Medicina and Noto VLBI Radiotelescopes: gravitational deformations evaluated with terrestrial laser scanning

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Abstract. The Medicina and Noto VLBI antennas are Az-El telescopes that experience gravitational deformations as they move in elevation. The ideal parabolic shape of the primary mirrors is therefore perturbed and the dishes are deformed according to the elevation pointing position of the antenna. Receivers at different frequencies, in particular the S/X geodetic receivers, are placed on the quadrupode, at the primary focus position; they also experience a displacement due to gravitational forces as the elevation changes. A third effect induced by gravity is the sag which might be possibly experienced by the dish as the elevation changes.

The determination of the contribution and magnitude of all the different effects are of primary importance. The realization of an elevation dependent gravitational deformation model that can be implemented in the VLBI data analysis is our target; it would allow to quantify and correct any bias of gravitational origin which affects the observations.

In order to face this complex task, terrestrial laser scanning and terrestrial observations have been applied to the antenna of Medicina and Noto.

The VLBI dishes' movements in elevation prevent full visibility of the inner part of the parabola from the ground: *ad hoc* supports were therefore installed nearby the antenna secondary focus allowing a complete laser coverage of the inner dish surface at different elevations.

The raw data acquired with the laser scanner intrinsically define clouds of points expressed with respect to an instrumental reference system; in order to connect the observed points to an external reference system, it is necessary to relatively align the different clouds using tie points and moreover ad hoc terrestrial surveys are required to frame the laser survey in to the external reference system.

The surveys and their results will be presented, along with the data analysis procedure and the most recently estimated deformations.

Keywords. Gravitational deformations, laser scanning, VLBI radiotelescope, terrestrial surveying.

1 Introduction

In order to determine the gravitational deformations that affect the dish when the VLBI telescope is moved in elevation, a test campaign concerning the use of terrestrial laser scanning was carried out at Medicina and Noto radioastronomical observatories. The primary mirror of the antenna is not visible from the ground, except for very low elevations. This certainly poses serious limits to the application of terrestrial methods for structure's topology reconstruction. The approach of external elevated platforms usually adopted in photogrammetry cannot be used in laser scanning surveys since there is a need of continuously stable supports. Therefore ad hoc manufactured supports were fixed close to the antenna secondary focus for a complete laser scanning of the dish surface at any elevation. The pulse laser used in these experiments has a resolution in range of about 1.5 mm at 50m. Both Noto and Medicina antenna's surface have been scanned at different elevation's positions of the dish. At both observatories, the entire surface of the primary mirror was completely retrieved merging the partially overlapping scans performed at two different standpoints: a number of technical and operational difficulties prevented the identification of a unique location from where the laser scanner could scan the entire surface of the dish in one unique run. Section 2 gives an overview of the peculiarities and common characteristics of the Medicina and Noto VLBI radiotelescopes. Section 3 summarises the field operations and the technical solutions that were adopted for the laser scanning survey; the data processing and related results follow in section 3.1. The topographic survey that was performed along with the scanning of the dish is described in section 4.

2 Medicina and Noto VLBI radiotelescopes

The radiotelescope of Medicina (Fig. 1) and Noto are formed by a primary parabolic mirror and a secondary hyperbolic mirror, or sub reflector, which is positioned approximately 9 meters apart from the primary one; the receivers used in the geodetic observations are located in the same position as the sub reflector (primary focus). The sub reflector is capable to move through a mechanism that slides forth and back according to the configuration adopted in the observations: when geodetic observations are performed, the sub-reflector is moved back and the S/X receivers placed on the quadrupode are precisely positioned in the primary focus.

Fig. 1 The VLBI Medicina antenna

The Noto VLBI antenna differs from the Medicina radiotelescope for its active surface. (Orfei et al. 2004). The active surface concept aims at compensating gravitational deformation effects of the antenna backup structure by moving the panels forming the antenna primary mirror. The deformation of the surface reduces the overall antenna gain and the effect is worse at higher frequencies.

The surface of the primary mirror can be represented by the equation of a generic rotational paraboloid having its vertex in the point (0,0,0) and its focus on the z axis (1).

$$\boxed{z = \frac{x^2 + y^2}{4f}} \quad (1)$$

If the antenna structure is deformed by gravity, the paraboloid might change its shape, position and orientation.

