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# ASTROMETRIC REDUCTION OF GEOSTATIONARY SATELLITES OPTICAL OBSERVATIONS FOR ORBIT DETERMINATION (PASAGE)

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## RESUMEN

El conocimiento de las efemérides de los satélites geostacionarios es de gran importancia para las agencias de control, tanto para programar maniobras como para comprobar sus resultados. El proyecto PASAGE (Posicionamiento Astrométrico de Satélites Geoestacionarios) tiene como principal objetivo determinar con precisión astrométrica estas efemérides desde telescopios basados en tierra, y la posterior determinación de sus órbitas. Para esta especial aplicación de la astrometría, hemos desarrollado técnicas y algoritmos especiales que nos permiten obtener las posiciones aparentes topocéntricas de los satélites geostacionarios con precisiones de décimas de segundo de arco, incluso desde lugares con alta contaminación lumínica.

## ABSTRACT

The precise knowledge of the ephemerides of the geostationary satellites is a key point in mission control for the satellite control agencies both for planning manoeuvres and for checking their results. The major goal of the PASAGE project (Astrometric Positioning of Geostationary Satellites) is to use earth-based astrometric observations for obtaining precise ephemerides and the subsequent orbit determination. In order to carry out this special ground-based astrometric application, we have developed special algorithms and techniques that make it possible for us to achieve accuracies of a few tenths of an arc second in the geostationary satellite apparent topocentric positions, even from places with high light pollution.

*Key Words:* astrometry — ephemerides — celestial mechanics

## 1. INTRODUCTION

Geostationary satellites are those that keep a fixed position in the rotating terrestrial reference system. As it is well known, that condition is met by the infinity equilibrium solutions of the dynamical problem in the rotating system, when considering only the action of an ideal spherical Earth; that is, equatorial and circular orbit with sidereal period. But these equilibria vanish when taking into account perturbations of the actual Earth shape, the Sun and Moon and solar radiation pressure. As a result, the satellites move away from their nominal position and the satellites' control agencies have to manoeuvre them to allow their station-keeping. Therefore, real-time knowledge of the satellite position and of the orbital parameters is of vital importance for programming and checking the results of their manoeuvres.

The ground-based astrometry is a precise alternative for the orbital control of the geostationary satellites, although always as a complementary method of the usual way of working, due to the dependence on meteo conditions and, of course, because we only can observe during night time.

In the PASAGE project (López Moratalla et al. 2006, 2008) we have developed original algorithms and reduction methods of special images obtained with the telescope parked, from which we can get apparent positions of geostationary satellites with an accuracy of a few tenths of an arc second. Optical observation of objects in geostationary ring, including space debris, is also carried out by other groups with several purposes; see for instance Alby et al. (2004), Beutler et al. (2005), Sabol & Culp (2001), and Schildknecht et al. (2004).

We are observing from the inside of the city of San Fernando, with the Real Instituto y Observatorio de la Armada (ROA) Gautier astrographic telescope, and from Observatorio Astronómico Nacional (OAN) del Llano del Hato, Mérida, Venezuela, in collaboration with the Centro de Investigaciones de Astronomía de Venezuela (CIDA). With quasi-simultaneous observations from these places and taking advantage of this long baseline, we plan to determine precise parallaxes and to achieve a much better satellite position. In addition, for synchronizing purposes and time scale comparison, the ROA Time and Frequency Laboratory is routinely working

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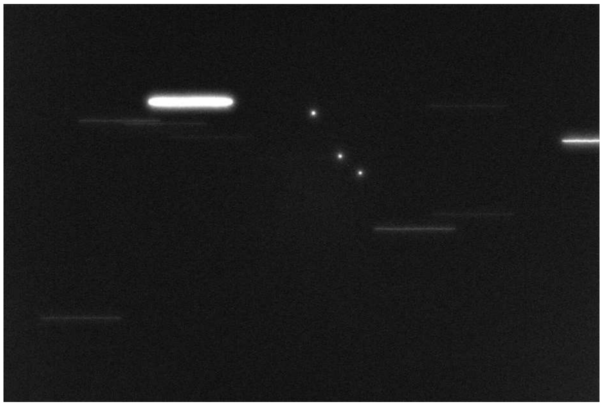

Fig. 1. Image taken from San Fernando centered in the Hispasat nominal position. There are clearly visible the moving background stars and three satellites: Hispasat1C, Hispasat1D and Spainsat, the satellites that the Hispasat Agency has at longitude 30° $W$.

with Two Way Satellite Time and Frequency Transfer (TWSTFT) and, as a subproduct, we have access to real-time topocentric pseudodistances to geostationary satellites.

