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2010 Katherine VLBI Observatory Local Tie Survey

Technical Report

Ryan Ruddick

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Australian Government
Geoscience Australia

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Executive Summary

The integrity and strength of multi-technique terrestrial reference frames, such as realisations of the International Terrestrial Reference Frame (ITRF), depend on the precisely measured and expressed local-tie connections between space geodetic observing systems at co-located observatories. Australia has several observatories which together host the full variety of space geodetic observation techniques, including Global Navigation Satellites Systems (GNSS), Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) beacons.

This report documents the technical aspects of the survey undertaken to determine the local-tie connections at the Katherine VLBI Observatory. The Observatory is located at the Charles Darwin University campus near Katherine in the Northern Territory. The Observatory has a 12 m radio telescope that is used for VLBI, co-located with two permanent GNSS sites, one of which contributes to the International GNSS Service (IGS) network. The survey was conducted in July 2010 by surveyors from Geoscience Australia. Precision classical geodetic observations were combined with geodetic GNSS observations to determine for the first time the relationship between the VLBI system invariant point (IVP) and the conventional reference points of the GNSS antennas and the surrounding survey control.

The results of this survey have been provided to the International Earth Rotation Service (IERS) for inclusion in the next realisation of the ITRF.

1 Introduction

1.1 Methodology

This report is not written to serve as a manual for precision geodetic 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 reports the results of each major computation step. For an in-depth analysis and justification of the approach taken the reader is referred to Dawson et al, 2007. For completeness the steps in our approach for observation and computation of local-ties relationships are as follows:

1.1.1 Field Observations

- The calibration of all geodetic instrumentation,
- The observation of a vertical geodetic network,
- The observation of a horizontal geodetic network,
- The observation of a GNSS network on at least three suitable survey marks,
- The observation of targets located on the observing system during rotational motion about each of its independent axis, including the observation of zenith angles to a staff on levelled survey marks for the precise determination of instrument height.

1.1.2 Data Reduction

- The reduction of the terrestrial geodetic observations, including correction for instrument and target bias, set reduction and atmospheric effects,
- The estimation of coordinates and their associated variance-covariance matrix in a local system, through a classical geodetic least squares adjustment (minimum constraint),
- The estimation of the system IVP, the axes of rotation and associated system parameters, such as axis orthogonality and offset,
- The analysis of the GNSS observations,
- The transformation (translation and rotation) of the terrestrial network, computed system IVP and variance-covariance matrix onto a global reference frame defined by the GNSS analysis.

1.1.3 Reporting

- The coordinate estimates and their associated variance-covariance information is provided to the IERS and made available on-line (<ftp.ga.gov.au>) in the form of a SINEX file.

1.2 Site Description and Contacts

The Katherine Observatory is located at the Charles Darwin University campus, near Katherine in the Northern Territory. The observatory was established in 2010 and has a VLBI telescope co-located with two permanent GNSS sites. The Observatory is operated by the University of Tasmania's School of Mathematics and Physics.

Before undertaking the survey the following people should be consulted in regards to site access, survey timing and interference with observing systems:

Site Contact: Tony Lyle – Charles Darwin University
Email tony.lyle@cdu.edu.au
Phone +61 8 8973 8308

Site Contact: Martin Ephgrave – Charles Darwin University
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Phone +61 3 6226 2410

GNSS Contact: Ryan Ruddick – Geoscience Australia
Email ryan.ruddick@ga.gov.au
Phone +61 2 6249 9426

2 Instrumentation

This section provides the specifications and calibration procedures of the equipment used in the survey.

2.1 Tachymeters, EDM and Theodolites

2.1.1 Description

A Leica TM30 (S/N 361445) total station was used to record all angles and distance measurements.

2.1.2 Specification

- EDM (infrared) distance standard deviation of a single measurement (DIN 18723, part 6): 0.6 mm $\pm$ 1 ppm.
- Angular standard deviation of a mean direction measured in both faces (DIN 18723, part 3): 0.3 mgon ($\approx 1^\circ$).

2.1.3 Calibration

The Leica TM30 (S/N 361445) was purchased new prior to this survey, the assumption was made that the instrument was in calibration upon delivery.

