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ABSTRACT

This is the Boeing Aerospace Company's report on the TOPEX Mission Option Study conducted for the Jet Propulsion Laboratory under Contract 956203.

Key Words

TOPEX
Options
Satellite
Subsystems
Candidate

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1.0 INTRODUCTION

1.1 Purpose

This document contains the report on the TOPEX Option Study conducted by the Boeing Aerospace Company (BAC) in performance of the Jet Propulsion Laboratory (JPL) Contract 956203.

1.2 Scope

The report is on the assessments conducted by BAC of candidate bus equipment from the Viking, Applications Explorer Mission (AEM), and Small Scientific Satellite (S-3) programs for application to the TOPEX Mission Options described in Exhibit 1 of the contract. The report also covers evaluations conducted of propulsion module equipment and subsystem candidates from the Applications Explorer Mission (AEM) Satellites and the Small Scientific Satellite (S-3) spacecraft for those TOPEX options.

In section 3 the BAC results for each of the study tasks 1 through 5 are provided, and brief descriptions of several subsystem concepts appropriate to the TOPEX options are given. These descriptions will consider performance characteristics of the subsystems.

In section 4 cost and availability information on the candidate equipment and subsystems will be provided.

Finally, section 5 gives a summary of the baseline system suggested by BAC and discusses considerations for a low cost TOPEX satellite.

2.0 TOPEX MISSION

2.1 Mission Description

The Ocean Dynamics Topography Experiment (TOPEX) is being developed by the JPL to establish a global model of the oceans using spacecraft-based, remote altitude measurement. Goals of the project are:

- To calculate the global distribution and variability of surface geostrophic currents using satellite altimetric measurements.

- To distribute these data to users (Principal Investigators) in a timely manner.

- To merge these surface observations with subsurface measurements over the global oceans for extended periods of time in order to study the general circulation of the ocean. This portion of the work will be conducted by a group of Principal Investigators chosen by NASA.

The experiment will map ocean topography utilizing corrected radar altimeter measurements made from a precisely known orbit over a three-to-five year period. Baseline project requirements and constraints were developed during Phase A mission and concepts study conducted by JPL. Additional study is required to assure TOPEX compliance with project cost constraints. Three mission options (including the baseline/Phase A conclusion) have been identified and are indicated below. The options employ somewhat different science payloads on the spacecraft, as well as other differences in mission operations, all intended to retain the mission scientific validity while exploring the cost-benefit options within the mission set. Each option provides for the NASA/ JPL selected system contractor to design, fabricate and test the satellite and to support the project during launch and operation of the mission.

2.2 Requirements Summary

The maximum TOPEX Option requirements can be summarized as follows:

2.2.1 Payload Accommodation

	Opt. 1	Opt. 2	Opt. 3
• Mass Requirements	190.5 kg	159.1 kg	210.1 kg
• Volume Requirements	TBD	TBD	TBD
• Power Requirements (24-32 VDC)	259 W	180 W	180 W
• Timing Signal	5 MHz	5 MHz	5 MHz
• Commands	20 @ 1/sec	20 @ 1/sec	20 @ 1/sec
· Data	16 bit	10 bit	16 bit
• Data Outputs	13,920 BPS	13,920 BPS	13,920 BPS
• Antenna			
· Size	2 m.dia	1 m.dia	1 m.dia
· Pointing at Nadir	$.15^0$	$.25^0$	$.25^0$
· Pointing Knowledge	$.05^0$	$.10^0$	$.10^0$
• Thermal			
· Operating	15 to 35°C	15 to 35°C	15 to 35°C
· Non-Operating	-20 to 60°C	-20 to 60°C	-20 to 60°C

2.2.2 Attitude Determination and Control

- Correction maneuvers as small as 10 mm/sec with accuracy of 1 mm/sec in track.
- Provide antenna pointing control/knowledge.
- Unmodeled accelerations $<10^{-10}$g.

2.2.3 Telecommunications

- TDRSS compatible uplink and downlink.
- Ground downlink capability - TDRSS compatible.

- Downlink on Q and I channels

	HIGH RATE		LOW RATE
TDRSS Q	480	-	48 KBPS
TDRSS I	2	-	2 KBPS
Ground Q	480	-	N/A KBPS
Ground I	2	-	N/A KBPS

2.2.4 Ascent Propulsion

- Shuttle Launched Mission ΔV

Option 1	550 m/sec
Option 2	390 m/sec
Option 3	290 m/sec

- Propulsion module shall be compatible with Space Shuttle vehicle.

2.2.5 Launch Vehicle Compatibility

Shuttle

- Shuttle command information relay at S-band to satellite at 1 KBPS - telemetry relay at 4 to 8 KBPS.
- Shuttle can supply 315 W power at 27 to 32 VDC.
- Envelope in Shuttle is a cylinder 4.57 m dia. x 18.3 m long

Delta

- 1334 kg injection capability for 3910
  1425 kg injection capability for 3920
- No injection propulsion module needed on TOPEX.
- Fitting standardized for the NASA multimission modular spacecraft.
- Envelope - Cylinder 2.18 m dia. x 4 m
  Tapered to a spherical nose 2.39 m beyond the cylinder.

2.2.6 Command and Data Handling

- 1 KBPS uplink - at least 512 commands to be stored - rollover in 6 days.
- Data storage @ 8 KBPS - playback rate up to 480 KBPS.

3.0 CANDIDATE EVALUATION

This section provides the BAC results for tasks 1 through 5 of the TOPEX Option Study.

3.1 Satellite Bus Candidate Identification

BAC has proposed to study the adaptation of the Swedish Space Corporations's Viking Satellite bus for the TOPEX options. This candidate was proposed principally because in an unmodified state it met the overall weight, volume and area over mass ratio requirements of the TOPEX mission. The following is a brief review of those considerations:

Based on the minimum payload carrying capability of the available launch vehicle options for TOPEX (1334 kg with the Delta 3910 vehicle) and the maximum instrument package mass for TOPEX (210.1 kg for Option 3) the TOPEX satellite bus should have a mass of less than 1123.9 kg. The unmodified Viking bus has a mass of 421 kg.

Considering the minimum volume envelope for TOPEX we see that the Delta launch vehicle constrains the platform to a cylinder 2.18 m in diameter and 4 m high. The unmodified Viking bus fits in a cylinder with a diameter of 1.84 m and a height of 0.49 m.

Exhibit 1 of the TOPEX Option Study specifies an area over mass ratio for each of the three options. The tightest requirement is for Option 1 and it specifies that the area over mass shall be less than 0.01 m^2/kg. The Viking satellite mass without the propulsion unit is (421-265) kg or 156 kg. The Option 1 payload for TOPEX is 190.5 kg. The Viking's edge on area is 1.84 x .49 or 0.9016 m^2. The TOPEX Option 1 payload is dominated by the 2 meter diameter parabolic antenna. Assuming a height of 0.5 m the edge on area of the antenna is 1 m^2.