## 2. OBSERVATIONAL TECHNIQUE

It is important to note that to perform geostationary astrometry we need to observe at the same time two kinds of objects: stars and satellites. The relative motion between them is almost equal to the sidereal time, so we have to develop special techniques to deal with these observations.

On the celestial sphere the geostationary satellites have nearly constant hour angle and declination, while we can consider that stars maintain constant right ascension and declination. Therefore, if we leave the telescope parked, without any tracking, the geostationary satellites will appear as point sources and the point spread functions (PSF) of the stars will be track-lines or stripes with a length proportional to the exposure time. With this kind of exposures (satellite tracking), we only need a stable equatorial platform. Note that while the satellite signal will continue to grow with the exposure time, the star signal will spread over a pixel line. For this reason the exposure time is a compromise between the best satellite signal and a little track length in order to maximize the number of useful stars in the field of view.

The satellite magnitude depends on the phase angle with the Sun. Then only a fraction of the orbit can be observed every night. It will be longer, the closer the satellite's nominal longitude is to the observer meridian. Every night the satellite appears weakest when its phase angle is nearly $7^h$ and it is brightest when in opposition. The magnitudes also vary along the year with the brightest occuring near the equinoxes and the faintest around the solstices. Depending also on the shape of each satellite we can expect to reach $5V$ or $6V$ around the equinoxes and $10V$ or $11V$ around solstices, both when near opposition. Eclipses of satellites are also produced around the equinoxes, with nearly seventy minutes of maximum time of occultation.

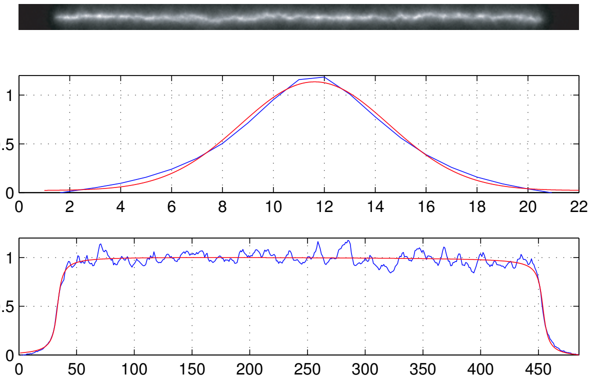

Fig. 2. Star track as it appears in the image, and its $y$ profile with a Gaussian fit and $x$ profile with a Tepui fit.

We have fixed the optimal exposure time from San Fernando to 15 sec, and we take one image every 2 min during the time while the satellite is visible, around 300 images per night. Figure 1 is one of these images, centered on the Hispasat nominal position (30° $W$). The image field of view is $27' \times 18'$.

The observed time determination is critical for the following satellite positioning calculation and it is a major subject in this observational technique. The whole error in dating the image goes directly into the satellite hour angle error.

## 3. IMAGE REDUCTION

### 3.1. *CCD reduction*

The satellite astrometric position is determined by the background star reduction to a reference catalog, Tycho2 in our case. Of course, first we have to obtain the Cartesian coordinates $(x_c, y_c)$ of the star tracks over the CCD. But the precise determination of the track centers is not a trivial matter and we had to develop original software. Once an initial position of each track is calculated by means of a step convolution, the precise track $y$ coordinate is determined by a Gaussian fit to the $y$ profile of the track-column added pixel values. The resulting added profile in the other dimension, the $x$ profile, is a step that is very well fitted with a *Tepui function* (Abad et al.

2003) and the center of the fitted function provides the track $x$ coordinate, see Figure 2.

We must note that the signal is added in the $y$ profile but not in the $x$ profile and thus the signal to noise ratio is around eight times greater in the $y$ profile. Hence, it is not strange that the $y$ star coordinate determination is always more accurate than the $x$ one.

The Cartesian satellite CCD coordinates are calculated by a classical 2D Gaussian fit.