2.2 Meteorological Sensor

2.2.1 Description

A NK Kestrel 4000 Pocket Weather Tracker (S/N 516991) was used to record meteorological observations (temperature, pressure and relative humidity).

2.2.2 Specification

- Temperature is accurate to 1.0°C between -29.0°C and 70.0°C.
- Pressure is accurate to 1.5 mb at 25°C between 750 mb and 1100 mb.
- Relative humidity is accurate to 3.0%.

2.3 Forced Centring

2.3.1 Description

An FG0L30 (S/N 609030) zenith and nadir optical plummet was used to centre and level all instrument and target setups.

2.3.2 Specification

- Accuracy is 1:30 000 (1 mm at 30 m).

2.4 Targets and Reflectors

2.4.1 Description

The standard target kit includes:

- 4 x Leica GDF21 tribrachs.
- 4 x Leica GZR3 prism carriers with optical plummet.
- 4 x Leica GPH1P precision prisms.
- 6 x Leica GMP101 mini prisms.

2.4.2 Calibration

The additive constant for the Leica GPH1P precision prism is -34.4 mm which was applied directly into the Leica TCA2003 total station. All prisms were calibrated on a tripod baseline at Geoscience Australia in July 2009. Approximate prism corrections of 0.0 mm were applied to observations during data processing.

Leica GMP101 mini prisms were calibrated at Geoscience Australia in July 2009. Approximate prism corrections of +18.5 mm were applied to observations during data processing.

2.5 Precision Levelling

2.5.1 Levelling Instruments

Refer to section 2.1 for a description of the Leica TM30 total station.

2.5.2 Levelling Rods

A fixed height stainless steel rod (ARGN3) approximately 1.6 m in height with Leica style bayonet mount on top for mounting a precision prism was used with a Leica bi-pod for stability.

A fixed height stainless steel stub (Stub3) approximately 0.2 m in height with Leica style bayonet mount on top for mounting a precision prism.

A height offset between the pole (ARGN3) and the stub (Stub3) was determined by observing both on a low mark. Multi-set, dual face observations were used to eliminate collimation effects. The resulting height offset was 1.4061 m.

2.5.3 Levelling Staff

A Topcon fibreglass levelling staff was used in the determination of precise instrument heights.

2.6 Tripods

2.6.1 Description

Leica GST20/9 heavy duty timber tripods with adjustable legs were used on all marks with the exception of the pillars.

2.7 GNSS Equipment

2.7.1 Description

Geodetic quality GNSS equipment was used in the survey, alongside the equipment used on the permanent GNSS sites KAT1 and KAT2. The GNSS kit used includes:

- Trimble NETR5 GNSS receiver (S/N 4614K01058)
- Leica AT504GG GNSS antenna (S/N 200687)

2.8 Site Specific Equipment

2.8.1 Description

- Bayonet style target mounts were installed at four locations on the underside of the dish of the VLBI telescope. The mounts have been left in place.
- Magnetic target mounts were used on the substructure of the telescope during rotations of the azimuth axis.

3 Measurement Network

3.1 Terrestrial Network

3.1.1 Primary Survey Control Points

Table 3.1 The primary survey control points observed during the survey.

Name	4-Char ID	DOMES	Description
GNSS KAT1	KAT1	59968M001	The intersection of the top of the stainless steel plate with the vertical axis of the 5/8 inch Whitworth threaded stainless steel spigot.
GNSS KAT2	KAT2	59968M002	The intersection of the top of the stainless steel plate with the vertical axis of the 5/8 inch Whitworth threaded stainless steel spigot.
KAT3	KAT3	-	The intersection of the top of the stainless steel plate with the vertical axis of the 5/8 inch Whitworth threaded stainless steel spigot.
VLBI KAT12	7375	59968S001	The intersection of the azimuth axis with the common perpendicular of the azimuth and elevation axes of the 12 m radio telescope.
KAT1 RM1	KRM1	-	Punch mark in the dome of a deep driven stainless steel rod.
KAT1 RM2	KRM2	-	Punch mark in the dome of a deep driven stainless steel rod.
KAT1 RM3	KRM3	-	Punch mark in the dome of a deep driven stainless steel rod.

