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Precise Optical Observations of Geostationary Satellites from Herstmonceux

Graham Appleby and Philip Gibbs
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Abstract: In this paper we outline the techniques that have been developed to obtain accurate directional observations of geostationary satellites in support of the COGEOS-2 Campaign. We use the Satellite Laser Ranging System at Herstmonceux in Southern England to track the satellites, and its sensitive TV systems to acquire and enable the recording of the apparent directions of the objects. We use the same system to record the directions of nearby catalogue stars in order to make small localized corrections to our telescope pointing model, and achieve estimated satellite directional accuracies of about 1-2". We have developed pre-processing software to aid confirmation of the identity of the observed satellites, noting that in some regions of the geostationary (GEO) band the separation of objects is of the order of only 0.1 degrees, so that confusion can sometimes occur. A series of observations has been obtained of MET 4 and MET 5 over the period 1992 November to 1994 October. The precise analysis of the observations is however hampered by their availability from only one site, and their frequent manoeuvres.

STATUS REPORT ON GEOSTATIONARY SATELLITE POSITIONING BY TIME MEASUREMENTS

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Abstract: Aiming to locate geostationary satellites, time comparison by TV method has been used; four campaigns of

few days to few weeks were organized between December 1991 and April 1994. From one campaign to the other, difficulties of different types mainly time synchronisation between laboratories and random jumps in the data were solved. Data processed by geometric approach showed that a precision of the order of 30 meters was achievable. This precision is confirmed by the first results obtained by a dynamical method of orbit recovery.

CCD Astrometry of Geostationary Satellites at the ZimmerWald Observatory

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Abstract: A technique is being developed at the Astronomical Institute in Berne to measure astrometric positions of fast moving objects with a CCD camera mounted on a medium size telescope. For geostationary satellites a precision of 0.3 to 0.7 arcsec (depending on the brightness of the object) for the measured position has been demonstrated. With the new telescope starting operation in fall 1995 an error of 0.1 to 0.3 arcsec is expected.

Keywords: CCD astrometry

OPTICAL OBSERVATIONS OF GEOSYNCHRONOUS SATELLITES - RESULTS

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Introduction: We use our ZEISS JENA wide-angle astrograph 300/1500 mm for the determination of geosynchronous satellite positions together with a new device for the interruptions of the star trails (Potthoff, 1993).

A shutter consisting of a rotating disk which is mounted within the dew cap of the astrograph is controlled by the special software of an embedded microcomputer and drived by a powerful stepping motor. The control device gives the possibility to choice observation times of 6, 8,10 or 12 minutes corresponding to the satellite magnitude and the actual atmospheric conditions. There are made two expositions with a stop of short time distance of 36 s on each photoplate. In this time interval the camera is removed in declination by hand.

By means of the shutter action there are generated 30 interruptions of the star trails; there are 5 groups each of them with 6 interruptions. These 5 groups of interruptions of each exposition are arranged symmetrically to the total observation time (Fig. 1).

The time moments of the beginning and the end of each shutter rotation are defined with an accuracy of 1 ms related to the UTC system of the German time transmitter.

ORBIT 10: adding the medium arc to the very short arc method

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Abstract: The very short arc (VSA) method is useful to solve for the coordinates and velocities of the SLR stations of a local network (continental scale) with 0-C residuals of the level of 1-2 cm. The results deriving from a 7 years data analysis confirm the high quality of this method. However, the VSA method does not allow us to solve for the geopotential coefficients, and therefore cannot be used as such for COGEOS. Moreover it is not robust enough with respect to the systematic observational errors. The Space Mechanics Group has therefore written a new code to be added to the original version of the software package ORBIT lO based on an enlarged arc period. This version of the program can be used to analyse the ETALON data, in the framework of COGEOS, namely to improve the knowledge of the resonant coefficients. In the future we will use it at the data compression stage in order to be able to discard the outlier points (or satellite passes) in a way which is both accurate and objective. In particular we plan to detect the systematic errors in the VSA version.

