TERRESTRIAL SURVEYING APPLIED TO LARGE VLBI TELESCOPES AND ECCENTRICITY VECTORS MONITORING

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Abstract: Large VLBI telescopes undergo gravitational deformations which affect both geodetic and astronomic observations as well as the real reference point (RP) position (i.e. the reference point which is directly linked to and determined by the physics of the VLBI observations). As a consequence, the accuracy of eccentricity vectors determined with high precision terrestrial observations strictly depends on the possibility of univocally defining the geodetic instrument's RP to be surveyed and estimated: technique dependent effects (e.g. gravitational and thermal deformations for VLBI, phase centre variations for GPS, etc) bias RP positions and weaken and perturb the information contained in the eccentricity. The impact on combined geodetic products is remarkable; a proper definition of space geodetic instruments' RP must therefore account for possible biases that modify its theoretical position. Whether the problem must be directly addressed by each technique-specific Service is still an open issue. Indirect approaches based on high precision terrestrial observations have proved to be additional, accurate and independent tools for determining and monitoring the eccentricities at co-location sites. Nevertheless, a deeper and rigorous investigation on RP location's variations is at least as important and it is nowadays fundamental for each space geodetic instrument. To this respect, we are presenting the investigations on VLBI telescope's RP position that were carried out at Medicina and Noto (Italy) on the 32 m antennas: trilateration, triangulation and laser scanning observations were applied and combined to monitor the gravitational deformations which affect the telescope's structure and to derive an elevation dependent correction function for radio signal path.

1. INTRODUCTION

The global geodetic network is an extraordinary observational tool capable of ensuring continuous provision and constant monitoring of main geodetic observables. Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Doppler Orbit determination and Radiopositioning Integrated on Satellite (DORIS) are the geodetic techniques that, to a various extent, contribute in studying the Earth: its shape, its gravity field and its rotational motion. The Global Geodetic Observing System (GGOS), the International Association of Geodesy's (IAG) fundamental scientific project, relies on the availability and quality of geodetic observations provided by each technique. To this respect, co-locations realized worldwide at several observatories are key elements of the geodetic network: co-located sites are fundamental for assessing the performances of each single geodetic instrument in monitoring geodetic parameters and for providing and ensuring the quality of combined geodetic products such as the International Terrestrial Reference Frame (ITRF) (Altamimi et al. 2007). In particular, this latter is a priority to GGOS (Altamimi et al. 2005) since it is a basic product for establishing a common and precise frame for integrated Earth observations and interoperability of geoscientific instruments.

Combinations of single techniques' frames as well as combinations of site specific geodetic parameters (e.g. Kruegel et al. 2007) rely on the availability of accurate intra site vectors (or eccentricities or tie's vectors) between the reference points of each co-located space geodetic instrument; in order to be effective, these vectors must be accurate at the mm level (Ray and Altamimi, 2005). A local tie is a difficult process where theory, practice and know-how must be opportunely blended with the purpose to recover the space geodetic instruments' reference point position as accurately as possible. Local ties are usually performed via terrestrial surveying measuring, in particular, zenith and azimuth angles, distances and height differences. On very small networks, these measurements can be performed very accurately and can effectively represent the fundamental data set for an independent estimation of the eccentricity and of the local ground control network. Although trivial, a first fundamental characteristic of the modern space geodetic global network should be highlighted at this point: the network is materialized by the ITRF tracking points (i.e. the points used as reference in the space geodetic observations) which can be very different from one another. In particular, according to the initial classification introduced for the MERIT (Monitor the Earth Rotation and Intercompare the Techniques of observations) project, tracking points can either be "classically" materialized using a geodetic marker (type M) or coincide with a conventional, instrument-dependent reference point (type S). If, in the first case, terrestrial surveying approach is very well suited and extensively used for surveying purposes, in the second case terrestrial observations must be exploited in such a manner that the position of the "S" tracking point is, to a certain extent, indirectly recovered.