The remainder of the payload consists of the 70 cm base laser retro-reflector and the altimeter and radiometer instruments. It is conservatively assumed that these are within 0.5 m^2 in edge on area. The resulting calculations are:

$$\frac{0.9016 + 1 + 0.5\ m^2}{156 + 190.5\ kg} = 0.00693\ m^2/kg$$

While the above considerations show that the unmodified Viking satisfies the TOPEX configuration boundaries, analysis of the functional requirements (see section 3.5 for a subsystem by subsystem analysis of the TOPEX requirements) for TOPEX against Viking, AEM, and S-3 shows that none of these satellite buses in an unmodified state will perform the TOPEX mission. The BAC study has considered subsystem concepts using elements of the AEM and S-3 designs and a baseline satellite concept has been formed around these for TOPEX. This concept is summarized in section 5.1 of this report.

3.2 Propulsion Module Candidate Identification

The Viking and S-3 spacecraft use Thiokol solid rocket motors for orbit adjust. These motors could be used for the ascent propulsion stage of a Shuttle launched TOPEX mission. A Hohmann transfer can be used with a pair of solid rocket motors to reach and circularize at the required operational altitude from a Shuttle orbit. This requires perigee ΔV's of approximately 279, 196, and 144 m/sec for Options 1, 2, and 3 respectively. The corresponding apogee kick ΔV's are 269, 191 and 142 m/sec.

Two Viking solid rocket motors (TE-M-442-2) could provide the ΔV's required for an Option 1 mission. This assumes placing a satellite of 1334 kg in an operational orbit, after separation of the ascent stage. The Delta payload equivalent mass is 1334 kg. The second stage solid rocket motors, and possibly the first as well, would have propellant off loaded and the first stage would have ballast added as required. Similarly, two S3-3 solid rocket motors (TE-M-521-5) would provide the ΔV's needed for the Option 2 mission. Mission Option 3 would be achieved by a pair of S3-1 solid rocket motors (TE-M-479) assisted by hydrazine thrusters as described below.

The orbital ascent would be performed under 3-axis control. At Shuttle release the spacecraft would be configured as shown in Figure 5.1.1. The first solid rocket motor burn would occur shortly after Shuttle release and would supply additional velocity sufficient to raise the apogee to the required operational altitude as shown in Table 3.2-1. The spacecraft would then perform a 180 degree pitch maneuver. Pyro actuated clamp release would allow spring separation of the spacecraft from the empty solid rocket motor. The spacecraft would then coast until apogee where the second solid rocket motor would be ignited to circularize the orbit. After the second stage solid propellant rocket motor burn another pyro actuated clamp release would allow spring separation of the second ascent propulsion stage. During the solid rocket burns four large hydrazine thrusters (numbered 9-12 in Figure 3.5.5-1) would be used for control to offset torques caused by alignment, positioning, and thrust vector errors of the solid rocket motors. These thrusters would also be used for vernier thrust magnitude adjustment at the end of a solid rocket motor burn to provide increased ΔV accuracy. The large hydrazine thrusters after initial orbital achievement would be cut off from further propellant supply by two valves in series in order to minimize propellant leakage. The orbit adjust subsystem thrusters described in paragraph 3.5.4 would be used to maintain 3-axis attitude control during all maneuvers.

It is anticipated that ascent propulsion structures, clamps, springs, and mechanisms weighing approximately 30 kg will need to be designed for the TOPEX Shuttle launch option. In addition, the Thiokol solid rocket motors will require propellant offloading and a triply redundant ignition system to meet Shuttle safety requirements.

Table 3.2-1 Propulsion Subsystem Motors and Thrust Levels#

Mission Option Altitude	I 1334 km	II 1000 km	III 800 km
Ascent Propulsion	7500 LB_f (TE-M-442-2)	3600 LB_f (TE-M-521-5)	2500 LB_f (TE-M-479)
Ascent Thrust Control	125 LB_f	75 LB_f	50 LB_f
Roll Control	11 LB_f	11 LB_f	11 LB_f
Pitch* and Yaw Control	42 LB_f	25 LB_f	17 LB_f

#Thrust levels are derived from preliminary analysis of forces needed to control alignment, positioning, and thrust vector disturbance torques.

*Pitch thrusters are also used for orbit trim.

The Heat Capacity Mapping Mission (HCMM) orbit adjust system study results will be included under section 3.5.4 of this report, because this unit would not be part of the separate propulsion module.

3.3 Development Status of Candidates

The BAC candidate bus is the conceptual design summarized in section 5.1 of this report. The development status of components of that concept is presented in Table 5.1-1.

The BAC candidate propulsion module is designed around Thiokol solid rocket motors which have been flown on the S-3 satellites or are part of Viking satellite design. The supporting structure and control electronics of the propulsion module would be new design around off-the-shelf components where applicable.

3.4 Description of Performance of Candidates

With respect to performance against the requirements of the TOPEX Mission options the BAC suggested conceptual design will be compatible for either

Shuttle or Delta launch. The payload accommodations requirements are met in all areas except for Option 1 antenna pointing accuracy. For Option 1, the suggested candidate would provide 0.17 1σ antenna pointing accuracy rather than the 0.15° required by TOPEX. The attitude determination requirements of TOPEX would be compatible with the BAC concept. By use of reaction wheels and magnetic torquing the on-orbit unmodeled accelerations would be minimized. On-orbit correction maneuvers would be controlled by using accelerometer controlled burns. The TDRSS compatible requirements have been integrated into the design of the candidate telecommunications equipment and requirements are met with a 3 db margin for the TDRSS link and a 6 db margin for the ground link. The ascent propulsion motor selections match the requirements for Options 2 and 3 closely; more significant vehicle ballasting would be required to fit the Thiokol TE-M-442-2 motors to the Option 1 mission requirements. The candidate command and data handling subsystem would be compatible with the onboard processing and storage requirements. The subsystem can handle payload and satellite subsystem interface communication and perform fault handling tasks. The real time command execution rate capability is 20 commands/second. The storage capacity with 24K memory words is 8K commands. The command uplink data rate is 1 kbps. Further study will be required to assess the 6 day clock rollover requirement as this requires a 46 bit clock which is larger than the available word length. The candidate spacecraft has at least 25 cm clearance on all sides for the Delta configuration and could be mounted crosswise in the Shuttle payload bay. The spacecraft will comply with all Shuttle payload and safety requirements.

3.5 Subsystem Descriptions

This section contains descriptive discussion of the studies conducted and results produced with respect to the major subsystem categories of the TOPEX mission satellite.

