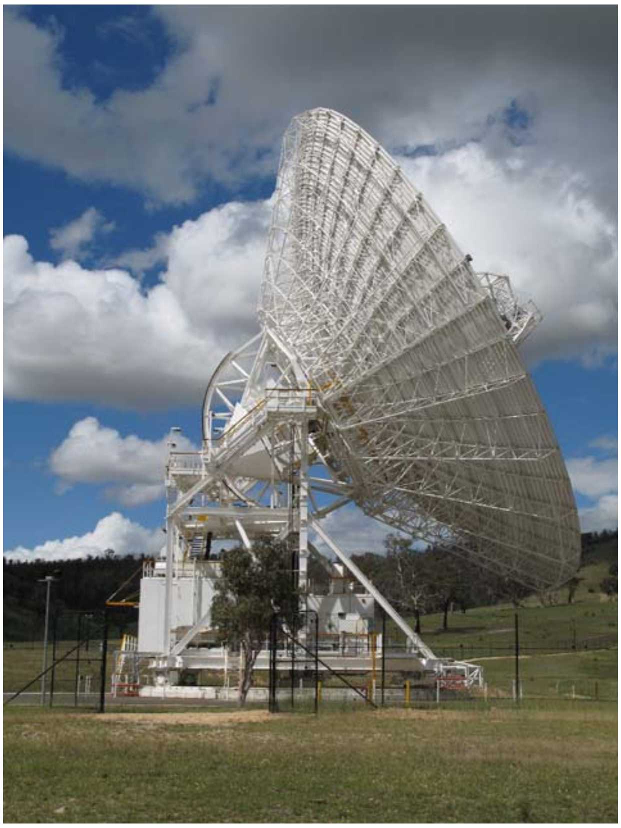
The 2007 Tidbinbilla Local Tie Survey

GEOSCIENCE AUSTRALIA
RECORD 2007/XX

by

A. Woods[1]



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Executive Summary

The integrity and strengths of multi-technique terrestrial reference frames such as ITRF2005 depend on the precisely measured and expressed local tie connections between space geodetic observing systems at co-located observatories. A local tie survey was conducted at the Tidbinbilla Deep Space Communications Complex, in the Australian Capital Territory, in October and November of 2007. The aim of the survey was to precisely measure the local terrestrial connection between the space-based geodetic observing systems co-located at the observatory, which include a GPS antenna and the DSS-45 radio telescope, used for very long baseline interferometry (VLBI). In particular, this report documents the indirect determination of the radio telescope invariant reference point (IVP). Attention is also paid to the indirect observation of the GPS antenna monument, which was not disturbed in the survey and observed from three newly established reference marks.

The last local tie survey conducted at Tidbinbilla was in 1995 by AUSLIG surveyors. This survey data was not processed until 2000. The 2007 local tie survey was well overdue and coincided with the completion of maintenance to the DSS-45 antenna. Precise levelling and traverse measurements were made between the permanent survey monuments surrounding the DSS-45 antenna and survey marks installed around the GPS antenna monument. Survey marks were monitored to ensure their stability as part of a consistent, stable terrestrial network from which local tie connections were made to the VLBI IVP and GPS antenna monument. The relationship between points of interest included the millimetre level accurate connections and their associated variance covariance matrix.

In this report, observational and analysis techniques are reviewed and results are given. In particular, the 2007 survey results are compared with those obtained at Tidbinbilla in 1995.

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Dawson, J., Sarti, P., Johnston, G. and Vittuari, L., 2007. Indirect Approach to Invariant Point Determination for SLR and VLBI Systems: An Assessment, J*ournal of Geodesy, Special Issue VLBI,* June 2007, Vol 81, No. 6-8.

Johnston, G., Dawson, J. and Naebkhil, S., 2004. The 2003 Mount Stromlo Local Tie Survey. *Geoscience Australia Record,* 2004/20, 25pp. *Available online:* <*http://www.ga.gov.au/image_cache/GA5653.pdf*>

Johnston G., and Digney P., 2002. Mt Stromlo Satellite Laser Ranging Observatory Local Tie Survey, Technical Report 9, *Australian Surveying and Land Information Group (AUSLIG) Geodesy Technical Report 9. Available online:* <*http://www.ga.gov.au/image_cache/GA5026.pdf*>

Johnston G., Dawson J., Twilley B. and Digney P., 2000. Accurate Survey Connections between Co-located Space Geodesy Techniques at Australian Fundamental Geodetic Observatories, *Australian Surveying and Land Information Group (AUSLIG) Geodesy Technical Report 3, available online: http://www.ga.gov.au/image_cache/GA5035.pdf*

Introduction

This report is not meant to serve as a manual for precision geodetic local tie surveys and it largely assumes that the reader has an understanding of the basic concepts of geodetic surveying. Furthermore, this report does not detail or justify the approach taken, but merely reports the results of each major computation step. However, for completeness, the steps in the approach used to observe and derive the local tie connection are as follows:

- *The calibration of all geodetic instrumentation including: total station instruments, levelling staffs, fixed height mounts, and reflectors (targets);*
- *High precision geodetic levelling (EDM-Height traversing) between survey marks surrounding the observatory;*
- *Observation of a horizontal geodetic network by application of terrestrial geodetic observations, including distances and directions to survey marks in the vicinity of the observatory;*
- *Observations to a number of targets positioned on the radio telescope during rotational motion about each of the systems' independent axes (azimuth and elevation). This included zenith angle observations to a staff on a levelled survey mark in the vicinity for precise height of instrument determination;*
- *Reduction of terrestrial geodetic observations, including corrections to observations for instrument and target bias, set reduction and atmospheric effects;*
- *Classical geodetic least squares (minimum constraint) adjustment of all terrestrial geodetic observations, resulting in terrestrial only coordinate estimates and their associated variance-covariance matrix (in the local system) of the geodetic network marks and targets positioned on the VLBI;*
- *Invariant reference point (IVP) modelling and estimation as well as estimation of the axes of rotation and associated system parameters such as axis orthogonality and the offset of the axes. This includes readjustment of the terrestrial only network;*
- *Transformation (translation and rotation only) of the readjusted terrestrial network and computed IVP coordinate variance-covariance matrix into a global reference frame including a geocentric variance-covariance matrix (estimated and a priori);*
- *Reduction of the complete solution to stations of primary interest and output of a SINEX format solution file.*

1. Site Description

The Tidbinbilla Deep Space Communications Complex is located approximately 20km South West of Canberra in the Australian Capital Territory. The DSS-45 antenna used for VLBI observations is co-located with a permanent GPS observing system (TIDB), which is part of the Australian Regional GPS Network (ARGN) and International GNSS Service (IGS) tracking network. Three survey monuments were established surrounding the GPS antenna monument, prior to undertaking the survey. It is from these survey marks and a network of survey marks surrounding the DSS-45 antenna that terrestrial connections were made to the space based observing systems, in particular the VLBI.

Table 1: List of globally important survey marks at the Tidbinbilla observatory.

Local Designation	Global/IERS Designation
AU017	TIDB 50103M108 TIDBINBILLA IGS GPS GM
TIDBINBILLA IVP	TIVP 50103S010 TIDBINBILLA DSS-45 VLBI IVP

