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# TOPEX/POSEIDON mission overview

Lee-Lueng Fu, Edward J. Christensen, and Charles A. Yamarone Jr.
Jet Propulsion Laboratory, California Institute of Technology, Pasadena

Michel Lefebvre, Yves Ménard, Michel Dorrer, and Philippe Escudier
Centre National d'Etudes Spatiales, Toulouse, France

**Abstract.** TOPEX/POSEIDON is the first space mission specifically designed and conducted for studying the circulation of the world's oceans. The mission is jointly conducted by the United States and France. A state-of-the-art radar altimetry system is used to measure the precise height of sea level, from which information on the ocean circulation is obtained. The satellite, launched on August 10, 1992, has been making observations of the global oceans with unprecedented accuracy since late September 1992. To meet the stringent measurement accuracy required for ocean circulation studies, a number of innovative improvements have been made to the mission design, including the first dual-frequency space-borne radar altimeter capable of retrieving the ionospheric delay of the radar signal, a three-frequency microwave radiometer for retrieving the signal delay caused by the water vapor in the troposphere, an optimal model of the Earth's gravity field and multiple satellite tracking systems for precision orbit determination. Additionally, the satellite also carries two experimental instruments to demonstrate new technologies: a single-frequency solid-state altimeter for the technology of low-power, low-weight altimeter and a Global Positioning System receiver for continuous, precise satellite tracking. The performance of the mission's measurement system has been tested by numerous verification studies. The results indicate that the root-sum-square accuracy of a single-pass sea level measurement is 4.7 cm for the TOPEX system and 5.1 cm for the POSEIDON system; both are more than a factor of 2 better than the requirement of 13.7 cm. This global data set is being analyzed by an international team of 200 scientists for improved understanding of the global ocean circulation as well as the ocean tides, geodesy, and geodynamics, and ocean wind and waves. The mission is designed to last for at least 3 years with a possible extension to 6 years. The multiyear global data set will go a long way toward understanding the ocean circulation and its variability in relation to climate change. A summary of the mission's systems and their performance as well as the mission's science team is presented in the paper.

## 1. Introduction

On August 10, 1992, the TOPEX/POSEIDON satellite was launched by an Ariane 42P rocket from the European Space Agency's Guiana Space Center in French Guiana. This space mission is conducted jointly by the United States National Aeronautics and Space Administration (NASA) and the French space agency, Centre National d'Etudes Spatiales (CNES). Using a state-of-the-art radar altimetry system, the satellite measures the precise height of the sea surface for studying the dynamics of the circulation of the world's oceans. The main science goal of the mission is to improve the knowledge of the global ocean circulation to an extent that will ultimately lead to improved understanding of the ocean's role in global climate change. Other applications include the ocean tides, geodesy and geodynamics, ocean wave height, and wind speed.

The scientific utility of satellite altimetry has been demonstrated by the Seasat mission (*Journal of Geophysical Research*, *87*(C5), 1982, and *88*(C3), 1983) and the Geosat mission (*Journal of Geophysical Research*, *95*(C3) and (C10), 1990). Also orbiting in space today is another radar altimeter aboard the European Space Agency's ERS 1 satellite [*Wakker et al.*, 1993]. Many interesting and useful results about ocean circulation have been obtained from these missions. However, the data from these missions were not sufficiently accurate for addressing many aspects of the large-scale ocean circulation because none of the missions were specifically designed and conducted for studying ocean circulation as is TOPEX/POSEIDON. To be useful for studying ocean circulation, especially at the gyre and basin scales, numerous improvements have been made in TOPEX/POSEIDON, including specially designed satellite, sensor suite, satellite tracking systems, and orbit configuration, as well as the development of an optimal gravity model for precision orbit determination and a dedicated ground system for mission operations. Another unique aspect of the mission was the formation of a Science Working Team early in the mission planning phase (5 years before launch) to ensure a close dialog between the science users and the mission development team.

Within 43 days from launch the mission's operation team completed satellite and sensor check out as well as the

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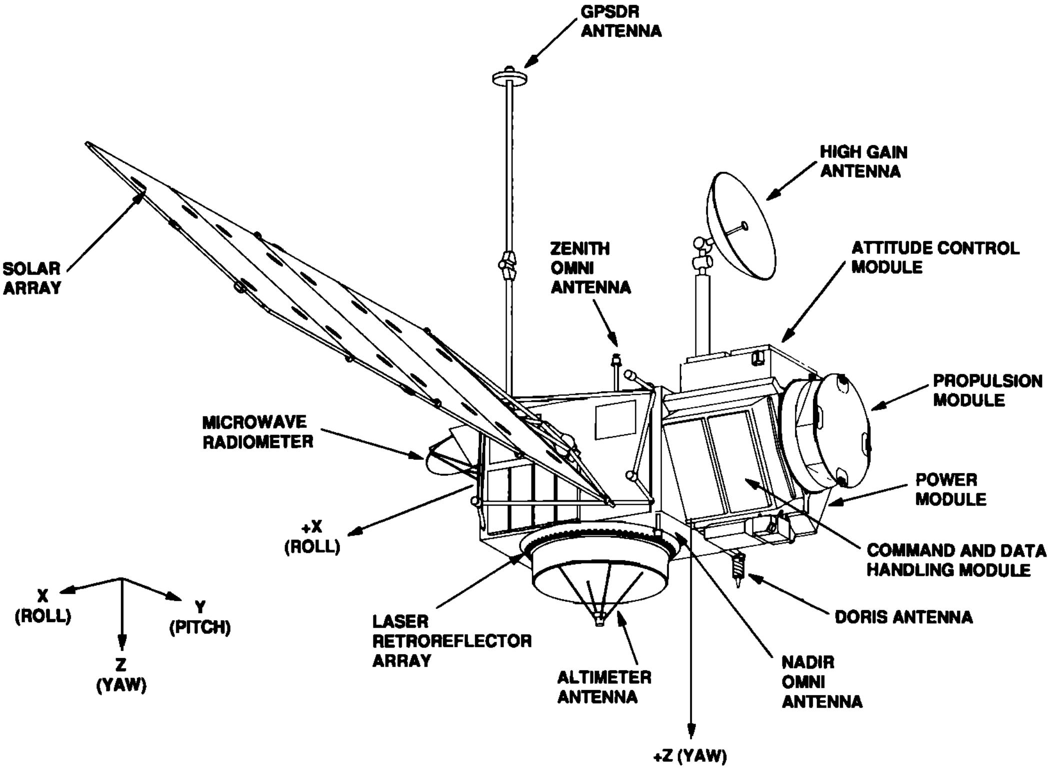

**Figure 1.** The TOPEX/POSEIDON satellite in its fully deployed configuration. The positive $x$ axis points toward the flight direction.

adjustment of the injection orbit into the operational orbit. Collection of science data began on September 23, 1992. Since then the satellite has been orbiting the Earth at an altitude of 1336 km with an inclination of 66 degrees, making sea surface height measurements along the same surface tracks, within ±1 km, every 10 days. The mission was designed to operate for a minimum of 3 years, with sufficient expendables carried to allow a 2-year extended mission if the satellite and sensors are still functioning properly at the end of the primary mission. Plans are also being developed for a 3-year extended mission.

During the first 6 months of the mission, the primary objective was to calibrate the mission's measurement system and verify its performance. The TOPEX/POSEIDON project established two dedicated sites for this calibration/verification effort: Point Conception off the coast of California, and Lampedusa Island in the Mediterranean Sea. Verification campaigns have also been conducted by the Science Working Team at a number of sites around the world. During this verification phase, the mission's Precision Orbit Determination Team used the various satellite tracking data to fine tune the gravity field model and other force models, as well as satellite tracking station coordinates for computing the precise orbit for the mission.

