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# Flight Dynamics Facility Operational Orbit Determination Support for the Ocean Topography Experiment*

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## ABSTRACT

The Ocean Topography Experiment (TOPEX/POSEIDON) mission is designed to determine the topography of Earth's sea surface across a 3-year period, beginning with launch in June 1992. TOPEX/POSEIDON is a joint venture between the French Centre Nationale d'Etudes Spatiales (CNES) and the United States National Aeronautics and Space Administration (NASA). The Jet Propulsion Laboratory (JPL) has been designated as NASA's TOPEX project center. However, the Goddard Space Flight Center (GSFC) Dynamics Facility (FDF) has the capability to operationally receive and process Tracking and Data Relay Satellite System (TDRSS) tracking data. Because these data will nominally be used to support the day-to-day orbit determination (OD) aspects of the TOPEX mission, the GSFC FDF has been designated to perform TOPEX operational OD.

The scientific data, by their nature, require stringent OD accuracy in navigating the TOPEX spacecraft. The OD accuracy requirements fall into two categories: (1) on-orbit free-flight and (2) maneuver. The maneuver OD accuracy requirements are of two types: (a) premaneuver planning and (b) postmaneuver evaluation. Analysis using the Orbit Determination Error Analysis System (ODEAS) covariance software has shown that, during the first postlaunch mission phase (Assessment Phase) of the TOPEX mission, some postmaneuver evaluation OD accuracy requirements cannot be met.

ODEAS results also show that the most difficult requirements to meet are those that determine the change in the components of velocity for postmaneuver evaluation. Additional ODEAS analysis is currently in progress to determine whether the postmaneuver evaluation requirements can be met by considering only those changes in velocity caused by changes in orbital elements that will result from a maneuver.

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# 1. INTRODUCTION

## 1.1 MISSION OVERVIEW

The Ocean Topography Experiment (TOPEX)/POSEIDON mission is a collaborative research effort of the United States National Aeronautics and Space Administration (NASA) and the French Centre Nationale d'Etudes Spatiales (CNES) and is designed to study the topography of the Earth's oceans over a period of 3 years. The information in this paper was derived primarily from Reference 1. Exceptions are noted throughout the paper.

Although, technically speaking, TOPEX refers to the NASA payload and POSEIDON refers to the CNES payload, use of the term TOPEX throughout this paper will imply both the TOPEX and POSEIDON payloads, unless otherwise stated. The TOPEX satellite, which is being built by Fairchild Space Systems Division (FSSD), is scheduled for a June 1992 launch by an Ariane 42P expendable launch vehicle from Kourou, French Guyana.

The overall goal of the TOPEX mission is to measure the height of the Earth's oceans, using radar altimetry, to increase knowledge of oceanic circulation and provide for improved models of ocean dynamics. Detailed mission goals include the following (see Reference 2 for more details):

- Measure the sea level to allow the study of ocean dynamics, including the calculation of the mean and variable surface geostrophic currents and the tides of the world's oceans
- Process and verify the scientific data and distribute them in a timely manner, together with other geophysical data, to the principal investigators
- Lay the foundation for a continuing program to provide long-term observations of the oceanic circulation and its variability

The TOPEX spacecraft will not be launched directly into its operational orbit; rather, it will be injected into a biased orbit and then, through a series of maneuvers, placed into operational orbit. The currently planned operational orbit requires a 10-day repeatable ground track to an accuracy of $\pm 1$ kilometer (km), with a 66.018 degree (deg) inclination, a semimajor axis of 7,714.408 km and an eccentricity of 0.00008.

The TOPEX spacecraft attitude is three-axis stabilized, Earth-pointing, and it rotates one revolution per orbit. In addition, the single solar array panel pitches to maintain its position with respect to the Sun.

During normal operations, the Tracking and Data Relay Satellite System (TDRSS) will be used for commanding, telemetry, and tracking functions. The Deep Space Network (DSN) 26-meter subnet will be used to support these functions during the TOPEX launch and during spacecraft emergency or contingency situations. A spacecraft emergency is an event in which the loss of the mission or spacecraft is possible. A spacecraft contingency is an event in which the mission cannot be successfully completed using TDRSS services.

