OPTICAL CAMPAIGN
FOR LOW EARTH ORBIT SATELLITES ORBIT DETERMINATION

Fabrizio Piergentili(1), Manfredi Porfilio(2), Filippo Graziani(3)

Università degli Studi di Roma "La Sapienza", Scuola di Ingegneria Aerospaziale
via Eudossiana 16, 00184 Roma, ITALY
Email: (1) fabrizio.piergentili@uniroma1.it (2) manfredi_porfilio@hotmail.com (3) gauss@caspur.it

ABSTRACT

After some years of observations of the geostationary ring, the Group of Astrodynamics of the University of Rome "La Sapienza" (GAUSS) performed in 2005 a test optical campaign addressed to low Earth orbit satellites orbit determination.

The objects Cosmos 1833 and Cosmos 2227 R/B (rocket body), chosen among the brightest, have been photographed by Collepardo Automatic Telescope equipped with a 40 cm Ritchey-Chrétien optical tube with focal reducer and a STL-1001E 1k×1k CCD (Charge Coupled Device). The field of view (FOV) exceeded 1°.

Various orbit determination methods, well known in the literature, have been studied in order to compare their capabilities: orbit determination based on the null eccentricity hypothesis, classical methods for the state determination from angles only and real-time filtering for updating the elements were tested and their results compared. In all cases a priori information were not exploited.

1. INTRODUCTION

In the last years the *Gruppo di Astrodinamica dell'Università degli Studi di Roma "La Sapienza"* (GAUSS) performed observations of the geosynchronous ring (see for instance Porfilio et al., 2003), also in the frame of the optical campaigns coordinated by IADC (Inter-Agency Space Debris Coordination Committee). A two-site campaign was also performed from Collepardo and Mallorca in September 2003 (Porfilio et al., 2004). The high Earth orbits are observed with telescopes in several countries (see for instance Africano et al., 2004, Schildknecht et al., 2004, Isobe and Tajama, 1997).

Recently, the awareness of the need of an orbiting objects European catalogue is arising. Therefore, observing and identifying objects in Low Earth Orbit (LEO) is mandatory. In this paper the results of the first test campaign carried out by GAUSS for LEO satellites are reported.

The observations were carried out with the Collepardo Automatic Telescope (CAT), equipped with a CCD whose pixel size is 24 μm; the angular accuracy of the measurements is about 10^{-4} rad. The CAT automation permitted a quasi-continuous objects tracking (based on the Two-Line Elements, TLE), increasing the number of available points for the orbit determination tests. The number of positions available for the test objects is 10 for Cosmos 1833 (over an arc 188 s long) and 13 for Cosmos 2227 R/B (over an arc 355 s long). The images were taken in star tracking mode, resulting in point-like stars and trailing satellites. This allows to easily recognize the star field in order to calculate the objects positions at the beginning and end of their traces.

Time referenced positions of the targets were used to derive their orbital parameters: several orbit determination methods have been tested, without using a priori information. The results have been compared with the TLEs.

Refining the orbital elements is definitely useful for re-entering objects which require an almost continuous monitoring. Up to date data must be available in order to keep an accurate control of the possible impact point.

The campaign main aim has been to verify the suitability of systems and methods. The experience would be very useful in case of possible future re-entry campaigns.

2. ORBIT DETERMINATION WITH THE ASSUMPTION OF NULL ECCENTRICITY

With the hypothesis of circular orbit two optical measurements suffice to determine the orbit. This assumption is valid for objects close to re-entry, as the eccentricity diminishes due to the drag.

For all the couples of observations, an orbit has been determined. The results are similar for all the couples, except for a few, typically composed of two measurements from the same photo (from each frame, the leading and trailing edge of the satellite streak are exploited to determine the angular position).

As an example, in Fig. 1 the estimated inclinations distributions for Cosmos 1833 and Cosmos 2227 R/B are depicted. The Cosmos 2227 R/B evaluations seem to be better as they are less dispersed. Nevertheless, due to a few very wrong measurements, the better standard deviation is that of Cosmos 1833 (see Tab. 1, "$e \equiv 0$" line, which contains the orbital parameters average values and their standard deviations). Of course, this would not happen disregarding maximum and minimum values of

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the distribution, which is a common procedure to reject the more erroneous results.

