PRECISE ORBIT DETERMINATION AT ESOC: EXPERIENCE, RESULTS AND IMPLICATIONS FOR FUTURE ESA MISSIONS

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ABSTRACT

A four year programme is currently underway in ESOC in order to develop the capability of supporting those future ESA near-earth missions that have stringent requirements on orbit accuracy. The activity is centred around an internally developed software system for orbit determination and covariance analysis which contains state-of-the-art models for a wide range of orbital perturbations and measurement types, and permits estimation and error analysis of geophysical and geodetic parameters in addition to the orbital states of the satellites. The implications for operational support of near-earth ESA missions are discussed. Some applications carried out to date, involving analysis of future mission requirements and processing of laser ranging and altimetry data, are described.

Keywords: Orbit determination, space geodesy, covariance analysis, satellite-to-satellite tracking, altimetry, earth rotation, laser ranging

1. INTRODUCTION

With the advent of a new generation of spacecraft for studying the earth's surface and interior, more and more stringent requirements are being placed on the precision with which the position and velocity of the spacecraft have to be computed. Radial position accuracy of better than 10 cm and along-track accuracy of better than 50 cm are typical of the orders of magnitude required for the application of radar altimetry to the determination of global ocean circulation and for the study of the dynamics of the earth and the determination of crustal movements by means of satellite tracking.

In order to ensure that adequate support for such missions can be provided by the Agency's Operations Centre, a four year programme has been initiated with the aim of upgrading available in-house software and expertise in this area. Already after some one and a half years significant results can be reported. In particular, it has been possible by participation in an international data reduction campaign to compare objectively the capabilities of our software, and the geodetic and geophysical results obtained, with those of other centres.

The paper outlines the objectives of this activity and summarises the current capabilities of the software. A number of selected applications which have been made to date are briefly described.

2. OBJECTIVES

The Precise Orbit Determination project for near-earth orbiters discussed in this paper is a natural extension and continuation of many years of orbit determination activity at ESOC. Beginning with the early ESRO satellites in the late 1960's (tracked by a few stations yielding inaccurate direction measurements, only when the spacecraft was close to the N-S or E-W axis of the interferometer), routine orbit determination has been carried out for 5 near-earth satellites (1969 - 74), for 10 spacecraft in geostationary transfer and synchronous orbits (1977 -), for 5 highly eccentric earth orbiters (1969 - 86), and for 2 interplanetary orbits (a spacecraft and a comet, 1986). The results of these determinations have been used not only for mission control purposes (station and manoeuvre scheduling, and spacecraft monitoring, for example), but have also provided essential inputs for the reduction of the data generated by many payload elements.

Orbit determination for these missions has been carried out, without exception, using in-house expertise and software. The new generation of ESA near-earth missions, starting with the European Retrieval Carrier EURECA and the first ESA Remote Sensing Satellite ERS-1, and proceeding to the in-orbit infrastructure concept initiated by the Columbus project, present many new features but also many which have been successfully handled in the past at ESOC.

High precision orbit determination for near-earth orbiters brings us into contact with the rapidly developing area of research represented by space geodesy, in which new highly accurate measurement techniques and data reduction procedures have revolutionised such fields as global and relative point positioning on the earth's surface, ship navigation, and geodynamics (the dynamics of the non-rigid earth). It was soon realised after the

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launch of the first artificial satellites that distance, doppler or angular measurements made from ground stations to satellites contain information not only on the satellite orbits but also on many other physical parameters which enter into the description of the orbital motion or that of the tracking measurements. Some of these parameters are of major interest in themselves. Examples are:

1. The earth's gravity field, which determines the principal characteristics of the orbit. Large data bases containing hundreds of thousands of preprocessed satellite tracking measurements provide the starting point for global geopotential models. The satellite orbital parameters are a byproduct in the data reduction process, and are eliminated as the normal equations are accumulated arc by arc.
2. A well-determined orbit can provide a stable reference which can be used to determine the positions (and velocities) of points on the earth as well as in space. By processing laser ranging or interferometric measurements, networks of globally distributed stations can be related to each other with an accuracy of a few cm.
3. The variable rotation of the earth and the direction of its instantaneous spin axis can be measured by a number of techniques, several of which involve tracking earth satellites. Again the satellite orbit has to be solved for in order to extract the necessary parameters.

