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# TOPEX/POSEIDON ON-BOARD EPHEMERIS REPRESENTATION PROCEDURE, PERFORMANCE, AND EXPERIENCE

**Ahmed B. Salama**
**Jet Propulsion Laboratory**
**California Institute of Technology**
**Pasadena, California**

**Robert K. Leavitt**
**Sterling Software, inc.**

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# TOPEX/POSEIDON ON-BOARD EPHEMERIS REPRESENTATION PROCEDURE, PERFORMANCE, AND EXPERIENCE*

**Ahmed H. Salama**†

**and**

**Robert K. Leavitt**‡

The TOPEX/POSEIDON satellite requires real-time on-board knowledge of the satellite and TDRS ephemerides for attitude determination and control and High Gain Antenna (HGA) pointing. The on-board ephemeris representation concept for the MMS (Multimission Modular Spacecraft) satellites has shown that compressing the predicted ephemeris in a Fourier Power Series (FPS) before uplinking in conjunction with the On-Board Computer (OBC) ephemeris reconstruction algorithms is an efficient technique for ephemeris representation. As an MMS-based satellite, TOPEX/POSEIDON has inherited the LANDSAT ephemeris representation concept which included a daily FPS upload. During the design phase of the mission, this concept was modified by extending the ephemeris representation duration to 10 days and a convenient weekly uploading was adopted without an increase in OBC memory requirements. This paper describes the success of TOPEX/POSEIDON on-board ephemeris representation modified concept in achieving mission requirements. The operational procedures and the lessons learned from operational experience are discussed. Emphasis is on the performance of the on-board ephemeris in routine operations as well as near maneuvers.

## INTRODUCTION

TOPEX/POSEIDON was successfully launched by an Ariane 42P from French Guiana on August 10, 1992, with injection occuring at 23:27:05 UTC, approximately 19

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† Member Technical Staff, Member AIAA. Affiliated with Jet Propulsion laboratory, California Institute of Technology, Pasadena, California

‡ Software System Engineer, Member AIAA. Affiliated with Sterling Software, inc.

min 57 sec after lift off. The primary goals of this joint US/France mission are to determine ocean surface height to an accuracy of 13 cm. (3 sigma) utilizing a combination of satellite altimetry data and Precision Orbit Determination (POD), to study ocean circulation and its interaction with the atmosphere, to better understand climate change, to improve knowledge of heat transport in the ocean, to model ocean tides, and to study the marine gravity field. To meet these science requirements, the TOPEX/POSEIDON satellite must point the altimeter antenna at the ocean local nadir with good accuracy. It must also point an articulated HGA at the NASA Tracking and Data Relay Satellite System (TDRSS) to allow communication and tracking for Operational Orbit Determination (OOD). This requires real-time on-board knowledge of the satellite. and TDRS c]knlic]-ides.

The on-board ephemeris representation concept for other MMS satellites (the TOPEX/POSEIDON satellite, is based on the MMS bus) has shown that compressing the predicted ephemeris in an FPS before uplinking, in conjunction with the OBC ephemeris reconstruction algorithms, is an efficient technique for ephemeris representation. As an MMS-based satellite, TOPEX-POSEIDON has inherited the LANDSAT ephemeris rc.presentation concept which included a daily FPS upload of a 37-hour ephemeris.

Reference (1) presents a modified concept for the TOPEX/POSEIDON satellite OBC ephemeris representation where duration is extended to 10 days and a convenient weekly uploading strategy is adopted without an increase in OBC memory requirements. During operations, this concept has shown a significant reduction of ground operations intensity, and TOPEX/POSEIDON Ground System (TGS) staffing demands. It also reduces the chance of undesirable automatic transition to Safe-Hold Mode (SHM) duc to TGS, Flight Operations System (FOS), or "TDRSS errors or delays.

The success of this concept is described in this paper. First, the ephemeris command loads functional design is presented, then the operational procedures used to compute satellite and TDRSS on-board ephemerides and uplink them to the satellite are discussed. It also addresses the performance of the on-board ephemeris, in terms of meeting accuracy requirements, and the. lessons learned from the operational experience in both routine operations and when mane. euvers are scheduled.

## OBC EPHEMERIS COMMAND LOADS FUNCTIONAL DESIGN

Certain elements of the satellite Command and Data Handling Subsyste.ii"] (C&DHS), in particular the OBC and its Flight Software (FSW), must be considered in the navigation design. The FSW design affects the ephemeris representation duration, and the redated operational navigation activities, timelines, and procedures. The limited OBC computational capability and ephemeris memory allocation require, efficient algorithms by which the Navigation Team (NAVT) represents the ephemeris. in addition to errors in the representation, the. OBC induces an additional maximum along-track position error of ≈200 meters duc to significant bit limitations. The on-board clink relative time. rolls over to zero after 1?..4?'7 days, allowing up to 2.427 days of margin to update the planned standard 10-day ephemeris load. Detail of sate.llitc impact on the navigation design can be found in Reference (2).

The ephemeris representation concept defined above includes both ground support activities and on-board functions. The models used arc basically FPS for ground support and the Hermite interpolation formula for on-board functions. For TOPEX/POSEIDON, the following modeling design assumptions have. been adopted:

1) A 42-coefficient FPS is used for each of the. six Cartesian state. vector components (the coefficients are estimated using the least-squarcx method).

