The 2003 Mount Stromlo Local Tie Survey

by

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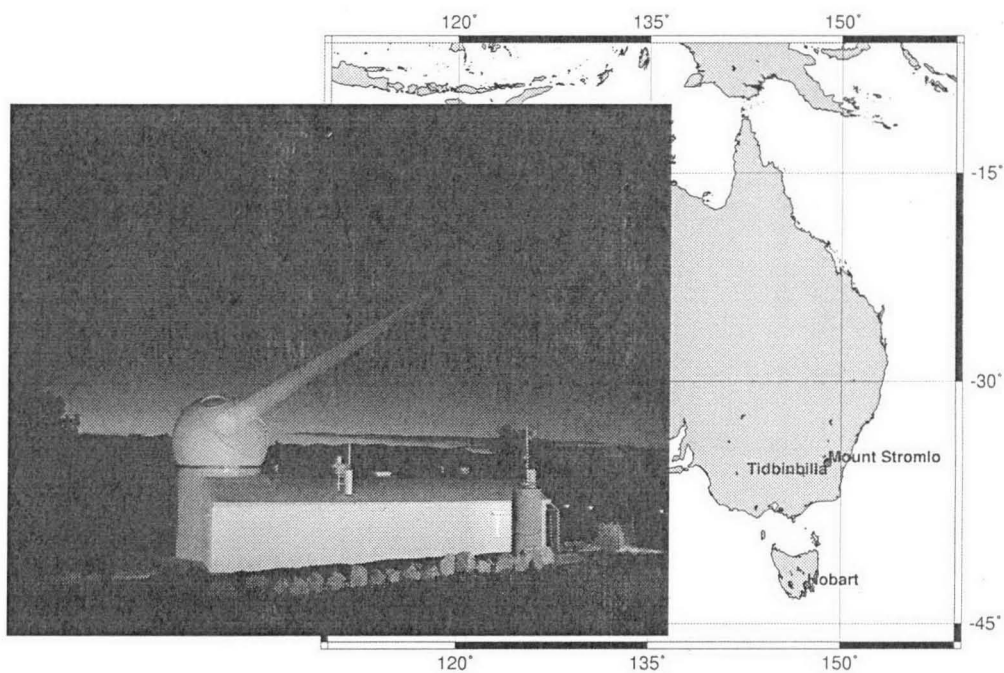
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Bibliographic reference: Johnston G., Dawson J., Naebkhil S., 2004. The 2003 Mount Stromlo Local Tie Survey. Geoscience Australia, Record 2004/20. 26pp.

Contents

Executive Summary

The integrity and strengths of multi-technique terrestrial reference frames such as ITRF2000 depend on the precisely measured and expressed local tie connection between space geodetic observing systems at co-located observatories. The destructive Canberra fires of January 2003 completely destroyed the Mount Stromlo Satellite Laser Ranging observatory including the SLR, DORIS, GLONASS and GPS located at the site. Fortunately, Geoscience Australia has routinely performed classical terrestrial surveys at Mount Stromlo, including surveys in 1999, 2002 and 2003 (post-fire). These surveys have included the determination of the SLR invariant point or IVP. Using existing undamaged survey pillars a consistent stable terrestrial network has been used to compute the relationship between the pre and post fire local tie connections. This relationship includes the millimetre level accurate connections and their associated variance covariance matrix and provides an un-broken contribution of the Mount Stromlo observatory to future terrestrial reference frames and other scientific outputs. In this report observational and analysis techniques are reviewed and results are given.

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 our approach for the observation and computation of local ties are as follows:

- *The calibration of all geodetic instrumentation including: total station instruments; levelling staffs; fixed height mounts; and reflectors (targets);*

- *The observation of a vertical geodetic network by application of geodetic levelling (in our case specifically EDM-Height traversing) to all survey marks in the vicinity of the observatory;*

- *The observation of a horizontal geodetic network by application of terrestrial geodetic observations, including angles and distances to all survey marks in the vicinity of the observatory;*

- *The observation of a Global Positioning System (GPS) network on suitable survey marks in the vicinity of the observatory (these marks are included in the geodetic levelling);*

- *The observation of targets located on the observing system (Satellite Laser Ranging or Very Long Baseline Interferometry instrumentation) during rotational motion about each of its independent axes. This includes zenith angle observations to a staff on a levelled survey mark in the vicinity for precise height of instrument determination;*

- *The reduction of terrestrial geodetic observations, including the correction of observations for instrument and target bias, set reduction and atmospheric effects, and includes the height of instrument determination from observations to a staff;*

- *Classical geodetic least squares (minimum constraint) adjustment of all terrestrial geodetic observations, including deflection of the vertical and geoid corrections (derived from the Australian national gravimetric geoid). This results in terrestrial only coordinate estimates and their associated variance-covariance matrix (in a local system) of the geodetic network and targets located on the SLR and/or VLBI instrumentation;*

- *Invariant Point (IVP) modelling and estimation, includes the estimation of IVP, the axes of rotation and associated system parameters such as axis orthogonality and the offset of the axes; Includes readjustment of terrestrial only network;*

- *Analysis of GPS observations. This results in GPS only coordinate estimates and associated geocentric variance-covariance matrix;*

- *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 apriori); The previous GPS analysis is used as the global reference frame realisation; and the*

- *Reduction of the complete solution to stations of primary interest (i.e. those with DOMES) and output of a SINEX format solution file including all apriori constraints.*

1. Site Description

The Mount Stromlo Satellite Laser Ranging (SLR) observatory, located in the Australian Capital Territory (ACT), is co-located with GPS, DORIS and GLONASS systems.

Table 1: List of globally important survey marks (with DOMES) at the Mount Stromlo SLR observatory.

Local Designation	Global/IERS Designation
STR2 (Fundamental Pillar)	STR2 50119M001
STR1 (Stromlo IGS/ARGN GPS)	STR1 50119M002
AU061 (Stromlo DORIS GM)	AU61 50119M004
MSPB (Stromlo DORIS post-fire)	MSPB 50119S004
MSOB (Stromlo DORIS pre-fire)	MSOB 50119S002
SLR IVP (Stromlo SLR pre-fire)	7849 50119S001
SLR IVP (Stromlo SLR post-fire)	7825 50119S003

The destructive Canberra fires of 18 January 2003 completely destroyed about 500 homes in Canberra together with the Mount Stromlo Satellite Laser Ranging (SLR) observatory. The SLR, DORIS, GLONASS and GPS located at the site were destroyed together with all the buildings in the locality. Fortunately, Geoscience Australia has routinely performed classical terrestrial surveys at Mount Stromlo, including surveys in 1999, 2002 and 2003 (post-fire). These surveys have included the determination of the SLR invariant point or IVP. Using existing undamaged survey pillars a consistent stable terrestrial network has been used to compute the relationship between the pre and post fire local tie connections. This relationship includes the millimetre level accurate connections and their associated variance covariance matrix and provides an un-broken contribution of the Mount Stromlo observatory to future terrestrial reference frames and other scientific outputs. In this report the ground survey observations from the 1999, 2002 and 2003 surveys are subject to a combined analysis.

2. Instrumentation

2.1 Tacheometers, EDMI, 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").
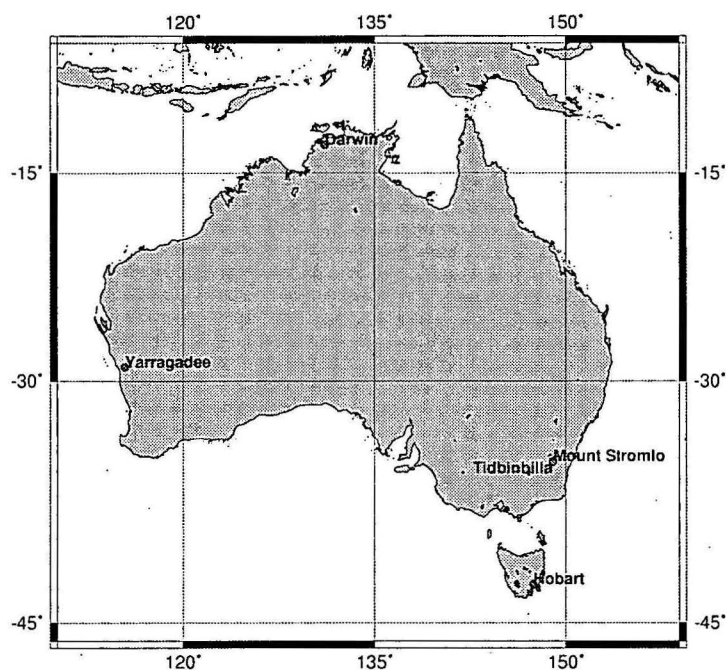
Figure 1: *Mount Stromlo Satellite Laser Ranging (SLR) Observatory. The co-located observatory includes SLR, GPS, DORIS and GLONASS systems.*

2.1.2 Calibration results

Calibration results presented here refer to 2003 survey equipment. For previous survey calibration results refer to Johnston *et al.* (2000) and Johnston & Digney (2002). The Leica TCA2003 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.
- Additive constant for Leica Retro-reflective tape is 0.0mm from front face.