A further complication originates when taking into consideration the different nature of space geodetic reference points. An attempt to rationalize this topic unavoidably deals with a fundamental trichotomy underlying the definition of space geodetic reference points that can be summarised as follows:

1. Electronic reference point is the point where the technique specific observable is acquired e.g. the phase centre of the GPS antenna, VLBI receiver and DORIS beacon and the photodetector in the SLR telescope.
2. Conventional reference point is the point identified by each specific technique service according to a theoretical definition e.g. the point of the fixed axis which is at minimum distance from the moving axis for VLBI telescopes; the Antenna reference Point (ARP) for GPS and DORIS; the intersection of the axes for SLR instruments.
3. Stochastic reference point is the outcome of an estimation procedure based on data processing, despite the particular kind of observations eventually processed (i.e. terrestrial or space geodetic).

Therefore, any attempt to estimate the position of a geodetic instrument results in defining point N.3, using observations acquired at point N.1 which are, in common practice conventionally referred to point N.2. This trichotomy originates part of the problems related to the definition and maintenance of space geodetic networks: unavoidably, point N.1 has to be linked to point N.2 (it is the point used to define the network) using technique dependent models (e.g. phase centre variations files in GPS) which are not perfect. Further troubles arise from the relative instability of point N.1, which can vary with time because of different reasons (e.g. gravitational deformations in VLBI telescopes).

This paper focuses on the different procedures that must be set up when aiming at defining point N.2 through terrestrial observations; on the surveying side, the different approaches that have been adopted are quite different and very likely have an impact on the final result (point N.3). In particular, there are basically three surveying approaches depending on the assumptions that can be reliably applied to the specific survey: a direct method, a hybrid method or an indirect method (Sarti and Angermann 2005). The consequences of such a choice are remarkable, both in terms of surveying strategy and efforts, computational capabilities (particularly at terrestrial data post-processing level) and amount of acquired measurements and information. Next Section 2 will focus on indirect method: characteristics, potentialities, flexibility and efficiency. It will shortly illustrate one of the most interesting aspects of indirect method: the geometric conditioning of terrestrial observations.

Section 3 presents some results that were obtained with the data acquired at the Italian VLBI-GPS co-location sites of Medicina: only the most relevant aspects will be discussed while the interested reader will be referred to proper literature.

Section 4 will give an outlook of the potentialities of terrestrial techniques applied to gravitational deformation monitoring of large VLBI telescopes such as those of Medicina and Noto, with particular emphasis on the realization of an elevation dependent model of signal path variation capable of realizing a specific antenna-dependent connection between point N.1 and point N.2.

2. REFERENCE POINT SURVEYING: INDIRECT METHOD

There are no precise and official guidelines regarding the terrestrial surveying approach to be applied when aiming at recovering the position of a space geodetic instrument's reference point. Despite eccentricity vectors estimation is the common and final objective of local ties, this task can be pursued in three ways, at least (Sarti and Angermann 2005):

- Direct method: the reference point of the space geodetic instrument is materialized by a geodetic marker; this latter may be surveyed directly (or via an ex-centre point of known eccentricity) and the tie vector's endpoints are estimated in a classical manner in the terrestrial data adjustment.
- Hybrid method: it mainly applies to VLBI and SLR instruments, where the tracking point is not identified by a geodetic marker (it is usually a type "S" point) and it is defined according to the axes of rotation of the telescope (see Sect. 1). Some targets are installed on the instrument's structure so as to "materialize" the axes of rotations and define the reference point (see e.g. Nothnagel et al. 2002).
- Indirect method: it entirely relies on geometric conditioning applied to observed targets' positions. For VLBI and SLR instruments, the targets are installed on the telescopes' structure which is moved (rotated) around its axes of rotation. A geometric model is applied to the circular paths scribed by the targets with the

purpose to define, as accurately as possible, the conventional reference point (see e.g. Dawson et al. 2005). Similarly, indirect method can be applied to GPS and DORIS instruments applying symmetry considerations on the terrestrial observations. A detailed discussion on indirect method applied to all space geodetic instruments can be found in Sarti et al. (2004).

