HIGH-PRECISION TRACKING CALIBRATION WITH THE ESA TENERIFE TELESCOPE

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Abstract

The European Space Agency (ESA) is installing at the Teide observatory of the Instituto Astrofisica de Canarias in Tenerife a one-meter telescope. It acts as a ground check-out terminal in connection with the ESA satellite project ARTEMIS/SILEX in the frame of the Data Relay and Technology Programme. In the past years a study was carried out by Zeiss and SIRA in order to analyse the optical system of the telescope with respect to the requirements for space debris observations as well as for satellite tracking. A 4k x 4k pixel CCD camera was installed. As the pointing measurements obtained from the CCD camera will be better than 0.5", the telescope can also be used for high-precision in-orbit calibration of tracking systems.

Introduction

In routine phase satellites are often tracked by a dedicated network of ground stations, which does not include sufficient redundancy in tracking capabilities for cost reasons. Typical cases for these dedicated systems are the tracking networks for satellites in geostationary positions. They are normally controlled by a single ground station, which also provides range and pointing angles for the orbit determination. Within such a limited tracking configuration any existing inconsistencies in the tracking measurements (incorrect calibrations, for instance) or evolving degradation in performance (on-board transponder aging, as example) can hardly be detected. Small offsets either in range, azimuth or elevation would deteriorate the knowledge of the orbit of the satellite. Orbit determination which relies on many ground stations and furthermore which has a significantly time-varying station-satellite geometry is not so prone to measurement biases.

For example the ESA satellite MARECS (Maritime European Communication Satellite) is tracked by a dedicated single ground station. MARECS has a geosynchronous orbit, is maintained at a longitude of 26° West and is tracked in C-band from Villafranca, Spain using range and antenna angles. The performance of the tracking measurements is about 5 m for the range data and about .007° for the angles. The achieved orbit determination accuracy lies in the order of 0.5 km. The single station tracking configuration is due to the use of the C-band frequency.

Certainly the tracking situation could become better in case commonly used frequencies are employed for the up- and downlink as more ground facilities would perhaps be available in the coverage zone. With the inclusion of measurements from additional ground stations, tracking inconsistencies could be detected and calibrated easier. However, range or Doppler tracking from an additional ground station would also require the change-over of the control to that station as this type of tracking requires the uplink chain. For this reason it is extremely useful to have an uplink independent tracking device, which could be employed, whenever required, for calibration purposes without any interruptions / disturbances on the operational set-up.

The one-meter telescope with the 4k x 4k pixel camera at the Teide observatory of the Instituto Astrofisica de Canarias in Tenerife provides this capability. The pointing measurements obtained from the CCD camera will be better than 0.5" and hence the telescope can be used for high-precision in-orbit calibration of tracking systems.

This paper describes the characteristics of the telescope, outlines the possibilities for the in-orbit calibration of ground tracking systems and considers the application for some future ESA satellites.

Description of the ESA Tenerife Telescope and the CCD Camera

The European Space Agency (ESA) is installing at the Teide observatory of the Instituto Astrofisica de Canarias in Tenerife a one-meter telescope with a 4k x 4k pixel CCD camera as a ground check-out terminal in connection to the ARTEMIS/SILEX Project in the frame of the Data Relay and Technology Programme. In the past years a study was carried out by Zeiss (Jena, Germany) and SIRA (Chislehurst, UK) in order to analyse the optical system of the telescope with respect to the requirements for space debris observations as well as for satellite tracking. The installation is in its final stage, acceptance tests have commenced and it is expected that the telescope could be used operationally from the year 2000 onwards.

The telescope[1] is a Zeiss 1m Ritchey-Chretien/Coude telescope supported by an English mount. The telescope can be operated in three optical configurations, i.e. the standard Ritchey-Chretien system, a modified Ritchey-Chretien mode with focal reducer and the Coude system. However, for the satellite tracking purposes the modified Ritchey-Chretien configuration (spherical secondary mirror and focal reducer) will be used. In this configuration the telescope is equipped with a 4k x 4k pixel CCD camera. The detector is located in the focal plane of the telescope and covers a field of view of 1° with an image scale of 0.6"/pixel. The detector consists of a mosaic of four EEV 42-40 devices each having 2k x 2k pixels. The read out of the four devices is synchronised to 100 nsec. In order to keep the read-out short, each EEV device is equipped with two output amplifiers and hence the 32 MB image data can be taken within 20 sec. The data output is transferred to a SUN workstation, where the image is reconstructed in memory and displayed. The user interface on the SUN workstation provides the capability to acquire exposures, visualise the images, evaluate their quality and store them on disc.