The verification phase was completed at the end of February 1993. A workshop involving the mission engineers and scientists was held then to review the verification results. The conclusions of the workshop indicated that all the measurement accuracy requirements had been met and many of the measurement performances had exceeded requirements. After minor modifications of the science algorithms based on the workshop results, the mission's ground system began processing and distribution of the geophysical data record (GDR), the baseline science data product of the mission, in late May 1993.

This paper provides a summary of the mission's major elements and the results of the verification phase, including an overall assessment of the mission's measurement performance. It is intended to serve as an overall reference for the other papers collected in this special issue.

## 2. The Satellite

The TOPEX/POSEIDON satellite is an adaptation by Fairchild Space of the existing Multimission Modular Spacecraft (MMS), which has successfully carried the payloads of the Solar Maximum Mission, Landsat 4 and Landsat 5. The MMS design was modified to meet the TOPEX/POSEIDON requirements. The satellite consists of the MMS bus and the instrument module which houses the instrument complement. Shown in Figure 1 is the fully deployed TOPEX/POSEIDON satellite featuring the major modules, sensors, and antennas.

Within the MMS, the command and data handling subsystem includes the on-board computer and tape recorder and provides control for all satellite engineering subsystems and sensors. The attitude determination and control subsystem and the propulsion subsystem control the satellite attitude and perform orbit-adjust maneuvers throughout the mission. The electrical power subsystem on the MMS provides power from the solar array and batteries to the satellite systems for the duration of the mission. The solar array is mounted to the instrument module, and its motion is controlled by the solar array drive assembly. The radio frequency communications subsystem includes the high-gain antenna and the omnidirectional antennas and provides forward- and return-link telecommunication capability. The satellite uses the Tracking and Data Relay Satellite System (TDRSS) for communications with the Project Operation Control Center at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology at Pasadena, California.

## 3. Science Instruments

There are six science instruments in the mission's payload, four from NASA and two from CNES. They are divided into operational and experimental sensors as follows. (1) Operational sensors: dual-frequency radar altimeter (ALT) (NASA); TOPEX microwave radiometer (TMR) (NASA); laser retroreflector array (LRA) (NASA); and Doppler orbitography and radiopositioning integrated by satellite (DORIS) dual Doppler tracking system receiver (CNES). (2) Experimental sensors: single-frequency solid-state radar altimeter (SSALT) (CNES); and Global Positioning System (GPS) demonstration receiver (GPSDR) (NASA).

The ALT, which is the first spaceborne dual-frequency altimeter, is the primary instrument for the mission [*Zieger et al.*, 1991; *Hayne et al.*, this issue]. The measurements made at two frequencies (5.3 and 13.6 GHz) are combined to minimize the errors caused by the ionospheric free electrons, of which the total content is obtained as a by-product of the measurement. The ALT was developed and built by the Applied Physics Laboratory of the Johns Hopkins University (APL/JHU) under contract to the Wallops Flight Facility of NASA's Goddard Space Flight Center (GSFC) on behalf of JPL. The ALT design is based on the previous Seasat and Geosat altimeters with significant improvements including the 5.3 GHz channel for the ionospheric measurement, a more precise height measurement, and longer lifetime.

The TOPEX microwave radiometer (TMR) makes use of the measurement of sea surface microwave emissivity at three frequencies (18, 21, and 37 GHz) to estimate the total water vapor content in the atmosphere; this estimate is used to correct for the water vapor-induced errors in the altimeter measurement. The 21-GHz channel is the primary channel for water vapor measurement. The 18-GHz and 37-GHz channels are used to remove the effects of wind speed and cloud cover, respectively, on the water vapor measurement. The TMR was developed and built by JPL's Observational Systems Division [*Ruf et al.*, this issue].

The Laser retroreflector array (LRA) built by APL/JHU under contract to JPL is used with a network of satellite laser ranging (SLR) stations managed by GSFC to provide satellite tracking data for precision orbit determination (POD) and calibration of the radar altimeter bias.

The DORIS tracking system of CNES provides another type of satellite tracking data using microwave Doppler techniques [*Nouel et al.*, 1988, this issue]. The system is composed of an on-board receiver and a network of ground transmitting stations. These stations, equipped with meteorological sensors measuring temperature, humidity, and atmospheric pressure for correcting for the atmospheric effects on the transmitted signals provide a quasi-continuous tracking of the satellite (80% of the time).

Both the SLR and DORIS data are used in the POD process, including gravity model tuning. The DORIS signals are transmitted at two frequencies (401.25 and 2036.25 MHz) to allow the removal of the effects of the ionospheric free electrons on the tracking data (N. Picot and P. Escudier, unpublished manuscript, 1994). Therefore the total content of the ionospheric free electrons can also be estimated from the DORIS data and used for the ionospheric correction for the SSALT. However, the electron content estimate from the DORIS data is based on slant range observation and must be interpolated to the altimeter nadir path, resulting in additional uncertainty in the path delay retrieval.

The two experimental instruments are intended to demonstrate new technologies. The successful operation of the SSALT, a solid-state Ku-band (13.65 GHz) altimeter, has validated the technology of a low-power, low-weight altimeter for future Earth-observing missions (O. Zanife et al., unpublished manuscript, 1994). It shares the same antenna with the ALT. Therefore the two altimeters cannot operate at the same time. During the initial 6-month verification phase of the mission, the CNES altimeter operated for 12.5% of the time to assess its performance. This 12.5% of operation time was optimized for the overflight of the SSALT over the two verification sites. Since the completion of the verification phase, the SSALT has been operating for one complete 10-day cycle approximately every 10 cycles (see section 5.1). The SSALT was designed by CNES and built by Alcatel Espace.

The GPSDR receives signals from the GPS constellation. With a combination of the GPSDR data and a number of GPS receivers on the Earth's surface, precise, continuous tracking of the satellite is made possible by using the technique of Kalman filtering and differential ranging. The continuous tracking has made POD possible with lesser need of accurate gravity and satellite force modeling. The successful operation of the GPSDR and the excellent quality of the orbit ephemerides produced from the experiment has demonstrated the technology for POD in the future [*Bertiger et al.*, this issue]. The GPSDR was developed and built by Motorola under contract to JPL.

## 4. Orbit Configuration

Many factors influence the determination of the mission's orbit configuration [*Parke et al.*, 1987]. The inclination and repeat period of the orbit determine how the ocean is sampled by the satellite. A major concern is aliasing the tidal signals into the frequencies of ocean current variabilities. Inclinations that lead to undesirable aliased tidal frequencies such as zero, annual, and semiannual, are to be avoided. In order to determine the ocean tidal signals from altimetry data and subsequently remove them from the data for the study of ocean circulation, inclinations that make different tidal constituents aliased to the same frequency should also be avoided. To satisfy these constraints and yet cover most of the world's oceans, an inclination of 66 degrees was selected.

For a single satellite mission, temporal resolution and spatial resolution are in competition: the higher the temporal resolution, the lower the spatial resolution, and vice versa. A repeat period of 9.916 days (nominally referred to as a 10-day repeat period) is the best compromise; it results in an equatorial cross-track separation of 316 km.