2.1 Radiotelescope’s deformations

Temperature variation, wind and gravity can induce remarkable deformations of the ideal radiotelescope structure and might not be negligible. Therefore, it is important to try to quantify the amount and magnitude of each perturbation and account for their contribution into the geodetic observations (Clark and Thomsen, 1988).

Thermal deformations can be monitored through temperature sensors positioned at different heights on the structure of the antenna.

All kind of deformations can be investigated with finite element modelling of the structure of the telescope; this approach has been tested by Clark and Thomsen (1988) and necessarily requires the availability of a reliable model of the antenna.

An alternative approach to investigate gravitational deformations is based on high precision terrestrial surveying. In particular we have simultaneously applied classical geodetic surveying (trilateration and triangulation) along with laser scanning, in order to investigate and quantify the amount of deformation that affect the dish and its structure when moving the telescope in elevation. The effects of gravity are assumed to be azimuth independent: therefore, only elevation movements have been applied to the structure explicitly assuming a deformation symmetry for any azimuth position.

3 Laser scanning surveys carried out in the Medicina and Noto observatories

The instrument that was used for this survey (Fig. 2) is a Trimble Mensi GS200 pulse laser: it is capable to acquire about 5000 points per second with a resolution of approximately 1.5 millimetre at 50 meters, using the time-of-flight method for

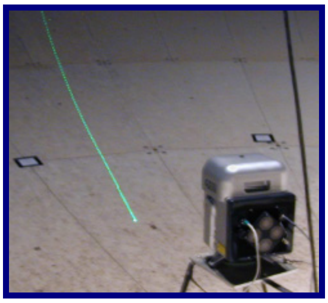


Fig. 2 The Trimble Mensi GS200 Laser System

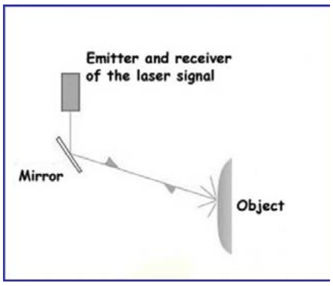


Fig. 3 The scheme of time-of-flight method

determining points positions (Fig. 3). In this case the laser beam hits the object, varying the azimuth and zenith angles.

The distance between the instrumental centre and the first reflecting point hit by the beam is determined by the measurement of the time-of-flight elapsing between the emission and the reception. This distance, combined with the two known output angles of the beam, allows determination of positions of the surveyed point. These coordinates are provided to the users in a Cartesian system (X, Y, Z), with its origin at the instrumental centre

The surveys were realized by moving the VLBI radiotelescopes at different elevations: 90, 75, 60, 45, 30 and 15 deg, with the scanning realized during the night, in order to reduce the effects induced by air refractivity (Fig. 4).

The surveys were carried out by placing the laser system inside the primary mirror on two standpoints (F1, F2) located near the secondary focus (Fig. 5). The technical characteristics of the instrument allowed a complete surveying of the whole surface of the primary mirror through a single standing; however, the lack of suitable standpoint locations, forced us to choose two different standpoint positions and to scan the dish in two separate, though overlapping, sessions.

A 2 cm sampling rate was adopted for the primary mirror while a 3 mm sampling rate was used on the 6 spherical targets that were positioned and surveyed as common points for the two different scans (Figs. 4 and 5).

3.1 Laser scanning data processing, post-processing and results

The acquired data sets were roughly cleaned by manually removing all the points that do not belong to the paraboloid. This was necessary since the primary mirror does not form a continuous surface: it is formed by panels that are separated by small gaps. Therefore, the laser beam occasionally passed through the gaps and hit the ground or parts of the

Fig. 4 The scanning session realized during the night

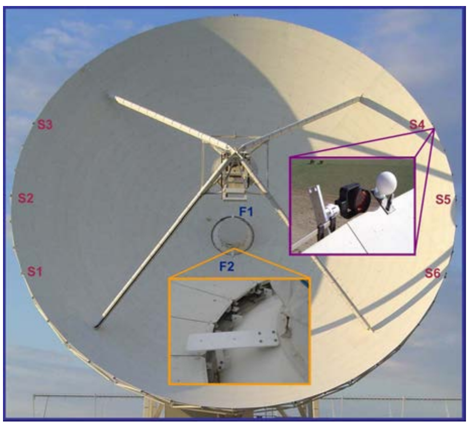


Fig. 5 Standpoints and target particular

lower structure of the antenna; these points had to be identified and removed.