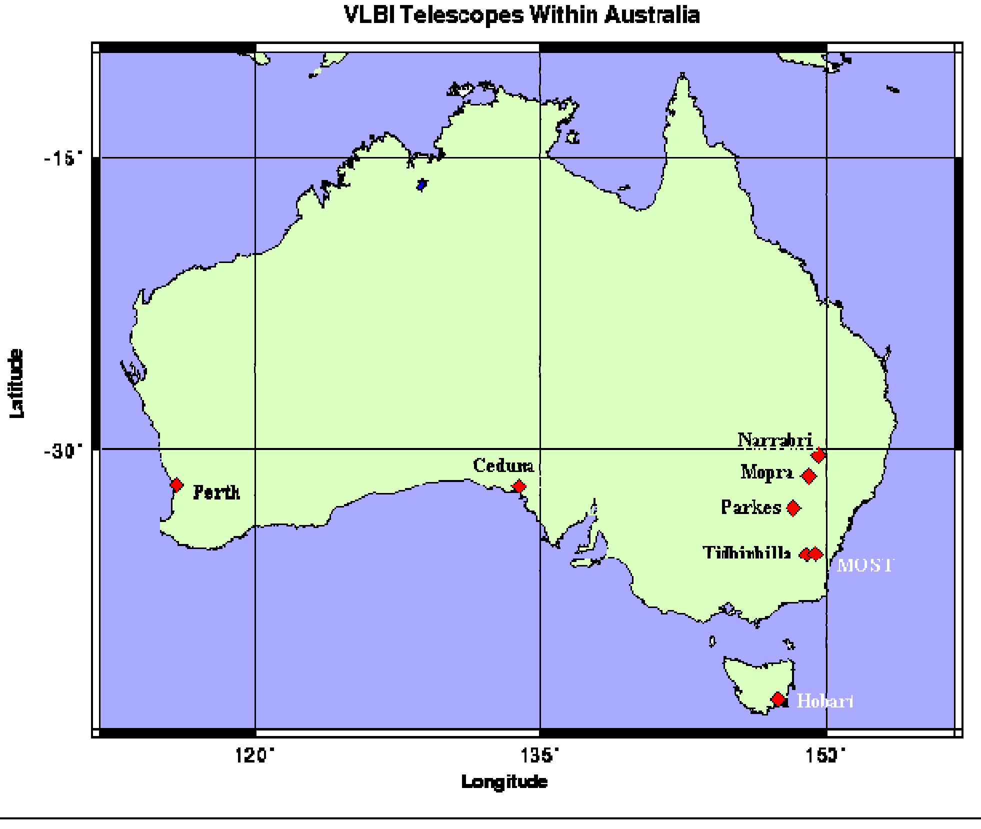


Figure 1*: Tidbinbilla Deep Space Communications Complexy. The co-located observatory includes VLBI and GPS systems. Image from CSIRO < http://www.atnf.csiro.au/vlbi/documentation/map.html>*

2. Instrumentation

2.1 Tacheometers, EDM, Theodolites

2.1.1 Description

Leica TCA2003 Total Station, SN 439124.

Specification:

- EDM (infrared) distance standard deviation of a single measurement (DIN 18723, part 6): 1mm + 1ppm;
- Angular standard deviation of a mean direction measured in both faces (DIN 18723, part 3): 0.15mgon (0.49”).

2.1.2 Calibration results

Calibration results presented here refer to 2007 survey equipment. For previous survey calibration results refer to Johnston *et al*. (2000) and Johnston and Digney (2002). The Leica TCA2003 Total Station was serviced by C. R. Kennedy (Sydney, Australia) in April 2007. The total station calibration was performed by Leica Geosystems AG Heerbrugg, Switzerland. Inspection date: 10th December 2001:

- EDM (Infrared) distance standard deviation: m_0 = 0.2mm (Distances from 19.5m to 501.5m). Distance linearity: ±0.3mm (Distances from 2.25m to 120m);

- Angular standard deviation horizontal: 0.09 mgon (0.29”) and vertical: 0.09 mgon (0.29”).

Reflector calibration:

- Additive constant for Leica GPH1P precision prism is -34.4mm which is applied directly in the total station. All prisms calibrated on a tripod baseline at Geoscience Australia, Symonston in May 2007. Approximate prism corrections of 0.0mm applied to observations in data processing.

- Leica Precision Micro-Prisms were calibrated at Geoscience Australia in May 2007. Approximate prism corrections of +17.8mm applied to observations in data processing.

Staff calibration:

- The level staff used for instrument heighting (refer section 4.1) was compared against a calibrated invar staff by Geoscience Australia.

2.1.3 Auxiliary equipment

Meteorological observations of temperature, pressure and humidity were recorded using a 4000 Pocket Weather Tracker (SN: 538391).

2.2 GPS Units

GPS observations were made at three monuments in the terrestrial network, namely AU017 (TIDB - permanent IGS station), AU031 and AU032 (observation pillars for DSS-45). The GPS analysis was undertaken within the International Terrestrial Reference Frame 2005 (ITRF2005) and was used to align the local terrestrial network to ITRF2005 at the epoch of survey in 2007.

***Figure 2**: Tidbinbilla permanent IGS GPS station*

2.3 Levelling

2.3.1 Levelling instruments

Leica TCA2003 Total Station, SN 439124.

Specification:

- EDM (infrared) distance standard deviation of a single measurement (DIN 18723, part 6): 1mm + 1ppm;
- Angular standard deviation of a mean direction measured in both faces (DIN 18723, part 3): 0.15mgon (0.49”).

2.3.2 Levelling Rods

Fixed height stainless steel rod (approximately 1.5m in height), fixed height stainless steel half rod (approximately 0.5m in height) and fixed height stainless steel stub (approximately 0.2m in height) with Leica bayonet mount for mounting precision prism (refer to section 4.2 for technique details).

2.3.3 Checks carried out before measurement

Multi-set (repetition), dual face observations were taken to each target eliminating collimation effects. No other pole calibration was required.

2.4 Tripods

Leica GST20/9 heavy duty fixed timber tripods were used for the survey.

2.5 Forced Centering Devices

The Wild ZNL optical plummet and Leica GXR3 prism carriers with optical plummet.

2.6 Targets, Reflectors

Total station target kits included:

- Leica GDF21 Tribrach;
- Leica GZR3 prism carrier with optical plummet;
- Leica GPH1P precision prism.

3. Measurement Setup

3.1 Ground Network

3.1.1 Listing

The following sites were included in the ground network:

Tidbinbilla IVP (TIVP): Domes 50103S010. The intersection of the azimuth axis with the common perpendicular of the azimuth and elevation axis of the Tidbinbilla, 34m azimuth-elevation, DSS-45 radio telescope.

AU017 (TIDB): Domes 50103M108. Mark refers to the centre of a small drill hole in the centre of a stainless steel plate set in the top of a 0.6m diameter reinforced concrete pillar protruding 0.5m above ground level (2.5m below ground) with a stainless steel plate set in the top. The pillar plate bears the inscription “TIDBINBILLA SPC-40 GPS STATION MARK JPL 4002-2 1992”. The pillar is in the centre of a 6m square post and rail fence enclosure. The fence does not obstruct the visibility horizon above 10 degrees elevation. The permanent IGS GPS antenna currently occupies this monument.

AU017 RM1: Punch mark in a stainless steel deep driven rod, 0.030m in diameter, set in concrete. Stainless steel rod, consisting of 0.5m and 1m lengths, thread and lock tight connected, driven to refusal at 3m. The mark is buried, protected by PVC pipe and a sprinkler valve box cover which are set in concrete. The survey mark was installed in 2007 and will serve as an observation station to the GPS monument and as a reference mark for the GPS monument.

AU017 RM2: Punch mark in a stainless steel deep driven rod, 0.030m in diameter, set in concrete. Stainless steel rod, consisting of 0.5m and 1m lengths, thread and lock tight connected, driven to refusal at 5m. The mark is buried, protected by PVC pipe and a sprinkler valve box cover which are set in concrete. The survey mark was installed in 2007 and will serve as an observation station to the GPS monument and as a reference mark for the GPS monument.

AU017 RM2: Punch mark in a stainless steel deep driven rod, 0.030m in diameter, set in concrete. Stainless steel rod, consisting of 0.5m and 1m lengths, thread and lock tight connected, driven to refusal at 3m. The mark is buried, protected by PVC pipe and a sprinkler valve box cover which are set in concrete. The survey mark was installed in 2007 and will serve as an observation station to the GPS monument and as a reference mark for the GPS monument.

NM C 194: Domes 50103M109. Centre-punched, star iron picket, driven to refusal and set in concrete. A small rock cairn covers the mark.

AU031, North Pillar: Concrete pillar approximately 0.3m diameter. The mark refers to the intersection of the top of the brass pillar plate with the vertical axis of a 5/8" ϕ Whitworth threaded brass spigot. Survey pillar is approximately 65m North of the DSS-45 antenna and serves as an observation point to measure targets on the radio telescope.

AU032, South Pillar: Concrete pillar approximately 0.3m diameter. The mark refers to the intersection of the top of the brass pillar plate with the vertical axis of a 5/8" ϕ Whitworth threaded brass spigot. Survey pillar is approximately 75m South of the DSS-45 antenna and serves as an observation point to measure targets on the radio telescope.

