Publication Year	2009
Acceptance in OA	2024-02-02T14:24:03Z
Title	Multi-technique approach for deriving a VLBI signal extra-path variation model induced by gravity: the example of Medicina
Authors	SARTI, PIERGUIDO, Abbondanza, C., NEGUSINI, MONIA
Handle	http://hdl.handle.net/20.500.12386/34699

Multi-technique approach for deriving a VLBI signal extra-path variation model induced by gravity: the example of Medicina

P. Sarti, C. Abbondanza, M. Negusini
Istituto di Radioastronomia (IRA) - Istituto Nazionale di Astrofisica (INAF), Via P. Gobetti, 101
40129 Bologna, Italy

L. Vittuari
DISTART, Universitá di Bologna, Viale Risorgimento, 2 40136 Bologna, Italy

Abstract. During the measurement sessions gravity might induce significant deformations in large VLBI telescopes. If neglected or mismodelled, these deformations might bias the phase of the incoming signal thus corrupting the estimate of some crucial geodetic parameters (e.g. the height component of VLBI Reference Point). This paper describes a multi-technique approach implemented for measuring and quantifying the gravity-dependent deformations experienced by the 32-m diameter VLBI antenna of Medicina (Northern Italy). Such an approach integrates three different methods: Terrestrial Triangulations and Trilaterations (TTT), Laser Scanning (LS) and a Finite Element Model (FEM) of the antenna. The combination of the observations performed with these methods allows to accurately define an elevation-dependent model of the signal path variation which appears to be, for the Medicina telescope, non negligible. In the range $[0, 90]$ deg the signal path increases monotonically by almost 2 cm. The effect of such a variation has not been introduced in actual VLBI analysis yet; nevertheless this is the task we are going to pursue in the very next future.

Keywords. VLBI, Radio telescope, Gravitational Deformation, Signal Path Variation

1 Introduction

When combining space geodetic solutions of independent terrestrial reference frames, considerable discrepancies at co-located sites are often found between VLBI solutions and tie vectors (Abbondanza et al, in press). These discrepancies might be induced by specific technique-dependent biases. In this respect, VLBI, more than other space geodetic techniques, may be affected by intrinsic instrumental deformations. These can be due to *(i)* environmental effects (i.e. variations in local temperature or wind load), *(ii)* the effect of gravity acting on the antenna structure. The state-of-the-art in VLBI thermal expansion modelling can be found in Nothnagel (2008). Modelling the deformations of a VLBI antenna still remains a complex task, which has not been yet thoroughly systematised within the VLBI data processing. Since the beginning of geodetic VLBI activity, gravitational deformations have been acknowledged as one of the factors which may introduce additional biases in the estimate of fundamental geodetic parameters (Carter et al, 1980; Campbell, 1987). Gravity deforms in a differential manner the structure of a steerable antenna, thus modifying the path length travelled by the radio signal hitting the primary reflector (PR). A clear insight on how a VLBI antenna can deform can be found in Clark and Thomsen (1988). They developed a comprehensive model applied to the 22-m diameters VLBI radio telescope at Fairbanks (Alaska). The deformational effect on the antenna was quantified through a FEM. According to Clark and Thomsen (1988), the signal path variation induced by gravity (δL) can be expressed as linear combination of three terms:

$$\delta L = \alpha_R \delta R + \alpha_V \delta V + \alpha_F \delta F \qquad (1)$$

where δR is the motion of the receiver, δV is the displacement of the PR, conveniently represented by its vertex's position, δF is the focal length variation. These displacements, as well as the signal extra path, are referred to the line of sight. The three linear coefficients α_R, α_V and α_F depend on the design of the VLBI telescope. We applied a multi-technique surveying approach to the VLBI telescope of Medicina with the aim of quantifying the effect of the three contributions to the signal path variation: *(i)* terrestrial LS was used in order to estimate the variation of the focal length of a best-fit paraboloid representing the PR; *(ii)* TTT allowed to quantify the receivers' displacement; *(iii)* a FEM of the Medicina VLBI telescope was used to quantify the vertex displacement.

