TOPEX/POSEIDON PRECISION ORBIT DETERMINATION PRODUCTION AND EXPERT SYSTEM

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ABSTRACT

TOPEX/Poseidon (T/P) is a joint mission between NASA and the Centre National d'Etudes Spatiales (CNES), the French Space Agency. The TOPEX/Poseidon Precision Orbit Determination Production System (PODPS) was developed at Goddard Space Flight Center (NASA/GSFC) to produce the absolute orbital reference required to support the fundamental ocean science goals of this satellite altimeter mission within NASA. The orbital trajectory for T/P is required to have a RMS accuracy of 13 centimeters in its radial component. This requirement is based on the effective use of the satellite altimetry for the isolation of absolute long-wavelength ocean topography important for monitoring global changes in the ocean circulation system. This orbit modeling requirement is at an unprecedented accuracy level for this type of satellite. In order to routinely produce and evaluate these orbits, GSFC has developed a production and supporting expert system. The PODPS is a menu driven system allowing routine importation and processing of tracking data for orbit determination, and an evaluation of the quality of the orbit so produced through a progressive series of tests. Phase I of the expert system grades the orbit and display test results. Later phases undergoing implementation, will prescribe corrective actions when unsatisfactory results are seen. This paper describes the design and implementation of this orbit determination production system and the basis for its orbit accuracy assessment within the expert system.

1. INTRODUCTION

The TOPEX/Poseidon Mission requires unprecedented orbit modeling to achieve its ocean science goals. (Ref.1) The satellite orbit must be determined with an RMS radial accuracy of 13 centimeters. This is an extremely stringent accuracy requirement for a satellite of this shape and altitude. T/P is in a circular orbit at 1340 Km altitude. It is inclined with respect to the equator by 66 degrees. It is a large satellite with a 28 m^2 single solar panel and weighs nearly 2500 kg. Three precise tracking systems are supporting T/P. Satellite laser tracking (SLR) is the baseline tracking network for the NASA portion of the mission. Currently, there are more than 30 worldwide laser stations providing data on T/P. DORIS is a one-way ground-to-satellite dual frequency Doppler tracking system developed in France which provides tracking data from a worldwide network of over 45 ground beacons. Unlike SLR, the DORIS systems are unaffected by weather and provide nearly continuous monitoring of the T/P orbit. Tracking of T/P by the Global Positioning System (GPS) through an inter-satellite signal is an experimental tracking mode being tested on T/P. The GSFC PODPS uses the complete set of laser and DORIS data to support its orbit computations. The altimeter data (which directly measures the height of the satellite above the ocean surface) is used within PODPS as an independent reference for radial orbit accuracy assessment.

To meet the orbit accuracy requirements for T/P, GSFC has produced improved gravitational models (Marsh et al., 1988 (Ref.6), 1990 (Ref.7); Lerch et al., 1992 (Ref.5)) and developed appropriate non-conservative force models taking into account the complex satellite form of the T/P spacecraft (Marshall et al., 1991 (Ref.8), 1992 (Ref.9)). There has been a great deal of progress made in both areas as verified by orbit analyses using the first two months of the T/P data now available. The routine determination of orbits having sufficient accuracy in a expedient fashion (25 working days after the completion of each 10 day repeat cycle of the satellite) necessitated the development of a production system. In order to satisfy these accuracy and time of delivery requirements, we have developed a production system called the Precision Orbit Determination Production System (PODPS) which performs the production task consistently, under strict configuration controls, and which has an expert component to insure that the required accuracy is achieved. If for some reason an unsuitable trajectory is produced, these orbits will be reprocessed in an attempt to remedy the problem. If however, the orbit cannot be improved to yield a trajectory which passes the quality control tests, the orbit is flagged to warn the ocean science community of the suspected degraded accuracy obtained during this cycle. This paper will describe the approach and design of PODPS which has been implemented to achieve its goals.

2. THE PRODUCTION SYSTEM

The objectives of this system are to automate, consolidate, and strictly control those functions necessary for routine determination of precise orbits : data import, data processing, orbit generation and evaluation, and archive. The system is designed to be portable. It is built in modular form; this design enables new requirements to be implemented as we gain experience with the T/P mission data sets. As they become defined, new capabilities are also easily implemented; therefore, the system has a wide variety of uses beyond the specific needs of the T/P mission.