3.1.2 Map of Network

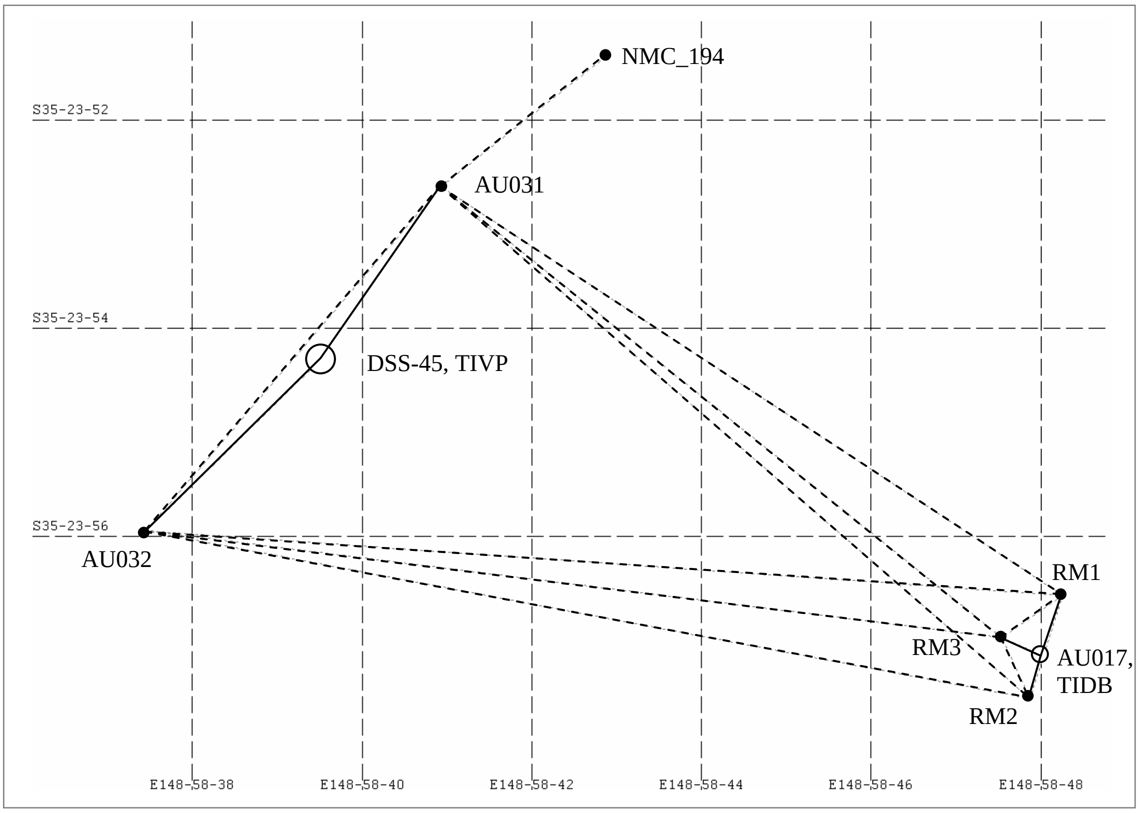


Figure 3: *Tidbinbilla 2007 terrestrial geodetic network. Terrestrial observations between stations are shown as inter-connecting lines.*

3.2 Representation of Reference Points

3.2.1 VLBI

The Tidbinbilla DSS-45 radio telescope very long baseline interferometry (VLBI) invariant reference point (IVP) is defined as the intersection of the azimuth axis with the common perpendicular of the azimuth and elevation axes (Johnston et al, 2004). In this survey, an indirect approach to invariant point, or system reference point, positioning was used to measure and thus derive the VLBI IVP. This involved the derivation of the independent axes of rotation of the radio telescope through a process of three-dimensional circle fitting to the three dimensional coordinates of targets observed on the telescope during rotational sequences. In the adjustment process, geometrical models describing target motion during rotational sequences were applied. The geometric models included inter-axis, inter-circle and inter-target conditions. These conditions are critical to the computation of unbiased IVP coordinates at the millimetre level for a radio telescope with rotational limits in elevation (Dawson et al, 2007).

Targets on the structure were observed as it was rotated about one axis while the telescope was held fixed in the other axis. This follows that a target located on a rigid body, rotating about one independent axis can be used to express a circle in 3D space. A 3D circle can be described by seven parameters, namely:

Circle centre (3 parameters)
Unit normal vector (3 parameters) perpendicular to the circle plane
Circle radius (1 parameter)

The method of IVP determination applied assumes that, during rotational sequences, targets follow a perfect circular arc in 3D space; that there is no deformation of the targeted structure during rotational sequences, and that the axis of interest can be rotated independently of the other axis. There are no assumptions of axis orthogonality, verticality, horizontality or the precise intersection of axes made using this IVP estimation technique.

The indirect geometrical models describing target motion during rotational sequences include several conditions:

- target paths scribe a perfect circle in 3D space during rotation about an independent axis;
- circle centres derived from targets rotated about the same axis are forced to lie along the same line in space;
- normal vectors to each circle plane derived from targets rotated about the same axis are forced to be parallel;
- orthogonality (or non-orthogonality) of the elevation axis to azimuth axis remains constant over all realisations of the elevation axis;
- identical targets rotated about a specific realisation of an axis will scribe 3D circles of equal radius;
- offset distance between the elevation axis and azimuth axis remains constant over all realisations of the elevation axis;
- distance between 3D circle centres for all realisations of the elevation axis are constant over all realisations of the elevation axis; and
- IVP coordinate estimates remain constant over all realisations (combinations) of the azimuth/elevation axis.

In addition, a constraint that the unit normal vector perpendicular to the plane of the circle must have magnitude one was required, as was a minimum of three rotational sequences to enable the solution of the equation of a circle. Multiple realizations of the elevation axis (i.e. orientated at multiple azimuths) were observed and computed. A least squares method was used for the computation of the axes of rotation and the IVP

The linearized equations take the form of two sets of equations, namely conditions and constraints with added parameters

$$Av + B\Delta = f$$
$$D_1\Delta + D_2\Delta' = h$$

where v is the parameter vector of residuals of the input classical adjustment results, Δ is the parameter vector of the circle parameters, Δ' is the parameter vector of the parameters associated with the IVP estimates, f and h are the constant vectors associated with the evaluation of the conditions and constraints respectively and A, B, D_1 and D_2 are matrixes of coefficients. The least squares solution is obtained from the following system of normal equations

$$\begin{bmatrix} -W & A^t & 0 & 0 & 0 \\ A & 0 & B & 0 & 0 \\ 0 & B^t & 0 & D_1^t & 0 \\ 0 & 0 & D_1 & 0 & D_2 \\ 0 & 0 & 0 & D_2^t & 0 \end{bmatrix} \begin{bmatrix} v \\ k \\ \Delta \\ k_c \\ \Delta' \end{bmatrix} = \begin{bmatrix} 0 \\ f \\ 0 \\ h \\ 0 \end{bmatrix}$$

where W is the weight matrix of the input coordinates derived from the classical adjustment and k and k_c are vectors of Lagrange multipliers required to satisfy the least squares criteria.

The solution to the normal equation system is iterated as required for the non-linear condition and constraint equations. An updated estimate of the input coordinates and their variance-covariance matrix is obtained together with an estimate of the IVP coordinate, their variance-covariance matrix and the inter-relating covariance matrix.

In order to generate the circles required for IVP determination, measurements were made to a number of targets placed on the radio telescope as it was rotated through several orientations. In particular, the targets on the structure were observed from two stand points as the radio telescope was rotated in azimuth (with the elevation set at approximately 89.5 degrees, vertical). Targets on the structure were observed from the same two stand points as the telescope was rotated in elevation (with the azimuth set orthogonal to the line of sight of the total station for each set of observation sessions).