Medium arc analysis of ETALON data with ORDIT 10

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Abstract: Using the ORBIT 10 software developed by the Space Mechanics Group of the University of Pisa, we have performed an analysis of the ETALON 1 tracking data provided by Telespazio. We have carried out a compression of five months of raw data in normal points and then tried to solve for the resonant geopotential coefficients. This was a first attempt to verify our capability to reach the high sensitivity that the COGEOS project is aiming at. Indeed, 5 months of ETALON 1 data have allowed us to determine the low degree and order resonant coefficients with a better accuracy than that reported in the JGM-2 model. While the results are very good for C_{22}, S_{22} more data and possibly also a better model are necessary to improve the current values of C_{32}, S_{32} as well.

Analysis of ESOC range data to METEOSAT satellites With ORBIT 10

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Abstract: Using the ORBIT 10 software developed by the Space Mechanics Group of the University of Pisa, we have performed an analysis of the Meteosat tracking data made available to us by the European Space Operation Center (ESOC). The aim of the work was mainly to asses the accuracy of these data. We also tried to solve for the geopotential coefficients of interest for COGEOS. The residuals amount to a few hundreds of metres, more than the internal accuracy estimated by ESOG. Future analysis of these data in combination with optical angular observation is likely to provide better results. We plan to do that when sufficient optical observations will be available.

Software for the analysis of photographic observations of geosynchronous satellites

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Abstract: Software developed for the orbit prediction and determination from the photographic observations of geosynchronous satellites is described. The force model of the geosynchronous satellite motion and the orbit adjustment procedure are discussed. Applications of the software in the analysis of the real data are shown. An example of satellite identification is given by comparing orbital elements derived from observations and published in the Geosynchronous Satellite Report.

Keywords: Artificial Satellites, Orbit Theory, Numerical Methods, Orbit Determination

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Temporal variations of the Earth's gravity field: long period analysis.

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Abstract: We present the main lines of a method dedicated to the study of the long period variations of the orbital parameters of a satellite. The purpose is to estimate some geophysical parameters playing a role in the orbital motion. The method is then applied to Lageos I to determine the secular variation of the Earth's oblateness (J_2) and the amplitude of the 18.6 years oceanic tide.

Keywords: Long period variations, Earth's oblateness, 18.6 years oceanic tide

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Non Gravitational Perturbations on ETALONs Satellites

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Abstract: I have estimated the effects of the main non-gravitational perturbations on the *ETALONs* satellites; in particular I have restricted my study to the accelerations coming from the following effects: i) direct and indirect visible radiation pressure, ii) thermal thrust effects from visible solar radiation, iii) thermal thrust effects from Earth infrared radiation. I discuss the results of this preliminary investigation and explain briefly their importance for future geodynamics studies.

Dynamics of 12~Hour Earth Satellites

David M. Lucchesi and Anna M. Nobili
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Abstract: Resonant Earth satellites are known to be especially suitable for recovering values of the resonant coefficients of the geopotential. Among them, 1 : 1 and 2 : 1 satellites (i.e. with 24 and 12-hour orbital period) are sensitive to harmonics of low degree and order whose values are the most important ones in the global model of the geopotential. The passive laser tracked *ETALON* satellites *(ETALON* 1 and 2, 12-hour period, Russian) are those which at present provide the best results. We investigate the dynamics of these satellites and compute the effects of the main resonant coefficients to make sure that they can be discriminated from the effects of non gravitational perturbations.

ATESAT: software tool for obtaining automatically ephemeris from analytical simplifications

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Abstract: ATESAT is a software tool for obtaining automatically analytical simplifications and ephemeris from them. In this paper we describe the characteristics of ATESAT. Two examples of application are presented.

