Estimation of the Focal Length Variation of Yebes Observatory 40-m Antenna

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Abstract Very Long Baseline Interferometry (VLBI) is one of the most accurate geodetic techniques, but its accuracy depends on considering various errors that affect the measurements, such as the gravitational deformation of the antenna. This deformation changes the antenna's structure and differs from the mathematical paraboloid. Knowing the magnitude of this side effect permits the correction of the effects to increase the accuracy of the results. The deformation of the 40-m antenna was modeled from points measured with two techniques: (1) Unmanned Aerial Vehicle (UAV) close-range photogrammetry; and (2) Terrestrial laser scanning with a scanner mounted on the vertex of the subreflector in upside-down position. After obtaining and filtering the 3D data, the deformation was modeled using the iterative methods of Least Squares Estimation (LSE) and Orthogonal Distance Regression (ODR). With these methods, the parameters that define the paraboloid, which describes the surface of the antenna, were found. Afterwards, using these latter determined parameters, the surface was modeled to analyze how much the measured points using the two implementations differ from the mathematical model.

Keywords VLBI, Photogrammetry, Terrestrial Laser Scanner, deformation, focal length

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1 Introduction

The Yebes Observatory (OY) is one of the Spanish Singular Scientific Technical Infrastructures (ICTS) for astronomy and the only one in Castilla–La Mancha. It is attached to the National Geographic Institute of Spain (IGNE). It has two world-class VLBI radio telescopes, a 40-m antenna and the RAEGE VGOS 13.2-m antenna, and is internationally recognized for the quality of its instruments.

Fig. 1: Yebes Observatory 40-m VLBI antenna.

The VLBI technique is one of the most accurate geodetic techniques, and for this purpose it is necessary to know precisely all the errors and effects affecting the measurements and the antennas. For this matter, it is necessary to know the deformation of the antenna at different elevations, in order to be able to correct the measurements for any possible errors that this may cause.

The main goal of the study is to model the deformation of the 40-m antenna of Yebes Observatory (Figure 1) for different elevations (5°, 25°, 45°, 65°, and 85°) and to calculate the variation of the focal length, which theoretically should be 15 m.

2 Survey and Filtering

Two types of measurements were taken: one using a Terrestrial Laser Scanner (TLS) and another using Photogrammetry with Drones (UAV-DAP). The drones campaign was done in collaboration with the Universitat Politècnica de València, Photogrammetry and Laser Scanner Research Group.

Different point clouds were obtained with both techniques. These point clouds have hundreds to millions of points: $\mathbf{X} = (X,Y,Z)^t$, which are given in the local coordinate system of the measuring instrument.

2.1 Terrestrial Laser Scanner

A Leica ScanStation $P40/P30$ laser scanner was mounted on top of the subreflector, as shown in Figure 2. The measurements were obtained in a local LS (X, Y, Z) coordinate system where the laser scanner is the origin. Then, a filtered point cloud of the antenna was used in the estimation.

Fig. 2: Leica ScanStation $P40/P30$ laser scanner.

2.2 Photogrammetry with Drones

Morning (AM) and evening (PM) observations were acquired with UAV-DAP close range photogrammetry (Figure 3). The measurements were taken using markers on the panels. Later, two point clouds were computed: a simplified after the external orientation and a dense cloud.

Fig. 3: Unmanned Aerial Vehicle.

3 Deformation Study

To study the deformation and calculate the parameters of the paraboloid that modeled the antenna, two kind of approaches were applied: Least Squares Estimation (LSE) and Orthogonal Distance Regression (ODR). The two methods are similar, but ODR is more robust and returns smaller errors.

The adjustments need the reference system of the point cloud transformed, so that the origin is the paraboloid's vertex, with a 3D-Helmert transformation, as shown in Equation 1 (Holst et al. (2012)):

$$(x,y,z)^t = R_x(\varphi_x)\cdot R_y(\varphi_y)\cdot \mathbf{X} + (x_v,y_v,z_v)^t, \qquad (1)$$

where $R_x(\varphi_x)$ and $R_y(\varphi_y)$ are the rotation matrices of the x-axis and y-axis, respectively, and $(x_v,y_v,z_v)^t$ is the translation vector, and these parameters will be part of the estimation process.

The parametric equation of the paraboloid is presented in Equation 2:

$$\frac{x^2+y^2}{4f}=z \tag{2}$$

Equation 2 can be expressed in its implicit form, as in Equation 3:

$$g:g(\mathbf{X},\mathbf{p})=x^2+y^2-4\cdot f\cdot z=0, \tag{3}$$

where $\mathbf{p}=(f,\varphi_x,\varphi_y,x_v,y_v,z_v)$ are the unknown parameters that will be estimated.

The first approach was the classical Least Squares Estimation, which is an adjustment of the observations $\mathbf{X}$ that are included in the implicit model of Equation 3. LSE is an iterative algorithm that uses a linearization of Equation 3 using Taylor series and needs the initialization of the parameters to estimate, p_0. The equation can be rewritten as:

$$g(\mathbf{X},p)=\omega+B\cdot e+A\cdot\Delta p \tag{4}$$

The main goal is minimizing the squared sum of the error e between the measurements and the fitted data. This will return the adjusted parameters as:

$$p=p_0+\Delta p \tag{5}$$

The second approach was the Orthogonal Distance Regression method (Holst et al. (2012)), which is very similar to LSE but uses two nested iterations:

1. In an inner iteration, it finds the orthogonal points to the given data that lay on the surface of the antenna, X_c , named contacting points. These points satisfy Equation 3.
2. In the outer iteration, it uses X_c to estimate the antenna parameters as is done in LSE.

