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

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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 Arianespace 42P 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. The accuracy of the measurement is attributed to the design and implementation of; the satellite and its instrument complement, the precision orbit 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 orbit determination process, and the verification process. In addition, current results provided by TOPEX/POSEIDON Science Investigators will be summarized.

I. Background

The TO PEX/POSEIDON mission, a joint French/U.S. collaborative effort, is obtaining spaceborne 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 the Seasat in 1978. Due to the results of Seasat and other subsequent altimetric missions in the 1980's, 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 was 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

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TOPEX/POSEIDON Project Manager

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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 operations plans. As a result of the Seasat altimetric performance it was clear that any SeaSat-like mission would require precise 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---Austin, under the sponsorship of the TOPEX/POSEIDON Project, Today's results, which include a sea-level measurement of less than 5 cm, can be attributed, to a significant degree, to this prelaunch 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 instruments, are provided to all science investigators. CNES provided a dedicated Ariane 42P, which launched the TOPEX/POSEIDON satellite into its orbit. CNES also provides a set of POSEIDON instrumentation, namely, the solid-state altimeter (SSALT) and the Dopper 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 experimental GPS receiver. NASA provides the tracking data relay system services to support command, control, and data acquisition and conducts the mission operations.

II. 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 maneuver adjustments to place it into its operational orbit. These six maneuvers placed the satellite into its operational orbit which is a 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 tidal 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 of315 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 within ±1 km, After insertion into the operational orbit maintenance maneuvers are required to maintain the ± 1 km ground track every 10 days, Six maintenance maneuvers have been performed during the first two years. The average time between these maneuvers was 117 days. The prelaunch requirement was 30 days maximum, 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 two 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.

III. 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 operationat and experimental sensors as follows:

(1) 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 by Satellite (DORIS) tracking System Receiver (CNES)

(2) Experimental Sensors
  (a) Single-Frequency Solid-State Radar Altimeter (SSALT) (CNES)

  (b) Global Positioning System Demonstration Receiver (GPSDR) (NASA)

The NASA ammeter operates at 13.6 GHz (Ku-band) and 5.3 GHz (C-band) simultaneously and is 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 provide a correction for 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-meter-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 the measurement of sea-surface microwave brightness temperature at three frequencies(18 GHz, 21 GHz, and 37 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 onboard receiver and a network of 40—50 ground transmitting 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 free electrons and tracking data. Therefore the total content of the ions-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 network with 14 stations. To date, the combination of the instrument set of the ALT, SSALT, TMR, LRA, DORIS, and the GPSDR have supported both the radar altimetry and precision orbit determination measurements to provide an unprecedented measurement of global sea level of less than 5 cm of uncertainty, This is an extreme improvement of the measurement of sea level available to oceanographers for deriving ocean circulation and is significantly less than the prelaunch requirement of 13.3 cm.

IV. Satellite System

A major contributor to the measurements which 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 Orbit 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 Figure 1. The satellite mass is about 2400 kg. it is about 5.8 meter 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 meter on a side and 0.5 meter deep. A propulsion module is attached to the end of the MMS bus, with an additional tank tucked inside the