Thus high precision orbit determination for near-earth orbits is of indirect interest in various scientific applications, whereby it is often difficult to separate the derivation of one set of physical parameters from another, since they can all affect to a greater or lesser extent the tracking measurements. Each researcher will select those data (orbits, measurement types) which are most sensitive to the parameters of relevance to his own area of study, but he will inevitably have to solve for (and eliminate) model parameters which have less interest for him, or make use of models which may even have been derived in parallel from the same data. Some will place most emphasis on the orbit determination itself, others on development of earth gravity and tidal models, others on earth rotation and polar motion determination, or on the determination of geodetic networks and their tectonic motions. However all these applications interact with one another, and can never be treated in isolation.

The aims of precise orbit determination activities at ESOC might then be summarised as follows:

1. Building on the considerable experience gained from many past missions, we seek to extend and apply the software tools for orbit determination and error analysis which have been developed in-house over a number of years. The outcome should be state-of-the-art software and models for determination of near-earth orbits, well-understood by the key users, and so maintainable and easily extendible as new possible applications are identified.
2. The emphasis is placed on the creation of a routine operational capability for support of future ESA missions requiring precise orbit determination. This implies a commitment to provide users of orbital data with a regular service and fast response time, implying highly automated and reliable software and procedures. This is a classical task for a spacecraft Operations Control Centre, and fully in line with the extensive experience of ESOC in satellite control and data processing.
3. Such an infrastructure activity is clearly of benefit to all our future operational orbit determination for near-earth missions, and compliments project-specific preparations underway for these missions. A software package is being developed which is generally applicable to all ESA near-earth missions being considered for the next decade, and relatively minor satellite-specific add-ons should be necessary (e.g. models for S/C geometry).

3. SOFTWARE

We first summarise the main modes of operation of the ESOC orbit determination software for near-earth orbits.

1. The principal mode involves the estimation of orbital and other model parameters from the tracking measurements.
2. A covariance/simulation mode permits prelaunch analysis of the orbit determination process. Flexibility in the choice of parameters to be estimated is essential. Selection of an appropriate set of 'consider parameters' allows a sensitivity analysis to be made of the influence of uncertain model parameters on the state being estimated, and on the propagated position and velocity and Keplerian elements.
3. The software can be used as an orbit integration tool.
4. A multi-satellite mode permits the simultaneous determination of several orbits from a combination of ground tracking and satellite-to-satellite tracking. Determinations and sensitivity analysis can be done in terms of both absolute and relative states (applications to rendez-vous and docking, and multi-satellite configuration maintenance).

All these functions are performed within a single program 'BAHN', by selection of relevant options. (A tracking data simulation program 'TRACK' is used in conjunction with mode 2.) The parameters to be estimated or considered can include: the position and velocity of the satellite(s) at the epoch; coefficients for surface forces (drag, solar radiation, albedo, IR); orbital manoeuvres; solid earth tides (k_2, h_2, l_2); station coordinates (and baselines); earth orientation parameters (pole, UT1); measurement and timing biases; ionospheric/tropospheric model parameters; and the gravitational constant for the earth. Measurement types which can be handled include range (1-, 2-, 4-way); doppler (as range-rate or range-difference); angular data; and satellite-to-satellite tracking data (SST, range or range-rate, 2-way, or 4-way including a ground station). Altimetry can currently be processed in an approximate way in the covariance mode.

The highest possible accuracy compatible with state-of-the-art models for coordinate systems (the J2000.0 inertial reference frame is used), orbit perturbations and tracking measurements is being aimed at. The estimation is performed by a classical Bayesian least squares algorithm.

Table 1 summarises some features of the models currently implemented. Among future developments foreseen are: implementation of a multi-arc capability; refined processing of altimetry within the orbit determination; estimation of gravity coefficients and parameters for frequency dependent tidal terms; and more refined models of surface forces.

