Oceanus®

Volume 33, Number 4, Winter 1990/91

Naval Oceanography

Oceanus®

The International Magazine of Marine Science and Policy
Volume 33, Number 4, Winter 1990/91 ISSN 0029-8182

Vicky Cullen, Editor
Mark Fitzgerald, Assistant Editor
Kathy Sharp Frisbee, Editorial Assistant
Robert W. Bragdon, Advertising Coordinator

The views expressed in *Oceanus* are those of the authors and do not necessarily reflect those of the Woods Hole Oceanographic Institution.

Editorial correspondence:
Oceanus Magazine,
Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts 02543.
Telephone: (508) 457-2000, extension 2386.

Subscription correspondence, U.S. and Canada: All orders should be addressed to *Oceanus* Subscriber Service Center, P.O. Box 6419, Syracuse, NY 13217. Individual subscription rate: $25 a year; Libraries and institutions, $80. Current copy price, $6.25; 25% discount on current copy orders for five or more. Please make checks payable to the Woods Hole Oceanographic Institution.
Subscribers outside the U.S. and Canada, please write: *Oceanus*, Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 2RU, England. Individual subscription rate: £24 a year; Students, £15; Libraries and Institutions, £43. Single-copy price, £7. Please make checks payable to Cambridge University Press.
When sending change of address, please include mailing label. Claims for missing numbers from the U.S. and Canada will be honored within three months of publication; overseas, five months.

WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

NAVAL OCEANOGRAPHY

Ben Franklin's Gulf Stream chart

ASW exercises over the Pacific


The Fleet Numerical Oceanography Center

 Oceanus (ISSN 0029-8182) is published in March, June, September, and December by the Woods Hole Oceanographic Institution, 9 Maury Lane, Woods Hole, Massachusetts 02543. Second-class postage paid at Falmouth, Massachusetts; Windsor, Ontario; and additional mailing points.
POSTMASTER: Send address change to *Oceanus* Subscriber Service Center, P.O. Box 6419, Syracuse, NY 13217.

Headings and Readings

U.S. Navy Photograph

USS *Billfish* surfaces near the North Pole

Cable-controlled Underwater Recovery Vehicle

© Patricia Lanza

Project Marco Polo students

THE COVER: Photographer Steve Kaufman captured USS *Will Rogers* (SSBN 659) during its departure from Holy Loch, Scotland. Photo courtesy of Yogi, Inc.

Oceanography and the United States Navy

RADM. G.L. Chesbrough and **RADM. R.F. Pittenger**
U.S. Navy
Oceanographer of the Navy

RADM. R.F. Pittenger
U.S. Navy, Retired
Oceanographer of the Navy (1988-1990)

Every U.S. ship, submarine, and aircraft now uses products and services provided by naval oceanography.

Why is oceanography important to the United States Navy? The Navy is a global organization. On every ocean of the world, every day, around the clock, thousands of American men and women are at work above, on, and below the ocean's surface. Whether on ships, in submarines, or airplanes, they must be prepared to confront the full force of Nature's furies. And they must be prepared, should a national emergency occur, to fight at sea. Oceanography, the study of the ocean environment, provides the advantage, the critical edge, when we must go "in harm's way."

Consider, if you will, setting out on a long drive. To travel "smart", you want the latest information available on the best routes, weather predictions, and areas of special interest. You could probably add to the list, but this type of information is generally what you pay for and expect from an efficient automotive travel company. Now think of setting out to sea in a ship that costs millions of dollars, with the lives of many sailors at stake, with an array of weapon systems sensitive to environmental conditions, confronting Nature's invariably unpredictable elements, and the possibility of having to fight at sea.

Naval oceanography can be considered the "wet" equivalent of the automotive travel company. However, the oceanographic products and services provided to our men and women at sea go far beyond a commercial automotive travel guide.

Oceanography must be able to provide information on ocean and atmospheric conditions as they vary from day-to-day, hour-to-hour. These conditions affect safety of passage, correct interpretation of sonar signals, and the effective operation of weapon systems. Consider some of the demands to which naval oceanography must be prepared to respond:

- Can a submerged submarine fix its position, target, and launch its missiles with assurance?
- Can we accurately account and compensate for ocean conditions, such as surface wind, waves, rain, Earth's gravity and magnetics, which may affect the launch and flight of a missile, as well as other weapon systems?

- Can we route our ships, submarines, and aircraft safely and quickly?
- Can we accurately forecast typhoon development and movement?
- Can we forecast the occurrence of openings (leads and polynyas) in the Arctic ice pack so that submarines can surface or communicate?
- Can we know the ocean environment well enough to assist in detecting a submerged enemy submarine?
- Can we describe the ocean environment well enough to optimize the use of sonar detection systems?
- Can we define and locate potential undersea hiding places?
- Can we acquire enough oceanographic information on coasts and harbors throughout the world to support any likely amphibious landings, mine warfare, or special warfare operations?