3.5.1 Structures

The Viking structural design provides capabilities appropriate to its

Ariane launch with another payload. .ts placement between the Ariane 3rd stage and the primary payload (SPOT) with the attendant structural interface and load requirements, was a driving consideration in the design of the Viking primary structure. That primary structure consists of a solid aluminum cylinder machined to produce the cross-sections and interfaces required. This cylinder transfers launch loads between Ariane and SPOT and also houses most of the Viking operational subsystem equipment. This cylinder also provides the base for attachments of the structure for the externally mounted payload instrumentation deck and solar panels. The perigee burn motor occupies one end of the cylinder while thermal control louvers and shunt heaters are exposed at the other (nearer to the payload deck).

Secondary structures include those which transfer loads from the perigee burn motor to the primary structure and support the octagonal payload deck, the solar panels, and the Viking subsystem components. The secondary structures use standard structural shapes and simple fittings, avoiding costly unique parts. (The payload deck to which customer furnished instruments are attached is mounted on the primary cylinder for alignment and receives secondary support from the solar array mounting structure.)

Examination of Viking structural characteristics for TOPEX application reveals only minimal commonality. First, the load carrying capabilities of the Viking cylinder are far greater than those required for TOPEX and retaining that design could thus constitute an unnecessary cost to the TOPEX program. Secondly, the TOPEX articulated solar panels would dictate a structural configuration significantly different from the support for body mounted panels used for Viking. Third, the approach to secondary structures for Viking, while it should be used to the greatest extent possible to control costs, is unlikely to prove adequate for the more stringent alignment and pointing requirements of the TOPEX instruments.

The AEM structural approach is a standard aluminum sheet and stringer design which provides a low cost and reliable design. Such a design would directly address the first two concerns from the Viking design, but the alignment stability of a structure of the AEM type would require special attention and the likelihood of design changes to conform to the TOPEX requirements would be significant.

Based on these considerations, TOPEX will require a new structural design. Low cost considerations will be applied to the constraints imposed by TOPEX scientific requirements, drawing on AEM and Viking techniques where possible. Requirements of alignment, stability, and view factors for the instruments will be addressed by an integrated structural and thermal design. Strength and stiffness factors will be tailored to the launch induced environment and launch vehicle interfaces will be provided with a preference for using standard adaptor equipment.

3.5.2 Telecommunications

The telecommunications requirements identified in the TOPEX Satellite Option Study, Exhibit 1 have been examined with the goal of providing a cost effective design. Because of the requirement for TDRSS compatibility the Viking, S-3, and AEM systems will not be applicable to TOPEX.

The basic telecommunications requirements (except for long service life) can be met with the NASA Standard Dual Mode (STDN/TDRSS) transponder by Motorola, a 20 watt power amplifier, a high power diplexer, RF switches, a low gain antenna and a high gain TDRSS-pointing antenna. It is noted that the requirement of a high data rate return link via TDRS requires the TDRS to be in the Single Access (SA) mode. For the 3 year to 5 year life mission, the transponder and the power amplifier require redundancy with suitable cross-strapping circuits.

The stressed links are the TOPEX-TDRS return links during the ascent and the operational phase. The ascent phase is the driver for the transmitter power level and the operational phase specifies the high gain antenna's gain. A 3 db margin assumed for the free space links points to a 20 watt transmitter and a 1.8 ft. diameter parabolic dish antenna. Antenna pointing may be effectively performed by providing step commands via the data link as well as by commands from the C & DH computer.

Use of the TOPEX-Ground link (Direct) requires the availability of S-band TDRSS compatible ground terminals. The 9 meter G-STDN ground terminals have been assumed to be converted to the TDRSS mode for this analysis. A 6 db margin is assumed for the direct links. The return link requires a 1 watt transmitter. In the forward link, the transmitter power must be low enough to prevent overdriving the Motorola transponder. The 1 kw - 10 kw GSTDN power level is too high and corrective measures are required at the ground site or in the satellite.

A detailed design study is required to achieve a reliable and low cost redundant cross-strapping concept. The design would be simplified if a 20 watt step-variable power amplifier were available. Currently Motorola is looking for support to develop such a power amplifier. Table 3.5.2-1 provides a listing of major components of the telecommunications subsystem.

Table 3.5.2-1 TOPEX Telecomm Parts

Item	Quantity	Source
NASA Standard Transponder (Motorola Dual Mode-STDN/TDRSS)	2	Motorola
20-Watt RD Amplifier	2	TRW (possibly Motorola)
High Power Diplexer (45 Watt Power Rating)	2	Wavecom
High Gain Antenna (1.8' Dish) with Gimbal	1	Boeing (like MVM-73)
Switches (Prelim.)		TRANSCO
DPDT	7	
SP-3T	2	

3.5.3 Electrical Power

The Viking power subsystem is a direct energy transfer approach wherein the power generated by the solar array is supplied directly to the loads and the battery without passing through any series connected power conditioning equipment. This results in a highly efficient and reliable system. The main bus power operates between 24 and 32 Vdc, the voltage limiter limiting the maximum voltage by dissipating excess energy through a shunt resistor panel.

An amp-hour meter integrates the battery current with time and monitors the battery state of charge (SOC). In addition, it provides a signal to the voltage limiter at 100% SOC. This signal causes the voltage to be switched from maximum charge level to one of seven preset (ground command selection) trickle charge levels. The trickle charge mode is also initiated by an over-temperature signal at a battery temperature of 36.7°C. Both of these trickle charge control signals can be overriden by ground command to return the voltage limiter to the maximum voltage setting of 31.2 $\pm$ 0.2 Vdc. In the discharge mode the amp-hour meter will provide a signal to the relay box to disconnect all non-essential loads should the battery SOC drop to 30% (as a result of failure to turn off payloads intended to be off during occultation). The disconnect signal is removed when the battery returns to 50% SOC.

Power distribution is provided by a Boeing built relay box.

For TOPEX we would recommend a direct energy transfer system based on the Viking concept. However, since the loads and cycling characteristics are significantly different from those of the Viking mission, adaptations of specific hardware in terms of power, cycling, and redundancy will be required. Individual components are discussed below.

The solar array for TOPEX, like those for Viking, AEM, etc., would be based on a Boeing made substrate (aluminum honeycomb) with the solar cells made and mounted by Spectrolab. Due to the nature of the orbit, articulation will be required after initial deployment.

These functions would be accomplished by means of techniques used for SAGE (AEM II), using redundant mechanical deployment and step motor driven articulation with an Adcole sunsensor providing the pointing signal. Based on the payload power loads for Option 1 of 263 W and the anticipated satellite loads of 251 W in sunlight (77.3 minutes minimum), 367 W during the 22 minutes of data transmission, and 259 W during (34.7 minute worst case) occultation, the solar array will be about 8.4 m^2. This provides 1230 Watts at the beginning of life (including effects of assembly losses, etc.) and 904 W at end of life (for a 10% margin at EOL). It is assumed that data transmission does not occur during occultation.

