Schedules) werden in Wien, Österreich erstellt und die Korrelation der Beobachtungen wird in Perth, Australien durchgeführt. Das AUSTRAL Beobachtungsprogramm beinhaltet verschiedene Experimente (astrometrisch und geodätisch) mit gegensätzlichen Zielen, weshalb die Methode zum Erstellen der Schedules den benötigten Anforderungen angepasst und erweitert werden muss. Wir diskutieren die verschiedenen Techniken, welche zum Erstellen dieser Schedules verwendet werden und präsentieren erste Resultate, die zeigen, dass das AuScope VLBI-Netzwerk Ergebnisse mit einem vergleichbaren Genauigkeitslevel wie globale VLBI-Experimente (durchgeführt vom International VLBI Service for Geodesy and Astrometry – IVS) liefert.

**Schlüsselwörter:** VLBI, AuScope, Beobachtungsplanung

## 1. VLBI introduction

Very Long Baseline Interferometry (VLBI) is one of the oldest space geodetic techniques. It uses radio telescopes to observe extra galactic radio sources (quasars) on the edge of the observable universe, which are assumed to be point-like and with no detectable proper motion. VLBI measurements of the positions of these fixed sources is used to define and maintain an inertial coordinate system which is used for many other applications. Furthermore, since VLBI-telescopes are fixed to the Earth's surface and the observed sources are fixed in the sky, a transformation from the terrestrial to the celestial system has to be implemented. As a result, transformation angles, the so called Earth Orientation Parameters (EOP), have to be estimated as well. VLBI is the only space geodetic technique which is capable of determining all five EOP (two angles for polar motion, one Earth rotation angle and two angles for nutation) at once.

One product which can only be derived from VLBI is the International Celestial Reference Frame (ICRF), with the newest realisation being the ICRF-2 (Ma et al. 2009). Furthermore, VLBI provides a major contribution to the International Terrestrial Reference Frame (ITRF), with the current release being the ITRF2008 (Altamimi et al. 2011). It is particularly important for the scale of the reference system. For more details on VLBI, see Sovers et al. (1998) or Schuh and Böhm (2013).

## 2. AuScope Network

The AuScope VLBI array (Lovell et al, 2013) consists of three recently constructed (finished in 2010) 12-m telescopes, located in Hobart (Tasmania), Katherine (Northern Territory) and Yarragadee (Western Australia), see Figure 1, from here on referred to as Hobart12m, Kath12m and Yarra12m respectively. Other telescopes, such as the 15-m antenna at HartRAO (Hart15m), South Africa and the 12-m antenna in Warkworth (Wark12m), New Zealand, contribute to AUSTRAL sessions on a regular basis. The 26-m telescope in Hobart (Hobart26m) and the 26-m telescope at HartRAO (Hart26m) are utilised occasionally for special experiments.

The aims of the AuScope VLBI network are geodetic and astrometric. On one hand, the coordinate time series of telescopes should be precise and as long as possible which represents a geodetic goal. On the other hand, the number of observations of new and poorly observed sources in the Southern Hemisphere should be increased which resembles an astrometric goal. These aims are somewhat contradictory and require specific scheduling optimization. The geodetic sessions are split into normal geodetic sessions and special campaigns such as twin and continuous experiments. Twin sessions are used to study the implementation of twin telescopes (such as the co-located 12-m and 26-m telescopes) into the current VLBI framework. The term "twin telescopes", in the context of the VLBI2010 Global Observing System

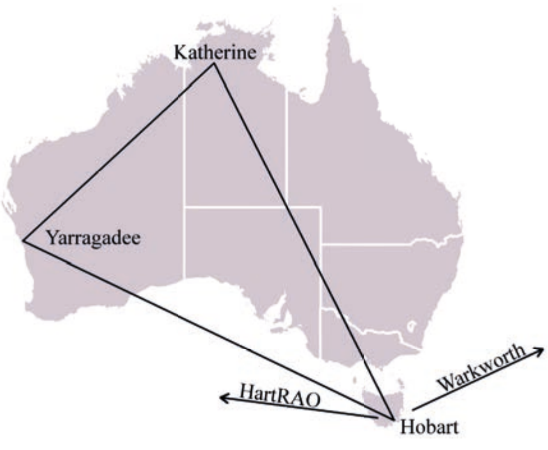



*Fig. 1: Map of AuScope VLBI stations*

(VGOS, Petrachenko et al. 2009), refers to two identical, fast slewing telescopes which is not the case presented here, where we have two completely different telescopes at the same site (usually named "sibling telescopes" in the literature). However, since we named these experiments twin sessions, it makes sense to maintain consistency and keep the term twin telescopes for two different antennas at the same site.