Can we route our ships, submarines, and aircraft safely and quickly?

Technology has evolved to a point where people and instruments can be sent to the deepest parts of the world's oceans. To do this safely requires detailed information of the ocean bottom. Those operating deep-diving Navy submarines and submersibles must be able to find their way and their position in an underwater world of perpetual darkness. Precise charts of the seafloor are vitally important to them.

Every United States ship, submarine, and aircraft now uses products and services provided by naval oceanography. From worldwide civil and military sources, weather and ocean observations, for example, are collected and analyzed by the Navy. These data are processed using sophisticated computer models, and weather and ocean forecasts are provided in near-real-time to Fleet commanders.

Special tailor-made services include naval oceanography's Optimum Track Ship Routing, a program that recommends the safest, most efficient, and economical passage for ships on the high seas. Use of this service, especially on long ocean crossings, has not only been vital to safety of ships, but has also saved millions of dollars in fuel. Naval oceanography now offers a similar service for military aircraft. Weather is seldom neutral; it favors those who know how to use it.

Today's naval oceanographers, military and civilian, investigate the nature and behavior of the oceans, conduct surveys to collect data on the composition and roughness of the ocean floor, and measure temperature, salinity, pressure, and other characteristics that influence the transmission of sound in the sea. This information is collected by Navy ships, submarines, aircraft, buoys, and "ships of opportunity." The data is then combined with historical records to predict the path sound will take as it moves through the water. This is essential. It enables us to locate and track submarines of potential adversaries and conceal our own.

Because United States ships operate in areas covered with ice, specially configured aircraft fly missions to profile ice ridges and water openings, to measure ice thickness, to monitor ocean conditions below the ice, and to record the movement of each ice pack.

Naval oceanographers use satellites to determine sea height, sea surface temperature, ocean currents, upwelling, water masses, and frontal boundaries. This type of information, essential in locating and tracking submarines, is provided in near-real-time to our Fleet commanders worldwide.

Satellites have proven to be powerful new oceanographic sensors. For example, after the National Aeronautics and Space Administration (NASA) launched Seasat in 1978, followed by Navy's Geosat, naval oceanographers using their satellite radar altimeters soon discovered 452 previously uncharted seamounts. Precise satellite radar altimeters are capable of constantly measuring distance from the satellite's orbit to the ocean surface. These seamounts were discovered because gravity attracts

USNS Maury *is a geophysical survey ship used for data collection by the Naval Oceanographic Office.*

Can we define and locate potential undersea hiding places?

water to massive areas, such as mountainous regions, and the surface of the ocean tends to mimic the shape of the landscape underneath.

In addition, Geosat became a valuable, all-weather means for locating the position of mesoscale oceanographic features, such as fronts and eddies. When in its oceanographic orbit, and until the final failure of the solar power panels in January 1990, Geosat data were readily available to both civilian and Navy users for research in ocean forecasting. The Navy is now actively planning a continuing series of radar altimeter satellites, referred to as the Geosat Follow-on.

The task of surveying the oceans, which comprise more than three-quarters of the Earth's surface, is an undertaking of enormous proportions, well beyond the resources of any one nation. In some cases, United States naval oceanography is engaged in cooperative agreements with established and emerging maritime nations, transcending political boundaries. Naval oceanographers, in specially-outfitted oceanographic survey ships, measure the water depths and variation in the Earth's magnetic field, determine gravity anomalies, and define the ocean floor's shape and texture. Using highly-precise, multi-beam bathymetric sonar systems, researchers are slowly painting a picture of the Earth's ocean floor.

As the articles in this special issue convey, naval oceanography today is an interlocking complex of disciplines. Naval oceanography has progressed from the mere act of collecting data for charts into a global pursuit using tools that enable us to venture deep into space or to the depths of the seas.

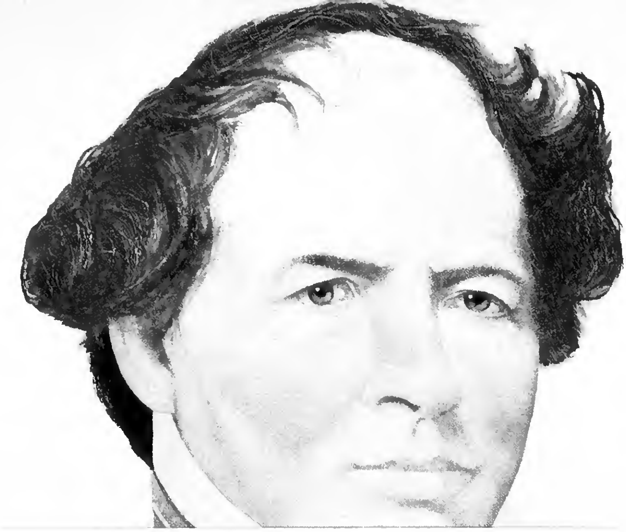
By its very scope, naval oceanography is an integral part of national activity in oceanography. The Navy has a long-standing commitment to coordinate and work with the national oceanographic community, and no where is this better illustrated than in naval oceanography's continuous ties to academia. For example, Navy owns six large oceanographic research ships that are operated by academic institutions for use in ocean science. R/V *Knorr*, operated by the Woods Hole Oceanographic Institution, is one of these ships. The academic institutions directly support Navy interests and, in turn, contribute to research accomplishments of the national and international communities. The latest and most modern of these vessels, R/V *Thomas G. Thompson*, was launched in July 1990 and will be delivered to the Navy by July 1991, for use by the University of Washington.

