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COMPATIBILITY OF TOPEX/POSEIDON TRAJECTORY PROPAGATION WITH JPL AND GSFC/FDF OPERATIONAL SOFTWARE

Ahmed Salama[1], Michael Nemesure[2], Joseph Guinn[1], Dave Bolvin[2], and Robert Leavitt[3]

ABSTRACT

Two independent trajectory software systems are used to perform the TOPEX/Poseidon operational orbit determination and propagation: the Goddard Trajectory Determination System (GTDS) at the GSFC/FDF and the Double Precision Trajectory System (DPTRAJ) at JPL. GTDS is used for operational tracking and TDRS-based orbit determination. DPTRAJ is used for ephemeris generation necessary to conduct day-to-day mission operations. This paper describes the DPTRAJ/GTDS trajectory comparison analysis conducted jointly by JPL and GSFC to ensure the compatibility of these two independent trajectory software systems.

INTRODUCTION

The Ocean Topography Experiment (TOPEX)/Poseidon spacecraft was launched on August 10, 1992 to study ocean circulation and its interaction with the atmosphere, to improve our knowledge of climate change and heat transport in the ocean, and to study the marine gravity field. These objectives are accomplished through accurate mapping of the ocean surface with a dual-frequency on-board altimeter and precision orbit determination.

Two independent Orbit Determination (OD) processes are associated with the mission. A Precision Orbit Determination (POD) process which is used to support analysis of the altimeter data, and an Operational Orbit Determination (OOD) process which is used to support the daily satellite operations. This paper is concerned only with the utilization of the OOD solutions in daily operational navigation. The OOD is the responsibility of the Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF). Using tracking data from the Tracking and Data Relay Satellite (TDRS) System (TDRSS), the FDF produces TOPEX/Poseidon and TDRS state vectors for transmission in the Extended Precision Vector (EPV) message format. These EPV solution sets are transferred to the Jet Propulsion Laboratory (JPL) via National Aeronautics and Space Administration Communications Network (Nascom) to be used by the Navigation Team (NAVT) as initial conditions for propagating the Operational Orbit Ephemeris (OOE). Operational navigation support procedures have been developed to ensure the compatibility of the FDF-estimated TOPEX/Poseidon and TDRS state vectors and the NAVT-generated OOEs (Fig. 1). The objective of this paper is to present the results of this activity for only TOPEX/Poseidon trajectories.

Two independent trajectory software systems are used to perform the above task: the Goddard Trajectory Determination System (GTDS) at the GSFC/FDF and the Double Precision Trajectory System (DPTRAJ) at JPL. GTDS is used for operational tracking and TDRS-based OD. DPTRAJ is used for OOE generation necessary to conduct day-to-day mission operations.

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[1] Jet Propulsion Laboratory, California Institute of Technology

[2] Computer Sciences Corporation

[3] Sterling Software, Inc.