The battery requirements are beyond the reasonable capacity of the Philco Ford units used for Viking. The load of 522 W for 34.7 minutes produces a drain of 302 watt hours which at a basic bus voltage of 26 V requires 11.6 ampere hours. Given the life cycle vs. depth of discharge characteristics of the Viking battery (average cycles to failure at 10% depth of discharge is 25,000 cycles) an inordinate number of batteries (10 base, plus redundancy) would be required to even minimally meet this requirement and still would not provide adequate reliability. Therefore, it would be appropriate to switch to 20 amp hour batteries, in which case three (with a fourth for redundancy) would experience a maximum depth of discharge of less than 20%.

Power and battery control would also require revision of the Viking system. To take advantage of considerable commonality with an existing design, the Xerox Electro-Optical Systems designs for the P78-1 and the P80-1 provide an excellent starting point, lacking an existing directly applicable unit. The units provided were a power control shunt regulator and a battery charge controller. The P78-1 units were designed for a system including a 300 W solar array and three 12 amp hour batteries. That design has been modified for P80-1 to accommodate a 1.5 KW array and two 35 amp hour batteries. Since the control functions remained the same, this modification entailed upgrading of power handling capability from 10 to 50 amps, and resizing the chassis while the control circuitry was carried over intact. The amperage upgrade required changes from 20 gage wire and 10 amp relays to 12 and 16 gage wire and 50 amp contractors. The P80-1 unit also incorporates several power distribution functions and design for STS compatibility (currently undergoing qualification testing for STS). For TOPEX a straightforward packaging redesign would be in order, expanding to accommodate control for 4 batteries instead of two. A trade study would establish the choice between retaining power distribution in the battery controller and using a reconfigured Boeing built Relay Box as is used on Viking. The P80-1 power control shunt regulator consists of two identical boxes capable of handling 1.5K watts and may be applicable to TOPEX as is or with minor de-rating. These systems are fully redundant, including majority vote control.

Pyrotechnique switching on Viking is fully redundant to ensure firing. It will be adapted to the specific TOPEX requirements and to STS if required. Table 3.5.3-1 provides a listing of the major components of the electrical power subsystem.

Table 3.5.3-1 TOPEX Electrical Power Parts

Item	Quantity	Source
Solar Array	8.4 m^2	Spectrolab
Batteries	4	GE Cells
Power Control Shunt Regulator	2	EOS P80-1 Type
Battery Charge Controller & Relay Box	1 ea. May be combined	
Wiring (may require uprating of gage & redundancy)	1 harness	Boeing - like Viking

3.5.4 Propulsion

Orbit trim and orbit adjust require multiple maneuvers. Of the Viking, AEM, and S-3 systems only the AEM-HCMM provides a candidate orbit maintenance system. The HCMM Orbit Adjust Subsystem (OAS) was a simple blowdown hydrazine system. It consisted of a tank, rocket engine, fill and drain valves, pressure transducer, heaters, thermostats, stainless steel plumbing and aluminum sheet metal and extrusion supporting structure. All joints except the engine assembly connection were brazed to minimize leakage.

Components used in the OAS were flight proven; however, some had minor modifications to adapt them to the peculiar requirements of the OAS. The tank outlets were changed to stainless steel tubing to permit brazing and the rocket engine incorporated two valves in series for redundancy.

Heaters with thermostat controls on propellant lines and on tank support structures maintained temperatures between 10 and 60 degrees C. Heaters on engine valves and on the thrust chamber permitted heating of these units by command prior to use. Thermal control of the OAS module using the thermostat controlled heaters was verified in base module thermal tests.

Redundancy was provided where propellant valve leaks were a possibility. The rocket engine had series redundant solenoid valves and the N_2 and N_2H_4 fill and drain valves had external caps for flight, providing redundant seals. The brazed plumbing met the 10^{-6} scc/sec leakage specification for the system. Only the single rocket engine B-nut attachment was not redundant; however, frequent leak tests ensured that thermal and vibration environments did not result in B-nut leaks.

The HCMM OAS, which was designed for a one year life, had a single 0.24 m diameter 4.74 kg capacity hydrazine tank and a single 1.29 N thruster. For the TOPEX mission this is clearly inadequate. Greater thrust level, increased propellant capacity, and redundancy are required.

For TOPEX missions the candidate orbit adjust subsystem is a new system that is an assembly of flight-proven components and concepts. It would employ HCMM like valves, leak protection, heaters, and sensors with several larger propellant tanks and redundant thruster pairs for increased reliability. Thruster force would be increased to provide more rapid response for the more massive TOPEX spacecraft, and to assist in ascent propulsion control as shown in Table 3.2-1. All propellant joints would be welded to prevent leakage, and definitive leak tests would be performed in conjunction with thermal and vibration testing. The thrust levels provided for orbit maintenance are well below the 10 mm/sec minimum ΔV increment allowed, and the 1 mm/sec accuracy requirement should not be a problem.

Four hydrazine propellant tanks, sized for the necessary ΔV requirements and margins, would be manifolded into two groups of two tanks. All tanks would have fill and vent valves with redundant external seals. Each tank pair would have two pyro valves (normally closed) in parallel so that failure of one valve to open will not prevent a tank from being used. Each pyro valve would be manifolded to two parallel redundant filters from which fuel would be directed in parallel to three latch type propellant isolation valves which isolate thruster groups. The four large hydrazine thrusters form one group and have a second isolation valve in series to reduce leakage throughout the operational life of the mission when these thrusters will not be used. The thrusters are located as shown in Figure 3.5.5-2.

The candidate equipment associated with the ascent phase propulsion module is described under Section 3.2 above.

3.5.5 Guidance and Control

The attitude control subsystems from the S3 and the Viking satellites, which are spinners, are not applicable for the TOPEX mission because of the nadir pointing requirement of the TOPEX experiments.

The candidate which BAC suggests for the guidance and control subsystem for the TOPEX mission options is modified from designs flown on the Boeing

AEM Satellites.

