Alvaro Santamaría-Gómez et al.: Estimation of the Invariant Reference Point: First Steps at Yebes, IVS 2012 General Meeting Proceedings, p.147–151
http://ivscc.gsfc.nasa.gov/publications/gm2012/santamaria-gomez.pdf

Estimation of the Invariant Reference Point: First Steps at Yebes

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Abstract

The relative position of the reference points of the different space geodetic instruments is a key issue in realizing the International Terrestrial Reference Frame. We present simulations carried out to estimate the invariant reference point (IRP) coordinates of the 40-m radio telescope at the Yebes observatory. From these simulations we draw conclusions concerning the impact of the number, the quality, and the geometry of the survey observations on the precision of the estimated IRP coordinates.

1. Introduction

The International Terrestrial Reference Frame (ITRF) is currently constructed from the combination of the terrestrial frames realized by the ground stations of four space geodetic techniques: Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), and Very Long Baseline Interferometry (VLBI) [1]. The combination of these four terrestrial frames is achieved thanks to the observation of the relative position vectors (local ties) between the ground stations belonging to different techniques at co-location sites. Furthermore, in order to avoid significant internal distortions of the combined reference frame, the local ties accuracy should be better than the individual space geodetic techniques, and an accuracy of better than 1 mm is usually demanded.

For the VLBI terrestrial frame, the position and velocity of any radio telescope are given for its reference point, the so-called invariant reference point (or IRP). In a Cassegrain-type radio telescope, the IRP is located on the azimuth axis and is realized by the projection of the elevation axis onto the azimuth axis, or equivalently, the nearest point of the azimuth axis to the elevation axis. This geometrically-defined point is usually not physically accessible. Therefore, the IRP coordinates with respect to a local coordinate system are indirectly estimated through survey observations to targets located on the revolving structure of the radio telescope. The approach being developed at the Yebes Observatory (IGN, Spain) is based on automated, unmanned, remote-controlled, and continuous survey observations. Some geodetic observatories have recently started to apply a similar approach [6]. This approach could also allow identification of station-dependent systematic errors as monument instabilities or radio telescope deformations [5].

On the basis of this approach, this paper presents the results of a simulation study carried out for the 40-m radio telescope at Yebes. Similar simulation studies have been undertaken for other radio telescopes [3]. In order to optimize the observing strategy, several scenarios with different geometric configurations, numbers of observations, and levels of precision were tested.

2. The IRP Estimation

Two different geometric approaches are currently used to estimate the IRP coordinates, namely the ‘circle fitting’ approach [2] and the ‘transformation’ approach [4]. The latter approach allows the IRP to be determined while the radio telescope is performing its inherent observations; i.e., no downtime of the radio telescope is required. This is a minor difference for current geo-VLBI operations, but it will become a significant advantage in the framework of the VLBI2010 project, where continuous observations are planned. Therefore, the method chosen at Yebes is based on the transformation approach.

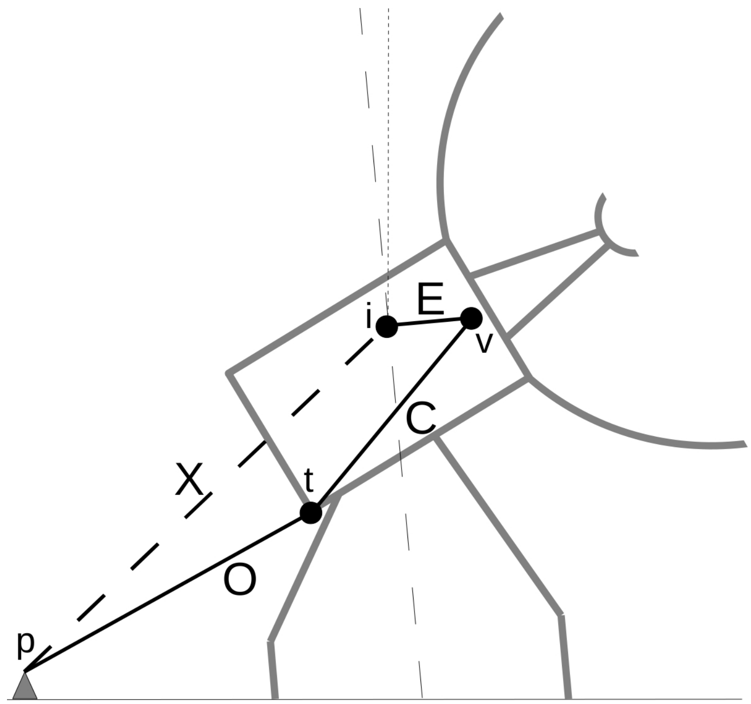

Figure 1. Schema of the IRP estimation approach.