This classification may be regarded as a general attempt to outline the basic principles of the surveying approaches that have been applied so far. Some surveys might have eventually mixed the different approaches, according to the experience, technical skills, local peculiarities and personal understandings of the teams involved in the surveys. The method adopted for surveying most likely has a remarkable impact on the eccentricity estimate; a pilot project was proposed as part of the activity of International Earth rotation and Reference systems Service (IERS) Working Group 2 on Site Survey and Co-location Sites: an eccentricity to be contemporarily surveyed at the same co-location site to test and to compare the three methods and to evaluate the possible discrepancies. Due to different reasons, the pilot project did not totally meet its objectives and this interesting issue has not been completely investigated, yet (for details see: http://www.iers.org/MainDisp.csl?pid=68-38)

2.1. Geometric conditioning

In order to recover VLBI and SLR reference points, indirect methods have been successfully applied in the past at different co-location sites (Johnston and Dawson 2004, Johnston et al. 2004, Sarti et al. 2004). The circular paths scribed by n targets during telescope's rotations are indirectly linked to the position of the reference point: the centres of the 3-D arcs belong to the axes of rotation and these latter locate, by definition, the reference point of the instrument. Figure 1 shows a rotation of target *j-th* around the azimuth axis for an AZ-EL telescope.

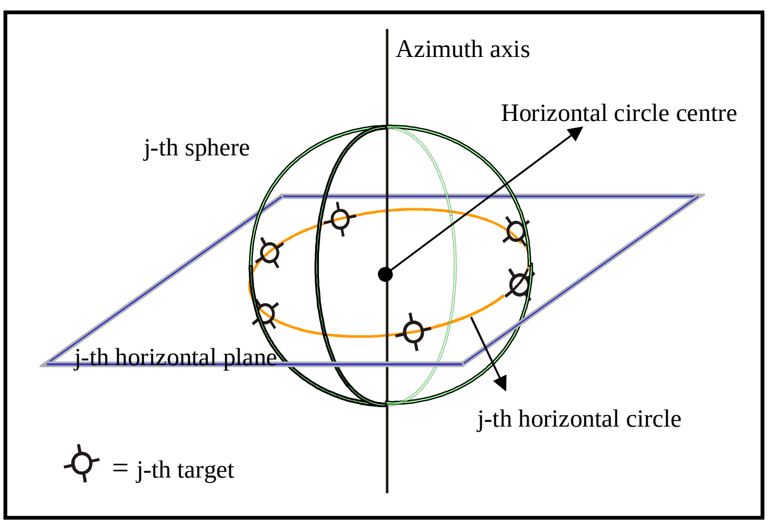

Figure 1: - Azimuth rotation, horizontal circle centre, sphere and plane

The intersection between the horizontal plane containing the target during its motion and the sphere centred on the azimuth axis determines the planimetric coordinates of the reference point. Analogously, the centres of the arcs scribed by the targets as the telescope moves in elevation belong to the elevation axis; for VLBI telescopes, the arcs are usually ¼ of a circle because they cannot rotate more than 90 deg in elevation; this is usually not the case in SLR systems. Figure 2 shows a rotation of target *i-th*: the vertical plane containing the arc, the corresponding sphere, the centre of rotation and the elevation axis are represented.