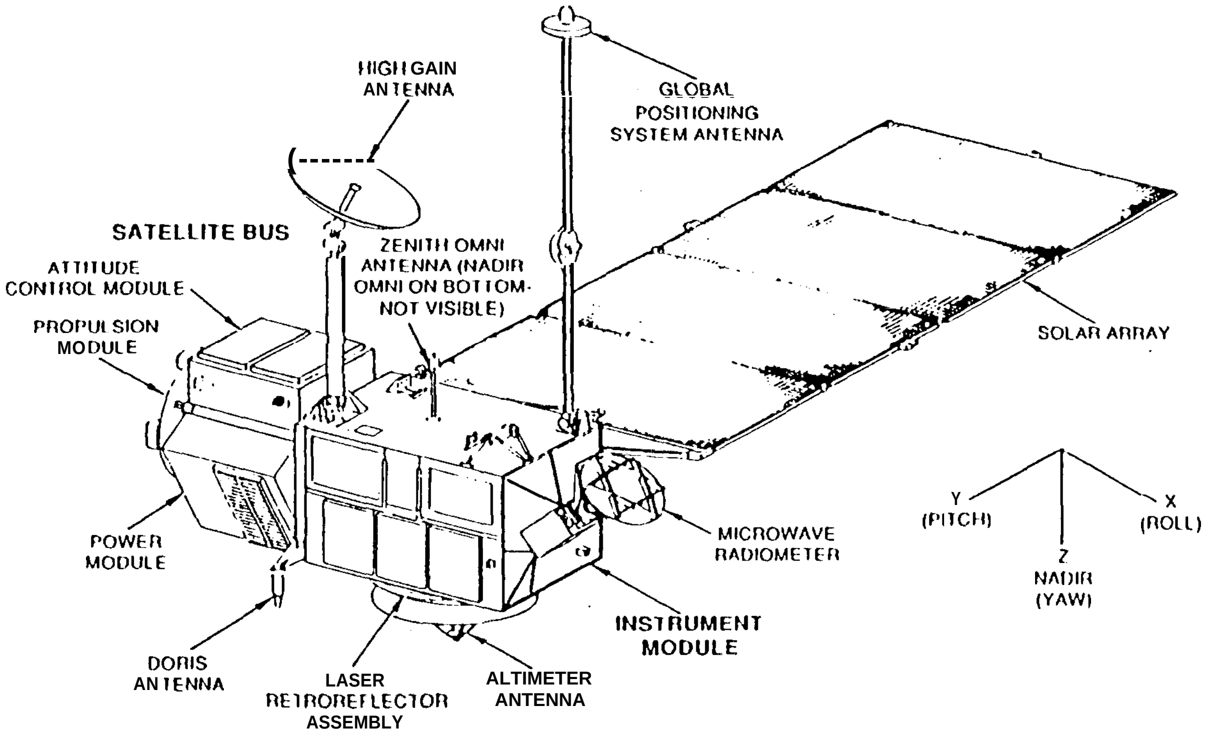

Figure 1. TOPEX/POSEIDON Satellite - Deployed Configuration (+Y View)

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 drive assembly and the control electronics for the High Gain Antenna (I-IGA) two-axis articulation. Mounted externally are the solar array, the HGA and the low-gain antennas (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 (IMIU) is included to connect these mission-unique designs to the standard MMS data system, The solar array is composed of four 3-m x 2-m panels, and provides 2260 watts 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 a 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 which slowly build up in this reference are removed by periodic measurements of sun and star positions, from the digital fine sun sensor, and the Advanced Star Trackers (ASTRAs), respectively. Since the “perfect’ attitude is in the model in the satellite, it was straightforward to include the geoid (the difference between the geometric and the 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 method selected for accomplishing this in a non- Sun-synchronous orbit is to rotate the solar arrays in 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 1°.

?-he 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 MMS-based power systems have experienced problems in-flight with these batteries, such that a special "TLC" 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 20 A, and the ratio of energy-in to energy-out to 105 &30A. 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 two 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 telemetry). 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 commanding 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.

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 kb/s data stream, and the 512 kb/s playback data 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, The maneuvers required to correct for launch vehicle errors and provide the additional delta velocity to attain the operational orbit needed to be on the order of several meters per second, with precision sufficient to avoid many trim maneuvers. The trim maneuvers, however, along with the maneuvers to maintain the orbit once established, are on the order of a few millimeters per second, with precision of a few percent, These maintenance maneuvers are needed since orbit drag will eventually reduce the orbit semi-major axis sufficiently to cause the ground track to stray outside of the ±1-km corridor.

These capabilities are provided by the monopropellant hydrazine blow-down system, with selectable combinations of four 22-N thrusters or four 1-N thrusters (eight additional 1-N thrusters are provided for attitude control during the maneuver). The OBC controls the total thrust on time and the firing pattern to assure that the net thrust vector is through the center of mass. The tanks carried 217 kg at launch, and currently have enough remaining to provide for many years of orbit maintenance, Should the need arise, the satellite could be moved to a lower orbit, out of the radiation environment,

Environmental Design

Thermally, the satellite operation is a reasonably steady-state consumer of power, and hence the thermal control is primarily passive. This is important to provide a constant thermal signature to the orbit determination process. For this satellite, 150 W of thermal radiation modelling error is equivalent to about 1 cm in radial orbit position uncertainty. The solar array is a large contributor to the orbit determination model, Its thermal design was carefully modelled to account for the solar radiation reflected and reradiated from the array. Because the array has a 50—10" 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 modelled in the ground-based 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 modelled, 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 at the part locations. Where needed, extra shielding, radiation-hard parts, or both were used. Processors were analyzed for single-event upset susceptibility, error detection and correction routines were employed (as in the ALT), or the impact was determined to be tolerable (as in the DORIS, SSALT, and GPSDR).