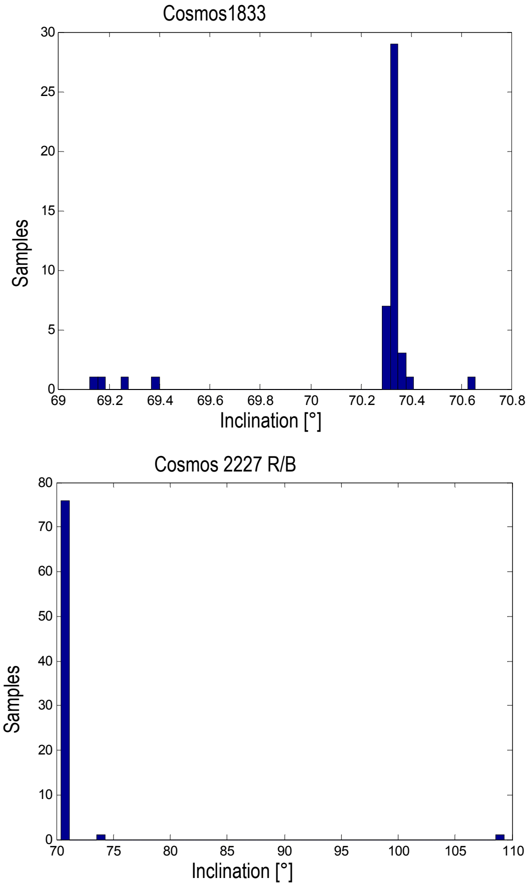

Figure 1. Cosmos 1833 and Cosmos 2227 R/B inclination evaluated with the null eccentricity assumption.

Similar considerations apply to the right ascension of ascending node (RAAN) and radius vector (≡ semi-major axis).

3. ORBIT DETERMINATION WITH THE LAPLACE AND GAUSS METHODS

The outcomes of these very classical methods (Escobal, 1965, Bate et al., 1971) strongly depend on the measures accuracy. The orbital parameters calculated averaging the results from all the possible groups of three measurements are not satisfactory, mainly due to a few definitely wrong estimates. An improvement would be obtained disregarding maximum and minimum values. Good results are also achieved considering the mode (i.e. the most frequent value). Of course, the mode depend on the dimension of the intervals in which the distribution is divided. Therefore, the mode approach has a statistical rather than a deterministic significance.
In Tab. 1 (rows “Laplace (6 angles)” and “Gauss (6 angles)”) the mode of the orbital parameters are reported together with the relevant intervals dimensions.
The mode suitability can be inferred from the histograms in Fig. 2, which illustrate the semi-major axis distribution for Cosmos 2227 R/B achieved with the cited methods. As a matter of fact the distributions asymmetry yield mean values quite far from the most frequent value.

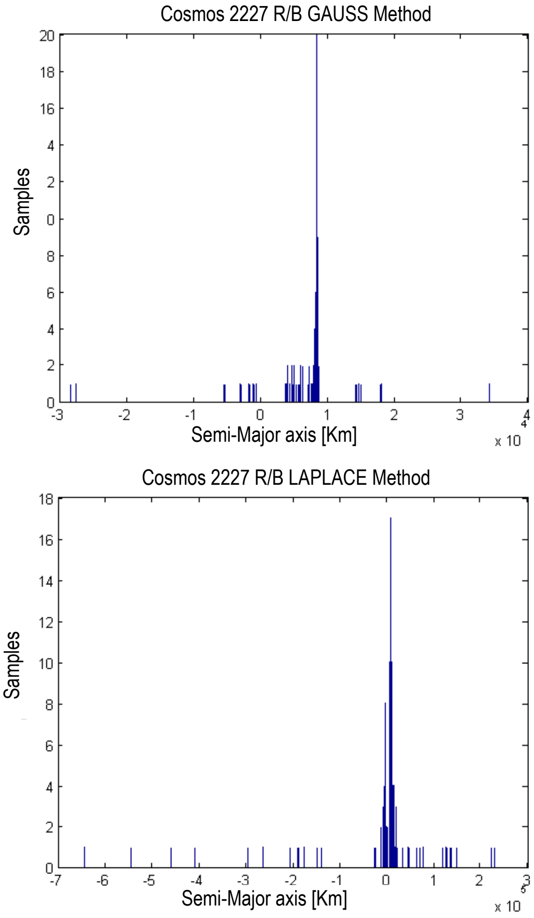

Figure 2. Cosmos 2227 R/B semi-major axis evaluated with Gauss and Laplace methods.