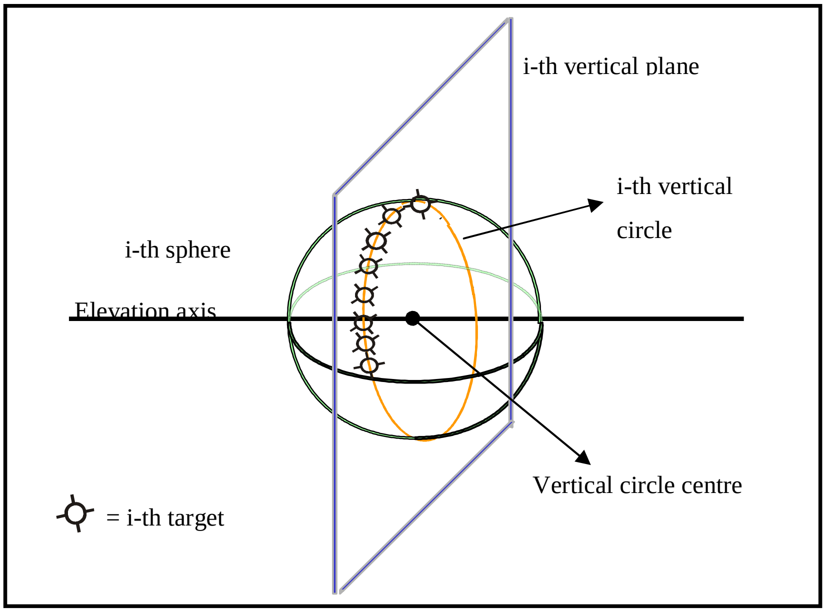

Figure 2: - Rotation in elevation of target *i-th*: definition of the elevation axis

A key issue pertaining to indirect method is the optimal selection of proper geometric conditioning applied to targets' coordinates obtained in the terrestrial data adjustment. Therefore, the problem reduces to a 3-D analytical geometry computation with redundant observations and it can therefore be treated in a statistical manner.

The conditions are applied to targets' positions *after* the terrestrial data adjustment with a house made software specifically developed for this task. The software may eventually read the output of the terrestrial data analysis, along with its full variance-covariance matrix so as to preserve the complete statistical information up to the final estimate of the eccentricity (Sarti and Angermann 2005). The software is capable to output the eccentricity in SINEX format.

The number and quality of geometric conditions can, to a large extent, be varied and this makes indirect method very flexible: it has been proved that the selection of conditions has an impact on the accuracy of the final reference point estimate (Dawson et al. 2007). Figure 3 shows how additional conditions can be introduced considering the various geometric elements:

- a parallelism condition between planes can be introduced, imposing that n targets rotating around the e.g. azimuth axis scribe circles contained in planes $\pi_i : ax + by + cz + d_i ; i = 1,\dots,n$ orthogonal to the same vector $\vec{v}_a = (a, b, c)$. Same consideration holds for the elevation axis: the planes will be mutually orthogonal to $\vec{v}_e = (d, e, f)$,

- another condition can be introduced imposing vector $\vec{v}_a$ to be orthogonal to vector $\vec{v}_e$, i.e. imposing the azimuth axis to be orthogonal to the elevation axis,
- the alignment condition of circles’ centres requires that they pertain to the same realization of the rotation axis,
- a further condition can be introduced on the radius of the circles: for any rotation of the same target around an axis, the radius of that circle must be constant,

Other conditions can be introduced in the post-processing software, according to the particular problem to be solved. The telescope axis offset, a fundamental quantity in VLBI data analysis, can also be introduced as an additional parameter to be solved for.

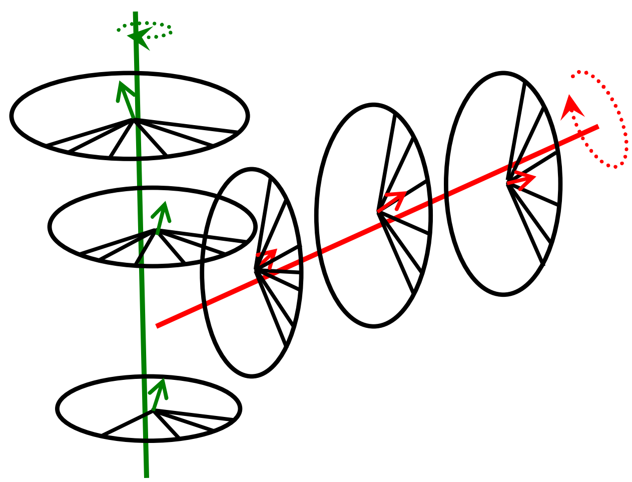

Figure 3 - targets’ rotations around the elevation (red) and azimuth (green) axes; circles’ centres, planes directions (arrows) and radius are shown.

