The Determination of Telescope and Antenna Invariant Point (IVP)

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1 Introduction

The development of multi-technique International Terrestrial Reference Frames such as ITRF2000 (Altamimi, 2002) has focussed attention on the need to precisely measure and express the local terrestrial connection between each of the complimentary space geodetic observation systems, such as GPS, GLONASS, SLR, VLBI and DORIS, at co-located geodetic observatories. Somewhat complicating this endeavour has been the difficulty of defining and measuring the relationship between the measurement reference points for each of the techniques. This is particularly the case for the SLR and VLBI observing systems where the reference point, sometimes referred to as the invariant reference point (IVP), is in general not able to be directly observed.

At Geoscience Australia an approach has been developed for estimating the observation reference point of such systems using an indirect technique of coordinating targets on the measurement systems during specific rotational sequences of the telescope/antenna system. Using a geometrical model the characteristics of the rotational axes, which importantly include their position and orientation in an arbitrary local geodetic datum, and the position of the invariant reference point can be estimated. This approach utilises full variance-covariance information of the target and local reference geodetic network and does not assume target symmetry about the final system reference point, idealised axis orientation (i.e. axis verticality/horizontality), axes orthogonality or precise intersection. Local terrestrial connections of an accuracy of 1mm (in the local frame) are routinely observed and computed between the GPS, VLBI, SLR, GLONASS and DORIS systems located in Australia, at Tidbinbilla, Yarragadee, Hobart and Mount Stromlo.

2 IVP determination

In the general case for both SLR and VLBI the IVP cannot be directly measured and must be determined indirectly by observation to targets on the system structure during rotational sequences. A rigorous least-squares analysis that utilises all target coordinates and their variance-covariance information can then be used to determine the system IVP.

There are three common system type characteristics, namely azimuth/elevation systems (fixed vertical axis); X/Y systems (fixed horizontal axis) and HA/DEC systems (fixed axis points to the celestial pole). Somewhat complicating reference point determination for many systems is

- the fixed (or primary axis) and the moving (or secondary axis) axis may not intersect (and are in some cases many metres apart, see Fig. 1);
- the system's structural design can constrain the visibility and hence the number and network design of line of sight observations;

- observations are generally made from below up onto the systems structure therefore limiting network design;
- often there are domes covering the structure that significantly limit visibility; and
- many system have limited rotational freedom reducing the reliability of axis determination.

3 Survey Accuracy

In order to make a significant contribution to the space geodetic technique comparison the accuracy of the local survey should match/better accuracy of the space geodetic techniques. At present a carefully observed terrestrial survey has an accuracy of around 1 mm in the local frame, however aligning a local survey to a global reference frame cannot be completed at the 1 mm level. A total error budget for a fully aligned local tie survey at the 3 mm accuracy level seems at this time achievable.

At Geoscience Australia classical geodetic observations including slope distance and vertical/horizontal angles and precise differential levelling are