The single scanning sessions (Fig 6) were aligned (Fig. 7) through six spherical targets serving as common points: they were placed on the external edge of the paraboloid (identified with the letter "S", Fig. 5).

In order to obtain a single cloud in the instrument's reference point, the two scanning sessions have been merged (Fig. 8).

Moreover, in order to determine the deformations of the primary mirror induced by gravity at different elevations, it is necessary to compare the different laser scanning sessions.

The best-fit paraboloid was computed, for each laser cloud acquired at varying elevations, writing a

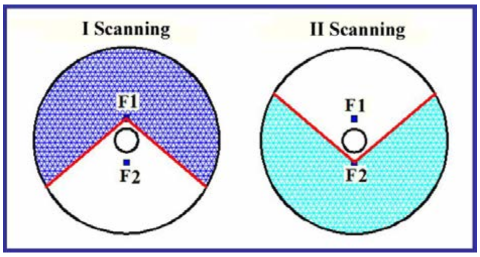


Fig. 6 The two scanning sessions

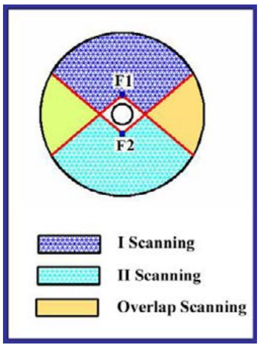


Fig. 7 Alignment Phase

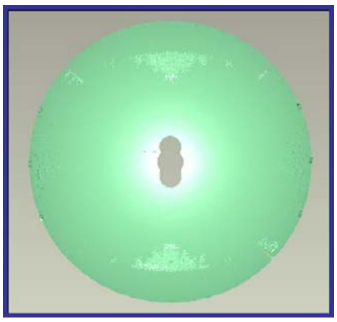


Fig. 8 Merge Phase

code in FORTRAN90; it can perform an estimation of:

- 3 translations which allow to place the origin of the frame into the vertex of the paraboloid.
- 2 rotations related to the x and y axes;
- the focal length of the best-fit paraboloid;
- the variance-covariance matrix and the correlation coefficients of the parameters;
- the residuals.

Such residuals were analyzed and used for selecting a better working data set on which the analysis was repeated.

The estimated parameters were used for roto-translating the clouds in a common frame where the vertex is placed in (0,0,0) and the Z-axis coincides with the axis of rotation. In this common frame we have computed the differences between the scannings carried out at different elevations.

Figure 9 shows the deformations between the scanning at 90 degrees and the one at 15 degrees for Medicina and Noto radiotelescopes. It has to be highlighted that for the Noto VLBI telescope, the active surface was permanently disabled during the scans.

The best-fit focal length varies as the elevation changes. The values determined for the radiotelescope of Medicina and Noto are shown in figure 10: the focal length decreases with elevation, suggesting an inward folding of the primary mirror

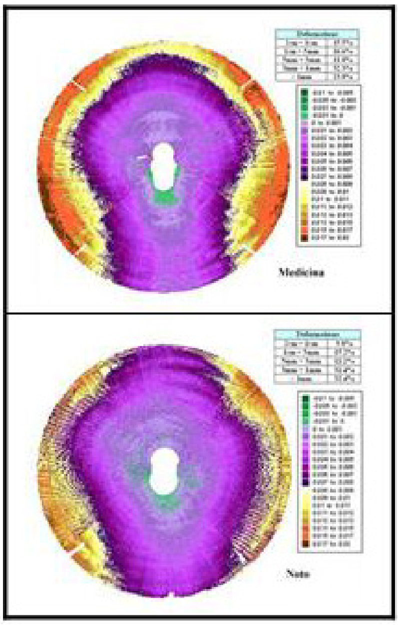


Fig. 9 The deformations between the scanning at 90 degrees and the one at 15 degrees

corresponding to an increasing concavity of the surface at lower elevations.