GPS and DORIS antennas can be also surveyed applying an indirect approach; in these cases the geometric conditions to be applied to terrestrial estimates are different. A trivial, though fundamental, aspect related to local tie surveying should be clearly underlined: the space geodetic instrument (particularly, GPS and DORIS) should not be removed and the receiver/antenna set up should not be changed for terrestrial surveying purposes, whenever possible. To this respect, indirect method can greatly contribute in ensuring consistency and coherence between the space geodetic data and the local tie information that are used for combined products estimation. Figure 4 shows the terrestrial surveying scheme of a permanent GPS antenna proposed by Sarti et al. (2004); the same approach can be applied to DORIS beacons surveying. The procedure is based on the indirect observation of the technique conventional point (N.2) by means of symmetry considerations. In particular, symmetrically coupled points on specific parts of the antenna are triangulated taking care of placing the reference point of the total station at the same height of the GPS ARP; the corresponding angular readings are averaged in order to obtain readings referred to the symmetry axis of the antenna. The corresponding new fictitious observations can be adjusted and conditioned for recovering the position of the antenna reference point (i.e. the conventional point).

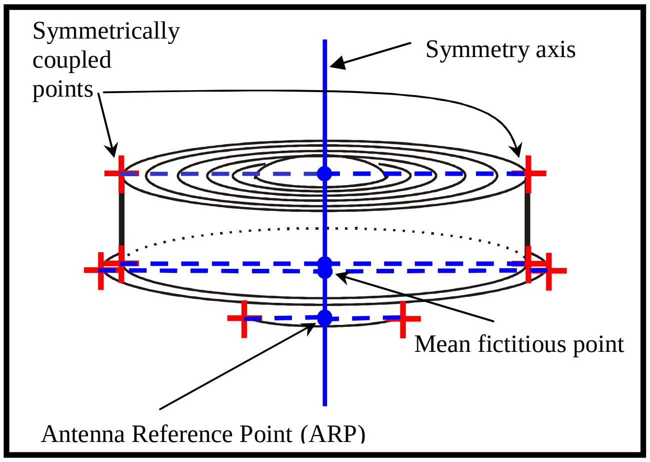

Figure 4: - GPS antenna surveying scheme: the position of the ARP is indirectly recovered performing triangulation on symmetrical points identified on the edge of the antenna and applying geometric conditions on fictitious points.

2.2. Local tie practice

Site eccentricity surveying procedures do not significantly differ from those adopted in other high precision terrestrial surveys; a summary of the basic requirements concerning surveying skills, instruments, devices and precautions can be found in Nothnagel (2005).

Technical aspects of eccentricity vectors' surveying have been discussed, in different detail, in a certain number of papers; a good selection can be found in (IERS 2005).

3. THE MEDICINA VLBI-GPS ECCENTRICITY

Since 2001, local ties in Medicina were performed every year; the only exception was 2004. Not every tie was carried out with terrestrial techniques; as stated in the previous section, indirect method uses 3-D coordinates of points as input of the post-processing geometric conditioning. Therefore, a GPS based approach to eccentricity vector estimation was tested in 2002 and 2006 with interesting results (Abbondanza et al. 2008). Local ties with terrestrial observations were completely performed in 2001, 2002, 2003, 2005 and 2007 and represent an interesting data set for evaluating the stability of the local ground control network and of the eccentricity vector. In particular, once the 2005 and 2007 surveys will be totally analyzed, the series of eccentricities in Medicina will represent a challenge for geodetic combination centres. The modules of the eccentricities, whose analysis has been completed, are contained in Table 1; the columns contain the estimates obtained with a different degree of conditioning, according to the possibilities illustrated in Section 2.1. In particular, cum1 applies a loosely conditioned solution; cum2 the parallelism between planes; cum3 parallelism and inter-axial orthogonality; cum4 adds to the previous cum3 the axis offset computation.

