TOPEX/POSEIDON MISSION: GLOBAL MEASUREMENTS OF SEA LEVEL AT UNPRECEDENTED ACCURACY*

CHARLES A. YAMARONE, JR.; EDWARD J. CHRISTENSEN
and LEE-HEUNG FU

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, M/S 264-686, Pasadena, CA 91109, U.S.A.

Abstract—This paper describes the TOPEX/POSEIDON mission, a joint project between the United States and France with particular emphasis on measurement capabilities and performance. The satellite has provided unprecedented measurements of global sea level since it was launched on 10 August 1992 from Kourou, French Guiana with an Ariane 4P launch vehicle. TOPEX/POSEIDON is comprised of two microwave radar altimeters, a microwave radiometer, and three precision tracking systems which combine to produce an overall global sea level measurement of less than 5 cm. Tire accuracy of the measurement is attributed to the design and implementation of the satellite and its instrument complement, the precision of its determination and tracking systems, the ground processing system, and the verification and calibration system. The satellite and measurement systems will be discussed, with an emphasis on the sensors, precision of determination proms, and the verification proms. In addition, current results provided by TOPEX/POSEIDON science investigators will be summarized.

1. BACKGROUND

The TOPEX/POSEIDON mission, a joint French/U.S. collaborative effort, is obtaining space-borne measurements of the ocean circulation with radar altimetry and with sufficient accuracy, precision, and repeatability to provide a data set that will allow a new understanding of the world’s ocean circulation.

The first satellite altimeter specifically designed for establishing the “proof of concept” of such measurements from space was flown on Seasat in 1978. Due to the results of Seasat and other subsequent altimetric missions in the 1980s, the United States and France started establishing plans for a specific mission tailored to optimize the study of ocean circulation. Initially, the Science Working Teams (SWT) and project engineering teams in the two countries were proceeding independently—the proposed U.S. mission being called the ocean Topography Experiment (TOPEX) and the French mission, as called ‘POSEIDON. By 1983, a joint study was initiated between the United States’ National Aeronautics and Space Administration (NASA) and France’s Centre National d’Etudes Spatiales (CNES) reasoning that a joint mission had the greatest probability of approval and success. This combined effort between France and the United States was called TOPEX/POSEIDON. From 1983 until the TOPEX/POSEIDON mission was approved by both NASA and CNES in fiscal year 1987, the science teams (which were eventually combined into one Joint Science Team) established science requirements and outlined science plans that would be established for conducting experiments. The science and engineering teams then established the technical definition of the mission, which included the sensor or instrument complement, satellite definition, orbit definition, launch vehicle requirements, and associated ground systems support, including the mission design and mission operation plans. As a result of the Seasat altimetric performance it is clear that any Seasat-like mission would require precise space and, as part of that, knowledge of the satellite orbit in space and, as part of that, knowledge of the gravity field was key. So during these years prior to launch, a strong effort to improve the gravity field knowledge was undertaken primarily at Goddard Space Flight Center (GSFC) and the University of Texas at Austin, under the sponsorship of the TOPEX/POSEIDON project. Today’s results, which include a geoid level measurement of less than 5 cm, can be attributed, to a significant degree, to this pre-launch focus on improving the gravity field knowledge.

The collaborative mission has both NASA and CNES sponsoring a joint Science Working Team having selected complementary science investigations. NASA and CNES have conducted a joint verification effort, which took place within 7 months after launch. Both NASA and CNES perform precision orbit determination and process data from their respective payloads of the satellite. All data have been exchanged and complete data sets, which contain all data derived from NASA and CNES

* Paper IAF-94-B-6-03 presented at the 45th Congress of the International Astronautical Federation, Jerusalem, Israel, 9-14 October, 1994.
instruments, are provided to all science investigators. CNES provided a dedicated Ariane 42P, which launched the TOPEX/POSEIDON satellite into its orbit. CNES also provided a set of POSEIDON instrumentation, namely the solid-state altimeter (SSALT) and the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) tracking system. NASA has provided the satellite bus and TOPEX instrumentation, which includes a two-frequency radar altimeter, microwave radiometer, laser retroreflector assembly, and an experimental GPS receiver. NASA provides the tracking data relay system services to support command, control, and data acquisition and conducts the mission operations.

