AD-A169 330 TIDAL DATA COLLECTION OPTIONS STUDY(U) NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY NSTL STATION MS C R HOLLAND NOV 85 NORDA-139 1/1

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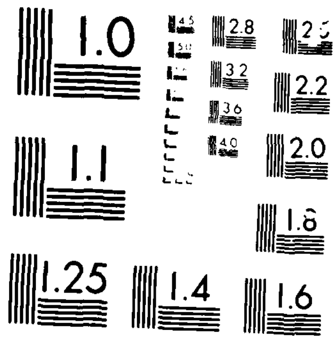
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**Naval Ocean Research and Development Activity**
November 1985 Report 139

# Tidal Data Collection Options Study





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# Foreword

For ships at sea the closest land is always straight down, and successful navigation in shallow coastal waters requires accurate nautical charts. Traditionally, nautical charts are produced from depth measurements made from a surface vessel. To incorporate tide fluctuation data, this survey must last 28-30 days so that depth measurements can be corrected for variability in sea surface height. This time-consuming method has resulted in a considerable backlog of needed surveys.

New technological developments have led to procedures that may enable surveyors to conduct bathymetric surveys from airborne platforms and thus reduce the survey backlog. This report examines potential options for collecting tidal data to support airborne bathymetric survey options.

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# Executive summary

In response to the Defense Mapping Agency (DMA) goal to "develop methods and systems for rapid and accurate collection of hydrographic data in coastal zones, and for the reduction and exploitation of hydrographic/bathymetric data to support both coastal operations and undersea weapon operations worldwide," NORDA was funded to study the problem of Rapid Hydrographic Data Collection. This study was to investigate all reasonable approaches to technically solving the issue of improved tidal data collection that supports both ship and aircraft collection systems, and to estimate the cost of each so that relative comparisons could be made. In conclusion, the study report was to recommend a "best" course of action to be followed in developing the final solution.

To put the problem into perspective, the study first defines the tidal measurement requirements. In essence they are height accuracy of ± 3 cm; sample rate of one measurement each hour; measurement duration of 30 days; and resulting data in digital format.

The study effort next defines three primary approaches: a measurement-only hardware approach; a calculation-only computer model approach; and a combinational approach that uses modeling based on a limited number of in situ "ground truth" measurements. Under the first approach, hardware only, six system concepts are examined: a shore-installed tide gauge system; a ship-launched/ship-recovered system; an air-launched/ship-recovered system; an air-launched/air-recovered data/ship-recovered system; an air-launched/air-recovered data/expendable system; and remote sensing systems. Under the second approach, calculate only, the ONR Tide Prediction Model is investigated. Under the third, combinational approach, computer modeling with validation of output achieved from limited in situ measurements is considered.

The analysis concludes that the combinational approach offers the lowest risk and is potentially the most cost-effective solution, since it minimizes the number of field tide measurements required to achieve validation of a powerful model, which can then produce detailed tidal corrections with high confidence.

To achieve this desirable result, the study recommends that an evaluation of the ONR Model be performed; a design study be funded to further define development details of a self-contained, solid state, in situ tide measurement system to provide the required ground truth measurements; and that one of the remote sensing techniques be studied further. Costs of the recommended future efforts are included.

# Contents

# Tidal data collection options study

## I. Introduction

For ships at sea the closest land is always straight down. For successful navigation in shallow coastal waters accurate nautical charts must always be available.

Traditionally, charts have been produced from soundings (depth measurements) made from a surface vessel, which surveys the area by following a serpentine pattern [1]. A vessel using this method can require many days to complete a bathymetric survey of a harbor or a short section of complex coastline. Simultaneously, tide fluctuation data is collected over a period of 28–30 days so that the depth measurements can be corrected for variability in sea surface height [2].

Collecting tide data as part of the bathymetric survey has not been a problem because of the slowness of surface ship soundings and the length of time required to survey even small areas. This slowness has, however, resulted in the generation of a considerable backlog of needed surveys and stimulated research and development efforts to produce a system(s) capable of greatly improved survey speed.

Developments have recently concentrated on making shallow-water soundings from airborne platforms (fixed wing and helicopter) using lasers, multispectral active/passive scanners, and electromagnetic techniques. It appears highly likely that one or more of these techniques will produce a workable airborne bathymetric survey system in the not-too-distant future. When such a system is placed in service, it will no longer be possible to collect the tidal correction data using the present procedure because neither the time nor the surface ship support personnel will be available.

### A. Study purpose

This study examines potential options for collecting tidal data to support airborne bathymetric survey operations. Such operations have the potential for covering hundreds of square miles of coastline in a few days of operation. Conversely, tidal fluctuations must be observed for a period of 28–30 days [3] to establish the proper tidal datum and correction factors; also tide data must be taken at a sufficient number of locations to account for distortions due to underwater topography.

### B. Study scope

This study considers first the operational requirements for tide data collection and then the methods for meeting these requirements. Operational requirements include accuracy specification, duration, sampling frequency, and data format. Methods for meeting these requirements include hardware approaches and computer modeling or some combination of both. This study includes estimates of time and cost to develop and implement each option that appears feasible.

### C. Study approach

This study is divided into seven sections and one appendix. Sections III and IV identify the hardware/software options, based on Section II requirements, that offer promise of meeting the tide measurement needs. Section V details the estimated cost in dollars and time to achieve the most promising options. Section VI recommends future actions that should be taken to achieve a final solution. Appendix A provides detailed supporting data and describes the calculation techniques used to generate the tables and figures in Sections II, III, IV, and V.

## II. Operational requirements

As stated, bathymetry measurements must be corrected for tidal fluctuations. In this section the need for these corrections will be explored in detail, the measurement characteristics defined, and the integration of these measurements into the final chart product examined.

### A. The need for tidal data

The fundamental purpose of a nautical chart is to tell the mariner the minimum depth of water he can expect under his boat under conditions of "fine" weather and no tides. From this one document and observations of local weather, the mariner can determine a safe course for his vessel and crew. If he also has access to tide prediction information, he can calculate what additional water depths may be available (on top of the chart minimums) due to the rhythmic rise and fall of the sea surface. How does one create such a useful nautical chart?

Traditionally, soundings have been made from a surface vessel using mechanical (leadline) or acoustic (fathometer) techniques while the vessel's position was determined through visual or electronic ranging. Normally, many hours or days are required to completely survey a harbor; during this time tides, winds, and barometric conditions are constantly changing the level of the sea surface. Each sounding, then, gives the depth of the water at one location at one instant in time. Associated with each depth measurement is a host of possible errors, with tidal fluctuations being a major contributor. Errors due to the effects of winds and unusual currents are somewhat beyond our present ability to accurately identify and remove. Tidal fluctuations, however, can be corrected provided that a sufficient time series measurement of water level changes is obtained.

A sufficient time series is one lunar cycle (28 days) with one or two extra days of overlap. Many forces, both celestial and terrestrial, combine to produce the tides [4]; the principal celestial ones are the sun and the moon. Each of these celestial bodies exhibits variability in its movements with respect to the earth and, therefore, variability in the tide-producing forces, which can be represented by "constituents." A total of 23 constituents plus nodal corrections should be considered in deriving the total tide-raising force. Each of these constituents is derived from the time series of water height (tide) measurements made at a tide gauge station. The next subsection considers the required characteristics of the time series measurements needed to resolve these constituents.

## B. Tidal data characteristics

The tidal time series data set consists of "raw" measurements of the sea surface height for each measurement instant over the measurement time period. The following specifications are used in making the measurements.

- Accuracy of water level measurement: ± 3.0 centimeters.
- Measurement (sample) interval: 1 sample/2 hours minimum, 1 sample/hour preferred.
- Measurement duration: 28 days minimum, 30 days preferred.
- Measurement reference (datum): land survey benchmark or transfer from "Standard Port."
- Data form: digital, compatible with processing computer.

## C. Area coverage considerations

Tidal fluctuations information is valid for just the immediate area in which it was collected and, actually, only for the time period over which it was collected. The data set is assumed to be representative of the true tides and can be extended forward and backward in time. The data set cannot, however, be accurately applied over a large area if the surrounding water depths vary much: horizontal water movement (tidal streams) is retarded in time and altered in direction by the presence of bars, shoals, and islands, so the tide does not change everywhere at the same time or rate or total amplitude everywhere [5]. Therefore, the tidal data collection must be planned using some knowledge of the bottom topography of the survey area. Tide stations must be set up at appropriate locations and intervening distances to ensure accurate and complete coverage of the true tidal field.

At present, the Naval Oceanographic Office (NAVOCEANO) establishes shore tide stations with separations of about 20 miles minimum and 100 miles maximum. These separations are based on the tidal complexity of the coastline being surveyed and do not provide optimum coverage in all cases, but are a reasonable compromise based on available manpower and equipment assets. One or two tidal shore stations are typically installed by NAVOCEANO personnel to support present surface ship bathymetric surveys, and are checked periodically for proper operation by members of the survey party making soundings in the survey area. This small number of tide stations is enough to give reasonable results for simple coastlines but becomes inadequate for complex coastlines. Since a number of days or weeks are usually required for surface ships to survey the bathymetry of a small coastal area, shore-based tide stations and their data are easily recovered by the survey party before moving to the next new area.

With the introduction of airborne bathymetric survey platforms, the area rate of coverage will increase dramatically. For example, as shown in Table 1, the Hydrographic Airborne Laser System (HALS) can cover about 96 square kilometers per hour, and the Multispectral Active/Passive Scanner (MAPS) covers about 180 square kilometers per hour. The Thematic Mapper (TM Sensor) can cover about 180 square kilometers per hour, and the Airborne Electro Magnetic (AEM) system can profile about 108 square kilometers per hour. It can be easily seen from Figure 1 that with just a few hours of operation using any one of these systems, a number of tide stations would need to be set up each and every survey day. Figure 1 represents the minimum number of new shore tide stations required each day under present NAVOCEANO procedures for minimum and maximum tide station spacing. For ideal tide measurements, the number would be even higher.

Table 1. Survey capabilities of proposed airborne bathymetric systems.

| PERFORMANCE PARAMETER | SYSTEM DESIGNATION HALS ① | MAPS ② | AEM ③ | TMS ④ |
|---|---|---|---|---|
| Forward Air Speed (P-3) | 100 m/s | 100 m/s | 100 m/s | 100 m/s |
| Swath Width (total) | 268 m | 500 m | 50 m | 500 m |
| Track Spacing | 300 m | 500 m | 300 m | 500 m |
| Operational Altitude | 500 m | 500 m | 50 m | 500 m |
| Area Coverage Rate | 96 Km²/HR or 37 mi²/HR | 180 Km²/HR or 70 mi²/HR | 108 Km²/HR or 42 mi²/HR | 180 Km²/HR or 70 mi²/HR |

① Hydrographic Airborne Laser System

② Multi-Spectral Active/Passive Scanner (now part of ABS Program)

③ Airborne Electro-Magnetic

④ Thematic Mapper Sensor (now called the NORDA Scanner)

Present assets clearly cannot even begin to cope with this tide measurement requirement. In addition, present plans call for using the NAVSTAR Global Positioning System (GPS) for navigation, thereby eliminating any need for surface ship or shore support for other survey purposes [6].

## D. Integration of tidal data

Bathymetry data must have tidal effects removed and be reduced to a common datum before it can be entered on a nautical chart. The preferred form of the data is computer-compatible digital so that the tidal constituent analysis and follow-on reductions can occur automatically. Presently, NAVOCEANO hand converts (digitizes) the tide station data from a strip chart "marigram" into a table of hourly water height numbers, which are then entered into a computer program that computes the tidal constituents, calculates the datum, and prints out a table of tidal corrections. These tidal corrections are then applied to the "smooth sheet" soundings that will be used in preparing the final nautical chart. In areas where tidal data cannot be obained or failure of a shore tide station resulted in loss of anticipated tidal data, NAVOCEANO uses computer-generated predicted tides based on the relatively simple motion of the sun and the moon.

# III. Hardware approaches

This section considers possible configurations for collecting the required tidal data using in situ sensors and data recording/telemetry techniques. The numbers of sensors required, data quality/quantity, and area of coverage are discussed as background to the hardware systems analysis.

One basic hardware concept is to replace what is now a shore-based, transit-surveyed tide station with a portable, self-contained, air- or ship-launched seabed tide measurement instrument. The number of such instruments needed depends somewhat on the underwater topography (which may be unknown). If unknown, a bathymetry overflight survey might be conducted prior to deploying the tide gauges. Consider that a "nominal" P-3 aircraft performing the survey will fly at a speed of around 100 meters per second (180-200 knots). With essentially 100% surface coverage it will survey approximately 50 square

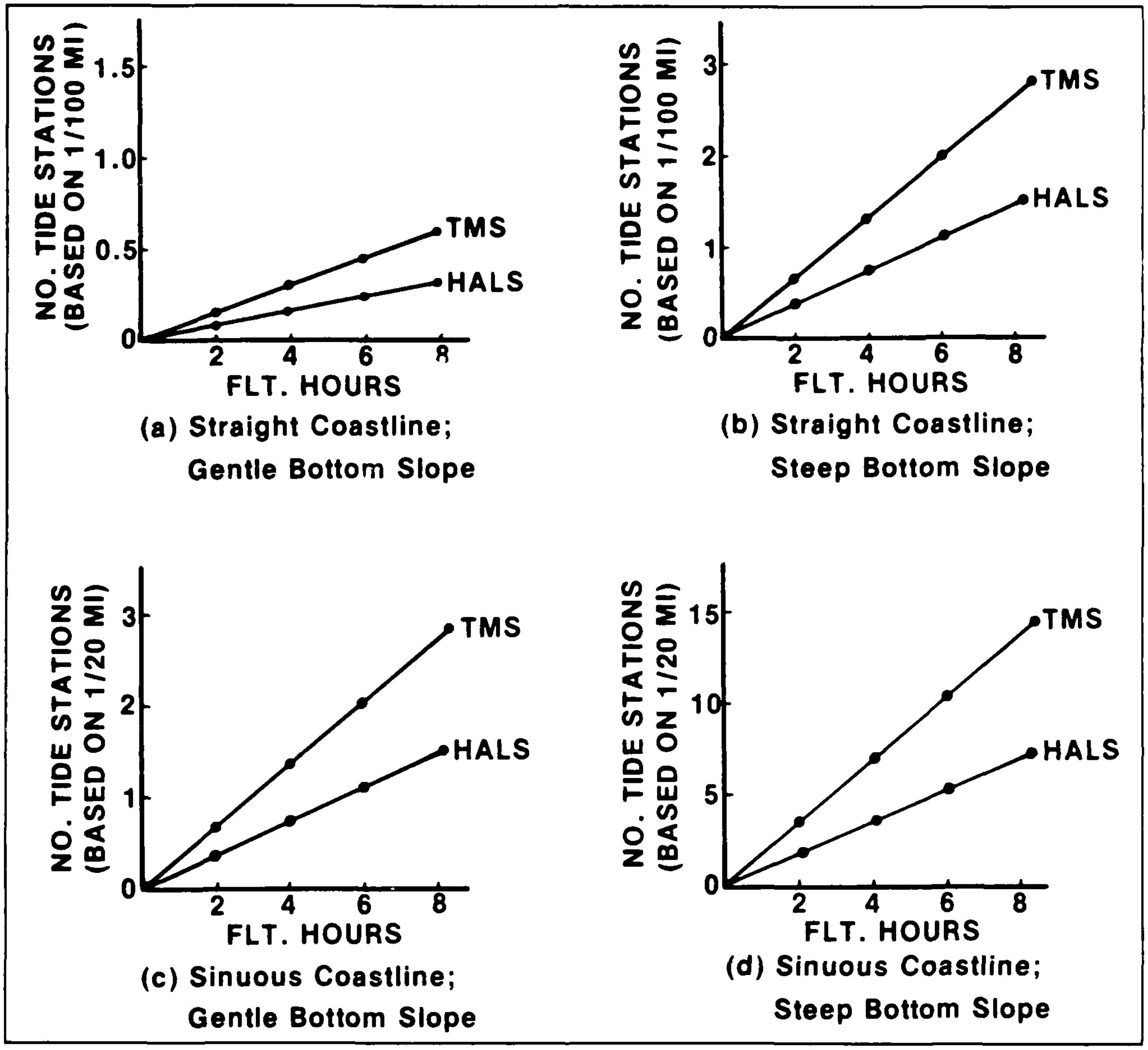



*Figure 1. Tide station requirements versus area coverage rates*

miles per hour or 400 square miles per 8 hour survey day. Based on NAVOCEANO's present ship surveys, an area of 400 square miles typically requires from 4 to 20 tidal stations (1 every 100 miles to 1 every 20 miles, depending on the degree of coastline "roughness"). For an airborne survey, this means the deployment of 2-10 tide gauges per day (see Fig. 1), or 10-50 gauges per week. Clearly, this is potentially an unacceptably large number, but it is probable that the airborne system will survey for only about half of an 8-hour flight.

Each tide sensor deployed must produce high-quality data with ± 3 cm accuracy over a continuous 30-day period at sample rates of one measurement per hour. Fortunately, using this rate totals only 720 water height measurements per location—a very small and, for solid state memory, easily stored data set. If a seabed gauge were used, the gauge must rest on the sea floor in a stable manner for the full 30 days without clogging or fouling. unfortunately, these requirements are not simple for shallow-water coastal environments.

In the following subsections, consideration will be given to how various deployment and recovery requirements might be satisfied using a ship, aircraft, or a combination of both.

## A. Ship-launched/ship-recovered system

This category has two considerations: installation, support, and recovery of improved shore stations; and deployment and recovery of seabed gauges.

### 1. Shore stations

The present technique used by NAVOCEANO is to install and support shore-based tidal data collection stations using the same personnel that set up and support the shore-based navigation and ranging stations for surface ship bathymetry operations. For airborne bathymetry operations using GPS, there will be no need for shore-based navigation; therefore, no shore support parties will be available for tide station support. Such a support team could be established using local boats and crews, however, with tide gauge installation and support coming from one or two TDY NAVOCEANO personnel.