Similar considerations apply to the eccentricity, RAAN and inclination.

3.1. Applying the Laplace method to the measurements fitted with the Least Square Method

It is possible to exploit more than three observations by using the Least Square Method (LSM) to fit all the observations, as a function of time, with a 2nd grade polynomial (Bate et al., 1971).
Polynomials of grade greater than 2nd do not provide significant improvements and sometime give worse results due to the increasing number of inflection points. However, a 4th grade polynomial provides outcomes similar to a 2nd grade one.
The results of the Laplace method improved with the LSM fitting of all observations are reported in Tab. 1 (line “Laplace with LSM”). The results are better than those of Laplace and Gauss methods without LSM; moreover, a deterministic (not only statistical) estimate

is achieved.

4. ORBIT DETERMINATION WITH THE EXTENDED KALMAN FILTER

The Extended Kalman Filter (EKF, Kalman, 1960, Grover Brown and Hwang, 1992, Welch and Bishop, 2004) can be usefully employed to improve a preliminary orbit with new observations. It allows real time orbit updating as soon as new measurements are available. The initial state vector could be provided by TLE or, as it has been here considered, from a first rough estimate of the orbit. In the reported cases, the orbit first estimates, have been achieved with the null eccentricity assumption from the first two observations. In case of more eccentric orbits, a first estimate should consist in a six-element orbit determination, hence exploiting three or more observations.

The results are reported in Tab. 1 (row "EKF").

The Fig. 3 shows the trace of the covariance matrix for Cosmos 2227 R/B. The covariance grows up during the state propagation and diminishes when a new measurement is input. The plot shape clearly shows convergence.

Similar outcomes have been achieved for the Cosmos 1833 covariance matrix but the convergence is less evident due to the lower number of points.

In Fig. 4 the eccentricity, semi-major axis, inclination and RAAN evaluated with the EKF are reported. It is apparent the convergence to definite values for the orbit shape parameters (a, e). The convergence is less evident for the orbital plane parameters (i, Ω), but in this case the preliminary data are already fair.

5. CONCLUSIONS

The Tab. 1 shows the results of orbit determination for Cosmos 1833 and Cosmos 2227 R/B achieved with the above considered methods.

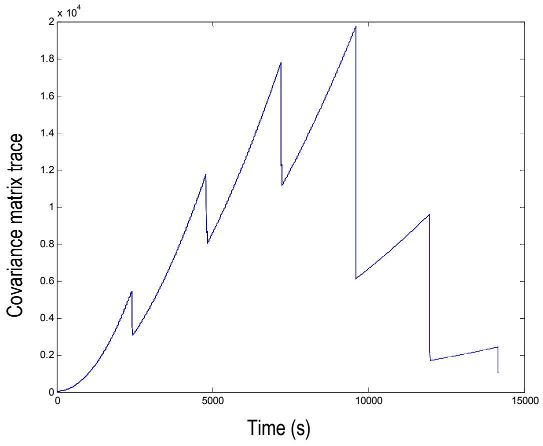

Figure 3. Trace of the EKF covariance matrix for Cosmos 2227 R/B.