### 3.2. *Catalog reduction*

With this observation method and especially when we are working with low signal to noise ratios, we do not have enough stars per image to perform a satisfactory classical reduction fit. But the parked telescope observing method allows us to carry out a complete catalog reduction of the stars in the images of the night as a whole, in order to get general plate constants per night. First we do an initial reduction by a 6-element weighted least-squares solution (around 600 condition equations per coordinate (1) and we obtain a preliminary set of plate constants that allows us to make the corrections for plate rotation, tilt and scale error, differential refraction and aberration, etc. Then we can eliminate those stars with great errors and after a second reduction we get the definitive plate constants matrix.

$$\begin{aligned} x_a - x_c &= a_1\, x_c + b_1\, y_c + c_1\,, \\ y_a - y_c &= a_2\, x_c + b_2\, y_c + c_2\,, \end{aligned} \tag{1}$$

where $(x_a, y_a)$ are catalogue coordinates, $(x_c, y_c)$ CCD coordinates and $(a_i, b_i, c_i)$ the least-squares calculated plate constants. Thus, $(x_s, y_s)$ will be the standard coordinates of the stars,

$$\begin{aligned} x_s &= x_c + a_1\, x_c + b_1\, y_c + c_1\,, \\ y_s &= y_c + a_2\, x_c + b_2\, y_c + c_2\,. \end{aligned} \tag{2}$$

This global reduction implies the assumption that the telescope pointing is absolutely constant, and thus the residuals of the standard coordinates with respect to the catalog coordinates as a function of time are the true variations of the pointing due to small telescope movements or sky fluctuations by anomalous refraction (see Figure 3).

Once we obtain the plate constants and the fluctuations for each image over the nominal telescope pointing, we can apply these corrections to the satellite position and then we obtain the true relative positions in time. That is to say, we have the unitary position vector that determines the apparent orbit of the satellite through the night. In Figure 4 we show the apparent orbits of the three Hispasat satellites during four days. Note that the red satellite was manoeuvred after the second night.

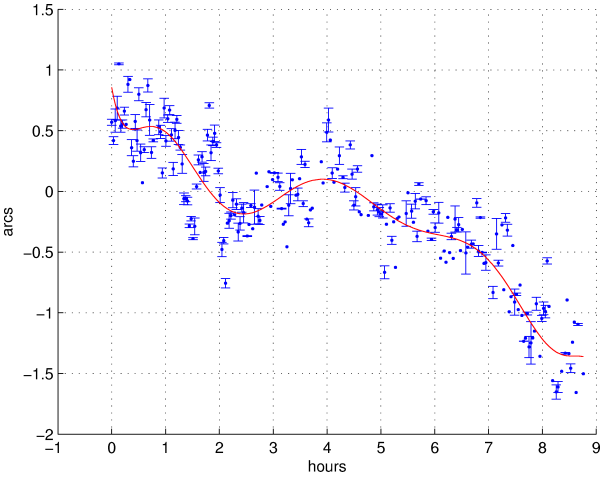

Fig. 3. Pointing variations (arc seconds) in the $y$ coordinate (*declination*) taken from San Fernando in one night. Each point is the relative declination of the image central pixel, and the error bars are the standard deviation of the solution of each star in the image.

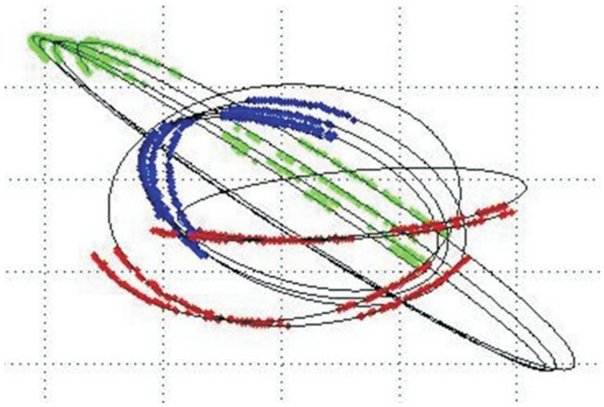

Fig. 4. Hispasat satellites apparent orbits from San Fernando during four days. The axes are oriented North is up and East left.