A block diagram of the Candidate Guidance and Control system is shown in figure 3.5.5-1. The AEM system consisted of two scanwheels which determined pitch and roll attitude errors from the horizon sensors mounted inside the momentum wheels. Control of the yaw axis in our candidate system is accomplished by the momentum bias provided by the scanwheels and a pitch momentum wheel. (See Figure 3.5.5-2 for the definitions of control axes.) Control torques in roll and yaw are provided by three electromagnets mounted along the three orthogonal axes of the spacecraft. The excitation current applied to these electromagnets is controlled to interact with the earth's magnetic field.to provide the control torques. Pitch control is provided by wheel speed control of the pitch wheel and the scanwheels. Desaturation of the three wheels is provided by controlled torquing from electromagnets. This system is the candidate for the on orbit operation of the TOPEX during the satellite data taking portion of the mission. This candidate produces no external forces to disturb the TOPEX.orbit. The attitude determination and control error signals, the drive signals and power amplifiers to drive the scan wheels, the pitch momentum wheel, and the three electromagnets are provided by an attitude control electronics unit. A magnetometer is included in the system to measure the earth's magnetic field to determine the power level to be applied to the electromagnets. This candidate system is essentially the same as the one flown on the AEM satellites except for the addition of the pitch wheel. Control by use of a pitch wheel is included in the ITHACO system for the ERBS satellite. The pitch wheel selected for our candidate system is a flight wheel built by Sperry and flown on the HEAO program.

The AEM system can provide attitude control of about 0.5 degrees (3σ) in pitch and roll during the nonthrusting data taking portion of the mission. Assuming that the required accuracies for pointing the TOPEX radar altimeter antenna are 1σ numbers, the candidate is capable of providing required control for options 2 and 3 and near satisfactory control for Option 1. Yaw control will be less than 2 degrees (3σ), however, yaw pointing errors do

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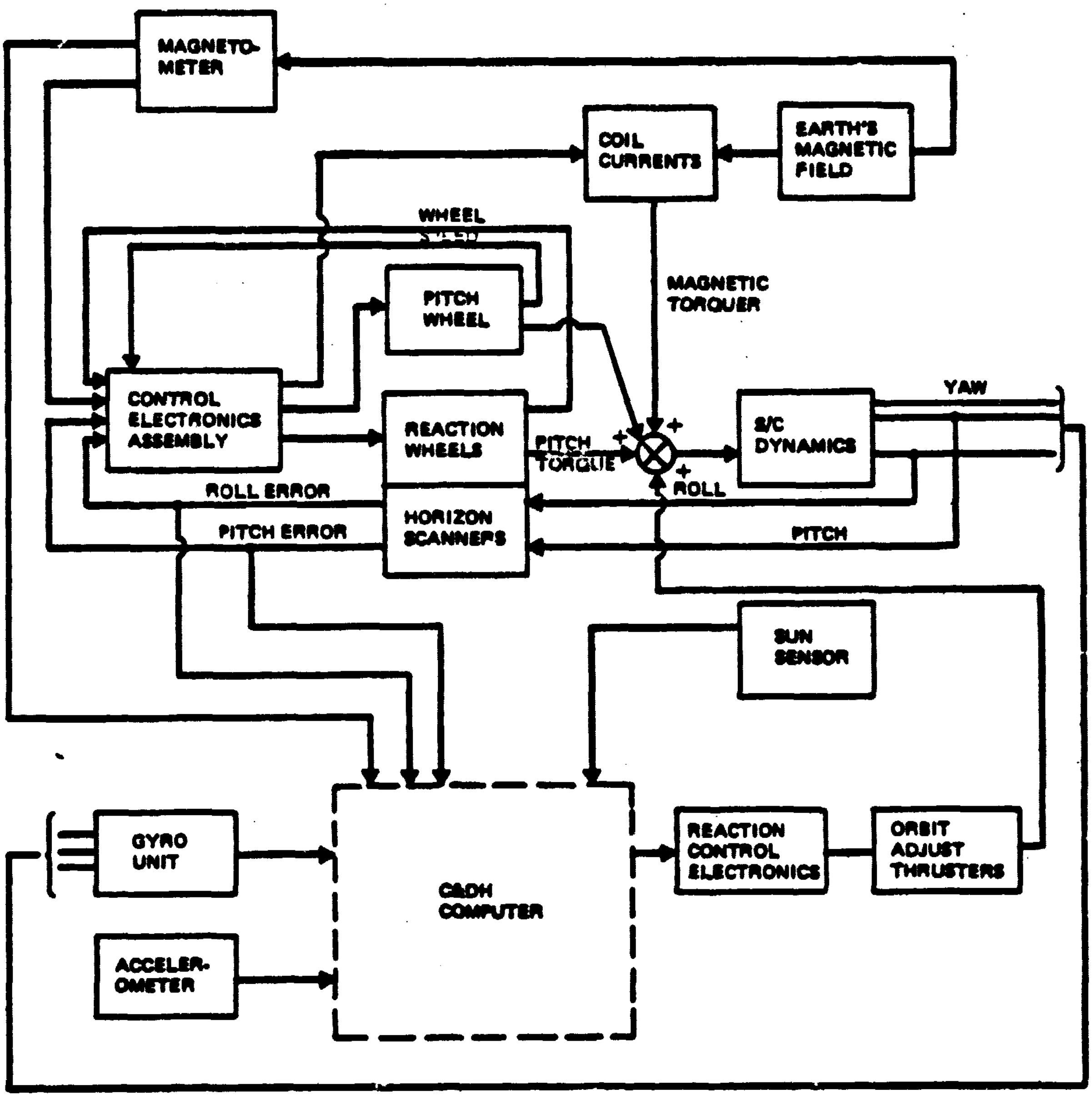

Figure 3.5.5-1. Attitude Determination and Control Subsystem Block Diagram

not contribute to pointing of the primary sensor set to the nadir. Attitude determination errors for the scanwheel system is less than 0.1 degrees (3σ) in pitch and roll. This satisfies 1σ attitude knowledge requirements for all three options. Attitude determination of the yaw axis is provided by the ADCOL sun sensor system that was used on the AEM. This data is transmitted to the ground for subsequent data analysis to obtain yaw attitude determination throughout the mission of up to 0.6 degrees (3σ).

The BAC candidate system provides attitude determination during ascent propulsion, orbit trim and orbit adjust by use of an on board gyro unit. The gyro unit is turned off between motor burns for on orbit operation. Integration of errors measured by the strapdown gyros is accomplished by computations in the on board computer, which is part of the Command and Data Handling subsystem (C&DH). Attitude errors are computed and orbit adjust thruster commands are generated by the C&DH computer. Thrust vector control torques during the injection motor solid rocket firings are provided by the orbit adjust thrusters which are located on the satellite to provide 3-axis control torques. Orientation of the orbit adjust thrusters is shown in Figure 3.5.5-2.

For thrust vector control during the solid rocket motor burns for orbit transfer, the candidate system uses thrusters 9 through 12 on Figure 3.5.5-2 for pitch and yaw control. These are operated in a normally on mode during those periods. This design was used successfully on the Boeing Burner II and Burner IIA programs. Roll control during orbit transfer burns will be provided by thrusters 5 through 8 operated in couples (see Figure 3.5.5-2 again).