The orbit determination package which is used is the GEODYN II program (Eddy et al., 1989 (Ref.3)) which is a state-of-the-art system developed at GSFC. GEODYN I and II have been used to perform precision orbit determination for over 20 years at GSFC. The software has been evolving over time to include sophisticated models for the forces arising from the static gravitational field, earth and ocean tides, relativity, atmospheric drag, direct solar radiation, Earth albedo, third body gravitational and satellite thermal imbalance effects which perturb the satellite's motion. The program uses sophisticated models to address the motion of the Earth within an inertial frame, and the motion of an observer on the Earth's surface (station tectonic, earth tidal and ocean tidal loading motions). Since 1982, a major undertaking has been the improvement of existing models of the Earth's gravitational field to meet the factor of five improvement required for T/P. The GEODYN II program has been the workhorse for this large effort. A gravitational field, represented as a spherical harmonic expansion complete to degree and order (70,70), has been determined from 31 satellites using over 2.5 million observations. This T/P pre-launch model is called the JGM-1 (Joint Gravity Model), being a model jointly determined by Goddard Space Flight Center and the Center for Space Research at the University of Texas in Austin. The error in the TOPEX/Poseidon orbit due to the static gravity field cannot exceed 10 centimeters RMS in the radial direction in order to meet the 13 centimeter RMS radial orbit accuracy required by the mission. JGM-1 will be updated through the incorporation of T/P SLR and DORIS tracking data producing JGM-2 (under development) to provide the gravity modeling for T/P throughout its observational phase of the mission. Consequently, following gravity and non-conservative force model verification, we can use the GEODYN II program with confidence for the production of the POE files.

2.1 Hardware Configuration

In anticipation of the rapid advances in hardware technologies, the PODPS system was designed to be portable across a wide range of computer environments. An early decision was made to create a menu-based system that would be written in Fortran so that it would port easily to different hardware platforms. This turned out to be an important consideration since our computational environment has evolved considerably over time, and our current configuration will likely continue to change in the near future. When we started our preparations for the T/P Mission, we were using a Cyber 205 super-computer supported by a "front-end" Amdahl V-7 running the IBM MVS operating system. Another Amdahl, the V-6, was concurrently running the VM operating system while an IBM 3081 ran both the MVS and VM operating systems. The GEODYN II program is really three programs, (1) a flexible tracking data reformatting package (TDF), (2) the GEODYN IIS package which generates data and interface files describing the desired orbit solution and (3) the GEODYN IIE system which is the computational engine performing the orbit determination solution. From 1982 onward, GEODYN IIE ran primarily on the Cyber, and through a redesign of code, was made to benefit from an extensive vectorization of its algorithms. The remainder of the GEODYN system ran on the AMDAHL or IBM using the MVS system. It 1986, the Cyber 205 and the Amdahls were replaced with a CRAY YMP super-computer.

The CRAY YMP is now our orbit computation hardware platform. Since PODPS is an operational system, a suitable backup capability (although with less "horsepower") is provided by the IBM 9021 which is the current front-end to the CRAY. At this point we are beginning to hear that the MVS system on the 9021 will likely be replaced during the mission timeframe with a UNIX operating system. This would bring the front-end into closer compatibility with the UNIX operating system on the CRAY which is running UNICOS. We have decided to integrate workstations into the hardware configuration of the PODPS system now that they have demonstrated enough CPU power to meet our needs. This will also provide hardware stability for the remainder of the T/P timeframe. Two HP 730 are now being phased into the system to provide backup capability and provide additional file service to the PODPS. Therefore, while undergoing development, the PODPS system had to be ported several times across systems as the computer environment around us changed. Currently, our prime system is on the CRAY and our backup system is on an IBM 9021 computer. We are in the process of porting the system to the HP 730s. Our combination of Fortran and UNIX will allow an easier transition, but not one completely free of pain. Planning for portability has been essential. Presently, our prime system is running on the CRAY YMP using the IBM 9021 as the file server. The next transition will be to make the HP both the file server and the platform for running the TDF and GEODYN IIS systems. At present, we foresee retaining the CRAY YMP for the computationally intensive GEODYN IIE work.

2.2 PODPS Software and Data Management Description

The menu program is written in Fortran 77. The system currently contains about 50 individual programs and requires over 100 files for each arc. The menu program is the driver for the system. The maximum depth for the menu is four levels. The main menu has six functions: Arc Selection, Schedule, Data Acquisition and Reformatting, Data Reduction and Orbit Verification, POE Generation and Archive and File Management Utilities. The Arc Selection allows a technician to choose the satellite and arc that they want to work with. The Schedule function displays the 22 work day schedule of tasks required in the processing of the specific POE arc. The Data Acquisition and Reformatting function imports laser, DORIS Doppler, altimeter, solar and magnetic flux, polar motion/earth rotation and SLR station eccentricity values. The user is transferred automatically to the NASA/Crustal Dynamics Data Information System (CDDIS) Vax computer where all the data sets are gathered. The SLR, DORIS, and eccentricity data are already on the CDDIS, the fluxes are obtained from a NOAA Vax in Colorado, and the polar motion and earth rotation values (which are being determined from a concurrent analysis of LAGEOS SLR data) are obtained from a CRAY YMP at the University of Texas in Austin. The set of station positions for this cycle consistent with the Earth orientation series are assembled. The data are reformatted. Normal points are created for laser data for those stations that do not supply station generated normal points. After the staging of this information, the real analysis can begin.