The purpose of the continuous sessions (15 consecutive days) is to practice and establish continuous operation and enable determination of geodetic parameters with the highest accuracy, much like the recent CONT14, IVS campaign which is a 15 day experiment that incorporates a global network of 17 stations. More information on the AuScope VLBI array can be found in Lovell et al. (2013).

## 3. Scheduling

Sessions with different aims need different scheduling strategies. In this section we will provide information on the scheduling strategies used for all previously mentioned session types.

All schedules are created in Vienna, Austria using the Vie_SCHED module (Sun et al. 2014) of the Vienna VLBI Software (VieVS, Böhm et al. 2012).

Catalogue files, including all the necessary station specific information, such as antenna hardware and observing sensitivity, are updated and maintained in Hobart which gives us the ability to apply changes fast and use up to date information to create the schedules.

### 3.1 Geodetic sessions

The aim of the geodetic sessions in general is to estimate precise station coordinates. To do so the largest error source, which is the troposphere, has to be eliminated in the best possible manner. The best way to estimate the wet part of the troposphere in a geodetic session, is to schedule as many observations as possible and to spread them evenly in different directions (elevations and azimuths). In this sense, the sky coverage for each station is maximized in the schedule. This approach is called a station-based scheduling strategy (Sun et al 2014). The same basic principle is also applied for the continuous sessions.

The following parameters are set for the creation of a station-based schedule:

- SNR (signal to noise ratio) targets of 15 and 20 in S- and X-band respectively

- Minimum Sun distance of 4°
- Strong sources (>0.5 Jy) from the Goddard Space Flight Center source catalogue are used
- Minimum scan length is set to be 20 s
- Maximum scan length is set to be 200 s
- The same source will not be observed twice in 30 min
- No constraints were set for slewing time

The continuous campaigns 15 consecutive VLBI sessions with identical network geometries. The aim is to estimate parameters with the highest possible accuracy (similar to a regular geodetic session). Shabala et al. (2015) pointed out that the biggest systematic source of error, which is not accounted for in VLBI, is the structure of sources. This implies that the observed radio sources are not necessarily all point-like and could have structure that varies in both space and time. To account for this systematic effect we create special schedules which we will refer to as "sidereal schedules" from here on. The basic idea is to keep the angle (azimuth and elevation) at which a source is observed from the telescopes the same for each day, resulting in a constant error due to source structure. This will not decrease the effect of source structure, but the systematics stay the same and thus better baseline length repeatability can be expected. In order to schedule a sidereal session the difference between a solar day and a sidereal day (as seen in Figure 2) has to be accounted for. At

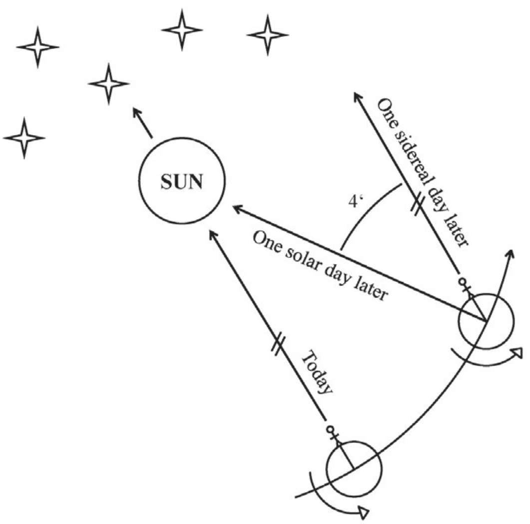



*Fig. 2: Sketch to illustrate the concept of a sidereal day, which is approximately 4 minutes shorter than a solar day*

a specific time on a sidereal day the geometry of the Earth w.r.t. the stars is always the same and therefore the angles between telescope and quasar are the same. A sidereal day is approximately four minutes shorter than a solar day.