The dynamic environment was dictated by the loads imposed by the Ariane-42P launch environment, Since these vehicles had not been flown before, the initial estimates had relatively large uncertainties, which eventually resulted *in* a late change upward in the acoustic loads, Nevertheless, the TOPEX/POSEIDON structural and dynamic design was demonstrated through coupled loads analyses, modal analyses and tests, and eventually one-axis sine vibration.

Sensor Integration

The satellite sensor operations scenario is very simple — the ALT is on, in track mode, with the radiometer acquiring data simultaneously. in parallel, the DORIS is on in 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 place of 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 rms. 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 between the requirement and the actual performance, Initally 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—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 the unprecedented knowledge of the satellite in space relative to the Earth's mass with an rms error of less than 4 cm.

Verification Process

During the first six 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 positionof the platform, and for calibrating ionospheric path delay, 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 Figure 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 guages.

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 (Fu, 1993). 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.

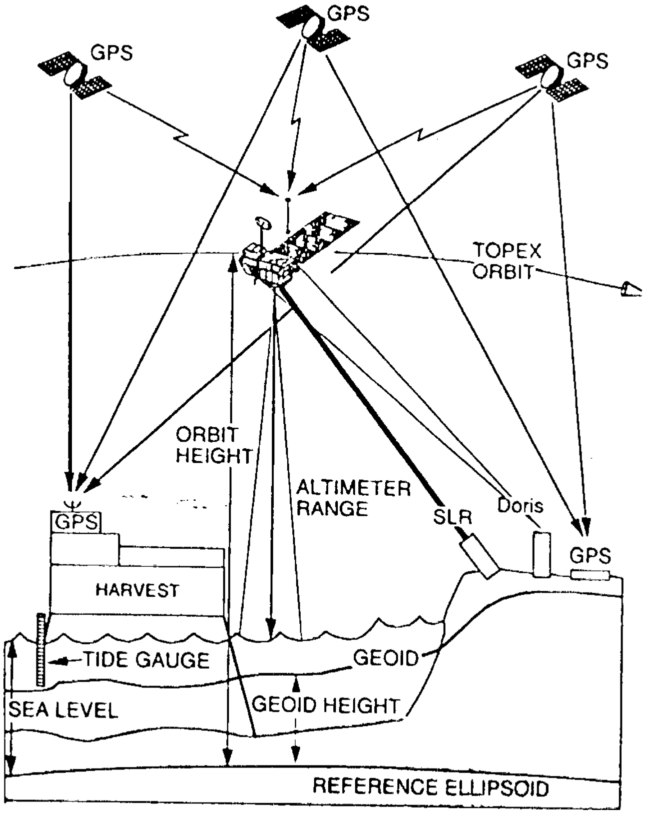

Figure 2. Calibration Methodology

V. Science

Current Results

As indicated previously, the major verification workshop, which took place in February 1993, at the Jet Propulsion Laboratory, Pasadena, California, 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 set is the preliminary assessment of the measurement accuracies. This is summarized in Table 1, The single-pass height measurement is less than 5 cm versus the requirement of over 13** cm. The major contributing factor to this performance is the radial height measurement performance or the orbit. The orbit error budget is summarized in Table 2.