The choice of appropriate reference systems in numerical integration of orbits

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Abstract: Looking for efficiency in numerical computation of perturbed Keplerian orbits, new formulations for orbital problems using ideal frames and quaternions for rotations

have been developed. Furthermore, some kind of regularization and a rescaling of the force linearizing the equations of motion and consequently to take a constant stepsize in the numerical integration has been performed. Several tests show that formulation using ideal frames and quaternions improves the classical integration in Cartesian coordinates and that regularized formulation is very adequate for high eccentric orbits and gives similar results for low eccentricities. In order to gain time in the numerical integration of long arcs, we have studied theoretically the construction and some properties of the multi-revolution methods and applied them to artificial satellites.

Perturbed Circular and Weakly Eccentric Orbital Motions - An Original Approach of Analytical Representation

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Introduction: The aim of this brief paper is to present broad outline of an original approach of analytical representation of orbital motion. Some of the related works have been achieved in the context of the COGEOS scientific program since the beginning of the 90's. The motivation behind this study is two-fold, namely the establishment of an unified theory for studying the effects of an extended central potential, an external potential, and non-gravitational forces acting on a motion initially circular, and second the determination of an accurate predictive solution, notably valid for e = 0 and i = 0 or P .

Before taking into account efficaciously all the required perturbations and besides the mathematical features of the Celestial Mechanics methods, the main technical difficulties for predictive purely analytical resolutions may be summarized as follows: large eccentricities, Singularities, resonances, critical inclination .... However, some of these difficulties simply express a kinematic problem related to the choice of used parametrizations and reference systems. Parametrizations are of two kinds: either in coordinates or in geometrical elements. In orbital motion representations, singularities are generally present using element variables rather than coordinate variables. As a consequence, independently of qualitative questions, it may be judicious to expand predictive theories directly in coordinate representations free of singularities rather than in elements...

Linearization and regularization techniques: comparison tests

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Abstract: Several transformations that increase the number of degrees of freedom, that linearize and regularize the equations of motion are presented. Several tests about their efficiency have been carried out. From this work, still in progress, we find that the transformations have similar behavior, although the new ones slightly improve the accuracy.

Keywords: linearization, regularization, canonical transformations.

From COGEOS I to COGEOS III

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Abstract: The historical aspects of COGEOS going from COGEOS I to COGEOS III are briefly recalled. Main results are given and prospects are proposed for COGEOS III.

Keywords: Space Mechanics, CCD, T.V. Time Measurements, Temporal variation of the gravity field.

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A brief history of the COGEOS research project

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The project COGEOS *(International Campaign of Optical Observations of Geosynchronous Satellites for Geodynamics)* has originated within the Space Mechanics Group of the University of Pisa, while it was involved in the development of a software package for satellite geodesy, in particular for *24-h* satellites. The original code was named ORBIT4 and came after others written by the group to investigate the motion of natural bodies in the solar system. It allowed to propagate the orbit of the satellite and to recover solve-for parameters by means of differential-correction methods. The major difference with respect to dealing with natural bodies was in the need to account for non-gravitational perturbations, due to the large value of the area-to-mass ratio in the case of any spacecraft. The largest non-gravitational perturbation for *24-h* is due to solar radiation pressure, and its effects can accumulate with time whenever the spacecraft is 3-axis stabilized or it is equipped with a despun antenna. A 24-h satellite in the equatorial plane of the Earth and almost circular orbit (1:1 resonant geosynchronous satellite) is ideal for determining the ellipticity of the equator, since the harmonic coefficients of the geopotential which express this ellipticity (C_{22} and **S22,** corresponding to the largest gravity anomaly after the Earth oblatness) are those which govern its slow (- 1000 *d* period) librational motion. Any other effect that accumulates over such timespan and cannot be adequately modelled sets a limit to the accuracy with which the resonant coefficients can be recovered and to the accuracy of the satellite tracking data which are required for this purpose. That is, accurate tracking data are worth having only as long as they are not deteriorated by the poor knowledge of the effects of solar radiation pressure.