2 Deformations of a VLBI telescope and impact on the RP estimation

VLBI observable is detected in the feed horn's phase centre (Electronic Point, EP). It is common practice, in VLBI data analysis, to refer the observations to the VLBI Invariant Point (IP), which is the projection of the moving axis onto that fixed. In order to do that, the distance between the EP and the IP must be known. For a VLBI telescope whose axes are not intersecting, this distance is the sum of *(i)* D_a, the projection of the axis offset onto the line of sight and *(ii)* D_b, the distance between the EP and the elevation axis. If, on one hand, the axis offset is assumed to be constant as the pointing elevation varies and what varies is its projection along the line of sight, on the other hand, due to the effects of gravitational deformations, D_b may undergo modifications depending on the pointing elevation. On the contrary, in common practice D_b is assumed to remain constant. If present, its variations may impact on the VLBI signal path and must be properly taken into account. Motions of the EP can be originated by deformations of the structure sustaining the receiver, i.e. the quadrupode and/or by a sag of the PR. Deformations of the PR must be considered as well, since they modify its shape and induce variations of the signal path length. These changes can be conveniently expressed by variations in the focal length of the best-fit paraboloid. An accurate quantification of the three terms in the equation (1) allows to determine variations of the distance D_b.

Six different surveys (2001, 2002, 2003, 2005, 2006, 2007) of the Medicina telescope were performed with the aim of determining as accurately as possible the tie vector between the VLBI IP and the GPS Antenna reference point. These tie vectors were estimated with an indirect approach: redundant observations of angles and distances between ground control points and targets applied to the telescope were acquired in order to recover the position of the IP. In this case, the IP is estimated according to geometrical/theoretical considerations, i.e. via the reconstruction of the position of the telescope rotation axes. It has been found that the estimation of the IP strictly depends on the location of targets applied to the VLBI telescope. This has been proven installing three groups of targets on different parts of the structure of the VLBI antenna: *(i)* on the top of the quadrupode (very close to the S/X receivers placed in the primary focus), *(ii)* on the edge of the dish, *(iii)* on a couple of steel rods attached to the antenna's structure very close to the elevation axis. These latter group of targets does not undergo deformations, as the antenna is steered in elevation, thus providing a more accurate estimate of the position of the elevation axis. With the indirect approach, the position of the VLBI IP is recovered following its theoretical definition, i.e. *(i)* estimating the two rotation axes of the telescope and *(ii)* projecting the elevation axis onto that fixed. It is common practice to rotate the telescope and to execute TTT at different azimuth and elevation positions on the targets applied to the antenna structure. These, during the rotations, ideally describe arcs of circles whose centres are related to the VLBI IP. Table 1 shows the Up component of the VLBI IP according to the three different groups of targets: a maximum difference by a magnitude of 1 cm has been found in the estimate of the IP height between the targets' groups I and III. Gravity deforms the antenna structure in a differential manner: targets applied to the quadrupode (Group I) and to the edge of the PR (Group II) experience higher deformations than those fixed on the steel rods (Group III). This causes the UP component of the VLBI IP to be biased. Since the targets of

Table 1. Dependency of the Up component of the VLBI IP on the targets' position applied to the telescope: **TG** in the first column indicates the Target Group; the coordinates of the Up component of the VLBI IP (second column) and their associated sigmas (third column) are expressed w.r.t a local topocentric reference frame.

TG	**UP VLBI IP (m)**	σ **(mm)**
I	17.6930	0.7
II	17.7003	0.8
III	17.7030	0.3

the Group III are free from the effect of gravitational flexure, they can be used in the computation of an accurate realization of the elevation axis. The relative displacement of the receiver and of the vertex can be referred to this latter, thus quantifying two fundamental contributions to D_b variations. Deformations of the PR must be determined as well: they intervene to modify the shape of the reflecting surface and also contribute to signal path length variation.