3.2 Representation of Reference Points

3.2.1 VLBI Reference Point

There is one radio telescope used for geodetic observations at the Katherine Observatory. The telescope is a 12 m VLBI2010 azimuth-elevation style and was established in 2010. The reference point of the telescope, referred to as the system invariant point (IVP), is a theoretical point defined by the intersection of the azimuth axis with the common perpendicular of the azimuth and elevation axes. An indirect survey was used to determine this point.

3.2.2 GNSS Reference Point

There are two permanent GNSS antennas at the Observatory. The antennas are mounted on pillars attached to bedrock with the antennas aligned to true north. The conventional reference point for the antennas is described as the intersection of the top of the stainless steel pillar plate with the vertical axis of the 5/8 inch Whitworth threaded spigot. In both cases this point corresponds with the antenna reference point (ARP). All of the antennas were removed during this survey.

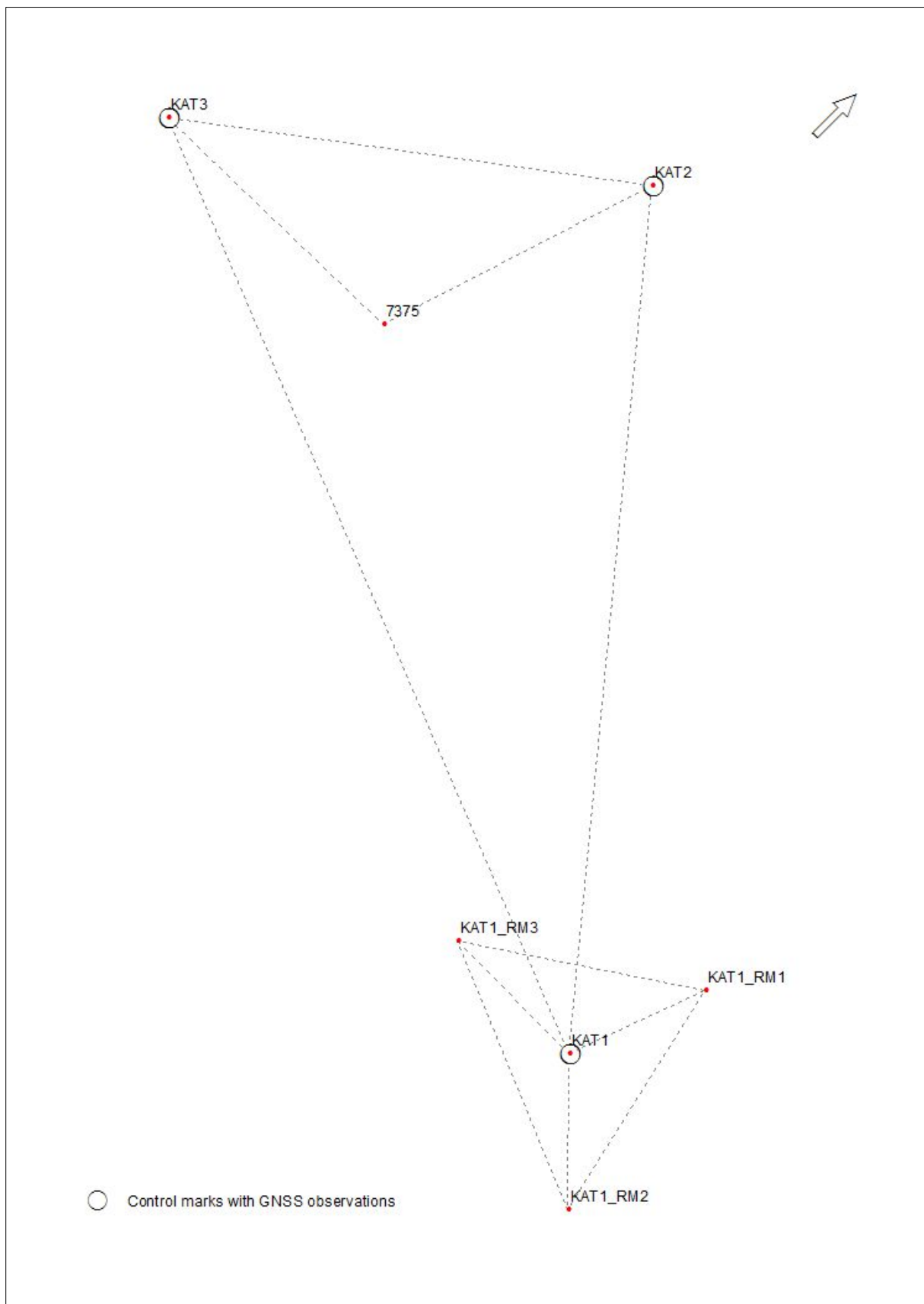


Figure 3.1 Katherine Observatory terrestrial survey network

4 Observations

4.1 Terrestrial Observations

4.1.1 Horizontal Control Survey

A terrestrial network survey was conducted between the permanent survey marks within the Katherine Observatory. Five sets of observations were completed at each standpoint; a set consists of a round of face left observations, followed by a round of face right observations to each of the visible survey marks. For each observation a horizontal direction, zenith angle and slope distance was recorded. At each instrument set-up atmospheric conditions (temperature, pressure and relative humidity) were recorded. Atmospheric conditions were applied during post-processing and not directly into the total station. Instrument and target heights were measured using an offset tape.

During the survey the GNSS antennas were removed and direct observations made to and from the survey pillars.

4.1.2 Vertical Control Survey

Precise levelling was conducted between the survey pillars and reference marks using the EDM height traversing technique (Reuger and Brunner 1981). Height difference observations were made using a Leica TM30 total station to a prism mounted on a fixed height stainless steel pole and to a fixed height stainless steel stub. Atmospheric conditions (temperature, pressure and relative humidity) were recorded every 30 minutes and entered directly into the total station.

Levelling loops to all monuments in the survey network were completed in both directions. Each instrument set-up involved reading three rounds of face left and face right observations to a single prism set-up over two marks.