2) The time span of the accurate Operational Orbit Ephemeris (OOE) used on the ground to develop the FPS is at least 10 days and the uplinked FPS is valid for the. same time span.

3) "1"0 optimize the performance of the ephemeris representation, a grid spacing, of JO min has been chew.n for the least-squares fit; the OBC recovers the ephemeris at these 10-min grid points.

4) The residuals of the fit are computed and uploaded to the OBC for only a 30-hour span giving increased accuracy over this limited span.

5) Two frequencies are included in the FPS, the satellite mean orbital frequency and the earth sidereal frequenc y.

6) 'l-he satellite mean orbital frequency is computed from the mean semi-tnajc)r axis which is obtained by suitably averaging the osculating sem i-major axis history defined by the. OOE.

7) A four-point Hermite interpolat ion formula is used by the. OBC to compute the position and the velocity of the sate.llite at any request time.

8) A convenient weekly uploading is adopted iri routine, operations.

The above modeling design assumptions provide an OBC ephemeris representation which meets the altimeter pointing accuracy requirements (see Reference 3). The allocation for ephemeris prediction error due to on-board representation and computation is 0.022 (1 sigma) deg. The corresponding allowable position error is about 2..9 km (1 sigma). Since the. TDRSS satellites are in geostationar y orbits, modeling design assumptions for the. representat ion of the TDRSS ephemerides are. expected to be relaxed. However, to reduce. ground operations complexity, the TOPEX/POSEIDON modeling assumptions are also adopted for TDRSS ephemerides with the exception that eight coefficients for' each of the six Cartesian state vector components arc. used instead of 42, and no residuals are required. At any time in the mission, only 2 TDRSS spacecraft arc utilized by the Project as assigned by the Network Control Center (NCC).

The Fourier coefficients are generated by fitting a truncated least-squares FPS to the. OOE (for TOPEX/POSEIDON). The. "1'1 DRS coefficients are obtained by fitting two other FPS to the TDRSS satellite ephemerides. Accuracy requirements necessitate computing these coefficients in double. precision. The coefficients are valid for 10 days.

Figure (1) shows the functional design of OBC Ephemeris Command Loads in which the interpolated ephemeris files produced from OOE/P-FILE (for TOPEX/POSEIDON) and the two TDRSS P-FILES are used as input to the FPS program. The FPS program implements the truncated least-squares FPS algorithm and produces, among other data, the Fourier coefficients and a 30-hour residual span.

The diagram also shows a technique by which the coefficients are validated. A program is used to convert the. output of the FPS program into OBC Ephemeris Command Loads. The command loads are then used as input to a software to simulate the