Table 1. Preliminary Assessment of Measurement Accuracies (1 sigma values in cm)

	ALT	Requirement
ALTIMETER RANGE(1)		
Altimeter Noise	1.7	2.0
EM Bias	2.0	2.0
Skewness	1.2	1.0
Ionosphere	0.5	2.2
Dry Troposphere	0.7	0.7
Wet Troposphere	1.2	1.2
Total Altimeter Range	3.2	4.0
Radial Orbit Height	3.5	12,8
Single-Pass Sea Height	4.7	13.4

(1) Based on l-see data rate and significant wave height (SWH) = 2m

Table 2. Error Budget for TOPEX/POSEIDION ORBIT (Radial Orbit Height)

Error Source	Mission Specification (cm)	Current Estimate (cm)
Gravity	10,0	2.0
Radiation pressure*	6.0	2.0
Atmosphere Drag	3.0	1.0
GM (Earth's Gravitational Coefficient)	2.0	1.0
Earth and Ocean Tides	3.0	1.0
Troposphere	1.0	<1.0
Station Location	2.0	1.0
RSS Absolute Error	12.8	3.5

*Solar, Earth and thermal radiation

This type of measurement, coupled with a very accurate caretaking of maintaining the orbit in a ±1-km repeat ground track every 10 days, yielded an excellent quality of data being provided to the principal investigators and associated oceanographers for the first two years of the mission, It should also be noted that the ground-processing systems at both the Jet Propulsion Laboratory in Pasadena, California, and at CNES in Toulouse, France, have produced data products (Geophysical Data Records) in an extremely timely manner. The systems which interface 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 ocean models for estimating the time involved in the three-dimensional field flow.
- The seasonal change of sea level in the Northern Hemisphere is approximately 50% larger than that in the Southern Hemisphere. This previously unknown asymmetry indicates that the air-sea-heat exchange is much stronger in the Northern Hemisphere.
- The TOPEX/POSEIDON data compares extremely well to the Pacific TOGA moored array, The comparison demonstrated the strength of that the TOPEX/POSEIDON sampling is detecting the 20-day instability waves that the TOGA array is not able to fully resolve.
- The geographically correlated orbit errors of TOPEX/POSEIDON have reached an unprecedented low level: 2 cm for the JGM-2 orbit and 1 cm for the JGM-3 orbit.
- The extremely low geographically correlated error has significantly enhanced the value of the data for studying the general circulation of the ocean. Demonstration has been made in the Atlantic Ocean,
- The new tide models derived from the TOPEX/POSEIDON data have reached 2--3 cm accuracy, a factor of two improvement of existing models.
- The new tide models have eliminated tides as a major error source for altimetric studies of ocean circulation.

These are just some of the science results from TOPEX/POSEIDON to date. There are a number of papers that can be used to obtain more information on the science results. Reference 1, 2, 5, 6, 7 and 8 are some of these.

Figures 3, 4, and 5 produced by Dr. Lee-Lueng Fu and his oceanographic group at the Jet Propulsion Laboratory, show some of the results from TOPEX/POSEIDON to date,

Conclusions

The TO PEX/POSEIDON mission has successfully completed its first two 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 ocean topography for science investigations. The overall measurement system has been providing data which have been assessed continuously over the two years with an rms accuracy of a single pass sea-level measurement that is less than 5 cm, This is a most significant improvement over the requirement of 13,7 cm. This overcall measurement performance being achieved can be attributed to a number of factors, starting with preproject planning. Recognition of the total mission as a measurement system in the preproject years was a factor. Strong collaboration and interaction between the science and engineering teams was also a key factor in obtaining these measurements today. The sensitivity of the engineering staffs at NASA and CNES to overall measurement requirements, which reflected into the design of the instrument suite as well as the satellite, was another factor. Total mission design, which later translated to mission operations, also maintained a high sensitivity to the objective of the measurement required. These are some of the key factors which have contributed significantly to the first two years of outstanding performance by TOPEX/POSEIDON.

However, all the major factors, management, scientific, and technical which contributed directly and indirectly to these outstanding two years have had a common critical characteristic across them all. TO PEW POSEIDON has been very fortunate to have a large percentage of all the men and women who have participated in it to be highly competent and extremely dedicated to this mission. This is the one overwhelming characteristic that has contributed most to TOPEX/POSEIDON's success.