4.2 GNSS Observations

Static GNSS observations were collected in a 24 hour session on the observation pillar KAT3, along with the two permanent GNSS sites KAT1 and KAT2.

4.3 Indirect Terrestrial Observations

4.3.1 VLBI Telescope

The VLBI telescope was observed from two instrument standpoints (KAT2 and KAT3). From each standpoint one set of observations was made to each of the visible targets. Each set of observations consists of a round of face left observations, followed by a round of face right observations. For each observation a horizontal direction, zenith angle and slope distance was recorded. Every 60 minutes

atmospheric conditions (temperature, pressure and relative humidity) were recorded. Atmospheric conditions were applied during the post-processing and not directly into the total station. After each set of observations the telescope was rotated in set increments for first azimuth and then elevation, until the telescope was rotated through 360° for azimuth and 180° for elevation.

At each standpoint the height of instrument was determined before and after each observation session using the technique described by Reuger and Brunner (1981). The measurement technique involved the observation of a single round of face left and face right vertical angles to specific graduations on a levelling staff (in this case 2.0, 1.6, 1.2 and 0.8 m) placed on two nearby, levelled survey marks.

4.3.1.1 Azimuth Axis

For the azimuth axis:

- Observations were made from the standpoints KAT2 and KAT3.
- Five mini prisms were mounted to the substructure of the telescope using magnetic mounts.
- The elevation axis was fixed at vertical (stowed).
- The azimuth axis was rotated in 20° increments through 360°.

4.3.1.2 Elevation Axis

For the elevation axis:

- Observations were made from the standpoints KAT2 and KAT3.
- Six mini prisms were mounted to the substructure of the telescope using a combination of magnetic mounts and fixed mounts that were drilled into specific points.
- The azimuth axis was fixed at 180° and 71° for the standpoints respectively.
- The elevation axis was rotated from 88° to 0° in 10° increments.

5 Data and Analysis

5.1 Process

The data analysis can be split into five steps:

- Data Reduction – angular sets reduced, prism offsets and atmospheric applied,
- GNSS Analysis – coordinates estimated in a global reference frame,
- Classic Geodetic Adjustment – coordinates estimated in a local reference frame,
- IVP Determination – system reference points and tie vectors estimated,
- Transformation – alignment of the survey to a global reference frame.