TABLE 1
Summary of models in BAHN program

Earth gravity field:	Choice of models such as GEM-10B, GEM-L2, PGS-S4, GRIM-3B Gravitational constant for earth may be held fixed or estimated
Luni-solar gravity:	JPL DE200/LE200 ephemeris
Radiation pressure:	Direct solar radiation pressure Latitude-dependent models for albedo and IR radiance (Vonder Haar)
Solid earth tides:	Global Love no. k2 for potential Global Love/Shida nos. h2, 12 for station uplift Frequency dependent corrections
Ocean tides:	Schwiderski model, giving corrections to gravity coefficients up to degree 6 and order 2 Ocean loading corrections to station heights
Numerical integration:	8th order Adams-Bashforth/Adams-Moulton predictor-corrector, initialisation by Runge-Kutta-Fehlberg algorithm of order 7(8) Partials computed by numerical integration of the variation equations
Coordinate system:	Mean equator and equinox of 2000.0 (='J2000.0')
Precession model:	IAU 1976
Nutation model:	IAU 1980 (Wahr)
Sidereal time:	New relationship between UT1 and GMST (Astronomical Ephemeris 1984)
Station coordinates, polar motion, earth rotation:	May be held fixed or estimated from the data
Troposphere:	Marini and Murray model

4. APPLICATIONS

In order to illustrate some of the applications of the software which have been made to date, two examples of covariance analysis and two examples of processing high precision data (SEASAT altimetry and Lageos laser ranging) are briefly described. Results obtained with the SEASAT laser and S-band doppler data are given in Refs. 1 and 2.

4.1 LAGEOS Covariance Analysis

In order to better understand the accuracy feasible for parameters estimated from Lageos laser data, and the relative importance of the various error sources, several runs were made of the BAHN program in its covariance mode. A 4 day arc from Dec. 1980 was taken, and the TRACK program was modified to read the times of the normal points actually available (from 6 stations) and to simulate range measurements at these times. These measurements were then input into BAHN. The error sources considered were earth gravity field (30% of difference between GEM-10 and GEM-L2, radiation pressure (3% error for direct solar radiation, 30% for albedo and IR), solid earth tides (3% error in k_2, 10% in h_2 and 1_2), station coordinates (10 cm), pole coordinates (10 cm), station timing (5 microsec), range biases (5 cm), and tropospheric propagation (1.25 cm at zenith, i.e. 0.5% of effect).

Estimating only the orbital parameters, the root sum square (rss) of all the error contributions gave 10, 40 and 45 cm respectively (rms) in the radial, along-track and cross-track components. The major contributions come from gravity model errors, pole and station coordinates.

If, in addition to the satellite position and velocity at the epoch, the coordinates of the pole and a coefficient (scaling factor) for direct radiation pressure are estimated, there is significant improvement in the out-of-plane component of the orbit. It is interesting to note that estimation of the solar radiation coefficient allows the error due to albedo radiation to be absorbed almost completely.

Table 2 illustrates what happens when in addition a constant along-track acceleration and the Love number k_2 are solved for. (In reality of course much longer, or multiple, arcs would be used to obtain a good determination of k_2.) There is a slight degradation in the rms along-track and out-of-plane components. k_2 is determined with a 1-sigma uncertainty of 0.037 (with respect to its nominal value of 0.30). The along-track acceleration, which normally has a value of the order of $3\text{x}10^{12}$ m/s^2 is not well determined, suggesting that in fact the level of gravity errors assumed may be too pessimistic, since estimates obtained from the real data are more stable than this.