The transformation approach is based on a spatial similarity transformation between two coordinate systems (see Figure 1): a coordinate system attached to the radio telescope (RCS) and a local coordinate system attached to the observatory (OCS). From Figure 1, for any orientation of the radio telescope, the observed vector (O) from an external observing instrument (p), with known position in the OCS, to a target (t) located on the radio telescope is the sum of three vectors:

- the IRP position in the OCS (vector X between p and i),
- the axis offset (vector E between i and v), rotated by the radio telescope azimuth angle, and
- the target position in the RCS (vector C between v and t), rotated by the radio telescope elevation and azimuth angles.

This can be summarized in the following expression:

$$O_a^t = R_a \left(E + C^t \right) + X \tag{1}$$

where R represents the rotation matrix between both coordinate systems, the subscript a represents each radio telescope orientation, and the superscript t represents each observed target.

To estimate a reliable IRP, the rotation matrix R has to allow extra unknown parameters relating both coordinate systems. These parameters correspond to the relative vertical inclination of the azimuth axis with respect to the OCS, the non-orthogonality between the azimuth and elevation axes, and the angular offsets for the azimuth and elevation readings of the radio telescope. All these parameters, together with the IRP coordinates and the axis offset, have been included in the geometric model and adjusted through a non-linear weighted least-squares inversion.

However, there are some assumptions behind the adopted approach. First, the azimuth and elevation values are used as input observations in the geometric model. They may be assumed to be error-free, but actually they may be randomly or systematically affected by unmodeled mechanical defects of the radio telescope (e.g., torsion, compression, bending, vibration, etc.) and by external effects like the wind. The uncertainties of the input orientation angles should be then taken into account. Further work out of the scope of this study is required to assess the impact of these effects on the estimation of the IRP coordinates.

Also, the vector C, given in the RCS, must be known a priori as an exact value. However, whereas the relative position of the targets can be precisely obtained by survey observations, determining their absolute positions in the RCS is not so straightforward. The circle fitting approach could be used to estimate the vector C and their uncertainties should be taken into account in the error propagation. Alternatively, we have added adjustments to the a priori target coordinates in our least-squares inversion. In this study, however, we held the target coordinates as fixed parameters but added simulated systematic errors (see Section 3).

Finally, the vector C may be also assumed to be time constant. However, this vector is actually affected by time-dependent deformations of the radio telescope structure (e.g., thermal and gravitational effects). The deformation of the vector C, unless corrected, will be absorbed by the estimated IRP coordinates. This implies that by integrating successive short observation spans, this approach could be used to monitor the time-variable deformations through the variations of the IRP coordinates [5], although the uncertainties of the estimated parameters will be increased. Nevertheless, it is also expected that, depending on the target locations, the deformation would propagate into the other estimated parameters in the form of systematic biases and increased uncertainty. Thus, the deformation will not likely translate 1:1 into a bias of the IRP coordinates. The mechanism of the propagation of the deformation of the radio telescope structure into the estimated parameters needs to be addressed in a future work, and it is out of the scope of this paper. For the simulations carried out in this study we assumed that the vector C is constant. Still, very short observation spans will be simulated to assess the suitability of this method to estimate the short-term deformations of the radio telescope.

3. Simulation

The simulations were carried out according to the following steps:

1. Simulating the coordinates of targets on the RCS: two targets were simulated to be located on both counterweights. Each target was simulated to consist of a hemispherical reflector (for instance by coupling four corner cube reflectors) in such a way to admit observations from everywhere in any radio telescope position. The counterweights were chosen because they move similarly (inversely) to the radio telescope main reflector but are less prone to ther-

mal/gravitational deformations. The coordinates of both targets in the RCS were extracted from the construction plans.