The mission is scheduled to last 3 years after launch, with a possible extension of 2 additional years. The mission's phases are launch, assessment, initial verification, observational, and extended observational. The definitions and activities of each phase are summarized in Table 1.

## Table 1. Mission Phases and Activities

| Phase/Definition | Activities |
|---|---|
| Launch Phase<br>From shipment of spacecraft (S/C) to launch site to injection of S/C into biased orbit | Prelaunch testing at Kourou<br>Injection into biased orbit<br>Orientation of S/C and deployment of the solar panel |
| Assessment Phase<br>First 30-35 days after injection into biased orbit, or until the S/C is placed in operational orbit | Check out S/C functions<br>Turn on and check out sensors<br>Move S/C to operational orbit<br>Complete assessment within 35 days |
| Initial Verification Phase<br>From end of assessment phase to 6 months after launch | Direct overflights of NASA and CNES verification sites<br>Intensive analysis of sensor performance<br>Verification within 6 months; finalized with a verification report<br>Development of TOPEX geopotential model [by Precision Orbit Determination (POD) group, Code 600] |
| Observational Phase<br>From end of initial verification phase to 3 years after launch | Continuous, routine collection of sensor data<br>Process data with verified algorithms and precision orbits to end of mission<br>Ground track maintenance maneuvers<br>Distribution of sensor data to principal investigators |
| Extended Observational Phase<br>From end of observational phase to 5 years after launch | Same as in the observational phase |

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Because the orbit determination (OD) requirements for the three post-assessment phases—initial verification, observational, and extended observational—are the same, the term "observational phases" will be used to characterize the requirements for all mission phases beyond the assessment phase.

## 1.2 SPACECRAFT DESCRIPTION

Figure 1 illustrates the TOPEX/POSEIDON spacecraft's deployed configuration, showing the approximate location of some of the scientific instruments and support systems. The spacecraft consists of two modules: the TOPEX/POSEIDON Instrument Module (IM), which contains the scientific instruments, and the Multimission Modular Spacecraft (MMS) bus, which includes the onboard attitude determination and control, communications, propulsion, and power subsystems. The spacecraft bus has a mass of about 2,650 kilograms (kg), an overall length of about 5.4 meters (m), and a diameter less than 3.8 m.