The control of the telescope and the CCD camera as well as the data handling is carried out through three computers, the Central Control Computer (CCC), the Telescope Control Computer (TCC) and the Off-line Processing Computer (OPC). The provision of CCD pointing data for the calibration of satellite tracking data is handled through the off-line processing system. The off-line data processing[2,3], developed by the Astronomical Institute University of Berne (AIUB), provides the following functions:

- Photometric and astrometric reduction of raw images, which implies the generation of master calibration frames by averaging small series of dedicated frames.
- Object search on frames using a masking technique.
- Determination of CCD coordinates for all objects. The centroids of the object images must be determined.
- Transformation of CCD coordinates to celestial coordinates using telescope pointing information.
- High precision astrometry to improve the celestial coordinates using astrometric reference star catalogues.
- Maintenance of a database with observation data and processing results.

In addition orbit determination and object identification can be carried out by the off-line data processing, which is required within the space debris application.

The main characteristics of the telescope are summarised below:

Location (Izana, Tenerife, Spain)		
	Longitude	343.5° East
	Latitude	28.5° North
	Altitude	2393 m
Telescope	Type	Ritchey-Chretien
	Aperture	1.000 m
Mount	Type	Parallactic (English mount)
	max. slew rate	2°/s
	max. acceleration	$0.5°/s^2$
Tracking Focus		
	Focal length	4.463 m
	Field of view	1.2° (diameter of .097 m)
	Spectral range	450 - 950 nm
	Transmittance	≥ 0.7
	Blur circle	80% in 15 micro m

CCD Camera Measurements and their Performance

As the validation tests of the telescope have commenced recently, not so many measurements are available to evaluate the actual performance. However, it is expected that at least the AIUB Zimmerwald performance[4] will be obtained as the set-up of the Tenerife telescope follows to some extent the Zimmerwald one. The performance figure is largely determined by the centroiding process and the astrometric information.

The centroid for even relatively faint object images can be determined with a precision of a tenth of a pixel using a simple intensity weighted average of the object pixels[5].

Astrometric measurements of satellites are made relative to astrometric reference stars and are, therefore, independent on the angular encoders of the telescope. The mapping scale, camera orientation and higher order distortions of the mapping are determined off-line using reference stars or star clusters. Part of the mapping transformation can be determined from the measurements of the satellites themselves. As astrometric catalogue the ACT reference catalogue[6] is used which is based on Hipparcos and Tycho stellar positions.

Series of short exposed frames are acquired while the satellite happens to have a close encounter with a reference star at the celestial sphere. In this way, errors in the mapping and in refraction affect the results only differentially. A GPS time receiver and a special shuttering technique[7] are used for time tagging the object image centroids to within 1 msec with respect to UTC.

With a similar measuring technique an astrometric accuracy of 0.5" to 0.8" was achieved with the old 0.5 m SLR telescope of the AIUB in Zimmerwald providing a mapping scale of 4.2"/pixel. With the ESA telescope an astrometric precision of the order of 0.1"-0.2" should be reached[8].

Based on the CCD devices, the pixel size and the processing technique, an accuracy of about 0.5" is estimated, which has been taken as input for the subsequent covariance analysis.

A possible lay-out of the CCD camera measurements is given in table 1.

Covariance Analysis

The investigation of the usefulness of the Tenerife telescope measurements for in-orbit calibration purposes is based on a covariance analysis.

The determination of the position and velocity of a spacecraft is influenced by a variety of error sources. There are first of all tracking measurement errors which could be divided between random errors and systematic or bias errors. Furthermore there are modelling errors not only in the generation of the satellite motion but also in the handling of the tracking data such as the consideration of the necessary corrections. All these types of errors can be considered within the covariance analysis module within the Precise Orbit Determination Software[9].