The Data Reduction and Orbit Verification function is the main workhorse of the system. Several types of orbit determinations are performed. First one starts with the POE data reduction. Each orbital solution is followed by the execution of a program called REP (Residual Analysis Program) which analyzes the orbital residuals and determines estimates of measurement and timing biases which reflect both orbit and data problems. REP creates delete cards for spurious observations to remove them from future POE data reduction runs. There is also an interactive graphics program called IRE (Interactive Residual analysis) where one can look at the residuals graphically and create delete cards for points not desired in future iterations. These files are included automatically in subsequent orbital solutions bringing the data verification aspects of the process into a state of convergence. When the orbit seems to be satisfactorily converged, the Overlap and High Elevation data tests are performed. The Overlap test uses 5 day overlap orbit determinations with the previous and next arc and compares the overlap orbits with the converged orbit. This checks for consistency of the orbit from arc to arc. The High Elevation test deletes all SLR passes that have elevations above some value, nominally 60 degrees, and recomputes a new orbit. The orbits are then compared and the omitted data residuals from the high elevation passes are used to project radial orbit error at the times of these independent data. The final tests use the altimetry data from the TOPEX/Poseidon satellite. The altimetry data residuals are computed from the converged POE orbit determined using SLR and DORIS and evaluated both geographically and in their temporal characteristics. Altimeter crossovers are determined for the arc and residuals are computed for them. At each step the desired information is being collected in worksheets for application of the expert system criteria that are to be applied to the arc. This includes displaying the worksheets created for each of these test activities.

The POE Generation function creates the Quick Look POE and the final POE. The Quick Look POE can be created in less than 1 week after the arc has been started. At this point, the data import has not been completed nor the orbit verified. The final POE is sent to JPL for inclusion on the altimeter Geophysical Data Records (GDRs), CNES for comparison with their orbits, the University of Texas for verification, and the University of Colorado for non-conservative force modelling evaluation. The Archive function archives the arc enabling its reanalysis should it become desirable.

The File Management Utilities help to manage the information of the system. The file structure and gathering of the appropriate information from the proper module is monitored automatically by this subsystem. Unfortunately, this is the most difficult element to make portable. Each computer has its own idiosyncrasies for disk and file management.

The above is a quick synopsis of the system which has been designed for easy use and provide the information for evaluation by the expert system. The system, force modeling and satellite sensor complement is currently undergoing extensive evaluation and verification. A workshop is scheduled to determine the appropriateness of having T/P enter its final Observational Phase. The production part of the mission begins after the Science Verification Workshop which is scheduled for February 1993 where this assessment will be made.

2.3 The Load Test

The PODPS system is being built in stages. Each stage includes a period of testing. One test that was performed before launch was the Load Test. This was a test using the SLR data taken on the Ajisai satellite. It checked the laser data sufficiency and availability timeline. It checked our ability to determine and orbit and produce a POE. The POE was distributed for format and interpolation checks. One month of Ajisai data was processed. The PODPS system used was completely housed on the CRAY and was used to evaluate the system in place at the time of T/P's launch. Unfortunately, Ajisai does not have altimeter or DORIS data so these parts of the system could not be checked using coincident actual observations. We nevertheless obtained orbits meeting or exceeding the accuracy goals we set for Ajisai during these tests. This testing also was useful in locating weaknesses in our file system and problems when the file server was not acting properly. We modified the system based on this experience.

2.4 The Expert System

The objectives of the expert system are to collect and present information required for the evaluation of the POE orbit quality. The aim is to automate this processing. It is also desired that the system evolve based on lessons learned.

Having the production system output a condensed summary of results called worksheets at each major operation is a big step towards creating an expert system. The actual process of creating the system is to identify what information is needed, where it can be obtained and how it should be evaluated. In essence, this is an effort to formalize and automate the experimental knowledge of our orbit analysts into an automated computer system.