2.1 Receiver's displacement

While the VLBI telescope is rotated in elevation, the position of the receiver varies describing arcs of circle. In ideal conditions (i.e. in absence of deformations), the distance between the receiver and the elevation axis is constant. Nonetheless, as mentioned in section 2, gravity acting on the quadrupode may induce considerable deformations. Its effect is variable and depends on the antenna pointing elevation e: the component of the gravity force along the line of sight is a $sin(e)$ function which increases from $e = 0$ deg to its maximum at the zenith ($e = 90$ deg). In case the movement of the receiver is affected by gravity, it deviates from a circular path and the EP modifies its relative distance $d(EP, a)$ w.r.t. the elevation axis a. Therefore any receiver's displacement induced by gravity results in a variation of the incoming signal path. It is, thus, necessary to monitor $d(EP, a)$ and to determine its variations (i.e. relative radial displacement, δR) at different antenna's elevations. In case of Medicina, this was done with two independent procedures: *(i)* classical geodetic observations *via* TTT on the targets applied to the quadrupode, *(ii)* with a FEM.

2.1.1 TTT on the quadrupode

Terrestrial triangulations and trilaterations on the three targets Ia, Ib, Ic applied to the quadrupode were performed with the aim of determining $\delta R = f(e)$ in case of a receiver placed in the primary focus w.r.t an elevation axis free from gravitational-dependent biases. As mentioned in section 2, indirect approaches permit an accurate estimation of the VLBI rotation axis, providing the terrestrial measurements are minimally affected by gravitational deformations. This was ascertained for the targets of the Group III. Insights about the specific indirect approach used for recovering the VLBI IP position and the rotational axis can be found in Sarti et al (2004). For each target of the group I, the corresponding $\delta R_i(e)$ has been determined. The behaviour of the three targets' displacement is found to be similar: it tends to decrease as the elevation angle e augments, from its maximum at 5 deg to the minimum at 90 deg. The general trend can be explained considering the action of gravity on the antenna's structure: as the telescope moves from 0 to 90 deg, the component of the gravity force along the line of sight increases, thus shifting the receiver toward the elevation axis. This results in a reduction of δR, when the elevation angle e increases.

2.1.2 FEM

An analysis with a FEM of the telescope was performed with the aim of investigating the effect of gravitational deformations on the quadrupode. Three nodal points, very close to the three targets of the Group I, were identified $(R1, R2, R3)$ and chosen to be representative of the deformations undergone by the quadrupode. In particular, six different models of the VLBI antenna at six elevation angles $(15, 30, 45, 60, 75, 90)$ deg were considered and used for the purpose of investigating gravitational flexure. The FEM was analysed with the ANSYS software (Hallquist, 1998): the relative displacements between the R_i and the elevation axis were computed. The agreement between the results obtained with FEM and those presented in section 2.1.1 is striking.

2.2 Vertex Motion

As the telescope is rotated in elevation, the vertex of the PR, analogously to the receiver, should ideally move on an arc of circle. Nonetheless, also in this case, gravity intervenes to deform this theoretical path: from 0 to 90 deg, the component of the force along the line of sight tends to increase, thus pulling the PR downward. This causes the vertex-to-elevation axis distance to be shortened. TTT could not be used for estimating the variation δV at different elevations, since the reticular structure of the telescope prevents from collimating targets in the vicinity of the vertex. Thus the FEM was used to derive the distances between a nodal point representative of the vertex and the elevation axis.