Table 2 shows the estimated cost (1985 dollars) of using local boats and NAVOCEANO personnel to install, support, and recover shore-based tide stations. The scenario envisioned follows: The flight plan of the airborne system is known some months in advance so that contact and contracts can be made with the local resources. At the agreed-upon time, NAVOCEANO personnel (one assumed) will arrive, with the necessary equipment having arrived some days before. The preplanned number of stations will be installed (this may occur before, during, or after the actual bathymetry flights) using the boat crew as assistants, and for station-checking support during the required 30-day period. Now, if the aircraft will be surveying a long, continuous stretch of coastline, the tide station installation team can keep moving steadily along the coast. If distances become too great for easy return to previously installed stations for checking on recording operations and the mechanical stability of the installation, it should be possible to train local personnel in the basics of checking operations (by observation only) and relaying status to the team periodically.

Examination of Table 2 reveals that the projected cost of installing tide stations worldwide does not vary a great deal ($1834–$2196). The real cost impact is related to the numbers of such stations that must be set up each year. Lines 7 and 8 of Table 2 place some likely bounds on the yearly cost based on the tide station requirements derived in Figure 1. Line 8, Table 2 shows that if the airborne system is flown very much, the tidal collection field support can become fairly expensive. The configuration and cost of a "typical" shore-based tidal data collection station is shown in Figure 2, and the estimated cost of developing an improved shore station is given in Table 3. A recent survey of commercially available tide gauges is described in reference 7.

### 2. Seabed gauges

With the development of suitable self-contained, seabed-mounted gauges, installation using local support becomes even easier because no periodic servicing is required prior to recovery. A possible scenario might be—NAVOCEANO personnel (one assumed) and gauges arrive. Using a combination of radio navigation (perhaps supplied by NAVOCEANO) and local visual ranges, the preplanned general location of the gauge is achieved by the boat and operator. The seabed gauge is then lowered over the side, released, and the actual position logged immediately after deployment. Each gauge is deployed in sequence until all have been deployed in the operating area. If the airborne system will be surveying a long stretch of coastline, the gauge deployment team can just keep moving along the coast, since no servicing of the seabed gauges is required prior to recovery 30 days later. If more than 30 days are required to deploy all the gauges in the operating area and the gauges have been designed to terminate data collection after 30 days and to wait quietly for recovery, there will be no need to return immediately to pick up the exhausted ones. Recovery, when it does occur, may be so simple (by acoustic interrogation, localization, and release recall) that local resources could be trained to peform the recovery unassisted.

***a. Seabed gauge development.*** Figures 3 and 4 illustrate one possible arrangement for a seabed-mounted gauge. The gauge would be self-contained and self-righting after deployment. One of the key features of any seabed gauge is that motions, such as settling, occurring after data collection has begun must be detected so that corrections can be made to the tidal height data. In the design, it will probably be necessary to have the gauge settle in place for a while prior to automatic initiation of data collection. Subsequent motion can be detected by simple internal tilt sensors that can identify undesirable motion, but not correct for it. If solid state electronics, memory, and long-life battery technologies are used in the gauge, it should be possible to produce a design that does not require the gauge pressure housing to be opened for any reason except repair. With this type of design, the gauge will be recharged and reset by means of an external pressure proof connector on the pressure housing. Internal status checks regarding system readiness, programming changes such as start/stop times and clock set, and removal of data from internal solid-state memory can also be accomplished through this same or a similar connector. Table 4

Table 2. Estimated cost of deploying shore-based tide stations using local resources.

| ITEM OF EXPENSE | NORTH ATLANTIC OR EUROPE | CENTRAL PACIFIC OR SOUTH ATLANTIC | MEDITERRANEAN | INDIAN OCEAN | SOUTH PACIFIC |
|---|---|---|---|---|---|
| 1. 30 ft. boat and crew of 2-3 | $500/day | $400/day | $600/ day | $500/day | $400/day |
| 2. Travel (NAVOCEANO Tech.) | $990/trip | $1493/ trip | $1808/ trip | $2363/ trip | $2011/ trip |
| 3. Per Diem (NAVOCEANO Tech.) | $122/day | $76/day | $100/ day | $53/day | $93/day |
| 4. Labor (NAVOCEANO Tech.) | $305/day | $305/day | $305/ day | $305/day | $305/day |
| 5. Instrument (per station) (1) | $1244 | $1244 | $1244 | $1244 | $1244 |
| 6. Total cost per station per trip (2) | $2033 | $1834 | $2196 | $1998 | $1896 |
| 7. Cost per year low rate (3) | $130K | $117K | $141K | $128K | $121K |
| 8. Cost per year high rate (4) | $488K | $440K | $527K | $480K | $455K |

**NOTES:**

**(1) Instrument initial cost & maintenance cost all divided by number of stations achieved over useful life.**

**(2) Based on 2 stations per flight day, 2 flight days per week, and 4 weeks per trip (requires one crew).**

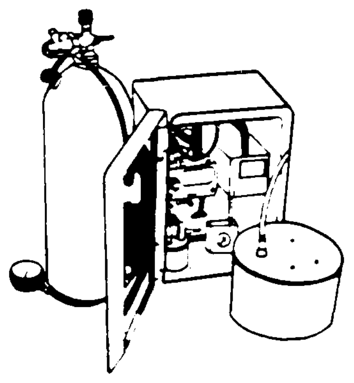
**(3) Based on 16 stations per trip and 4 trips per year.**

**(4) Based on 30 stations per trip and 8 trips per year.**

**(5) See Appendix A, Section 4.0 for calculation details.**

details the anticipated cost in time and dollars to develop an acceptable seabed gauge for surface ship launch and recovery.

*b. Data extraction.* Because the seabed gauge is self contained, it will not be necessary to open the gauge at any time to recover data or recharge the system for its next data collection operation. Tidal height information, as well as motion detection and timing information, can be removed under external computer control and processed immediately if desired. For this scenario to occur, the data



STANDARD SYSTEM WITH CHART RECORDER: $2750.00
OPTIONAL DIGITAL PRINTER: $450.00
TOTAL: $3200.00

*Figure 2 Typical shore based bubbler tide station*

extraction must take place at some location ashore, but it need not be far from the area where the data is first collected. For example, a dedicated data extraction, recharging, and reprogramming set could be built that would extract the data from a number of gauges and transfer it to another medium, such as magnetic tape, for bulk shipment to the central bathymetry data processing facility. Such a set could be a very compact microprocessor-based unit, providing all the necessary support for a large number of seabed gauges, except maintenance, which must occur at a properly equipped repair facility. Table 5 gives a cost and time estimate for developing the data extraction recharging and reprogramming set.

## B. Air-launched/ship-recovered system

The primary difference between this approach and the one discussed above using a seabed gauge is that this seabed gauge is air launched at the time the airborne bathymetry

Table 3. Cost and time estimate for developing a solid state shore tide station.

| Development Tasks | Development Time (1) FY1 | FY2 | FY3 | FY4 | FY5 |
|---|---|---|---|---|---|
| Specification of functional requirements | (5) | | | | |
| Paper design of solid state station | (10) | | | | |
| Breadboard and test specialized circuits | (10) | | | | |
| Fabricate prototype station | (40) | (10) | | | |
| Laboratory test prototype station | | (10) | | | |
| Controlled field test of prototype station | | (15) | | | |
| Modifications based on test results | | (20) | | | |
| Fabricate final model | | (20) | (30) | | |
| Laboratory test of final model | | | (5) | | |
| Field test final model | | | (30) | | |
| Prepare production documentation | | | (10) | | |
| Prepare final report | | | (15) | | |
| Place production order | | | | ▲(2) | |
| **Development cost by FY** | **$65K** | **$75K** | **$90K** | | |

(1) Cost shown in ($K) on time line for each task by FY.
(2) Estimated unit production cost is $7K

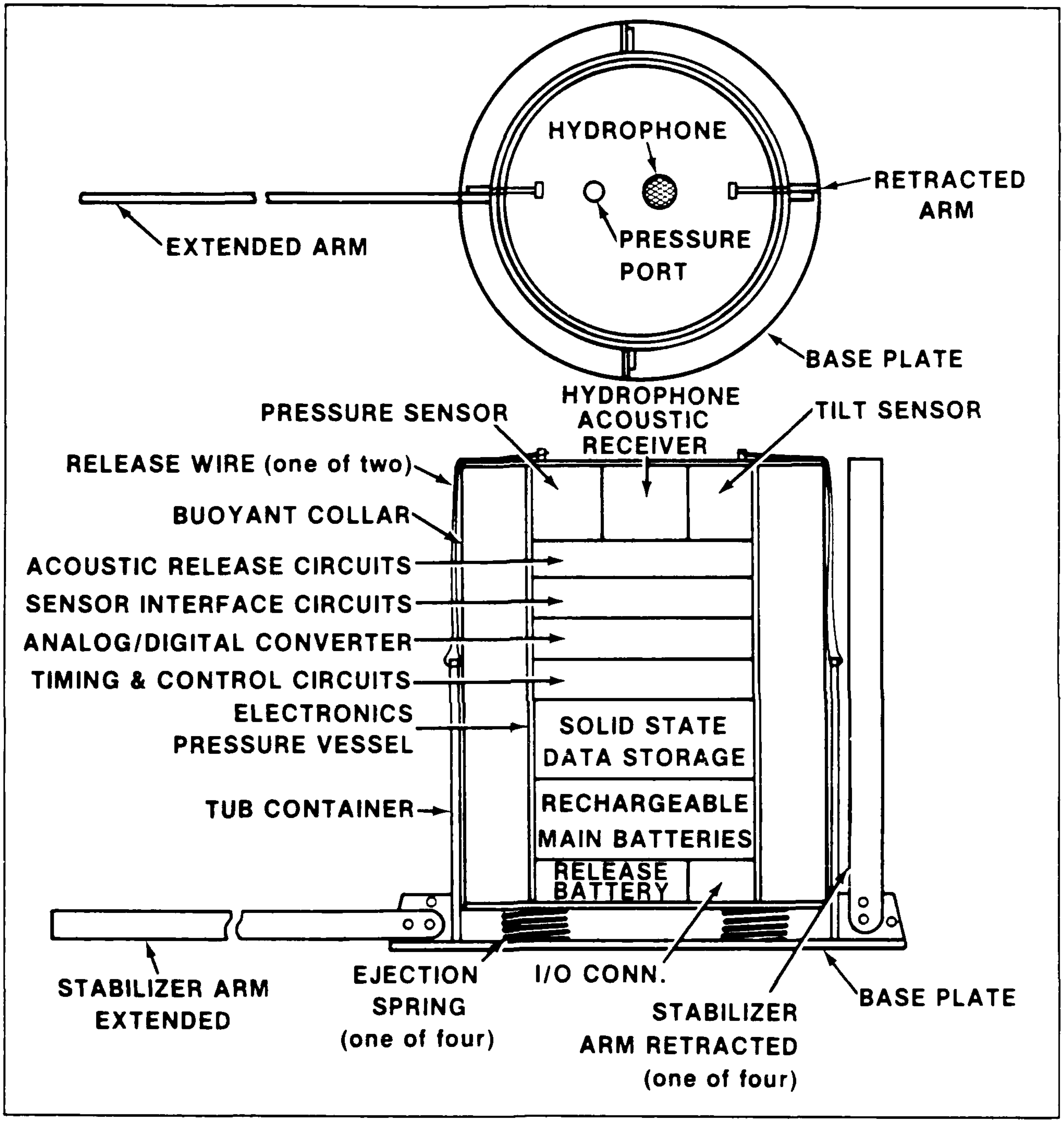



*Figure 3. Design concept for a ship launched, self contained seabed tide gauge*

survey is being conducted. Positioning of the gauges will need to be preplanned with the release point precomputed, taking into account the trajectory after launch. At the launch point, the gauge is released and allowed to parachute to the surface of the water where the chute is disconnected upon impact. The gauge then settles to the bottom in a manner identical to the ship-deployed seabed gauge discussed in Section III.A. Collection, storage, and extraction of data can also occur in similar fashion. With careful design, it is conceivable that previously deployed gauges could be recycled in the field by recharging internal batteries, reprogramming start-stop times,

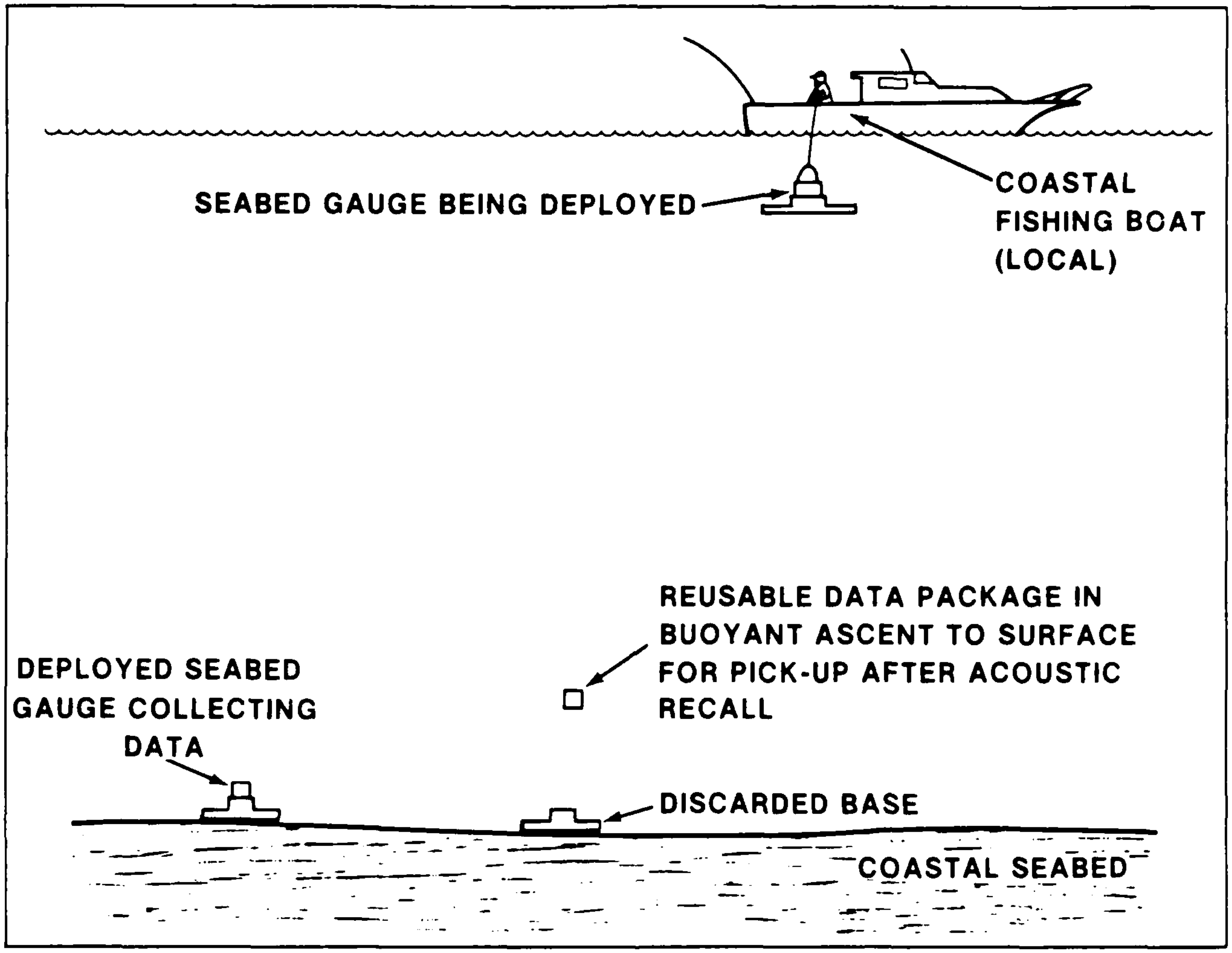



*Figure 4. Deployment concept for a ship-launched, self-contained seabed tide gauge*

checking operating status, and reloading into a new, modular air deployment canister with parachute. Such a design would readily permit air or surface launch and rapid recycling of gauges with a minimum of different assemblies. Figures 5 and 6 illustrate an "artist's" concept of what the air-launched package might look like. Table 6 gives cost and time estimates for its development. It will also be necessary under this scenario to have the field team use the checkout and data extraction set discussed in Section III.A.

## C. Air-launched, air-recovered data/ ship-recovered sensor

In this concept, the air-launched seabed gauge is given additional sophistication so that the 30 days' worth of tide data can be quickly extracted during a second flyover. The gauges, devoid of data, are then picked up at some later time by contracted "locals," who need to learn only a minimum amount to be successful in recovering the recyclable gauges. Deployment, operation, recovery, and recycling of this gauge configuration is very similar to the gauge discussed in Section III.B, except for data extraction. Airborne data recovery would be initiated during the second flyover by deploying a small, self-contained, expendable acoustic pinger, which transmits a coded message that causes all gauges within range to deploy a surfacing and inflatable antenna. As the aircraft circles the area, a coded radio frequency (RF) message is transmitted to each gauge and identifies which gauge is to reply next with a complete "dump" of data memory. When all gauges have responded, the aircraft departs the area. Within a relatively short time after command antenna deployment (say, 2 hours), the inflatable antenna scuttles

Table 4. Cost and time estimate for developing a ship-deployed seabed gauge.

| Development Tasks | Development Time (1) FY1 | FY2 | FY3 | FY4 | FY5 |
|---|---|---|---|---|---|
| Specification of functional requirements | (8) | | | | |
| Paper design of seabed gauge | (17) | | | | |
| Breadboard and test specialized circuits | (30) | | | | |
| Fabricate prototype gauge | (60) | (80) | | | |
| Laboratory test of prototype | | (30) | | | |
| Controlled field test of prototype | | (20) | (20) | | |
| Modifications based on test results | | | (45) | | |
| Laboratory test of final unit | | | (20) | | |
| Field tests of final unit | | | (50) | | |
| Analysis of final test results | | | (15) | (20) | |
| Prepare production documentation | | | | (40) | |
| Prepare final report | | | | (30) | |
| Place production order | | | | | ▲(2) |
| **Development cost by FY** | **$115K** | **$130K** | **$150K** | **$90K** | |

(1) Cost shown in ($K) on time line for each task by FY.