Staff calibration:

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

Figure 2: Mount Stromlo Satellite Laser Ranging (SLR) system. The Mount Stromlo fire damage. Bottom; Satellite Laser Ranging station post-fire. Top left; International GPS Service (IGS) station STR1 monument relatively un-damaged. Top right; Satellite Laser Ranging station post-fire with International GLONASS Service (IGLOS) station in the foreground.

2.1.3 Auxiliary equipment

Meteorological observations were recorded by the Mount Stromlo (SLR) meteorological station.

2.2 GPS Units

Continuous GPS observations, over the period February 2000 to December 2002, were made at two monuments in the terrestrial network, namely STR1 (permanent IGS station) and STR2 (permanent IGLOS station). The GPS analysis undertaken within the International Terrestrial Reference Frame 2000 (ITRF2000) was used to align the local terrestrial network to ITRF2000.

2.2.1 Receivers

```
+SITE/RECEIVER
*SITE PT SOLN T DATA_START__ DATA_END____ DESCRIPTION
 STR1  A ---- P 00:055:00000 02:365:86369 AOA SNR-12 ACT
 STR2  A ---- P 00:055:00000 02:365:86369 JPS LEGACY
-SITE/RECEIVER
```

2.2.2 Antennas
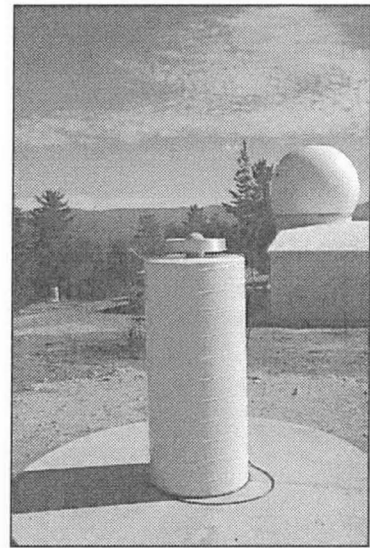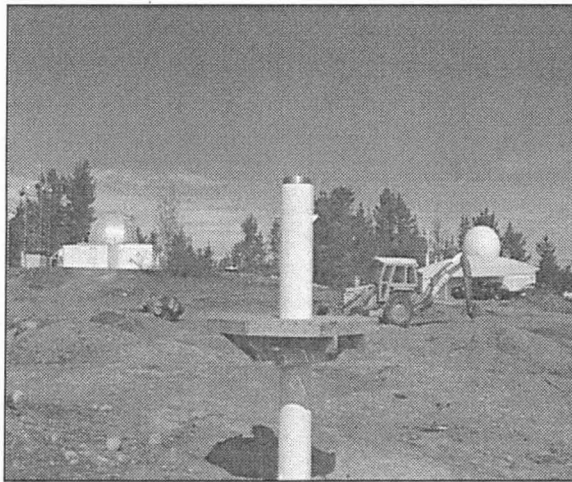
Figure 3: Left: Mount Stromlo permanent GPS station STR1 50119M002. Right: Mount Stromlo permanent GPS and GLONASS station STR2 50119M009

```
+SITE/ANTENNA
*SITE PT SOLN T DATA_START__ DATA_END____ DESCRIPTION
 STR1  A ---- P 00:055:00000 02:365:86369 AOAD/M_T
 STR2  A ---- P 00:055:00000 02:365:86369 JPSREGANT_DD_E
-SITE/ANTENNA
```

2.2.3 Analysis software, mode of operation

Refer to section 5.2.1.

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 with Leica bayonet mount on top 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 are taken to each target eliminating collimation effects. The offset in length between the 1.5m pole and the 0.2m stub used on pillars is determined by observing both on a low mark and calculating the offset. No other pole calibration is required.

2.4 Tripods

Leica GST20/9 Heavy duty timber tripods.

2.5 Forced centering devices

Leica Zenith & Nadir Plummet S/N F.NR.272713

2.6 Targets, reflectors

Total station target kits include:

- 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 are included in the ground network:

AU045 (STR2): STR2 50119M001 (sometimes referred to as STRR). The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot. This pillar plate is set into the top of the fundamental survey pillar at the Stromlo Satellite Laser Ranging station. The Stainless steel pillar plate is inscribed with "AU045 Fundamental Pillar".

AU046: The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot. This pillar plate is fixed on top of North Calibration Pillar 1. The Stainless steel pillar plate is inscribed with "AU046". This mark is 0.183m below AU052 (STR1).

AU047: The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot. This pillar plate is fixed on top of Calibration Pillar 2. The Stainless steel pillar plate is inscribed with "AU047".

AU048: The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot. This pillar plate is fixed on top of Calibration Pillar 3. The Stainless steel pillar plate is inscribed with "AU048".

AU049: The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot. This pillar plate is fixed on top of Calibration Pillar 4. The Stainless steel pillar plate is inscribed with "AU049".

AU050: The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot. This mounting is on top of the north equipment pole protruding from the roof of the observatory. This mark was destroyed in the 2003 fire.

AU051: The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot. This mounting is on top of the south equipment pole protruding from the roof of the observatory. The DORIS antenna is mounted directly above this point. This mark was destroyed in the 2003 fire.

AU052: STR1 50119M002. The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot The Stainless steel pillar plate is inscribed with "AU052".. This pillar plate is bolted on top of the north calibration pillar at the Stromlo Satellite Laser Ranging station, and is 183 mm vertically above a similar mounting which is used for the Laser calibration target. This mounting for the calibration target is known as AU046.

AU054: The intersection of the top of the brass pillar plate 0.15m in diameter with the vertical axis of a 5/8" Whitworth threaded brass spigot. This pillar plate is set into the top of 0.3m concrete pillar, which is 1.28m high. The Pillar is located to the west of the observatory.

AU055: Centre punch mark on head of brass bolt set with resin in concrete drain directly in front of SLR observatory entrance. It is placed such that line of sight into the SLR telescope pillar base ("Fire Place") was possible. This mark remains after the rebuild.

AU056: The intersection of the vertical axis of a 6m pin, with the horizontal plane coinciding with the concrete base of the mirror 7 mount in the SLR telescope pillar base ("Fire Place"). This pin was directly under mirror 7. This mark was destroyed in the fire.

AU060: The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot. This mounting is on top of the western equipment pole protruding from the roof of the observatory. The post fire SLR meteorological equipment is mounted adjacent to this point.

AU061: The intersection of the top of the stainless steel pillar plate with the vertical axis of a 5/8" Whitworth threaded stainless steel spigot. This mounting is on top of the eastern equipment pole protruding from the roof of the observatory. The post fire DORIS antenna is mounted adjacent to this point.

AU046R, AU047R, AU048R, AU049R: SLR calibration targets (during 2003 survey only) on pillars **AU046, AU047, AU048, AU049** respectively.

IVP Stromlo SLR: 7849 50119S001 (pre-fire instrument). The intersection of the azimuth axis and elevation axis of rotation of the Mt Stromlo Satellite Laser Ranging telescope.

IVP Stromlo SLR: 7825 50119S003 (post-fire instrument). The intersection of the azimuth axis and elevation axis of rotation of the Mt Stromlo Satellite Laser Ranging telescope.

DORIS (MSOB): MSOB 50119S002 (pre-fire instrument). The intersection of the vertical axis of the DORIS antenna with the plane coinciding with the reference height line marked on the DORIS antenna. The DORIS antenna is mounted on a steel stanchion on the roof of the Stromlo SLR observatory. Mark is directly above **AU051**.

DORIS (MSPB): MSPB 50119S004 (post-fire instrument). The intersection of the vertical axis of the DORIS antenna with the plane coinciding with the reference height line marked on the DORIS antenna. The DORIS antenna is mounted on a steel stanchion on the roof of the Stromlo SLR observatory.

SR1526: Levelling benchmark at south-west end of the observatory. It consists of a stainless steel rod with a centre punch mark at the top. The mark is under a steel cover plate. Mark was destroyed during observatory construction.