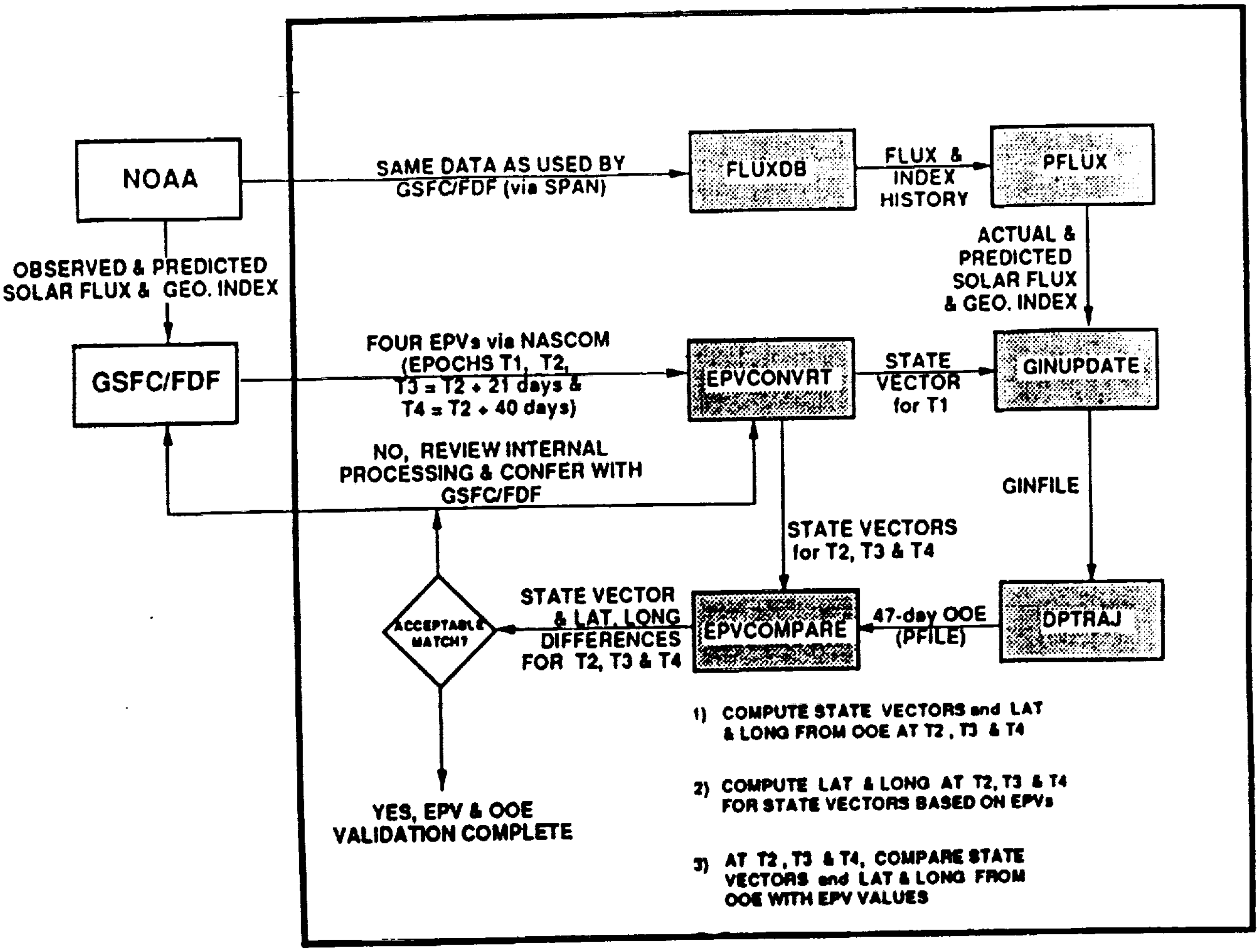

Figure 1. OOE Generation & EPV Validation Procedure

This paper describes the GTDS/DPTRAJ trajectory comparison analysis conducted jointly by the authors and their colleagues. The paper discusses both the TOPEX/Poseidon mission requirements as they related to OOE accuracy requirements and the error budget developed to meet these requirements. The operating procedures used to generate orbit solutions at GSFC/FDF, to transfer these solutions to JPL, and to process the solutions at JPL are also addressed. A description of each force model enhancement to GTDS and DPTRAJ motivated by the TOPEX/Poseidon mission is presented followed by a discussion of the DPTRAJ/GTDS comparison tests and test results. Finally, the lessons learned from JPL and GSFC/FDF experiences, providing joint flight dynamics operational navigation support for TOPEX/Poseidon are presented.