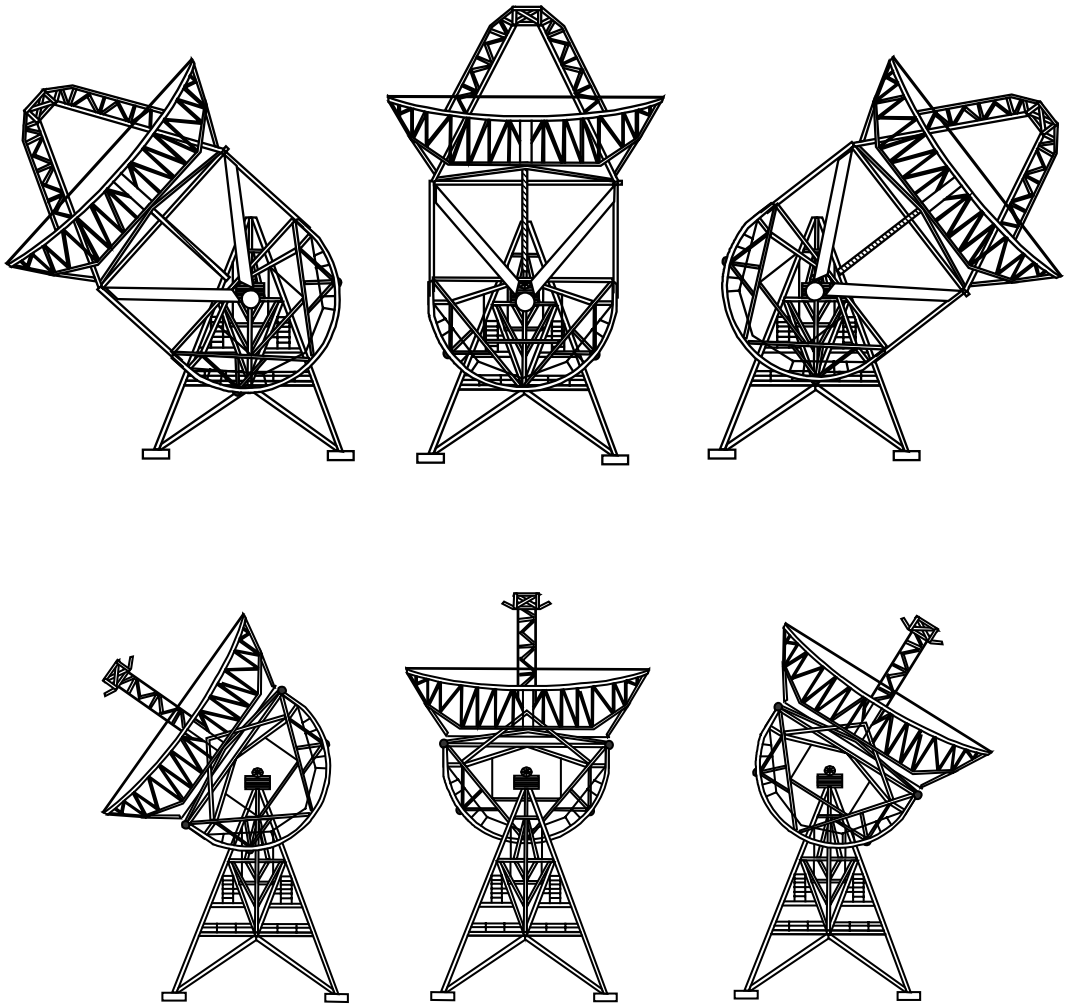

Figure 1. An X/Y antenna design. Top; view along the rotation of the X (primary) axis. Bottom; view along the rotation of the Y (secondary) axis (90° to top view). Note that this antenna design is similar to the Hobart VLBI system.

used. Precise differential levelling is used for the transfer of height and the precise height of instrument determination. Observations into the antenna/telescope system are generally made from multiple instrument standpoints, but the final network design depends on system configuration. The observations made from the standpoints are also made from within highly over-determined local geodetic network.

The classical geodetic observations are reduced in a pre-processing step that includes observation reduction, formatting, application of observation corrections including theodolite error, atmospheric, prism offsets, geoid corrections. Classical least squares geodetic adjustment is undertaken using the propriety software GEOLAB 2.4d.

4 Assumptions

The Geoscience Australia indirect approach to the determination of a system IVP relies on a number of assumptions, namely; during rotational sequence target paths scribe a perfect circular arc in 3D space (that is, there is no deformation of targeted structure during rotational sequence and there is no axis wobble error); and the primary axis can be held fixed during rotational sequence of secondary axis.

5 Axis Determination

A circular arc in space can be described by seven parameters, namely three circle centre parameters, three normal parameters (i.e. a normal vector to the plane of the circle) and a radius parameter, see Fig. 2. Initially individual circle arcs are determined from each target observed during the rotational sequence. The axes are computed using in-house developed least squares analysis software that inputs the coordinate values and variance-covariance matrix from the classical geodetic adjustment. The estimation of 3D circle parameters is undertaken constraining circle parameters where appropriate i.e. a target observed from two difference standpoints should define two circles with equal radius parameters and two targets observed on an identical axis should define two circles with equal normal parameters, see Fig 3. Residual analysis and outlier detection is also performed at this stage on the computed in-plane and out-of-plane residuals, see Fig. 4.