4.2 Satellite-to-Satellite Tracking (SST)

Satellite-to-satellite ranging will be performed between EURECA and the geostationary spacecraft Olympus, and the data will be processed at ESOC. Among future SST missions involving higher precision tracking and applications to gravity

TABLE 2

Error sensitivity for determination of pole, Cr, T and k2

4 day Lageos arc, December 1980
Errors (1-sigma) in: arc seconds for pole (xp,yp)
10^{-12} m/s^2 for along-track acc. T

Error source	xp	yp	Cr	T	k_2
Gravity field	0.0003	0.0001	0.004	10.1	0.002
Albedo radiation	0.0000	0.0000	0.011	0.3	0.001
IR radiation	0.0000	0.0000	0.000	0.0	0.000
Solid earth tides:					
station uplift	0.0001	0.0001	0.002	0.2	0.000
Station coordinates	0.0049	0.0022	0.025	6.7	0.017
Station timing	0.0001	0.0002	0.001	0.6	0.001
Range bias	0.0025	0.0005	0.016	3.7	0.009
Troposphere	0.0010	0.0002	0.007	1.6	0.004
Noise	0.0011	0.0007	0.013	3.1	0.006
Total	0.0055	0.0024	0.035	13.1	0.021

Cr = coeff. of direct solar radiation pressure
T = constant along-track acceleration
k_2 = Love No. for solid earth tides

TABLE 3

Orbit error sensitivity for ERS and POPSAT (SST)

RMS errors in cm (1-sigma).

Error Source	ERS Radial	ERS Along	ERS Cross	POPSAT Radial	POPSAT Along	POPSAT Cross
Gravity field	61	177	54	2	5	3
Gravity parameter	2	1	1	4	2	2
Drag	1	14	2	-	-	-
Solar radiation	3	7	2	3	7	1
Albedo radiation	1	3	1	0	0	0
IR radiation	0	0	0	0	0	0
Solid earth tides:						
(1) external potential	1	1	6	0	0	1
(2) station uplift	0	0	0	0	0	0
Pole position xp	0	1	0	0	2	1
Pole position yp	0	3	0	0	6	0
Station coordinates	1	3	3	2	5	7
Station timing	0	0	0	0	1	0
Range bias	0	1	0	0	1	1
Range-rate bias	0	2	1	1	4	1
SST range-rate bias	0	19	7	-	-	-
Troposphere	1	2	1	1	2	2
Noise	0	2	1	0	1	1
Total	62	178	55	6	13	8

field modelling and oceanography could be a combination of POPSAT (Precise Orbit Positioning Satellite) tracking an ERS class satellite (5900 and 800 km orbits respectively, with inclinations of 98.6 deg). POPSAT would be tracked by range and range-rate measurements from a mission execution network of 16 stations (assumed measurement noise 10 cm and 0.1 mm/s, biases 5 cm and 0.1 mm/s) while ERS might be tracked by 2 stations ranging (10 cm noise and bias). In addition an inter-satellite doppler link is assumed, with 0.2 mm/s noise and 0.2 mm/s bias (measurement sampling for all systems: 20 s).

An error analysis of a 1 day determination of both spacecraft was performed, using the error model of Ref. 3, where an error analysis made at the University of Delft using the NASA program ORAN is presented. Station coordinates are assumed known to 10 cm, pole position to 2 masec (6 cm), and tropospheric refraction to 2% of the effect. The ionospheric contribution to the propagation delay can be almost entirely removed by the use of two frequencies (S-/X-band). Gravity field errors are simulated as 30% of the difference between GEM-10 and GEM-10B, the gravity parameteris assumed to be known to 0.01 ppm, k2 for the solid earth tides to 10%, direct solar radiation pressure to 3%, albedo and IR to 20%, and drag to 5%, using the MSIS density model. The difference in the orbital nodes assumed was 45 deg.

The rms accuracies obtained for the ERS and POPSAT positions as a result of the various error sources are given in Table 3. The POPSAT orbit is assumed to be determined by ground tracking alone, ERS by ground tracking and SST. The results compare very well with the ORAN analysis of Ref. 3. As in other cases investigated, the most important error source by far is the gravity model. The SST range-rate bias is the second most important model error for the lower spacecraft, followed by air drag.