(2) Estimated unit production cost is $18K.

and leaves nothing on the surface to attract attention or act as a snag point for local fishing operations. Surface ship recovery later would be the same as that suggested for the seabed gauge of Section III.B. Figure 6 (left side) illustrates the concept for an air-deployed gauge with airborne data recovery capability. Table 7 gives cost and time estimates for its development. Since data is retrieved in the field by the aircraft (and considering the sophistication of the gauge), it will probably be necessary to service the gauge at some central recycling facility; the field checkout and reprogramming set will not be necessary in this concept.

## D. Air-launched, air-recovered data/ expendable sensor

Solid-state electronics technology has progressed in recent years to the point where size and cost have been greatly reduced while performance has significantly increased. Examples include the all-solid-state digital watch, AM/FM portable stereo radios, hand-held electronic calculators, and the personal computer (PC). Through the use of large-scale integration (LSI) and very-large-scale integration (VLSI) techniques, the cost of many items places them into a "throwaway" category. It might be possible to apply this technology to the development of an expendable seabed tide gauge that can be air launched, commanded to deliver up its collected data during a second overflight, and then left in place to slowly disintegrate. The airborne deployment of such a gauge and subsequent data extraction procedures would be very similar to that discussed in Section III.C. Figure 7 illustrates one concept of how such an expendable gauge might look. Table 8 gives cost and time estimates for its development. It should be noted that this concept has the highest risk of all proposed in terms of the accuracy of the cost estimate and the ease with which success can be achieved.

### 1. Development risks

The major risk lies in the area of cost, not technical difficulty. If the technology were not sufficiently developed, it would not be possible to develop the hardware necessary

Table 5. Cost and time estimate for developing a data extraction/text set.

| Development Tasks | Development Time (1) FY1 | FY2 | FY3 | FY4 | FY5 |
|---|---|---|---|---|---|
| Specification of functional requirements | (5) | | | | |
| Paper design of Tide Gauge Test Set | (10) | | | | |
| Breadboard and test specialized circuits | (15) | | | | |
| Fabricate prototype test set | (70) | | | | |
| Laboratory tests of prototype | | (15) | | | |
| Modifications based on test results | | (30) | | | |
| Laboratory tests of final unit | | (15) | | | |
| Field verification of performance | | (20) | | | |
| Prepare production package (if desired) | | | (35) | | |
| Prepare final report | | (15) | | | |
| **Development cost by FY** | $100K | $95K | $35K (if desired) (2) | | |

(1) Cost shown in ($K) on time line for each task by FY.

(2) Estimated unit *production* cost is $18K.

to support the other tide measurement concepts discussed in this section. It should be accepted that the technology exists but that a key question is how the technology will be packaged into a low-cost gauge? The correct answer is, I believe, the development of a VLSI "chip set" wherein all the system functions, signal conditioning circuits, and perhaps even the sensors themselves are contained on a small number of easily interconnected semiconductor integrated circuits. Such a chip set can now be developed at relatively low cost by using a technology that the Defense Advanced Research Projects Agency (DARPA) has been developing for the past few years, called the Silicon Foundry (see subsection 2 below). Whether or not the final cost supports true throwaway utilization will also depend on the volume used over a period of 3–5 years or the period over which one procurement contract can provide all the needed gauges.

It is doubtful that NAVOCEANO will require more than a few hundred expendable gauges per year. Figure 8 illustrates the number of expendable gauges that might typically be required for a variety of airborne bathymetric operations. Figure 8 is based on the tide station requirements of Figure 1 for a maximum 8-hour day of flight operations. What this figure shows is that for a reasonable mix of situations, anticipated yearly consumption of gauges (300–1000) will not yield production buys large enough to secure the types of economies seen in the expendable bathythermograph, sonobuoy, and consumer entertainment markets (typically 10,000 or more units per buy).

## 2. Silicon foundry

In the mid-1970s DARPA began an ambitious program to develop a capability within the silicon microchip industry to custom design and manufacture integrated circuits at significantly lower cost. Up to that time, development costs were often a few hundred thousand dollars per design and the resulting parts could be sold for a few tens of dollars (or less), only if the parts were mass produced by the hundreds of thousands or millions. This situation prevented low-volume users, who might really benefit from the small size, reduced power, and higher reliability, from obtaining these advantages without paying a

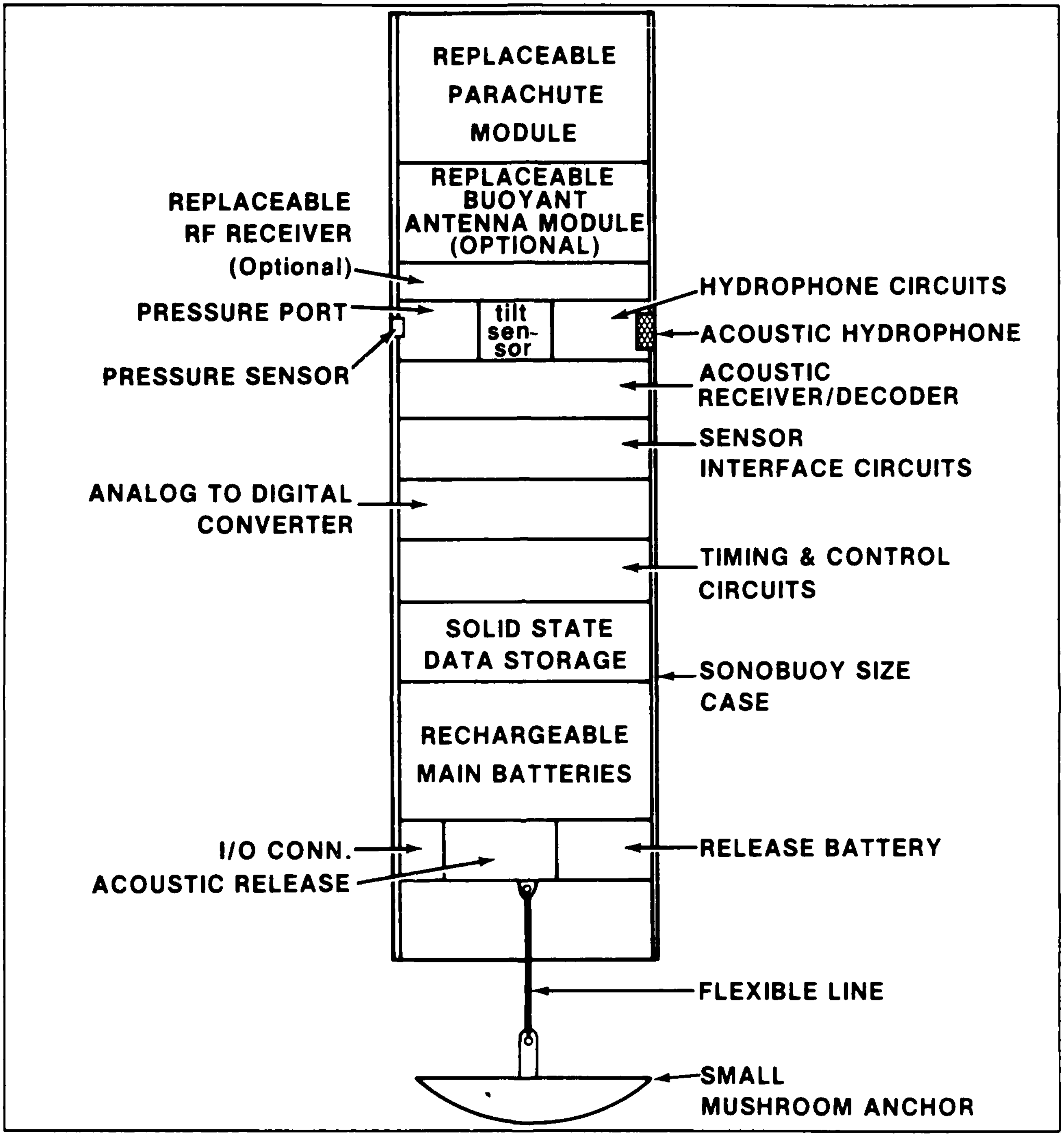



*Figure 5. Design concept for an air launched, self contained seabed tide gauge*

premium price to obtain them. Since many military applications fell within this category, DARPA set out to eliminate or to reduce this barrier as much as possible. Over the last 8 or so years considerable progress has been made and continues to be made. Through the use of new computer tools for automated layout, mass production, small batch prototype production, and high speed testing, the price for developing a custom-integrated circuit is now in the few-thousand-dollar category. To develop a chip set of, say, 5 ICs, would cost about five times as much

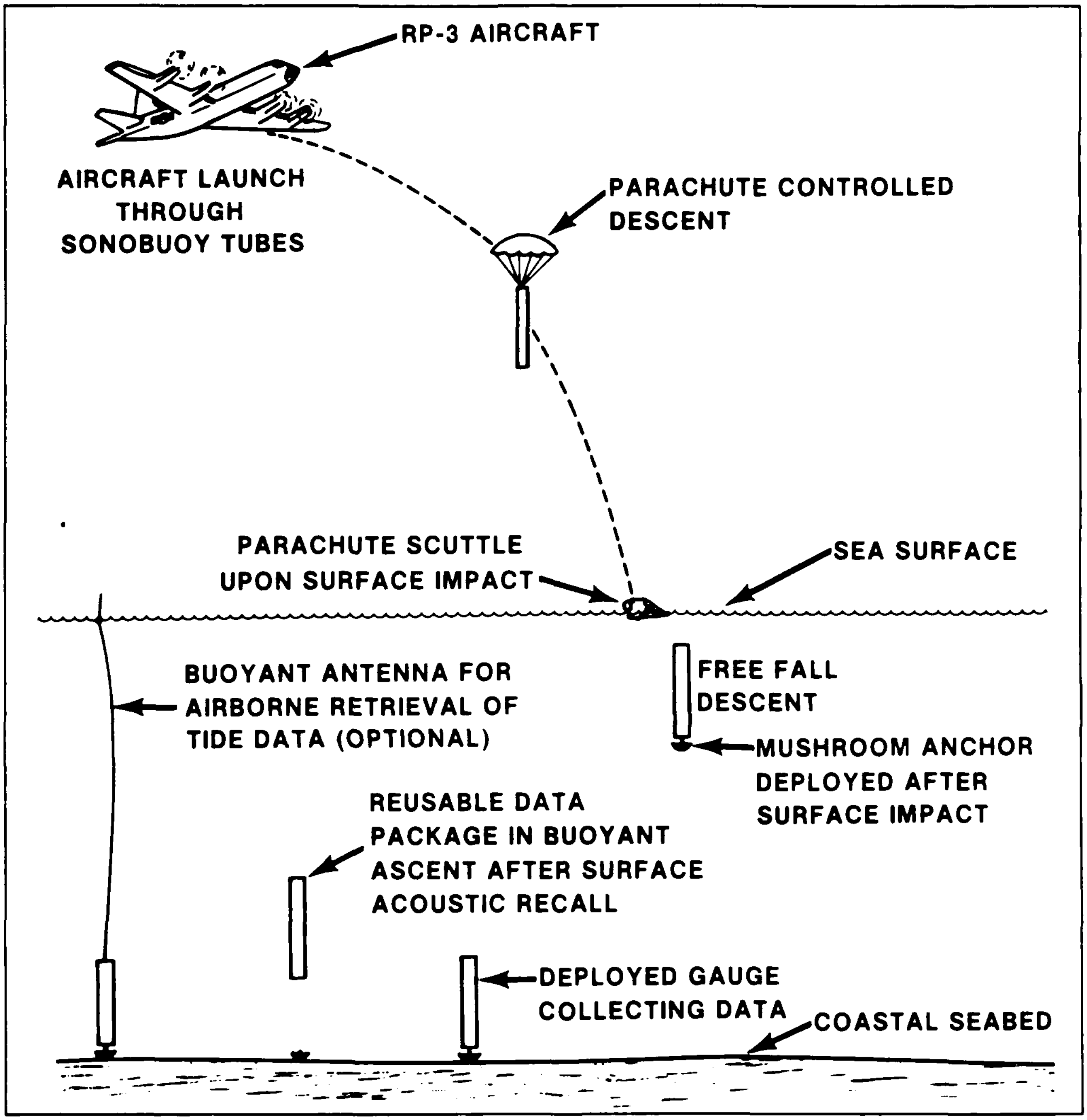



*Figure 6 Deployment concept for an air launched, self contained seabed tide gauge*

## E. Other hardware concepts considered

Other potential ways can be used to measure tidal fluctuations instead of in situ measurement using tide gauges or calculating the expected fluctuations using a computer model. Most of these other techniques are based on various types of remote sensing. Although many of these approaches are very appealing because they offer the potential for rapid coverage of large areas, the prospect of measuring the tides without physically having to go to the area, and the ability to measure the tides for more than one season of the year, most do not currently appear feasible for the following reasons.

Table 6. Cost and time estimate for developing an air-launched seabed tide gauge.

| Development Tasks | Development Time (1) FY1 | FY2 | FY3 | FY4 | FY5 |
|---|---|---|---|---|---|
| Specification of functional requirements | (15) | | | | |
| Paper design of air launched gauge | (35) | | | | |
| Breadboard and test of specialized circuits | (30) | | | | |
| Fabricate prototype gauge | (50) | (120) | | | |
| Laboratory tests of prototype | | (40) | | | |
| Initial air launch tests of prototype | | (15) | (15) | | |
| Modifications based on test results | | | (95) | | |
| Laboratory test of modified unit | | | (15) | | |
| Air launch tests of modified unit | | | (15) | (15) | |
| Fabrication of air certification units | | | | (100) | |
| Perform air certification tests | | | | (40) | |
| Analyze field test results | | (10) | (10) | (20) | |
| Prepare production documentation | | | | | (60) |
| Prepare final report | | | | | (40) |
| Place production order | | | | | ▲(2) |
| **Development cost by FY** | **$130K** | **$185K** | **$150K** | **$175K** | **$100K** |

(1) Cost shown in ($K) on time line for each task by FY.
(2) Estimated unit production cost is $25K

## 1. Satellite radar altimetry

In this approach, a pulsed radio frequency signal is repeatedly bounced off the surface of the ocean and the distance traveled precisely determined. By knowing the accurate location of the satellite for each distance measurement, it is possible to determine the location of the ocean surface to an accuracy of 2-4 inches. By comparing subsequent distance measurements, the change in surface height due to all the forces associated with tidal fluctuations (including the effects of winds, barometric pressure, and water flowing over bottom topography) may be determined. This remote measurement of tides is essentially the same kind of measurement that would be obtained from a seabed gauge, except for a couple of problems. First, the satellite radar altimeter, from its lofty perch, has an ocean surface footprint or sampled area of about 1 x 5 miles (Seasat-type performance), meaning that for harbors and complex-shaped coastal areas tidal variations over small horizontal distances of a few miles will never be resolved. Second, and much more important because radar signals are reflected by trees, houses, etc., the return signals to the satellite become quite distorted at distances of about 6-12 miles from any coastline and are unusable at distances of 2-5 miles. Considering the accuracy, the limits on horizontal resolution, and the inability to make measurements close to shore, the present satellite radar altimeter technology is not going to solve the tidal measurement problem. Despite the fact that Seasat failed only three months after achieving orbit, data analysis has confirmed its usefulness as a remote sensor of surface height fluctuations in open ocean areas. Perhaps it will be retrieved by the Shuttle and repaired.

Even if Seasat is not repaired, plans have been made to use other satellite radar altimeters, Geosat and Topex. Geosat was recently launched by the Navy (March 85), and NASA plans to launch Topex in the late 1980s. These new satellite radar altimeters promise improved accuracy and, perhaps, with better data processing, closer operation

Table 7. Cost and time estimate for developing an air-launched seabed tide gauge with airborne data recovery.

| Development Tasks | Development Time (1) FY1 | FY2 | FY3 | FY4 | FY5 |
|---|---|---|---|---|---|
| Specification of functional requirements | (15) | | | | |
| Paper design of air launched gauge | (40) | | | | |
| Breadboard and test of specialized circuits | (35) | | | | |
| Fabricate prototype gauge | (60) | (130) | | | |
| Laboratory tests of prototype | | (45) | | | |
| Initial air launch tests of prototype | | (15) | (20) | | |
| Modifications based on test results | | | (105) | | |
| Laboratory test of modified unit | | | (15) | | |
| Air launch tests of modified unit | | | (15) | (20) | |
| Fabrication of air certification units | | | | (110) | |
| Perform air certification tests | | | | (40) | |
| Analyze field test results | | (10) | (15) | (25) | |
| Prepare production documentation | | | | | (65) |
| Prepare final report | | | | | (45) |
| Place production order | | | | | ▲(2) |
| **Development cost by FY** | **$150K** | **$200K** | **$170K** | **$195K** | **$110K** |

(1) Cost shown in ($K) on time line for each task by FY.

(2) Estimated unit production cost is $35K.

to coastlines. It is a technology that bears tracking, but not one that can be relied on to provide tidal data at present or for the near-term.

## 2. Satellite laser altimetry

Perhaps the problems of the radio frequency radar beam can be solved by replacing it with a beam of laser light. The laser beam would certainly have a much smaller footprint, would not suffer as much from reflections when the coastline was approached, and holds the potential for greater height measurement accuracy because of its higher operating frequency. While this approach may provide a successful tide measurement tool, no such system is in orbit today and none are planned for launch in the next 10 years.

## 3. Satellite color photogrammetry

Some analysis techniques make use of false and real colors, as well as color changes, to determine the height of jungle canopies and the depth of coastal oceans. Although this type of technique may offer some tidal measurement help in special cases, it typically suffers from two serious limitations. First, color changes in the coastal regions are affected by such things as storm-disturbed bottom sediments, biological blooms, industrial waste discharges, and changes in incident solar energy, in addition to water level fluctuations. These factors must be determined precisely before serious attempts can be made to determine actual changes in water heights. This determination of "water quality" can easily consume more time and resources than making direct tidal measurements. Second, if the water quality is known quite well, the accuracy with which the depth changes can be determined is poor compared to that required for bathymetry work because of the complex and, at present, not well understood ways in which light energy propagates into, through, and out of the ocean medium. Considering the complexity of this technique, it is doubtful that it will become a viable method for measuring tidal fluctuations at any time in the foreseeable future.