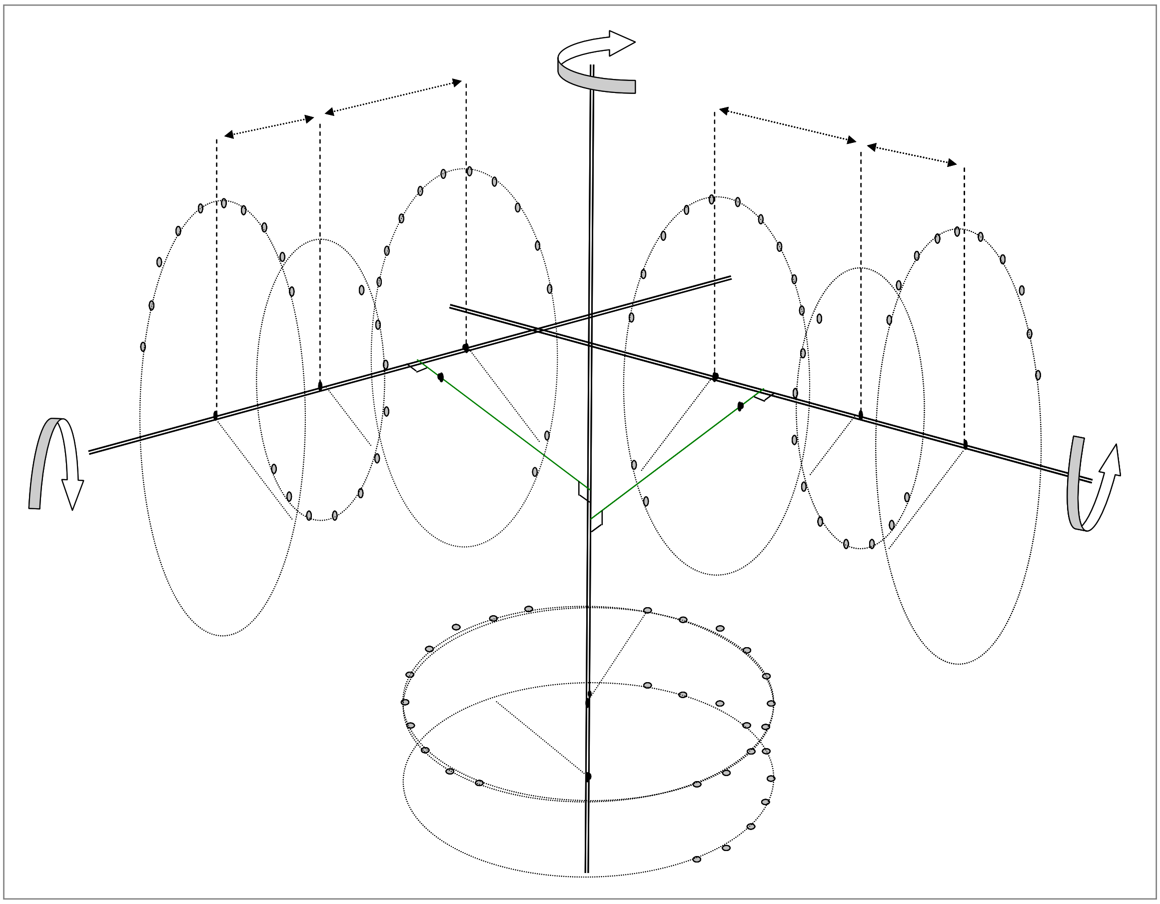


Figure 4: IVP model. Circle centres derived from targets observed while being rotated about the same axis are forced to lie along the same line in space. Normal vectors to the circle plane derived from targets observed while being rotated about the same axis are forced to be parallel. Note that to simplify the diagram only two targets are shown on the azimuth axis and three targets are shown on the elevation axis. The two realisations of the elevation axis allow for the constraint of the circle radius parameters, as can the inter-circle centre distances. The angle between the elevation and azimuth axis (i.e. axis orthogonality) should be constant over all realisations of the elevation axis. The IVP estimate should be constant over all realisations of elevation/azimuth axis combinations.

Table 2: 2007 Tidbinbilla radio telescope local tie survey IVP determination observations

Axis	Number of targets	Description / Comment
Azimuth	4	Elevation axis fixed at 89.5°, vertical Azimuth axis rotated in 20° increments through the full 360° Telescope observed from two standpoints: AU031, AU032 4 × Leica Precision Mini Prisms
Elevation	6	Azimuth axis set orthogonal to line of sight (140° and 320°, and 120° and 300°) Elevation axis rotated in ~10° increments through 90° Telescope observed from two standpoint: AU031, AU032 6 × Leica Precision Mini Prisms

3.2.2 SLR

There are no SLR facilities at the Tidbinbilla Deep Space Communications Complex.

3.2.3 GPS

In the case of Tidbinbilla, the GPS antenna monument pillar AU017 (TIDB) was observed indirectly from the three surrounding reference marks. The GPS antenna was not disturbed during the survey. Rather, observations were taken to the antenna from three reference marks (stainless steel deep driven rods), which were installed around the GPS antenna, approximately 20m set back. These will serve as permanent reference marks for the GPS antenna. At each reference mark, horizontal and zenith angle observations were taken to the base of the centring stub attached to the GPS antenna. This stub forms into a point directly over the AU017 pillar plate centre punch. Therefore, triangulation of angular observations was used in the adjustment to determine the horizontal position of the GPS antenna. To support visibility under the GPS antenna, the protective dome was removed.

To determine the change in height between the GPS antenna and the surrounding survey marks, total station levelling observations were taken to the top of the antenna choke ring. Level observations were taken at three points around the choke ring to verify level. An antenna offset of 0.102m (top of choke ring to antenna reference point) and centring stub offset of 0.0614m were subtracted to get the level of the antenna monument (refer to TIDB IGS site log).

GPS observations (seven full days) were collected over AU031 and AU032, as well as the permanent GPS station AU017 (TIDB). This GPS data was used to derive the baselines between the survey pillars and thus orientate the network.

3.2.4 DORIS

There are no DORIS facilities at the Tidbinbilla Deep Space Communications Complex.

3.2.5 GLONASS

GLONASS is not observed at the Tidbinbilla Deep Space Communications Complex.

4. Observations

4.1 Conventional Survey

4.1.1 Network Survey

A terrestrial network survey was conducted between the permanent survey monuments within the Tidbinbilla Deep Space Communications Complex. Leica Precision-Prisms were measured using the Leica TCA2003 total station, which recorded horizontal and vertical directions as well as slope distances. Five rounds of face left, face right observations were taken from each standpoint to the surrounding, visible survey marks. Approximate target heights and instrument heights were measured with a measuring tape for each set of observations. For each instrument setup, meteorological information (temperature, pressure, humidity) was recorded and applied, as well as prism offset corrections, to observations as part of data pre-processing. The survey marks included in the survey are listed in Table 3.

Table 3: Survey marks included in the 2007 Ceduna local tie survey

Established survey marks	Newly established survey reference marks for GPS
AU017 (TIDB)	RM1
AU031	RM2
AU032	RM3
NMC_194	

Survey marks, RM1 RM2 and RM3, were established prior to commencing the survey. These survey marks were installed to serve as reference marks for the GPS antenna monument. They were positioned to ensure visibility to the base of the GPS antenna while also connecting into the existing control marks efficiently.

4.2 Levelling

High precision levelling was conducted between the survey pillars and temporary Reuger heighting pins, using the EDM-height traversing technique (Johnston et al, 2002). Height difference observations were made using a Leica TCA2003 Total Station sighting to a Leica precision prism mounted on a fixed height prism pole (approximately 1.5m in length), fixed height stainless steel half rod (approximately 0.5m in height) and fixed height stainless steel stub (approximately 0.2m in height).

Levelling loops covering all monuments in the survey network were completed in both directions. Each instrument setup involved recording five rounds of face left, face right observations, to the prism set up over two survey marks. A 50m tape was used to measure between the survey marks so that the total station could be set up approximately half way between points. Temperature, pressure and humidity readings were entered into the total station prior to observing so that the instrument derived parts per million (ppm) values could be applied to measurements. Levelling data sets were processed through least squares adjustment software, prepared by Geoscience Australia, to derive adjusted height differences between all survey marks.

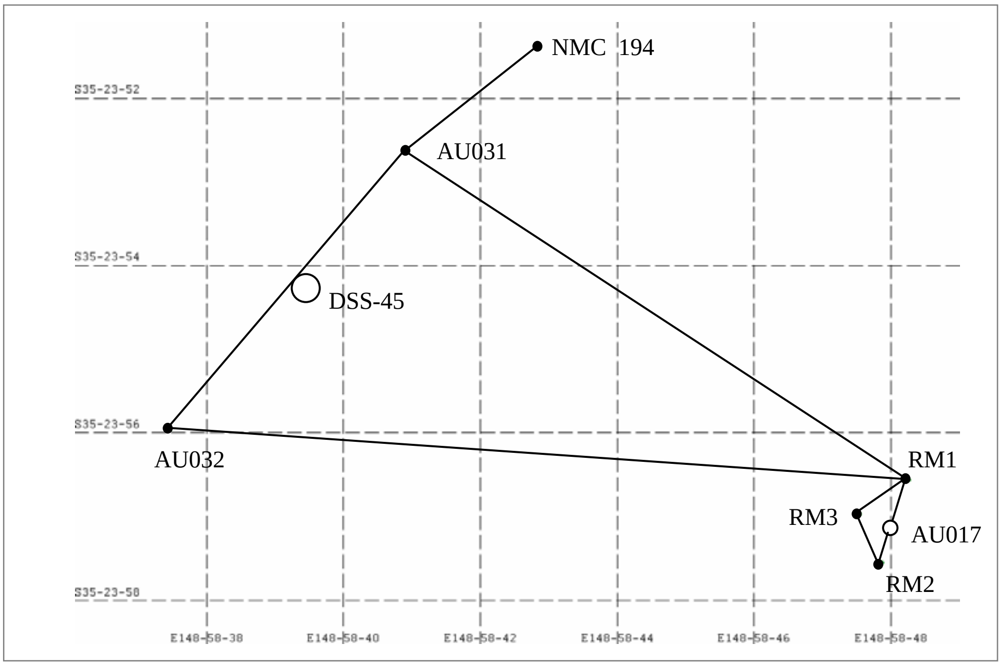


***Figure 5**: Tidbinbilla survey levelling observations.*

4.3 VLBI

4.3.1 Azimuth Observations

Observations were taken from two separate instrument stations (AU031, AU032) to four Leica precision micro-prisms, attached to the radio telescope structure using special magnetic mounts, as the telescope was rotated in azimuth (with the telescope elevation locked at 89.5°, vertical). Figure 6 shows the positioning of targets on the telescope structure. Targets were placed on structural components of the radio telescope, predominantly on the trunnion supports. The telescope was rotated through the full 360 degrees at 20 degree increments. All visible targets were measured with each orientation. Two targets were observed through approximately 200° to 240° of arc, while the other two were only observed through 120° to 140° of arc. It was not possible to measure all targets at each orientation as targets were often obstructed by the telescope structure.