For orbit trim and orbit adjust maneuvers, the orbit adjust thruster set 1 through 8 (see Figure 3.5.5-2) is used for 3 axis control and for linear thrusting. Three axis control is required for the velocity maneuvers since the momentum wheel control system has limited authority and would not maintain orientation accuracy during the periods of linear thrusting.

To control the magnitude of linear thrusting the orbit adjust thrusters are operated in a pulse width modulated mode from commands generated by the C&DH

	INJECTION	ON-ORBIT
PITCH CONTROL	10,12	1,4 OR ,3
YAW CONTROL	5, 6, 7, 8	5,8 OR 6,7
ROLL CONTROL	9, 11	5,7 OR 6, 8

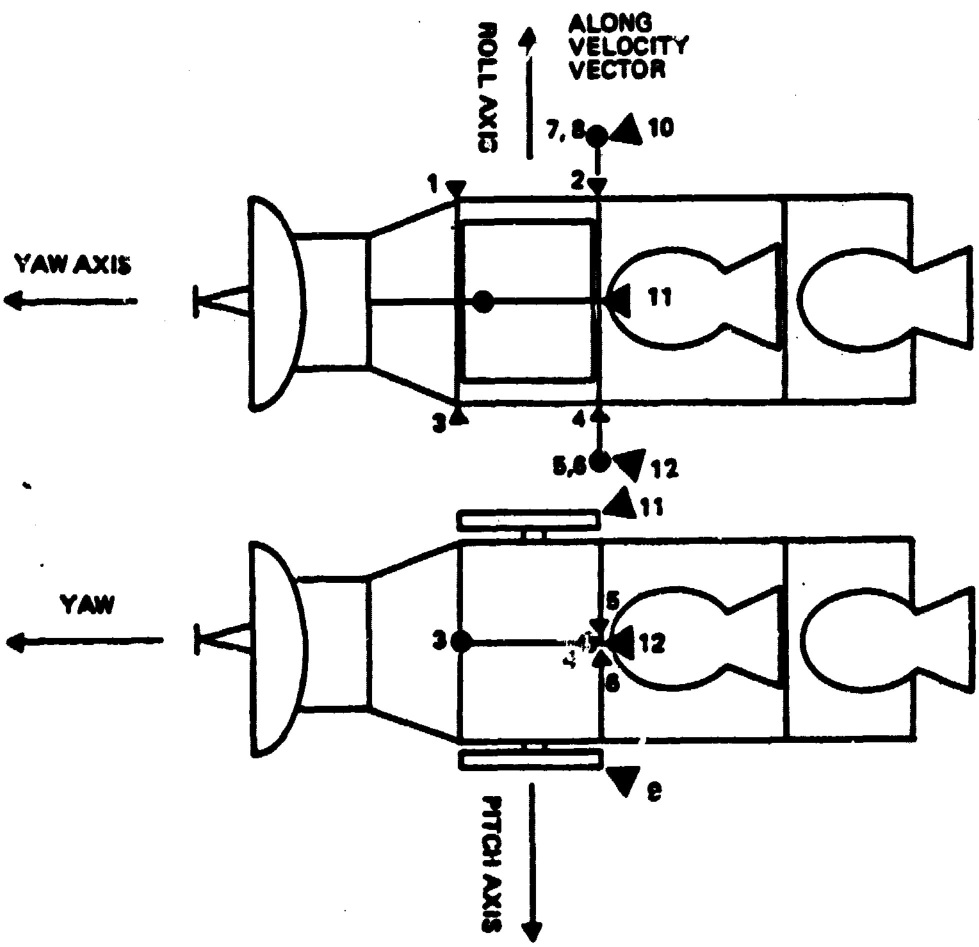

Figure 3.5.5-2. TOPEX Satellite (STS Launched Configuration) Reaction Control Orientation

computer. Accelerometer outputs are used to generate errors between the commanded and actual ΔV magnitude. The computer shuts off the thrusters when the integral of the measured pulses matches the commanded ΔV.

A summary of the guidance and control subsystem equipment is given in Table 3.5.5-1.

Table 3.5.5-1 TOPEX Guidance & Control Parts

Subsystem Assembly	Quantity	Source
Scanwheel B	2	Ithaco (NOAA, AEM)
Electromagnets - 200 Amp m^2	3	Ithaco (Viking)
Magnetometer		Ithaco (AEM)
Magnetometer Electronics	1	Ithaco (AEM)
Control Electronics for AEM type system	1	Ithaco (AEM, ERBS, NOAA)
Sun Sensor	1 set	Adcole (AEM, Viking)
Pitch Wheel - 40.7 N.M. Sec	1	Sperry (HEAO)
Gyro Unit	1	Kearfott SKIRO III
Accelerometer	1	? (SERT II)
Reaction Control Drive Electronics	1	New

3.5.6 Command and Data Handling Subsystem

The TOPEX satellite requires a redundant Command and Data Handling (C&DH) capability in order to protect against single point failure and meet the five year extended mission life requirements. The C&DH subsystem must provide TDRSS compatible interfaces with the satellite telecommunications for accepting redundant forward link command channels and providing redundant I&Q return link telemetry channels in accordance with NASA Goddard Specification S-813-45. In addition, the C&DH subsystem must interface with other satellite subsystems and payload elements.

Viking, AEM, and S3 C&DH subsystems do not meet these requirements. They are single thread systems that are not TDRSS compatible. Furthermore, command processing is at a rate of one command every two seconds with a 600 kbps command uplink. In addition, there is no onboard computational capability for Guidance and Control needs, nor is there logic to control switching between redundant components.

To meet TOPEX requirements the proposed candidate C&DH subsystem is the NASA standard Multimission Modular Spacecraft C&DH subsystem supplied by Fairchild. This system provides a modular redundant design that can be modified and repackaged to meet the TOPEX mission requirements. This subsystem has been employed in a number of NASA programs. The IBM NSSC-1, the Litton 4516-E or other computers could be used with the MMS data bus architecture. Onboard computation will be needed for ascent control in the Shuttle launch option and orbit trim maneuvers, but not for normal on orbit attitude control operation, as this is handled by analog devices in the Ithaco electronics package. Thus computer memory requirements should be considerably relaxed. Further study of the onboard data processing and memory storage requirements would be necessary to size and define the computational elements and to make a cost effective selection for TOPEX. In addition to design, areas requiring further consideration include signal conditioning, quantity and location of Remote Interface Units (RIU's), secondary power capacity and efficiency, command and measurement interfaces, shielding, and grounding.

Tape recorders are recommended for the mass storage requirements. The Odetics DDS-3100 series tape recorder is recommended for further study toward meeting the TOPEX requirements.

Efratom Inc., the supplier of ultrastable oscillators to the Air Force GPS satellites, indicates that the C&DH subsystem requirement can be readily met from a number of off-the-shelf designs. Further study is recommended before selecting a candidate approach.