2. MISSION OVERVIEW

On August 10, 1992, the United States and France launched their joint TOPEX/POSEIDON satellite from Kourou, French Guiana, on an Ariane 42P launch vehicle. Since then, the satellite has been measuring, with unprecedented accuracy, the height of the sea surface relative to the Earth’s center of mass on a global basis every 10 days. The satellite was designed for a minimum lifetime of 3 years, with the possibility of going to 5 years. Due to the success of the mission, NASA is planning to fund the operation of the satellite for a total of 6 years. This is the first satellite altimetry mission specifically designed and conducted for the study of ocean circulation. TOPEX/POSEIDON uses a radar altimeter system to measure the height of the sea surface, which allows the mapping of the topography of the oceans. This mapping in turn is used for the study of the world’s oceans. Additionally these measurements are used for the study of the oceans’ tides, as well as marine geodesy and geophysics.

After launch on August 10, 1992, the satellite went through a series of maneuvers to place it into its operational orbit. These six maneuvers aligned the satellite into the current circulation orbit at an altitude of 1334 km, an inclination of 66°, and a repeat period of 10 days.

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 frequencies of ocean-current variabilities. Inclinations that lead to undesirable aliased tide frequencies—such as zero, annual, and semi-annual—are to be avoided. In order to determine the ocean tidal signals from the altimetry measurement and subsequently remove them 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° 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 10 days (9.916 days to be exact) was selected; it resulted in an equatorial cross-track separation of 315 km.

To maximize the accuracy of orbit determination, a high orbit altitude is preferred because of reduced atmospheric drag and gravity forces acting on the satellite.

To satisfy this requirement, an altitude of 1334 km was selected. Since then, great care has been taken by the mission operations personnel at the Jet Propulsion Laboratory (JPL) to maintain an orbit which, in 10 days, provides complete ocean global Coverage and has repeat tracks with ±1 km. After insertion into the operational orbit, maintenance maneuvers are required to maintain ±1 km ground track every 10 days. Six maintenance maneuvers have been performed during the first 2 years. The average time between these maneuvers was 117 days. The pre-launch requirement was 30 days to minimize perturbations to the precise orbit determination process. This performance by flight operation, particularly the navigation team, is another example of operational sensitivity to the overall measurements required of TOPEX/POSEIDON and another positive contributing factor to the success of TOPEX/POSEIDON during these first 2 years. After a successful verification process, concluding in February 1993, the mission has been providing global sea-level measurements with less than 5 cm (rms) of error since May 1993.

3. SENSORS

One of the key factors contributing to the success of the mission was the original mission design, which provided for an instrumentation set that minimizes the errors in the altimetric measurements and all the collaborating measurements. There are six science instruments in the mission payload, four provided by NASA and two by CNES. These instruments are divided into operational and experimental sensors as follows:

(I) Operational sensors

(a) Dual-Frequency Radar Altimeter (ALT) (NASA)
(b) TOPEX Microwave Radiometer (TMR) (NASA)
(c) Laser Retroreflector Array (LRA) (NASA)
(d) Doppler Orbitography and Radiopositioning Integrated Satellite (DORIS) tracking system receiver (CNES)

(II) Experimental sensors

(a) Single-Frequency Solid-State Radar Altimeter (SSALT) (CNES)
(b) Global Positioning System Demonstration Receiver (GPSDR) (NASA)

The NASA altimeter operates at 13.6 GHz (Ku-band) and 5.3 GHz (C-band) simultaneously.
the prime instrument for the mission. The measurements made by this instrument at the two frequencies not only provide precise altimeter height measurements over the oceans, but also contribute to the first order of errors caused by the ionospheric free electrons. The ALT also allows a total electron content to be a by-product of the mission. The SSALT operates on a single frequency of 13.65 GHz and is a solid-state low-power altimeter, which is the model for future altimeters for Earth observations. Both the NASA altimeter and the CNES altimeter share a 1.5-m-diameter antenna. Only one altimeter is operated at any given time. This was facilitated by having a predetermined altimeter sharing plan agreed to by both CNES and NASA prior to launch. Another key sensor that contributes significantly to the precise measurement of the sea level is the microwave radiometer. This instrument uses a measurement of sea-surface microwave brightness temperature at three frequencies (18.7, 36.5, and 91.6 GHz) to correct for the total water-vapor content in the atmosphere along the beam of the altimeter. This provides a path-length delay correction in the altimeter measurement that is due to water vapor. Basically, the altimetric measurement is provided by NASA's ALT and CNES' SSALT.