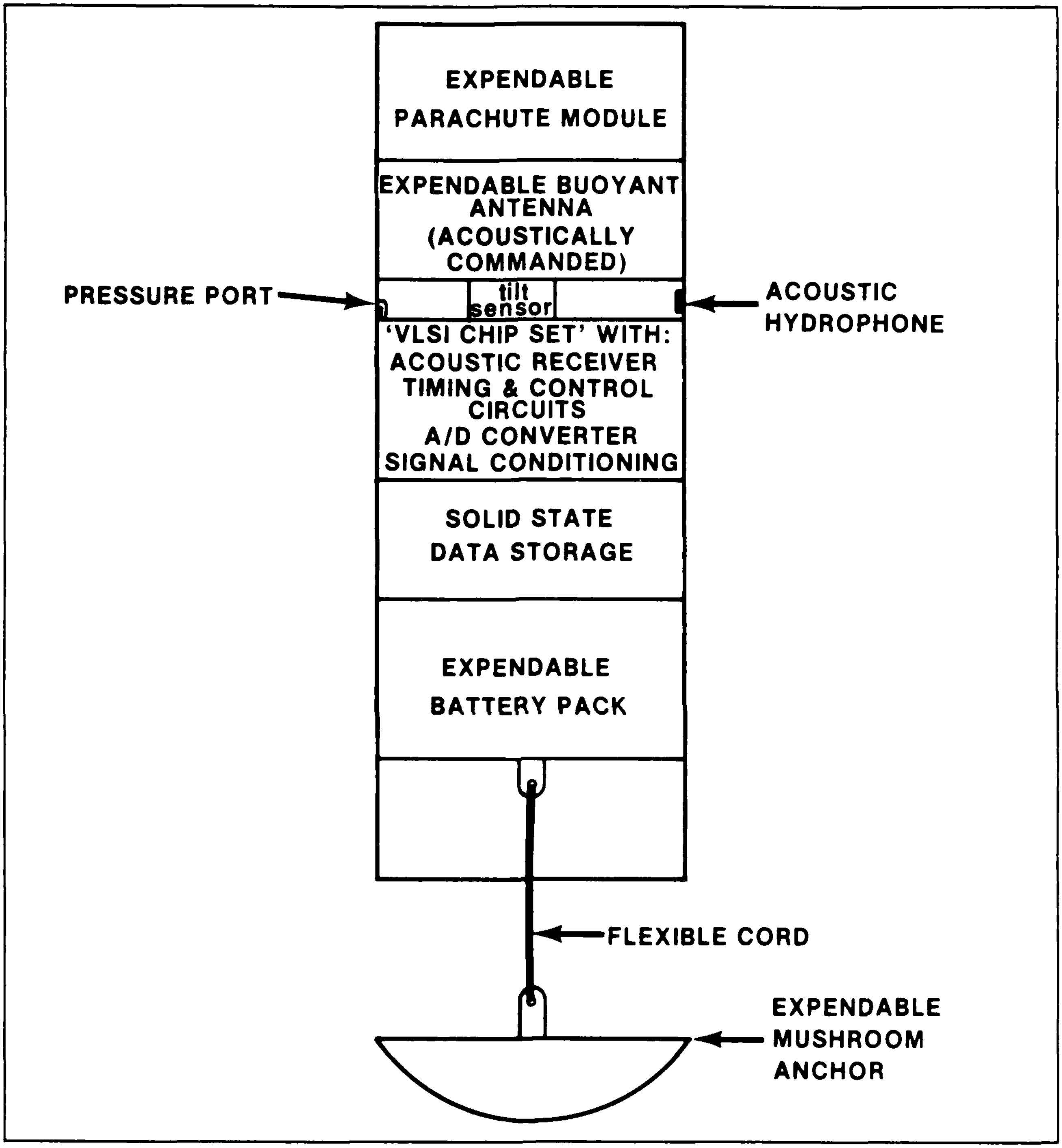



*Figure 7 Design concept for an air-launched expendable seabed tide gauge*

## 4. Aircraft remote sensing

Some of the remote sensing problems of large footprint, reflections from nearby objects, and cloud cover might be solved by mounting the sensor in an aircraft and flying fairly close to the ocean surface while making measurements. If this measurement technique is used to establish tidal fluctuations, then the aircraft must fly over the same area at intervals of one or two hours for the full 28–30 days, clearly an unacceptable requirement. If, however, the tidal datum is already known, then all that

Table 8. Cost and time estimate for developing an air-launched expendable seabed tide gauge with airborne data recovery capability.

| Development Tasks | Development Time (1) FY1 | FY2 | FY3 | FY4 | FY5 |
|---|---|---|---|---|---|
| Specification of functional requirements | (20) | | | | |
| Paper design of expendable gauge | (30) | | | | |
| Development of prototype chip set | (100) | | | | |
| Fabricate prototype expendable gauge | | (200) | | | |
| Laboratory tests of prototype | | (50) | | | |
| Limited air launch tests of prototype | | | (50) | | |
| Modify design of chip set | | | (50) | | |
| Modify package design(reduce cost) | | | (75) | | |
| Fabricate second prototype gauge | | | (50) | (50) | |
| Laboratory and field test prototype II | | | | (75) | |
| Analyze field test results | | | (20) | (20) | |
| Fabricate air certification units | | | | (100) | (100) |
| Perform air certification tests | | | | | (75) |
| Prepare production documentation | | | | | (75) |
| Prepare final report | | | | | (50) |
| Place production order | | | | | (2)▲ |
| **Development cost by FY** | **$150K** | **$250K** | **$245K** | **$245K** | **$300K** |

(1) Cost shown in ($K) on time line for each task by FY. (2) Estimated unit production cost is $4-8K.

is needed to determine the tidal corrections is an accurate measure of the height of the water surface above datum at the time of the bathymetry measurement. An airborne bathymetry platform that can accurately position itself above the geoid and determine the location of the sea bottom and sea surface with respect to itself could possibly make the tidal correction measurement at the same time that it makes the bathymetry measurement.

The Hydrographic Airborne Laser Sounder (HALS), one of the bathymetry systems being considered, has the necessary characteristics and may, through the Global Positioning System (GPS), have the positional accuracy to take advantage of this concept. One of the many questions that will need to be answered is the accuracy of GPS in determining spatial location using the most accurate relative positioning mode (such as phase comparison). If relative position can be determined accurately enough, then absolute spatial position may be determined from knowing the geoid-related location of the aircraft just prior to takeoff from an airport and transferring it by relative incremental changes. Of course, many factors can affect the accuracy and success of this technique. Such factors include the accuracy of relative positioning using GPS, the ability to accurately measure markers at airports around the world, the likelihood of knowing the tidal datum or of establishing it by transfer from a "standard port," and the ability to combine all the data into an accurate time series data set from which the tidal corrections can be extracted. An in-depth study, much beyond this present effort, will be required to properly define the practicality of this "remote sensing" tidal measurement concept.

# IV. Modeling approaches

This section considers the feasibility of calculating the tidal fluctuations as opposed to measuring them. Considerable advances have been made in recent years in computer modeling of many complex, dynamic phenomena

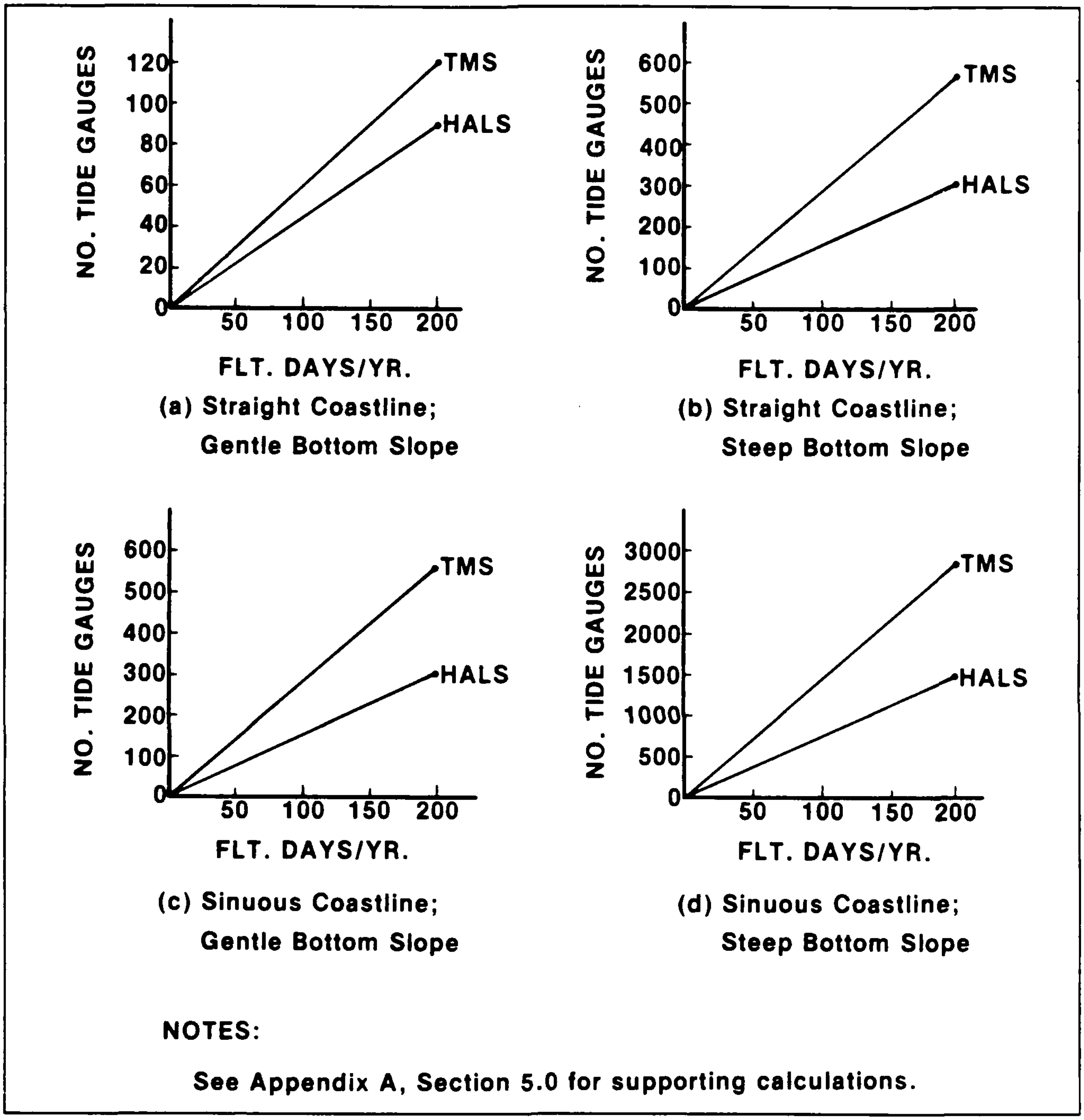



*Figure 8 Anticipated usage of expendable tide gauges for airborne bathymetry operations*

Since the celestial forcing functions of the sun and moon are well understood regarding tides, and since finite element computer calculation techniques are well developed, it appears that given the proper boundary conditions the tides could be accurately calculated. The Office of Naval Research (ONR) has pursued this very concept in recent years under a project known as the ONR Tide Prediction Program. In the next subsection the results of this research will be analyzed.

## A. The ONR Tide Prediction Program

The model developed under this program is based on finite element computation techniques. It can accept as input the gravitational forcing functions of the sun and the moon, the local winds and wind history, the barometric pressure history, and the bottom bathymetry and coastline configuration as boundary conditions. It should be noted that a number of computer programs exist for calculating the tidal fluctuations from a knowledge of the gravitational forces of the sun and the moon. NAVOCEANO has a program that is used to calculate tides for survey areas where tidal data is not available, so the concept is not new. What is new and potentially beneficial about the ONR approach is the ability to calculate tides at many points essentially simultaneously and with great accuracy (assuming the input conditions are all accurately known).

### 1. Model inputs

The ONR Tide Prediction Program requires as a minimum inputs on the sun and moon-tide rising forces, the bathymetry, and the configuration of the coastline. Accurate inputs are extremely important, as this obviously determines the accuracy of outputs. For bathymetry measured to International Hydrographic Organization (IHO) standards and coastline delineations based on geodetic survey-produced topographic maps, the present output tidal accuracy is claimed to be ± 5.0 centimeters, which is close to the IHO standard of ± 3 centimeters.

As part of the input requirements, the user must establish the finite element grid pattern by graphically dividing up the surface over which the tides will be calculated into squares (or rectangles). This is accomplished by specifying the element size and the area over which it applies. Since a number of element sizes and areas may be specified, it is possible to increase the number of tidal calculations made in areas where relatively small horizontal movements can result in important differences in the stage of the tide at any instant in time.

If wind information regarding speed, direction, and duration and/or the variation in barometric pressure with time is known, the model permits these additional forces to be superimposed onto the final tide fluctuation solution.

### 2. Model outputs

The model produces plots and/or tabulations of the relative tide level at each finite element node, as a function of the calculation times specified, and of the tidal currents (speed and direction) at each node for the same time period. As stated before, the claimed accuracy on tide level is ± 5.0 cm with highly accurate inputs.

### 3. Required computation time and cost

The model can be run on a number of different computers so the computation time can vary considerably. The cost, however, will not vary as much because the faster computers (shorter computation time) cost proportionately more to use on a per-hour basis. For a VAX 750 with an FPS-120B Array Processor, it takes about 2 hours of computation to produce 2 weeks of tidal predictions where the time interval between data points is 3 minutes. Assuming a cost of $200 per computer hour, the cost of the run would be $400. The size of the area covered is dependent on the finite element size(s) chosen and the distribution of elements within the area(s) of interest; a maximum of 75,000 elements is possible. Assuming an average element size of one square mile, the model would produce predicted tides for a coastal area approximately 300 miles by 300 miles ($5^\circ$ x $5^\circ$ grid). Of course, the grid does not need to be square and can cover much larger (or smaller) areas as required.

### 4. Model applicability

The model theoretically applies equally well to all parts of the world with the proviso that in some areas of the world the tides are extremely difficult to predict using any technique. Even in these regions, however, with proper "ground truthing" the model can potentially do an acceptable job.

### 5. Present model deficiencies

The greatest impediment to using the model is the fact that it has been well validated for only one area, the New York Bight. While validation is technically straightforward, it can be costly and time consuming. The payoff, however, is potentially very high because once confidence has been gained through validation efforts, the model can be reapplied to that same area with little or no revalidation.

## B. Modeling with ground truthing

Normally one does not like to accept the output of a computer model without some assurance that the calculation results are valid. The most difficult hurdle in the way of gaining acceptance of a new computer model is in building confidence that the output is, with high probability, valid. The most straightforward way to validate a model is to test it exhaustively against known data. In situations where the input conditions vary widely and existing data sets for extensive comparison are not normally available, exhaustive validation is usually impossible. There is, however, a compromise position wherein the model is relied upon because it has been validated in a somewhat similar situation and (this is the important part) there is just enough of a data set to reasonably assure that the present situation really is similar.

For bathymetric surveys, one can measure all the required tide data (as discussed in Section III), attempt to compute and thereby predict all the needed values, or blend these two approaches by measuring only enough tidal data to demonstrate confidence in the model results. As discussed in the next section, the optimum approach appears to be to select the most cost-effective technology offered in Section III, apply it sparingly to achieve that small but important "ground truth" data set for reasonable validation of a comprehensive computer model, and then rely heavily on the validated tide prediction model for generating the tidal datum and corrections.

# V. Summary of findings

In the next subsections, the most important features of the tide measurement approaches considered will be reviewed as a frame of reference for Section VI, Recommendations.

## A. Summary of hardware approaches

Two direct tidal measurement approaches offer promise of solving the problem: the use of shore-installed tidal stations and the use of seabed-installed tide gauges. For the seabed gauge there were three installation approaches: launch and recovery by surface ship; launch by aircraft and recovery by ship (there were two variations of this combination); launch by aircraft with aircraft recovery of data, but no recovery of an expendable tide gauge. Table 9 defines these six tidal measurement hardware approaches and compares them qualitatively. Figures 9, 10, 11, and 12 summarize and compare the estimated cost of implementing each of the six approaches for two selected operating areas. The areas chosen were based on the calculation results shown in Table 2. It appears from the calculations done to create Table 2 that the area of the world in which the tide measurement instrument is going to be used will not have much of an impact, the major costs being labor and instrument costs. For this reason, only the least and most expensive areas from Table 2 have been used to compare the six approaches. Additionally, the comparisons have been divided into two groups for each geographical area. Group I compares costs of utilizing each method without regard to development costs (the assumption is that someone else pays the bill). Group II

Table 9. Qualitative comparison of the tidal measurement hardware methods evaluated.

| METHOD DESCRIPTION | DEVELOPMENT RISK | DEVELOPMENT COST | DEVELOPMENT TIME | EASE OF FIELD USE | OPERATIONAL COST | COST EFFECTIVENESS |
|---|---|---|---|---|---|---|
| No. 1 - Shore installed tide gauges using commercially available equipment (1985) | None | None | None | Hardest | Medium | High |
| No. 2 - Shore installed tide gauges using an improved solid state gauge | Low | Low | Short | Hard | Lowest | Highest |
| No. 3 - Ship deployed self-contained solid state seabed gauge with Data Extraction /Test Set | Low | Medium | Short | Moderate | Low | High |
| No. 4 - Air deployed self-contained solid state seabed gauge with surface ship recovery | Medium | High | Medium | Easy | Medium | Medium |
| No. 5 - Air deployed self-contained solid state seabed gauge with surface ship recovery of gauge and airborne recovery of data | High | High | Long | Easy | High | Low |
| No. 6 - Air deployed expendable seabed gauge with airborne recovery of data | Highest | Very High | Longest | Very Easy | Very High | Very Low |