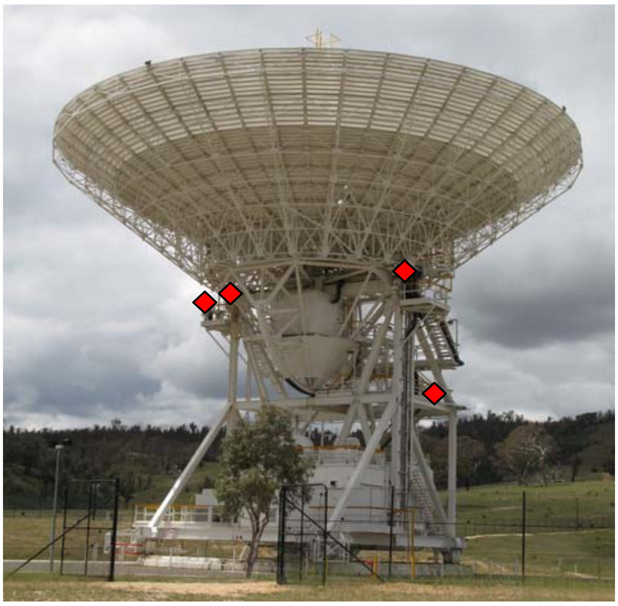
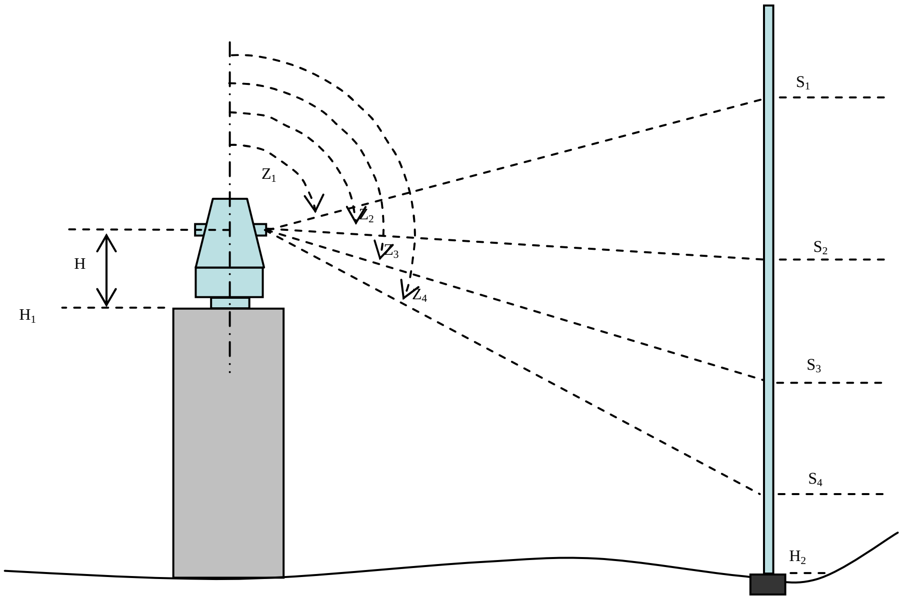


Figure 6: *VLBI Azimuth rotation - survey target positions on telescope structure*

The standard measurement procedure involved setting up on one of the survey observation pillars (AU031, AU032). Atmospheric information (temperature, pressure, humidity) was recorded at the start of each instrument setup and was later applied to the observations in post processing using software developed at Geoscience Australia. Target heights were measured at each prism, using a box tape, as a rough initial guide to target height. These heights were updated later in post processing.

The Reuger heighting technique (Reuger & Brunner, 1981) was applied, at the beginning and end of each observation session, using temporary survey pins located in close proximity to the instrument setup point (15m). This measurement technique involved the observation of one round of FL/FR vertical angles to specific graduations on a levelling staff (0.8m, 1.2m, 1.6m, 2.0m) placed on a levelled survey mark (Figure 7). This technique works best when the mid graduation of the levelling staff are approximately horizontal to the instrument trunnion axis (90 degrees). Height differences computed as part of the levelling survey (refer to section 4.2) were utilised to determine the precise height of instrument.



$$H = \frac{S_2 \cot Z_1 - S_1 \cot Z_2}{\cot Z_1 - \cot Z_2} - (H_1 - H_2)$$

Figure 7: *Total station instrument heighting technique, where S_n are staff readings; Z_n are zenith angles (Rueger & Brunner, 1981).*

The observation pillars served as the back sight for the radio telescope target survey and a single set of dual face pointings were made to the back sight and as many of the four targets placed on the telescope structure as visible. Observations were taken to the targets on the antenna when it was positioned at 89.5° elevation and zero azimuth. Observation sets were taken to the antenna targets as the radio telescope was re-orientated in azimuth at separate 20 degree increments until it had completed a full 360 degree rotation.

4.3.2 Elevation Observations

A similar procedure to that described above was followed for observations to the targets positioned on the antenna as it was rotated through elevation settings. Observations were taken from two instrument set up locations (AU031, AU032) to six *Leica* targets placed on the radio telescope (as shown in Figure 8) as the telescope was rotated in elevation, with the telescope azimuth set on a bearing orthogonal to the total station line of sight. These directions were approximated in the field (Bearing of 140° (320°) and 300° (120°) for observations from AU032 and AU031, respectively). The radio telescope can only move through 90° of arc in elevation. Therefore, only quarter arcs of target rotation were observed. This is not ideal for the circle fitting procedure of the IVP determination, but a common structural constraint of such telescopes. In this survey, the telescope was rotated through 90 degrees at 10 degree increments. Then rotated 180° in azimuth and rotated a further 70° in elevation. This was done in attempts to build a more complete arc for the rotation in elevation. The radio telescope was rotated by the computer system, controlled by a telescope operator.

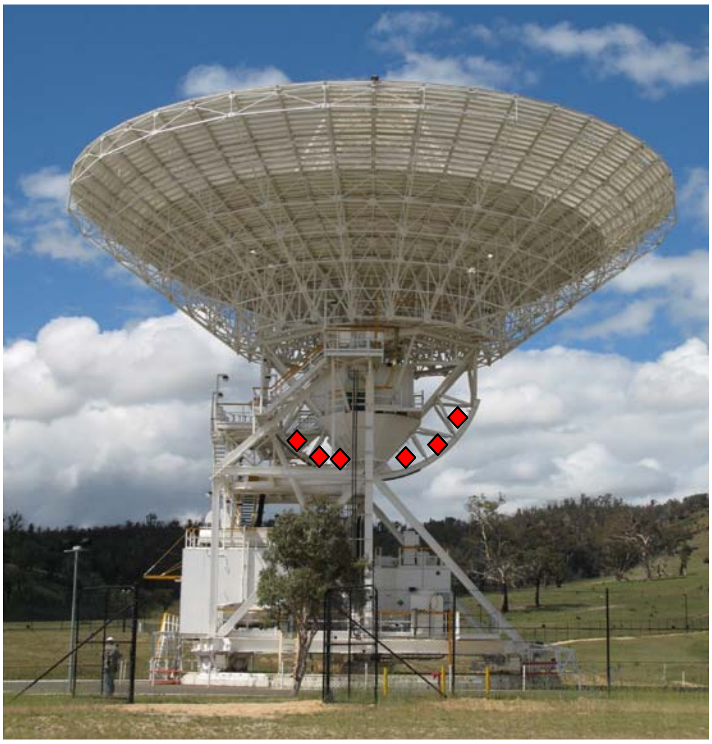


Figure 8: *Elevation rotation - survey target positions on telescope structure*

Reuger heighting observations were taken to a nearby ground mark (pre-levelled) at the beginning and end of the survey. These measurements were used to derive the instrument height accurately, which was important for the observation of target elevations. In conducting the survey, the observation pillars served as the back sight and single sets of dual face pointing were made to the back sight and the six targets placed on the radio telescope. Observations were taken to the targets at 10 degree increments of the VLBI as it was rotated through elevation settings.