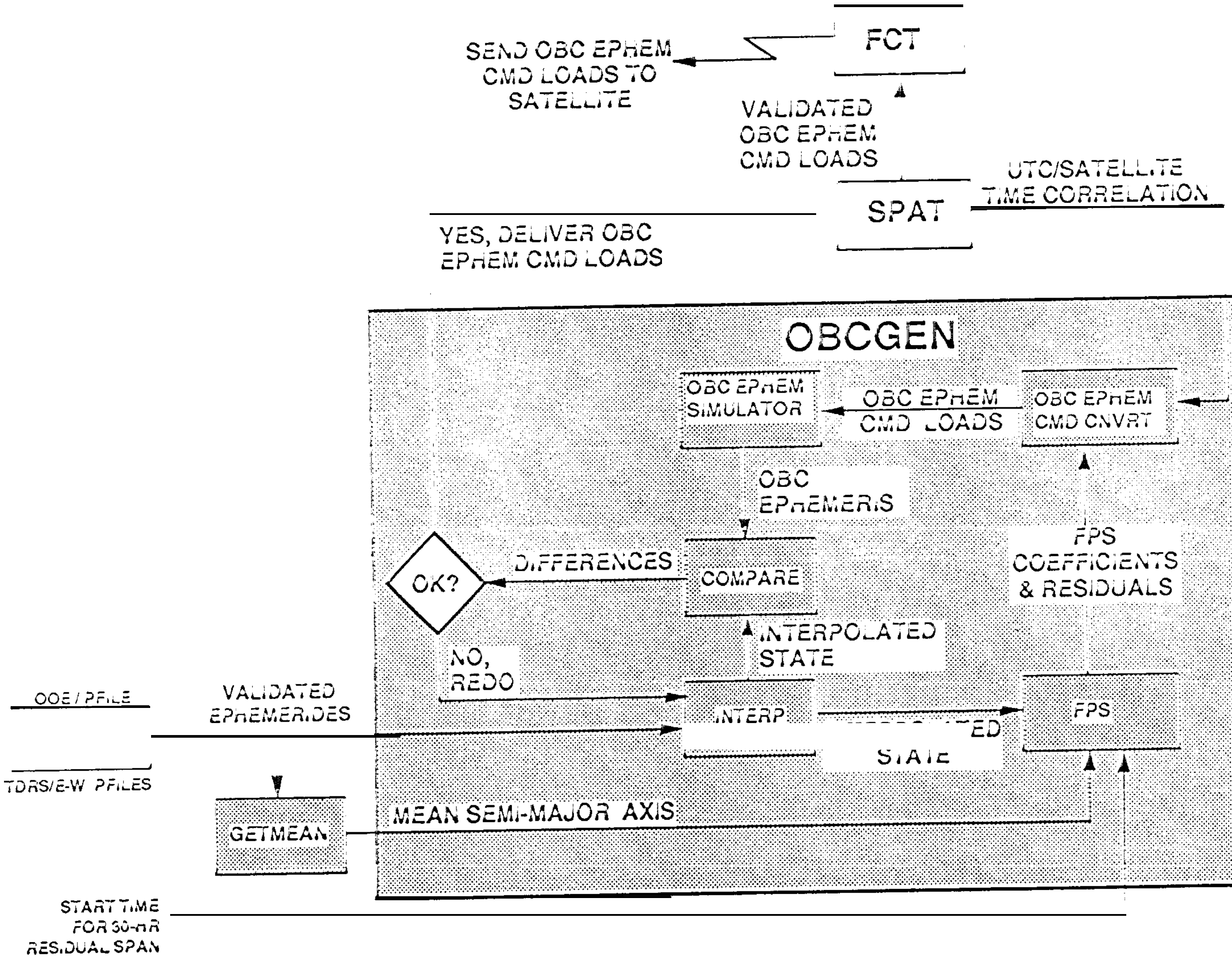



Figure 1 Functional Design

performance of the on-board computer and to reproduce the OBC ephemerides for both TOPEX/POSEIDON and the '1"1>1<SS satellites. Comparison with the. 0017P-I(11 .E and the TDRSS P-FI [ .ES determines that the OBC command loads are valid before delivery to the Satellite, Performance Analysis Team (SPAT). If not, the entire process is re-examined by the NAVT. Delivery to SPAT takes place only if the difference. in altimeter pointing produced by the two files is less than the MSRD (Mission and Systems Requirements Document) requirements at all grid points within the 10-day representation period.

The OBC command load is a binary data file obtained from the coefficients and residuals files. This command load is generated by the OBC EPHEM CMD CNVRT software shown in Figure (1). in addition to the FPS and residuals, the command load file also contains the TOPEX/POSEIDON mean orbit frequency, the Earth's sidereal frequency, reference times of the 1 0-da y span, the. start time of the 30-hour residual span and grid spacing.

## OBC EPHEMERIS COMMAND LOADS PROCEDURE

The functional design, together with an upload strategy, have been implemented in a procedure for gene.t sting and verifying OBC ephemeris command loads. This procedure describes the strategies for generation and delivery of the OBC ephemeris command loads in both routine cruise operations and when maneuvers are scheduled. One important characteristic of this procedure is the variability of the timeline for delivery of the OBC command loads for different phase.s of the. mission; e.g., post-launch, assessment, and observational phases for both routine times and times which include maneuvers. For instance, the weekl y delivery of the command loads in routine operations of the observational phase is tied to the Wednesday reception of the Flight Dynamics Facility (FDF) OOD solutions. This is in contrast to the post-launch and assessment phases of the mission when multiple loads may be required. The following describes various delivery schedules for different phases of the mission.

### Pre-Launch Loading

Prior to launch, the NAVT produced ten ephemeris loads, each corresponds to a launch day arid time in a 10-day launch period, The plan was for the satellite contractor to preload the appropriate. ephemeris for a specific launch day a few hours before launch. This ephemeris was valid until the. first planned uplinking. It was used on-board to check out the. attitude control system and to compute the. orbit plane-sun angle in case. of an early S1 IM episode.

### Post-Launch Phase

During the first 12 hours of the mission, four Extended Precision Vector (EPV) solution sets were received from the FDF at 4, 5.S, 7.5, and 9.S hours after injection to determine the injection conditions. Two ephemeris loads were produced based upon the 7.5 and 9.5 hr ephemeris files as primar y and backup, respectively. It was the 7.5 hour ephemeris load that was uplinked and used by the OBC to converge. the Kalman filter of the attitude control system and perform the yaw acquisition.

### Assessment Phase

The assessment phase. involved an intense period of satellite initialization, performance assessment and calibration, sensor initialization, and acquisition of the operational orbit. Six maneuvers were performed during the assessment phase to acquire the operational orbit. Two ephemeris loads were produced and uplinked around each maneuver. A ple.dieted post-burn ephemeris load based upon the maneuver design was uplinked as part of the maneuver block and used by the OBC 30 min after burn centroid. Based upon post-maneuver OD solutions, an actual post-maneuver ephemer is load was uplinked about 12 hours after burn centroid and used by the OBC about 2 hours later (see section on accuracy requirements).

## Observational Phase (Routine operations)

in routine cruise operations, an ephemeris load is uplinked to the. spacecraft every Thursday evening (Fri morning UTC). This weekly delivery of the command load is tied to the Wednesday reception of EPV's.

## Observational Phase (Maintenance Maneuvers)

The propulsive maneuvers in the observational phase occur near the transition between the. 10-day orbit repeat cycles. A predicted post-maneuver OBC ephemeris is uplinked prior to the burn as part of the maneuver block. If the actual maneuver execution time arid/or performance deviates sufficiently from predicted values, a new upload is prepared and uplinked based upon the post-maneuver OOE. If the prediction is judged adequate (see section on accuracy requirements), the predicted load remains in the OBC for the normal period of one week.