To maximize the accuracy of orbit determination, a high

**Table 1.** Characteristics of the Operational Orbit

| Parameter | Value |
|---|---|
| Semimajor axis, km | 7714 |
| Eccentricity | 0.0006 |
| Inclination, deg | 66.0 |
| Reference equatorial altitude, km | 1336 |
| Nodal period, s | 6745.8 |
| Cycle (127 revs) period, days | 9.9156 |
| Inertial nodal rate, deg/d | 2.08 |
| Longitude of equator crossing of pass 1, deg | 99.92 |
| Ground track equatorial spacing, km | 316 |
| Acute angle of equator crossings, deg | 39.5 |

orbit altitude is preferred because of the reduced atmospheric drag and gravity forces acting on the satellite. A major disadvantage of a high orbit is the increased power needed by the altimeter to achieve the required level of signal-to-noise ratio. A compromised orbit altitude is in the range of 1200 to 1400 km. The exact altitude that allows the orbit to satisfy all other constraints and fly over the two verification sites is 1336 km. Shown in Table 1 are the characteristics of the mission's operational orbit.

## 5. Mission Operations

Mission operations (e.g., satellite control and data processing) are conducted by JPL at Pasadena, California. CNES has implemented an Information Processing Center at Toulouse, France, for CNES sensor control and data processing via an interface with the ground system at JPL. A top priority for mission operations is to maximize the collection of high-quality data and to process and distribute them in a timely manner. Through a series of six orbit maneuvers, the mission's navigation team adjusted the altitude, inclination, and eccentricity of the satellite's orbit to the specifications of the mission's operational orbit. After this milestone, the satellite's ground track has been maintained within 1 km from the nominal tracks since mid October 1992 (Figure 2). Periodic orbit maintenance maneuvers have been performed to strictly observe this requirement. In order to minimize the impact to science investigation, special efforts are made to maximize the period between the orbit maneuvers and to conduct the maneuvers over land.

After the operational orbit was achieved, the collection of the mission's science data began. The data have been

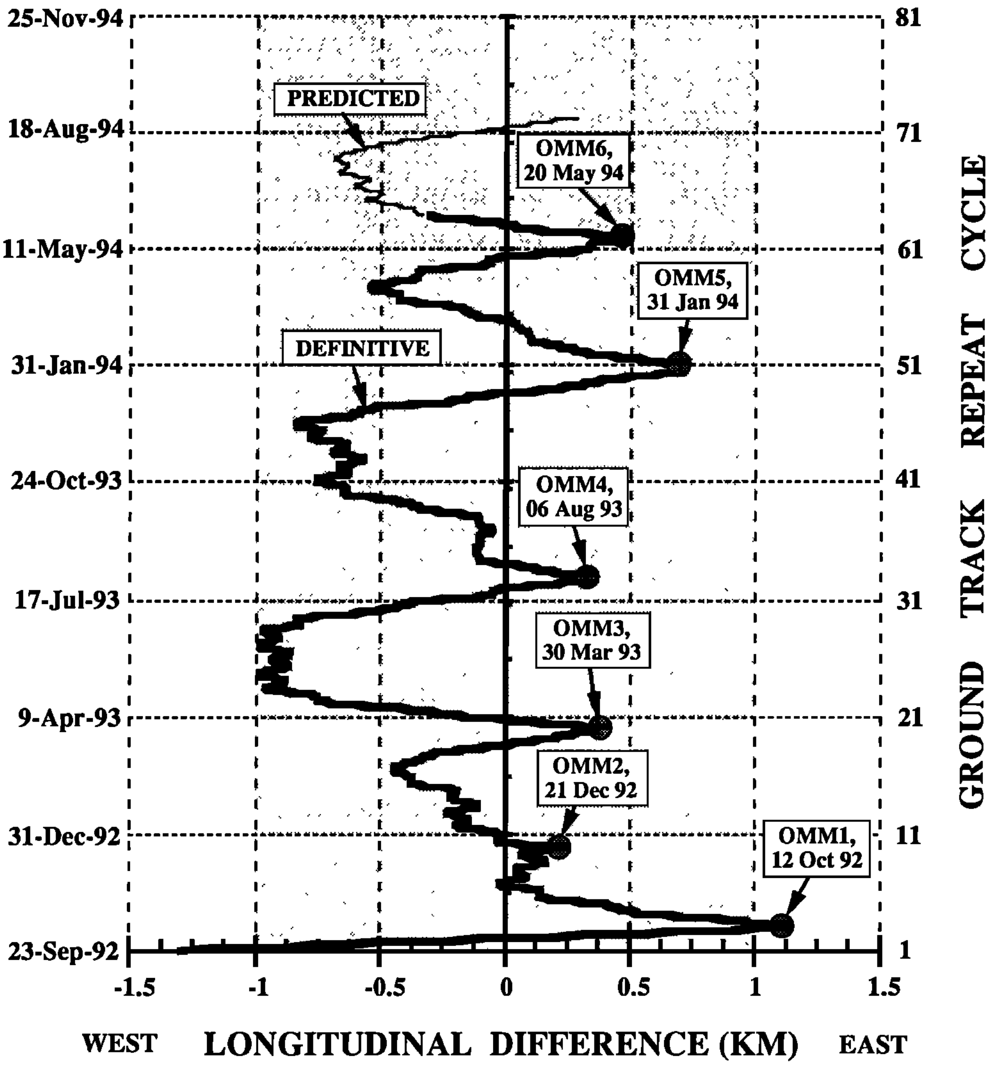

**Figure 2.** The time history of the distance between the actual ground tracks and their nominal locations at the equator. The first six Orbit Maintenance Maneuvers (OMM) are indicated.

grouped into 10-day orbit cycles with each cycle starting at the equatorial crossing of 99.92°E.

### 5.1. Verification

Verification of the performance of the satellite and the instruments and the integrity of the science data is a continuing process involving the participation of both mission engineers and scientists. During the first 6 months of the mission, an intensive verification campaign was conducted jointly by NASA and CNES to calibrate and validate the satellite measurements against in situ observations at the two verification sites. In addition, the satellite laser ranging and the DORIS data were used to calibrate and validate the POD process before the production of the GDR.

NASA instrumented an oil platform (owned by Texaco) 12 km west of Point Conception, California, to obtain data on sea level and related parameters [*Christensen et al.*, this issue]. Sea level measurements were made by an acoustic device and pressure gauges mounted on the oil platform of which the geocentric location was precisely determined by GPS and local surveys. The sea level data along with the various precision orbit ephemerides based on the laser, the DORIS and GPSDR data were used to determine the distance between the satellite and the sea surface; this distance was then compared to the altimeter range measurement to determine the altimeter bias and bias drift [*Christensen et al.*, this issue]. Other instrumentation at the oil platform included a GPS receiver for determining the absolute height of the platform and the total electron content, a surface pressure gauge for dry tropospheric correction, and an upward-looking water vapor radiometer for the wet tropospheric correction.

The primary CNES verification site was in the vicinity of Lampedusa Island in the Mediterranean Sea [*Ménard et al.*, this issue], including a small islet, Lampione, located 18 km west of Lampedusa Island. The instrumentation configuration included a laser on Lampedusa, two tide gauges on Lampione, two tide gauges on the west side of Lampedusa, a DORIS station on Lampedusa, two ground-based radiometers, a meteorological station, two GPS receivers (for ionospheric measurement), and two GPS buoys south of Lampione.

In addition to these two dedicated verification experiments, numerous studies have been conducted by the mission's Science Working Team to assess the performance of the mission's measurement system [e.g., *White et al.*, this issue; *Born et al.*, this issue; *Busalacchi et al.*, this issue; *Mitchum*, this issue]. The results from such studies form the core of this special issue. A summary of the measurement assessment is given in section 6.