A direct comparison of the eccentricity's components (or coordinates) computed with different surveys' data sets has to take into account local frame repeatability and stability as well as the alignment procedure and the orientation of the eccentricity vector into the global

ITRFyy frame (Abbondanza et al. 2008); the modules can be straightforwardly compared, instead.

	cum1	Cum2	cum3	cum4
TER 2001	62.7646 (0.7)	62.7646 (0.7)	62.7646 (0.7)	62.7646 (0.7)
TER 2002	62.7673 (0.4)	62.7672 (0.4)	62.7672 (0.4)	62.7672 (0.4)
TER 2003	62.7653 (0.2)	62.7654 (0.3)	62.7654 (0.3)	62.7654 (0.3)
ABS 2002	62.7697 (1.5)	62.7690 (2.0)	62.7691 (2.0)	62.7691 (2.0)
ABS 2006	62.7679 (0.8)	62.7674 (0.8)	62.7673 (0.3)	62.7667 (0.8)
ABS–TER 2002	0.002	0.0018	0.0018	0.0018

Table 1 - The module of the eccentricity vectors estimated with the data sets acquired in 2001, 2002 and 2003 with terrestrial and/or GPS observations. The different solutions correspond to a varying degree of conditioning applied in the computation.

It is important to highlight that, for indirect method, the conventional point estimation process depends on the location of the targets on the telescope structure. This latter deforms differentially under the effect of gravity and the ideal circular motion of the targets is modified according to the local deformation of the structure, with a direct impact on the reference point estimation. In order to evaluate this effect, three groups of targets have been placed on (i) a steel rod firmly attached to the elevation bearing housing (where the gravitational deformations of the structure are almost zero) (ii) the external edge of the dish (iii) top of the quadrupode. The circular paths of these groups of targets were used to estimate the Up component of the conventional reference point; as shown in Table 2 the estimate obtained using the targets on the steel rod and that on the quadrupode is almost 1 cm, far beyond the 1 mm limit accuracy desired on reference point estimate.

	Quadupode targets	Edge of the dish targets	Steel rod targets
VLBI RP Up (m)	17.6933 ± 0.0007	17.7003 ± 0.0008	17.7030 ± 0.0003

Table 2 - Value of the VLBI reference point Up component estimated using groups of targets located on different parts of the antenna and experiencing different gravitational deformations. The maximum difference is close to 1 cm.

It is therefore clear that the location of the targets is crucial in order to obtain unbiased estimates of the conventional reference point positions, since the formal precision is very high in all three cases.

4. OUTLOOK

As stated in the previous sections, observations of targets' rotational sequences are a source of information regarding the deformations induced by gravity on the telescope structure. In particular, a certain number of targets can be placed on selected parts of the structure and their relative positions can be observed and eventually compared with other methods valuable for deformation studies, such as Finite Element Model (FEM) or laser scanning surveying. Comparisons between (i) deformation patterns obtained with terrestrial triangulation and trilateration and terrestrial laser scanning and (ii) deformation patterns derived by terrestrial triangulation and trilateration and FEM were performed on both the Medicina VLBI telescope and the Noto VLBI telescope. In particular, the deformations which are currently being investigated refer to (i) the position of the vertex of the primary mirror, (ii) the position of the receiver and (iii) the surface of the dish; these are the variations that directly affect the radiosignal path and, consequently, the performances of the VLBI radiotelescopes (Clark and Thomsen 1988). The preliminary results are very interesting: the deformations agree in magnitude and sign and the integration of the results is nowadays being accomplished.

A final remark on terrestrial laser scanning: it has been applied on both telescopes for determining the shape of the primary mirror at six different elevations, starting from 90 deg to 15 deg, in steps of 15 deg. The general response of the structure to elevation changes has been clearly identified; the scanned clouds of points are now being used to study the relative deformations affecting the dish and their effect on the signal path variation.

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