## 4. PRELIMINARY ORBIT DETERMINATION

From the topocentric directions of the satellite we can now deal with the calculation of the preliminary orbital elements and their variation. We can achieve this with the implementation of any classical celestial mechanics method for only-angular data. For the determination of preliminary orbital parameters we have implemented the Herget method. Then, taking $n$ topocentric directions as data input to Herget and repeating the calculation with the following $n$ data

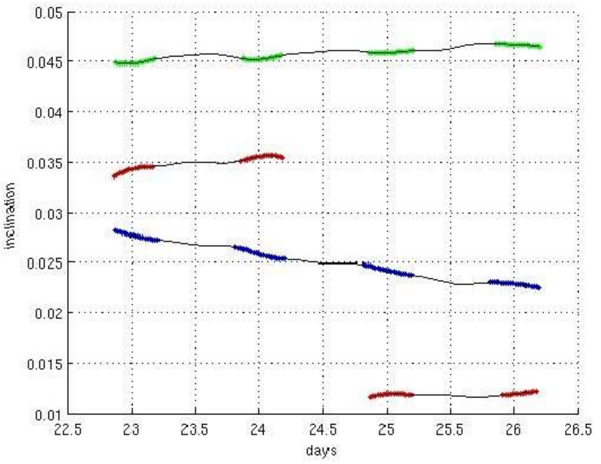

Fig. 5. Orbit inclination (deg) vs. time (days) after applying Herget's method to the topocentric positions of Figure 4. Note the inclination drop of the red satellite after it has been maneouvred.

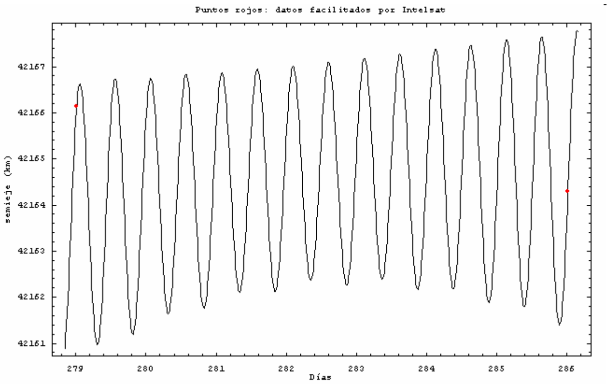

Fig. 6. Intelsat707 semiaxis (km) solution vs. time (days) from TWSTFT data plus angular data. The red points are the data supplied by Intelsat Agency.

we can determine the orbital elements in time. For example, in Figure 5 we have the results of the inclination calculation for the three Hispasat satellites from the data of Figure 4 after applying the Herget method to 16 topocentric position every 10 minutes. That is to say, as we take images every 2 minutes, in this example we calculate a set of orbital parameters every 10 minutes in 32 minutes of the orbit.

With images of the same satellite taken at the same time from Llano del Hato (OAN), Venezuela, we will be able to determine the parallax and then the distances, so we will be able to greatly improve the orbit parameter determination.

In addition, the ROA Time and Frequency Department routinely carries out the Two Way Satellite Time and Frequency Transfer (TWSTFT) with other Time Laboratories for synchronizing and comparison of time scale purposes through geostationary satellites which support this system. As a TWSTFT subproduct, we can directly calculate topocentric distances, which combined with astrometric angular data, allows us an easy and efficient computation of the orbital parameters. Figure 6 shows the computed Intelsat707 semiaxes (black line) and the data provided by Intelsat Agency website (red points). TWSTFT distances also can be used for validating the other methods. A comparison of the topocentric distances to Intelsat707 by TWSTFT and those computed from only-angular data by the Herget method is shown in Figure 7.

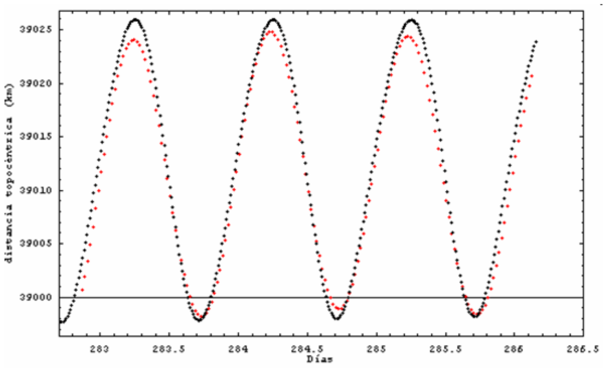

Fig. 7. Intelsat707 topocentric distances. Black: obtained from TWSTFT; Red: calculated from only-angular data by the Herget method. For colors, see the electronic version of this paper.

Although these results are coherent, we know that the Herget method is only an approximate solution, and we are going to implement a numerical integration of the perturbed equations of motion which we hope will greatly improve the current orbit determination of geostationary satellites.

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