The ephemeris command load is a joint effort between the NAVT, the. Satellite Performance Analysis Team (SPAT), the Mission Planning and Sequence Team (MI'S]"), and the. Flight Control Team (FCT) with NAVT as the prime contributor. The procedure starts with an input from NAVT to MPST in the form of a Sequence Request (SR) to be implemented in the Sequence of Events (SOE) and the Space Flight operations Schedule (SFOS). The SR contains the command loads file name and an uplink window. In case of conflicts or problems, the NAVT updates the SR with a Sequence Change Request (SCR). The SPAT provides NAV with the. UTC/satellite time correlation table anti validates the command syntax of the OBC ephemeris command load files supplied by the NAVT. The FCT dews the translation of the loads and uplink the files to the spacecraft.

When the NAVT receives the appropriate. satellite and TDRS EPV's, OOE files are produced which cover the 10-day OBC ephemeris time span. As Figure (1) indicates, the INTERP program reads these OOE's and provides FPS with interpolated files to be compressed into a set of 42 least-square.s coefficients and residuals for each Cartesian position and velocity component. The residuals of least-squares fit cover only a 30-hour span with an input start time. For TDRS, only 8 coefficients are estimated arid no residuals. GETMEAN is then run to provide FPS with sate.llite mean semi-major axis from which the mean orbital frequency is computed. The UTC satellite Time Correlation File obtained from the SPAT, together with the FPS coefficients and residuals, are processed to produce the OBC Ephemeris Command Loads in a format readable by the satellite OBC. These loads arc then input to an OBC Ephemeris Simulator to perform NAVT internal consistency checks to verify that the FPS representation accurately matches the original OOE. Once this validation has been completed, the Command Loads are delivered to the SPA"]' for final validation before translation and uplink to the satellite by the FCT.

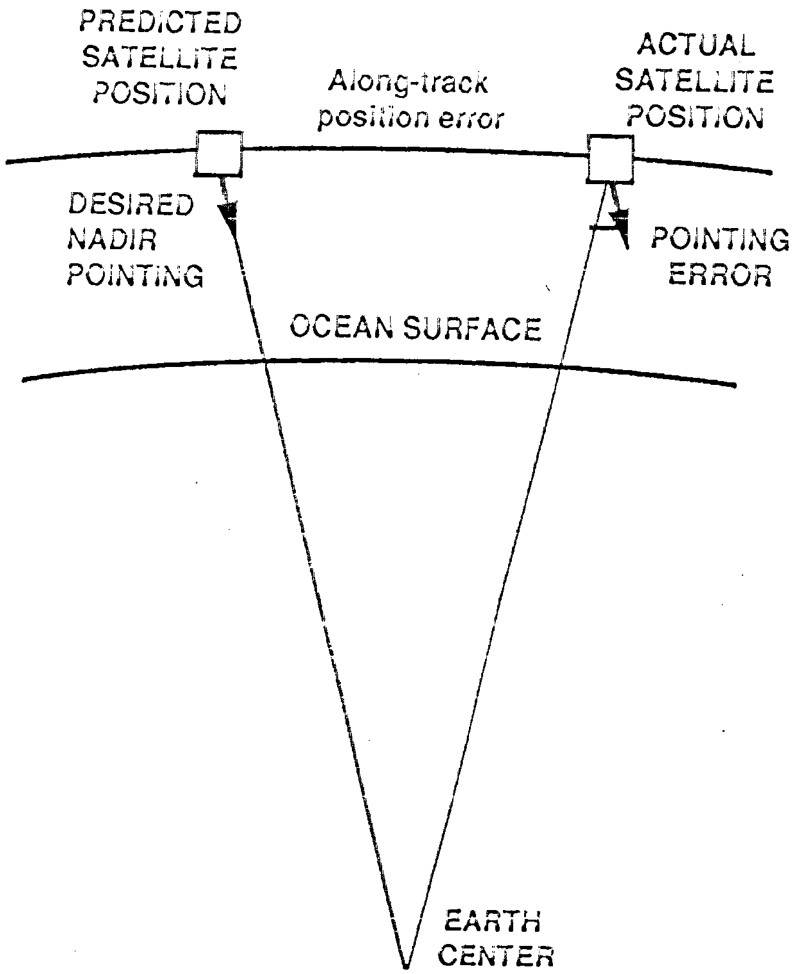
On the day of the uplink of the OBC command loads, an upload plan is prepared. The plan describes how various reference times of the loads arc determined and how the time for resetting the on-board computation of the orbital plane-sun angle based upon the. new ephemeris is set. The reference time.s include, Tenable: the times at which the. satellite, and TDRS ephemerides arc enabled, Tstart: the time at which the OBC starts to compute the coefficients of the Hermite interpolator for the. first set of grid points, and $T_{use}$: the time at which the OBC starts using the. new ephemeris. in case of predicted post-burn command loads (loads based upon maneuver design), the plan also relates the reference times to the end of the burn time.