The differences of the best-fit focal lengths with respect to the theoretical length vary between 1.8 and 2.2 cm and almost 4 cm when the antenna is at 15 deg elevation, respectively for Medicina and Noto VLBI telescopes (Fig. 11).

4 Terrestrial surveys carried out in the Medicina and Noto observatory

In order to connect and frame the laser scanned surfaces to an external topocentric reference frame, common points were observed through a terrestrial survey (Fig. 12). A coupling of spheres and retro-reflecting prisms allowed the observation of common points with both laser and triangulation so as to derive transformation parameters. These common points were physically placed on the external part of the VLBI dish. Sphere's centres can be surveyed by the laser system. Spheres'centres can also be located with total stations using triangulation and symmetry considerations. Simultaneously, retro-reflecting prisms can also be surveyed with total stations. A detail of the couple sphere-prism is shown in Figure 12.

A complete survey of the network as well as the external surveying of the prisms at the different scanning elevations was performed (Figure 13). The terrestrial data were adjusted with the "STAR*NET" (Sawyer, 2001), a least squares analysis software that outputs estimated coordinates as well as a full variance-covariance matrix.

The positions of the retro-reflecting prisms at different elevation allowed the computation of transformation parameters that were applied to the sphere in order to translate the laser clouds into the topocentric frame (Fig. 14); this could realize a direct link between the local ground control network and the laser survey.

In the external reference frame and for different elevations of the VLBI dish the position in space of the vertex of the best fitting paraboloids were computed. Figure 15 shows the position of the best fit vertex in the local frame for the Medicina antenna.

5 Discussion

The laser technique that was adopted for the Medicina and Noto VLBI antennas supplied interesting results that must be combined with information derived by other observing approaches (see e.g. Bolli et al. 2006). In particular, the deformation determined with topographic surveys exploited both with terrestrial and GPS observations

Elevation (deg)	Focal Length of the best-fit paraboloid (m)	
	Medicina	Noto
90	10.2411 ± 0.0001	10.2373 ± 0.0001
75	10.2398 ± 0.0001	-
60	10.2383 ± 0.0001	-
45	10.2334 ± 0.0001	10.2304 ± 0.0001
30	10.2262 ± 0.0001	10.2268 ± 0.0001
15	10.2162 ± 0.0001	10.2190 ± 0.0001

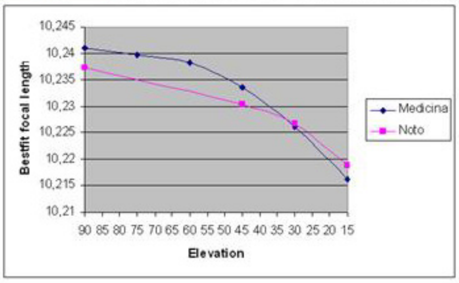


Fig. 10. The variation of the Best-fit Focal length (m) respect to the elevation (deg)

Theoretical Focal Length (m)	Elevation (deg)	Differences with Best-Fit Focal Length(m)	
		Medicina	Noto
10.2590	90	0.0179	0.0217
	75	0.0192	-
	60	0.0207	-
	45	0.0256	0.0286
	30	0.0328	0.0322
	15	0.0428	0.0401

Fig. 11 The differences of the best-fit focal lengths with respect to the theoretical length

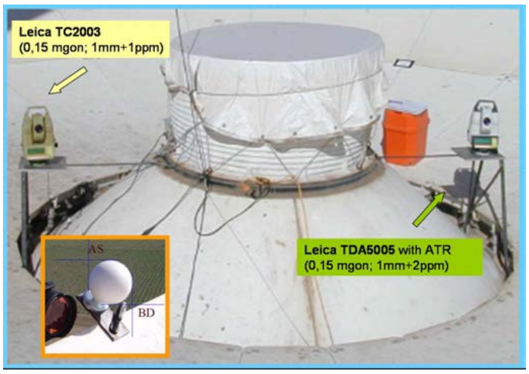


Fig. 12 Total station self centering system for the connection of the targets (spheres) to the local frame

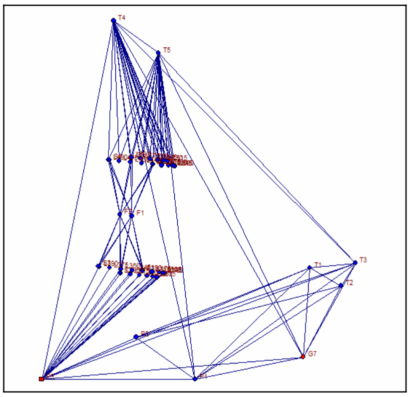


Fig. 13 The local ground control network, F1 and F2 standpoints in the dish and the retro-reflecting prisms surveyed at different elevations.