2.3 Deformation of the PR

The gravity force is applied on the whole surface of the PR, thus modifying its theoretical shape. In order to recover the actual shape of the PR, a LS survey was performed in September 2005 at different elevations $(90, 75, 60, 45, 30, 15)$ deg. A detailed discussion concerning the surveying approach and the results obtained can be found in Sarti et al (2009). Under the action of gravity, the PR experiences an inward folding, as the elevation decreases from 90 to 0 deg. At each elevation, the focal length of a best fit paraboloid was estimated thus proving that it smoothly increases from (10.2165 ± 0.0001) m at 15 deg to (10.2403 ± 0.0001) m at 90 deg (Sarti et al, 2009).

3 Results

According to equation 1, in order to derive δL the three terms $(\delta R, \delta V, \delta F)$ have to be combined through the corresponding α_i coefficients. With geometrical considerations Clark and Thomsen (1988) show that $\alpha_V = -1 - \alpha_R$ and $\alpha_F = 1 - \alpha_R$, where α_R can be related to the geometrical features of the PR:

$$\alpha_R = \frac{8f^2}{r_0^2} ln(1 + \frac{r_0^2}{4f^2}) - 1 \qquad (2)$$

In case of Medicina, $\alpha_R = 0.56$, $\alpha_V = -1.56$, $\alpha_F = 0.44$. In practice, these coefficients relate a displacement in the position of the receiver or the vertex and a change in focal length, all determined along the line of sight, to a change in signal path along the same direction. δL can be fit by a monotonically increasing function which ranges between 0 mm at 0 deg to a maximum of about 19 mm at 90 deg. A detailed discussion about the combination of surveying approaches, their consistency, the complete data analysis and the provision of the interpolating functions which represent the signal path variation to be applied to the VLBI observable can be found in (Sarti et al, submitted).

4 Conclusions

It is important to consider the effects of gravity on large VLBI telescopes: it has been demonstrated that, when estimating the VLBI IP with indirect approaches, gravitational deformations may induce remarkable biases (up to 1 cm), depending on the locations of targets used for recovering the elevation axis. Furthermore gravitational deformations produce significant variations of the optics of the VLBI system, thus modifying the pathlength of the signal. These variations must be investigated and accurately quantified. With this purpose, we applied a combination of three different approaches (TTT, LS and FEM), which allowed to validate results concerning the quadrupode's deformations. An elevation-dependent function of δL was determined: it quantifies the path variation to be applied to the VLBI observable in order to account for the gravitational effects. Such a variation attains the maximum value of approximately 19 mm, smoothly increasing its length from low elevation to the zenith.

References

Abbondanza C, Altamimi Z, Sarti P, Negusini M, Vittuari L (in press) Local effects of redundant terrestrial and GPS-based tie vectors in ITRF-like combinations. J Geod

Campbell J (1987) Very long baseline interferometry. In: Turner S (ed) Lecture Notes in Earth Sciences. Applied Geodesy

Carter E, Rogers AEE, Counselman CC, Shapiro II (1980) Comparison of geodetic and radio interferometric measurements of the Haystack-Westford base line vector. J Geophys Res 85:2685–2687

Clark TA, Thomsen P (1988) Deformations in VLBI antennas. Tech. rep., 100696, NASA, Greenbelt, MD

Hallquist JO (1998) LS-DYNA Theoretical Manual. Livermore Software Technology Corporation, 2876 Waverley Way, Livermore CA 94550-1740

Nothnagel A (2008) Conventions on thermal expansion modelling of radio telescopes for geodetic and astrometric VLBI. J Geod DOI 10.1007/s00190-008-0284-z

Sarti P, Sillard P, Vittuari L (2004) Surveying co-located space geodetic instruments for ITRF computation. J Geod 78(3):210–222

Sarti P, Vittuari L, Abbondanza C (2009) Laser scanner and terrestrial surveying applied to gravitational deformation monitoring of large VLBI telescopes' primary reflector. J Surv Eng http://dx.doi.org/10.1061/(ASCE)SU.1943-5428.0000008

Sarti P, Abbondanza C, Vittuari L (submitted) Gravity dependent signal path variation in a large VLBI telescope modelled with a combination of surveying methods. J Geod