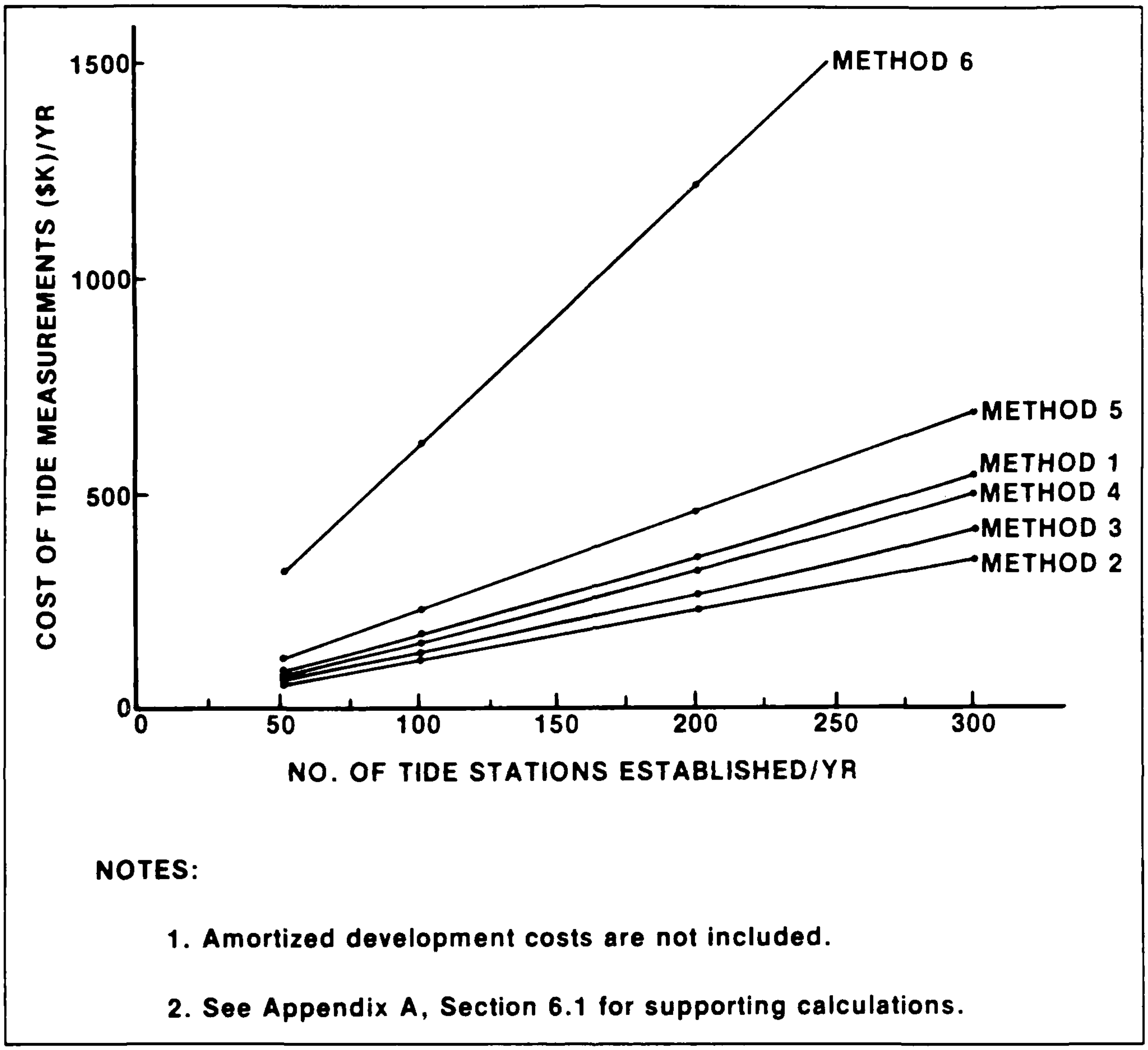



*Figure 9 Summary of estimated cost to measure tides in central Pacific or South America (Group I.*

comparisons include the estimated development costs of each method distributed over the usage (defined as the number of stations established each year). See Appendix A, Section 6.0, for calculation details.

The following general conclusions can be inferred from a study of the cost estimate summary curves:

1. From Figure 9, if development costs are ignored, methods 2, 3, and 4 appear to be somewhat cheaper than method 1, which is similar to the technique presently used to support surface ship bathymetry operations. This result is due to the greater deployment efficiency and lower maintenance achievable from modern solid-state technology (provided it is implemented properly).

2. If development costs are included as shown in Figure 10, only method 2 appears cheaper. This result is due to the expensive development costs associated with achieving the greater efficiency and lower maintenance pointed out above. It should be noted that method 3, while more expensive, may provide operational benefits that have not been factored into this study. One such benefit might be the freedom from finding and supporting (or protecting) a shore installation site. Another benefit might be the

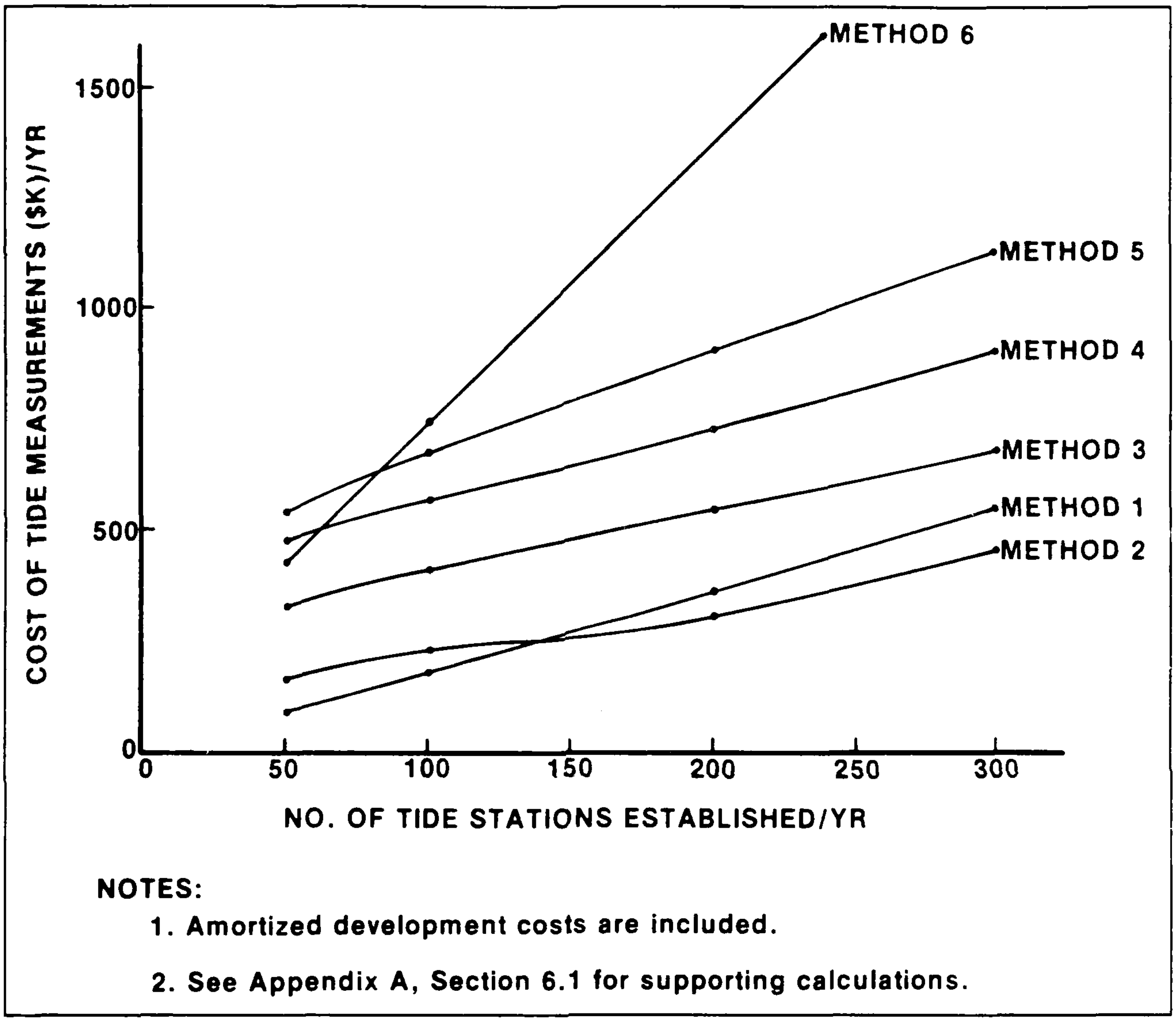



*Figure 10 Summary of estimated cost to measure tides in central Pacific or South America (Group II*

ability to place tide gauges at both near-shore and offshore locations where complex tidal conditions are anticipated because of very rough bottom topography.

3. As anticipated, Figure 11 shows that use of each method in a more expensive area of the world simply shifts all costs upward, but does not change the order or ranking of the approaches.

4. The results shown in Figure 12 are likewise similar to Figure 10, but shifted upward slightly.

5. Method 6, the expendable seabed gauge, does not appear attractive in any of the comparisons. This is because the sophistication required of the gauge will make it a fairly expensive throwaway unless a very large number of units are produced, and that is not likely in this situation. In addition, distributing the development cost over a relatively small number of production units (Fig. 10) makes the situation even worse.

6. While not a method subjected to detailed analysis in this study, the concept of measuring the water height above datum as part of the bathymetry data collection operation (see Section III.E.4) should be given further consideration if an airborne system will be used that can accurately determine the location of the sea surface and the bottom with respect to the aircraft location. Under the somewhat "special" conditions required for this concept to work, there will be no need for any surface support

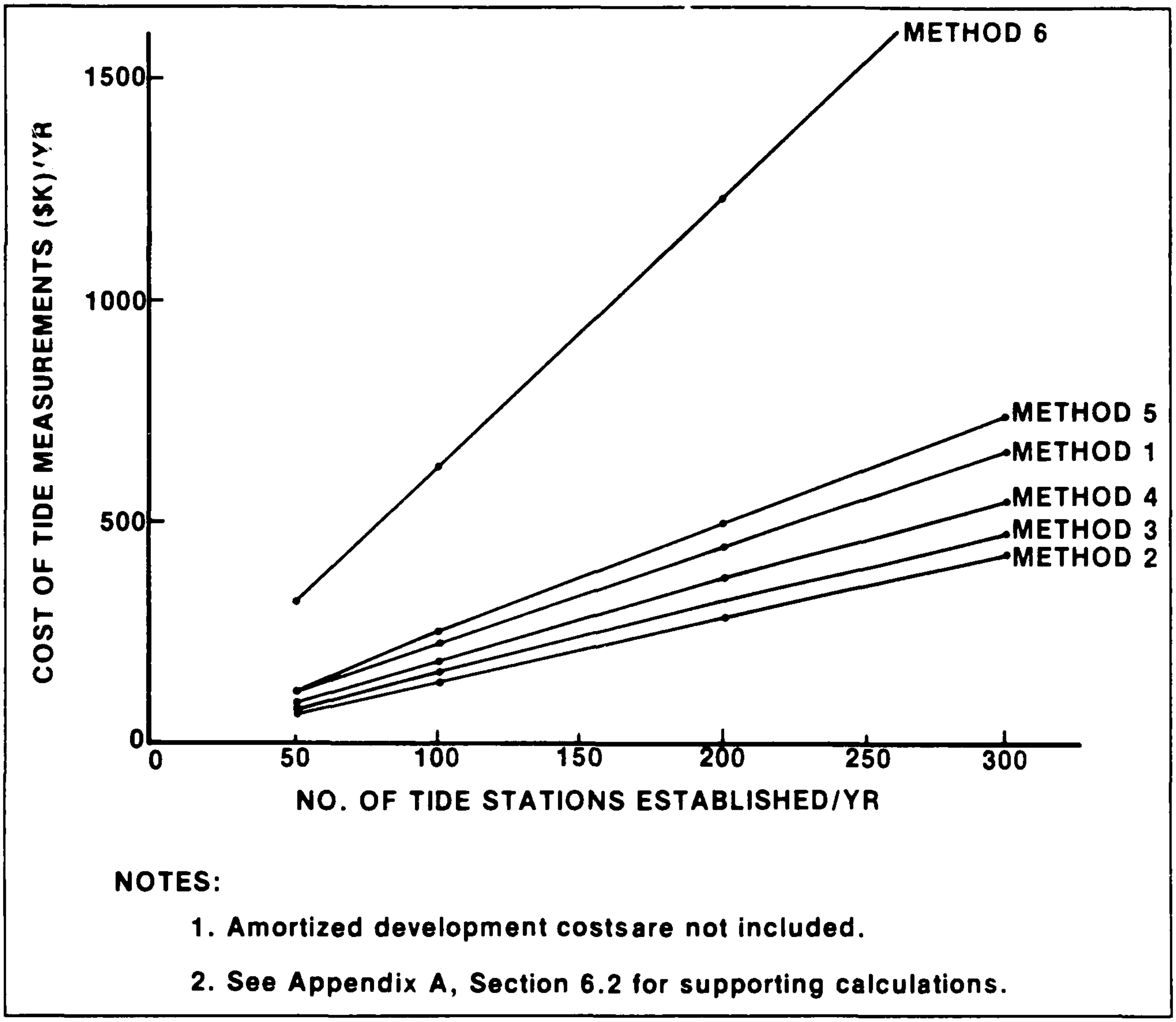



*Figure 11. Summary of estimated cost to measure tides in the Mediterranean (Group I)*

or direct tide measurement equipment. The major cost, once the appropriate attitude sensors are in place on the aircraft, will be the extra data processing required to determine and apply the tidal corrections to the bathymetry depth measurements, assuming that the method is technically feasible.

## B. Summary of software approaches

Under computer calculation of tidal fluctuations, two approaches were considered: calculation with and without ground truthing. It was determined in Section IV that computer calculation of tides can be quite inexpensive, provided there is good reason to have high confidence in the accuracy of the model outputs. It was further pointed out that one can achieve all the confidence necessary to verify a model by checking it against known data if one is willing to pay the price (which often becomes prohibitive if validation is desired for all possible conditions). Figure 13 gives the estimated cost for verifying or validating a tide prediction model on the basis of the number of data station measurement sets required and the five geographical areas of Table 2; see Appendix A, Section 7.0 for supporting calculations. From Figure 13, the following general conclusions can be drawn:

- The estimated cost of validating a model for a single location using five data station measurement sets will range from $21.5K to $24.7K, depending on location.

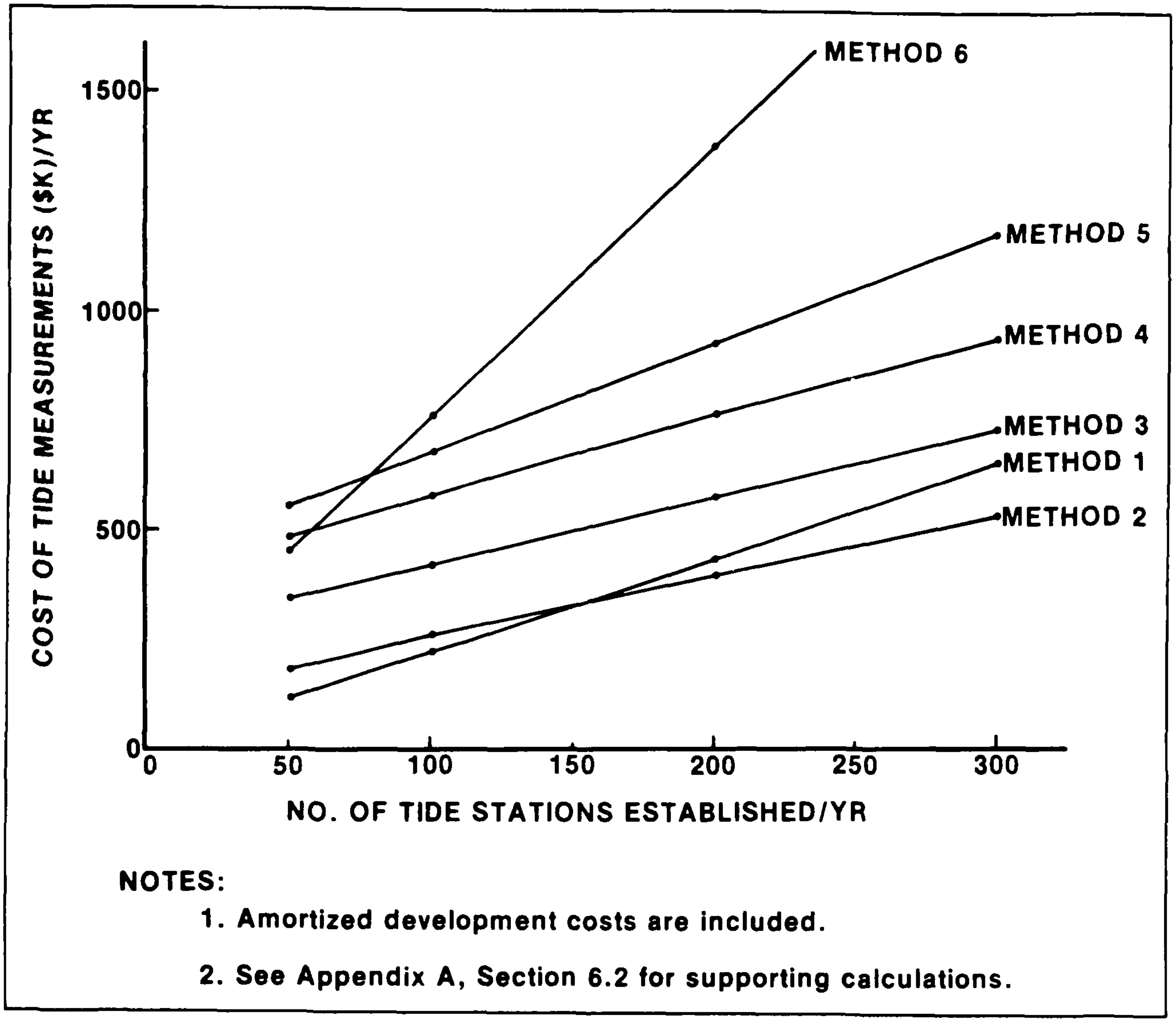
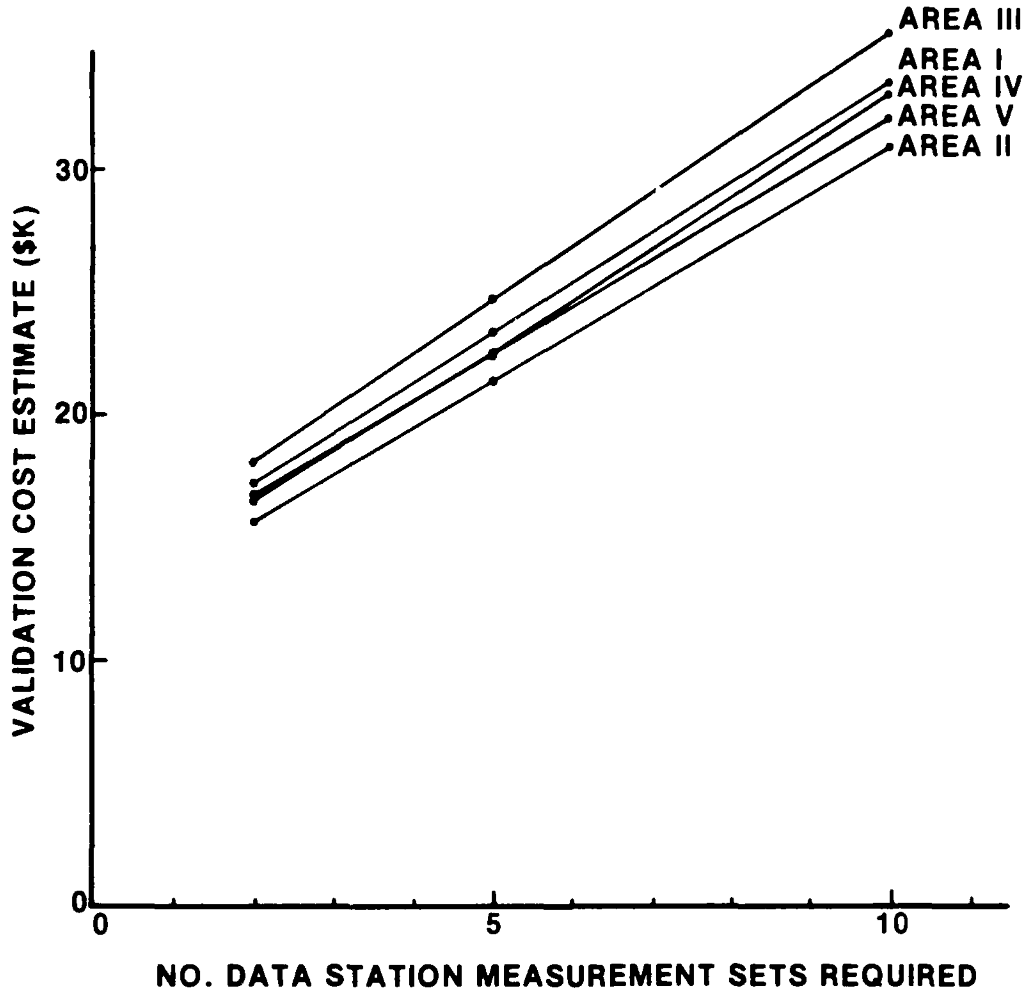