TRIG: is the original Stromlo geodetic survey mark. It is a .303 cartridge case set in concrete, beneath a steel quadrapod.

3.1.2 Map of Network

Figure 4: The Mount Stromlo (1999/2002/2003) terrestrial geodetic network. Terrestrial observations between stations are shown as inter-connecting lines.

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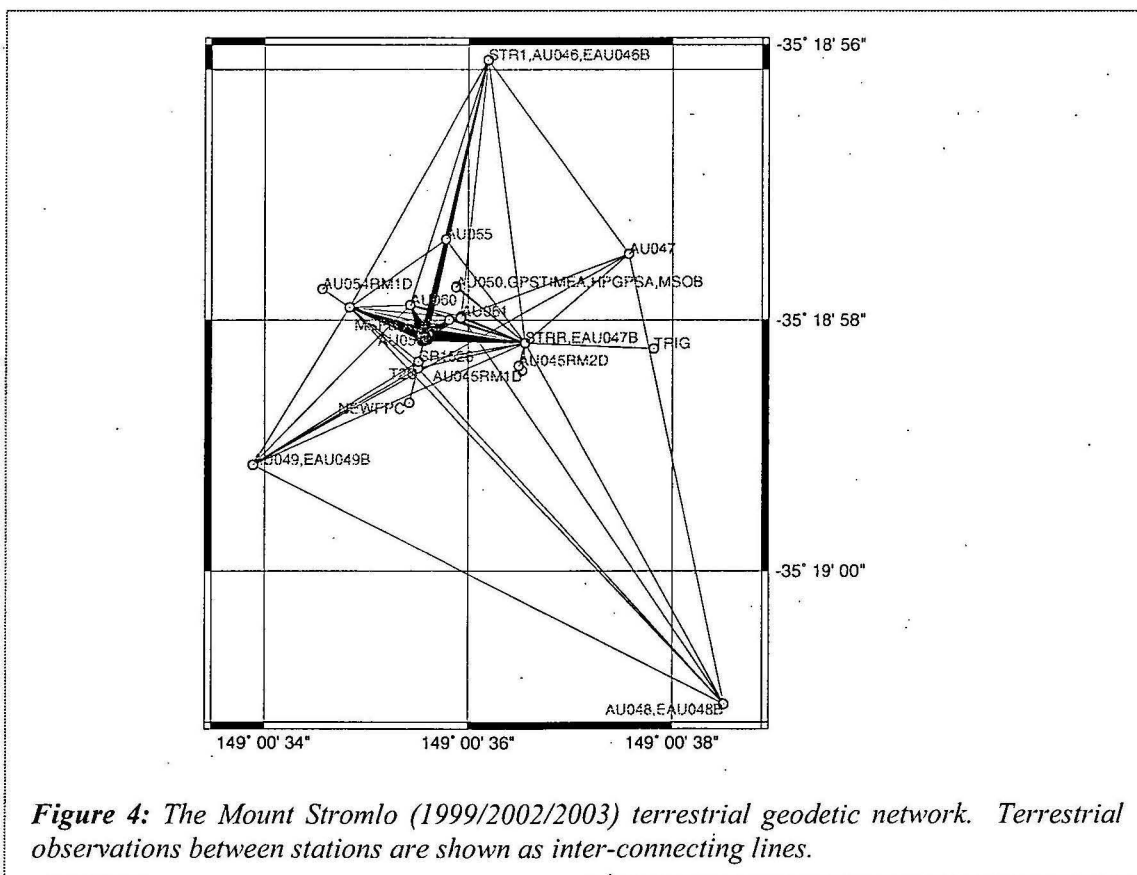
3.2 Representation of Reference Points

3.2.1 VLBI

No VLBI at Mount Stromlo, although Tidbinbilla (*1545 50103S010*) is approximately 20 km away.

3.2.2 SLR

The Mount Stromlo Satellite Laser Ranging (SLR) invariant reference point or IVP is defined as the intersection of the azimuth axis with common perpendicular of the azimuth and elevation axes. A method based on 3-dimensional circle fitting is applied as the basis for IVP determination. Three dimensional coordinate observations to targets on the SLR telescope during rotational sequences are used to determine the independent axes of rotation. Multiple realization of the elevation axis (i.e. observed at multiple azimuths) are observed and computed. A least squares method is used for the computation of the axes of rotation and the IVP. A target located on a rigid body, rotating about one independent axis can be fully expressed as a circle in 3-dimensional space. This circle can be described by seven parameters, namely the circle centre (3 parameters), a unit normal vector (3 parameters) perpendicular to the plane of the circle and a circle radius parameter (1 parameter). A constraint that the unit normal vector perpendicular to the plane of the circle must have magnitude one is required, as is a minimum of three rotational sequences to enable the solution of the equation of a circle.

The method makes the following assumptions: during rotational sequence target paths scribe a perfect circular arc in 3D space; there is no deformation of targeted structure during rotational sequence; there is no wobble error; and the axis of interest can be rotated independently of the other axis. No assumptions of axis orthogonality, verticality/horizontality or the precise intersection of the axes are made.

The indirect geometrical model includes a number of conditions, including:

- Target paths during rotation about an independent axis scribe a perfect circle in space;
- 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 each circle plane derived from targets observed while being rotated about the same axis are forced to be parallel;
- The orthogonality (or non-orthogonality) of the elevation axis to the azimuth axis remains constant over all realisations of the elevation axis;
- Identical targets rotated about a specific realisation of an axis will scribe 3-dimensional circles of equal radius;
- The offset distance between the elevation axis and azimuth axis remains constant over all realisations of the elevation axis;
- The distance between 3-dimensional circle centres for all realizations of the elevation axis are constant over all realisations of the elevation axis; and
- The IVP coordinate estimates remain constant over all realisations (combinations) of the azimuth/elevation axis;

Because the 3-dimensional circle (described by seven parameters) includes a normal vector to the circle plane, the following constraint is also applied;

- The unit normal vector perpendicular to the circle plane is of magnitude one;

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

$$
\begin{bmatrix}
-W & A' & 0 & 0 & 0 \\
A & 0 & B & 0 & 0 \\
0 & B' & 0 & D_1' & 0 \\
0 & 0 & D_1 & 0 & D_2 \\
0 & 0 & 0 & D_2' & 0
\end{bmatrix}
\begin{bmatrix}
v \\
k \\
\Delta \\
k_c \\
\Delta'
\end{bmatrix}
=
\begin{bmatrix}
0 \\
f \\
0 \\
h \\
0
\end{bmatrix}
$$

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.

Figure 5: 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.

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.

Results from the 1999 survey are detailed in Johnston *et al* (2000). Results from the 2002 survey are detailed in Johnston and Digney (2002). In this report the analysis provides a combined survey result including the relationship between the pre- and post- fire SLR IVP and DORIS instrumentation (the GPS and GLONASS pillars remained undamaged). The IVP determination from the 1999 survey is excluded in this analysis for simplicity and only the 2002 and 2003 surveys are incorporated (although the independent IVP results from the 1999 survey are compared to later surveys in section 5.7).

Table 2: Mount Stromlo 2002 survey IVP determination observations

Axis	Number of targets	Description/Comment
Azimuth	4	*Elevation axis fixed at 90° from zenith;* *Azimuth axis rotated in 20° increments;* *Azimuth axis can rotate through 360°;* *System was observed from three standpoints, namely AU045, AU052 and AU054* *2 x targets were Leica precision prisms* *2 x targets were retro-reflective tape targets (on mount)*
Elevation 1st realization	3	*Elevation axis rotated in 5° increments;* *Elevation axis can rotate through 175°;* *Elevation axis realized from observations from AU045* *Targets were Retro-reflector tape.*
Elevation 2nd realization	3	*Elevation axis rotated in 10° increments;* *Elevation axis can rotate through 175° ;* *Elevation axis realized from observations from AU054* *Targets were Retro-reflector tape.*

Table 3: *Mount Stromlo 2003 survey IVP determination observations*

Axis	Number of targets	Description/Comment
Azimuth	3	*Elevation axis fixed at 90° from zenith;* *Azimuth axis rotated in 20° increments;* *Azimuth axis can rotate through 360°;* *System was observed from three standpoints, namely AU045, AU060 and AU061;* *Targets were Leica precision micro-prisms mounted magnetically onto the telescope.*
Elevation 1st realization	3	*Elevation axis rotated in ~10° increments;* *Elevation axis can rotate through 180°;* *Elevation axis realized from observations from the AU045;* *Targets were Leica precision micro-prisms mounted magnetically onto the telescope.*
Elevation 2nd realization	3	*Elevation axis rotated in ~10° increments;* *Elevation axis can rotate through 180° ;* *Elevation axis realized from observations from the AU060.* *Targets were Leica precision micro-prisms mounted magnetically onto the telescope.*

3.2.3 GPS

In the case of Mount Stromlo the GPS antenna (STR1) is removed during the survey and the monument is observed directly.