### 5.2. Altimeter Antenna Sharing

An important task for the mission operation is to operate the two radar altimeters (ALT and SSALT) according to the mission plan. During the verification phase, the priority was to share the verification site overflights equally between the two altimeters. The SSALT was operating for 12.5% of the time, including 60% of the overflights of the Lampedusa verification site and 40% of the Harvest site. This 12.5% also included a 3-day subcycle every 5 cycles. Upon the completion of the verification phase, it was felt that complete cycles of 10-day SSALT data were more desirable for science applications as well as certain performance evaluations (e.g., the sea state bias). Therefore the SSALT has been operated for one complete 10-day cycle approximately every 10 cycles since April 1993, with the exact schedule determined so as to minimize the residual ionospheric errors (after the correction using the DORIS data). Coordination with certain field campaigns to validate the SSALT was another factor in formulating the antenna sharing plan.

### 5.3. Data Processing and Distribution

The primary data product for scientific research is the GDR, which includes the altimeter sea level height measurements, associated corrections, ancillary data, and measurement locations based on the precision orbit ephemeris. The GDR, based on algorithms validated by the Science Working Team, has been generated on a global basis since late May 1993. The format of the GDR is similar to that of Seasat and Geosat; however, the content of the data is larger [*Callahan*, 1994; *Archiving, Validation, and Interpretation of Satellite Data in Oceanography (AVISO)*, 1992]. The data return rate has been greater than 98% without systematic data losses over any geographic regions.

NASA and CNES are processing the GDR for each agency's own altimeter measurement. The data flow is illustrated in Figure 3. The NASA GDR (designated as GDR-T), which contains the data during the ALT operation, is available on magnetic tapes after about 1 month after data reception via the JPL Physical Ocean Distributed Active Archive Center (PO-DAAC). The CNES GDR (GDR-P), containing the data during the SSALT operation, is combined with the NASA GDR to form the merged GDR (M-GDR), which is available on CD-ROMs about 45 days after the data reception via the French data agency, AVISO. The JPL PO-DAAC is also producing identical merged GDR CD-ROMs on a similar schedule.

NASA and CNES are also making quick-look data available, on a best-effort basis, within 7 days from data reception via electronic transmission to operational users for environmental monitoring purposes. This quick-look data are based on an operational orbit ephemeris (as opposed to the precision orbit ephemeris) that has an accuracy of 10 cm (the radial component), which is not as good as the precision orbit but is more than an order of magnitude better than the original specification for the quick-look data. TOPEX/POSEIDON is the first ocean research mission that delivers high-quality data on a near-real time basis.

### 5.4. Anomalies

There were two anomalies in the satellite system during the early phase of the mission. First, the pointing error of the altimeter boresight was anomalously high during the first 2 months of the verification phase. The problem was corrected in December 1992 after a series of altimeter boresight calibrations, attitude system calibrations, and flight software corrections. Figure 4 shows the history of the altimeter pointing during cycles 4–14. The off-nadir angle has settled to about 0.05 degrees since day 355 (December 20, 1992). The $1\sigma$ requirement for the pointing control is 0.08 degrees. Therefore since December 20, 1992, the altimeter pointing has exceeded the requirement.

The second anomaly was the failure of one of the two star trackers of the satellite's attitude control system on November 25, 1993. This failure was probably caused by a single event upset and the damage might not be permanent. Recy-

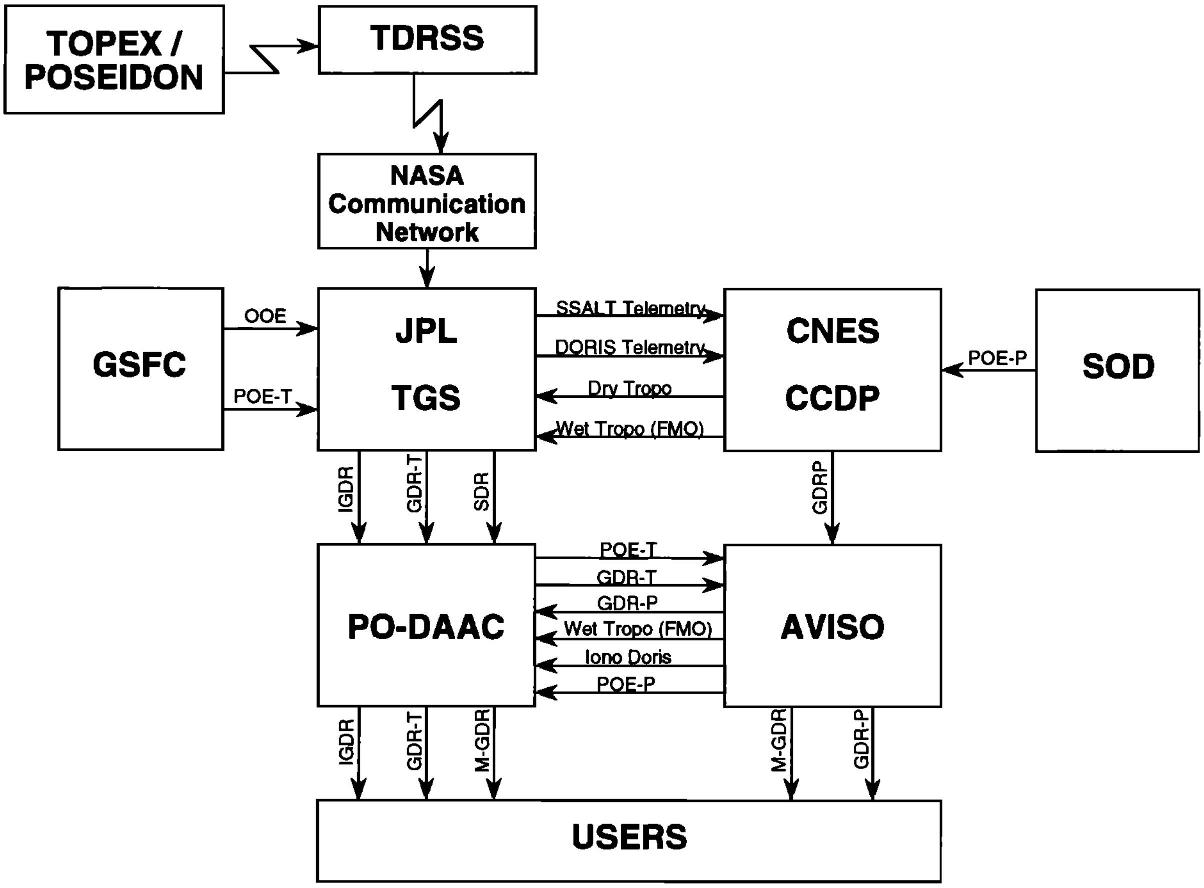

**Figure 3.** Flow chart for the data streams among the various data processing and archiving facilities of the TOPEX/POSEIDON mission. TGS is TOPEX Ground System; OOE, Operational Orbit Ephemeris; POE, Precision Orbit Ephemeris; IGDR, interim geophysical data record (quick look data); SDR, sensor data record; and CCDP, Centre de Controle DORIS POSEIDON.

cling its power may bring it back. However, the combination of the remaining star tracker and the digital fine Sun sensor is able to meet (or exceed) the attitude performance requirement. Since recycling power is not straightforward and involves risk, no attempts have been made to revive the failed star tracker.

## 6. Assessment of the Measurement System

The mission's primary measurement is the height of the sea surface relative to a reference ellipsoid. The sea surface height is derived by subtracting the altimeter range measurement (the altitude of the satellite above the sea surface) from the altitude of the satellite above the reference ellipsoid obtained from the POD. The accuracy of the sea surface height is thus determined by the accuracies of both the altimeter and the POD.