*Figure 12 Summary of estimated cost to measure tides in the Mediterranean (Group II).*

- The estimated cost of validating a model for five different locations using five data station measurement sets each will range from $108K to $124K.
- The cost of validating a model for worldwide applications (50 locations) using 5 data sets for each of four seasons for each location will approach $4.6 million. Clearly, this cost is prohibitively expensive; but if the validation can be achieved with 5 data sets for only one season of the year, the cost decreases to $1.15 million. While this cost may still seem high, it compares with the cost that will be expended each and every year to directly measure the tides, as shown by Figures 9-12.

## C. Combinational approach

From what has transpired so far in this quest for a solution to the airborne bathymetry tide determination problem, it appears fairly clear that a "measure the tides only" approach will be quite costly in terms of equipment development and deployment, and a "calculate the tides only" approach will be quite risky in terms of correctness of the results unless a very expensive validation effort is performed. Perhaps the "optimum solution" exists somewhere in between, with an approach that favors calculation whenever there is high confidence in a correct output, with validation coming from either a relatively few in situ measurements or an extensive set of in situ




**NOTES:**

1. **Each cost curve specifies one geographical area as a function of the distance from NSTL (NAVOCEANO).**
2. **If more than one geographical area is required, determine total cost by multiplying cost of each area by the number of different station locations for that area; then add all area costs to obtain the total cost (See Appendix A, Section 7.0 for details).**

*Figure 13 Estimated cost of validating a tide prediction model worldwide*

measurements. The first part of this approach is, of course, much easier to accept than the last part because it will always be difficult to determine the amount of data required to validate a computer model. As experience is gained, however, and especially as the data base of verified situations grows, it should become easier and easier to achieve that level of satisfactory confidence where detailed tidal corrections can be made and relied upon.

# VI. Recommendations

Having explored a number of hardware and software alternatives, what is the best course of action for DMA to follow in providing NAVOCEANO with the ability to cost effectively determine tidal corrections for airborne bathymetric data? While the "best" and final answer is not completely clear, the path that leads in the correct direction, and should be taken, is clear. The following is recommended:

- The ONR Tide Prediction computer model should be acquired from its developer (it is Navy-owned) and subjected to a series of tests to evaluate its applicability to "real world" bathymetry needs. This evaluation should involve NAVOCEANO and make use of their tidal data archives to determine the ability of this model to predict tidal fluctuations for a variety of operational areas where the tides have already been measured and are reasonably well understood. This evaluation should determine, to the extent the data base will allow, the ease with which the model can be fitted to known data and the quantities of known data required to reasonably validate the model for a specific area. If the model proves highly successful and easy to use, consideration should be given to its near-term inclusion into NAVOCEANO's set of tide prediction tools.

It is estimated that \$50K-\$75K will be required for this evaluation. NORDA is recommended as the technical agency to carry out this evalulation.

- An engineering design effort should be commissioned to explore in more detail the difficulty and actual cost of developing an improved solid-state tide station (Method 2) for shore-based measurements and a self-contained seabed gauge for air launch/surface ship recovery (Method 4). The purpose of this design effort is to verify the development estimates of this study and confirm the hypothesis that self-contained tide measurement systems based on modern solid-state technology can provide cost-effective measurements. Either of these tide measurement systems can perform the task of supplying ground truth data for validation of the computer model used to provide detailed tide calculations. The design study should also ascertain which one of the systems can best provide the needed data.

It is estimated that an additional \$50K-\$75K will be required to complete this second task. NORDA is recommended as the technical agency to perform the work.

- A study effort should be funded to evaluate in detail the feasibility and likely cost of using the airborne platform and bathymetry sensor to determine tidal height above a known datum simultaneously with determining water depths. This study should address the accuracies, both required and achievable, for determining aircraft position with respect to the geoid, the sea surface, and the known datum; the probability of having known datums and airport geodetic bench marks; and the postdata collection data processing required to extract and apply the tidal corrections.

It is estimated that \$50K-\$75K will be required to perform this study because of the difficulty that will be experienced in obtaining some of the needed data. NORDA is recommended as the technical agency to perform this additional study effort.

# VII. References


1. *Proceedings of The Hydrographic Society Symposium on Depth Measurement and Sonar Sweeping*, Special Publication No. 5, April 1976.

2. *Proceedings of The Hydrographic Society Symposium on Tide Recording*, Special Publication No. 4, April 1976.

3. *Admiralty Manual of Hydrographic Surveying, Volume Two, Chapter 2, Tides and Tidal Streams*, Report N.P. 134b(2), published by The Hydrographer of the Navy, Taunton, Somerset, 1969.

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5. *Admiralty Tidal Handbook No. 2—Datums for Hydrographic Surveys*, Report N.P. 122(2), published by the Hydrographic Department, Admiralty, 1975.

6. *The Airborne Bathymetric Survey System*, NAVOCEANO draft description of anticipated system operations, July 1985.

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# Appendix: Supporting calculations

## 1.0 Introduction

This appendix provides details on the assumptions made and methods used in calculating values for the tables and figures in this study report. In a study of this type where development costs and cost intercomparisons are key issues, the variety of questions that can be asked are almost limitless. What has been given in the various tables and figures is basic information. ''Bottom line'' costs are calculated for specific examples based on the basic information.

In this appendix, the sources for the basic information will be documented, as well as details of the methods used in converting basic information into ''bottom line'' results. These details are given for two reasons. First, so the reader can follow the author's line of reasoning and thought processes in defining the examples and calculating the costs of implementation. And second, so that the reader could, using different assumptions but following the same line of reasoning, calculate the cost of ''at if'' combinations.

If I have achieved these two objectives, then this appendix will be a useful addition to the report.

## 2.0 Calculation of area coverage rates

The basic data regarding platform speed, swath width, track spacing, and operational altitude shown in Table 1 of the report came from Mr. Michael Harris (NORDA Code 350). The area coverage rates are calculated by multiplying the track spacing by the forward air speed and the number of seconds in one hour. This total area/hour is then reduced to square kilometers/hour and square miles/hour. No allowances have been made for the time lost in making turns when following a serpentine pattern. The area coverage rate values of Table 1 are somewhat high, therefore, but represent a ''worst'' case in terms of required tide measurement support. Example calculations for HALS and TMS are shown below.

### 2.1 Calculations for HALS

$268 \text{ m} \times 100 \text{ m/s} \times 3600 \text{ s/hr} = 96{,}480{,}000 \text{ m}^2\text{/hr}$

or $96{,}480{,}000 \text{ m}^2\text{/hr} \div (1000 \text{ m}) \times (1000 \text{ m})\text{/km}^2 = 96.48 \text{ km}^2\text{/hr}$

since 1 mile = 1609 m and $1 \text{ mi}^2 = 2{,}588{,}881 \text{ m}^2$ then

$96{,}480{,}000 \text{ m}^2\text{/hr} \div 2{,}588{,}881 \text{ m}^2\text{/mi}^2 = 37.27 \text{ mi}^2\text{/hr}$

### 2.2 Calculations for TMS

$500 \text{ m} \times 100 \text{ m/s} \times 3600 \text{ s/hr} = 180{,}000{,}000 \text{ m}^2\text{/hr}$

or $180{,}000{,}000 \text{ m}^2\text{/hr} \div 1{,}000{,}000 \text{ m}^2\text{/km}^2 = 180 \text{ km}^2\text{/hr}$

or $180{,}000{,}000 \text{ m}^2\text{/hr} \div 2{,}588{,}881 \text{ m}^2\text{/mi}^2 = 69.53 \text{ mi}^2\text{/hr}$

## 3.0 Calculation of tide station requirements

Mr. Arthur Najjar (NAVOCEANO Code 8400) indicated that shore-installed tide stations are typically installed by NAVOCEANO surface hydrographic units at 100-mile intervals for very straight coastlines with relatively little abruptness in the bottom bathymetry. If the coastline is quite irregular (sinuous) and/or the bottom topography exhibits sharp relief, the spacing of shore gauges could be on the order of 20 miles apart. These two figures, 100-mile spacing and 20-mile spacing, represent not the best case and worst cases but, rather, something closer to the mean of the best and worst cases. There are situations (but not often) when tide stations can be safely spaced more than 100 miles apart and situations (perhaps more likely) when spacing should be closer than 20 miles.

Using these two spacings, the area coverage rates from Table 1, and two types of bottom shapes, the number of tide stations required per flight hour for HALS and TMS can be calculated and plotted as shown in Figure 1 of the main text. The two bottom types selected are: gentle slope where airborne bathymetry can be conducted for up to 10 miles offshore, and steep slope where airborne bathymetry can be conducted for only 2 miles offshore.

It should be noted that the number of tide stations calculated is for shore-installed gauges only, with spacings of 20 miles or 100 miles. No offshore seabed gauges are needed since the maximum offshore distance being surveyed is 10 miles. The calculations shown below are for production of Figure 1d. The calculations for the other parts of Figure 1 are similar.

### 3.1 Calculations for HALS

For a sinuous coastline with steep sloping bottom, the spacing of tide stations is one for each 20 miles and airborne bathymetry surveying can be conducted out to 2 miles offshore. At 37 mi²/hr coverage rate, (37 mi²/hr ÷ 2 mi (offshore)) × 8 hrs = 148 shoreline miles covered per 8 hrs. At one gauge per 20 miles, 7.4 gauges per 8 hrs must be installed. Note that the number of gauges required is a linear function of time (straight line plot).

### 3.2 Calculations for TMS

At 70 mi²/hr, (70 mi²/hr ÷ 2) × 8 hours = 280 shoreline miles per 8 hours; or 280 ÷ 20 = 14.0 tide stations installations per 8 hours.

## 4.0 Calculation of tide station estimated deployment costs

Table 2 of the main text is designed to get a handle on what it will likely cost to support an airborne bathymetry system, using a shore-based tide station approach similar to that now being used for surface ship bathymetry. It was decided not to assume that NAVOCEANO would supply people, equipment, and work boats because this clearly highest cost approach was not something NAVOCEANO considered feasible. Instead, the assumptions are that NAVOCEANO would send one technician with the appropriate number of tide station instruments and he or she would use local contract labor and boats for installation and operation over the 30 day period.

### 4.1 Assumptions

The following basic cost figures were used in constructing Table 2.

- Approximate annual cost of field technician: $38K (data supplied by Mr. George Dupont, NAVOCEANO Code 8400).
- Cost of local boat and crew for the five specified areas of the world: $400–$600/day (data compiled by Mr. Robert Brown, NORDA Code 252, from sources shown in Figure A1 of this appendix).
- Cost of travel to the specified areas: see Figure A2 (data supplied by Ms. Jan Lewis and Ms. Sue Spiess of NAVOCEANO Code 4200).
- Instrument cost for each tide station of $6,000 and annual maintenance of 2 man days per month (24 man days per year)—(data Supplied by Mr. Paul Taylor, NAVOCEANO Code 8400).

The labor cost per day for the field technician is figured as 52 weeks of 40 hours, less 26 days of annual leave (208 hours), less 8 days of sick leave (64 hours), less 8 paid holidays (64 hours)—or 2080 − 336 = 1744 hours for $38,000 = $21.79/hour or $174/day (regular time). In any field operation there is almost always overtime (often the incentive to go in the first place). Assuming 12 hours per day, 6 days per week, and time and a half for overtime, ∴ the actual cost will be more like ($21.79/hr × 8 + ($21.79/hr × 1.5 × 4) = $305/day or $1830 per work week.

The instrument costs per station are figured at 30 installations per lifetime (about 4 setups in the field per year for almost 8 years) for $6000, plus maintenance of 24 man days per year, which gives $6000 ÷ 30 set ups + (2 man days maintenance per month × $174 per man day) = $200 + $348 = $550 per one month (30-day) setup.

It is estimated that a single technician with assistance from local resources can install approximately 5 stations per work week with 20-mile separation between stations, or approximately 3 stations per week with 100-mile separation. The average is, therefore, 4 stations per work week for one technician.

### 4.2 First example

To calculate installation costs per station (line 6 of Table 2 in the report) assume that 4 stations are installed per week for 4 weeks. The cost per station is calculated for the North Atlantic or Europe:

**1.0 Costs of Hiring Local Observers to Retrieve Data**

Mr. Marshall Jennings—U.S. Geological Survey
Mr. Tom McAuliffe—Naval Oceanographic Office
Mr. Mike Jeffries—Naval Oceanographic Office
Mr. Paul Taylor—Naval Oceanographic Office

**2.0 Costs of Data Collection Platforms**

Mr. Don Rapp—U.S. Geological Survey
Mr. Charlie Anderson—U.S. Geological Survey

**3.0 Contracting of Boats and Crews**

Mr. Craig Willett—Naval Oceanographic Office
Mr. Art Najjar—Naval Oceanographic Office
Mr. Scott Ebrite—Naval Oceanographic Office

**4.0 Availability of Fixed Tidal Stations**

Mr. Doug Scally—National Data Buoy Center

*Figure A1. Data sources on rental cost for local boats and crews.*

| | | Air Fare (Round Trip) | Daily Per Diem |
|---|---|---|---|
| **Area 1—North Atlantic or Europe** | | | |
| London, England | | $941 | $131 |
| Stockholm, Sweden | | $1051 | $131 |
| Reykjavik, Iceland | | $978 | $105 |
| | Avg = | $990 | $122 |
| **Area 2—Central Pacific or South Atlantic** | | | |
| Buenos Aires, Argentina | | $2134 | $81 |
| Recife, Brazil | | $1500 | $50 |
| Honolulu, Hawaii | | $578 | $50 |
| Nairobi, Kenya | | $1761 | $80 |
| | Avg = | $1493 | $76 |
| **Area 3—Mediterranean** | | | |
| Athens, Greece | | $1291 | $62 |
| Cario, Egypt | | $1387 | $77 |
| Muscat, Oman | | $2747 | $160 |
| | Avg = | $1808 | $100 |
| **Area 4—Indian Ocean** | | | |
| Bombay, India | | $2559 | $76 |
| Diego Garcia | | $2238 | $20 |
| Port Elizabeth, South Africa | | $2293 | $62 |
| | Avg = | $2363 | $53 |
| **Area 5—South Pacific** | | | |
| Osaka, Japan | | $1441 | $117 |
| Christchurch, New Zealand | | $2045 | $63 |
| Perth, Australia | | $2449 | $76 |
| Singapore | | $2109 | $116 |
| | Avg = | $2011 | $93 |

*Figure A2. Average travel and per diem costs to five areas of the world.*

Cost of local boat—
$500/day × 6 days/wk × 4 wks = $12,000/trip
Cost of travel—
$990 for 1 technician = 990/trip
Cost of per diem—
$122/day × 7 days/week × 4 wks = 3,416/trip
Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320/trip
Cost of instruments—
4/wk × 4 wks × $550 each = 8,880/trip
Total Cost = $32,526/trip

This total trip cost provides 16 tide station installations, or a cost per installation of $32,526 ÷ 16 = $2033 per station per trip. If more than 4 stations per week are required, an additional technician and boat will be needed for each group of 4 (or part thereof) stations, but the cost per installed station will remain just about the same.

The cost calculations for low and high installation rates per year is simply the cost per station per trip times the number of installed stations per trip times the number of trips per year.

### 4.3 Second example

The cost per installed station for the Central Pacific or South America is calculated.

Cost of local boat—
$400/day × 6 days/wk × 4 wks = $9,600/trip
Cost of travel—
$1493 for 1 technician = 1,493/trip
Cost of per diem—
$76/day × 7 days/wk × 4 wks = 2,128/trip
Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320/trip
Cost of instruments—
4/wk × 4 wks × $550 each = 8,800/trip
Total Cost = $29,341/trip

Therefore, the cost per installed station is $29,341 ÷ 16 = $1834 per trip.