4.0 COST AND AVAILABILITY INFORMATION

This section provides the cost and availability information against the work breakdown structure defined under Task 6 of the Contract Statement of Work. The system to which this information applies is the suggested concept identified in Section 5.1 of this report.

4.1 Cost Information

The cost information developed for the conceptual satellite for TOPEX Options 2 or 3 is given by Table 4.1-1.

4.1.1 Groundrules and Assumptions

1. This is a planning estimate only.

2. The estimate uses a mix of parametrically derived values and some direct inputs for NASA standard hardware.

3. Estimate in 1982 dollars, no fee included.

4. Hardware quantities and developmental status are summarized in Table 4.1-1. Maximum use of off-the-shelf hardware is attempted.

5. It was necessary to add a cost category called "Other" to the JPL WBS. This category covers system engineering, systems test and tooling.

6. The estimate is based on the protoflight concept where the test hardware becomes the flight hardware. Minimum hardware is built; the only extra hardware is in telecommunications and Guidance and Control.

7. This estimate covers contractor cost only and has no allowance for changes or spares.

Table 4.1-1 TOPEX Planning Estimate

1982 $ (Millions)

Item	Qty.	Design	Development Engineering	Test and Flight Hardware	Total
A. Management			5.4	2.0	7.4
B. Flight Hardware					
Structure	1	New	3.1	2.1	5.2
Telecommunications#	1.2	80% OTS	12.9	10.3	23.2
Electrical Power	1	80% New	2.8	1.2	4.0
Propulsion	1	80% OTS	4.0	2.3	6.3
Guidance & Control	1.2	80% OTS	4.2	2.0	6.2
Airborne Supt. EQ	1	New	2.8	1.9	4.7
C. Ground Supt. EQ	1 set		2.2*	In Development Value	2.2
D. Software			3.8		3.8
E. Other			7.3	1.0	8.3
TOTAL			48.5	22.8	71.3

#Includes C&DH subsystem

*Includes GSE hardware

OTS = Off-the-Shelf

4.2 Availability Information

The availability information for the BAC concept according to the work breakdown structure of the TOPEX option study contract is given by Table 4.2-1.

Table 4.2-1 Availabilities Relative to TOPEX

Item	Availability
A. Management	Currently Boeing Aerospace management is readily available for new programs.
B. Flight Hardware	
i. Structures	New design - would require 2½ to 3 years design, development, manufacturing & test flow time.
ii. Telecommunications	See Table 3.5.2-1 for source indication of various telemetry system components. The NASA standard C&DH system supplier (Fairchild) quotes 30 month delivery on that system.
iii. Electrical Power	Mostly new design. Note the P80-1 power distribution system is currently under development at EOS. Flow times of 20 to 25 months are typical for solar arrays.
iv. Propulsion	Mostly off-the-shelf solid and hydrazine thrusters. Rocket Research quotes 12 to 18 months for delivery of the hydrazine thrusters. For Thiokol TE-M-442-2 solid rocket motor, deliveries of 30 months are typical.
v. Guidance & Control	Mostly off-the-shelf components and existing designs from Ithaco, Kearfott and Sperry. See Table 3.5.5-1 for list of components. Delivery time for the SKIRU III has been identified as 18 to 22 months. The reaction wheels would be about 20 months.

Table 4.2-1 Availabilities Relative to TOPEX
(continued)

Item	Availability
vi. Airborne Support Equipment	New design
C. Ground Support Equipment	New design for special support equipment. The VAX 11-780 dedicated computer delivery was quoted as 9 months.
D. Software	New based on existing programs for guidance and control, command processing, and fault tolerant processing.

5.0 CONCLUSIONS

In this section the suggested baseline concept is summarized and a discussion of low cost considerations is provided.

5.1 Suggested Baseline System

The satellite concept suggested by the Boeing Aerospace Company for TOPEX Option 2 and an STS launch is shown by Figure 5.1-1. For Option 3 the configuration would be similar, except for use of TE-M-479 solid rocket motors rather than TE-M-521-5 motors. For Option 1 again the configuration would be similar except TE-M-442-2 solid rocket motors would be used and a different instrument configuration would be mounted. The hydrazine thrusters for each option would be sized as appropriate. For Delta launches the solid rocket motor module and the large canted hydrazine thrusters would be excluded. A list of components for the suggested concept is given by Table 5.1-1.

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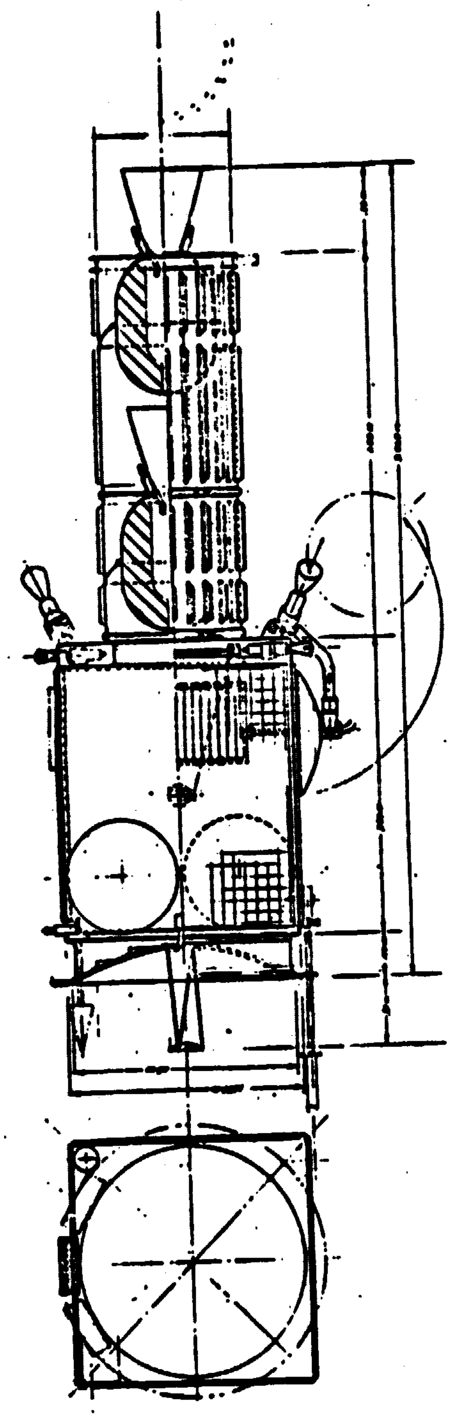