## ACCURACY REQUIREMENTS AND PERFORMANCE

The altimeter electrical axis is aligned to the spacecraft z-axis which is pointed to the local geodetic nadir. Reference (3) indicates that the overall pointing error requirement (half-cone angle) is 0.07 degrees (1 sigma), Portions of this overall error have been allocated to the OOE generation and OBC ephemeris representation processes. A 0.015 degrees (1 sigma) pointing error is the amount allocated to errors in ephemeris prediction over 7-day prediction period due to operational OD and OOE generation. A 0.022 degrees (1 sigma) pointing error is allocated to FPS representation and computation and limitation of the OBC over the 10 days representation span, Figure (?.) shows the relationship between along-track error and nadir pointing error both graphically and quantitatively. "This indicates that the 1 sigma along-track prediction error in the OOE after 7 days should be less than about 2 km, and the corresponding OBC representation error should be less than about 2.9 km within 10 days. To ensure that the command loads, as used by the OBC, meet mission requirements, extensive checking and review is conducted before uplinking. A software simulator (Reference 4) emulating the. limitations and performance of the OBC is used to reconstruct the ephemeris from the command loads. Figure (3) shows a typical example of one of these checks. The figure gives the TOPEX/POSEIDON along-track and nadir pointing differences between those of the simulator and the ground ephemeris (001{). Both the along-track and nadir-pointing errors are well within the requirements. The OOE is also validated by comparing the state. vectors extracted from it with the FDF EPV's at specified epochs.

A factor related to accuracy, performance, and numerical stability of the algorithms used is the accuracy of the mean semi-major axis used to compute the mean orbital frequency of the satellite. The mean semi-major axis is computed by averaging the osculating semi-major axis obtained from the OOE over the 10-day span. It has been found that an inconsistency between the man orbital frequency and the OOE used by the Fourier power series least-squares method could lead to accuracy degradation or even numerical instability in the coefficients. It has also been found that to avoid these. problems, the mean semi-major axis has to be known to an accuracy of about 10 meters. Our averaging technique can give the. mean semi-major axis to one meter accuracy.

A few months after launch, some glitches in the satellite ephemeris-related telemetry data had been observed. A similar phenomenon had also been observed in the ground processing of the flight software generation of these. data, The glitches were in the form of spikes in the on-board computation of the roll/pitch/yaw attitude errors and rates and the orbital plane.-sun angle which are. functions of the OBC ephemeris. These glitches were first thought to be inaccuracy in the NAVT processing of the command loads. Subsequent analysis showed that the glitches were flight software related (Reference 5). The reference also suggested two solutions to the problem, The first is for the NAVT to ensure that the least significant word of Tuse in the command loads be. non zero. The second fix recommends a patch to the flight software. The first solution was adopted.




| Pointing error (deg) | 1σ Along-track position error (km) | 3σ Along-track position error (km) |
|---|---|---|
| 0 | 0 | 0 |
| 0.015 | 2.01952048 | 6.05856143 |
| 0.022 | 2.96196337 | 8.8858901 |
| 0.1 | 13.4634698 | 40.3904095 |
| 0.2 | 26.9269397 | 80.7808191 |
| 0.3 | 40.3904095 | 121.171229 |
| 0.4 | 53.8538794 | 161.561638 |