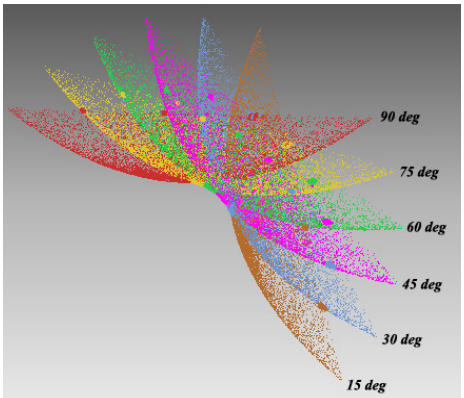
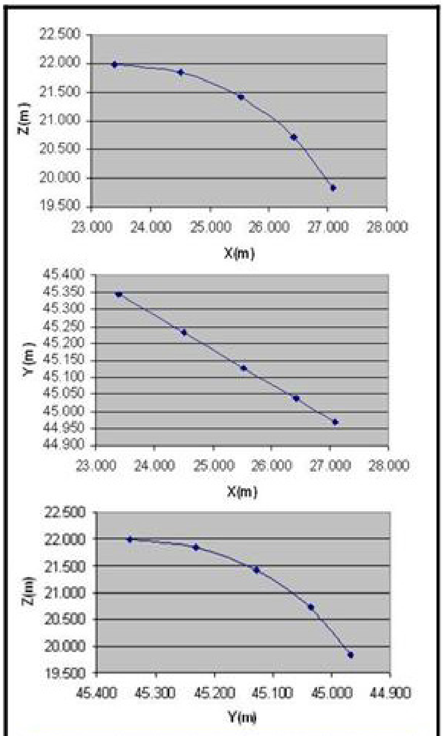


Fig. 14 Medicina scanning session inserted in the external reference system



Elevation (deg)	X (m)	Y (m)	Z (m)
30	27.092	44.968	19.845
45	26.414	45.037	20.733
60	25.531	45.127	21.414
75	24.502	45.232	21.842
90	23.400	45.344	21.988

Fig. 15 Medicina antenna: the vertex of the different best fit paraboloids in the external reference system

represent a set of measurement with which the laser scanning results must be integrated. Furthermore, telescope dependent parameters coming from self-calibrating procedures based on astronomical observations must also be integrated and serve as touchstones that must be referred to and compared: this might represent an effective way to link the physical observing point to the theoretical/geometrical reference point. In particular, the focal length variation and its effect on geodetic data processing is a parameter that must be carefully investigated. The combination of the laser scanning results with the topographic results is a complex, though necessary, task in order to obtain a wider view on the deformations that affect the VLBI radiotelescope, quantify their contributions and try to meet the challenging 1-mm accuracy target.

References

Bolli P, Montaguti S, Negusini M, Sarti P, Vittuari L, Deiana GL (2006). Photogrammetry, laser scanning, holography and terrestrial surveying on the Noto VLBI dish. *Int. VLBI Service for Geodesy and Astrometry 2006 General Meeting Proc.* edited by Dirk Behrend and Karen Baver, NASA/CP-2006-214140, 172-176.

Clark T. A, P. Thomsen (1988). Deformations in VLBI Antennas. *Nasa Technical Memorandum 100696.*

Orfei A, M. Morsiani, G. Zacchiroli, G. Maccaferri, J. Roda, F. Fiocchi (2004). An active Surface for Large Reflector *Antennas. IEEE Antennas and Propagation Magazine*, 46, 4, 11 – 19.

Sawyer R. (2001). STAR*NET-PRO V6 least squares survey network adjustment. *Program reference manual.* Oakland, CA.