### 6.1. Altimeter Performance

There are various sources of error in the altimeter height measurement. They are discussed as follows.

**Measurement noise.** Spectral analysis was performed to estimate the noise in both the ALT and the SSALT range measurements. A large number of data segments of 10-s duration (62 km in distance along track) at 10-Hz data rate (10 data points per second) were analyzed. The noise level was determined by the white noise level at the high-frequency end of each spectrum. Displayed in Figure 5 are the plots of the instrument noise at 1-Hz data rate as a function of significant wave height (SWH) for both the ALT and the SSALT. The ALT noise varies from 1.7 cm at 2 m SWH to a relatively stable value of 2–2.5 cm for SWH larger than 3 m. The SSALT had a higher noise level, especially before cycle 41. Based on simulations and waveform retracking, the SSALT on-board algorithm coefficients have been adjusted since cycle 41. This adjustment has improved the SSALT noise figure by 20%, varying from 2 cm at 2 m SWH to 2.8 cm at 5 m SWH.

**Mispointing and skewness effects.** Due to the simplified calculation performed on the altimeter waveform on board the satellite, altimeter range, SWH, and AGC (automatic gain control, a quantity used for calculating the normalized radar backscatter coefficient) need to be corrected on the ground for the effects of sea state and altimeter pointing angle [*Chelton et al.*, 1989]. The correction was implemented in the form of polynomials for the ALT [*Hayne et al.*, this issue] and table look-up for the SSALT (O. Zanife et al., unpublished manuscript, 1994). The coefficients of the polynomials and table look-ups were estimated by analyzing simulated altimeter waveforms before launch and revised by analyzing the real waveform data collected after launch. *Rodriguez and Martin* [this issue a] made extensive comparisons of the GDR data with results from retracking the

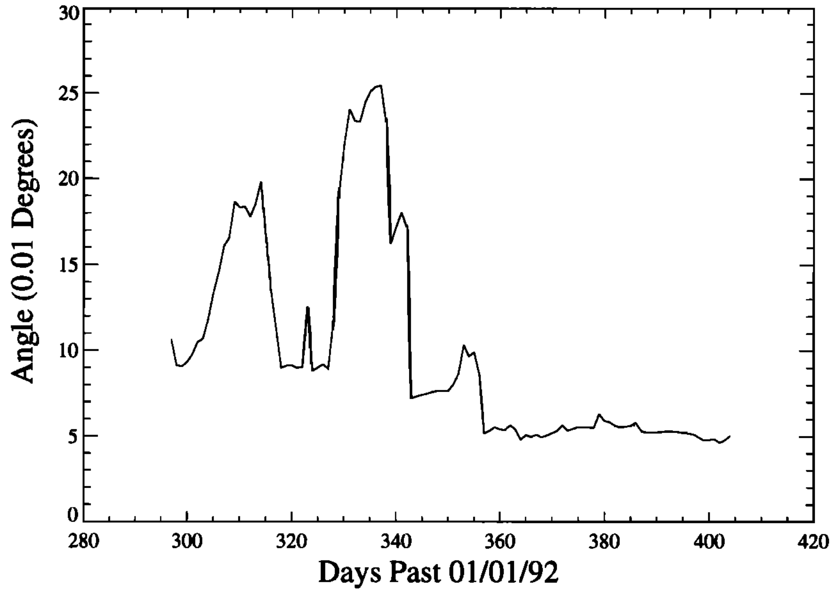

**Figure 4.** The time history of the daily averaged altimeter off-nadir pointing angle from cycles 4–14.

waveform data. They reported that the residual errors after the correction were largely caused by the effects of the skewness of the ocean surface specular point probability density function not accounted for by the GDR corrections. Such comparisons are a test of the effectiveness of the GDR correction algorithm. The estimated RMS skewness-induced error is 1.2 cm for the Ku band and 2.2 cm for the C band [*Rodriguez and Martin*, this issue a]. The error occurs

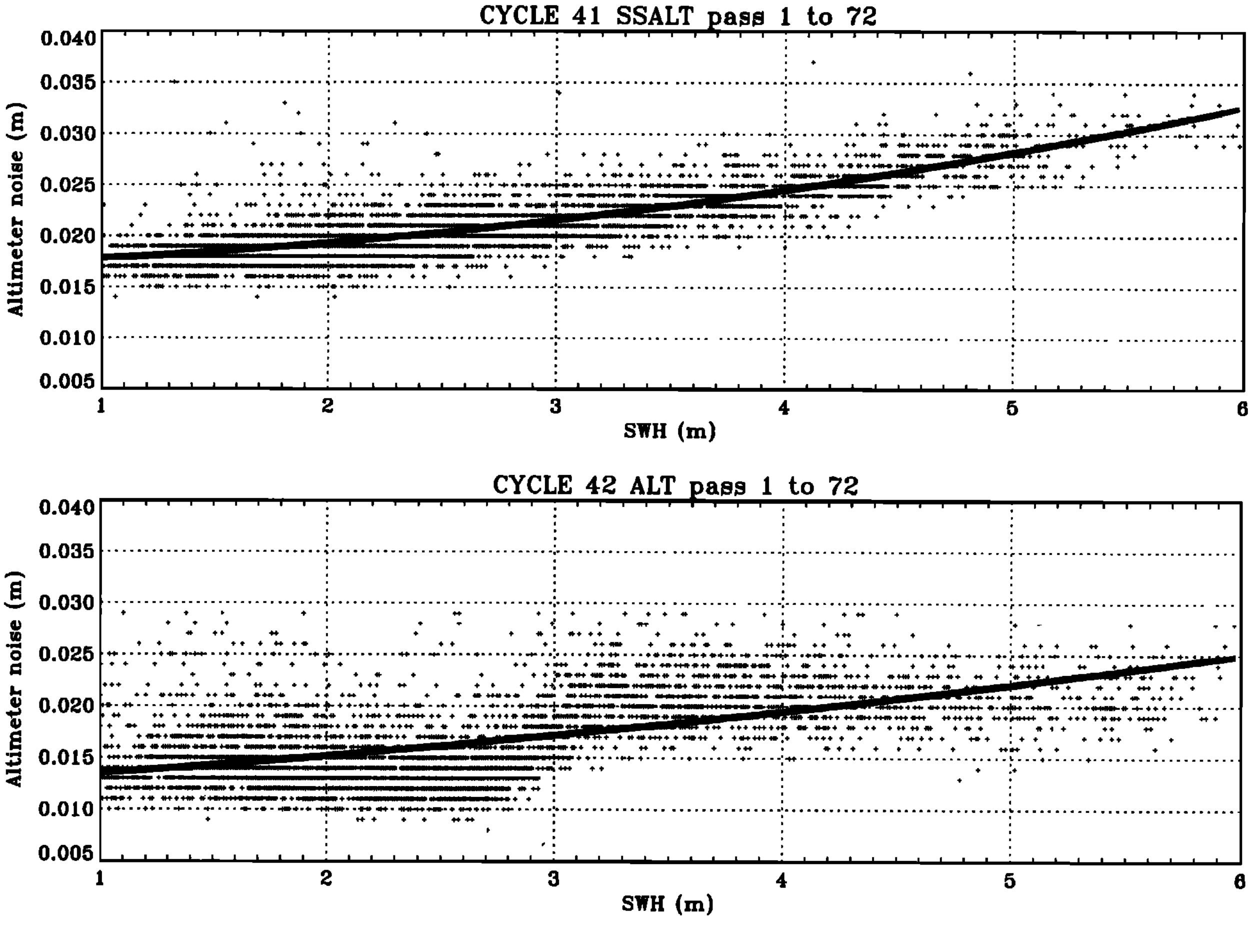

**Figure 5.** Estimation of the altimeter noise for the (top) SSALT and the (bottom) ALT as a function of significant wave height (SWH). The curves are quadratic least squares fits to the data.

primarily at scales larger than about 600 km. Similar analysis was performed on the SSALT waveform data. The result suggests that the skewness-induced error in the SSALT data was also about 1.2 cm (E. Rodriguez and O. Zanife, personal communication, 1994).