ACCURACY REQUIREMENTS ON THE OOE

The TOPEX/Poseidon project has imposed several accuracy requirements on TOPEX/Poseidon operational navigation support. The primary driver behind these requirements is a ±1 km error tolerance on the equator crossings of the satellite ground track to maintain ground track repeatability. Orbit Maintenance Maneuvers (OMM) used to maintain this ground track must be planned and evaluated to a commensurate accuracy level based on the OOE's. More specifically, a 30-day OOE must have a 1σ error of no more than 250 meters in equator crossing location. To ensure this level of accuracy, an error budget was prescribed (Ref. 1) that apportioned the overall error allowance for the OOE's among the identified error sources. The one error source of interest here is the trajectory software modeling errors. Ref. (1) indicates that the 1σ value of this error must be no more than 40 meters in equatorial crossing longitude after 30 days (Table 1). A 5 meter (out of the 3σ 120 meters) longitude difference at equator crossings after 30 days was allocated as a derived requirement for JPL-FDF trajectory prediction software comparisons. This 5 meter tolerance was chosen during software development as an achievable objective. It is more of a goal than a requirement. Joint mission support by the NAVT and GSFC/FDF thus demands a high level of consistency between GTDS and DPTRAJ. Both systems must, for example, model atmospheric drag and geopotential forces consistently and utilize common drag and solar radiation pressure spacecraft cross-sectional area profiles.

Table 1. Predicted Ephemeris Error Budget

ERROR COMPONENT	Equator Crossing Error at 30 days (1 Sigma Random or max. systematic) (m)
Definitive OD (all sources)	75
Prediction error (Nature's unpredictability after the definitive OD interval: density, UTI)	130
Prediction Trajectory Software Modeling Errors	**40**
Maneuver Execution	70
Geopotential tuning limitations	10
Total error (Uncorrelated errors)	171
Total error	221
Allowable error	250 (TBR)
Margin available: (Uncorrellated)	79
(Correlation - 1)	29

BACKGROUND

Extensive effort was made during the mission development phase to ensure the compatibility of DPTRAJ and GTDS. This effort began in 1987 (Ref. 2 and 3) by identifying the force models to be used in the two organizations to support TOPEX/Poseidon operational navigation. Over the years many cases have been established to allow for a model-by-model comparison between DPTRAJ and GTDS.

Although extensive effort was made during the software development phase to eliminate inconsistencies between the two systems (Ref. 4 and 5), it was not feasible to eliminate all inconsistency. DPTRAJ and GTDS utilize different modeling design implementations, input/output interfaces, numerical strategies, and, in some cases, different force models. For example, DPTRAJ uses a variable-step integrator with the terrestrial dynamical time as an independent variable whereas GTDS uses a fixed-step integrator with A.1 time as an independent variable. In addition, DPTRAJ uses a conical umbra shadow model for solar radiation pressure modeling whereas GTDS uses a cylindrical umbra shadow model. A paramount objective of this work was to quantify the effect on OOE error of system inconsistency and to ensure conformity with the error budget. To this end, ten tests were designed and performed during the pre-mission phase to allow for a model-by-model comparison between DPTRAJ and GTDS. After launch, upon the discovery of an unanticipated thrust-like perturbation, an eleventh test was devised to ensure consistency of thrust modeling.

SOLUTIONS AT FDF

TOPEX/Poseidon operational navigation is supported by TDRSS, which consists of a set of five geostationary relay spacecraft, called TDRSs, the White Sands Ground Terminal (WSGT) located at White Sands, New Mexico and the Bilateration Ranging Transponder System (BRTS). Routinely, TOPEX/Poseidon is supported by two of the five TDRSs, an "east" and a "west" TDRS, which provide two-way range and one-way and two-way Doppler tracking measurements, as well as spacecraft commanding and telemetry support. BRTS provides ground-based range and two-way Doppler measurements for use in TDRS orbit determination.

The FDF generates OOD solutions for TOPEX/Poseidon using the GTDS. GTDS uses a batch weighted least-squares estimation algorithm, in conjunction with TDRSS one-way and two-way Doppler tracking measurements, to minimize the summed-squared differences between observed and calculated values of selected tracking measurements over an OOD solution arc. TOPEX/Poseidon range measurements are excluded from the solutions because of current limitations in solving for uncorrected biases which have been found to reduce the orbit solution quality. The estimated parameters consist of the TOPEX/Poseidon position, and velocity, onboard ultrastable oscillator frequency bias and drift, and a single along-track thrust scaling parameter. TDRS OOD solutions are generated prior to and separately from the TOPEX/Poseidon OOD solutions using BRTS tracking measurements. The TDRS OOD solutions are then used in generating the TOPEX/Poseidon OOD solutions.