3.3.4 DORIS

The position of the DORIS antennas (pre-fire and post-fire) was determined indirectly by observation to the sides of the antenna at the physical red marker line. Observations are reduced by averaging and then intersected in the geodetic adjustment in the conventional manner.
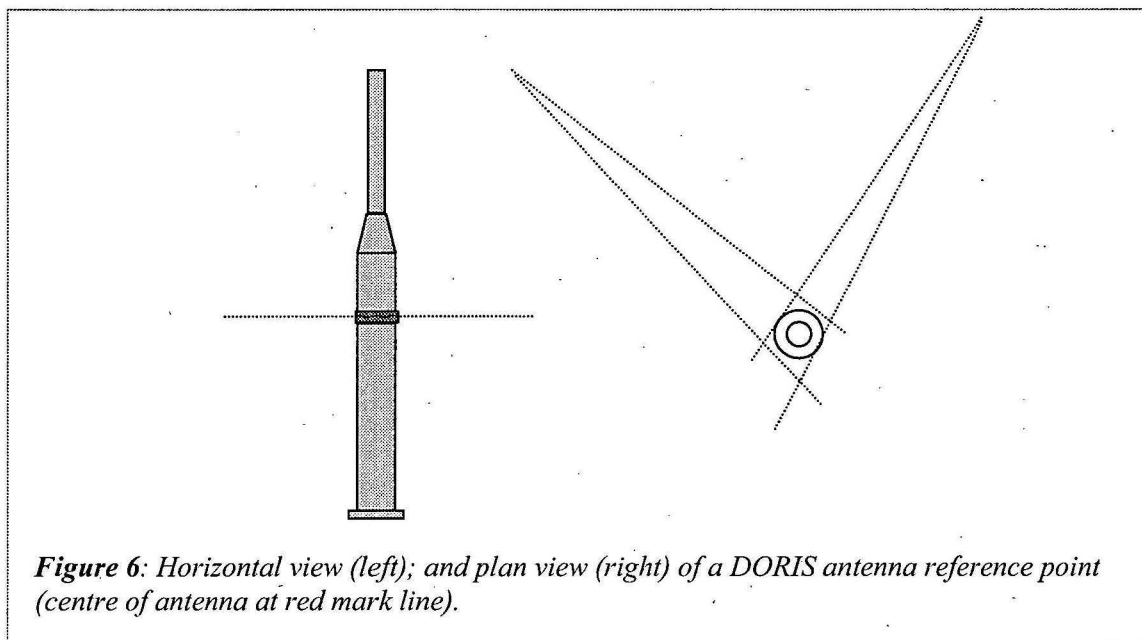
Figure 6: Horizontal view (left); and plan view (right) of a DORIS antenna reference point (centre of antenna at red mark line).

3.3.5 GLONASS

In the case of Mount Stromlo the GLONASS antenna is removed during the survey and the monument is observed directly.

4. Observations

4.1 Conventional survey

Generally five sets of observations were completed at each standpoint. A set consists of a round of face left observations, followed by the reverse round of face right observations. Slope distances and zenith angles were recorded for each observation as well. Atmospheric corrections were not applied in the instrument, but later applied to distances in post processing using conventional correction formulae and local meteorological observations.

The heights of instrument were observed using the technique illustrated in following figure. Vertical angles are observed to graduation boundaries on a normal levelling staff. This technique routinely returns values for height of instrument accurate to 0.1mm. The technique is strongest when the mid height of the levelling staff is approximately horizontal

from the instrument trunion axis. The technique relies on the height difference between the ground marks (H_1 and H_2) being determined independently to these observations. In the case of this survey the monuments were included in the levelling survey discussed in 4.2.

Observations to the targets during these rotational sequences consisted of a single set of dual face pointings, commencing and terminating on an external reference object (network station) for orientation.

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

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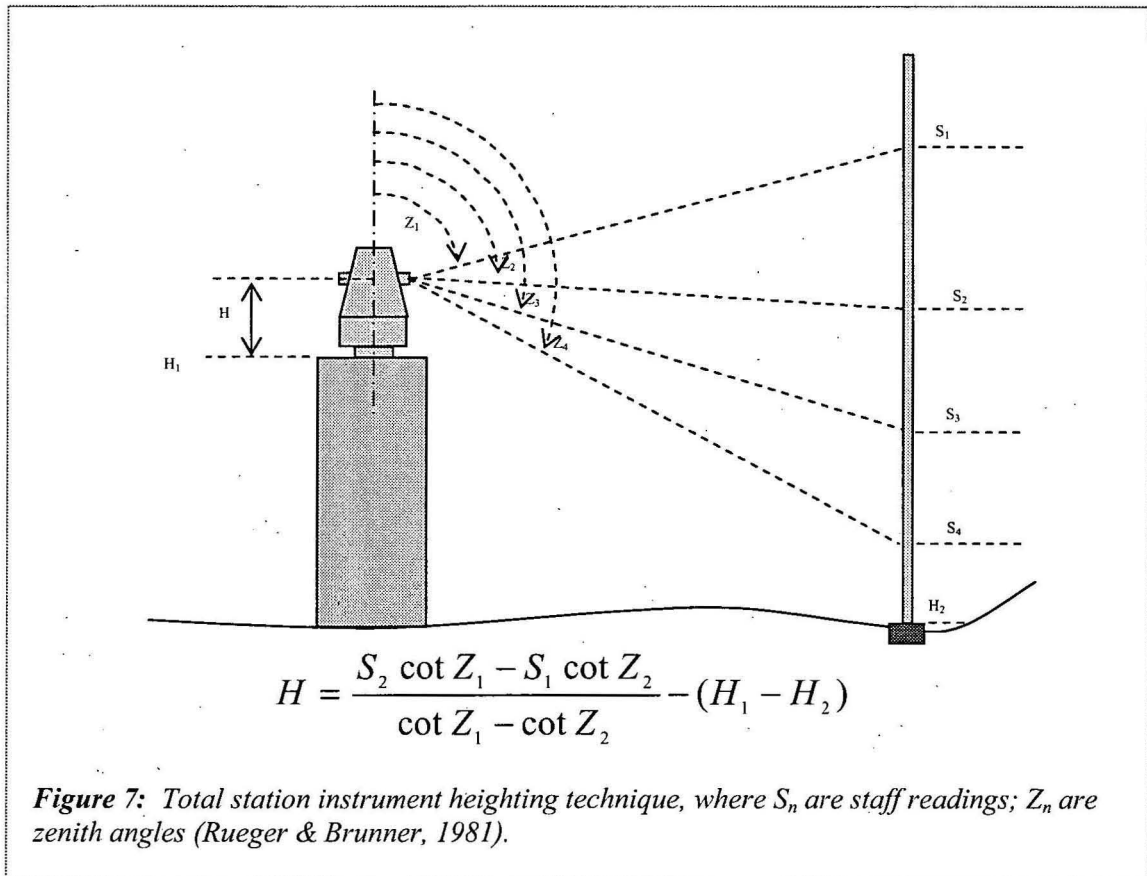
4.2 Levelling

The levelling for this survey was carried out using the EDM-height traversing technique. It comprises height difference observations to a prism mounted on a fixed height prism pole, which is braced by a bi-pole and placed over the survey mark. Differential heighting can then be achieved. This technique minimises thermal expansion effects and refraction caused by thermal flux since the lines of sight are near to parallel along the ground surface.

Where pillar monuments are used a fixed height prism mounting stub (approximately 0.2m in length) which screws directly onto the 5/8" Whitworth threaded stainless steel spigot is used.

Levelling loops covering all the monuments in the network were completed in both directions. The results were then adjusted in the least squares sense giving adjusted height differences between all marks.