References

1. Lee-Lueng Fu, Charles A. Yamarone, Edward J. Christensen, 'TOPEX/POSEIDON Mission Early Results,' presented at the 44th IAF Congress, October 1993, Graz, Austria.
2. Lee-Lueng Fu, Edward J. Christensen, Charles A. Yamarone, 'TOPEX/POSEIDON Mission Overview," submitted to JGR for special issue, 1994.
3. TOPEX/POSEIDON Project - Project Plan, Document JPL D-3635, Rev. A, dated July 1989.
4. TOPEX/POSEIDON Project - Mission Plan, Document No. D-6862, Rev. C, dated August 1991.
5. B. D. Tapley, J. C. Ries, G. W. Davis, R. J. Eanes, B. E. Schutz, C. K Shum, M, M. Watkins, Univ. Texas-Austin, J. A. Marshall, R. S. Nerem, B. H. Putney, Goddard Space Flight Center, S. M. Klosko, S. B, Luthcke, D. Pavlis, R. G, Williamson and N, P. Zelensky, Hughes STX Corporation, 'Precision Orbit Determination,' submitted to JGR for special issue, 1994,
6. L-L. Fu, M. Lefebvre and C. Wunsch, 'Precise Measurement of Sea Level from Space: The TOPEX/POSEIDON Mission,' submitted to JPL for special issue, 1994.
7. C. Wunsch, J.-F. Minster, L. Fu and C. Koblinsky, "The General Circulation and its Variability from TOPEX/POSEIDON Observations," submitted to JGR for special issue, 1994.
8. Lee-Lueng Fu, 'Global Sea Surface Height from TOPEX/POSEIDON: A Preliminary Look,' submitted to JGR for special issue, 1994.

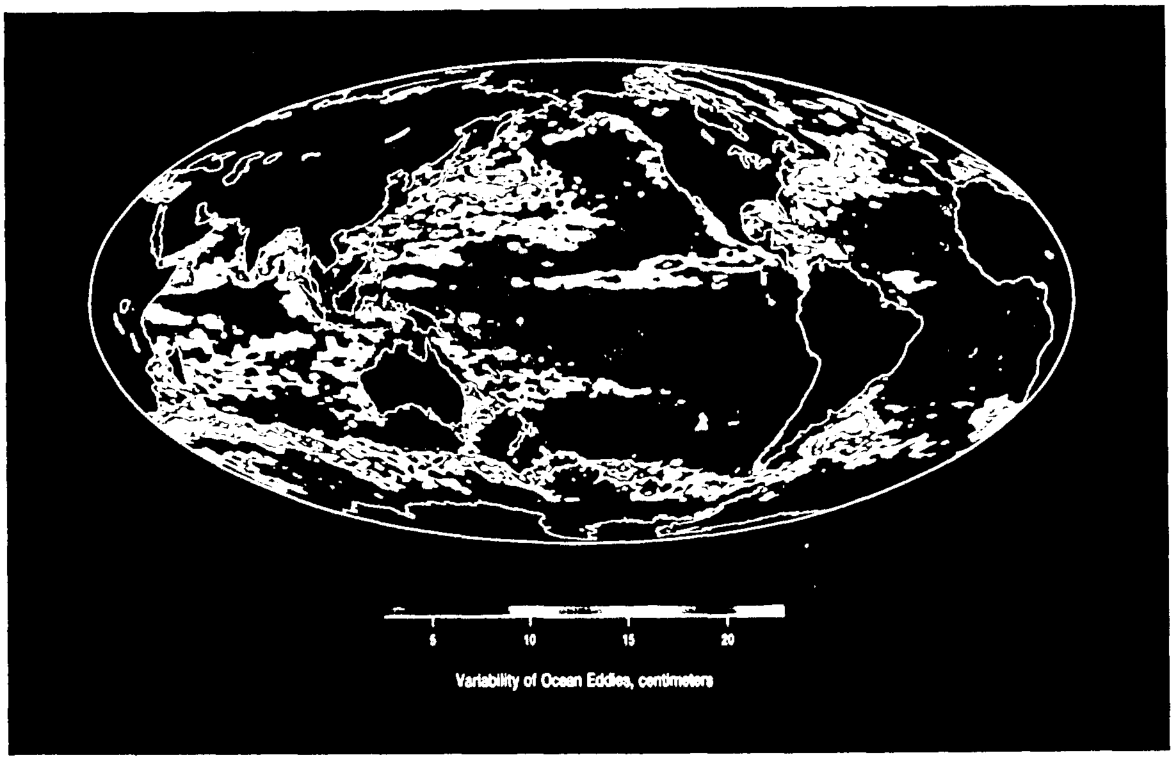

Figure 3. Variability of Ocean Eddies, centimeters

Ocean Eddies. Eddies are swirls of water currents that are spun off from a main current or that are forced by wind; whirlpools are one type of eddy. Ocean eddies may persist for weeks to 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,

This 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 scale below the image indicates the size of typical changes in the height of the sea surface in difference regions.