### 4.4 Third example

The cost per installed station for the Mediterranean is calculated.

Cost of local boat—
$600/day × 6 days/wk × 4 wks = $14,400/trip
Cost of travel—
$1808 for 1 technician = 1,808/trip
Cost of per diem—
$100/day × 7 days/wk × 4 wks = 2,800/trip
Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320/trip
Cost of instruments—
4/wk × 4 wks × $550 each = 8,800/trip
Total Cost = $35,128/trip

Therefore, the cost per installed station is $35,128 ÷ 16 = $2,196 per trip.

The calculations for tide station installed costs for the Indian Ocean and South Pacific areas are performed in the same way. The results are shown in Table 2 of the main text.

## 5.0 Calculation of expendable tide gauge usage

These calculations are based on the tide station requirements established for Figure 1 of the main text and calculated in Section 3.0 of this appendix. Using the graphs of Figure 1 and assuming that a flight day might be as long as 8 hours of surveying, we can easily calculate the number of tide gauges required as a function of the number of flight days accomplished per year. Because the maximum distance surveyed offshore for the four defined conditions is 10 miles and gauges are typically not needed any closer together than 20 miles, the number of seabed expendable gauges required is equal to the number of shore-based gauges required per given length of coastline. The major installation difference with the expendable gauges is that they will be deployed somewhat offshore instead of near the beach.

Using Figure 1c for an example and assuming 20 flight days per year, which is probably a little beyond the maximum expected, we calculate 2.8 × 200 = 560 gauges to support TMS and 1.5 × 200 = 300 gauges to support HALS (see Figure 8c in the main text). The calculations for the other graphs of Figure 8 are made in similar fashion resulting in the straight line plots shown.

## 6.0 Calculation of cost estimate summaries

In this section the costs of fielding each of the six hardware approaches is calculated for two geographical areas of the world and for the situation where development costs are distributed over the number of instruments built. The resulting figures (9, 10, 11, and 12) present a summary comparison of the relative costs of using each method to solve the tide measurement problem. As pointed out in the main text, the two geographical areas selected represent (based on Table 2) the least and most expensive areas for conducting tide measurement surveys, although from Table 2 it is not expected that the cost of a particular method will be greatly affected by the geographical location selected. For each calculation involving distribution of development cost, these costs have been spread over an 8-year period and apportioned to the anticipated number of gauges built during this time. An 8-year period was chosen for the distribution because it represents about the longest time that an electronic system (the tide gauge) can be used before its technology is so outdated that it must be replaced.

The calculations given below draw heavily on the data given in Table 2 of the main text, supported by Section 4.0 of this appendix. Because of the complexity of these calculations, they are given in detail for each of the two defined areas, with and without distribution, even though the methodology is the same for each.

## 6.1 Central Pacific or South America

Method 1: Shore-installed tide gauges using commercially available equipment (see Table 2 of Report).

Cost per station = $1,834; therefore, the cost for 100 stations is $183K, the cost for 200 stations is $367K, and the cost for 300 stations is $550K. There is no development cost to consider as it is built into the commercial price of a gauge.

Method 2: Shore-installed tide gauges using an improved solid-state gauge. It is assumed that because this gauge requires the same amount of setup time (but less maintenance) that one field technician supported by a local boat and crew can install and service an average of 6 stations per week instead of the 4 assumed for method 1. From Table 3, the development cost is estimated to be $230K, and the per-station production (manufacturing) cost is estimated at $7K each. The cost of instruments is based on 30 installations per lifetime plus maintenance of 6 man days per year (one-half man day per month), which gives $7,000 ÷ 30 + 0.5 man days/month × $174/man day = $233 + 87 = 320 per each one-month setup. The cost per installed station without distributed development costs for the Central Pacific or South America areas is calculated.

| | |
|---|---|
| Cost of local boat— | |
| $400/day × 6 days × 4 wks = | $9,600/trip |
| Cost of travel— | |
| $1493 for 1 technician = | 1,493/trip |
| Cost of per diem— | |
| $76/day × 7 days/wk × 4 wks = | 2,128/trip |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320/trip |
| Cost of instruments— | |
| 6/wk × 4 wks × $320 each = | 7,680/trip |
| Total Cost = | $28,221/trip |

The cost per installed station is, then, $28,221 ÷ 24 = $1,176 without development costs. The additional cost per installation of distributing development costs will depend on the number of instruments built and how many times each is used. Assuming N stations used per year and that each station is needed for 4 different installations per year, then N ÷ 4 instruments must be purchased (each having a useful life of almost 8 years). The distributed development cost would then be ($230,000 ÷ 8N) × 4 = ($230,000 ÷ 2N). Therefore, the following calculations complete the cost per station and cost of tide measurements needed for Figure 10, Method 2.

At 50 stations per year, the cost per station is $1,176 plus ($230,000 ÷ 100) = $1176 + $2300 = $3476 each, or $174K for 50 stations.

At 100 stations per year, the cost per installation is $1,176 plus ($230,000 ÷ 200) = $1,176 + $1,150 = $2,326 each, or $233K for 100 stations.

At 200 stations per year, the cost per installation is $1,176 plus ($230,000 ÷ 400) = $1,176 + $575 = $,751 each, or 305K for 200 stations.

At 300 stations per year, the cost per installation is $1,176 plus ($230,000 ÷ 600 = $1,176 + $383 = $1,559 each, or $468K for 300 stations.

Method 3: Ship-deployed, self-contained, solid-state seabed gauge with field support Data Extraction/Test Set. This type of gauge requires essentially no setup time and very little checkout time (using the Data Extraction/Test Set). It is assumed that because of the short installation time, one field technician supported by a local boat and crew can deploy an average of 1.5 stations per day, or 9 stations per week. From Table 4, the development cost is estimted to be $485K for the seabed gauge, and the production (manufacturing) cost is estimated at $18K per gauge. From Table 5, the development cost is $230K for the Data Extraction/Test Set, and the production cost is estimated to be $20K per set. The cost of instruments is based once again on 30 installations per lifetime plus maintenance of 12 man days per year (one man day per month), which gives $18,000 ÷ 30 plus 1 man day/month × $174/man day = $600 + $174 = $774 per gauge for each 30-day setup. To the per-gauge instrument cost must be added the per-station usage cost of the Data Extraction/Test Set and an acoustic release for recovery of each gauge from the sea floor. The Data Extraction/Test Set cost will be the price ($20,000) ÷ (8 years × 36 stations/trip × 4 trips/year), which is the number of times the set will be used over its lifetime plus the maintenance cost per trip of (1 man day/month × $174/man day) ÷ 36 gauges/trip = $17.36 + $4.83 = $22.19. The cost per station of the acoustic release, whose cost is estimated to be $15K is ($15,000) ÷ (8 × 36 × 4) plus maintenance of (1 × 174) ÷ 36 = $13.02 + $4.83 = $17.85. The total per-station cost for instruments is, then, $774 + $22.19 + $17.85 = $814.

The cost per installed seabed gauge without development costs for the Central Pacific or South America area is calculated.

| | |
|---|---|
| Cost of local boat— | |
| $400/day × 6 days × 4 wks = | $9,600/trip |
| Cost of travel— | |
| $1,493 for 1 technician = | 1,493/trip |
| Cost of per diem— | |
| $76/day × 7 days/wk × 4 wks = | 2,128/trip |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320/trip |
| Cost of instruments— | |
| 9/wk × 4 wks × $814 each = | 29,304/trip |
| Total Cost = | $49,845/trip |

The cost per deployed seabed gauge is, then, $49,845 ÷ 36 = $1,385 without development costs. The additional cost per-gauge deployment when development costs are distributed depends on the number of seabed gauges built and the number of times the Data Extraction/Test Set is used. If, as in Method 2, we assume N seabed gauges deployments per year and that each gauge is deployed 4 times per year, then N ÷ 4 gauges must be purchased (each having a useful life of almost 8 years). The distributed development cost would then be ($485,000 ÷ 8N) × 4. If the useful life of the Data Extraction/Test Set is also 8 years and it is used N times per year, then the distributed development cost per use is the (Development Cost ÷ 8N). The following calculations include development costs in the cost of each deployment.

At 50 stations per year, the cost per station is $1385 plus ($485,000 – 100) plus ($230,000 ÷ 400) = $1385 + $4850 + $575 = $6810 each, or $341K for 50 stations.

At 100 stations (gauge deployments) per year, the cost is $1,385 plus ($485,000 ÷ 200) plus ($230,000 ÷ 800) = $1,385 + $2,425 + $288 = $4,093 each, or $410K for 100 stations.

At 200 stations per year, the cost is estimated to be $1,385 plus ($485,000 ÷ 400) plus ($230,000 ÷ 1,600) = $1,385 + $1,213 + $144 = $2,742 each, or $548K for 200 stations.

At 300 stations per year, the cost is estimated to be $1,385 plus ($485,000 ÷ 600) plus ($230,000 ÷ 2,400) = $1,385 + $808 + $96 = $2,289 each, or $687K for 300 stations.

Method 4: Air-deployed, self-contained, solid state seabed gauge with surface recovery of gauge and use of Data Extraction/Test Set. Since the gauges will be deployed as part of the airborne bathymetric survey, no significant cost is seen for the deployment. Recovery and data extraction will require local boat and crew support and use of the Data Extraction/Test Set similar to that calculated for Method 3. The cost of instruments will change, however, because of the more sophisticated and expensive air-deployed seabed tide gauge. From Table 6, the development cost is estimated to be $740K for the air-launched gauge, and the production cost is estimated at $25K per gauge. Using the 30 installations lifetime once again (Note: 30 successful launches and recoveries may be optimistic) and estimating 1.5 man days per month of maintenance due to the greater gauge sophistication, the per-deployment gauge cost without distribution of development costs is $25,000 ÷ 30 plus 1.5 times $174 = $833 + $261 = $1,094 per each 30-day setup. To this cost must be added the cost of the Data Extraction/Test Set usage and the cost of an acoustic release system (estimated at $15K per system), of which there are a number of commercial units available. The cost of including the Data Set and Release is ($20,000 + $15,000) ÷ (8 years × 36 recoveries/trip × 4 trips/year) = $30 per usage. The grand total for instruments is $1,094 plus $30 = $1,124 per station.

The cost per air-deployed seabed gauge for the Central Pacific or South America is calculated to be:

| | |
|---|---|
| Cost of local boat— | |
| $400/day × 6 days/wk × 4 wks = | $9,600/trip |
| Cost of travel— | |
| $1,493 for 1 technician = | 1,493/trip |
| Cost of per diem— | |
| $76/day × 7 days/wk × 4 wks = | 2,128/trip |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320/trip |
| Cost of instruments— | |
| 9/wk × 4 wks × $1,094 each = | 39,384/trip |
| Total Cost = | $59,925/trip |

The cost per air-deployed gauge is, then, $59,925 ÷ 36 = $1,665 without development costs. The additional cost per-gauge deployment when development costs are included can be calculated in the same manner as Method 3. For the air-launched tide gauge the distributed development cost is ($740,000 ÷ 2N), where N = the number of gauge deployments per year. For the Data Set, the distributed development cost is ($230,000 ÷ 8N). There is no distributed development cost for the acoustic release, as it is already included in the purchase price. The calculations for inclusion of development costs are

At 50 stations established per year, the cost is $1665 plus ($740,000 ÷ 100) plus ($230,000 ÷ 400) = $1665 + $7400 + $575 = $9640 each, or $482K for 50 stations.

At 100 stations (gauge deployments) per year, the cost is $1,665 plus ($740,000 ÷ 200) plus ($230,000 ÷ 800) = $1,665 + $3,700 + $288 = $5,563 each, or $565K for 100 stations.

At 200 stations per year, the cost is estimated to be $1,665 plus ($740,000 ÷ 400) plus ($230,000 ÷ 1,600) = $1,665 + 1,850 + $144 = $3,659 each, or $732K for 200 stations.

At 300 stations per year, the cost is estimated to be $1,665 plus ($740,000 ÷ 600) plus ($230,000 ÷ 2,400) = $1,665 + $1,233 + 96 = $2,994 each, or $898K for 300 stations.

Method 5: Air-deployed, self-contained solid state seabed gauge with airborne data collection and subsequent surface recovery of the gauge itself. With airborne data collection it will not be necessary to have data extracted in the field by the surface recovery group, but the test set portion of the Data Extraction/Test Set will still be needed. In addition, data receiving and recording equipment will be needed in the aircraft to capture the telemetered tidal data during the subsequent flyover. The cost of this equipment is established to be $100,000 and it should have the same 8-year useful life. The cost of the subsequent flyover should also be taken into account, since it is required by this method of collecting the tidal data. It is estimated at $850/flight hour, based on information from Navy Squadron VX-1, and will require about 10 hours per trip. From Table 7, the development cost for the air-deployed gauge with data telemetry is $825,000, and the per unit production (manufacturing) cost is estimated to be $35,000 each. Using a mission life of 30 launches and 2 man days of maintenance per gauge per month, and including the per unit cost of the Data Test Set and aircraft receiver/recorder electronics, the cost for instruments is calculated as ($35,000 ÷ 30) plus 2 × $174/man day plus $30 per station for the Test set and acoustic release plus ($100,000) ÷ (8 years × 36 stations per trip × 4 trips/year) for the receiver/recorder equipment = $1,167 + $348 + $30 + $87 = $1,632 per station.

The cost per air-deployed seabed gauge with data telemetry for the Central Pacific or South America is calculated

| | |
|---|---|
| Cost of local boat— | |
| $400/day × 6 days/wk × 4 wks = | $9,600/trip |
| Cost of travel— | |
| $1,493 for 1 technician = | 1,493/trip |
| Cost of per diem— | |
| $76/day × 7 days/wk × 4 wks = | 2,128/trip |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320/trip |
| Cost of instruments— | |
| 9/wk × 4 wks × $1,632 each = | 58,752/trip |
| Cost of flyover— | |
| $850/hr × 10 hrs/trip = | 8,500/trip |
| Total Cost = | $87,793/trip |

The cost per air-deployed gauge is, then, $87,793 ÷ 36 = $2,439 without development costs. The additional cost per-gauge deployment when development costs are included can be calculated in the same manner used for methods 3 and 4. For the gauge, the distributed development cost is ($825,000 ÷ 2N), where N = the number of gauge deployments per year. For the Data Set, the distributed development cost is ($230,000 ÷ 8N). There are no development costs for the acoustic release or the aircraft receiving/recording equipment, as it is already included in the purchase price. The inclusion of development costs produces the following total costs.

At 50 stations per year, the estimated cost is $2439 plus ($825,000 ÷ 100) plus ($230,000 ÷ 400) = $2439 + $8250 + $575 = $11,264 each, or $563K for 50 stations.

At 100 stations per year, the cost is $2,439 plus ($825,000 ÷ 200) plus ($230,000 ÷ 800) = $2,439 + $4,125 + $288 = $6,852 each, or $685K for 100 stations.

At 200 stations per year, the cost estimate is $2,439 plus ($825,000 ÷ 400) plus ($230,000 ÷ 1,600) = $2,439 + $2,063 + $144 = $4,646 each, or $929K for 200 stations.

At 300 stations per year, the cost estimate is $2,439 plus ($825,000 ÷ 600) plus ($230,000 ÷ 2,400) = $2,439 + $1,375 + $96 = $3,910 each, or $1,173K for 300 stations.

Method 6: Air-deployed expendable seabed tide gauge with airborne data collection. With this method it will not be necessary to use any surface support. The aircraft can deploy the expendable gauges at the appropriate intervals during bathymetric surveying and recover the data during a subsequent flyover. Using the assumption of 36 deployed gauges per survey trip and 4 such trips per year, a calculation can be made for the cost of instruments. From Table 8, the expendable gauge development cost is estimated to be $1,190K with the per unit production cost estimated to be $4K-$8K (assuming some economics of scale can be realized). There will be no maintenance cost, as the gauges are tested after initial manufacture but not reused. For calculating costs without distributing development costs, the per-unit cost of gauges will be assumed to be $6K (the average of the $4K-$8K range). The cost, then, per air-deployed expendable gauge for the Central Pacific or South America is calculated.

| | |
|---|---|
| Cost of instruments— | |
| 36 gauges/trip × $6K/gauge = | $216,000/trip |
| Cost of flyover— | |
| $850 hr × 10 hours/trip = | 8,500/trip |
| Cost of receiver/recording equipment— | |
| $100,000 (8 yrs × 4 trips/yr) = | 3,125/trip |
| Total Cost = | $227,625/trip |

The cost per gauge of deployed gauges is $227,625 ÷ 36 = $6,323 without distribution of development costs. The additional cost per gauge deployment when development costs are distributed can be calculated based on the number of gauges deployed per year times the number of years that the development technology will be used. If the life of the developed technology is assumed to be 8 years, then the additional cost per deployed gauge is ($1,190,000 ÷ 8N), where N = the number of gauges built and deployed per year. The calculations for including development costs are

At 50 expendable tide stations per year, the cost is $6,323 plus ($1,190,000 ÷ 400) = $6,323 + $2,975 = $9,298 each, or $465K for 50 stations.

At 100 expendable tide stations per year, the cost is $6,198 plus ($1,190,000 ÷ 800) = $6,198 + $1,488 = $7,686 each, or $769K for 100 stations.

At 200 expendable stations per year, the cost is $6,198 plus ($1,190,000 ÷ 1,600) = $6,198 + $744 = $6,942 each, or $1,388K for 200 stations.

At 300 expendable stations per year, the cost is $6,198 plus ($1,190,000 ÷ 2,400) = $6,198 + $496 = $6,694 each, or $2,008K for 300 stations.

## 6.2 Mediterranean

The following calculations give the estimated costs for each of the six methods for the highest cost geographical area of Table 2.

Method 1: Shore installed tide gauges using commercially available equipment (see Table 2 of the main text). Cost per station is $2,196; therefore, the cost for 100 stations is $220K, the cost for 200 stations is $439k, and the cost for 300 stations is $659K. There is no development cost to consider, as it is already included in the commercial price of the gauge.