DATA TRANSFER TO JPL

EPV state vectors are transmitted from GSFC/FDF to JPL via Nascom in series of 4800-bit data blocks with each block containing an EPV message. During routine operations, the TOPEX/Poseidon OOD solution arc is 7 days 10 hours long and OOD is performed every Monday, Wednesday, and Friday. For each of these OOD solutions, four state vectors are transmitted via Nascom in the EPV format to the TOPEX NAVT at JPL. These vectors have epochs at the start and end of the OOD arc, the start of the OOD arc plus 24 hours, and the end of the OOD arc plus 7 days. On Wednesdays, the vector with epoch at the end of the OOD arc plus 7 days is replaced with a vector with epoch at the end of the OOD arc plus 14 days. These vectors are used to monitor the spacecraft ground track and produce trajectory products as well as to quality assure the OOEs generated by the NAVT.

In addition to routine OOD, the FDF provides special OOD support for TOPEX/Poseidon OMMs. TOPEX/Poseidon OMMs occur every 4 to 6 months in the current low-solar-activity environment and are designed to raise the semi-major axis to maintain the groundtrack to within the required ±1 kilometer band. In support of these maneuvers, the FDF generates and delivers a set of premaneuver state vectors and several sets of postmaneuver OOD state vectors to the TOPEX NAVT in addition to the routine OOD. For each OOD maneuver solution, state vectors are delivered with epochs at the start and the end of the OOD arc. These state vectors are used to assist the NAVT in evaluating maneuver performance and calibrating the thrusters.

JPL PROCESSING

An ephemeris file for either TOPEX/Poseidon or a TDRS is generated by DPTRAJ for each set of EPV state vectors provided by GSFC/FDF. In addition to EPV state vectors, other inputs to this process include general navigation input parameters, gravity field coefficients, solar and geomagnetic activity data, polar motion and timing parameters, and anomalous thrust model parameters. All of these inputs are incorporated into the process by the software module GINDRIVE, which produces a Namelist-type file for DPTRAJ.

Each set of EPV state vectors is validated using the generated ephemeris. The first EPV state vector of the set supplies DPTRAJ with its initial epoch and state vector to integrate the satellite's equation of motion over the required time span. For validation, the remaining EPVs are compared with their corresponding state vectors extracted from the ephemeris.

PROPAGATION MODELS

The following are the major force models used in DPTRAJ and GTDS for TOPEX/Poseidon (Models used as a rapid preliminary orbit propagation tool to condition maneuver requirements for subsequent precision prediction can be found in Ref. 6):

- Geopotential Model

The model that had been used during the pre-launch analysis phases was Goddard Earth Model (GEM)-T3. Subsequently, a slightly refined version of GEM-T3, referred to as Joint Gravity Model (JGM)-2, was selected for mission support. JGM-2 models the Earth's geopotential using an expansion of the solution to the Laplace equation, $\nabla^2\Psi(r,\phi,\lambda) = 0$, in spherical harmonics with respect to a body-fixed frame up to degree and order 70. A truncated 20 x 20 version is used for operational navigation because of computational limitation at JPL.

- Luni-Solar Gravity

The gravitational perturbations of the Sun and Moon can be modeled adequately by considering these perturbing bodies as point masses in both systems.

- Solid Earth Tides Model

The solid Earth Tides model provides an adjustment to the quadrupole term of the geopotential model to compensate for the deformation of the solid portion of the Earth induced by the combined tidal effects of the Sun and the Moon. The model includes a lag angle between the azimuthal component of the position of the disturbing body and the stretching axis. The model also includes a Love number which serves as a proportionality constant for the effect. As implemented in GTDS and DPTRAJ, the model yields an additive adjustment to the gravitational force on the spacecraft.