4.4 DORIS and MET Station

The change in height between the GPS antenna monument and MET station ground mark was observed as part of the level survey. The height difference from the ground mark to base of the pressure sensor was measured by Tidbinbilla DSCC staff with a box tape. The change in height was forwarded to astronomy researchers. The change in height observed from the GPS antenna monument to the ground mark below the MET pressure sensor is: -4.3410m

There are no DORIS facilities at the Ceduna radio observatory.

4.5 GPS

Static GPS data was collected over the two survey observation pillars, in addition to the GPS data observed over the permanent GPS station (TIDB). GPS antennae were set up over the pillars and left to run for seven full days.

```
+SOLUTION/EPOCHS
*CODE PT     SOLN   T      _DATA_START_ __DATA_END__ _MEAN_EPOCH_
TIDB   A      1      P      07:317:00000 07:323:86400 07:320:43200
AU31   A      1      P      07:317:00000 07:323:86400 07:320:43200
AU32   A      1      P      07:317:00000 07:323:86400 07:320:43200
-SOLUTION/EPOCHS
```

4.6 General Comments

None.

5. Data Analysis and Results

The flow chart of the analysis process used for the Tidbinbilla survey is detailed in Figure 9. Coordinate solutions are generated in three steps: first at the completion of the classical geodetic adjustment (*Step A*); second at the completion of the geometrical modelling where the impact of the geometrical model is propagated throughout the input classical adjustment results (*Step B*); and third after transformation (*rotation and translation*) of the 'geometrically modified` solution onto the required global reference frame (*Step C*).

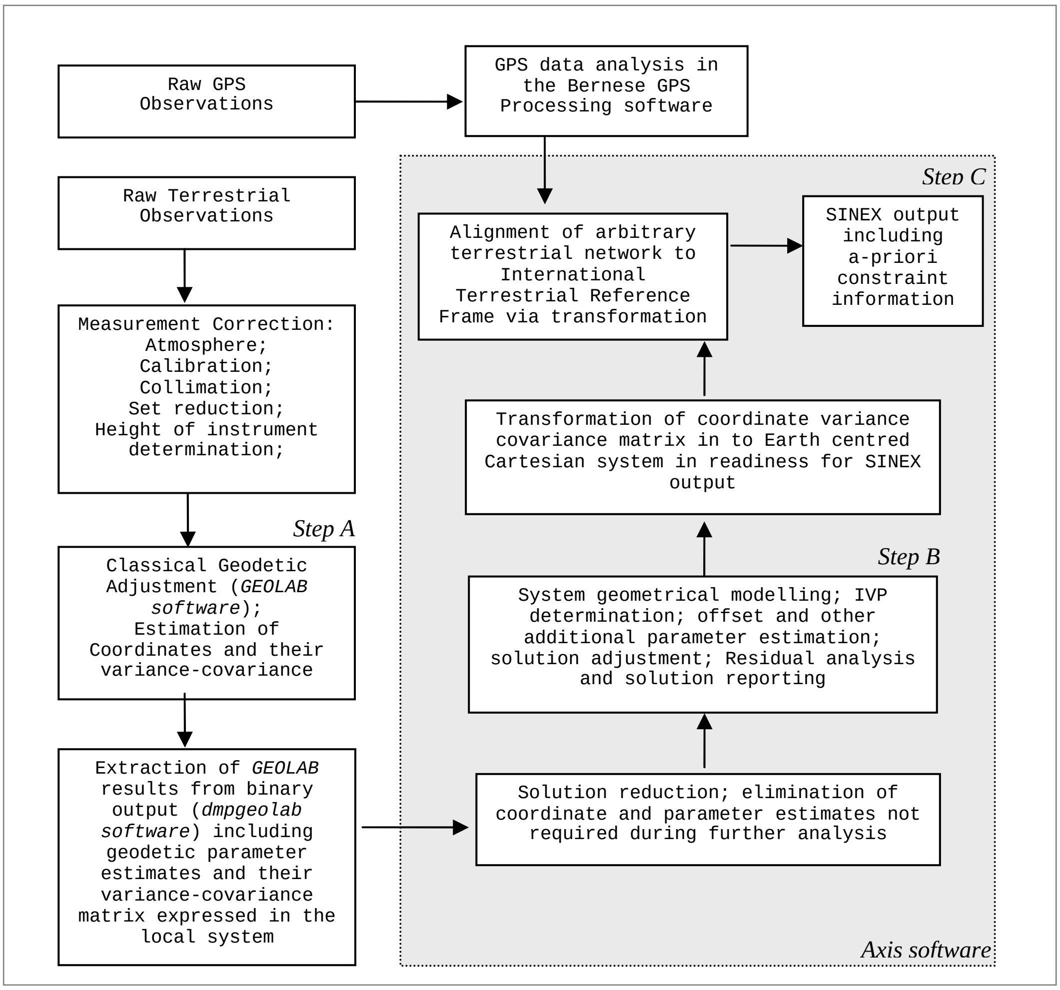


Figure 9*: Analysis process for the reduction of local survey data.*

5.1 Data Pre-processing

5.1.1 Levelling

Levelling GSI files were edited and passed though Geoscience Australia's levelling1.exe software to derive changes in height between survey marks. Levelling misclosures were noted as being well within zero order levelling requirements. Levels were determined for survey marks with AU017 fixed in height. Orthometric height differences were noted between survey marks for use in the adjustment.

Table 4: Tidbinbilla terrestrial levelling survey results. Orthometric height differences (m)

From	To	∆ Height
TIDB	RM1	-0.4978
TIDB	RM2	-1.6397
TIDB	RM3	-1.3980
TIDB	AU031	-3.4870
TIDB	AU032	-7.7239
TIDB	NMC194	-2.1618
TIDB	MET BM	-4.3410

5.1.2 Reuger heighting

Reuger heighting observations, recorded during the VLBI survey, to the survey pins close by instrument stations were extracted from the FLD files and entered into an excel spreadsheet set up to derive instrument heights from vertical angles read to a levelling staff. The mean height of instrument value was computed from a number of observation sets.

5.1.3 Network survey

GSI files were reformatted into FLD files using in house software developed by Geoscience Australia, *GSI2FLD*. Meteorological data and prism correction data were entered into the FLD files. These files were then run through the Geoscience Australia developed *Angles*.exe to generate IOB files. The vertical angles and slope distance values were then entered, with heights of instrument computed through the Reuger heighting technique, into a spreadsheet set up to derive heights of targets using these observations. The height of target and height of instrument values were entered into the IOB files for the relevant observation sets. Orthometric height difference values derived through the levelling data processing were added to the IOB file. Corrections for the geoid and deflection of the vertical were added to the IOB file to be applied as part of the classical geodetic adjustment. Measurement precision estimates were also added to the IOB file for each observation type. The precision values entered included:

Slope distance: 0.0005m + 1ppm
Horizontal direction: 1 second
Zenith angle: 2 second
Orthometric height difference: 0.0002m

5.2 Classical Geodetic Adjustment

Classical geodetic adjustment was undertaken using *GeoLab* version 2.4d geodetic adjustment software. Prior to this, three dimensional coordinates for the permanent IGS GPS pillar (TIDB) and the AU032 observation pillar were constrained in the IOB files as the primary constraint on the network. The IOB file was run through the *GeoLab* version 2.4d geodetic adjustment software until coordinates converged, with derived coordinates repeatedly being added to the IOB file as initial coordinate estimates in the adjustment process. Once convergence was reached, the primary constraint on the network was loosened up to act as a minimum constraint with TIDB held fixed in latitude, longitude and height and AU032 only held fixed in latitude, allowing for movement in the east-west directions and also in height. The final adjustment was run.

5.2.1 Topocentric coordinates and covariances

Geodetic coordinates (GRS80 Ellipsoid) provided in the arbitrary local terrestrial system before alignment to the ITRF2005 at epoch 12:00 15 November 2007 are given below.

Table 5: Tidbinbilla terrestrial survey results. GRS80 ellipsoid. Heights are ellipsoidal, aligned to arbitrary local frame using GPS observations.

STATION				LATITUDE				LONGITUDE	HEIGHT (M)
TIDB 50138M001	S	35	23	57.13154	E	148	58	47.99564	665.3490
RM1	S	35	23	56.56366	E	148	58	48.26414	664.8512
RM2	S	35	23	57.55359	E	148	58	47.87915	663.7095
RM3	S	35	23	56.97159	E	148	58	47.54573	663.9511
AU031	S	35	23	52.64007	E	148	58	40.93541	661.8613
AU032	S	35	23	55.94502	E	148	58	37.45289	657.6252
NMC194	S	35	23	51.40529	E	148	58	42.86712	663.1866

5.2.2 Correlation matrix

The computed correlation matrix was too large to be included in this report, please refer to the SINEX file (see section 5.5) for further information of this type.