**EM bias.** It is well known that the radar backscatter cross section is larger at wave troughs than at wave crests [e.g., *Walsh et al.*, 1989]. Therefore altimeter-measured sea surface height is biased toward wave troughs and this bias is called the electromagnetic bias, or EM bias. EM bias is roughly proportional to the height of waves and is normally expressed in terms of a percentage of SWH. The percentage has been found to be sensitive to wind speed; a quadratic dependence on wind speed was used in the NASA GDR algorithm [*Callahan*, 1994; *Hevizi et al.*, 1993]. Because the EM bias is dependent on the radar frequency, the coefficients in the algorithms for the Ku and C band are slightly different.

Analyses of the correlation between the altimeter height and SWH suggest that there is a residual EM bias error of about 1% of SWH in the GDR [*Rodriguez and Martin*, this issue b]. For a typical 2-m SWH the residual EM bias error is about 2 cm. The present CNES EM bias algorithm is based on the method of *Fu and Glazman* [1991] that parameterizes the EM bias in terms of a quantity called the pseudo wave age. The performance of this algorithm is somewhat inferior to the NASA algorithm and shall be replaced in the future by the new EM bias parameterization of *Gaspar et al.* [this issue], of which the performance is similar to that of the NASA algorithm.

**Ionospheric error.** The range delay caused by the ionospheric free electrons is retrieved by the dual-frequency measurements of the ALT when it is in operation. When the SSALT is in operation, this correction is derived from the dual-frequency signals received by the DORIS receiver. The ALT retrieval is the most direct method of estimating the first-order ionospheric error, whereas the DORIS approach requires space-time interpolation to the altimeter nadir path. However, there are two error sources in the ALT retrieval: the noise in the altimeter measurements and the residual frequency-dependent EM bias and skewness bias. The former is estimated to be about 0.5 cm at 1 Hz data rate and can be reduced to about 0.2 cm by averaging over 100 km along track [*Imel*, this issue]. The latter has to do with the frequency dependence of the EM bias and the skewness bias.

The difference between the residual Ku and C band EM bias was found to be less than 0.5% of the SWH [*Imel*, this issue; *Stewart and Devalla*, this issue], resulting in an error in the ionospheric range delay retrieval of 0.2 cm for a typical 2-m SWH (based on the formula of *Callahan* [1994]). As noted above, the skewness bias is also frequency dependent, i.e., 1.2 cm for the Ku band and 2.2 cm for the C band (RMS estimates based on waveform retracking). Because the Ku and C band errors are uncorrelated, they introduce another 0.45-cm error into the ionospheric correction. Because there is little ionospheric signal variance at wavelengths shorter than 100 km [*Imel*, this issue], the noise reduction by averaging over 100 km is valid and the resulting noise estimate is thus 0.2 cm. However, this averaging is not performed on the GDR and is left to the user to apply. The errors caused by the EM bias and skewness bias cannot be reduced by the averaging because their scales are much larger than 100 km. Thus the total ionospheric correction error is about 0.53 cm (the root-sum-square of 0.2, 0.2, and 0.45 cm).

The RMS error of the DORIS-derived correction is estimated to be 1.7 cm by comparison with the ALT dual-frequency measurement [*Zlotnicki*, this issue; N. Picot and P. Escudier, unpublished manuscript, 1994]. However, the error has a geographic pattern with the largest values located in the tropics and subtropics.

**Wet tropospheric error.** The water vapor in the troposphere causes delay in the propagation of radar signal. This "wet tropospheric error" is related to the total columnar water vapor content in the altimeter nadir path. The brightness temperatures measured in the three frequency channels of the TMR were used to retrieve the wet tropospheric correction. By comparing the TMR observations with ground-based water vapor radiometer and radiosonde observations, the RMS accuracy of the wet tropospheric correction is estimated to be about 1.1 cm [*Ruf et al.*, this issue]. Another correction available on the GDR is provided by the French Meteorological Office (FMO), based on products issued by the European Center for Medium-Range Weather Forecast (ECMWF). The RMS difference between this correction and the TMR-based correction is about 3 cm [*Stum*, this issue]. *Morris and Gill* [this issue] found an average improvement of 2.3 cm over the Great Lakes when the TMR correction was used instead of the FMO/ECMWF correction.

**Dry tropospheric error.** The radar signals are also delayed by the dry air mass of the troposphere, at a rate of 0.27 cm per mbar of atmospheric sea level pressure. The correction for this dry tropospheric error is made by using the sea level pressure product of the ECMWF provided by the FMO. The RMS accuracy of the correction is estimated to be 0.7 cm based on an assumption of an RMS 3-mbar accuracy for the atmospheric pressure product.

**Altimeter bias and drift.** Determination of the bias in the altimeter height measurement and its possible drift in time was a major objective of the verification experiments conducted at the two verification sites. Based on the first 36 cycles of data, a bias estimate of −14.5 ± 2.9 cm was obtained for the ALT height measurement [*Christensen et al.*, this issue]. The negative value indicates that the altimeter range is measured short. No unambiguous drift in the bias estimates has been determined. A longer data set is required for a more definitive result.

The bias in the SSALT measurement was estimated to be 1.0 ± 2.4 cm [*Menard et al.*, this issue]. The relative bias between the ALT and the SSALT measurements was investigated by a number of groups based on direct analysis of the altimeter data [e.g., *Le Traon et al.*, this issue; *Morris and Gill*, this issue]. The results are consistent with the findings at the two verifications sites to the extent of the error estimates.

All the bias estimates are dependent on the particular EM bias algorithms used. With the various EM bias corrections applied, the ALT bias ranged from −13.1 cm to −17.1 cm, whereas the SSALT bias ranged from −0.2 cm to 9.5 cm [*Christensen et al.*, this issue]. The definitive ALT and SSALT bias estimates quoted in the preceding two paragraphs were based on the NASA GDR algorithm [*Callahan*, 1994; *Hevizi et al.*, 1993] and the new algorithm of *Gaspar et al.* [this issue], respectively.

**Significant wave height and radar backscatter coefficient.** *Callahan et al.* [this issue] compared the SWH and the normalized radar backscatter coefficient (called sigma-naught) measured by the ALT to both Geosat and buoy observations. They found that the ALT sigma-naught was biased higher than the Geosat sigma-naught by 0.7 dB. After removing this bias, the wind speeds derived from the ALT sigma-naught using a Geosat algorithm agreed with the buoy observations within 2 m/s. Monthly histograms of both SWH and sigma-naught agree fairly well with the Geosat results. The SWH agrees with the buoy observations within 0.2 m.