### 3.2 Astrometric sessions

The aim of the AUSTRAL astrometric sessions is to generate observations of new or poorly observed sources. Historically there has always been fewer VLBI telescopes in the south, and therefore the observational history of the ICRF is highly imbalanced and southern sources are much less often observed and show higher positional uncertainties than northern ones (Ma et al. 2009). For the scheduling of the AUSTRALs, we use a special source list with new and poorly observed southern sources which is provided through private communication with O. Titov. It is updated on a regular basis and flux densities (the nominal strength of a source) are amended if necessary. The strategy for scheduling these experiments is slightly different from the one used for geodetic sessions. For astrometric sessions the scheduling is optimised to cover the entire celestial sky while for geodetic sessions the individual sky coverage at each station is considered. With this approach we can generate observations of as many sources as possible and still have an acceptable sky coverage at each station. This approach is called a source-based scheduling strategy.

Following parameters are set for the creation of the schedule (not listed parameters are the same as in the geodetic schedule):

- A special source list is maintained
- The maximum scan length is set to be 500 s

### 3.3 Special experiments

Sessions which use a combination of smaller (Hobart12m and Hart15m) and larger (Hobart26m and Hart26m) telescopes at the same site are called twin experiments. The aim of these sessions is to investigate the managing of twin telescopes in the scheduling, observation, correlation and analysis procedures. Combining different telescopes such as these (in terms of sensitivity and slew speed) in a single schedule is a complex task and is not yet included in the scheduling software packages by default.

In a first experiment two different schedules, one with the 12-m and 15-m telescopes and one with the 26-m telescopes were drafted and combined afterwards. The fact that no connecting observations between the two sub-networks were scheduled caused trouble in the analysis chain and led to a subsequent separation of the original schedule into two sessions. This, however, will be corrected in the future.

Another twin experiment, which was conducted recently, included the Hobart26m telescope in a normal geodetic AuScope session. The aim was to schedule as many observations as possible with the Hobart12m – Hobart26m baseline and then test analysis implementations, such as combined troposphere and clock parameters.

In recent times (19.10.2014 and 09.01.2015) two experiments were performed with the aim of testing relativity. To do so observations in a short interval (3 minutes) of a quasar which came close to the Sun were included in the schedule. The sources 1334-127 and 1908-201 were used in the first and second session respectively. Only strong sources (>1 Jy) were used for these sessions.

### 3.4 Comparison of schedules

In Figure 3 the sky plots (for Hobart12m) of an astrometric (AUST72) and a geodetic session (AUST66) are compared. Both sessions use the same network which consists of the Hobart12m, Kath12m, Wark12m and Yarra12m telescopes. One can see that an astrometric session generates far fewer observations than a geodetic session (15 versus 75 sources in this case). This is due to the smaller source list and weaker sources (that require longer integration times) used in the astrometric mode. The source list for the astrometric session includes only sources with negative declination, which can be seen in the sky plot. The optimisation criteria for geodetic sessions is the individual sky coverage at each station which results in many observations at different elevations and azimuths, the distribution can be seen in the sky plot.

No constraints on slew time are set in the astrometric and geodetic schedules. This is justified by the fact that only fast antennas are observing in the network. Since weaker sources are used in an astrometric schedule the observing time is longer, and therefore less time is spent on slewing (e.g. 70 % of the total time is spent on observing and 7 % on slewing for the AUST72 session). In the geodetic mode only strong sources are utilised. Therefore, less time is spent on observing sources and more on slewing between observations (e.g. 49 % of the total time is spent on observing and 24 % on slewing for the AUST66 session).