4.3 SEASAT Altimetry Cross-Overs

A detailed analysis has been made of a 23 day arc of altimetry data from the SEASAT mission, as a first step towards implementation of altimetry measurements in the orbit determination process, and as a method of assessing the radial orbit errors remaining on the PGS-S3 ephemeris computed at NASA/GSFC and available on the JPL altimetry tapes used. The cross-over technique is based on two assumptions (Refs. 4, 5, 6): firstly that the height of the ocean surface is constant at the intersection of an ascending and a descending pass, after all known time varying effects have been removed (tides, barotropic effects, currents); and secondly that over a limited area (e.g. 30 deg x 30 deg in latitude and longitude) the radial orbit error can be modelled by a slope and bias on each arc. A least squares adjustment of all bias and slope parameters is performed so as to minimise the sum of the squares of the cross-over residuals, defined as the difference between the altimeter residual for the ascending arc and that for the intersecting descending arc. The rms cross-over residual is a measure of the remaining radial orbit error.

With the determined orbit corrections, the altimeter measurements can be used to derive a mean sea surface over the region, either with respect to a reference ellipsoid or with respect to a geoid. Fig. 1 shows the sea surface topography deduced in this way for an area between New Zealand and American Samoa. In order to bring out the fine detail, the topography is plotted with respect to the PGS-S4 geoid. The region covers two 10 km deep trenches, the Kermadec and Tonga Trenches, which are clearly visible in the plot. The a priori rms cross-over residual for this area was 3.5 m after adjustment this reduced to 17 cm.

4.4 Project MERIT

An important step forward in our precise orbit determination activities resulted from participation in the MERIT project. This was an international measurement and data reduction campaign aimed at intercomparing the various techniques available for monitoring polar motion and earth rotation (classical astrometry, VLBI, satellite and lunar laser ranging, satellite doppler), and at the same time the results derived by different centres using the same data and standard models, but different reduction methods and software (Ref. 7). In this way it was possible to compare the results obtained with our software from reduction of a large amount of Lageos laser ranging data with results obtained by the NASA/GSFC program GEODYN, the University of Texas (CSR) program UTOPIA, the DGFI software MGM, and others, as well as making absolute comparisons with those obtained by a completely independent, very precise technique, Very Long Baseline Interferometry (VLBI).

The approach which we adopted and the results obtained have been documented elsewhere (Refs. 8, 9, 10), and only a very brief summary can be given here. The data were processed in monthly arcs, solving for the spacecraft position and velocity at the epoch, a radiation pressure coefficient, an along-track drag constant, the coordinates of the pole, regularised universal time UT1R (UT1 with shorter period tidal effects removed), the rate change of UT1R (= 'excess length of day', LOD), and the geocentric coordinates of the 20 laser stations involved. The coordinates of the 17 stations ranging during the 3 month period from October to December 1983 were first determined, with a simultaneous adjustment of pole and earth rotation (5 day resolution for the latter, in 3 one month arcs). The longitude of one station was held fixed, and BIH values for the earth rotation parameters (pole, UT1R-TAI and its rate) were taken for the first 5 day sub-arc. The 14 monthly arcs were then processed in a solution for the orbital state, the 5 day resolution earth rotation parameters (pole, UT1R and its rate), and the coordinates of the 3 stations which were not in the global solution. The only parameter not adjusted in this process was the value of UT1R for the first 5 day sub-arc (centred at 7 September 1983), which was fixed to the BIH value, in order to resolve the singularity in the orbit node.

The mean value of the rms laser range residuals over the monthly arcs was 14.5 cm. The arcs had 5 day overlaps, and in these the rms discrepancies between consecutive solutions were 24, 68 and 43 cm respectively in the radial, along-track and cross-track components. A signal could be identified in the element discrepancies which could be explained at least partially by the neglected S_2 atmospheric tide.

An example of a comparison with an independent solution for the pole and UT1R is given in Fig. 2. The rms agreement was 3 masec in xp and 4 masec in yp (1 masec = 3 cm). The agreement with the VLBI UT1 estimate was 1.45 ms rms over the 14 month period (Ref. 10). This reduced to 0.7 ms after removal of a linear trend of 0.1 ms/d. The pole and LOD estmates agreed with two other independent Lageos series (CSR, DGFI) to 2-3 masec and 0.1 ms/d respectively.