### 6.2. Precision Orbit Determination Performance

The uncertainty in the radial component of the satellite orbit has long been the largest error source in satellite altimetry. A long-lead effort to improve the knowledge in the Earth's gravity field was funded by the TOPEX/POSEIDON project as a key step toward a significant improvement in the POD capability to meet the mission's science goals [*Marsh et al.*, 1988, 1990; *Tapley et al.*, 1988; *Lerch et al.*, 1993]. The postlaunch gravity improvement activities were conducted as a joint effort by GSFC, the University of Texas at Austin, and CNES [*Nerem et al.*, this issue a]. This gravity improvement effort, as well as the satellite's comprehensive tracking system (the satellite laser ranging plus the DORIS system as the baseline system with the GPSDR as an experimental system), has made the TOPEX/POSEIDON POD a revolutionary achievement [*Tapley et al.*, this issue a; *Nouel et al.*, this issue]. Other factors for the achievement include a joint American and French effort in the development and improvement of force modeling, reference systems, station coordinates and numerical methods. The resulting RMS accuracy for the baseline precision orbits (used for producing the GDR) computed by using the laser and DORIS data is estimated to be 3.5 cm [*Tapley et al.*, this issue a; *Nouel et al.*, this issue]. Most of the error is random and can be reduced by time averaging. The systematic component, which is correlated geographically and cannot be reduced by time averaging, is estimated to be less than 2 cm. Both the United States and France are producing independent precision orbit products with comparable accuracies. The U.S. effort is led by the GSFC with support from the Center for Space Research of the University of Texas at Austin and the Colorado Center for Astrodynamics Research of the University of Colorado at Boulder. The French effort is conducted by the Service d'Orbitographie Doris (SOD) at CNES.

Precision orbit is also computed at JPL using the GPS tracking data [*Bertiger et al.*, this issue]. Because of the quasi-continuous tracking of the satellite via the GPS constellation, the orbit solution is less dependent on the gravity model and has been demonstrated to be useful for studying the geographically correlated error in the laser/DORIS orbit. The accuracy of this so-called reduced dynamic orbit solution is estimated to be 3 cm. The differences between the GPS-based orbit and the laser/DORIS-based orbit were shown to be related to the geographically correlated errors in the latter due to its gravity model errors [*Christensen et al.*, 1994]. However, when the antispoofing (an operation conducted by the U.S. Air Force periodically for military purposes) is in operation, the accuracy of the GPS-based orbit is slightly degraded (with errors about 4–5 cm (W. Bertiger, personal communication, 1994)).

### 6.3. An Error Budget

Shown in Table 2 is an estimate of the error budget, based on the discussions given above, for the sea surface height measured by TOPEX/POSEIDON. Separate estimates are given for the TOPEX system (the ALT with the NASA algorithms and orbit) and the POSEIDON system (the SSALT/DORIS with the CNES algorithms and orbit). The error is given in terms of root-sum-square for 1/s data rate and 2 m SWH. The total measurement error, 4.7 cm for the TOPEX system or 5.1 cm for the POSEIDON system, is significantly less than the mission requirement, which specifies a total error of 13.7 cm, of which 12.8 cm was allocated to the POD. The superb POD performance is thus the key to achieving the overall accuracy in the sea surface height measurement. For the first time the users of altimetry data are no longer required to reduce orbit errors using empirical techniques that often have reduced ocean signals as well. This improvement is especially critical to the study of the large-scale ocean dynamics, a major objective of the mission [e.g., *Stammer and Wunsch*, this issue; *Tapley et al.*, this issue b; *Nerem et al.*, this issue b; *Fu and Pihos*, this issue]. *Tsaoussi and Koblinsky* [this issue] estimated the error covariance for the ocean topography and current velocity based on the measurement error budget.

There are a number of verification studies that have validated the error budget estimate. For example, *Morris and Gill* [this issue] compared the ALT measurements to simultaneous tide gauge measurements taken around the Great Lakes, where natural variabilities were very small. They found an overall RMS difference of 3 cm between the two measurements. However, the comparison only applies to the temporally varying component of the measurement. Therefore the 3-cm difference is actually smaller than the estimated total error of 4.7 cm, which contains the time-invariant systematic component as well. Comparisons of the TOPEX/POSEIDON observations to open-ocean tide gauge observations showed general agreement within 5 cm [*Mitchum*, this issue; *Nerem et al.*, this issue b].

## 7. Tidal Errors

As the accuracy of the altimetric measurement of sea level has reached a level that allows the detection of the large-scale weak signals of ocean currents, one has to be concerned with the residual tidal signals in the data. The tides are composed of the ocean tides and the body tides (including both the solid Earth tides and the ocean loading tides). Both components have been corrected for in the GDR by model predictions [*Callahan*, 1994]. The accuracies of the body tide models are probably better than 1 cm, whereas the accuracies of the ocean tide models are the main concern.

Two ocean tide models are supplied in the GDR: the Schwiderski model [*Schwiderski*, 1980a, b] and the Cartwright and Ray model [*Cartwright and Ray*, 1990]. The global RMS difference between these two models is about 6 cm, with peak differences being as large as 15–20 cm [*Cartwright and Ray*, 1990]. This difference is a rough measure of the accuracies of these models. More detailed studies of the two models have indicated that the global RMS errors are of the order of 5 cm for both models with the Cartwright and Ray model being slightly better [*Ray*, 1993; *Molines et al.*, this issue; *Wagner et al.*, this issue]. Im-

**Table 2.** Assessment of Measurement Accuracies

| | TOPEX | POSEIDON |
|---|---|---|
| Altimeter | | |
| Altimeter noise* | 1.7 | 2.0 |
| EM bias | 2.0 | 2.0 |
| Skewness | 1.2 | 1.2 |
| Ionosphere | 0.5† | 1.7‡ |
| Dry troposphere | 0.7 | 0.7 |
| Wet troposphere | 1.1 | 1.1 |
| Total altimeter range§ | 3.2 | 3.7 |
| Precision orbit determination | | |
| Radial orbit height‖ | 3.5 | 3.5 |
| Sea surface height | | |
| Single-pass sea surface height | 4.7 | 5.1 |

One sigma values in centimeters.

*Altimeter noise is based on 1-sec average at 2 m significant wave height. The SSALT noise estimate is based on the data collected since Cycle 41 after the adjustment of the SSALT on-board algorithm.

†Assuming that the noise has been reduced by averaging over 100 km along track.

‡Based on DORIS data.

§Altimeter bias and bias drift not included.

‖Based on the JGM-2 gravity model.

proved models have recently been developed for TOPEX/POSEIDON applications, ranging from a hydrodynamic model [*Le Provost et al.*, this issue] to models based on the TOPEX/POSEIDON data, such as empirical models [*Schrama and Ray*, this issue; *Wagner et al.*, this issue; *Ma et al.*, this issue] and inverse models [*Egbert et al.*, this issue]. By comparison to in situ observations, the accuracies of these models are estimated to be about 3 cm. Further improvement is expected when longer data sets from the mission are used for model development in the future.

## 8. Science Investigations

Science investigations using the unique capabilities of TOPEX/POSEIDON are being carried out by the members of the Science Working Team (SWT), consisting of 38 principal investigator teams selected by NASA and CNES through the process of Announcement of Opportunity. Most of the principal investigators have a team of coinvestigators, resulting in a science team totalling more than 200 members. The selection was made based on the scientific merit of the proposed investigations and their relevance to the mission's science goals. Although the mission's data are available to the general public without exclusive use by the SWT, the SWT constitutes a nucleus for the science investigations using the data. The principal investigators and the subjects of their investigations are listed in Table 3. There are 16 principal investigators from the United States, 13 from France, two from Japan, two from Australia, and one from each of the following countries: United Kingdom, South Africa, Germany, Norway, and the Netherlands. The reader is referred to *TOPEX/POSEIDON Science Working Team* [1991] for a detailed description of the mission's science plan.