The scheduling performed in Vienna is subject to steady improvement. In Figure 4 we show the total number of scans (black), the scans per hour (red) and the scan lengths (blue) for the observed AUSTRAL sessions. Astrometry sessions are marked in green. It is noted that the data

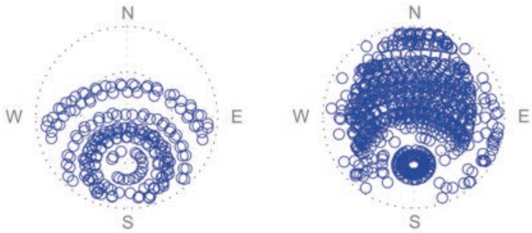



*Fig. 3:* *Sky plot for the Hobart12m station, for the astrometric session, AUST72 (on the left) and the geodetic session, AUST66 (on the right)*

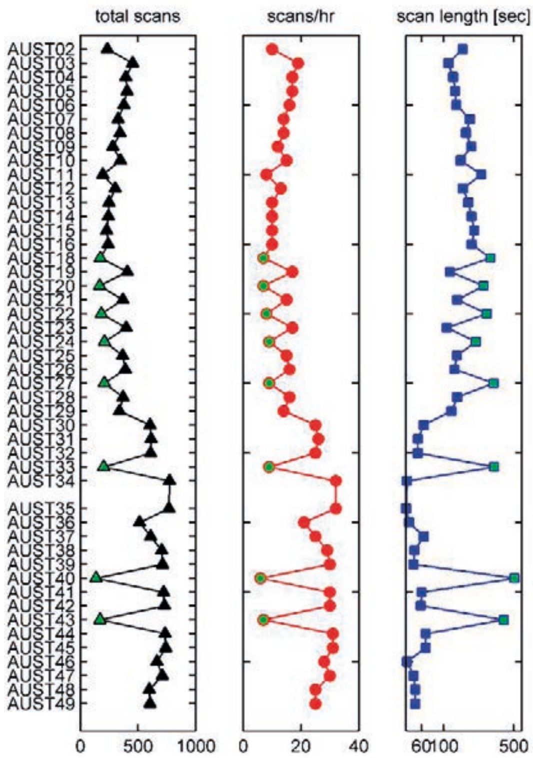



*Fig. 4:* *Statistics of AuScope VLBI sessions. The plot on the left depicts the total number of scans per session. In the middle plot the average scans per hour per session are illustrated. On the right side the average scan length per session can be seen. Astrometric sessions are marked in green.*