5.2 Data Reduction

5.2.1 Orthometric Levelling

5.2.1.1 Procedure

The levelling observations were reduced using Geoscience Australia's levelling reduction application. Height differences were determined between all survey marks. The misclosure was noted as being well within zero order specifications. The results were added into the survey adjustment with a precision of 0.0002 m.

5.2.1.2 Results

Table 5.1 Orthometric heights (in metres) derived with respect to KAT1 from the 2010 survey compared with the surveys undertaken by the Northern Territory surveys at the time of construction (2009) and after a period of settlement (2010a). The precisions for the height differences are also listed for the points used in the classic geodetic adjustment.

KAT1 to ...	2009	2010a	2010b	σ (m)
KRM1	-1.4194	-1.4188	-1.4184	-
KRM2	-1.9164	-1.9165	-1.9166	-
KRM3	-1.9345	-1.9344	-1.9345	-
KPBM	-1.1679	-	-1.1679	-
KAT2	-0.0815	-0.0814	-0.0823	0.0002
KAT3	-1.5468	-1.5463	-1.5474	0.0002

5.3 Data Processing

5.3.1 Geodetic Adjustment

5.3.1.1 Procedure

The geodetic adjustment was undertaken using DynaNet (v 3.08) (Fraser et al, 2013). In the adjustment KAT1 was minimally constrained to its ITRF2008 coordinates along with an azimuth of 321°07'10.23" to KAT2. The angular observations were given a precision of 1.5" and the slope distances given a base precision of 1.0 mm. The estimated coordinates and associated variance-covariance matrix in a local topocentric system was outputted as a SINEX file.

5.3.1.2 Results

Table 5.2 Local topocentric vectors (in metres) between KAT1 and the surrounding survey control from 2010.

KAT1 to ...	de	dn	du
KAT2	-82.7837	102.6664	-0.0839
KAT3	-142.2530	58.9130	-1.5492

5.3.2 GNSS Analysis

5.3.2.1 Procedure

GNSS data analysis was undertaken using the Bernese (v 5.00) GNSS processing software. ITRF2008 coordinates of the permanent GNSS station KAT1 59968M001 were adopted and GPS L1 only observation used in a local solution. No troposphere models were estimated and observations processed to a cut off angle of 10°. IGS final orbit, Earth orientation parameters and elevation dependent antenna phase centre models were applied.

5.3.2.2 Results

Table 5.3 Cartesian coordinates (in metres) with 1 σ precision estimates, aligned to the ITRF2008 coordinates of KAT1 from the GNSS analysis.

Station ID	X	Y	Z
KAT1	-4147413.5095 $\pm$ 0.0000	4581462.6994 $\pm$ 0.0000	-1573359.5716 $\pm$ 0.0000
KAT2	-4147369.2450 $\pm$ 0.0006	4581537.0846 $\pm$ 0.0006	-1573260.0286 $\pm$ 0.0002
KAT3	-4147316.9098 $\pm$ 0.0006	4581567.8857 $\pm$ 0.0006	-1573302.0444 $\pm$ 0.0002

5.4 IVP Determination

5.4.1 Procedure

The geometrical modelling and adjustment processes were undertaken in Axis (v 1.08) (Dawson et al, 2007). The SINEX file containing the estimated coordinates and variance-covariance matrix in a local topocentric reference frame was used as input for Axis.

The method of IVP determination involves the derivation of independent axes of rotation of the telescope through a process of 3-dimensional circle fitting to the 3-dimensional coordinates of targets observed at points on the telescope during rotational sequences. A least squares method was used for the computation of the axes of rotations and the system IVP. The method works on the basis that a target located on a rigid body, rotating about one independent axis can be fully expressed as a circle in 3-dimensional space and described by seven parameters:

- A circle centre (3 parameters),
- A unit normal vector, perpendicular to the circle (3 parameters),
- A circle radius (1 parameter).