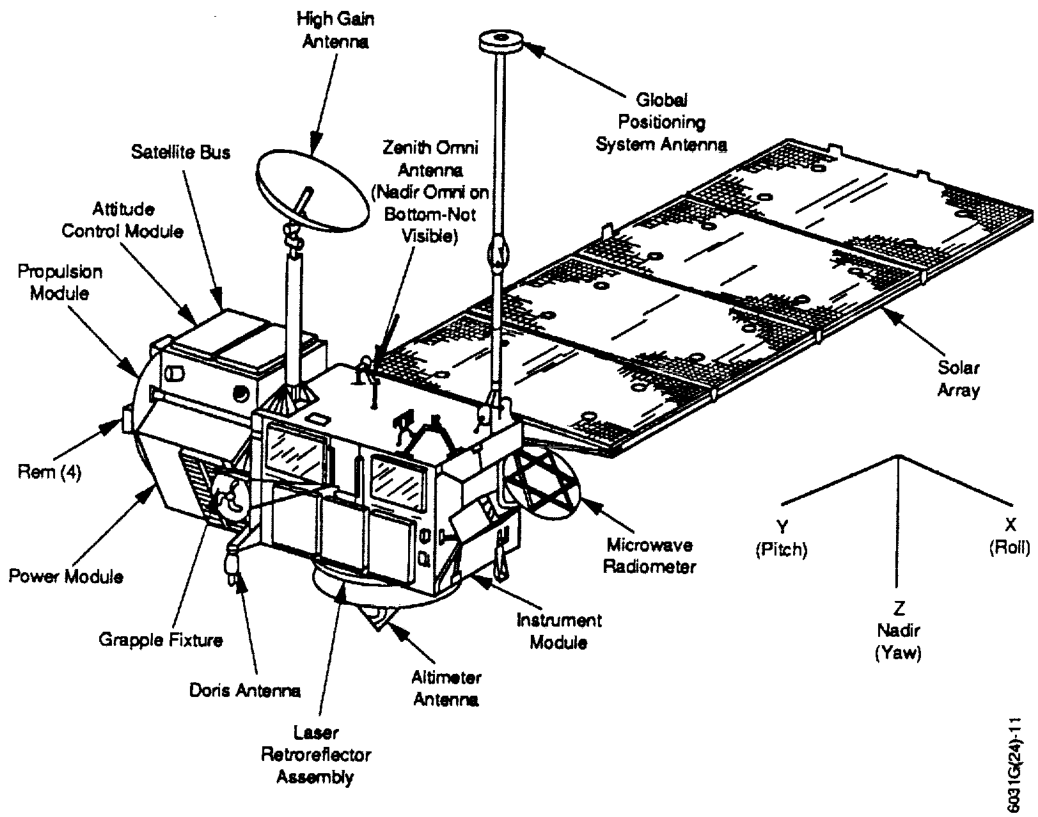


**Figure 1. TOPEX Satellite Deployed Configuration**

The IM is made up of the TOPEX (NASA) payload and the POSEIDON (CNES) payload.

Table 2 describes the instruments in the TOPEX payload; Table 3 describes the instruments in the POSEIDON payload; and Table 4 describes each subsystem of the MMS bus.

# 2. OPERATIONAL SUPPORT OVERVIEW

## 2.1 JPL RESPONSIBILITIES

The Jet Propulsion Laboratory (JPL) has been designated as the NASA TOPEX project center and will be responsible for

- Mission operations planning, including maneuver planning
- Flight operations control, which will be performed by the TOPEX Project Operations Control Center (POCC)
- Processing and distribution of the scientific data.

## Table 2. TOPEX Payload Description

| Instrument | Purpose |
|---|---|
| Dual-frequency radar altimeter | Provide altimeter measurements (Ku-band)<br><br>Provide ionospheric correction to the altimeter measurements (C-band) |
| Three-channel microwave radiometer | Provide wet tropospheric correction to the altimeter measurements |
| Laser Retroreflector Array (LRA) | Provide laser ranging data for height calibration and precision tracking |
| Global Positioning System Demonstration Receiver (GPSDR) | Provide experimental POD data |
| Frequency Reference Unit (FRU) | Provide a timing source for the GPSDR, TDRSS, and DSN |

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## Table 3. POSEIDON Payload Description

| Instrument | Purpose |
|---|---|
| Solid-state experimental radar altimeter | Provide altimeter measurements (Ku-band) |
| Determination of Orbit Radiopositioning Integrated from Satellite (DORIS) dual-frequency Doppler tracking system receiver | Provide Doppler-based POD data |

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Table 4. MMS Bus Description

| Subsystem | Purpose |
|---|---|
| Radio frequency communications subsystem (RFCS) | Handles spacecraft radio frequency (RF) communications as well as ranging and Doppler functions |
| Command and data handling subsystem (CDHS) | Processes spacecraft commands and telemetry, including data recording and playback functions |
| Attitude determination and control subsystem (ADCS) | Maintains spacecraft attitude |
| Propulsion subsystem (PS) | Provides fuel and thrusters for attitude and orbit control |
| Signal conditioning and control unit (SC&CU) | Provides command/telemetry, heater control, and pyrotechnic control interface functions |
| Electrical power subsystem (EPS) | Derives raw power from the solar array mounted on the IM |
| Thermal control subsystem (TCS) | Monitors and controls the thermal properties of the spacecraft |

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The TOPEX POCC will be the interface with the FDF for operationally navigating the TOPEX spacecraft.

## 2.2 GSFC/FDF RESPONSIBILITIES

The GSFC/FDF is a TOPEX support center whose primary responsibility will be to perform operational OD for TOPEX. This designation was made because the FDF has the capability to operationally receive and process TDRSS tracking data, which will nominally be used to support the TOPEX mission. TOPEX OD support includes performing definitive OD and performing orbit predictions for quality assurance, acquisition data generation, and scheduling purposes. The JPL POCC support will consist of using the FDF's OD solution to perform operational orbit predictions for mission planning. According to the current plan, JPL will perform all attitude-related support and all mission analysis and maneuver support (exclusive of OD).