Satellite geodesy is an expensive branch of science by definition, since it requires launching (and tracking) of artificial satellites around the Earth as the only means to obtain knowledge about the global structure of our planet. It has long been pointed out by Desmond Ring Hele, one of the fathers of space geodesy, that the dynamics of satellites which are resonant with the geopotential (i.e. such that the ratio of the orbit period of the satellite to the rotation period of the Earth is close to the ratio of two integer numbers) is essentially dictated by the resonant coefficients and therefore allows one to recover their values more accurately than non resonant satellites. The values of the resonant coefficients determined in this way can then be taken as known parameters in the determination of the geopotential, thus helping to improve the accuracy of the global models. Especially so in the case of low degree and order coefficients, since a poor knowledge of their values does obviously spoil the entire model. Hence the importance of geosynchronous satellites, whose motion is governed by the low degree and order coefficients with $m \sim 0$ and $(1 - m)$ even, the most important ones being C_{22} and S_{22}.

Unfortunately, no geosynchronous LAGEOS has ever been launched, which would mean the best observational data (by laser tracking) and the smallest effects from solar radiation pressure (on a compact, passive, cannon-ball satellite). COGEOS was meant as a cheap experiment in space geodesy in the absence of a geosynchronous LAGEOS: it was based on active commercial geosynchronous satellites and (passive, from the viewpoint of the satellite) optical observations to be conducted worldwide. As such it was proposed to JAG (International Association of Geodesy) and established by JAG and COSPAR (Committee on Space Research) as a Subcommission of CSTG (International Coordination of Space Techniques for Geodesy and Geodynamics). In spite of such high level appraisal, it was only after it obtained funding as a twinning research contract within the scientific programme of the Commission of the European Community (in the field of *Earth Sci*ences) that it became possible to carry out the COGEOS project. Accurate observational techniques (also of a new type) and space geodesy software codes could then be developed in Europe, in some cases with the contribution of eastern European scientists. Further-more, new analytical and semi-analytical satellite theories were put forward thanks to the renewed interest in the scientific objectives of our project. Collaboration with European institutions like ESOC, which operates the meteorological METEOSAT satellites of Europe, has been positive and extremely helpful; COGEOS has served as a stimulating starting point for the Space *Debris* research project of ESA (European Space Agency) which has been set up to investigate the dynamical evolution of all objects which orbit the space around our planet after more than 35 years since the launch of the first artificial satellite. Space geodesy codes have been developed and used also to analyze LAGEOS data; one of the results, obtained with multiarc methods, is the determination of a network of European tracking stations to the cm level. The relevance of this result from the viewpoint of plate tectonics motion and continental drift is apparent. The launch by the Russians of the ETALONs (12-h, passive, cannon-ball satellites covered with corner cube laser reflectors) and the availability of laser tracking data to these satellites have found the COGEOS team well prepared; these data have been used for improving our current knowledge of the ellipticity of the equator. Yet, the most intriguing open question is still about a possible change with time of the J_{22} coefficient; similarly to the finding of a non-zero J_2 value, it would provide indications (or pose more tight constraints) on the global structure of the Earth. For this purpose we still need an appropriate, accurately tracked geosynchronous satellite to be kept close to the same nominal longitude for long enough time (maybe years); it would be like a sensitive gravimeter in space which can tell us whether the Earth underneath has changed over such a span of time. No commercial geosynchronous satellite does probably last long enough for this purpose; however, the European series of METEOSAT satellites may be the right candidates, one after the other to be such sensitive, long-term gravimeters for measuring the changing geopotential.

Although not fully completed, and in spite of all difficulties which inevitably arise in the organization of observational campaigns worldwide, COGEOS has provided a wealth of scientific achievements through the active collaboration of an increasing number of European scientists. Funding from the Commission of the European Community, albeit limited, is what has made this collaboration possible and we therefore wish to express our gratefulness for having been given this

opportunity.

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