In fact, the analysis consists of two parts:

- Generation of the tracking measurements

For the generation of the tracking measurements a set of nominal orbital parameters, the model of the spacecraft motion, the location of the tracking stations and the envisaged sequence as well as the assumed tracking errors is required. With this information the time intervals are determined during which the spacecraft is visible over the individual ground stations and the measurement sequence will be generated.

- Covariance analysis

For the processing of the simulated tracking measurements a very similar set of input parameters is used as for the generation part. However, for all the input data the associated errors (type as noise or bias and the error value itself) have to be specified.

Fundamentally, the weighted least squares principle has been adopted to establish the covariance matrix of the parameters to be estimated or considered, i.e. state vector plus auxiliary parameters.

Examples for application of CCD Measurements

Obviously a typical application of the CCD measurements within orbit determination lies in the area of improving the calibration parameters of a single station tracking configuration for satellite in geosynchronous orbits. The ESA Tenerife telescope is located at a longitude of 16.5° West and assuming a minimum elevation of 20°, all satellites in geosynchronous positions with longitudes ranging from 74° West up to 42° East could be observed.

The usefulness of the CCD measurements for this type of application is illustrated for the above mentioned ESA satellite MARECS (longitude of 26° West, tracked in C-band from Villafranca, Spain using range and antenna angles).

The covariance analysis is based on the following performance of tracking measurements:

Villafranca	range	noise of 5 m,	bias uncertainty of 25 m
	azimuth	. 007°	.007°
	elevation	.010°	.010°
CCD data	right ascension	.5"	. 5"
	declination	.5"	. 5"

Because of this particular station-satellite geometry and because of the performance of the range measurements an offset of the Villafranca angle data can be estimated (and which actually is done within the routine operations). However, the offsets can only be determined to an accuracy of about .0025° for the azimuth component and to about .0009° for the elevation angle. This results in a positional accuracy of about 500 m[10]. Supplementing the Villafranca tracking with CCD measurements (during 3 nights within a week) the offset of the angular data could be determined up to a level of .0009° for azimuth and elevation, however, clearly under the assumption, that the offset of the antenna is consistent at all to this level of precision. Applying the improved knowledge of the angular data within the covariance method a spacecraft positional accuracy of 180 m instead of previously 500 m could be obtained.

The usefulness of the CCD measurements for the improvement of the orbit determination relying on single station tracking has been demonstrated for the Villafranca-MARECS configuration. The applicability of CCD data for the improvement of single station tracking is not only limited to geosynchronous orbits, orbit determination for other orbit types could also benefit from the CCD measurements, however, coverage constraints have to be taken into account. Whereas satellites in geosynchronous orbits within the appropriate longitude interval could in principle be observed every night, there might be severe limitations for highly eccentric orbits, i.e. subsatellite location of perigee has to be close to Tenerife with its passage during night.

Within the ESA Scientific Satellite Programme CLUSTER and INTEGRAL are the next future spacecraft to be tracked by a single ground station, for which the coverage aspect as well as the contribution of the Tenerife CCD measurements will be analysed.

CLUSTER will be launched in Mid 2000 into an eccentric polar orbit with a perigee height of 19000 km, an apogee height of 119000 km and an argument of perigee of 0°. The satellites (in fact there are 4 satellites) will be tracked from Villafranca, Spain (range and Doppler only) during the routine phase. For this orbit type the satellites could be observed from Tenerife for about 4 hours around perigee (i.e. below geosynchronous altitude) in favourable conditions, when the subsatellite location of the perigee is close to the longitude of Tenerife.

INTEGRAL will be launched in Spring 2001 into an eccentric orbit with a perigee height of 10000 km, an apogee height of 153000 km, an inclination of 51.6° and an argument of perigee of 300° . The ground track will be repetitive, as the orbit will have a period of 72 hours. The satellite will be tracked from Redu, Belgium (range and Doppler only) during the routine phase. Also for this type of orbit the visibility from Tenerife following perigee and below geosynchronous altitude is more than 2 hours.