Over 200 quantifiable criteria related to orbit performance have been identified in all of the functions described above. These criteria were chosen because it is anticipated that the accuracy of the orbits is sensitive to them, it is measurable and its measure will predict the accuracy of the orbits by itself or in conjunction with other criteria. Our most experienced orbit analysts created the lists based on their experience in assessing orbit accuracy. It is anticipated that some of the criteria will be eliminated and others added as a result of on-orbit experience with T/P. A "straw-man" value for each criteria was determined by performing error analyses. In addition, the criteria were evaluated during the Load Test. The modules of the production system were modified to output the information to worksheets. Once the required information is collected, software was written to perform the analysis and score each arc. The passing or failing of a specific test criteria is classified as either a deficiency check or a test of critical failure. Suggestions are given to the technicians as to actions to be taken in cases of failure and possible causes for the anomalous result.

The current expert prototype system applies the most important 120 criteria to evaluate the quality of the candidate orbit. A pass/fail threshold value determined from pre-launch simulations is assigned to each of these criteria. Since the criteria vary in significance, a pre-launch weight has also been assigned so that an overall score for the orbit accuracy can be determined. The choice of criteria, criteria pass/fail values, and criteria weight values are expected to evolve as we gain experience processing TOPEX data. Nevertheless, this extensive automated testing process ensures detailed scrutiny of each of the resulting orbits.

The criteria are grouped into seven test categories: Data Import, Data Reduction, tracking data Residual Analysis, High Elevation Pass, Orbit Overlap direct comparison, Altimeter Range residual analysis, and Altimeter Crossover residual analysis. A final sanity check is also made on the POE just before export. Figure 1 provides a qualitative overview of the information content of the various orbit quality tests. As shown, the use of independent altimeter data is expected to contain the most information concerning orbit quality. The challenge is to extract the orbit quality information from altimeter data. No one test can provide sufficient conditions to fully assess a given orbit's quality; however, certain criteria, if failed, cause the orbit to be deemed of insufficient accuracy for release to the project. Orbit accuracy will be estimated using the combined results from all the tests, and will be based on our understanding of the nature of geographically correlated and time-varying orbit error.

Figure 1

TOPEX PODPS INDICES OF ORBIT QUALITY ASSURANCE

TESTS	INTERNAL CONSISTENCY	ORBIT PRECISION (TIME VARYING)	ORBIT PRECISION (GEOGRAPHICALLY CONRRELATED)	ORBIT ACCURACY (VS PRECISION)
Data reduction statistics	**			
Laser residual analysis	***	*	*	
Orbit overlap comparison	****			
Altimeter crossover analysis		***		*
Altimetor residual analysis		****	***	**
High elevation pass data subset*			**	***

* Weak
**** Strong   Extemely limited distribution

An overview of the nature of the testing follows. The Data Import criteria provide a sufficiency and sanity check on the tracking, polar motion, solar flux, and other data collected for input to the data reduction step. For example, if there is a sufficiently large gap in the tracking data, the operator will be alerted to this condition and advised to modify the parameterization of the non-conservative force model parameters in the data reduction. The data reduction statistics output from GEODYN, such as the rms fit on the data, are compiled and displayed. Pre-launch simulations have shown that the rms of fit on the data will be about 1/2 the rms of the total orbit error. In a separate program, the timing and offset bias is estimated for each pass of the tracking data residuals. The Residual Analysis statistics aid in data editing and provide the first estimate of the along-track orbit error. The High Elevation Pass test takes advantage of the high precision offered by laser tracking. SLR high elevation passes, removed from a subset solution, provide an independent absolute estimate of the radial orbit error. However precise, this orbit test is limited both temporally and spatially over the small subset of the high elevation passes selected. The Orbit Overlap test directly compares the trajectories from two 10-day solutions over 5 days of overlapping data. This is an excellent test of orbit precision, but since common errors will cancel, cannot directly estimate orbit accuracy but checks consistency with a high degree of confidence.

Altimeter data offers a direct measurement of the satellite height relative to the sea surface. In order to use altimeter range for evaluating the radial orbit accuracy, the distance from the sub-satellite sea surface to the geocenter must be modeled. Although altimeter precision is good to 2 cm, considerable error is introduced modelling several oceanic features including the mean sea surface height (geoid) and sea surface variable topography due to tides and changes in the boundaries of the current systems. The sum of modeling errors is expected to total about 20 cm rms over a 10 day period. One may ask how can this measurement be used to test orbit accuracy to 13 cm ? There are two means. Most of the 20 cm is due to the geoid error which varies only spatially, and, as the satellite samples it, at a higher frequency than orbit error. Altimeter crossover measurements are formed by differencing two altimeter ranges taken at the intersection of an ascending and descending pass. The crossover residual thus contains only time- varying error, of which orbit error is by far the major component. In the second approach orbit error can be estimated from altimeter range residuals using an empirical function with the following form:

$$\Delta h = a + (b\cos(\omega_t) + c\sin(\omega_t))$$

(bias) (1 cycle/rev)

$$+ d\cos(2\omega_t) + e\sin(2\omega_t)$$

(2 cycle/rev)

$$+ f(t - t_{mid})\cos(\omega_t) + g(t - t_{mid})\sin(\omega_t)$$

(bow tie)