The method of IVP determination makes assumptions that:

- During a rotational sequence target paths scribe a perfect circular arc in 3-dimensional space,
- There is no deformation of the targeted structure during rotational sequence,
- There is no wobble error,
- The axis of interest can be rotated independently of the other axis.

No assumptions of axis orthogonality, verticality / horizontality or the precise intersection of axes are made.

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

- Target paths during rotations 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 derived from targets observed while being rotated about the same axis are forced to be parallel,
- The orthogonality of the primary axis to the secondary axis remains constant over all realisations of the secondary axis,
- Identical targets rotated about a specific realisation of an axis will scribe 3-dimensional circles of equal radius,
- The offset distance between the primary and the secondary axis remains constant over all realisations of the secondary axis,
- The distance between 3-dimensional circle centres for all realisations of the secondary axis are constant over all realisations of the secondary axis,
- The IVP coordinate estimates remain constant over all realisations (combinations) of the primary/secondary axis.

In addition, a constraint that the unit normal vector perpendicular to the plane of the circle must have a magnitude of one applied and a minimum of three rotational sequences for each target was required to enable the solution of the equation of a circle.

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

$$Av + B\Delta = f \quad (1)$$

$$D_1\Delta + D_2\Delta' = h \quad (2)$$

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 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 matrices of coefficients. The least squares solution is obtained from the following system of normal equations:

$$\begin{bmatrix} -W & A^t & 0 & 0 & 0 \\ A & 0 & B & 0 & 0 \\ 0 & B^t & 0 & D_1^t & 0 \\ 0 & 0 & D_1 & 0 & D_2 \\ 0 & 0 & 0 & D_2^t & 0 \end{bmatrix} \begin{bmatrix} v \\ k \\ \Delta \\ k_c \\ \Delta' \end{bmatrix} = \begin{bmatrix} 0 \\ f \\ 0 \\ h \\ 0 \end{bmatrix} \quad (3)$$

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

The solution to the normal equation is iterated as required for 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.

The solution for the IVP included 690 observations to 22 targets. There were 2 estimates of the IVP for the point 7375 59968S001 which were constrained together through 38 separate constraints. The resultant linear system for the network was 690 x 690 with 1112 degrees of freedom. The computed variance factor was 0.181. The maximum circle fit residual was 1.0 mm.

5.4.2 Results

Along with the coordinate estimates and associated variance-covariance matrix in a local reference frame, the following system parameters specific to the telescope were determined:

- The azimuth axis deflection of the vertical is 0°00'11.01".
- The orthogonality of the azimuth to elevation axis is 89°59'20.50".
- The offset distance between the azimuth and elevation axis is 0.0031 m.

Table 5.4 Local topocentric vectors (in metres) between 7375 and the surrounding survey control from 2010.

7375 to ...	de	dn	du
KAT1	97.1717	-59.3554	-4.9592
KAT2	14.3883	43.3114	-5.0408
KAT3	-45.0813	-0.4420	-6.5058

5.5 Global Alignment

The estimated coordinates in a local reference frame are usually aligned during this step to a global reference frame, such as an ITRF realisation, using the estimated GNSS coordinates. The transformation, a translation and rotation only (6 parameters), is performed using Axis (Dawson et al, 2007). In this situation the global transformation was not undertaken due to a significant difference in the GNSS derived and orthometric derived height of KAT2.

The alignment of the survey from the classical adjustment was used.

Table 5.5 Final Cartesian coordinates (in metres) with 1σ precision estimates, aligned to the ITRF2008 coordinates of KAT1 and an azimuth between KAT1 and KAT2 as calculated from the GNSS observations.

Station ID	X	Y	Z
7375 59968S001	-4147354.5837 $\pm$ 0.0003	4581542.3983 $\pm$ 0.0004	-1573303.3059 $\pm$ 0.0003
KAT1	-4147413.5095 $\pm$ 0.0000	4581462.6994 $\pm$ 0.0000	-1573359.5716 $\pm$ 0.0000
KAT2	-4147369.1902 $\pm$ 0.0002	4581537.0941 $\pm$ 0.0002	-1573260.0990 $\pm$ 0.0003

5.6 Comparison

There are no previous surveys to compare the results with.

References

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