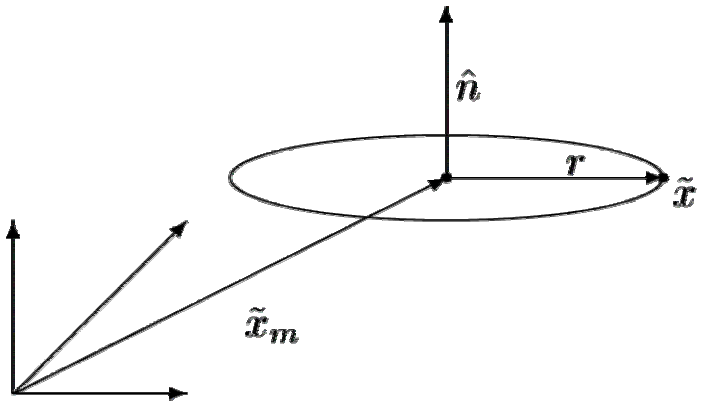

Figure 2: The seven parameters of a circle in 3-dimensional space.

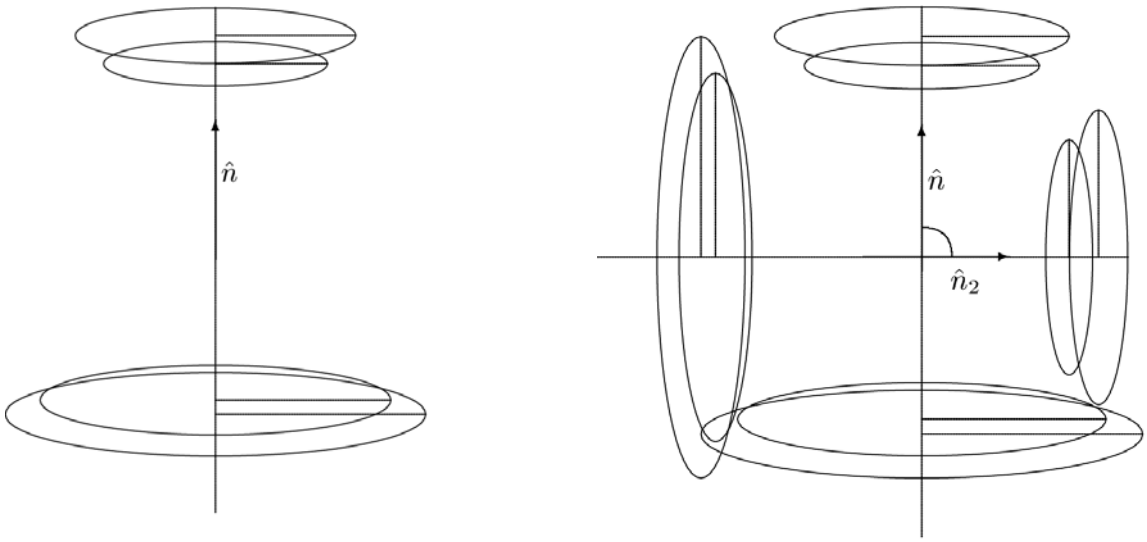

Figure 3. Inter-circle parameter relationships. Left; multiple target arcs share common normal vector parameters. Right; identical targets observed from different standpoints share common radius parameter estimates.

6 IVP determination

The determination of the IVP can then follow using the axis parameter and their associated variance-covariance matrix computed previously. In the case of intersecting systems (i.e. where the primary and secondary axes intersect), such as the Yarragadee SLR, the IVP can be computed using least square estimate of intersection point of the axes. Of course the assumption of precise intersection should first be tested both experimentally and from engineering data (if available).

In the case of non-intersecting systems, such as the Hobart VLBI, the IVP can be determined by the least squares estimate of the common perpendicular of the axes. The IVP is defined as the intersection of the primary axis and the common perpendicular between the primary and secondary axes, see Fig. 5.