5.2.3 Reference temperature

No thermal deformation corrections have been applied for structural expansion of the radio telescope structure.

5.3 IVP Determination

At this stage three dimensional coordinates had been computed for each target at each orientation of the radio telescope. These points were used to derive three dimensional circles in space, which were used to determine the VLBI IVP.

The .par, .con and .inv propriety binary *GeoLab* format files generated from the *GeoLab* adjustment were run through the Geoscience Australia developed *dmpgeolab* software to extract the solution data, including a full variance-covariance matrix, and create an ASCII format .vcv file required for the IVP determination software *axis*, developed by Geoscience Australia. The .vcv file was placed into a directory with the *axis* software along with a setup.axs file. The setup file was edited repeatedly to derive estimates of circle parameters for each target and each rotation sequence. Once initial estimates were refined for all target rotation sequences, geometric constraints were added. Initial constraints introduced included:

- ENORMAL, NNORMAL, UNORMAL – used to constrain normal parameters together;
- TOUCH – used to force two axes to touch each other (in 3D) at some reference point;
- RADIUS – used to constrain circle arc radius parameters together;
- CENTRE – used to constrain together centre to centre distances;
- UCENTRE – used to constrain circle centre up parameters together.

With updated circle parameter estimates for each target rotation sequence, IVP coordinates were derived. Additional constraints were introduced to constrain separate IVP realisations. Constraints applied included:

- OFFSET – used to constrain the computed offset to be identical for independent IVP estimates;
- ORTHOG – used to constrain the orthogonality between three axes;
- UIVP – used to constrain the individual IVP determination in the up component together.

5.4 Transformation

This procedure produced the final IVP coordinate estimates. The *axis* software was used to transform (through translation and rotation only) the terrestrial network and computed IVP coordinates with the variance-covariance matrix from a local to a global reference frame. Coordinates derived from the processing of the GPS data collected on site were used to align the network solution to the global reference frame, ITRF2005. Three alignment stations (TIDB, AU031 and AU032) with XYZ earth-centred Cartesian coordinates were specified as stations for the local to global transformation.

5.5 SINEX File Generation

A SINEX format solution file was created using the *axis* software. The SINEX naming convention adopted by Geoscience Australia for local survey data is:

XXXNNNNYYMMFV.SNX
where

XXX is a three character organisation designation;
NNNN is a four character site designation;
YY is the year of survey;
MM is the month of survey;
F is the frame code (G for global frame; L for local frame); and
V is the file version.

The SINEX file corresponding to this report is ***AUSTIDB0711GA.SNX***, and can be found at ftp://ftp.ga.gov.au/sgac/sinex/ties/. This is the most up-to-date SINEX file generated for a Tidbinbilla local tie survey and may be submitted to the International Earth Rotation Service (IERS).

5.6 GPS

GPS data analysis was undertaken using the Bernese GPS processing software version 5.0. International Terrestrial Reference Frame 2005 (ITRF2005) coordinates of the permanent GPS station, TIDB were adopted for the observation session. Both L1 and L2 observations were used and no troposphere models were estimated. The observations were processed to a 10° cut-off. Carrier phase ambiguities were resolved to their integer values. The final International GPS Service (IGS) orbits and Earth orientation parameters were used in the processing. IGS recommended constant and elevation dependent antenna phase models were also applied.

Table 6: Tidbinbilla 2007 GPS survey results. GRS80 ellipsoid. Heights are ellipsoidal. Aligned to ITRF2005 at 12:00 15 November 2007.

STATION	LATITUDE	LONGITUDE	HEIGHT(m)
TIDB 50103M108	S 35 23 57.13154	E 148 58 47.99564	665.3489
AU31	S 35 23 52.64002	E 148 58 40.93541	661.8591
AU32	S 35 23 55.94502	E 148 58 37.45286	657.6223

5.7 Additional Parameters

Additional system parameters were computed during the IVP estimation process.

For the telescope IVP ***(TIVP)*** the azimuth axis deflection from the vertical was estimated as 10.7" at an azimuth of 58° 08' 55.9". The orthogonality (or non-orthogonality) of the azimuth to the elevation axes was estimated to be 89° 59' 34.6". The offset distance between the azimuth and elevation axis was estimated to be 8.0 mm (-5.1mm, 6.2mm, -0.1mm in East, North and Up, respectively).

Table 7: Tidbinbilla, final results, topocentric vectors between radio telescope IVP **(TIVP)** and observed points in the Tidbinbilla network.

Station	East (m)	North (m)	Up (m)	Range (m)
TIDB	210.0838	-83.0822	-9.0375	226.0963
NMC194	80.6586	93.4149	-11.1964	123.9254
RM1	216.8602	-65.5794	-9.5354	226.7597
RM2	207.1436	-96.0906	-10.6772	228.5955
RM3	198.7296	-78.1521	-10.4350	213.7992
AU031	31.9077	55.3567	-12.5208	65.1094
AU032	-55.9805	-46.5085	-16.7578	74.6839

5.8 Discussion of Results

Table 8: Tidbinbilla, final results, cartesian coordinates (metres), ITRF2005 at 12:00 15 November 2007 and final precision estimates (1σ, millimetres)

Station	X (m)	σ	Y (m)	σ	Z (m)	σ
TIDB	-4460996.5323	0.3	2682557.0876	0.6	-3674443.1999	0.3
TIVP	-4460935.8167	0.8	2682765.7219	0.7	-3674380.7110	0.8
NMC194	-4461015.9363	1.8	2682719.7841	2.1	-3674298.0788	1.9
RM1	-4461008.3654	0.9	2682556.2964	0.7	-3674428.6442	1.0
RM2	-4460987.4142	1.0	2682555.0349	0.7	-3674452.8537	1.0
RM3	-4460992.1518	0.8	2682567.7024	0.7	-3674438.3716	0.8
AU031	-4460970.9940	0.2	2682749.6439	0.6	-3674328.3346	0.5
AU032	-4460872.1727	0.2	2682792.7710	0.6	-3674408.9150	0.2

Table 9: Tidbinbilla, final results, geographic coordinate, ITRF2005 at 12:00 15 November 2007.

Station	Latitude			Longitude			Ellip. Height
TIDB	-35	23	57.13153	148	58	47.99563	665.3489
TIVP	-35	23	54.43606	148	58	39.67109	674.3824
NMC194	-35	23	51.40527	148	58	42.86711	663.1871
RM1	-35	23	56.56366	148	58	48.26413	664.8510
RM2	-35	23	57.55358	148	58	47.87914	663.7092
RM3	-35	23	56.97158	148	58	47.54572	663.9509
AU031	-35	23	52.64006	148	58	40.93541	661.8619
AU032	-35	23	55.94499	148	58	37.45287	657.6250

Table 10: Tidbinbilla, final results, cartesian difference vectors (metres). Aligned to ITRF97 at 1997.0 on the GRS80 ellipsoid.

From	To	∆X (m)	∆Y (m)	∆Z (m)	Range
2007					
TIVP	TIDB	-60.7166	-208.6345	-62.4875	226.0963
TIVP	AU031	-35.1776	-16.0774	52.3766	65.1096
TIVP	AU032	63.6442	27.0485	-28.2041	74.6838
TIVP	NMC194	-80.1201	-45.9366	82.6323	123.9254
TIVP	RM1	-72.5498	-209.4253	-47.9317	226.7595
TIVP	RM2	-51.5986	-210.6872	-72.1412	228.5954
TIVP	RM3	-56.3362	-198.0197	-57.6593	213.7994
1995					
TIVP	TIDB	-60.7284	-208.6318	-62.4956	226.0992
TIVP	AU031	-35.1806	-16.0790	52.3753	65.1105
TIVP	AU032	63.6411	27.0471	-28.2051	74.6811
TIVP	NMC194	-80.1275	-45.9324	82.6338	123.9296

The least squares solution of the VLBI IVP position included: 32 targets; 2 IVP estimates (constrained together); 636 pseudo-observations; 267 unknowns; 410 conditions; 48 constraints and 209 additional constraints. The resultant linear system was 1570 x 1570 with degrees of freedom 1036. The computed variance factor was 0.0081. IVP model (circle) fit residuals were 0.5mm Root Mean Square Error (RMS) for the in-plane residuals and 0.6mm for the out-of-plane residuals.