The science plans addressed by the principal investigators were formulated several years ago with a primary focus on the analysis of the altimetry data per se. There are many new opportunities emerging from more recent developments. An important task for the SWT and the science community at large is to merge the TOPEX/POSEIDON data with other types of data and create a more comprehensive data set for the description of the global ocean circulation. Coincident with TOPEX/POSEIDON have been a variety of oceanographic and meteorological observations conducted as part of the World Ocean Circulation Experiment and the Tropical Ocean and Global Atmospheric Program. The TOPEX/POSEIDON data are providing a framework to integrate these in situ observations into a synthesis of the global ocean circulation.

It is well known that a single satellite does not provide sufficient sampling to cover the complete spectrum of oceanic variabilities. However, TOPEX/POSEIDON is providing the first accurate observation of the large-scale (larger than the mesoscale) part of the spectrum, the part that is least known from the past data. On the other hand, the ERS 1 altimeter data can be combined with the TOPEX/POSEIDON data to provide a more complete coverage in both spectral and physical domains (the latter refers to the areas between 66 and 82 degree latitude not covered by TOPEX/POSEIDON). The TOPEX/POSEIDON data, being more accurate than the ERS 1 data, can be used to calibrate the ERS 1 data at the large scale (P.-Y. Le Traon et al., unpublished manuscript, 1994).

To address many of the aspects of the ocean's role in climate change such as the transport of heat and carbon dioxide, one ultimately has to synthesize the TOPEX/POSEIDON data with the in situ data using an ocean general circulation model. This synthesis process can be treated as an estimation problem, or "data assimilation," a term derived from meteorology [e.g., *Blayo et al.*, this issue]. The result will lead to an optimal description of the state of the ocean circulation, which will be used in a variety of applications to the climate problems, including initialization of air-sea coupled models.

## 9. Conclusions

The TOPEX/POSEIDON mission has successfully completed its first one and half years' operation. The satellite and the instrument suite are healthy and performing nominally. Key milestones during this period of operation include the completion of the verification phase and the production and distribution of the mission's baseline data products. The results of the verification studies have indicated that the mission's performance has exceeded the requirements. The RMS accuracy of a single-pass sea level measurement is 4.7 cm for the TOPEX system and 5.1 cm for the POSEIDON system; both are more than a factor of 2 better than the requirement of 13.7 cm. The satellite ground tracks have remained within 1 km from the nominal tracks for more than 98% of the time. The data return rate has been greater than 98%.

The data processing and distribution has been proceeding on schedule. The NASA data product, containing only the data during the ALT operation that accounts for 90% of the time, is distributed on magnetic tapes within about 45 days from data reception. The CNES data product, containing the complete data from both the ALT and the SSALT, is distributed on CD-ROMs within about 60 days from data reception. The JPL PO-DAAC is producing CD-ROMs that are identical to the CNES products with a comparable delivery schedule.

**Table 3.** TOPEX/POSEIDON Principal Investigators

| Name | Institution | Investigation |
|---|---|---|
| S. Arnault | Universite Paris VI, France | tropical Atlantic Ocean |
| F. Barlier | Groupe de Recherches de Geodesie Spatiale, France | western Mediterranean Sea |
| G. Born | University of Colorado, United States | weakly defined ocean gyres |
| C. Boucher | Institut Geographique National, France | terrestrial reference systems |
| D. Burrage | Australian Institute of Marine Sciences, Australia | North-Australian tropical seas |
| A. Cazenave | Groupe de Recherches de Geodesie Spatiale, France | marine geophysics |
| D. Chelton | Oregon State University, United States | Antarctic Circumpolar Current |
| R. Cheney | NOAA/National Geodetic Survey, United States | ocean dynamics and geophysics |
| J. Church | Commonwealth Scientific and Industrial Research Organization, Australia | South Pacific, the Southern, and the Indian Oceans |
| P. De Mey | Groupe de Recherches de Geodesie Spatiale, France | data assimilation by ocean models |
| Y. Desaubies | Institut Francais de Recherche pour l'Exploration de la Mer, France | western equatorial Atlantic Ocean |
| L.-L. Fu | Jet Propulsion Laboratory, United States | gyres of the world oceans |
| M. Grundlingh | National Research Institute for Oceanography, South Africa | oceans around South Africa |
| S. Imawaki | Kyushu University, Japan | western North Pacific Ocean |
| E. Katz | Columbia University, United States | tropical Atlantic Ocean |
| C. Koblinsky | NASA Goddard Space Flight Center, United States | ocean circulation and the geoid |
| C. Le Provost | Institut de Mechanique de Grenoble, France | global ocean tides |
| T. Liu | Jet Propulsion Laboratory, United States | heat balance of global oceans |
| R. Lukas | University of Hawaii, United States | tropical ocean dynamics |
| Y. Menard | Groupe de Recherches de Geodesie Spatiale, France | geophysical validation of altimetry |
| J. Minster | Groupe de Recherches de Geodesie Spatiale, France | mesoscale and basin-scale ocean variability |
| J. Mitchell | Naval Oceanographic and Atmospheric Research Laboratory, United States | midlatitude western boundary currents |
| M. Ollitrault | Institut Francais de Recherche pour l'Exploration de la Mer, France | South Atlantic Ocean |
| L. Pettersson | University of Bergen, Norway | Nordic seas |
| J. Picaut | Groupe SURTROPAC, ORSTOM, New Caledonia | tropical Pacific Ocean |
| R. Rapp | Ohio State University, United States | mean sea surface and gravity |
| B. Sanchez | NASA Goddard Space Flight Center, United States | global ocean tides |
| J. Schroeter | Alfred Wegener Institute for Polar and Marine Research, Germany | ocean circulation modeling |
| J. Segawa | University of Tokyo, Japan | marine geodesy and geophysics |
| A. Souriau | Groupe de Recherches de Geodesie Spatiale, France | plate motions |
| T. Strub | Oregon State University, United States | equatorial and eastern boundary currents |
| C.-K. Tai | NOAA/National Geodetic Survey, United States | Pacific Ocean |
| B. Tapley | University of Texas at Austin, United States | ocean surface topography |
| P. Tarits | Institut de Physique du Globe de Paris, France | altimetry analysis with sea floor electric data |
| J. Wahr | University of Colorado, United States | oceanic effects on the Earth's interior |
| K. Wakker | Delft University of Technology, Netherlands | orbit computation and sea surface modeling |
| P. Woodworth | Proudman Oceanographic Laboratory, England | marine research |
| C. Wunsch | Massachusetts Institute of Technology, United States | global ocean circulation |

The mission's ground system also produces, on a best effort basis, quick-look data products, which are available within 7 days from data reception to the operational users through an electronic medium. TOPEX/POSEIDON is the first ocean research mission that delivers high-quality data on a near-real time basis.

The two experiments of the mission, the SSALT and the GPS-based POD, were successfully carried out. These achievements have demonstrated new technologies for future altimetry missions, which will be conducted in a more streamlined and cost-effective manner for monitoring the global ocean circulation on a long-term basis.

The mission's data are being analyzed by an international team of some 200 scientists for studying the global ocean circulation, as well as the ocean tides, geodesy and geodynamics. The results of the verification work and preliminary science investigations constitute the core of this special issue.

The mission lifetime was designed for a minimum of 3 years with a possible extension to 6 years. This multiyear global data set, when integrated with other types of data and synthesized by numerical ocean models, will go a long way toward understanding the ocean circulation and its variability in relation to climate change.

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E. J. Christensen, L.-L. Fu, and C. A. Yamarone Jr., JPL MS-300-323, 4800 Oak Grove Drive, Pasadena, CA 91109-8099.

M. Dorrer, P. Escuchier, M. Lefebvre, and Y. Menard, Centre National d'Etudes Spatiales, 18 Ave. Edouard Belin, 31055 Toulouse Cedex, France.

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