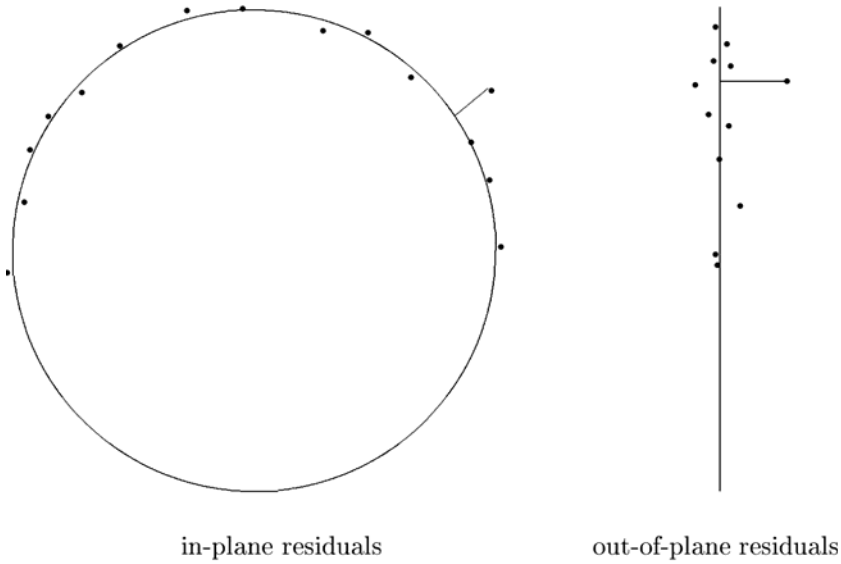

Figure 4: Circle fitting residuals.

The determined coordinates of the IVP and all stations important for co-location and their associated variance-covariance information is then ex-

tracted from the analysis software and input into the GEOLAB geodetic adjustment software. The geodetic adjustment output is then translated directly into SINEX format output.

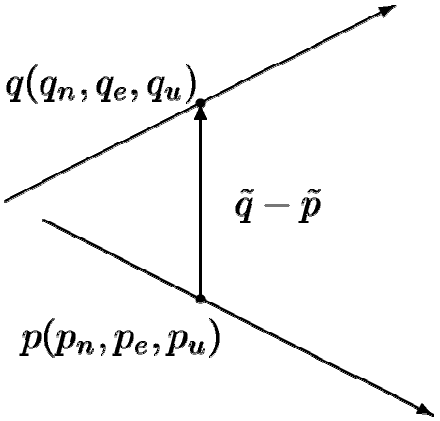

Figure 5: The common perpendicular of secondary axis (top) and primary axis (bottom) gives the IVP at the intersection with the primary axis. Point P gives the adopted definition of the IVP.

7 Australian Precision Survey Results

The number of target pointings onto the observatory structure made during the rotational sequences for each survey is summarised in Table 1. In general the systems are rotated to maximise the arc length of the target trajectory in 10° increments, although in many cases physical obstruction and rotational freedom limit the number of observations.

Table 1: Number of target pointings onto system structure.

Observatory (date)	Target-shots
Mount Stromlo (1999)	373
Mount Stromlo (2001)	224
Yaragadee (1998)	285
Yaragadee (2001)	243
Tidbinbilla DSS45 - 34m (1995)	101
Hobart - 26m (1995)	91
Hobart - 26m (2002)	298

In Table 2 the Root Mean Square (RMS) of the in-plane and out-of-plane residuals to the primary axis determination of each of the Australian observatory surveys are given. The larger RMS values of the out-of-plane residuals at Tidbinbilla and Hobart are thought at this time to result from the use of retro-reflective tape targets and as of yet un-modelled structural deformation of the antenna systems. Table 3 shows the in-plane and out-of-plane residuals of the secondary axis determination of each of the Australian observatory surveys.

Table 2: Root Mean Square (RMS) of in-plane and out-of-plane observation residuals to primary axis.

Observatory (date)	System Type	RMS in-plane residual (mm)	RMS out-of-plane residual (mm)
Mount Stromlo (1999)	AZ/EL	1.1 (AZ)	0.7 (AZ)
Mount Stromlo (2001)	AZ/EL	0.5 (AZ)	0.7 (AZ)
Yarragadee (1998)	AZ/EL	0.6 (AZ)	0.4 (AZ)
Yarragadee (2001)	AZ/EL	0.5 (AZ)	0.4 (AZ)
Tidbinbilla (1995)	AZ/EL	0.8 (AZ)	8.9 (AZ)
Hobart (1995)	X/Y	0.2 (X)	4.0 (X)
Hobart (2002)	X/Y	0.3 (X)	7.9 (X)

Table 3: Root Mean Square (RMS) of in-plane and out-of-plane observation residuals to secondary axis.