FDF support activities for the various mission phases are described below:

- *Prelaunch*: Support during this period will consist of requirements analysis, system definition and specification, software development, software testing, interface testing, and mission simulation activities.

- *Launch*: The FDF support will consist of monitoring the Launch Trajectory Acquisition System (LTAS) data from the Ariane launch vehicle.

- *Assessment*: During this period, the FDF will provide pre- and postmaneuver OD support to move the spacecraft from the biased orbit to the operational orbit; it will also provide orbit product support.
- *Initial Verification*: During this period, the FDF will provide routine OD, generate orbit products, and support pre- and postmaneuver OD for periodic ground-track maneuvers necessary to maintain the operational orbit.
- *Observational and Extended Observational*: The FDF will support the same activities described in the initial verification phase.

# 3. ORBIT DETERMINATION ACCURACY REQUIREMENTS

## 3.1 MANEUVER SUPPORT REQUIREMENTS

Orbit maneuvers will take place in the assessment and the observational phases; however, the purpose of the maneuvers will be different. In the assessment phase, the TOPEX spacecraft will be moved from its biased orbit into its operational orbit through a series of maneuvers, spaced roughly 3 days apart, over a period of approximately 20 days. In the observational phases, maneuvers will be performed approximately every 30 days to maintain the 10-day repeat groundtrack cycle for the operational orbit.

Three different types of maneuvers—coarse, calibration, and precision—will support the TOPEX mission. Coarse maneuvers are high-thrust, performed only in the assessment phase and used to move the spacecraft from the biased orbit into the operational orbit. Here, high thrust means the change in the velocity resulting from the maneuver will be greater than 100 millimeters/second. Calibration maneuvers are equivalent to coarse maneuvers, except they will be used to calibrate the thrusters. Precision maneuvers are low-thrust maneuvers and will be performed in the last stages of the assessment phase to achieve the operational orbit. Low thrust means the change in the velocity resulting from the maneuver will be less than 100 millimeters/second. Precision maneuvers will also be performed in the observational phases to maintain the spacecraft groundtrack.

For each maneuver type, the TOPEX project has defined a set of premaneuver planning requirements and a set of postmaneuver evaluation requirements. Requirements for premaneuver planning OD define constraints on the accuracy of the osculating orbital parameters at the maneuver ignition. It should be noted that these requirements need to be met 24 hours prior to maneuver ignition. Therefore, an OD solution must be obtained 24 hours prior to maneuver ignition, and then propagated up to the maneuver ignition. Postmaneuver evaluation OD requirements involve constraints on osculating orbital parameter changes that may arise from velocity increments at the maneuver time. These requirements must be met 24 hours after the maneuver burnout. Tables 5 and 6 give the operational OD requirements for maneuver planning and maneuver evaluation (Reference 3), respectively. Note that the requirements for the precision maneuver are independent of mission phase.

## 3.2 ON-ORBIT SUPPORT REQUIREMENT

In addition to maneuver OD support, on-orbit free-flight OD will also be performed during the observational phases. This on-orbit, or routine, support consists of performing OD on a

**Table 5. TOPEX OD Requirements on Predicted Osculating Elements Used in Premaneuver Planning**

| Parameter | Calibration Maneuver | Coarse Maneuver | Precision Maneuver |
|---|---|---|---|
| Semimajor axis (m) | None | None | 1 |
| Period (msec) | 4 | 4 | None |
| Eccentricity | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ | $5 \times 10^{-6}$ |
| Inclination (deg) | $1 \times 10^{-3}$ | $1 \times 10^{-3}$ | $1 \times 10^{-4}$ |
| Argument of latitude equivalent along track error (m) | 670 | None | None |

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**Table 6. TOPEX OD Requirements on Postmaneuver Evaluation of Changes in Osculating Parameters**

| Parameter | Calibration Maneuver | Coarse Maneuver | Precision Maneuver |
|---|---|---|---|
| Radial velocity (mm/sec) | | | |
| 5.0 lbf thruster | 10 | 10 | N/A |
| 0.2 lbf thruster | 2 | N/A | 2 |
| Cross-track velocity (mm/sec) | | | |
| 5.0 lbf thruster | 20 | 20 | N/A |
| 0.2 lbf thruster | 10 | N/A | 10 |
| Along-track velocity (mm/sec) | | | |
| 5.0 lbf thruster | 4 | 4 | N/A |
| 0.2 lbf thruster | 0.1 | N/A | 0.1 |
| Inclination (deg) | None | $5 \times 10^{-4}$ | $1 \times 10^{-4}$ |
| Semimajor axis (m) | None | None | 0.2 |

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weekly basis using maneuver-free tracking data. The solution resulting from this 7-day OD arc will be used by JPL to perform long-term (30-day) predictions for mission planning purposes. Table 7 presents the single routine support requirement.