The greatest changes in sea-surface height, over **25** centimeters (indicated by white), correspond to the most rapidly rotating eddies. These occur mainly in regions where strong ocean currents are located - including the Gulf Stream off the east coast of the United States, 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.

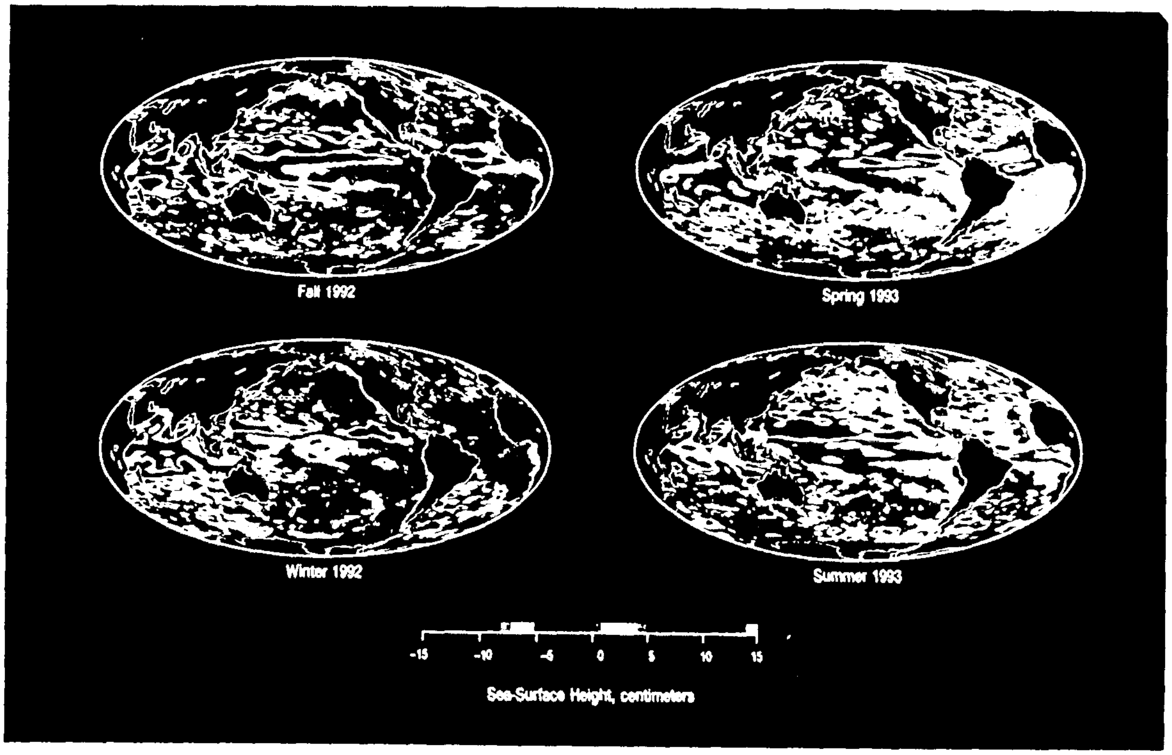

Figure 4. Sea-Surface Height, Centimeters

Ocean Seasons. These four maps are based on observations of sea level made by the Earth-orbiting TOPEX/POSEIDON satellite, during the four seasons from September 1992 through August 1993. Each map represents a seasonal variation of sea level from its annual average.