Figure 2 Nadir Pointing Geometry

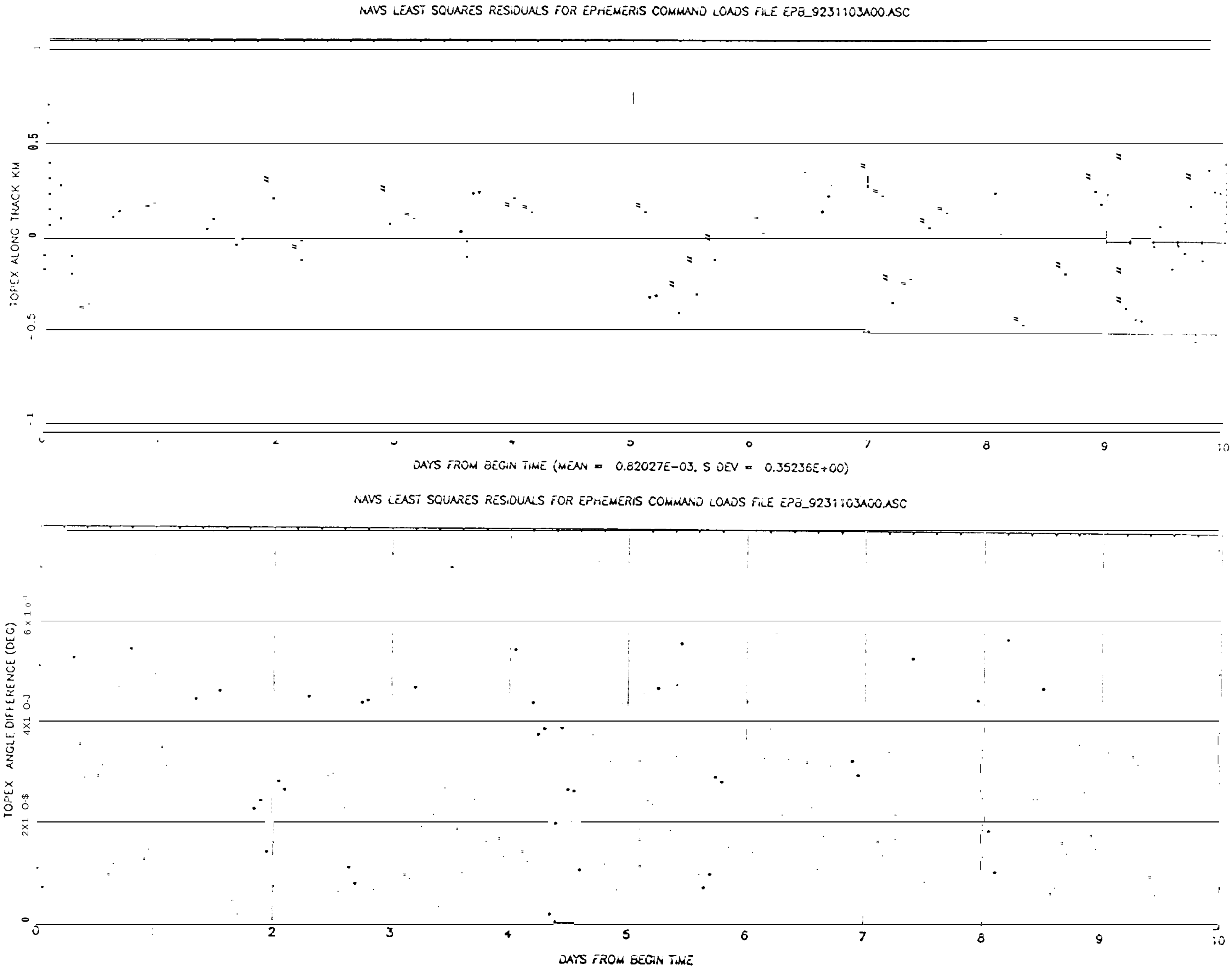



Figure 3 Along-Track and Nadir Pointing Difference

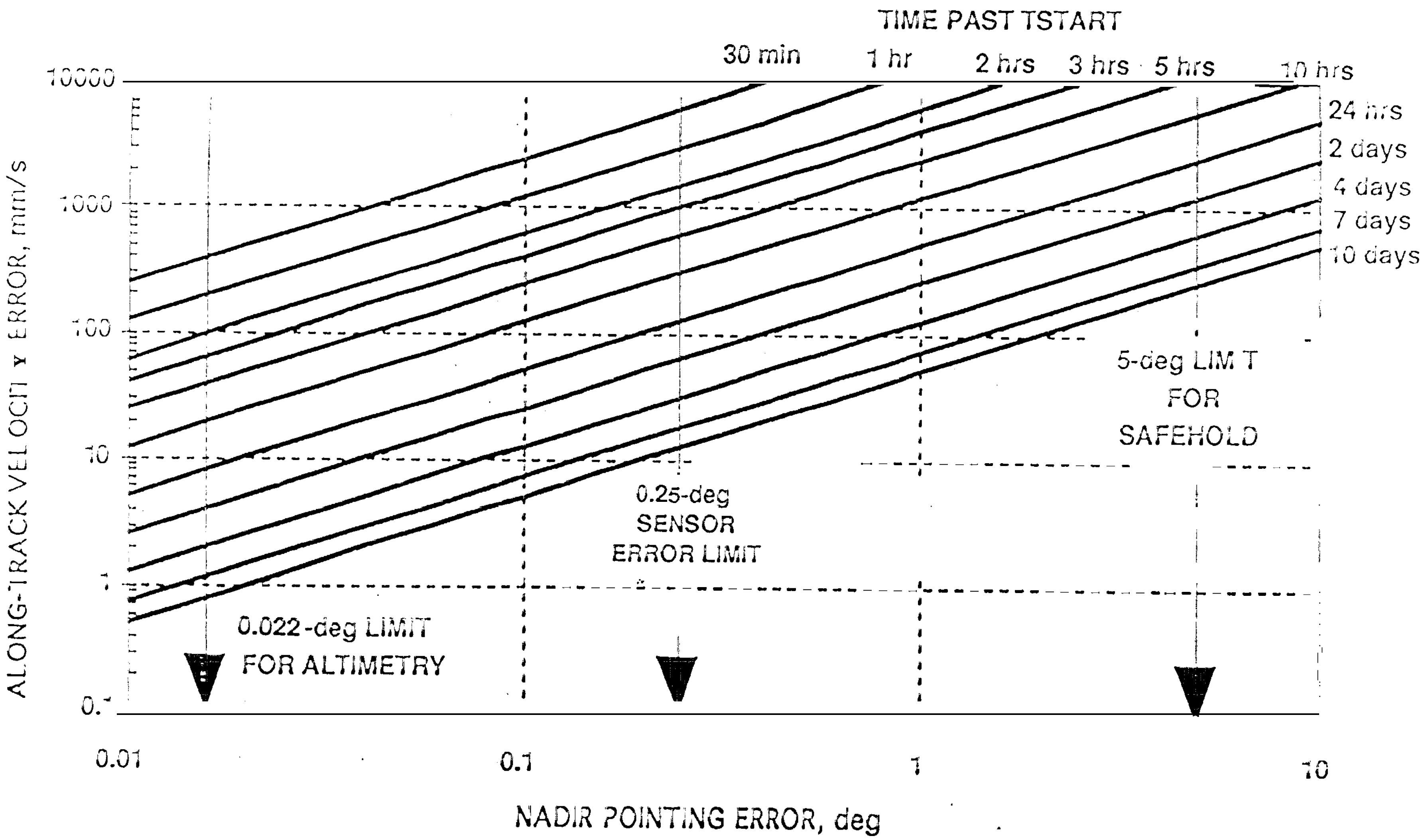



Figure 4 Nadir Pointing Error vs OBC Ephemeris Accuracy

in addition to the extensive. checking and re.view described above to ensure that the command loads meet mission requirements in routine operations, extra care is requiredwhen maneuvers (both retargeting and maintenance) arc performed. When a maneuver is scheduled, a predicted post-burn command load is produced based upon the maneuver design and uplinked prior to the burn as part of the. maneuver block. If 1) the magnitude of the maneuver is sufficiently large, 2) the actual maneuver execution time is largely different, 3) the satellite execution of the maneuver deviates sufficiently from nominal, and/or 4) there is a final tweak based upon latest OD solutions prior to the maneuver, then an update to the predicted post-burn ephemeris may be necessary to meet mission requirements. If the. prediction is judged adequate, the predicted load remains in the OBC for the. normal period of onc week. 'I'he NAVT has developed a procedure to determine whether or not an update, to predicted loads is required. The procedure uses the along-track velocit y execution errors obtained from the 01) solutions received a few hours after the burn to ensure that the predicted post-burn ephemeris still meets mission requirements. A quick-look chart to determine the validity of the predicted ephemeris over the representat ion length (from the initial epoch) is shown in Figure (4). It gives how long the command load is still valid as a function of the along-track velocity error for three levels of accuracy requirements. The 0.022 degrees is the pointing accuracy of the altimeter at the local nadir which is being used in the observational phase of the mission. '] 'he 0.25 degrees is the sensor pointing error limit which was used during the assessment phase. The 5 degrees limit is the criterion for avoiding the safehold mode. This chart was used extensivel y during. the assessment phase where all six maneuvers necessi tatc an update to the predicted command loads within a certain period of time.