Figure 8: *Mount Stromlo survey levelling observations. Direct observations between stations are shown as inter-connecting lines.*
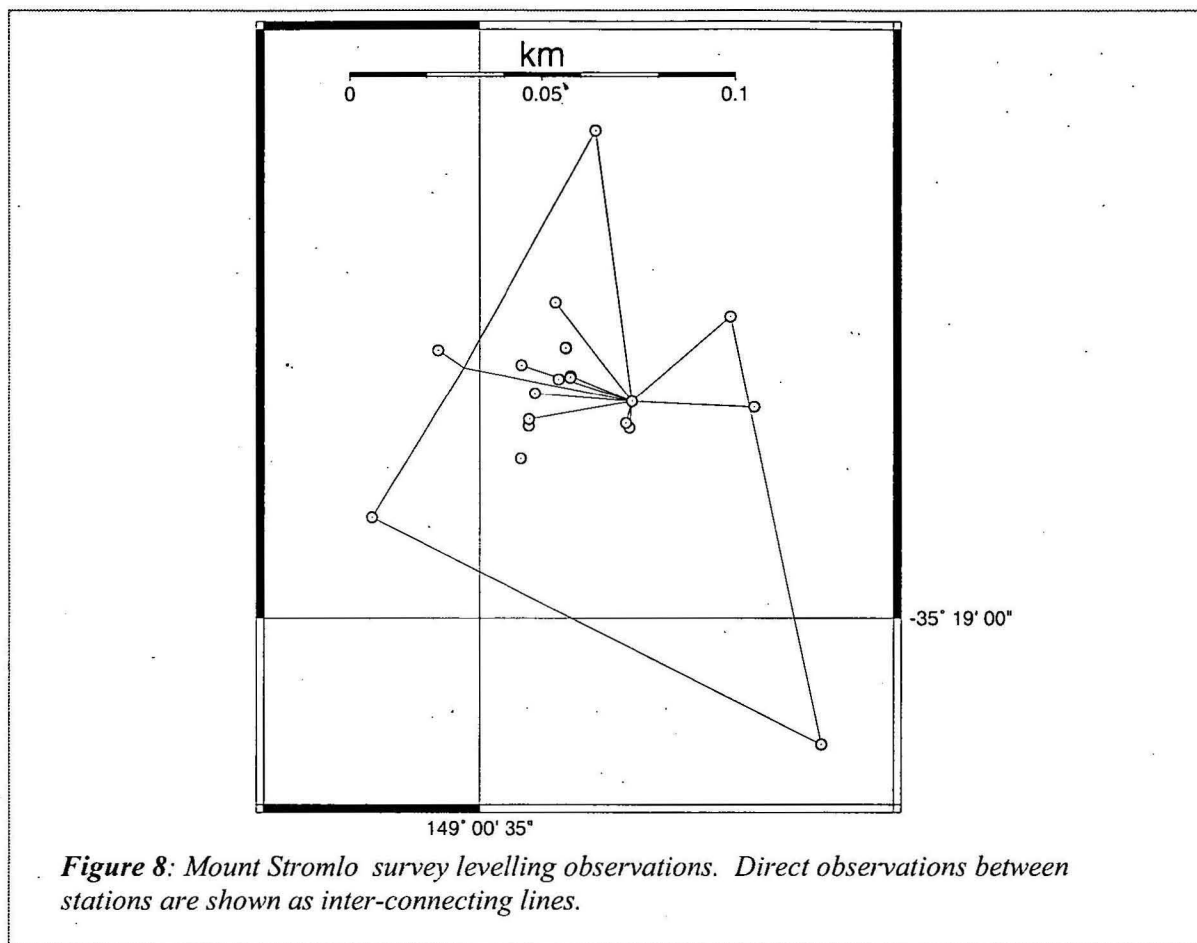
4.3 *GPS*

```
+SOLUTION/EPOCHS
*CODE PT SOLN T _DATA_START_ __DATA_END__ _MEAN_EPOCH_
 STR1  A    1 P 00:055:00000 02:365:86369 01:209:86384
 STR2  A    1 P 00:055:00000 02:365:86369 01:209:86384
-SOLUTION/EPOCHS
```

4.4 General comments

None.

5. Data Analysis and Results

The flow chart of the analysis process used for the Mount Stromlo survey is detailed in the below figure. Coordinate solutions are generated in three steps; firstly at the completion of the classical geodetic adjustment (*Step A*); secondly 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 thirdly after transformation (*in the case of Mount Stromlo no transformation is undertaken*) of the 'geometrically modified' solution onto the required global reference frame (*Step C*). In this report the results of *Step A* are reported in

section 5.1.2 and 5.1.3; and the results from *Step C* are reported in section 5.2.2, the results from *Step B* are not reported.
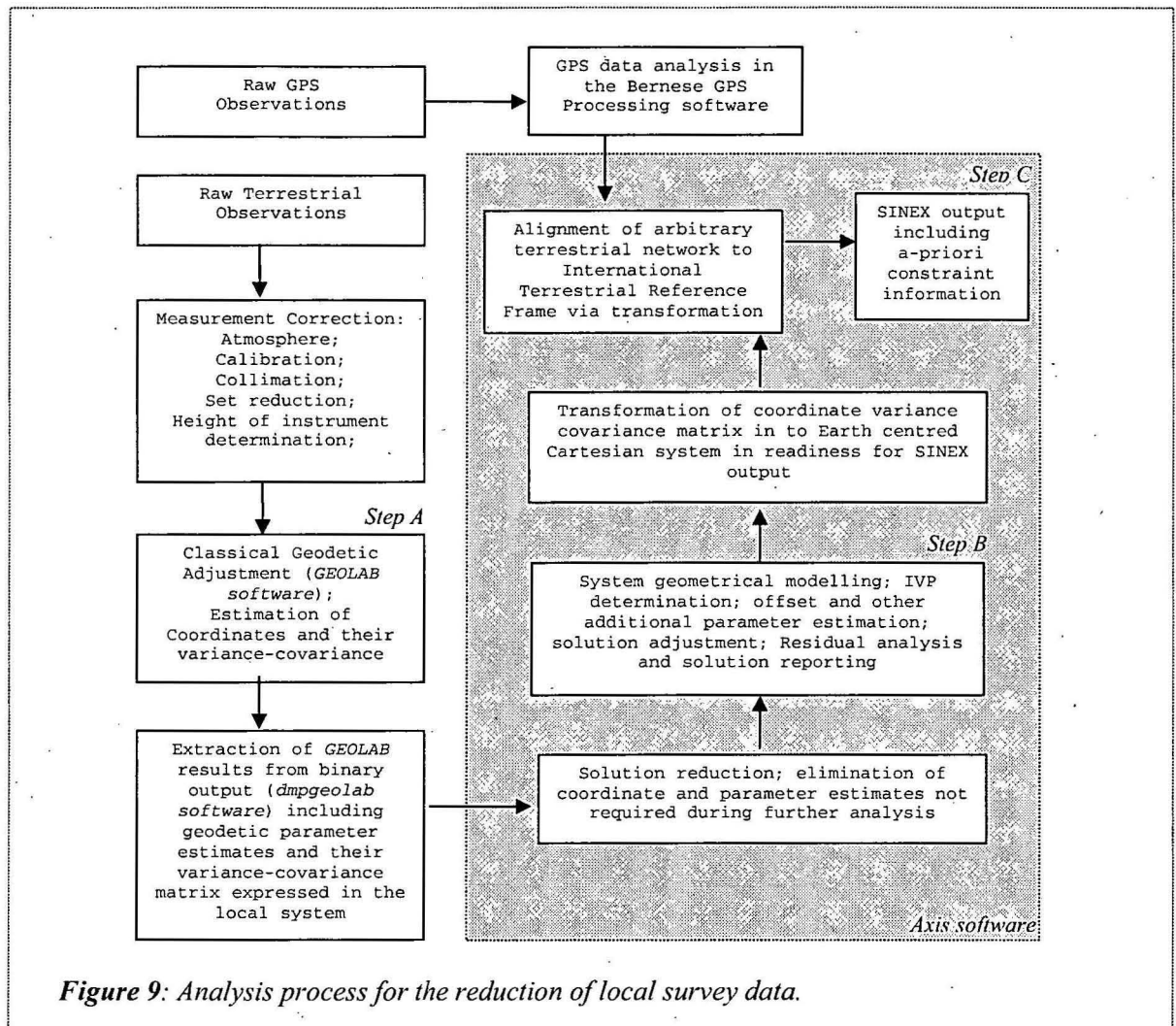
Figure 9*: Analysis process for the reduction of local survey data.*

5.1 Terrestrial Survey

5.1.1 Analysis Software

Classical geodetic adjustment is undertaken in *GEOLAB* version 2.4d. Deflections of the vertical and geoid undulation corrections were applied using *AUSGEOID98* (Johnston & Featherstone, 1998). Extraction of the solution data, including a full variance-covariance matrix, from the propriety binary GEOLAB format into ASCII format is undertaken using the Geoscience Australia developed *dmpgeolab* software (version 0.00). The geometrical modelling, adjustment and transformation processes are undertaken in the Geoscience Australia developed *axis* software (version 1.01).