**Table 7. TOPEX Requirement on Long-Term Predictions for the Observational Phases**

| Parameter | On-orbit requirement |
|---|---|
| Equator longitude crossing (m) | 225 m after 30 days of prediction past end of data span assuming no errors in solar flux in the predicted interval |

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## 4. ERROR ANALYSIS RESULTS

The Orbit Determination Error Analysis System (ODEAS) was used to estimate the OD capabilities corresponding to the requirements given in Section 3.0. These capabilities are a result of simulations using a weighted Baysian least squares process.

Two 3-sigma error models have been used in this analysis. The first, referred to as the nominal error model (Table 8), represents the 1990 capabilities of the GTDS program to support the TOPEX mission. The second model, called the optimistic error model, assumes zero errors in the Earth mass constant (GM) and geopotential field. It also assumes station location component uncertainties of 1 meter. These two models give bounds on the expected OD capabilities.

Table 9 presents the requirements and the corresponding maneuver planning OD capabilities using a 3-day definitive period and a 24-hour prediction. The only requirement that is not met involves the semi-major axis in conjunction with the nominal error model. Failure to meet this constraint is a result of the uncertainty in the gravitational field of the Earth, which uses the GEM 9 model. The a priori sigma for this error source will be reduced substantially with the use of the GEM T2 gravity field representation, which is currently available and is expected to be incorporated into GTDS by the time of launch. It is therefore reasonable to assume that all requirements on osculating elements for maneuver planning will be achieved.

Before discussing the postmaneuver evaluation OD analysis results, it is important to note that the JPL perceived the need for a math process corresponding to that used for maneuver evaluation of deep space trajectories. This process assumes a data span that includes tracking data before and after a maneuver and solves for the epoch state vector at the beginning of the data span and velocity increments at the time of the maneuver. Currently, the ODEAS covariance program does not have the capability to model maneuvers in this manner.

These ODEAS limitations have introduced the need for a mathematical technique that approximates, as closely as possible, the desired procedure. The selected process assumes

**Table 8. Error Sources and Associated 3-Sigma Uncertainties for the Nominal Error Model**

| Parameter | 3-Sigma Uncertainty | | |
|---|---|---|---|
| GM | GM x (3 x $10^{-7}$) | | |
| Gravity Field | 135%(GEM9 – GEM7)$_{(1,1)}$ THROUGH $_{(21,21)}$<br>PLUS<br>100%(GEM9)$_{(22,22)}$ THROUGH $_{(30,30)}$ | | |
| $C_D$ | 30% when not solved for | | |
| Solar Flux (watts/$m^2$/Hz) | Nominal = 225 | | |
| $C_R$ | | | |
| TOPEX | 30% | | |
| TDRS-E | 2% | | |
| TDRS-W | 2% | | |
| Station Positions<br>Ascension BRTS<br>Alice Springs BRTS<br>White Sands BRTS<br>White Sands GRND | | | |
| Local X | 15 m | | |
| Local Y | 15 m | | |
| Local Z | 30 m | | |
| Troposphere | 45% | | |
| Ionosphere | | | |
| From Stations | 100% | | |
| From TDRS-E | 100% | | |
| From TDRS-W | 100% | | |
| Measurements | Noise | Weight Sigma | Bias |
| BRTS Range (m) | 1.5 | 3.0 x $10^{-4}$ | 7.0 |
| TDRSS Range (m) | 1.5 | 90.0 | 7.0 |
| TDRSS R/R (mm/sec) | | | |
| 2-Way | 2.82 | 100.0 | 0.0 |
| 1-Way | 4.00 | 4.0 | 0.0 |