The solution for the tracking network coordinates agreed to about 6 cm with those Lageos solutions, after adjustment for a 7-parameter transformation to remove systematic differences of origin, reference axis orientation and scale (Table 4). The relatively large z-rotation Rz of 6.7 m is due to the arbitrary choice of one longitude made in order to fix the terrestrial reference frame. The other two solutions were derived from much larger data sets and agree somewhat better with each other (2-4 cm).

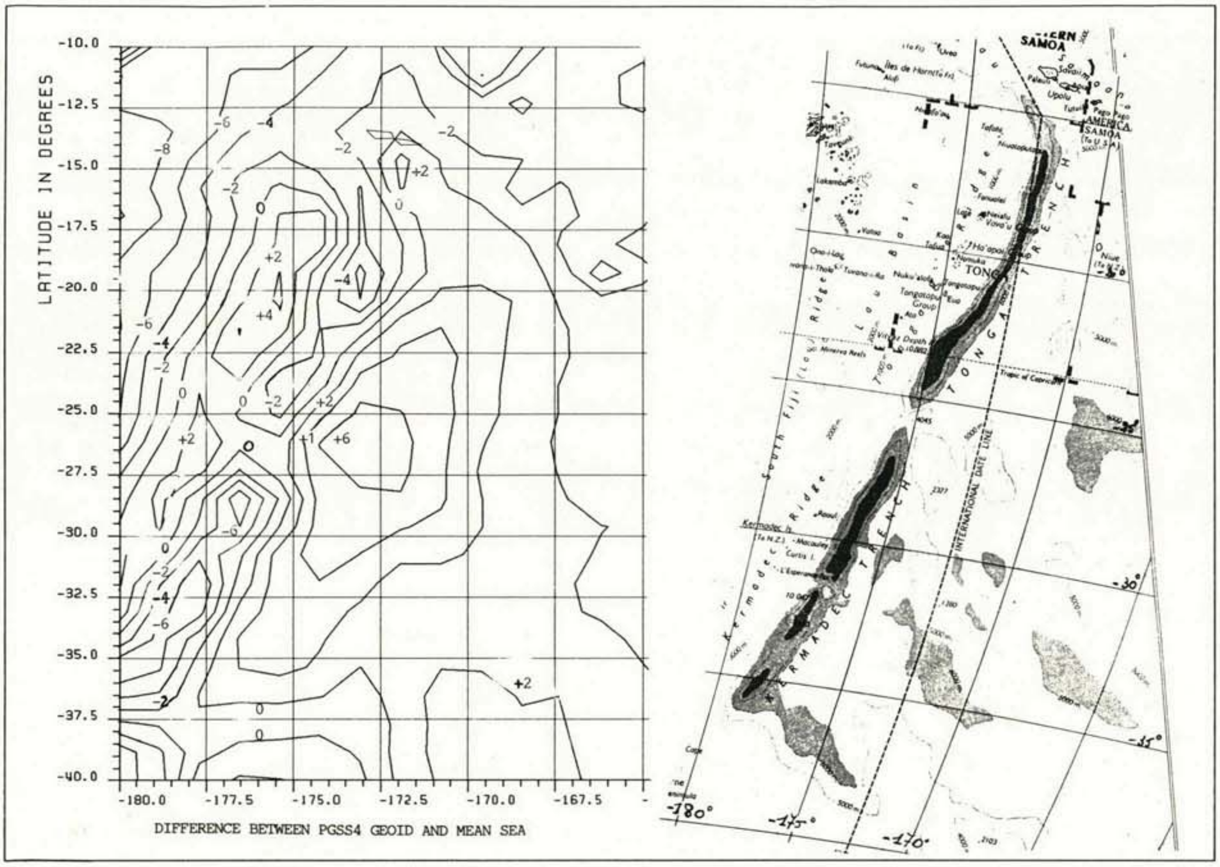

Figure 1: Sea surface topography from SEASAT altimetry: Kermadec and Tonga Trenches