5.1.2 Topocentric coordinates and covariances

Geodetic coordinates (GRS80 Ellipsoid) provided in the arbitrary local terrestrial system before alignment to the ITRF2000 are given below:

Table 4: Mount Stromlo terrestrial survey results. GRS80 ellipsoid. Heights are ellipsoidal, arbitrary local frame.

STATION		LONGITUDE			LATITUDE		HEIGHT (M)
	T2C	149	0	35.50259	-35	-18 -58.38678	798.4878
	TRIG	149	0	37.81782	-35	-18 -58.23026	801.4448
STR2 50119M001		149	0	36.55558	-35	-18 -58.18199	802.5289
	AU046	149	0	36.18784	-35	-18 -55.92246	799.7978
	AU047	149	0	37.57257	-35	-18 -57.47271	807.2183
	AU048	149	0	38.50905	-35	-19 -1.05753	801.5923
	AU049	149	0	33.88641	-35	-18 -59.15602	794.5575
	AU050	149	0	35.88177	-35	-18 -57.72982	802.7786
	AU051	149	0	35.80792	-35	-18 -57.99835	802.7731
STR1 50119M002		149	0	36.18784	-35	-18 -55.92246	799.9806
	AU055	149	0	35.77534	-35	-18 -57.35549	798.5758
	AU056	149	0	35.56806	-35	-18 -58.11699	799.3767
	AU060	149	0	35.42647	-35	-18 -57.88006	803.4251
AU61 50119M004		149	0	35.93058	-35	-18 -57.97225	804.3352
MSPB 50119S004		149	0	35.80790	-35	-18 -57.99826	803.4073
	AU046R	149	0	36.18762	-35	-18 -55.92325	799.9019
	AU047R	149	0	37.57169	-35	-18 -57.47300	807.3228
	AU048R	149	0	38.50839	-35	-19 -1.05687	801.6973
	AU049R	149	0	33.88721	-35	-18 -59.15552	794.6631
MSOB 50119S002		149	0	35.92795	-35	-18 -57.98266	804.9669
	HPGPSA	149	0	35.88259	-35	-18 -57.73843	802.9073
	NEWFPC	149	0	35.41872	-35	-18 -58.66234	799.0374
	SR1526	149	0	35.50800	-35	-18 -58.33221	798.4888
	EAU046B	149	0	36.18789	-35	-18 -55.92306	799.8995
	EAU047B	149	0	37.57196	-35	-18 -57.47306	807.3234
	EAU048B	149	0	38.50881	-35	-19 -1.05690	801.6953
	EAU049B	149	0	33.88706	-35	-18 -59.15575	794.6601
	GPSTIMEA	149	0	35.87568	-35	-18 -57.73673	802.9260
	U045RM1D	149	0	36.52772	-35	-18 -58.40630	800.9497
	U045RM2D	149	0	36.49137	-35	-18 -58.36587	800.9829
	U054RM1D	149	0	34.56783	-35	-18 -57.75293	797.2043

Figure 10*: Mount Stromlo Pure Terrestrial Network, error ellipses are 95% confidence. Error ellipses to targets on the Satellite Laser Ranging (SLR) system during rotational sequences are not shown. Direct observations between stations are shown as inter-connecting lines (excluding IVP observations).*
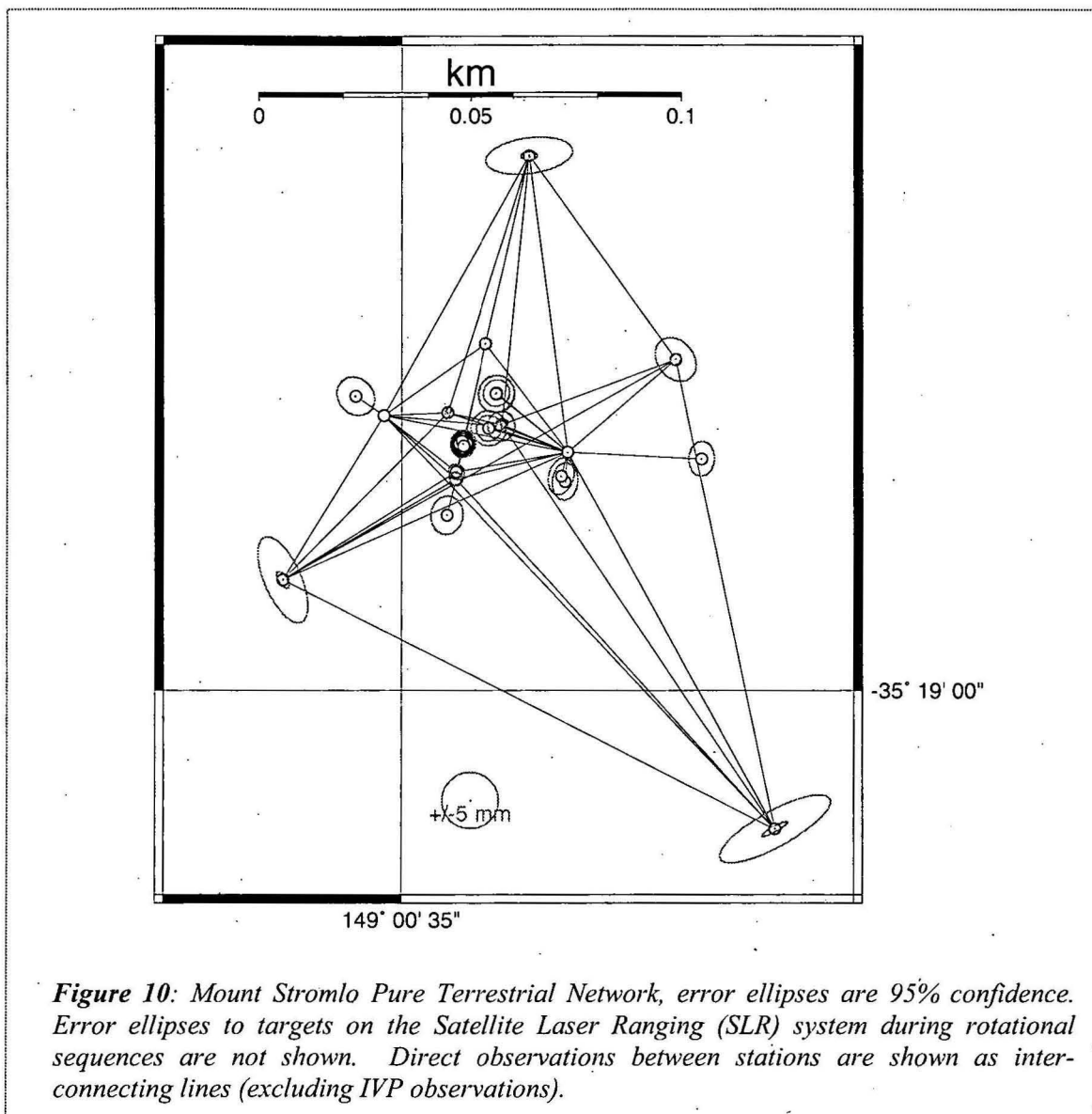
5.1.3 Correlation matrix

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

5.1.4 Reference temperature

No thermal corrections have been applied for structural expansion of the SLR instrument. Since the structure is small, thermal deformation is ignored.

5.2 GPS

5.2.1 Analysis software

The GPS data analysis was undertaken using the Bernese GPS Processing Software Version 4.2 (Hubentobler U., S. Schaer, P. Fridez, Bernese GPS Software Version 4.2, *Astronomical Institute, University of Berne, 2001*). International Terrestrial Reference Frame 2000 (ITRF2000) coordinates of the permanent GPS monument, *STR1 50119M002*, were adopted at the epoch of observation. Both L1 and L2 observations were used and no troposphere model parameters were estimated. The observations were processed to a 10° cut-off. Carrier phase ambiguities were resolved to their integer values in all cases. Final International GPS Service (IGS) orbits and Earth orientation parameters were used for computations. IGS recommended constant and elevation dependent antenna phase models were applied.