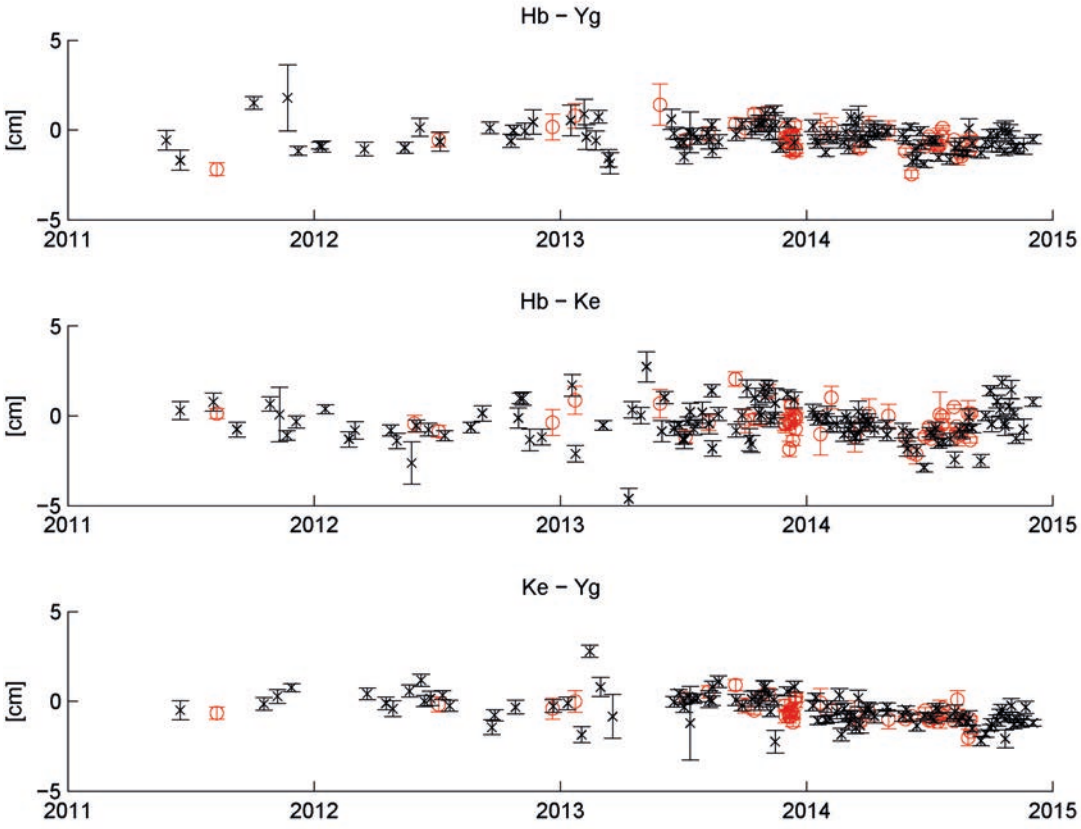



*Fig. 5: Estimates and formal errors of AuScope baselines, from IVS-R1 and IVS-R4 sessions (in black), and from AuScope sessions (in red)*

are from actual observed and correlated scans, which can differ from the original schedules due to bad observations or failures. The gradual improvement of scan length and scans per hour is clearly visible. This is due to the continuous enhancements of scheduling strategies and fine tuning of parameters as well as the improvement of data acquisition at the stations.

## 4. Results

In this section we will provide some results from the AUSTRAL sessions. Figure 5 depicts the baseline estimates and formal errors between the three AuScope VLBI telescopes. The results are from standard global IVS-R1 and IVS-R4 sessions where the AuScope VLBI network participated and from the AUSTRAL sessions (in red). We find good agreement between the estimates and formal errors from the AUSTRAL sessions and from the IVS sessions. Some systematic effects are still present in some baselines. The reason for this has not yet been identified and is subject to further research.

Table 1 lists the weighted root mean square error (wrmse) of the previously mentioned baselines calculated once from the IVS-R1/R4 sessions and once from the AuScope sessions. Overall the wrmse of baselines estimated with the AuScope sessions is better.

Figure 6 illustrates the distribution of source observations in the IVS-R1/R4 and AuScope VLBI sessions. One can see that the AuScope VLBI

| | Ke-Yg | Hb-Ke | Hb-Yg |
|---|---|---|---|
| IVS-R1/R4 | 6,2 | 10,1 | 6,5 |
| AuScope | 4,6 | 7,3 | 6,9 |

*Tab. 1: Weighted root mean square error of Australian baselines for R1/R4 and AuScope sessions in mm*

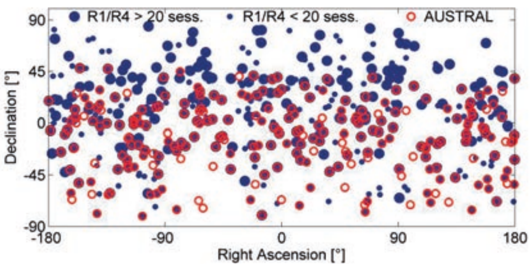



*Fig. 6: The sky distribution of sources observed in IVS-R1/R4 and AuScope VLBI sessions. The size of the markers refers to the number of sessions this source was observed in.*

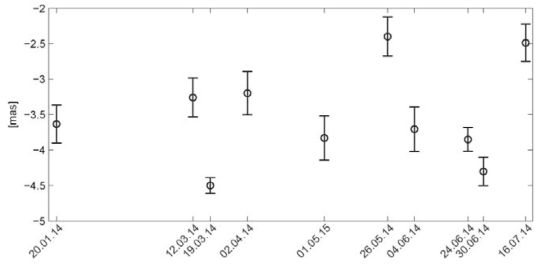



*Fig. 7: Time series of the declination of the source 0758-737 estimated from AuScope VLBI sessions in 2014. This source has never been observed in S/X-band before and might complement future realizations of the ICRF.*

network mainly observes sources in the Southern Hemisphere whereas the IVS-R1/R4 sessions by comparison observe primarily sources north of the Equator.