A key parameter in determining the sea level from space is the precise knowledge of where the satellite is located in space. This, called precision orbit determination (POD), is the measure of the satellite's orbital distance from the Earth. When this is combined with the radar altimeter measurement, the difference is the sea level, which is the primary measurement of the mission. In order to know the precise location of the satellite in space, three instruments are carried on TOPEX/POSEIDON to contribute to that objective. Two are operational instruments and one is an experimental instrument. The NASA precision orbit determination is derived from the LRA, which interfaces with the satellite laser-ranging stations on the ground. The retroreflector cube corners are mounted in trays around the exterior of the altimeter antenna. This array provides a bright retroreflector, which provides a strong signal return to the ground-based laser receivers. The data from the satellite laser network then provides an input to the precision orbit determination process.

The prime source of the CNES-derived precision orbit determination is provided by the French DORIS tracking system. The DORIS system had been previously demonstrated successfully by France's SPOT-2 mission. DORIS is composed of an array of bright retroreflectors and a network of 40-50 ground stations, which provide all-weather global tracking of the satellite. The signals are transmitted on two frequencies to allow removal of the effects of the ionosphere on the electron tracking data. Therefore the total content of the ion-free electrons can be estimated from the DORIS data and used for the ionosphere correction of the SSALT. A third instrument that provides a data source for precision orbit determination is the Global Positioning System (GPS) Demonstration Receiver. This experimental system has demonstrated that highly accurate orbits can be derived from the use of the GPS system. The GPS precision orbit determination system is a global differential GPS system that uses the onboard receiver and a global GPS tracking system.
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network with 14 stations. To date, the combination of the instrument set of the ALT, SSALT, TMRR, LRA, DORIS, and the GPSDR have supported both the radar altimetry and precision orbit determination measurements to provide unprecedented measurement of global sea level to less than 5 cm of uncertainty. This is an extreme improvement on the measurement of sea level available to oceanographers for deriving ocean circulation and is significantly below the prelaunch requirement of 13.3 cm.

4. SATELLITE SYSTEM

A major contributor to the measurements of TOPEX/POSEIDON has been making is the satellite. The selection and design of the TOPEX/POSEIDON satellite and instrument set, which operates at an altitude of 1334 km, required instrumentation that would survive and perform in a radiation environment that is significantly above what most Earth-orbiting satellites endure. The satellite design also provides a high degree of sensitivity to the requirements of the Precision Orbi-Determination Team. This requires a high degree of knowledge of the thermal condition of the satellite and knowledge of the inclination of the solar panel with respect to the Sun. This satellite design and implementation was highly sensitive to providing a platform for the total measurement required for TOPEX/POSEIDON.

Satellite configuration

The satellite is shown in Fig. 1. The satellite mass is about 2400 kg. It is about 5.8 m long, and consists of two elements, the Multimission Modular Spacecraft (MMS) and the Instrument Module (IM).

The MMS is a flight-proven NASA satellite bus, which has a triangular cross-section, composed of three subsystem modules—the Modular Attitude Control System, the Modular Power System, and the Command and Data Handling System arrayed on a triangular structure, with a propulsion module on the end of the structure. Each subsystem module is housed in a rectangular box about 1 m on a side and 0.5 m deep. A propulsion module is attached to the end of the MMS bus, with an additional tank tucked inside the triangular structure. Other elements of the MMS include the pyrotechnic functions for mechanical deployments, etc., and the ESAM, which contains the Earth Sensor Assemblies (ESAs).