At temperate latitudes (20 to 50 degrees north and south), the seasonal sea-level change is dominated by the heating and cooling of the upper layer of the oceans. The highest sea level is observed in fall when the temperature of the upper ocean layer is highest after the solar heating of summer, The lowest sea level is found during the spring off the east coast of the continents in the Northern Hemisphere, where the cold continental winds, blowing from continent to ocean during the winter, remove an enormous amount of oceanic heat, The average seasonal sea-level change is about twice as large in the Northern Hemisphere as in the Southern Hemisphere. This is partly the result of the larger oceanic areas in the Southern Hemisphere, which moderate seasonal changes.

In the tropics, the sea level is primarily controlled by wind. The zonal bands of high and low sea levels across the Pacific and Atlantic Oceans correspond to the seasonal variations of the equatorial counter-current systems in response to the seasonal cycle of the equatorial trade winds. These eastward-flowing currents reach their maximum strengths during November and minimum during May. The sea-level change in the Indian Ocean is the most seasonal among the three oceans. As a result of seasonal monsoon winds, patterns of high and low sea levels that are mirror images can be seen six months apart.

These first global views of the oceans' "four seasons" are possible because TOPEX/POSEIDON is measuring global sea-level variability with an unprecedented accuracy, After several years of observations, oceanographers will create a very precise description of the seasonal and year-to-year changes in the world-ocean surface circulation, Incorporating these data into global ocean models will lead to a much better understanding of the oceans' role in climate change.

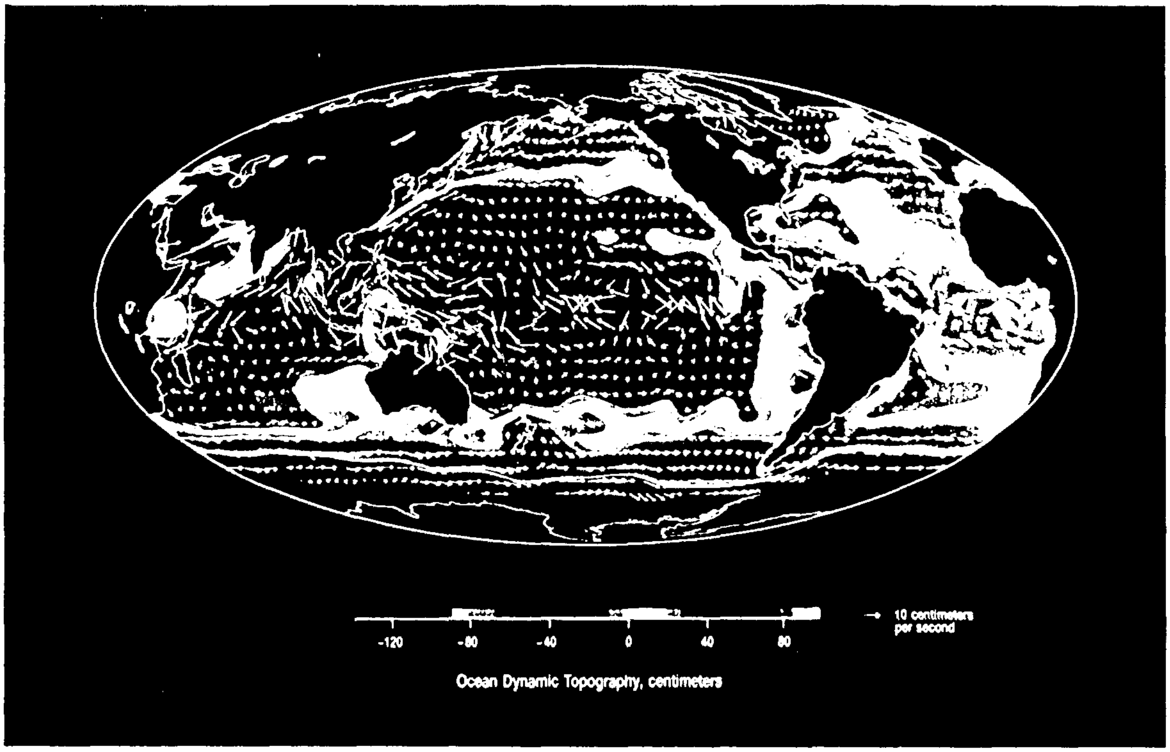

Figure 5. Ocean Dynamic Topography, centimeters

The Oceans' 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 for 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 meters. 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 centimeters per second 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 oceans' 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.