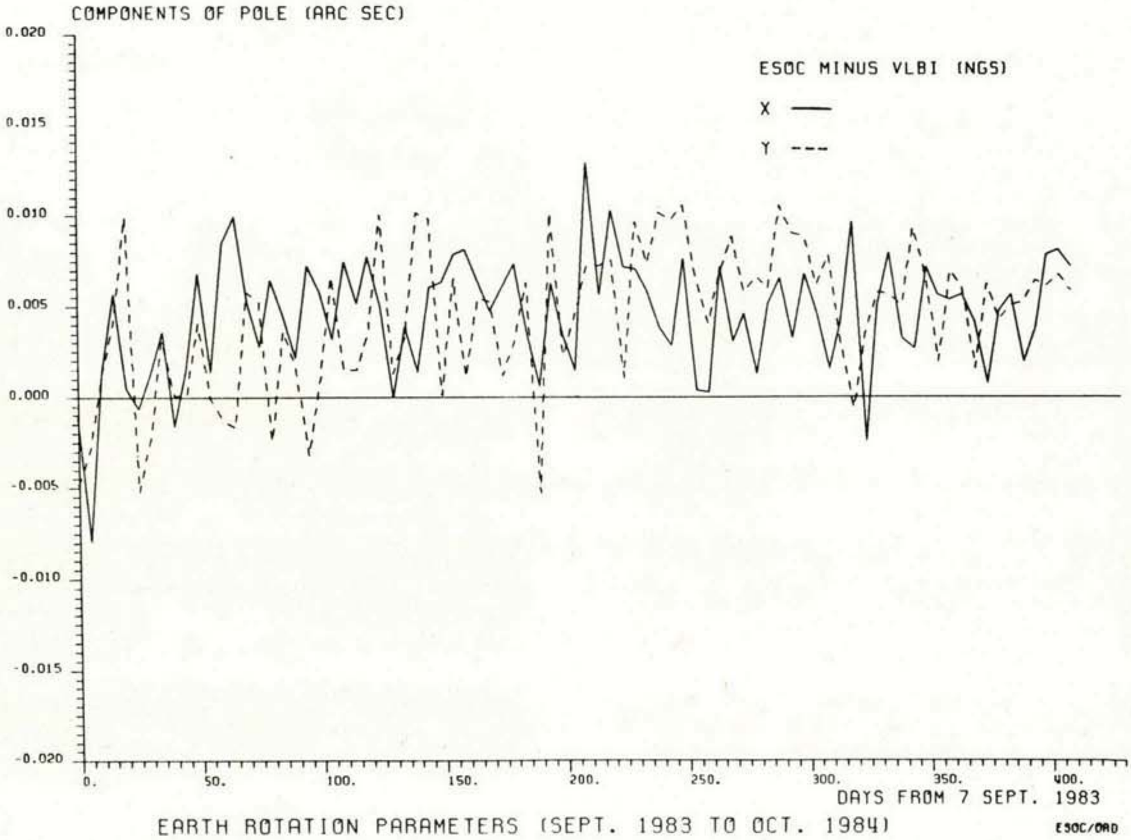

Figure 2: Comparison with VLBI series ERP (NGS) 85 R 01

TABLE 4

Comparison of station coordinate solutions

	Dx	Dy	Dz	Rx	Ry	Rz	Scale	Rms difference		
		cm			masec		10-9	long	lat cm	alt
DGFI-ESOC	-1.4	1.1	13.0	-1.4	15.1	-202.7	-6	6.6	5.2	5.7
CSR -ESOC	-0.7	1.4	2.4	3.8	13.8	-202.3	0	6.6	6.5	3.7
CSR -DGFI	0.6	0.3	-10.6	5.2	-1.3	0.5	6	2.0	2.4	3.6

Station sets are SSC(DGFII) 85 L 04, SSC(CSR) 84 L 02

5. CONCLUSIONS

The objectives of the precise orbit determination activity at ESOC for near-earth orbiters have been outlined, and a brief overview given of the software being developed. The four examples chosen to illustrate current capabilities (Lageos covariance analysis, satellite-to-satellite tracking, SEASAT altimeter cross-overs, and Lageos laser ranging for geodynamics studies) indicate that significant progress has been made towards achieving those objectives.

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