5.2.2 Results

Figure 11: Mount Stromlo GPS baseline time series between STR1 and STR2. Analysis indicates inter-pillar stability at the 1mm level although a sub-millimetre annual signal remains in the baseline (at this time most likely explained by pillar motion).
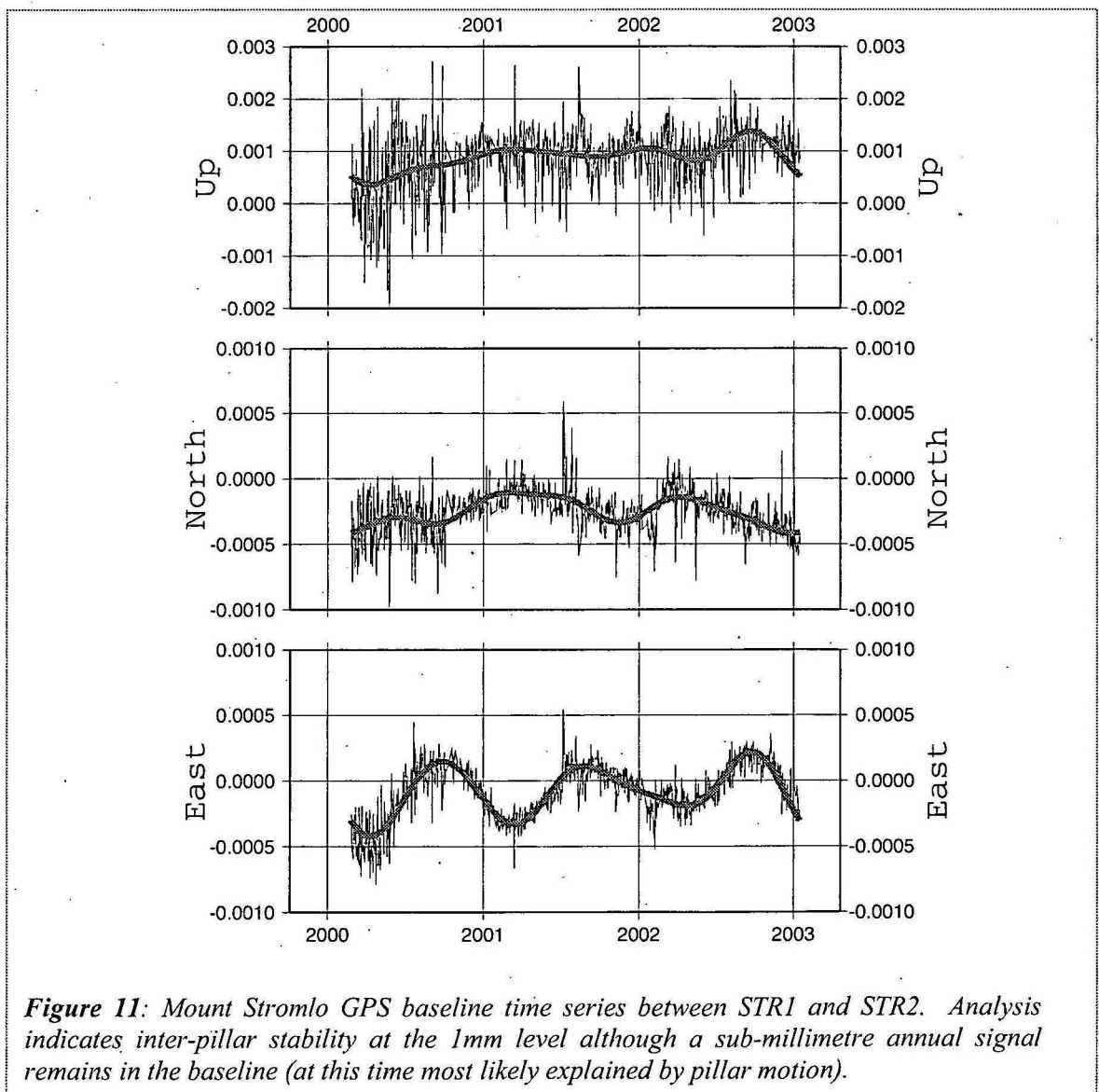
Table 5: *Mount Stromlo 2003 GPS survey results, GRS80 ellipsoid. Heights are ellipsoidal, ITRF2000 at 28 July 2001.*

```
 STATION                 LONGITUDE          LATITUDE      HEIGHT (M)

 STR1 50119M002     149    0  36.18783  -35  -18 -55.92240    799.9777
 STR2 50119M001     149    0  36.55558  -35  -18 -58.18199    802.5289
```

5.3 Additional Parameters

Additional system parameters were computed during the IVP estimation process.

For the IVP *7849 50119S001* the azimuth axis deflection from the vertical was estimated as 4.5" at an azimuth of 0° 18' 28.5". The orthogonality (or non-orthogonality) of the azimuth to the elevation axes was estimated to be 89° 55' 31.8". The offset distance between the azimuth and elevation axis was estimated to be 0.9 mm.

For the IVP *7825 50119S003* the azimuth axis deflection from the vertical was estimated as 48.8" at an azimuth of 243° 7' 52.5". The orthogonality (or non-orthogonality) of the azimuth to the elevation axes was estimated to be 89° 59' 25.9". The offset distance between the azimuth and elevation axis was estimated to be 0.4 mm.

Table 6: *Mount Stromlo, final results, topocentric vectors between SLR IVP (7825 50119S003) and permanently mounted calibration pillar reflectors.*

```
 STATION    EAST (M)    NORTH (M)      UP (M)    RANGE (M)

 AU046R     15.6583     67.6127     -5.1257     69.5912
 AU047R     50.6243     19.8456      2.2953     54.4237
 AU048R     74.2868    -90.6180     -3.3310    117.2230
 AU049R    -42.4574    -32.0131    -10.3644     54.1747
```

5.4 Transformation

Due to lack of GPS stations (i.e. only a two station network) the arbitrary terrestrial network was not aligned to the International Terrestrial Reference Frame by means of a six parameter transformation (three translations and three rotations) as is the usual approach. The network was aligned in azimuth using the GPS baseline between STR1 and STR2.

5.5 Description of SINEX generation

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 ***AUSSTRO0312GA.SNX***, and can be found at ftp://ftp.ga.gov.au/sgac/sinex/ties/. This file supersedes the SINEX file aus00c05.snx submitted to the International Earth Rotation Service (IERS) in 1999 for the ITRF2000 computation.

5.6 Discussion of results

Table 7: *Mount Stromlo, final results, geodetic coordinates, GRS80 ellipsoid (degrees, minutes, seconds, metres), ITRF2000 at 28 July 2001.*

STATION		LONGITUDE			LATITUDE		HEIGHT (M)
STR2 50119M001	149	0	36.55558	-35	-18	-58.18199	802.5289
STR1 50119M002	149	0	36.18784	-35	-18	-55.92246	799.9807
AU61 50119M004	149	0	35.93057	-35	-18	-57.97225	804.3352
MSOB 50119S002	149	0	35.80790	-35	-18	-57.99826	803.4073
MSPB 50119S004	149	0	35.92795	-35	-18	-57.98266	804.9669
7849 50119S001	149	0	35.56803	-35	-18	-58.11693	804.0794
7825 50119S003	149	0	35.56781	-35	-18	-58.11688	805.0273

Table 8: *Mount Stromlo, final precision estimates of the geodetic coordinates (1σ, metres).*

STATION	LONGITUDE (M)	LATITUDE (M)	HEIGHT (M)
STR2 50119M001	0.0001	0.0001	0.0001
STR1 50119M002	0.0001	0.0003	0.0012
AU61 50119M004	0.0008	0.0007	0.0010
MSOB 50119S002	0.0023	0.0028	0.0019
MSPB 50119S004	0.0024	0.0026	0.0026
7849 50119S001	0.0007	0.0005	0.0011
7825 50119S003	0.0006	0.0008	0.0009

Table 9: *Mount Stromlo, final results, cartesian coordinates (metres), ITRF2000 at 28 July 2001.*

STATION	X (M)	Y (M)	Z (M)
STR2 50119M001	-4467074.6878	2683011.8687	-3667007.8238
STR1 50119M002	-4467102.6351	2683039.4916	-3666949.5228
AU61 50119M004	-4467071.0251	2683028.0876	-3667003.5930
MSOB 50119S002	-4467068.3830	2683030.1159	-3667003.7108
MSPB 50119S004	-4467071.2739	2683028.3143	-3667004.2200
7849 50119S001	-4467063.9203	2683034.5043	-3667007.0839
7825 50119S003	-4467064.5814	2683034.9078	-3667007.6305