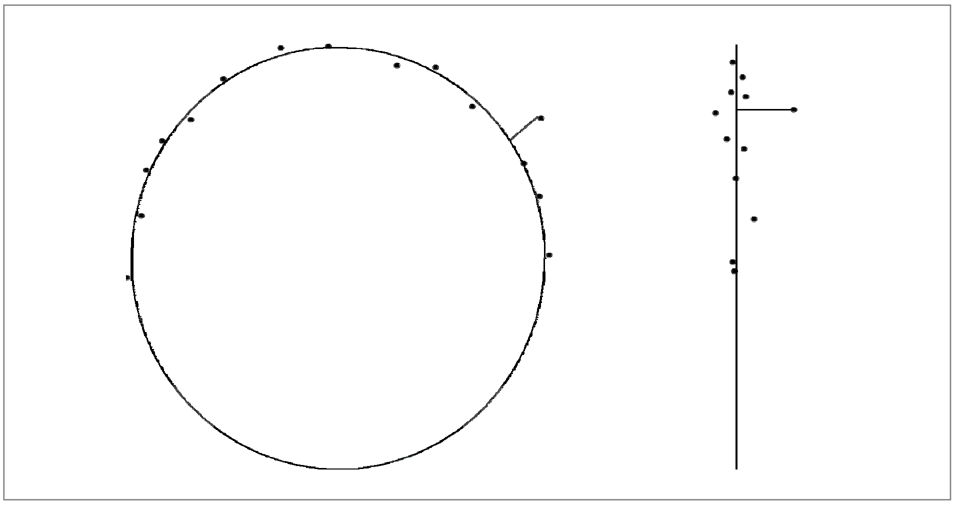


Figure 11*: Circle fitting residuals; left in-plane residuals; right out-of-plane residuals.*

5.9 Comparison with Previous Surveys

The 2007 Tidbinbilla local tie survey highlighted errors in the height difference between survey pillars used in the 1995 local tie survey. Detailed inspection of the data used in the 1995 local tie survey adjustment identified that the GPS baselines were relied upon as the primary observable for height differences in the survey. No precise levelling height difference observations were used. Extended investigation found that there were unmodelled systematic errors in the GPS processing, resulting in the use of incorrect height differences between stations, particularly from TIDB to each of the observation pillars. This led to error in the heights placed on the observation pillars and thus the derived telescope IVP height was in error.

Table 12: Height differences, comparison between years and GPS and precise levelling observed height differences.

FROM	**TO**	**2007 Precise Δ Height**	**2007 GPS Δ Height**	**1995 GPS Δ Height**	**1993 Precise Δ Height**
TIDB	TIVP	+9.0335		+9.0196	
TIDB	NMC194	-2.1618		-2.1688	-2.1578
TIDB	AU031	-3.4870	-3.4898	-3.4983	-3.4871
TIDB	AU032	-7.7239	-7.7266	-7.7358	-7.7242
AU031	AU032	-4.2369	-4.2368	-4.2375	-4.2371

Table 12 highlights the differences in observed height changes between stations. The precise levelling height differences observed in 2007 and 1993 agree extremely well. Precise levelling was completed at Tidbinbilla in 1993 to connect the new survey pillars into the national survey mark network. The GPS height differences for 2007 agree relatively well with the 2007 precise levelling, with 2.8mm maximum difference and agreement at 0.1mm between the observation pillars. The GPS height differences from 1995 do not agree well with any of the other surveys. Discrediting there use as the height observations in the 1995 local tie survey adjustment.

To quantify the differences between the 1995 and 2007 surveys two separate adjustments and IVP determinations were run. Each was aligned to the same reference frame as the 1995 local tie survey (ITRF97 @ 1997.0) although in one the observation station AU032 was held fixed in height, while in the other the continuous GPS pillar (TIDB) was held fixed in height. The first adjustment allowed comparison of the IVP determination technique, working directly from the observation pillars (Table 13 and Table 14). The second adjustment provided a true measure of the difference between the 1995 and 2007 solutions, transferring the effect of the erroneous height observation throughout the network and into the IVP estimate (Table 15 and Table 16).

Table 13: XYZ Residuals between the 1995 and 2007 surveys. Aligned to ITRF1997 at epoch 1997.0, with observation pillars held fixed in height to support comparison of IVP determination.

Station Name	X (mm)	Y (mm)	Z (mm)
TIDB	8.6	-4.5	6.9
TIVP	-3.2	-1.8	-1.2
NMC194	4.2	-6.0	-2.7
AU031	-0.2	-0.2	0.1
AU032	0.1	-0.4	-0.2
RMS	**3.3**	**2.6**	**2.2**

Table 14: East, North and Up Residuals between the 1995 and 2007 surveys. Aligned to ITRF1997 at epoch 1997.0, with observation pillars held fixed in height to support comparison of IVP determination.

Station Name	E (mm)	N (mm)	Up (mm)
TIDB	-0.6	0.0	-11.9
TIVP	3.2	0.1	2.2
NMC194	3.0	-6.1	-3.9
AU031	0.3	0.1	0.0
AU032	0.4	-0.2	0.0
RMS	**1.5**	**1.3**	**3.6**

Table 13 and 14 indicate relatively small differences between the derived IVP coordinates between the 1995 and 2007 surveys. These data sets have been adjusted with the observation pillars held fixed to provide a true indication of the positioning of the IVP relative to the observation stations between 1995 and 2007. The tables also highlight the large discrepancy in the height component of TIDB, relative to the observation stations. The differences noted in NMC194 are not given much attention as this station was only loosely connected into the 2007 survey network.

Table 15: XYZ Residuals between the 1995 and 2007 surveys. Aligned to ITRF1997 at epoch 1997.0, with GPS pillar (TIDB) held fixed in height to support comparison of overall solution.

Station Name	X (mm)	Y (mm)	Z (mm)
TIDB	0.3	0.5	0.1
TIVP	-11.3	3.1	-8.0
NMC194	-3.5	-1.3	-9.1
AU031	-8.0	4.6	-6.5
AU032	-8.4	4.7	-7.2
RMS	**6.3**	**2.8**	**6.2**

Table 16: East, North and Up Residuals between the 1995 and 2007 surveys. Aligned to ITRF1997 at epoch 1997.0, with GPS pillar (TIDB) held fixed in height to support comparison of overall solutions.

Station Name	E (mm)	N (mm)	Up (mm)
TIDB	-0.6	0.8	-0.1
TIVP	3.2	0.0	13.8
NMC194	2.9	-6.1	7.2
AU031	0.2	0.0	11.3
AU032	0.3	-0.3	12.0
RMS	**1.4**	**1.4**	**8.9**

Table 15 and Table 16 show the actual differences in the final derived coordinates of the stations in the Tidbinbilla local tie surveys between 1995 and 2007. Table 15 indicates that the major difference is in the height component which relates to the incorrect height difference used between survey pillars in the 1995 surveys.

6. Planning Aspects

There are two permanent observation pillar monuments, three GPS ground reference mark pins, one other ground survey mark (NMC194) and the permanent GPS pillar at the observatory. The total station can be set up directly on the observation pillars. However, tripods are required to set up instruments over the ground marks. Four tripods should be utilised in the survey (minimum three).

Magnetic mounted micro-prisms are placed on the telescope for the observation of the telescope through changes in orientation. Effort was made to place the targets on structural features of the radio telescope. Similar target locations should be used in the future surveys.

A telescope operator is required on site to drive the telescope throughout the local tie survey. The telescope can be controlled by computed in the control room at the base of the telescope. Request a site safety induction prior to starting work on site. Otherwise, one observatory technician will have to accompany survey personnel on site at all times.

The observation of GPS data is a significant component of the overall survey. The observation of suitable data spans needs to be considered in the context of normal terrestrial survey activities. During the 2007 survey, GPS data was collected over the observation pillars (AU031 and AU032) for a full week. Close proximity to the Canberra office allowed repeated visits to site.

Adequate time should be allocated to complete the local tie survey. At least four full days are required to conduct the local tie survey. The work involving the telescope can be completed in one full day, or two half days (half azimuth, half elevation). It takes approximately two hours to setup for the radio telescope azimuth/elevation surveys. VLBI elevation observation from one setup takes approximately two hours (observing five targets). VLBI azimuth observation from one setup takes approximately two hours (observing four targets). A survey assistant is required during this part of the survey to rotate targets towards the instrument operator. The survey assistant needs to be patient and climb all over the telescope reorientating targets. Reuger heighting is required before and after VLBI observation sessions. The terrestrial network survey takes approximately one full day. The levelling survey should be allocated half a day.

While local tie surveys are significant for reference frame definition, every attempt should be made to minimise disruption to normal radio telescope activities. The timing of future surveys needs to be negotiated with the Tidbinbilla astronomers to avoid unnecessary negative impact on observing schedules.

7. References

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7.3 Location of observation data and results archive

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