Observatory (date)	System Type	RMS in-plane residual (mm)	RMS out-of-plane residual (mm)
Mount Stromlo (1999)	AZ/EL	1.1 (AZ)	0.7 (AZ)
Mount Stromlo (2001)	AZ/EL	0.5 (AZ)	0.7 (AZ)
Yarragadee (1998)	AZ/EL	0.6 (AZ)	0.4 (AZ)
Yarragadee (2001)	AZ/EL	0.5 (AZ)	0.4 (AZ)
Tidbinbilla (1995)	AZ/EL	0.8 (AZ)	8.9 (AZ)
Hobart (1995)	X/Y	0.2 (X)	4.0 (X)
Hobart (2002)	X/Y	0.3 (X)	7.9 (X)

In Table 4 the RMS of the distance of the estimated IVP to each of the estimated axes are given. A large IVP to axis distance is indicative of the non-intersection of the axes. The estimated offset between the primary and secondary axes are also given, at Hobart an offset of 8.193 metres exists.

Table 4: Per target RMS distance of IVP to axis.

Observatory (date)	System Type	RMS IVP to axis distance (mm)	Primary axis to Secondary axis distance (mm)
Mount Stromlo (1999)	AZ/EL	3.6	1.9
Mount Stromlo (2001)	AZ/EL	1.6	0.8
Yaragadee (1998)	AZ/EL	0.6	0.3
Yaragadee (2001)	AZ/EL	1.2	0.4
Tidbinbilla (1995)	AZ/EL	7.0	7.6
Hobart (1995)	X/Y	-	8193.2
Hobart (2002)	X/Y	-	8193.0

As an additional quality check of the estimation process the Root Mean Square (RMS) minimum distance between each of the estimated axes can be computed and reviewed, see Table 5.

Survey to survey repeatability can also be reviewed as a check on the computation process. From Table 6 it can be seen that terrestrial tie repeatability is at the 1mm level. The exception to this is Yaragadee, which is thought to be indicative of the non-stability of the Yaragadee survey network. This has

been confirmed through precise levelling between all station marks at the Yaragadee observatory.

Table 5: Per target RMS distance of axis to axis distance (East, North, Up).

Observatory (date)	NorthRMS IVP to axis (mm)	East RMS IVP to axis (mm)	Up RMS IVP to axis (mm)
Mount Stromlo (1999)	0.1	0.3	2.1
Mount Stromlo (2001)	0.9	1.0	0.9
Yaragadee (1998)	0.4	0.3	0.4
Yaragadee (2001)	0.4	0.2	0.9
Tidbinbilla (1995)	2.3	4.1	0.9
Hobart (1995)	0.7	1.6	0.8
Hobart (2002)	0.4	1.6	0.4

Table 6: Survey to survey repeatability. Direct vector comparison from the observatory primary reference mark to the system IVP. An additional direct vector comparison between the Yaragadee GPS and SLR is also given.

Observatory	IVP	East IVP to reference mark (mm)	North IVP to reference mark (mm)	Up IVP to reference mark mm)
Mt Stromlo (1999-2001)	SLR	-0.3	-0.4	0.4
Yarragadee (1998-2001) (from IGS GPS YAR1)	SLR	0.0 (-0.8)	1.9 (1.5)	-1.3 (-4.2)
Hobart (1995-2002)	VLBI	-1.2	-0.3	-0.4

8 Final Remarks

To date terrestrial tie survey precision at each of the Australian geodetic observatories is approximately one millimetre (in the local frame). The further error due to the alignment to the International Terrestrial Reference Frame is more difficult to quantify but is assumed to be of the level of three millimetres but is heavily dependent on the quality/correctness of the associated GPS analysis used for alignment to the global frame.

Survey results indicate to date that the use of retro-reflective tape produces unsatisfactory results at the precision demands of this application and therefore there use in the future is to be avoided. The impact of differential refraction is yet to be fully quantified and may be significant particularly on VLBI surveys where survey observations are generally made from ground level up over several tens of metres onto the VLBI antenna structure. Structural deformation of the VLBI structure has not yet been incorporated in to the IVP determination process and remains a challenge for future survey analysis.

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References

Altamimi-Z.; Sillard-P.; Boucher-C., ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications. J. Geophysical Research, 107, ETG 2-1 to ETG 2-19, 2002.