Method 2: Shore-installed tide gauges using an improved solid-state gauge. The calculations will be the same as for method 2 under Subsection 6.1 except for the travel, per diem, and local vessel support costs. The cost per installed station without development costs for the Mediterranean is calculated.

| | |
|---|---|
| Cost of local boat— | |
| $600/day × 6 days/wk × 4 wks = | $14,400/trip |
| Cost of travel— | |
| $1,808 for 1 technican = | 1,808/trip |
| Cost of per diem— | |
| $100/day × 7 days/wk × 4 wks = | 2,800/trip |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320/trip |
| Cost of instruments— | |
| 6/wk × 4 wks × $320 each = | 7,680/trip |
| Total Cost = | $34,008/trip |

The cost per installed station is, then, $34,008 ÷ 24 = $1,417 without distributed development costs. The additional cost per station when development costs are distributed is calculated.

At 50 stations per year, the estimated cost is $1,417 plus ($230,000 ÷ 100) = $1,417 + $2,300 = $3,717 each, or $186K for 50 stations.

At 100 stations per year, the estimated cost is $1,417 plus ($230,000 ÷ 200) = $1,417 + $1,150 = $2,567 each, or $257K for 100 stations.

At 200 stations per year, the estimated cost is $1,417 plus ($230,000 ÷ 400) = $1,417 + $575 = $1,992 each, or $398K for 200 stations.

At 300 stations per year, the estimated cost is $1,417 plus ($230,000 ÷ 600) = $1,417 + $383 = $1,800 each, or $540K for 300 stations.

Method 3: Ship-deployed, self-contained, solid-state sea bed gauge with field support Data Extraction Test Set. The calculations for the Mediterranean area follow the same line of reasoning as for method 3 under Subsection 6.1. The cost per deployed station without development costs being included is calculated.

| | |
|---|---|
| Cost of local boat— | |
| $600/day × 6 days/wk × 4 wks = | $14,400/trip |
| Cost of travel— | |
| $1,808 for 1 technician = | 1,808/trip |
| Cost of per diem— | |
| $100/day × 7 days/wk × 4 wks = | 2,800/trip |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320/trip |
| Cost of instruments— | |
| 9/wk × 4 wks × $814 each = | 29,304/trip |
| Total Cost = | $55,632/trip |

The cost per deployed seabed gauge is $55,632 ÷ 36 = $1,545 without development costs. The additional cost per station when development costs are included is calculated.

At 50 stations per year, the estimated cost is $1,545 plus ($485,000 ÷ 100) plus ($230,000 ÷ 400) = $1,545 + $4,850 + $575 = $6,970 each, or $349K for 50 stations.

At 100 stations per year, the estimated cost is $1,545 plus ($485,000 ÷ 200) plus ($230,000 ÷ 800) = $1,545 + $2,425 + $288 = $4,258 each, or $426K for 100 stations.

At 200 stations per year, the estimated cost is $1,545 plus ($485,000 ÷ 400) plus ($230,000 ÷ 1,600) = $1,545 + $1,213 + $144 = $2,902 each, or $580K for 200 stations.

At 300 stations per year, the estimated cost is $1,545 plus ($485,000 ÷ 600) plus ($230,000 ÷ 2,400) = $1,545 + $808 + $96 = $2,449 each, or $735K for 300 stations.

Method 4: Air-deployed, self-contained, solid-state seabed gauge with surface recovery of gauge and use of Data Extraction Test Set. The calculations for the Mediterranean follow the same line of reasoning as used for method 4 in Subsection 6.1. The cost per deployed gauge is calculated without development costs.

| | |
|---|---|
| Cost of local boat— | |
| $600/day × 6 days/wk × 4 wks = | $14,400/trip |
| Cost of travel— | |
| $1,808 for 1 technician = | 1,808/trip |
| Cost of per diem— | |
| $100/day × 7 days/wk × 4 wks = | 2,800/trip |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320/trip |
| Cost of instruments— | |
| 9/wk × 4 wks × $1,094 each = | 39,384/trip |
| Total Cost = | $65,712/trip |

The cost per air-deployed gauge is $39,384 ÷ 36 = $1,825 without development costs. The additional cost per gauge deployment when development costs are included can be calculated using the procedure shown for method 4, Subsection 6.1.

At 50 stations (gauge deployments) per year, the cost is $1,825 plus ($740,000 ÷ 100) plus ($230,000 ÷ 400) = $1,825 + $7,400 + $575 = $9,800 each, or $490K for 50 stations.

At 100 stations (gauge deployments) per year, the cost is $1,825 plus ($740,000 ÷ 200) plus ($230,000 ÷ 800) = $1,825 + $3,700 + $288 = $5,813 each, or $581K for 100 stations.

At 200 stations per year, the cost is estimated to be $1,825 plus ($740,000 ÷ 400) plus ($230,000 ÷ 1,600) = $1,825 + $1,850 + $144 = $3,819 each, or $764K for 200 stations.

At 300 stations per year, the cost is estimated to be $1,825 plus ($740,000 ÷ 600) plus ($230,000 ÷ 2,400) = $1,825 + $1,233 + $96 = $3,154 each, or $946K for 300 stations.

Method 5: Air-deployed, self-contained, solid-state seabed gauge with airborne data collection and subsequent surface recovery of the gauge. The cost calculations for the Mediterranean follow the procedure used for method 5 in Subsection 6.1. The cost per gauge deployment without including development costs is calculated.

| | |
|---|---|
| Cost of local boat— | |
| $600/day × 6 days/wk × 4 wks = | $14,400/trip |
| Cost of travel— | |
| $1,808 for 1 technician = | 1,808/trip |
| Cost of per diem— | |
| $100/day × 7 days/wk × 4 wks = | 2,800/trip |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320/trip |
| Cost of instruments— | |
| 9/wk × 4 wks × $1,632 each = | 58,752/trip |
| Cost of flyover— | |
| $850/hr × 10 hrs = | 8,500/trip |
| Total Cost = | $93,580/trip |

The cost per air-deployed gauge is $93,580 ÷ 36 = $2,599 without development costs. The additional cost per station (gauge deployment) when development costs are included is calculated.

At 50 stations per year, the estimated cost is $2,599 plus ($825,000 ÷ 100) plus ($230,000 ÷ 400) = $2,599 + $8,250 + $575 = $11,424 each, or $571K for 50 stations.

At 100 stations per year, the estimated cost is $2,599 plus ($825,000 ÷ 200) plus ($230,000 ÷ 800) = $2,599 + $4,125 + $288 = $7,012 each, or $701K fOr 100 stations.

At 200 stations per year the estimated cost is $2,599 plus ($825,000 ÷ 400) plus $230,000 ÷ 1,600) = $2,599 + $2,063 + $144 = $4,806 each, or $961K for 200 stations.

At 300 stations per year, the estimated cost is $2,599 plus ($825,000 ÷ 600) plus ($230,000 ÷ 2,400) = $2,599 + $1,375 + $96 = $4,070 each, or $1,221K for 300 stations.

Method 6: Air-deployed expendable seabed tide gauge with airborne data collection. Estimated cost calculations for this method are identical to those of method 6, Subsection 6.1, because there are no surface support costs and, therefore, no effect due to geographical location.

## 7.0 Calculation of model validation cost estimates

For estimation purposes, it will be assumed that Method 1, use of commercially available shore-based tide station, is selected. Each data station measurement set consists of 30 days of tide measurements at a single location. A technician using local boat support can install and maintain up to 4 stations per week in one relatively localized area. And, last, no more than 10 data sets are required to characterize the tidal conditions of a single location for a given time of year. The following calculations estimate the costs of achieving the various required measurement sets for the North Atlantic or Europe (area I).

For collection of 2 tidal data sets the cost will be

| | |
|---|---|
| Cost of local boat— | |
| $500/day × 6 days (install + service) = | $3,000 |
| Cost of travel— | |
| $990 for 1 technician = | 990 |
| Cost of per diem— | |
| $122/day × 7 days/wk × 4 wks = | 3,416 |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320 |
| Cost of instruments— | |
| $1,244 each × 2 stations = | 2,488 |
| Total Cost = | $17,214 |

For collection of 5 tidal data sets for one location of area I:

| | |
|---|---|
| Cost of local boat— | |
| $500/day × 11 days (install + service) = | $5,500 |
| Cost of travel— | |
| $990 for 1 technician = | 990 |
| Cost of per diem— | |
| $122/day × 7 days/wk × 4 wks = | 3,416 |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320 |
| Cost of instruments— | |
| $1,244 each × 5 stations = | 6,220 |
| Total Cost = | $23,446 |

For collection of 10 tidal data sets for one location of area I:

| | |
|---|---|
| Cost of local boat— | |
| $500/day × 19 days (install + service) = | $9,500 |
| Cost of travel— | |
| $990 for 1 technician = | 990 |
| Cost of per diem— | |
| $122/day × 7 days/wk × 4 wks = | 3,416 |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320 |
| Cost of instruments— | |
| $1,244 each × 10 stations = | 12,440 |
| Total Cost = | $33,666 |

The estimated costs of achieving tidal measurement sets for the central Pacific or South Atlantic (area II) are calcualted.

For collection of 2 tidal data sets for one location of area II:

| | |
|---|---|
| Cost of local boat— | |
| $400/day × 6 days (install + service) = | $2,400 |
| Cost of travel— | |
| $1,493 for 1 technician = | 1,493 |
| Cost of per diem— | |
| $76/day × 7 days/wk × 4 wks = | 2,128 |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320 |
| Cost of instruments— | |
| $1,244 each × 2 stations = | 2,488 |
| Total Cost = | $15,829 |

For collection of 5 tidal data sets for one location of area II:

| | |
|---|---|
| Cost of local boat— | |
| $400/day × 11 days (install + service) = | $4,400 |
| Cost of travel— | |
| $1,493 for 1 technician = | 1,493 |
| Cost of per diem— | |
| $76/day × 7 days/wk × 4 wks = | 2,128 |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320 |
| Cost of instruments— | |
| $1,244 each × 5 stations = | 6,220 |
| Total Cost = | $21,561 |

For collection of 10 tidal data sets for one location of area II:

| | |
|---|---|
| Cost of local boat— | |
| $400/day × 19 days (install + service) = | $7,600 |
| Cost of travel— | |
| $1,493 for 1 technician = | 1,493 |
| Cost of per diem— | |
| $76/day × 7 days/wk × 4 wks = | 2,128 |
| Cost of labor— | |
| $305/day × 6 days/wk × 4 wks = | 7,320 |
| Cost of instruments— | |
| $1,244 each × 10 stations = | 12,440 |
| Total Cost = | $30,981 |

The estimated costs of achieving tidal measurement sets for the Mediterranean (area III) are calcualted.

For collection of 2 tidal data sets for one location of area III:

Cost of local boat—
$600/day × 6 days (install + service) = $3,600

Cost of travel—
$1,808 for 1 technician = 1,808

Cost of per diem—
$100/day × 7 days/wk × 4 wks = 2,800

Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320

Cost of instruments—
$1,244 each × 2 stations = 2,488

Total Cost = $18,016

For collection of 5 tidal data sets for one location of area III:

Cost of local boat—
$600/day × 11 days (install + service) = $6,600

Cost of travel—
$1,808 for 1 technician = 1,808

Cost of per diem—
$100/day × 7 days/wk × 4 wks = 2,800

Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320

Cost of instruments—
$1,244 each × 5 stations = 6,220

Total Cost = $24,748

For collection of 10 tidal data sets for one location of area III:

Cost of local boat—
$600/day × 19 days (install + service) = $11,400

Cost of travel—
$1,808 for 1 technician = 1,808

Cost of per diem—
$100/day × 7 days/wk × 4 wks = 2,800

Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320

Cost of instruments—
$1,244 each × 10 stations = 12,440

Total Cost = $35,768

The estimated costs of achieving tidal measurement sets for the Indian Ocean (area IV) are calculated.

For collection of 2 tidal data sets for one location of area IV:

Cost of local boat—
$500/day × 6 days (install + service) = $3,000

Cost of travel—
$2,363 for 1 technician = 2,363

Cost of per diem—
$53/day × 7 days/wk × 4 wks = 1,484

Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320

Cost of instruments—
$1,244 each × 2 stations = 2,488

Total Cost = $16,655

For collection of 5 tidal data sets for one location of area IV:

Cost of local boat—
$500/day × 11 days (install + service) = $5,500

Cost of travel—
$2,363 for 1 technician = 2,363

Cost of per diem—
$53/day × 7 days/wk × 4 wks = 1,484

Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320

Cost of instruments—
$1,244 each × 5 stations = 6,220

Total Cost = $22,887

For collection of 10 tidal data sets for one location of area IV:

Cost of local boat—
$500/day × 19 days (install + service) = $9,500

Cost of travel—
$2,363 for 1 technician = 2,363

Cost of per diem—
$53/day × 7 days/wk × 4 wks = 1,484

Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320

Cost of instruments—
$1,244 each × 10 stations = 12,444

Total Cost = $33,107

The estimated costs of achieving tidal measurement sets for the South Pacific (area V) area are calcualted.

For collection of 2 tidal data sets for one location of area V:

Cost of local boat—
$400/day × 6 days (install + service) = $2,400

Cost of travel—
$2,011 for 1 technician = 2,011

Cost of per diem—
$93/day × 7 days/wk × 4 wks = 2,604

Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320

Cost of instruments—
$1,244 each × 2 stations = 2,488

Total Cost = $16,823

For collection of 5 tidal data sets for one location of area V:

Cost of local boat—
$400/day × 11 days (install + service) = $4,400
Cost of travel—
$2,011 for 1 technician = 2,011
Cost of per diem—
$93/day × 7 days/wk × 4 wks = 2,604
Cost of labor $305/day × 6 days/wk × 4 wks = 7,320
Cost of instruments—
$1,244 each × 5 stations = 6,220
Total Cost = $22,555

For collection of 10 tidal data sets for one location of area V:

Cost of local boat—
$400/day × 19 days (install + service) = $7,600
Cost of travel—
$2,011 for 1 technician = 2,011
Cost of per diem—
$93/day × 7 days/wk × 4 wks = 2,604
Cost of labor—
$305/day × 6 days/wk × 4 wks = 7,320
Cost of instruments—
$1,244 each × 10 stations = 12,440
Total Cost = $31,975

To validate a model worldwide might require 50 geographical locations with 5 data sets for each location for each of the four seasons of the year (20 data sets per location or 1,000 data sets total). The cost of collecting all this validation data can be calculated assuming that 10 locations come from within each of the 5 areas:

Cost of Area I—
$23,446 (5 sets) × 4 seasons × 10 locations = $937.8K
Cost of Area II—
$21,561 (5 sets) × 4 seasons × 10 locations = 862.4K
Cost of Area III—
$24,748 (5 sets) × 4 seasons × 10 locations = 989.9K
Cost of Area IV—
$22,887 (5 sets) × 4 seasons × 10 locations = 915.5K
Cost of Area V—
$22,555 (5 sets) × 4 seasons × 10 locations = 902.2K
Total Cost = $4,608 K

If the validation can be achieved with 5 data sets for only one season of the year, the cost would decrease to $1,152K.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

ADA 169330

# REPORT DOCUMENTATION PAGE

| | |
|---|---|
| 1a REPORT SECURITY CLASSIFICATION<br>Unclassified | 1b RESTRICTIVE MARKINGS<br>None |
| 2a SECURITY CLASSIFICATION AUTHORITY<br><br>2b DECLASSIFICATION DOWNGRADING SCHEDULE | 3 DISTRIBUTION AVAILABILITY OF REPORT<br>Approved for public release; distribution is unlimited. |
| 4 PERFORMING ORGANIZATION REPORT NUMBER(S)<br>NORDA Report 139 | 5 MONITORING ORGANIZATION REPORT NUMBER(S)<br>NORDA Report 139 |
| 6 NAME OF PERFORMING ORGANIZATION<br>Naval Ocean Research and Development Activity | 7a NAME OF MONITORING ORGANIZATION<br>Naval Ocean Research and Development Activity |
| 6c ADDRESS (City, State, and ZIP Code)<br>Ocean Acoustics and Technology Directorate<br>NSTL, Mississippi 39529–5004 | 7b ADDRESS (City, State, and ZIP Code)<br>Ocean Acoustics and Technology Directorate<br>NSTL, Mississippi 39529–5004 |
| 8a NAME OF FUNDING SPONSORING ORGANIZATION<br>Naval Ocean Research and Development Activity<br>8b OFFICE SYMBOL (If applicable) | 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER |
| 8c ADDRESS (City, State, and ZIP Code)<br>Ocean Acoustics and Technology Directorate<br>NSTL, Mississippi 39529–5004 | 10 SOURCE OF FUNDING NOS<br>PROGRAM ELEMENT NO / PROJECT NO / TASK NO / WORK UNIT NO |

11 TITLE (Include Security Classification)
Tidal Data Collection Options Study

12 PERSONAL AUTHOR(S)
C. R. Holland

| 13a TYPE OF REPORT | 13b TIME COVERED | 14 DATE OF REPORT (Yr., Mo., Day) | 15 PAGE COUNT |
|---|---|---|---|
| Final | From ______ To ______ | November 1985 | 38 |

16 SUPPLEMENTARY NOTATION

| 17 COSATI CODES | | | 18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |
|---|---|---|---|
| FIELD | GROUP | SUB GR | tides, navigation, bathymetric survey |

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

In response to the Defense Mapping Agency (DMA) goal to "develop methods and systems for rapid and accurate collection of hydrographic data in coastal zones, and for the reduction and exploitation of hydrographic/bathymetric data to support both coastal operations and undersea weapon operations worldwide," NORDA was funded to study the problem of Rapid Hydrographic Data Collection. This study was to investigate all reasonable approaches to technically solving the issue of improved tidal data collection that supports both ship and aircraft collection systems, and to estimate the cost of each so that relative comparisons could be made. In conclusion, the study report was to recommend a "best" course of action to be followed in developing the final solution.

| | |
|---|---|
| 20 DISTRIBUTION AVAILABILITY OF ABSTRACT<br>UNCLASSIFIED UNLIMITED ☐ SAME AS RPT ■ DTIC USERS | 21 ABSTRACT SECURITY CLASSIFICATION<br>Unclassified |
| 22a NAME OF RESPONSIBLE INDIVIDUAL<br>C. R. Holland | 22b TELEPHONE NUMBER (Include Area Code)<br>(601) 688-5423 — 22c OFFICE SYMBOL<br>Code 252 |

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE

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SECURITY CLASSIFICATION OF THIS PAGE

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7-86