Where:

ω_t = orbit frequency

t = time from the arc start

t_{mid} = time of the arc midpoint from arc start

This function contains the dominant error signal expected for radial orbit error, containing the familiar bowtie, once-per-rev, and twice-per-rev terms (see Colombo, 1984 (Ref.2); Engelis, 1987 (Ref.4)).

For an example, Figure 2 shows the Altimeter Range Expert System Summary using 8 days of actual T/P data acquired during its Cycle 1 altimeter data to evaluate a preliminary POE. The shape of the estimated orbit error is shown in Figure 3. From these and other tests the orbit error is estimated to be at or slightly higher than the 13.2 cm allowed. These results are very encouraging since they are based strictly on pre-launch models and considerable improvement is expected following gravity and non-conservative force model tuning using the T/P tracking data.

Figure 2

SUMMARY SUBSECTION EXPERT SYSTEM
ALTIMETER RESIDUALS RESULTS

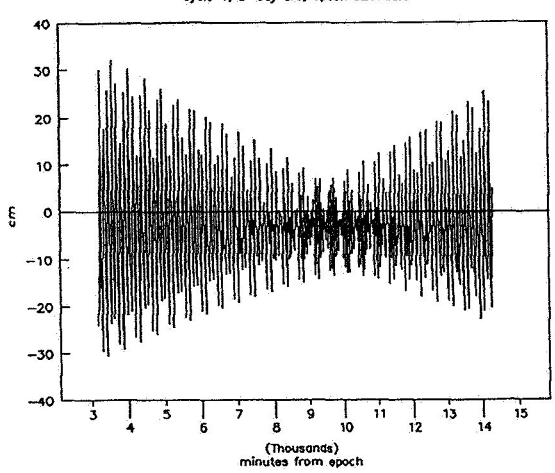
MODULE	TEST#	TEST DESCRIPTION	UNITS	RESULT		CRITERIA	P/F	SCORE
RESIDA	1	RMS OF ERROR FUNC.	CM	12.467	LE	10.000	F	0.2467
RESIDA	2	AMPLITUDE OF 1 C/R	CM	10.991	LE	7.000	F	0.5701
RESIDA	3	AMPLITUDE OF 2 C/R	CM	9.850	LE	3.000	F	2.2834
RESIDA	4	AMPLITUDE ARC MODU C/R	CM	10.508	LE	7.000	F	0.5012
RESIDA	5	RMS RESID (ALT)	CM	25.366	LE	25.000	F	0.0146
RESIDA	6	PERCENT ALT EDITS	%	1.325	LE	10.000	P	-0.8675
RESIDA	7	ALTIM TIME ERROR	MS	-4.819	LE	5.000	F	-0.1811
RESIDA	8	ALTIM BIAS	CM	-3.237	LE	15.000	P	-11.7631
RESIDA	9	RMS ALTIM: NE	CM	29.414	LE	25.000	F	0.1766
RESIDA	10	RMS ALTIM: NW	CM	20.563	LE	25.000	P	-0.1775
RESIDA	11	RMS ALTIM: SE	CM	23.428	LE	25.000	P	-0.0629
RESIDA	12	RMS ALTIM: SW	CM	19.536	LE	25.000	P	-0.2168
RESIDA	13	RMS RESID POST-FT	CM	21.853	LE	15.000	F	0.4568

COMPRISED OF 13 TESTS
SHOWING 6 PASSED AND 6 FAILED

Figure 3

TOPEX Orbit Error Est from Altim Resid

Cycle 1, 8-day arc, epoch 920925.0



3.0 CONCLUSION

A production and expert system has been created to produce highly accurate orbits for the TOPEX/Poseidon Mission. The radial accuracy requirement is 13 centimeters RMS. A prototype of the system is now operating. It is written in Fortran 77 using UNIX scripts and designed to be portable. This system offers us advantages for it both produces and quality checks the orbits for T/P. It can locate poorer performance for a particular arc, allowing special attention to be paid to its improvement. It also allows us to alert the science community when an orbit's accuracy is suspect. The uniform approach is anticipated to provide uniformly accurate orbits. This system has wide ranging applications for other missions requiring precision orbit determination.

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