2. Simulating the radio telescope orientations: several sets of azimuth/elevation values were simulated to be homogeneously distributed on a hemisphere. Sets of 100, 400, 700, and 1000 orientations were simulated. These values were chosen due to the fact that, for the 40-m radio telescope at Yebes, the largest VLBI experiment had ∼400 observed sources, and based on the radio telescope turning velocity and acceleration, the largest number of orientations it could ever have in 24 hours is ∼1000.

3. Simulating the observing instruments: one, two, and three robotic total stations were simulated to be separated by 120° in azimuth from the radio telescope. The distances to the radio telescope were not considered as they were simulated by the different precision levels of the survey observations, assuming survey errors to be proportional to the separation distance.

4. Simulating the survey observations: the coordinates of the observed targets in the OCS were estimated using Equation 1 where all the parameters (IRP coordinates, axis offset, vertical inclination, azimuth/elevation offset, and non-orthogonality) were set to zero. The target occultation behind the radio telescope structure was taken into account based on the target location, the radio telescope orientation, and the location of the observing instrument.

5. Simulating survey errors: to simulate random survey errors, white noise amplitudes of 0.5, 3, 6, and 9 mm (standard deviation) were added to the error-free target coordinates previously estimated in the OCS. In addition, to simulate systematic errors in the RCS and OCS, the same white noise amplitudes were added to the a priori known target coordinates in the RCS. We considered 0.5 mm as the upper (optimistic) precision level taking into account that the radio telescope is never stopped during a VLBI session.

This sequence was repeated 1000 times with different numbers of observations, numbers of observing instruments, and precision of the target coordinates, resulting in 46 different scenarios. For each simulated scenario, the repeatability of the 1000 estimates allowed us to infer the precision of the estimated IRP coordinates.

4. Results

In this section we show the precision of the IRP coordinates after reducing the simulated target coordinates under several observing scenarios. Table 1 shows the precision of the IRP coordinates (3D component at 2 sigma confidence level) for the 46 scenarios simulated.

Taking an upper limit of 1 mm for the IRP precision, the requisites of the survey observation in terms of the number of observing instruments, the number of observations, and the precision of the coordinates will be assessed. Specifically, the objective of the simulation was to tune the observing procedure by answering three main questions:

- Is it enough to use only one observing instrument? Or, how much is the precision improved by using additional observing instruments? One observing instrument would be appropriate only with highly precise target coordinates (∼0.5 mm) or with very many observations (∼1000) and a precision better than 3 mm. The precison is improved by 57% and 68% using two and three observing instruments, respectively.

Table 1. Precision (two sigma) of the estimated IRP coordinates (3D component) with respect to the number of observing instruments, the number of observations, and the target errors (all values in mm).

	1 Instrument				2 Instruments				3 Instruments			
# Obs / Error	0.5	3	6	9	0.5	3	6	9	0.5	3	6	9
1000	0.20	0.90	1.84	2.74	0.04	0.40	0.78	1.18	0.02	0.30	0.60	0.86
700	0.22	1.08	2.18	3.22	0.08	0.48	0.94	1.40	0.02	0.36	0.70	1.08
400	0.30	1.58	2.96	4.38	0.12	0.62	1.26	1.84	0.06	0.48	0.92	1.40
100	0.58	2.84	5.42	8.12	0.24	1.22	2.36	3.56	0.18	0.90	1.78	2.68

- Is it enough to use the radio telescope orientations of a current 24-hour VLBI session at Yebes? Current 24-hour sessions would only be suitable with highly precise target coordinates (~0.5 mm) or with at least two observing instruments. With Intensive and dedicated radio telescope orientations (>1000 in 24-h) it would be possible to use only one observing instrument if the target coordinates are observed with a precision better than 3 mm.
- What is the required precision for the target coordinates? Using one observing instrument, it should be better than 1 mm with the number of observations in a 24-hour VLBI session at Yebes. With more observations (orientations or instruments), the precision requirement is reduced to 3 mm.

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