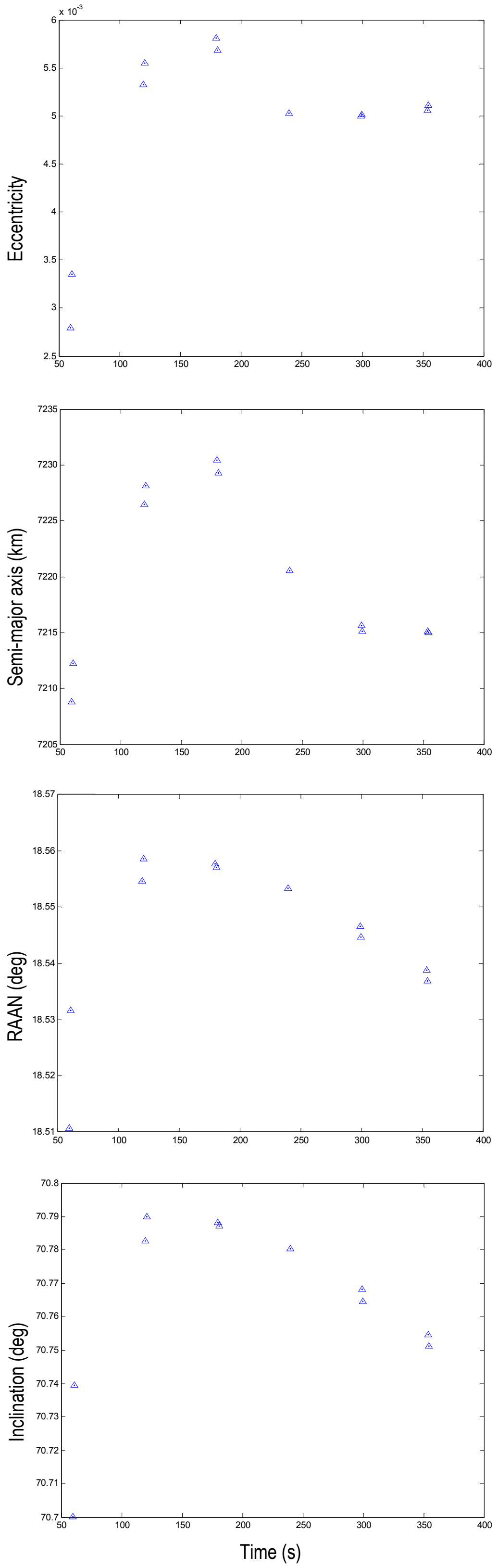

Figure 4. Cosmos 2227 R/B parameters evaluated with the extended Kalman filter.

Table 1. Eccentricity (e), semi-major axis (a), inclination (i) and right ascension of ascending node (Ω) determination for Cosmos 2227 R/B and Cosmos 1833.

	Cosmos 2227 R/B				**Cosmos 1833**			
	e	a (km)	i (deg)	Ω (deg)	e	a (km)	i (deg)	Ω (deg)
$e \equiv 0$	–	7218 ± 322	71.2 ± 4.4	20.8 ± 20.5	–	7180 ± 47	70.2 ± 0.3	9.6 ± 0.4
Laplace (6 angles)	0.03 ± 0.004	7050 ± 174	70.8 ± 0.05	18.6 ± 0.3	$0.028 \pm 3\cdot10^{-4}$	7250 ± 218	71.8 ± 0.04	10.4 ± 0.3
Gauss (6 angles)	0.13 ± 0.003	8355 ± 13	70.9 ± 0.05	18.7 ± 0.3	$0.019 \pm 2\cdot10^{-4}$	7375 ± 30	70.6 ± 0.1	10.2 ± 0.3
Laplace with LSM	0.12	6590	71.2	18.8	0.013	7295	70.8	9.7
EKF	0.005	7215	70.8	18.5	0.009	7177	70.7	9.9
TLE	0.0006	7221.6	71.02	18.09	0.0008	7228.3	70.91	9.61

We do not report the results for the argument of perigee (because for almost circular orbits it is bad-determined) and anomaly (as the direction of the satellite is well estimated).

The results can be compared with the TLE which can be assumed as a good evaluation of the real orbit. The EKF seems to provide the better outcomes, particularly for the hard-to-determine eccentricity. However, notice that the small number of measurements makes this method heavily dependent on the initial estimate of the state vector. The orbital plane is well determined with all methods. The semi-major axis is well calculated with the assumption of circular orbit, but this depends on the examined orbits which are actually almost circular.

The Laplace and Gauss methods results are based on the mode determination, hence they are depending on the intervals dimension chosen for the distribution.

The results carried out with the Laplace method based on the data LSM fitting are better for Cosmos 1833 than for Cosmos 2227 R/B. This depends on the measuring accuracy.

The EKF is the only method, among the ones here considered, which might be used for real time filtering of the data in a re-entry campaign, when the elements need to be often updated due to the uncertainties affecting the orbit propagation. Theoretically it could be even used for updating the TLE, but in this case a great number of measurements must be available: the TLE (obtained taking into account many observations) show a precision which can not be improved with the few observations achieved in the test campaign here described.

6. REFERENCES

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