The mission-unique elements of the satellite are in the IM. "The sensor electronics are mounted within the module, as are the solar array and the control electronics for the HGA in Antenna (HGA) two-axis articulation. Mounted externally are the solar array, the HGA and the low-gain antenna (Omnis) for telecommunications, and the Frequency Reference Unit (FRU). The FRU is an ultrastable oscillator, which supplies a 5-MHz signal to the ALT and other derived frequencies to other subsystems. A special interface unit (IMI U) is included to connect these mission-unique designs to the standard MMS data system. The solar array is composed of four 3 x 2 m panels, and provides 2260 W of power after 5 years in orbit. It articulates about the –Y axis. The HGA and the GPS receiver antenna are mounted on masts in order to avoid RF interference with the articulating solar array.

Attitude control

The satellite attitude is defined by the model of the orbit (the ephemeris) carried in the onboard computer (OBC). Once it is established by using external references, the attitude is maintained by the inertial reference unit. The errors* slowly build up in this reference are removed by periodic measurements of sun and stars positions, from attitude and the sun sensor, and the Advanced Star Trackers (ASTRAS), respectively. Since the "perfect" attitude is in the model in the satellite, it was straightforward to control.

| Table 1. Preliminary assessment of measurement accuracies (1 sigma values in cm) |
|-----------------------------------|--------|--------|
| Altimeter range                   | Alt    | Requirement |
| Altimeter noise                   | 1.7    | 2.0     |
| EM bias                           | 2.0    | 2.0     |
| Skewness                          | 1.2    | 1.0     |
| Ionosphere                        | 0.8    | 2.2     |
| Dry troposphere                   | 0.7    | 0.7     |
| Wet troposphere                   | 1.2    | 1.2     |
| Total atmospheric range           | 3.2    | 4.0     |
| Radial orbit height               | 2.5    | 12.8    |
| Single-pass scale height          | 4.7    | 13.4    |

* Based on 1 e data rate and significant wave height (SWH) ~ 2 m.
Tab 2. Error budget for TOPEX/POSEIDON orbit (Radial Orbit Height)

<table>
<thead>
<tr>
<th>Error source</th>
<th>Mission specification (c)</th>
<th>Current estimate (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Radiation</td>
<td>6.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>GM (Earth's gravitational coefficient)</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Earth &amp; ocean tides</td>
<td>3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Station location</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>RSS absolute error</td>
<td>12.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>

1 Solar, Earth & thermal radiation.

include the geoid (the difference between the geometric and geodetic Earth) in the model. Attitude errors are removed by exciting the proper electromagnetic torquer and thus creating a torque using the Earth's magnetic field to correct the error. The onboard parameters must be updated once a week.

TOPEX/POSEIDON carries Earth Sensor Assemblies, which are used early to establish the operational attitude control mode and whenever emergencies might require them. In initial operations in flight, it was determined that the satellite was not pointing perfectly, as observed in altimeter and Earth sensor data. Since all of the attitude sensor data are referenced to the OBC ephemeris, the software contains parameters that set the biases for each sensor. By using the model estimates, and adjusting the biases analytically, a “best” set of parameters can be estimated to minimize the pointing error, including the altimeter-sensed error. This was successfully done in the initial verification operational period, as is explained later.

Electrical power

In order to provide adequate electrical power to the satellite subsystems, the satellite was designed to maintain the solar array normal to the Sun. The

![Image of ocean eddies](https://example.com/oceaneddies.jpg)

Fig. 3. Variability of ocean eddies (cm). Ocean eddies are swirls of water current that are spun off from a roiling current or that are forced by wind; whirlpools are one type of eddy. Ocean eddies may persist for weeks or months, have diameters of tens to hundreds of kilometers, and extend to great depths in the oceans. These currents play an important role in ocean circulation by transporting an enormous amount of heat as well as salt, nutrients, and other chemical substances in the oceans. For example, eddies carry warm water from the equator to the poles. Eddies may be thought of as oceanic “weather” and thus play a critical role in Earth’s climate and biogeochemical systems.

The image, created from TOPEX/POSEIDON data, shows the locations of eddies and the average sea-surface height changes they caused in Earth’s oceans over one full year, from September 1992 to September 1993. The sea level below the image indicates the size of typical changes in the height of the sea surface in different regions.