The astrometric sessions, observed with AuScope, are primarily dedicated to finding new suitable sources for the ICRF and generating observations to poorly observed sources. Overall, we found eleven (three were previously only observed in single X-band; five are non-defining and three are VCS sources, in both cases with a small number of observations) suitable sources for the ICRF, more details can be found in Plank et al. (2015). Faint sources, such as 0758-737 (the flux density was found to be 0.11 Jy in X-band and 0.21 Jy in S-Band) were observed, but many observations were lost due to the small dish size of the antennas. However, sources, such as 1842-289, with flux densities of 0.35 Jy in X-Band and 0.24 Jy in S-Band have a higher success rate. Therefore, a reasonable limit for flux densities is somewhere between 0.2 and 0.3 Jy for the current astrometric settings.

Besides using the AUSTRAL astrometric sessions to increase the number of observations of poorly observed sources in the south, we also search for new sources potentially suitable for future realizations of the ICRF. In Figure 7 the time series of the declination of the source 0758-737, a source that has never been observed at S- and X-band before, is shown. The right ascension experiences no significant offset and is therefore not illustrated. Estimates from this source (up to –4 mas) reveal an offset with respect to the a-priori coordinate, which was taken from previous single frequency X-band observations. On one hand, this could suggest that the data obtained from dual frequency, S- and X-band, observations are more accurate than data from single frequency X-band observations only. On the other hand, it could be an indicator that the center of emission is frequency dependent. However, recent observations with the New Technology Telescope (NTT, ESO) in Chile revealed that the radio source 0758-737 is well aligned with a foreground star (less than 2”, O. Titov, private communication). Therefore, the data could also suggest that the offset is due to a constant light deflection effect.

## 5. Conclusion

The AuScope VLBI network takes part in different (geodetic, astrometric and special) AUSTRAL experiments with contrasting goals. Distinct scheduling strategies have to be applied to accomplish the desired results. A close cooperation between scheduler, observer and correlator is maintained which facilitates the adaption and enhancement of the scheduling strategy to meet the desired goals.

The results from the geodetic VLBI experiments suggest that the regional AUSTRAL sessions deliver reasonable results which are comparable with estimations from global IVS-R1 and IVS-R4 sessions. However, some baselines experience a systematic movement which can be seen in both the IVS and the AuScope sessions. The reason for this movement is not yet clear and is subject to further research.

The astrometric sessions provide observations of new and poorly observed sources in the south, that can be used to expand catalogues of reference sources in the south and to improve source positions.

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**Contacts**

**Univ.Ass. Dipl.-Ing. David Mayer**, Technische Universität Wien, Department für Geodäsie und Geoinformation E120.4, Gußhausstraße 27-29, 1040 Wien, Austria.
E-Mail: david.mayer@geo.tuwien.ac.at

**Univ.-Prof. Dr. Johannes Böhm**, Technische Universität Wien, Department für Geodäsie und Geoinformation E120.4, Gußhausstraße 27-29, 1040 Wien, Austria.
E-Mail: Johannes.Boehm@geo.tuwien.ac.at

**Dr. James Lovell**, University of Tasmania, School of Physical Sciences, Private Bag 37, Hobart, Tas 7001, Australia.
E-Mail: jim.lovell@utas.edu.au

**Dr. Lucia Plank**, University of Tasmania, School of Physical Sciences Private Bag 37, Hobart, Tas 7001 Australia.
E-Mail: lucia.plank@utas.edu.au

**Dr. Jing Sun**, National Key Laboratory of Science and Technology on Aerospace Flight Dynamics, Beijing Aerospace Control Center, Beijing, China.
E-Mail: sunjing@shao.ac.cn

**Oleg Titov, Ph.D.**, PO Box 378, Canberra ACT 2601, Australia.
E-Mail: oleg.titov@ga.gov.au

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