- Atmospheric Drag

The greatest influence of atmospheric drag on TOPEX/Poseidon is the orbital decay in terms of semi-major axis reduction. It is modelled as a function of atmospheric density and the velocity of the satellite relative to the atmosphere. Density is a conflicated function of solar and geomagnetic activity, satellite geometric parameters, and diurnal, annual, and latitudinal-seasonal variations. Both DPTRAJ and GTDS use the same solar and geomagnetic activity data supplied by the National Oceanic and Atmospheric Administration (NOAA). The Jacchia-Roberts atmospheric density model is used in both systems.

- Solar Radiation Pressure:

The solar radiation pressure (SRP) has effects on TOPEX/Poseidon that exceed those of atmospheric drag, however, this perturbation can be modeled reasonably well . The effect of the numerical integration due to the extremely rapid changes in the radiation pressure perturbation when the satellite passes through the Earth's shadow has been investigated. A conical model that allows for no integrator restarts has been implemented in the JPL DPTRAJ software. GTDS does not restart the integration either upon entry to or exit from its cylinder shadow model.

- Variable Mean Area Model

The variable mean area (VMA) model allows for a variable mean spacecraft cross-sectional area for the purpose of computing perturbations due to atmospheric drag and SRP. The model provides for distinct SRP and atmospheric drag area profiles. Either area profile is driven by a parameter called β', which is the compliment of the angle between the Earth-sun vector and the spacecraft orbital angular momentum vector. Based on nominal attitude control, referred to as "full sinusoidal steering yaw", a table of atmospheric drag and SRP cross-sectional area values at integral values of β' has been developed as an input to GTDS and to DPTRAJ. Area values at intermediate points are obtained through linear interpolation. When the spacecraft is under fixed-yaw steering attitude control, the VMA drag area profile is overridden with constant area values.

- Thrusting Effects

Shortly after launch, OD solutions indicated orbital decay levels about 60 times larger than could be explained by atmospheric drag (Ref. 7). Later, orbit trend analysis indicated a presence of body-fixed residual along-track forces comparable to drag which caused either orbital decay or boost depending on the satellite attitude and solar array articulation mode. Consequently, plans with the FDF were made to estimate an along-track thrust τ, instead of the drag multiplier, where the along-track thrust is measured in $(1 + \tau)$ micro Newtons. To ensure the compatibility of thrust modeling between DPTRAJ and GTDS, the NAVT added to the DPTRAJ force model a continuous finite burn with duration equal to the length of the OD arc and force equal to $(1 + \tau)$ micro Newton.

TRAJECTORY COMPARISON TESTS

In all, eleven trajectory comparison tests were conducted in preparation for this paper. They are similar, though not identical, to the tests originally performed during the pre-launch analysis phases of TOPEX/Poseidon. The current set of tests is in line with the present operational support configuration (the configuration has evolved somewhat since the original tests were performed). The tests provide a model-by-model comparison between GSFC and JPL trajectory software. Each test involves propagating for 30 days a single initial state vector independently with DPTRAJ and GTDS. A comparison of the ascending node equator crossing longitude and time of crossing were examined at regular intervals during the 30-day period.

The first test in the series utilized the simplest force model (all perturbations were turned off). With successive tests, various combinations of force models were included. The last test duplicates the operational support configuration.

The tests were as follows:

1. Point mass earth

This test excludes all perturbations; only the point-mass effect of the Earth is modeled. Ephemeris discrepancies will arise only from integration and implementation differences.

2. Earth gravitational perturbations

This test adds to Test 1 terms of the JGM-2 geopotential model up to 20 x 20. Additional ephemeris discrepancies will arise from differences in geopotential model implementation and in inertial to earth-fixed coordinate transformations.

3. Earth, Sun, and Moon gravitational perturbations

This test adds to Test 2 the point-mass effects of the Sun and Moon. Close agreement for this test would confirm consistency in solar and lunar ephemerides.