Table 10: *Mount Stromlo, final precision estimates of the cartesian coordinates (1σ, metres).*

```
STATION              X (M)        Y (M)        Z (M)

STR2 50119M001       0.0001       0.0001       0.0001
STR1 50119M002       0.0008       0.0005       0.0007
AU61 50119M004       0.0009       0.0008       0.0008
MSOB 50119S002       0.0021       0.0022       0.0022
MSPB 50119S004       0.0025       0.0025       0.0026
7849 50119S001       0.0009       0.0007       0.0008
7825 50119S003       0.0007       0.0007       0.0009
```

Table 11: *Mount Stromlo, final results, cartesian difference vectors (metres).*

```
FROM STATION         TO STATION        X(M)       Y(M)       Z(M)

7849 50119S001  -  STR2 50119M001    -10.7675   -22.6356    -0.7399
7849 50119S001  -  STR1 50119M002    -38.7148     4.9874    57.5611
7849 50119S001  -  AU61 50119M004     -7.1048    -6.4167     3.4910
7849 50119S001  -  MSOB 50119S002     -4.4627    -4.3884     3.3732
7849 50119S001  -  MSPB 50119S004     -7.3536    -6.1900     2.8639
7849 50119S001  -  7825 50119S003     -0.6611     0.4035    -0.5466

7825 50119S003  -  STR2 50119M001    -10.1064   -23.0391    -0.1933
7825 50119S003  -  STR1 50119M002    -38.0537     4.5839    58.1077
7825 50119S003  -  AU61 50119M004     -6.4437    -6.8202     4.0376
7825 50119S003  -  MSOB 50119S002     -3.8017    -4.7919     3.9197
7825 50119S003  -  MSPB 50119S004     -6.6925    -6.5934     3.4105
7825 50119S003  -  7849 50119S001      0.6611    -0.4035     0.5466
```

The least squares solution of the SLR IVP position included; 36 targets; 5 IVP estimates (constrained together); 1284 pseudo-observations; 252 unknowns; 69 additional unknowns; 846 conditions; 76 constraints and 178 additional constraints. The resultant linear system was 2705 x 2705 with degrees of freedom 2063. The computed variance factor was 0.00899. IVP model (circle) fit residuals were 0.9 mm Root Mean Square Error (RMS) for the in-plane residuals and 0.7 mm for the out-of-plane residuals.

The Root Mean Square Error (RMS) of the terrestrial coordinate observations to the IVP model were 1.1, 0.5 and 0.5 millimetres in the east, north and up components respectively, although antenna specific GPS antenna phase centre variations remain un-modelled in this analysis.
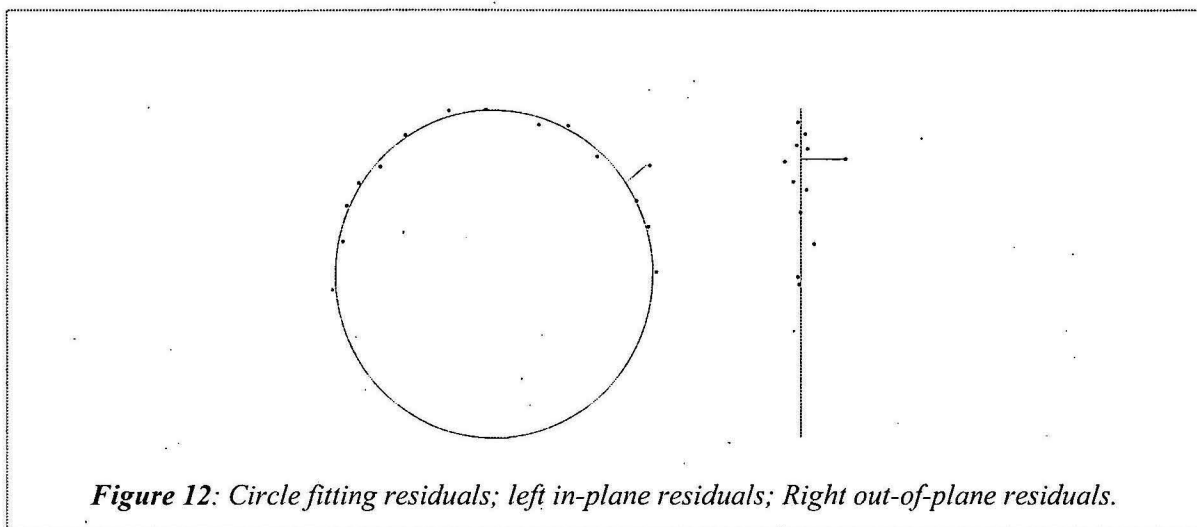
Figure 12: Circle fitting residuals; left in-plane residuals; Right out-of-plane residuals.

5.7 Comparison with previous surveys

In general there is good agreement between the 1999, 2002 and 2003 surveys. Because of this network stability the network realisations have been combined to provide a consistent multi-year local frame at the Mount Stromlo observatory.

Table 12: Residual between the combined survey and the 1999 survey.

Station Name	North (mm)	East (mm)	Up (mm)
AU045	0.1	-0.4	-0.4
AU046	1.4	-0.1	1.0
AU047	-0.7	-0.1	0.4
AU048	-1.3	0.9	-1.8
AU049	-0.1	-0.4	0.0
AU052	0.4	-0.3	1.2
AU054	0.1	0.3	-0.5
RMS	0.8	0.5	1.0

Table 13: Residual between the combined survey and the 2002 survey.

Station Name	North (mm)	East (mm)	Up (mm)
AU045	0.4	0.1	-0.1
AU046	1.3	-0.1	0.4
AU047	0.4	-0.1	0.1
AU048	-1.2	0.2	-0.5
AU049	0.2	0.3	-0.1
AU052	0.0	-0.4	0.3
AU054	-0.2	0.1	-0.0
RMS	0.6	0.2	0.3

Table 14: Residual between the combined survey and the 2003 survey.

Station Name	North (mm)	East (mm)	Up (mm)
AU045	-0.4	-1.2	0.1
AU046	-1.3	0.3	0.1
AU047	-0.1	0.3	-0.0
AU048	1.5	0.4	-0.0
AU049	1.5	0.6	-0.1
AU052	-1.5	0.2	-0.0
AU054	0.4	-0.6	-0.0
RMS	**1.2**	**0.6**	**0.0**

Table 15: AU054 difference from the 1999 position

	Delta East (mm)	Delta North (mm)	Delta Up (mm)
1999 survey	0.0	0.0	0.0
2002 survey	-2.1	-2.6	-1.0
2003 survey	-3.8	-0.9	-0.1

The replacement of axis bearings in the SLR system in late 2001 may account for the small differences between the 1999 determination of the *7849 50119S001* to the 2002 determination, namely -0.8, 0.4, -0.6 mm east north up components respectively. In the following table the positions of *7825 50119S003* relative to *7849 50119S001* are given for interest. Please note that the new SLR system was constructed in approximately the same horizontal position as the old system but approximately 0.95 metres higher.

Table 16: IVP determination coordinate relative to SLR IVP 7825 50119S003

	East (mm)	North (mm)	Up (mm)
7849 50119S001 1999 survey	5.1	-1.9	-948.6
7849 50119S001 2002 survey	5.9	-2.3	-948.0
7825 50119S003 2003 survey	0.0	0.0	0.0

6. Planning Aspects

The Mt Stromlo SLR facility uses a fully enclosed telescope space to avoid dust, pollen and moisture influences on the telescope optics. During the local tie survey a secondary window is removed from the surrounding dome allowing observational access. Care should be taken during the survey to avoid rain or dusty periods.

The calibration pillars are free standing steel poles with an external steel shroud. The ladder and standing platforms are fixed to the external shroud. However, motion of the shroud still manages to translate into centre pole movement. As such observations to the calibration pillars should not be undertaken while people are present on the structure.

The coordinates of the calibration pillar monuments are derived through the survey process. The computation of the effective point of reflection of the EOS calibration reflectors relies upon the measurement of the prism offset and height external to the survey process. For this survey this has been completed on the Watson EDM baseline, Australian Capital Territory (ACT). In the future more in-depth analysis of these prisms offsets needs to be completed.

For observations from the two roof mounted poles (AU060 and AU061), a scissor lift basket or scaffolding needs to be used to ensure the safety of the observer, as well as minimising the vibration or impact on the roofing through which the pillars pass. A safety harness should also be used.

The timing of future surveys needs to be negotiated with the contract operator (EOSSS) to avoid unnecessary negative impact on ranging productivity, especially for high priority satellite missions.

7. References

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