Table 2 provides a summary of the observability of these satellites from Tenerife, gives the overall achievable orbit determination accuracy as well as the expected spacecraft position errors during the Tenerife coverage. For both satellites the positional errors as seen from Tenerife are in the order of 500 m, which is significantly larger compared to the CCD measurement performance. Hence the CCD data would be useful for the verification of the estimated orbit determination accuracy as well as for the in-orbit calibration of the tracking systems.

It is proposed to use the CCD measurements from the Tenerife telescope for the in-orbit calibration of the tracking systems for these two satellites.

Conclusions

Especially single station tracking is very sensitive to uncalibrated systematic offsets (incorrect calibrations, for instance) in tracking measurements or evolving degradation in performance (on-board transponder aging, for example), and this makes it necessary to have a good a priori knowledge of the tracking facilities. The ESA Tenerife telescope with its very accurate CCD camera provides a good mechanism to verify the performance of single station tracking systems and to re-calibrate them, if necessary.

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Table 1: Possible Example for Data Format, close to ODPS format:

S	Date			Time	(UTC)		Name	RA(h.mmss)	DE(d.mmss)	dRA(s)	dDE(")	E	S
*	****	**	**	**	**	*******	*****	**********	***********	******	******	*	*
1	1995	01	03	22	49	43.2752	Met 4	5.02322803	-6.4904647	0.0257	0.391	2	1
1	1995	01	03	22	49	47.5910	Met 4	5.02366316	-6.4904190	0.0257	0.391	2	1
1	1995	01	03	22	49	52.5911	Met 4	5.02416692	-6.4901908	0.0257	0.391	2	1
1	1995	01	03	22	49	57.5915	Met 4	5.02466892	-6.4900163	0.0257	0.391	2	1
1	1995	01	03	22	50	02.5912	Met 4	5.02517086	-6.4858974	0.0257	0.391	2	1
1	1995	01	03	22	50	07.5911	Met 4	5.02567255	-6.4858461	0.0257	0.391	2	1
1	1995	01	03	22	50	12.5916	Met 4	5.03017575	-6.4855644	0.0258	0.391	2	1
1	1995	01	03	22	50	17.5913	Met 4	5.03067046	-6.4855690	0.0258	0.391	2	1
1	1995	01	03	22	50	27.5911	Met 4	5.03167230	-6.4852292	0.0258	0.391	2	1
1	1995	01	03	23	00	45.2510	Met 4	5.13359496	-6.4620298	0.0257	0.384	2	1
1	1995	01	03	23	00	55.2516	Met 4	5.13459490	-6.4617346	0.0257	0.384	2	1
1	1995	01	03	23	01	00.2514	Met 4	5.13509203	-6.4615765	0.0257	0.384	2	1
1	1995	01	03	23	01	05.2319	Met 4	5.13558723	-6.4614487	0.0257	0.384	2	1
1	1995	01	03	23	01	15.2512	Met 4	5.14059051	-6.4610726	0.0256	0.384	2	1
1	1995	01	03	23	01	20.2511	Met 4	5.14109708	-6.4610393	0.0256	0.384	2	1

Col 1: Selection flag, 1: observation selected, 0: rejected
Col 2-7: Light arrival date and time, UTC
Col 8: Short object designation
Col 9-10: Right ascension and declination
Col 11-12: Formal errors from astrometry in RA and Decl
Col 13: Equinox (1: B1950, 2: J2000)
Col 14: System (1: standard, 2: mean, 3: apparent)

Table 2: Tracking Conditions from Tenerife for CLUSTER and INTEGRAL

	CLUSTER	INTEGRAL
Orbit Period	57.1 hrs	3 sidereal days
Perigee coverage from Tenerife	during one season for several non-subsequent nights	every half year for about 2 months every night
Typical coverage		
start: true anomaly/altitude	32 / 23 Mm	80 / 19 Mm
end: true anomaly/altitude	87 / 37 Mm	117 / 40 Mm
duration	2.4 hrs	2.0 hrs
Orbit determination accuracy		
worst case along the orbit	1700 m	1900 m
during Tenerife visibility	800 m	550 m
error seen from Tenerife	550 m	490 m
expressed as angle	.0010°	.0009°