To study how well the ephemeris command loads are performing over extended periods of time, the NAVT has developed a dynamic scheme to examine the overall performance between successive maintenance maneuvers. The procedure compares predicted loads with the definitive ephemeris obtained from after-t}]c-fact definitive arcs provided by OD. Such comparison is shown in Figures (5) and (6) for all loads between Orbit Maintenance Maneuvers 1 and 2 (OMM1 and OMM2). Between OMM1 and 0MM2 there were 9 loads as shown in Figure (S). They start with the load of sequence #242 and end with the load of sequence #2.50. The figure also shows the uplink date of these loads, the EPV's used to produce the OOE's, and the definitive arcs used to compare the ephemeris command loads. The nadir pointing computed by the software simulator which emulate the limitations and performance of the OBC has been compared with the nadir pointing obtained from the definitive ephemeris. The results are shown in Figure (6) where the top figure shows the nadir pointing error against time for all loads and the bottom figure shows the man error plus/minus one-sigma error statistics. These figures show that the OBC ephemeris performance is as expected and all mission requirements arc met.

## CONCLUSION

The TOPEX/POSEIDON on-board ephemeris representation concept has shown a significant reduction of ground operations intensity, and staffing demands. It also reduces the chance of undesirable automatic transition to safe-hold due to Mission Operations System (MOS) or TDRSS errors or delays. In addition, the OBC ephemeris performance is as expected and all mission requirements are met.