4. Solid-Earth Tides

This test adds to Test 3 the solid-Earth tides effects on the geopotential. Additional ephemeris discrepancy would be negligible because of the simplicity of the tides model.

5. Expanded Gravity Field

This test adds to Test 4 terms of the JGM-2 geopotential model up to 26 x 26. Ephemeris discrepancy somewhat more than that seen for Test 4 would be expected.

6. Solar Radiation Pressure

This test adds to Test 1 perturbations due to SRP on the satellite. Additional ephemeris discrepancy would arise from shadow model differences (conical umbra for DPTRAJ and cylindrical umbra for GTDS), both directly and from interplay between the shadow crossings and the numerical integrator. In this test, constant spacecraft cross-sectional area is used in the SRP computations. As Ref. (3) indicates, a small difference is expected in this test.

7. Variable Mean Solar Radiation Pressure Area Model

This test adds to Test 6 the VMA model for the SRP. Additional ephemeris discrepancy would be negligible because VMA implementations in DPTRAJ and in GTDS are virtually identical.

8. Atmospheric Drag

This test adds to Test 1 perturbations due to atmospheric drag. The Jacchia-Roberts atmospheric density model is used for both systems. Common solar flux values and geomagnetic indices are input. Additional ephemeris discrepancy would arise from minor implementation differences. In this test, constant spacecraft cross-sectional area is used in the drag computations.

9. Variable Mean Atmospheric Drag Area Model

This test adds to Test 8 the VMA model for the atmospheric drag. Additional ephemeris discrepancy would be negligible because VMA implementations in DPTRAJ and in GTDS are virtually identical.

10. Combined

This test combines all perturbations and modeling configurations used for the operational support of the mission with the exception of thrust modeling. Ephemeris discrepancy must not exceed the allowance prescribed by the error budget.

11. Operational Test

This test incorporates all perturbations and modeling configurations currently used for the operational support of the mission. It adds to Test 10 a thrust model. The need to account for thrust-like perturbations was not identified until after launch.

RESULTS AND FUTURE CONSIDERATIONS

Excellent model-by-model agreement between GTDS and DPTRAJ has been achieved. This allows either system to be used for operational navigation support. Figure (2) shows that differences in Earth-fixed longitude at equator crossings after 30 days were less than 75 centimeters. While good orbit prediction agreement between the two systems was observed, the above figure is not necessarily a worst case. Sometimes longitude difference between the two systems exceeded the 5 meter goal. Figure (3) shows a one-year statistics of the longitude difference.