The greatest changes in sea-surface height, over 25 cm (indicated by white), correspond to the most rapidly changing eddies. These occur mainly in regions where strong ocean currents are located, including the Gulf Stream off the east coast of the United States, the Kuroshio off the coast of Japan, the Loop Current in the Gulf of Mexico, the East Australian Current, the Agulhas Current south of South Africa, the convergence of the Brazil Current and the Falkland Current off the central east coast of South America, and the Mozambique Current between Madagascar and Africa. A chain of secondary highs can be seen north of Antarctica, along the path of the Antarctic Circumpolar Current.
method selected for accomplishing this in a non-Sun-synchronous orbit is to rotate the solar arrays in a one-axis, and rotate (yaw) the satellite as the other degree of freedom. The satellite's attitude control concept is well suited to this, as the location of the Sun is well known in the satellite orbit model. The precise array (pitch) angle is controlled by the Solar Array Drive Assembly (SADA), which employs a digital counter to maintain the proper angle within 10°.

The electrical power for the satellite on the nightside of the Earth (occultation) is supplied by three NASA standard nickel-cadmium batteries, which are recharged during the Sun-lit portion of the orbit. Recent NASA projects with MS-based power systems have experienced problems in-flight with these batteries, such that a special "1.1C" management strategy was adopted from launch on TOPEX/POSEIDON. Specific control of the charging profile in the charge controller and off-setting the array pitch angle to the Sun by about 50° are used to maintain the peak charge current at less than 20A, and the ratio of energy-in to energy-out to 10.5 ± 3%. These measures and the fact that, for TOPEX/POSEIDON, the power subsystem structure was designed with heat pipes to maintain uniform battery temperatures have provided an environment in which the batteries have behaved very well for the nearly 2 years of operation to date.

Command and data handling

The satellite sensors acquire data continuously at a rate of 16 kb/s (including engineering and status
These data are recorded onboard and replayed through the NASA Tracking and Data Relay Satellites (TDRSs) three times each day.

To provide data to the ground in all of the planned modes of ground system operations, the satellite acquires both the sensor data and the engineering and status data from the support subsystems in two formatted data streams. The basic engineering data are provided in a 1 kb/s data stream. This stream can be provided to the ground as a separate channel, and also is embedded in the various 16 kb/s data streams available. The satellite has three NASA Standard Tape Recorders on which all acquired data are recorded for later playback to the ground. The strategy for doing this is a function of the ground data acquisition services being used, as will be discussed later.

Satellite commands can be accomplished with real-time ground commands executed immediately on the satellite, or by onboard stored commands contained in the onboard computer. Most planned sequence tasks are accomplished with the stored sequence.

The onboard computer also contains monitoring programs, which will detect out-of-tolerance conditions in attitude control, thermal, power, and operational state functions, and will provide safing actions based on the problem detected.

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**Fig. 5. Ocean dynamic topography (cm).** The ocean's Dynamic Topography. The seas of Earth are in constant motion. Large systems of highs and lows (similar to hills and valleys) develop in the oceans' surface as a result of sea currents. These highs and lows are permanent features of ocean circulation; their existence and basic structure do not change, but the details of these systems are constantly changing. Scientists have devised a way to measure these changes in height by defining the oceans' dynamic (changing) topography as a measure of sea level relative to the Earth's geoid, a surface on which Earth's gravity field is uniform. Using the Earth-orbiting TOPEX/POSEIDON satellite, oceanographers can form the first time map ocean topography with enough accuracy to study the large-scale current systems of the world's oceans. From these ocean topography maps, oceanographers can calculate the speed and direction of ocean currents in the same way that meteorologists use maps of atmospheric pressure to calculate the speed and direction of winds.

This map of ocean dynamic topography was produced using data obtained by the TOPEX/POSEIDON radar altimeters during the period September 1992 to September 1993, the satellite's first year of operation. The total relief (from high to low) shown in this image is about 2 m. The maximum sea elevation is located in the western Pacific Ocean northeast of the Philippines, and the minimum sea elevation is around Antarctica. In this image, ocean currents are represented by white arrows. The longer the arrow, the greater the speed of the current. Speeds greater than 10 cm/s are represented by thick arrows. Only average speeds of large currents are shown.