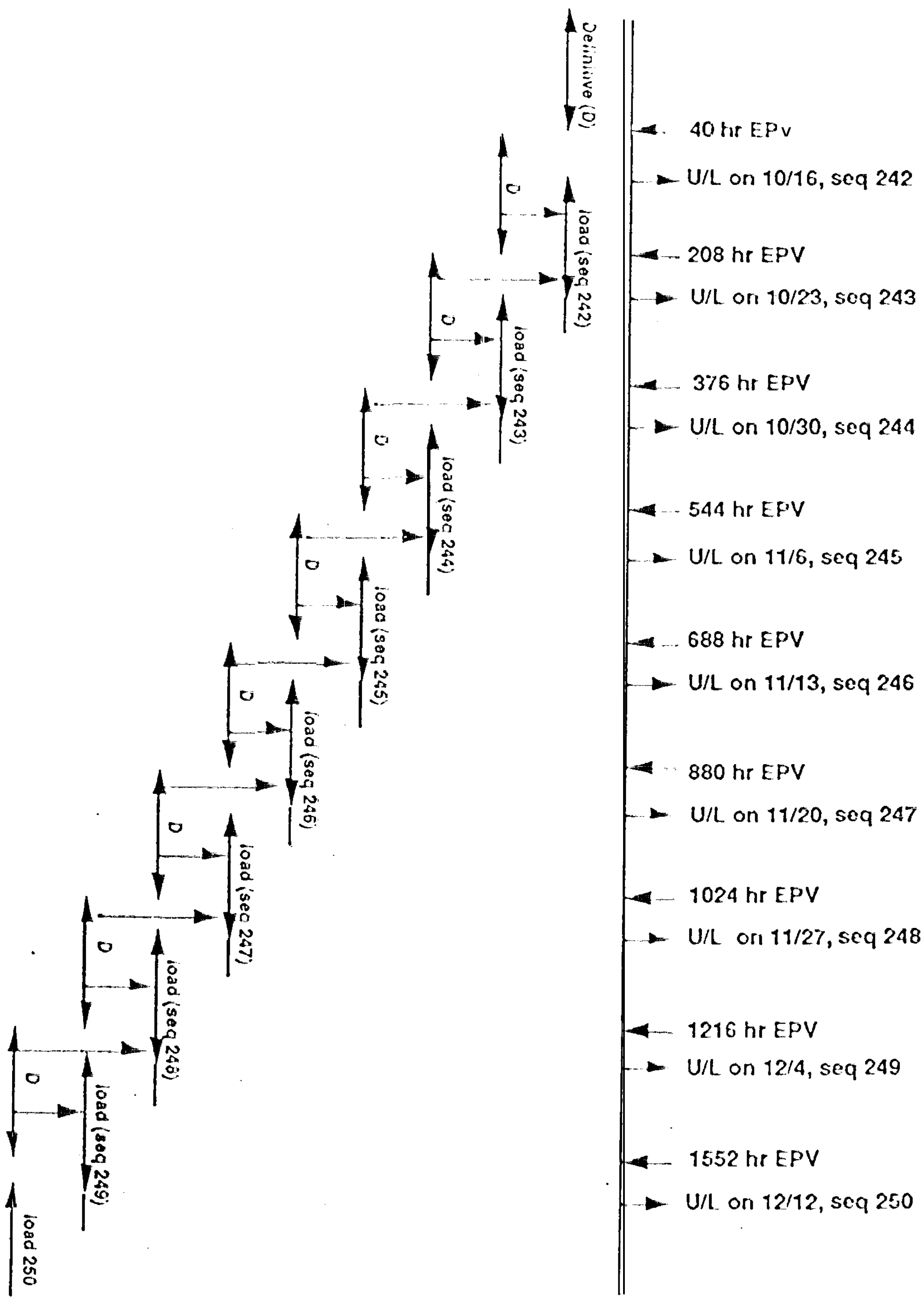



Figure 5 Definitive vs Prediction for Loads Between OMM1 and OMM2

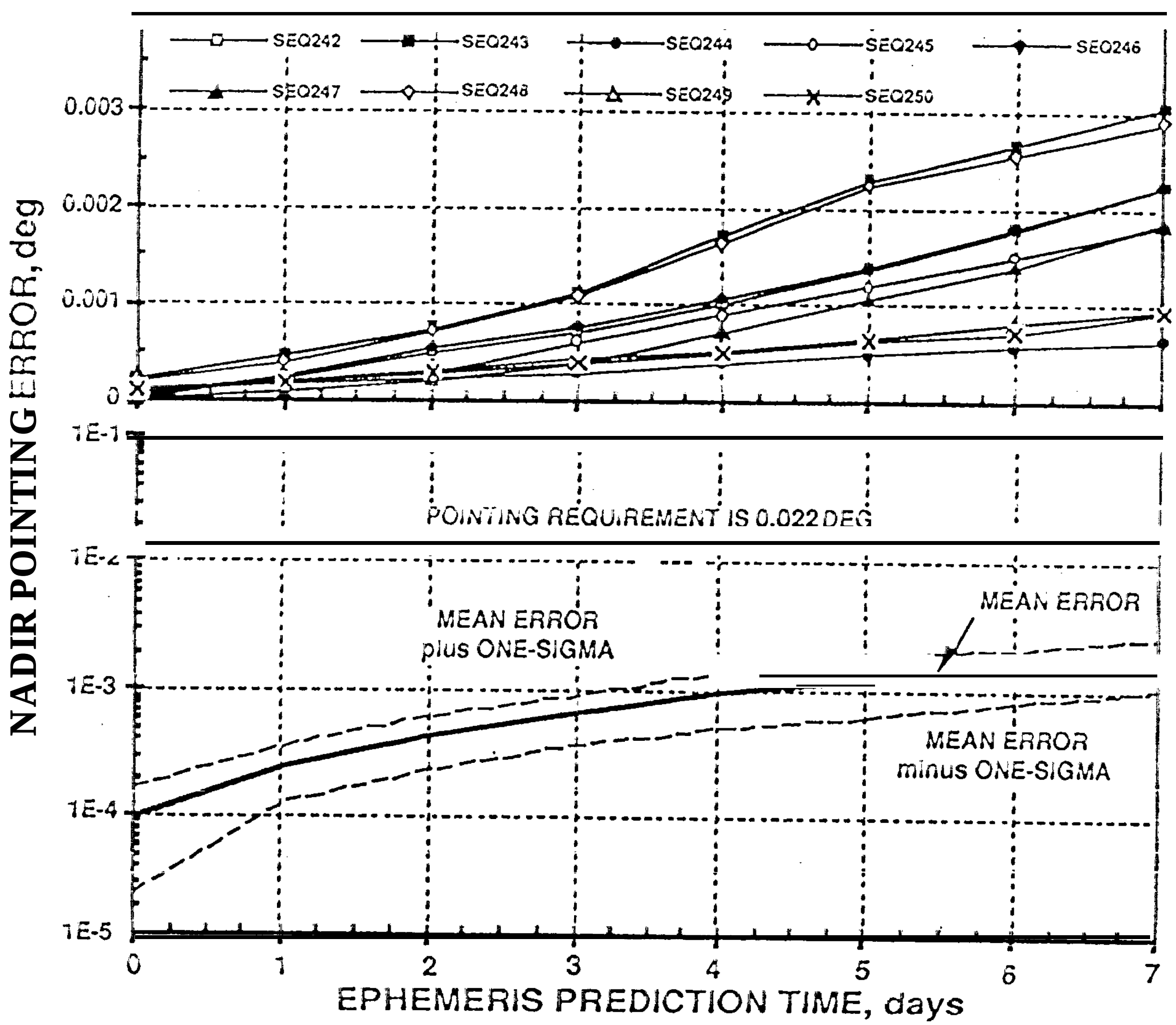



Figure 6 Nadir Pointing Accuracy of OBC Ephemeris

## ACKNOWLEDGMENT

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