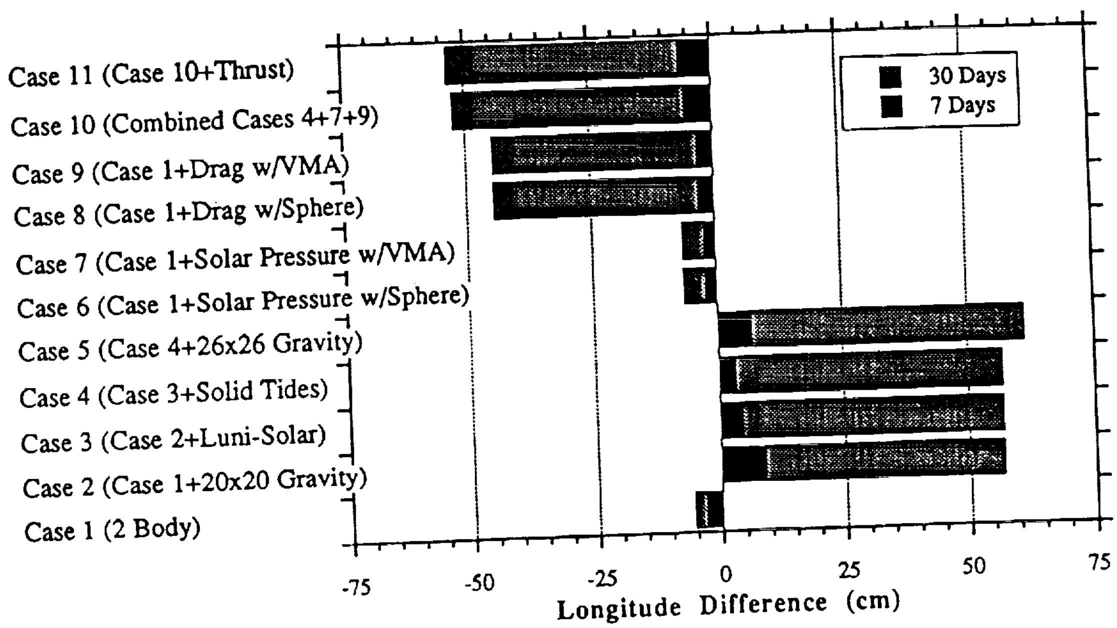

Figure 2. Trajectory Comparison Results
JPL (DPTRAJ) - GSFC (GTDS)

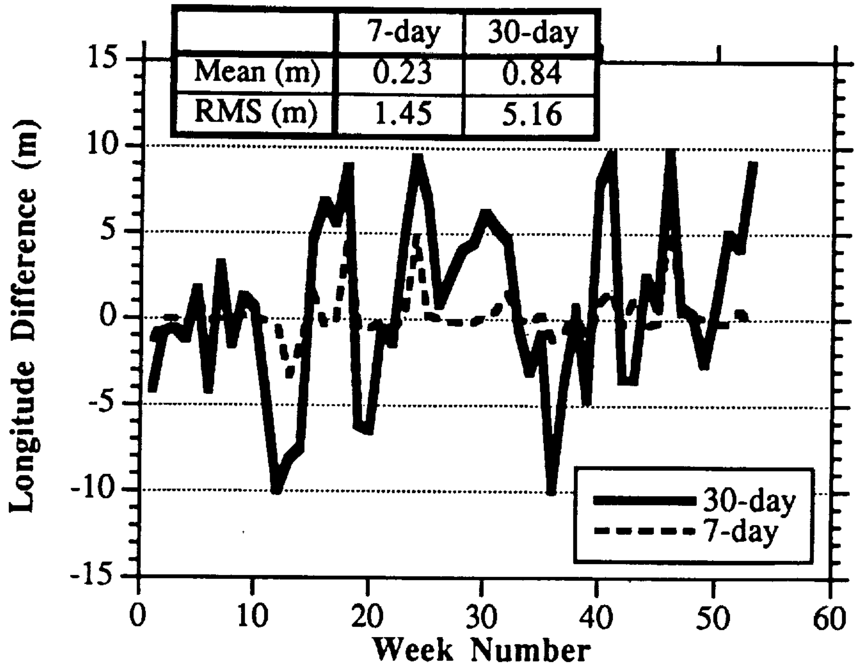

Figure 3. One-Year Trajectory Comparison Results

LESSONS LEARNED

Below are the lessons learned while performing the DPTRAJ/GTDS trajectory comparisons:

Lesson 1: Perform the trajectory calibration analysis as early as possible.

Calibrating any two complex software systems such as DPTRAJ and GTDS can be a tedious and time-consuming process because of the large number of variables involved. Recognizing this fact, the FDF and the NAVT initiated the trajectory calibration effort almost three years before launch. As a result of this early start, both teams had more than sufficient time to identify, analyze and correct several discrepancies between DPTRAJ and GTDS.

Lesson 2: When software is developed, all constants should be user modifiable.

When performing a trajectory calibration analysis, it is critically important to ensure that both software systems use the same modeling constants. It is equally important that the user be able to easily modify any constants which must be changed for compatibility. In the case of the DPTRAJ/GTDS trajectory calibration, most modeling constants were easily modified, since the constants where input by the user and not hardcoded within the software. Had the constants been hardcoded, the trajectory calibration analysis would have required significantly more time and effort.

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