In the Northern Hemisphere, ocean currents flow clockwise around the highs of ocean topography and counterclockwise around the lows. This process is reversed in the Southern Hemisphere. The ocean's major current systems—such as Kuroshio (south and east of Japan), the Gulf Stream, and the Antarctic Circumpolar Current—are clearly visible in the image.
Since the OBC orbit models know where the TDRSs are in the satellite coordinate frame, the OBC is able to command the pointing of the antenna.

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Telecommunications

The normal data acquisition service utilized is the NASA TDRS System (TDRSS), This requires communicating through a geosynchronous relay satellite. The HGA is required to provide sufficient link gain to relay the 16 kbps data stream and the 512 kbps playback stream in the normal operations scenario. This antenna must be pointed at the TDRS in use. The OBC orbit models know where, in the satellite coordinate frame, the TDRSs are, and so the OBC commands the pointing of the antenna.

Orbit acquisition and maintenance

Two very different levels of satellite maneuver capability are present in the satellite design—operational maneuvers and trim (or maintenance) maneuvers of a few millimeters per second. Operational maneuvers are required to correct for launch vehicle errors and provide for additional delta velocity to attain the operational orbit needed with sufficient precision to avoid may trim maneuvers. Trim maneuvers are to maintain the orbit, once established, to a precision of a few percent.

Environmental design

Thermally, the satellite operation is a reasonably steady-state consumer of power and hence the thermal control in primarily passive. This is important to provide a constant thermal signature to the orbit determination process. For this satellite, 150 W of solar radiation error is equivalent to about 1 cm in radial position uncertainty. The solar array is a large contributor to the orbit determination model. Its thermal design was carefully modeled to amount for the solar radiation reflected and radiated from the array. Because the array has a 5°-100 temperature differential from sunside to shaded side of the array, the array warps from a planar surface. This provides significant forces to the satellite. These forces have been modeled in the orbit determination process. With the canting of the array away from sun-normal, in order to control battery charge current, a new force has been observed on the satellite. This "anomalous force" also was modeled, in this case after launch, to account for its effect on precision orbit determination and also on the predicted time for orbit maintenance maneuvers.

The satellite was very carefully designed to minimize the impact of the radiation environment. The solar array was oversized sufficiently to account for the degradation due to solar and trapped radiation, with a safety factor of 2. Thus, the array puts out excess power early in the mission and this allows the array pitch-angle offset. The MMS was analyzed for parts susceptibility. Methods such as ray tracing were used to calculate the specific radiation levels expected extra shielding, etc. Processors were determined to be SSALT and radiometer acquiring data simultaneously. In parallel, the DORIS is on the receive mode (operated through CNES), and the GPSDR is operating as an experiment. The integration of these sensors is, however, somewhat more involved, For equipment safety reasons, since the ALT and SSALT share the same antenna, it is a requirement that the SSALT and ALT not be in track mode simultaneously. The SSALT is operated in the ALT about 10% of the time.

Precision orbit determination

The TOPEX/POSEIDON mission requires that the radial position of the satellite be determined with an accuracy of better than 13 cm. The total mission performance to date has this requirement being accomplished at less than 4 cm. The process and the activities before launch contributed significantly to this difference. The requirements and the actual performance. Initially the TOPEX Project had established the TOPEX Precision Orbit Determination Team, which was a joint effort between NASA Goddard Space Flight Center and the University of Texas at Austin, with the collaboration of the University of Colorado and the Jet Propulsion Laboratory. During the years prior to launch, this
Precision Orbit Determination Team defined, improved, and calibrated the precision orbit determination processing system. After a joint project was established with CNES, the team was enhanced with French participation. Significant accomplishments included increasing the accuracy of the gravity and surface force models, and also improving the performance of the satellite laser-ranging systems used by NASA for the precision orbit determination, as well as the DORIS of the tracking system used by CNES for its precision orbit determination. Results of all these efforts prior to launch led to orbit accuracies for TOPEX/POSEIDON that are significantly improved over the original mission requirement. Performance of the Precision Orbit Determination Team is a collaborative effort between NASA and CNES and the total analyses use all data types in one fashion or another to provide the best orbits available to the scientific community. Primarily, use is made of laser and DORIS data and some selected gravity field tuning has used GPS data. This has provided unprecedented knowledge of the satellite in space relative to the Earth's mass with an rrs error of less than 4 cm.