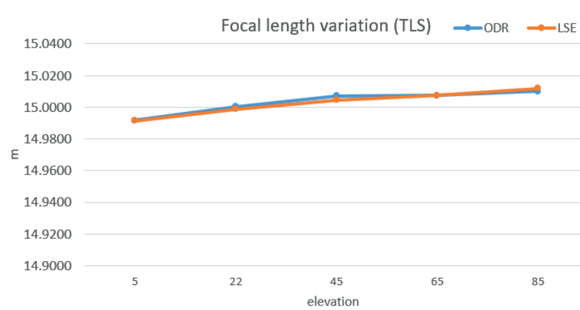
4 Results

The parameters of the model were obtained with LSE and ODR for both techniques. In this study we will focus on the variation of the focal length, as is shown in Table 1.

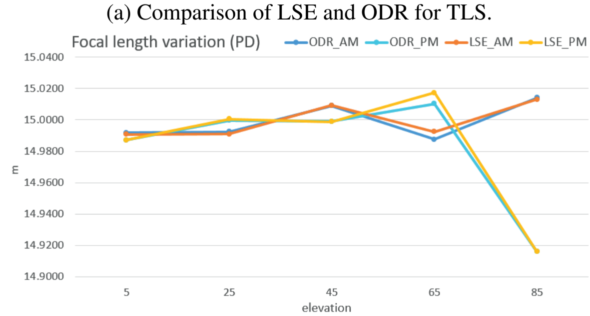
Table 1: Comparison of the focal length variation obtained with LSE and ODR for TLS and Drone-AM and Drone-PM.

Method	Technique	5°	25°	45°	65°	85°
LSE	TLS	14.991	14.998	15.004	15.007	15.011
	Drone-AM	14.990	14.990	15.009	14.992	15.013
	Drone-PM	14.987	15.000	14.998	15.017	14.916
ODR	TLS	14.991	15.000	15.007	15.007	15.010
	Drone-AM	14.991	14.992	15.009	14.987	15.014
	Drone-PM	14.987	14.999	14.999	15.010	14.916

These results are also shown in Figure 4, where the methods LSE and ODR are compared for each technique. With the TLS both methods do not differ much, and the variation of the focal length has almost the same behavior. On the other hand, with the UAV-DAP both methods differ a lot more, and that might be due to poor lighting conditions. In addition, the automatic point recognition software used for the markers did not recognize some of them correctly, so the errors in the 65° and 85° clouds are larger. **Then these results should not be considered, and the point cloud should be reprocessed.**



(a) Comparison of LSE and ODR for TLS.



(b) Comparison of LSE and ODR for Drone-AM and Drone-PM.

Fig. 4: Focal length variation comparison.

The errors obtained for both methods have different magnitudes: LSE errors are around 2 mm and ODR errors are less than 0.03 mm.

Lastly, with the TLS the measured point and the adjusted data were compared so the deformation of the antenna can be studied. In Figure 5 those differences are shown that vary from -5 mm to 5 mm and can be appreciated that there is a diagonal line where the model and the measurements differ the most. This might be due to an error in the calibration of the TLS (Holst et al. (2016)) and will be addressed in future studies.

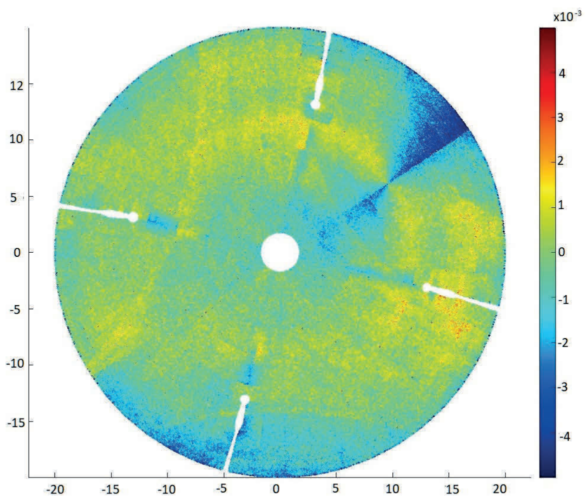


Fig. 5: Comparison between measured points of the 40-m antenna with TLS and modeled ones from LSE at 45° elevation in mm.

5 Conclusions

As shown in this study, the focal length variation with the elevation and other parameters that describe the antenna surface are estimated using LSE and ODR. It has been shown how it varies for the different observations depending on the method used, the type of measurements, and whether it is AM or PM.

On one hand, it can be observed that in Table 1 and in Figure 4b the afternoon values measured with UAV-DAP differ greatly from the theoretical focal length of 15 m. This might be caused by poor lighting and a failure in the markers recognition software. For these reasons, these results should not be considered, and the point cloud should be reprocessed, taking into account these issues in future surveys.

On the other hand, as mentioned above, there is a misalignment in the model generated with the TLS, and it is due to a failure in the calibration of the TLS but can be corrected.

Lastly, after considering these results, new measurements and approaches will be taken into account so the errors encountered in this study are eliminated.

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