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**Table 9. OD Requirements and Capabilities on Predicted Osculating Parameters Used in Maneuver Planning**

Definitive period = 3 days
Solar flux = 225

| Parameter | Maximum 3-Sigma Error | | |
|---|---|---|---|
| | Most Stringent Requirement | Capability | |
| | | Nominal | Optimistic |
| Semimajor axis (m) | 1 | 3.0 | 0.1 |
| Period (msec) | 4 | 3.9 | 0.1 |
| Eccentricity | $5 \times 10^{-6}$ | $0.7 \times 10^{-6}$ | $0.4 \times 10^{-6}$ |
| Inclination (deg) | $1 \times 10^{-4}$ | $0.6 \times 10^{-4}$ | $0.2 \times 10^{-4}$ |
| Along track (m) | 670 | 29 | 16 |

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instantaneous maneuvers and involves the differencing, parameter-by-parameter, of two error budgets at the time of the maneuver. The first error budget is obtained from tracking data covering only the postmaneuver time interval. The second error budget is obtained from tracking data covering only the premaneuver time interval.

Table 10 summarizes the requirements and OD capabilities for postmaneuver evaluation of the errors in the changes of parameters. The results indicate that the nominal error model produces change-of-parameter errors that are larger than the requirements for all parameters except the inclination. The optimistic error model produces errors in the changes of parameters that exceed the requirements for only the radial and along-track components of velocity. All results are based on 3 days of premaneuver tracking data and 24 hours of postmaneuver tracking data.

Additional analysis is currently in progress to determine the error in the components of velocity assuming the errors were limited to those associated with the orbit elements. Preliminary results show that the errors in the along-track component noted in Table 10 are reduced from 2.8 and 2.4 millimeters/second for the nominal and optimistic models to 0.18 and 0.06, respectively. These latter values meet, or only slightly exceed, the requirement of 0.1 millimeters/second noted in Table 10. Additional simulations, which assume a lower mean value of solar flux, indicate a corresponding reduction in the errors of all parameters.

Table 11 presents the requirement and orbit prediction capability for the error in the equator longitude crossing. As can be seen, the requirement is easily met. For a complete description of the analysis procedures, see References 4 and 5.

**Table 10. OD Requirements and Capabilities on Postmaneuver Evaluation of Changes in Osculating Parameters**

Premaneuver orbit = 3 days
Solar flux = 225

| Parameter | Maximum 3-Sigma Error | | |
|---|---|---|---|
| | Most Stringent Requirement | Capability | |
| | | Nominal | Optimistic |
| Velocity (mm/sec) | | | |
| Radial | 2.0 | 13.0 | 8.9 |
| Cross track | 10.0 | 14.0 | 7.1 |
| Along track | 0.1 | 2.8 | 2.4 |
| Inclination (deg) | $1.0 \times 10^{-4}$ | $0.6 \times 10^{-4}$ | $0.3 \times 10^{-4}$ |
| Semimajor axis (m) | 0.2 | 0.39 | 0.12 |

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**Table 11. Orbit Prediction Requirement and Capability for the Error in the Longitude of the Equator Crossing**

| Parameter | Maximum 3-Sigma Error | | |
|---|---|---|---|
| | Requirement | Capability | |
| | | Nominal | Optimistic |
| Equator longitude crossing after 30 days prediction past the data span (m) | 225 | 40 | 30 |

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## 5. CONCLUSIONS

The error analysis results using the ODEAS program supports the following conclusions:

- All premaneuver planning OD requirements on the predicted osculating elements can be met using a 3-day OD arc with a 24-hour prediction.
- Some postmaneuver evaluation OD requirements cannot be met using a 3-day premaneuver OD arc and a 24-hour postmaneuver arc.
- The long-term (30-day) prediction requirement for the equator longitude crossing can be met.

The above conclusions are based on the results using the optimistic error model, which assumes zero errors in the geopotential model and station location position errors of 1 m. In truth, the errors associated with the GEM T2 geopotential model, to be used for TOPEX operational support, lie somewhere between the nominal and the optimistic model errors. However, based on preliminary analysis results, the GEM T2 geopotential errors are closer to the optimistic model errors than to the nominal model errors.

## 6. ACKNOWLEDGMENTS

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