Verification process

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 and verification effort: Point Conception off the coast of California, and Lampedusa Island in the Mediterranean Sea. Verification campaigns have also been conducted by mission scientists 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 and other force models, as well as tracking station coordinates for computing the precise orbit for the mission.

At Point Conception, NASA installed sophisticated scientific equipment on an oil platform, which is owned and operated by Texaco Oil Company, to obtain surface measurements used for calibrating the two altimeters. The instrument complement consists of three tide gauges for measuring sea level, a GPS receiver for measuring the position of and Doppler, a water vapor radiometer for calibrating tropospheric path delay, and ancillary equipment used to measure relative humidity, barometric pressure, water temperature, water conductivity, and air temperature. The calibration methodology is illustrated in Fig. 2 where, as the satellite overflies the platform, it is observed by laser, GPS, and DORIS tracking systems. The altitude of the satellite at the time-of-closest approach to the platform is determined using precision orbit determination techniques. The position of the verification site is established by reducing data obtained from a GPS receiver located at the site, In situ measurements of sea level relative to the GPS receiver are obtained from tide gauges.

The Verification Phase was completed at the end of February 1993. A workshop involving the mission engineers and scientists was then held 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 [1]. After minor modification of the science algorithms based on the workshop results, the mission's ground system began processing and distributing the Geophysical Data Record (GDR) and the baseline science data product of the mission in late May 1993.

5. SCIENCE

Current results

As indicated previously, the major verification workshop took place in February 1993 at the Jet Propulsion Laboratory, Pasadena, California, and provided the initial evaluation of the mission performance. Subsequent to that, the Science Working Team met in Toulouse, France, in December 1993, to reassess the results of the data being provided by the TOPEX/POSEIDON mission and also to further exchange preliminary science results from the mission. One of the key factors in evaluating the TOPEX/POSEIDON data act is the preliminary assessment of the measurement accuracies. This is summarized in Table 1. The single-pass height measurement error is less than 5 cm versus the requirement of over 13 cm. The major contributing factor to this performance is the radial height measurement per.

This type of measurement, coupled with a very accurate caretaking of the orbit in a ±1 km repeat groundtrack every 10 days, yields an excellent quality of data being provided to the principal investigators and associated oceanographers for the first 2 years of the mission. It should also be noted that the ground-processing systems at both the Jet Propulsion Laboratory in Pasadena, California, and CNES in Toulouse, France, have produced data products (Geophysical Data Records) in an extremely timely manner. The systems with and provide data directly to the users are the Physical Oceanography Distributed Active Archive Center (PODAAC) at JPL and AVISO at CNES, Toulouse, France. They have been extremely responsive to the needs of the science users and effective with timely data deliveries. This has been a significant factor contributing to the success of TOPEX/POSEIDON to date.

Some of the current science results include:

- The TOPEX/POSEIDON data show very good agreement with ocean models indicating that the data can be successfully assimilated into global
The TOPEX/POSEidon mission has successfully completed its first 2 years of operation. The satellite, instrument complement, and the ground system, have been performing very well in providing unprecedented measurement accuracy in support of global oceanography. Scientific results have been very promising.

The seasonal variations of the mean wave number 2 anomalies have been significant in the Southern Ocean and the North Atlantic Ocean. The amplitude has been examined as a key factor in the surface wave energy. The seasonal change of the mean wave number 2 anomalies is approximately 3 times greater in the Southern Hemisphere than in the Northern Hemisphere.

The TOPEX/POSEidon data have reached 2 cm accuracy, a factor of 2 improvement over prior altimeter measurements. The TOPEX/POSEidon data have reached 2-3 cm accuracy in support of global oceanography. The TOPEX/POSEidon data have been performing well in providing unprecedented measurement accuracy in support of global oceanography. The TOPEX/POSEidon data have been performing well in providing unprecedented measurement accuracy in support of global oceanography.

The new tide models derived from the TOPEX/POSEidon data have replaced model tide JGM-2 with a factor of 2 improvement over prior altimeter measurements. These new tide models are being used to study the ocean circulation.

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