FIGURE 5.1-1 TOPEX SATELLITE CONCEPT

TABLE 5.1-1 COMPONENTS FOR THE TOPEX SATELLITE CONCEPT

SUBSYSTEM	COMPONENT	QUANTITY	SOURCE	DEVELOPMENT STATUS
Structures	Aluminum sheet and stringer plus attachment mounting fixtures	1	Boeing	New
Telecommunications (including C&DH)	Transponders	2	Motorola	Designed
	20 watt R.F. Amplif.	2	TRW	Designed for NASA unique IUS
	High Power Diplexer	2	Wavecom	
	High Gain Antenna	1	Boeing	Like design for MVM-73
	Switches			
	DPDT	7	Transco	
	SP-3T	2		
	C&DH Subsystem	2	Fairchild	Flown on MMS
	NSSC-1 Computer	2	IBM	Flown on MMS
Electrical Power				
	Solar Array	8.4 M^2 of Cells	Boeing/Spectrolab	New
	Batteries	4	Ford/G.E.	New
	Power shunt Regulator/battery Charge controller	2	E.O.S.	Being developed for P80-1

TABLE 5.1.-1 Continued

SUBSYSTEM	COMPONENT	QUANTITY	SOURCE	DEVELOPMENT STATUS
Propulsion	Ascent motors	2	Thiokol TE-M-521-5	Flown on S3-3
	Large hydrazine thrusters	4	Rocket Research	Flown on Voyager
	Small hydrazine thrusters-pitch control	4	TRW NASA Standard 5 Newton thrusters	Flown on FLTSAT COM
	Small hydrazine thrusters-yaw, roll, control	4	Rocket Research	Flown on Titan III
	Tanks, Plumbing and drive electronics	1 set	Boeing & Others	New Configuration
Guidance & Control	Scanwheels	2	Ithaco	Like Flown on NOAA, AEM
	Electromagnets	3	Ithaco	Like design for Viking
	Magnetometer	1	Ithaco	Like flown on AEM
	Control Electronics	1	Ithaco	Like flown on AEM
	Sun Sensor	1 set	Adcole	Like flown on AEM

TABLE 5.1-1 Continued

SUBSYSTEM	COMPONENT	QUANTITY	SOURCE	DEVELOPMENT STATUS
Guidance & Control	Pitch Wheel	1	Sperry	Flo. on HEAO
	Gyro Package	1	Kearfott	SKIRO III
	Accelerometer	1		Flown on SERT 2

5.2 LOW COST CONSIDERATIONS

Cost is a function of experience and approach. Boeing has developed considerable experience and expertise in the small, low cost spacecraft business and has the intention of remaining a leader in this market. With the Modular Experimental platform for Science and Applications (MESA) Boeing is attempting to improve the predictability and cost performance of future small spacecraft. This is done in a number of ways that might prove useful for the TOPEX program. First, every effort will be made to use relatively low-cost, reliable, flight-proven, off-the-shelf components. Second, use of established design approaches and manufacturing techniques and processes reduces risk as well as cost. Third, use of a small experienced design and manufacturing team reduces communication difficulties and learning curve inefficiencies. Close access to a diversified, expert technical staff and extensive test facilities ensures a quality product that meets a customer's technical requirements. Fourth, discussion of alternative mission designs and cost/benefits trades can often lead to a more cost effective mission than might be the case if the contractor simply responds to initial mission requirements without carefully considering and discussing cost implications with the customer.

In preparing this report a number of alternative design issues arose that involve mission benefit/cost tradeoffs where further discussion or study beyond the scope of this contract could significantly affect the TOPEX mission design. Some of these issues are listed as follows:

1. If it is feasible to use a somewhat slower command processing rate (0.5 Hz vs 1.0 Hz) it may be possible to use a considerably less expensive encoder, decoder, command processor - the Gulton system flown on HCMM, SAGE, and SME.

2. An alternate design concept for the guidance and control subsystem is possible for missions carried by the Delta booster. For these missions an orbit transfer stage is not required and the guidance and control subsystem described in paragraph 3.5.5 of this report could be simplified with the added benefit of higher reliability and lower cost.

The changes to the system described would be to replace the pitch momentum wheel with a much larger wheel to increase the bias angular momentum. The recommended wheel is the Sperry model 35 which has a momentum capability of 569 n-m-sec. This change would eliminate the need for a gyro package. It would also eliminate the need for the four large hydrazine thrusters, and would allow all of the remaining hydrazine thrusters to be NASA standard 5 newton thrusters.

For this system the same technique of acquiring the initial referances that was employed on the AEM spacecraft would be employed. The initial tumbling rates would be reduced to a small value using only electromagnets. Control of the rest of the mission would be done using the momentum exchange system and the electromagnets. If the velocity control burns are kept to a small magnitude, the bias wheel can maintain sufficient accuracy to control the burns. Initial orbit trim would have to be done in several short burns with about one orbit in between for the control system to damp the errors. A velocity change of 63 meters per second could be accomplished in approximately 1.5 days. Orbit adjust burns of less than 2 m/sec could be done with a delay of about one orbit before data taking is resumed. The one orbit delay would be used to decrease the velocity change induced attitude errors to within the desired accuracy.

To utilize this approach for a Shuttle launch the spacecraft would have to be transferred to the final orbit using a spin stabilized stage. The ascent stage would have to be designed to spin about the axis of minimum moment of inertia which is an unstable spin configuration. The damping caused by the 100+ kg of hydrazine would probably result in very large wobble of the spacecraft for the second burn. Without a considerably deeper analysis this approach for a Shuttle launch would entail considerable risk.

3. In paragraph 3.2 of this report, a solid rocket motor ascent stage is proposed. Time was not available for cost/performance analysis to detemine if a hydrazine or bipropellant ascent stage would be a better option. Such

a study should be performed.

4. The requirement that time tag resolution be less than 4 μs with turnover greater than 8 years means that 46 bits of clock information is required. An understanding of where this much information is really needed could affect computer design, bandwidths, and processing requirements.

5. The Boeing candidate TOPEX design concept calls for considerable ballast to reach the 0.01 m^2/kg area/mass ratio required for Mission Option I, and to match solid rocket ascent motor capabilities for a Shuttle launched mission. Can mission value be increased by using this available mass for low power, low data rate experiments such as materials space environment exposure testing? Investigating other experiments which could be usefully employed would be an area deserving further thought.

6. If mission requirements allow, would a cost/performance trade allow replacing the onboard computer with a simple sequencer? Note that attitude control does not require extensive computation if orbit trim maneuvers need not be completed quickly.

7. Is it possible to avoid taking data in eclipse periods so as to reduce electrical power requirements? This would increase system reliability, reduce cross sectional area to improve staying time, reduce battery requirements, simplify TDRSS communication requirements, and prolong mission life.

For these and other reasons, future study and customer/contractor discussion of TOPEX mission requirements and spacecraft conceptual design would be useful.