The end result of Navy commitment to oceanography is to expand our knowledge of our planet, to protect our national security, and to bring our ships home safe and sound.

Through the years, there have been important spin-offs from naval oceanography into the civil sector. The Navy supports and conducts research and data collection in such areas as marine meteorology, marine biofouling, ocean forecasting, satellite sensors, plate tectonics, acoustic tomography, search and rescue, high-resolution bathymetry, and the unique Arctic ocean basin characteristics. Today there is a new awareness of the benefits offered by the dual-application of defense technology and data to national problems and priorities. Naval oceanography's ability to collect, analyze, and process massive amounts of environmental data, coupled with its extensive oceanographic data bases, places the Navy in a particularly important position to respond to the urgent, growing national and international need to deal with such matters as global climate change and environmental protection.

A strong program in naval oceanography is vital, not only for the Navy's global mission, but for many other related national interests. Researchers still have much to learn about the environment in which Navy submarines, ships, and aircraft operate. The Navy is committed to a strong program in oceanography, and this means that programs, ships, satellites, and educational resources will be there in the future. The end result of this commitment is to expand knowledge of our planet, to protect our national security, and to bring our ships home safe and sound.

RADM. G.L. Chesbrough assumed the position of Oceanographer of the Navy on October 1, 1990. RADM. R. F. Pittenger (Ret.) served as Oceanographer of the Navy from 1988 through 1990 and was recently appointed Arctic Coordinator for the Woods Hole Oceanographic Institution.



"... I yet feel that until I took up your work I had been traversing the ocean blindfold."

– Captain Phinney of the clipper *GERTRUDE*, in a letter to Maury

Oceanus®
The International Magazine of Marine Science & Policy

Domestic Subscription Order Form

(U.S. & Canada only)

Please enter my subscription as follows:

Make checks payable to Woods Hole Oceanographic Institution

Individual Subscription—
- ☐ one year (4 issues) at $25.00
- ☐ two years (8 issues) at $45.00
- ☐ three years (12 issues) at $65.00

(Canadian subscribers add $3.00)

Library or Institution—
- ☐ one year (4 issues) at $80.00

Students—
- ☐ one year (4 issues) at $20.00

Please send my subscription to:

Name (please print) ______________________

Address ______________________

City State Zip ______________________

Please send a GIFT subscription to:

Name (please print) ______________________

Address ______________________

City State Zip ______________________

For Gift Subscriptions: Donor's Name ______________________ Address ______________________

12/90

Oceanus®
The International Magazine of Marine Science & Policy

International Subscription Order Form

(outside U.S. & Canada)

Please enter my subscription as follows (prepayment required):

Individual Subscription—
- ☐ one year (4 issues) at £24.00

Students—
- ☐ one year (4 issues) at £15.00

Library or Institution—
- ☐ one year (4 issues) at £43.00

Make cheques payable to:
Cambridge University Press

Please send my subscription to:

Name (please print) ______________________

Address ______________________

City Province Country ______________________

Please send a GIFT subscription to:

Name (please print) ______________________

Address ______________________

City Province Country ______________________

For Gift Subscriptions: Donor's Name ______________________ Address ______________________

12/90

tems, researchers are slowly painting a picture of the Earth's ocean floor.

As the articles in this special issue convey, naval oceanography today is an interlocking complex of disciplines. Naval oceanography has progressed from the mere act of collecting data for charts into a global pursuit using tools that enable us to venture deep into space or to the depths of the seas.

The end result of Navy commitment to oceanography is

By its very scope, naval oceanography is an integral part of national activity in oceanography. The Navy has a long-standing commitment to coordinate and work with the national oceanographic community, and no where is this better illustrated than in naval oceanography's continuous ties to academia. For example, Navy owns six large oceanographic research ships that are operated by academic institutions for use in ocean science. R/V *Knorr*, operated by the Woods Hole Oceanographic Institution, is one of these ships. The academic institutions directly support

PLACE
STAMP
HERE

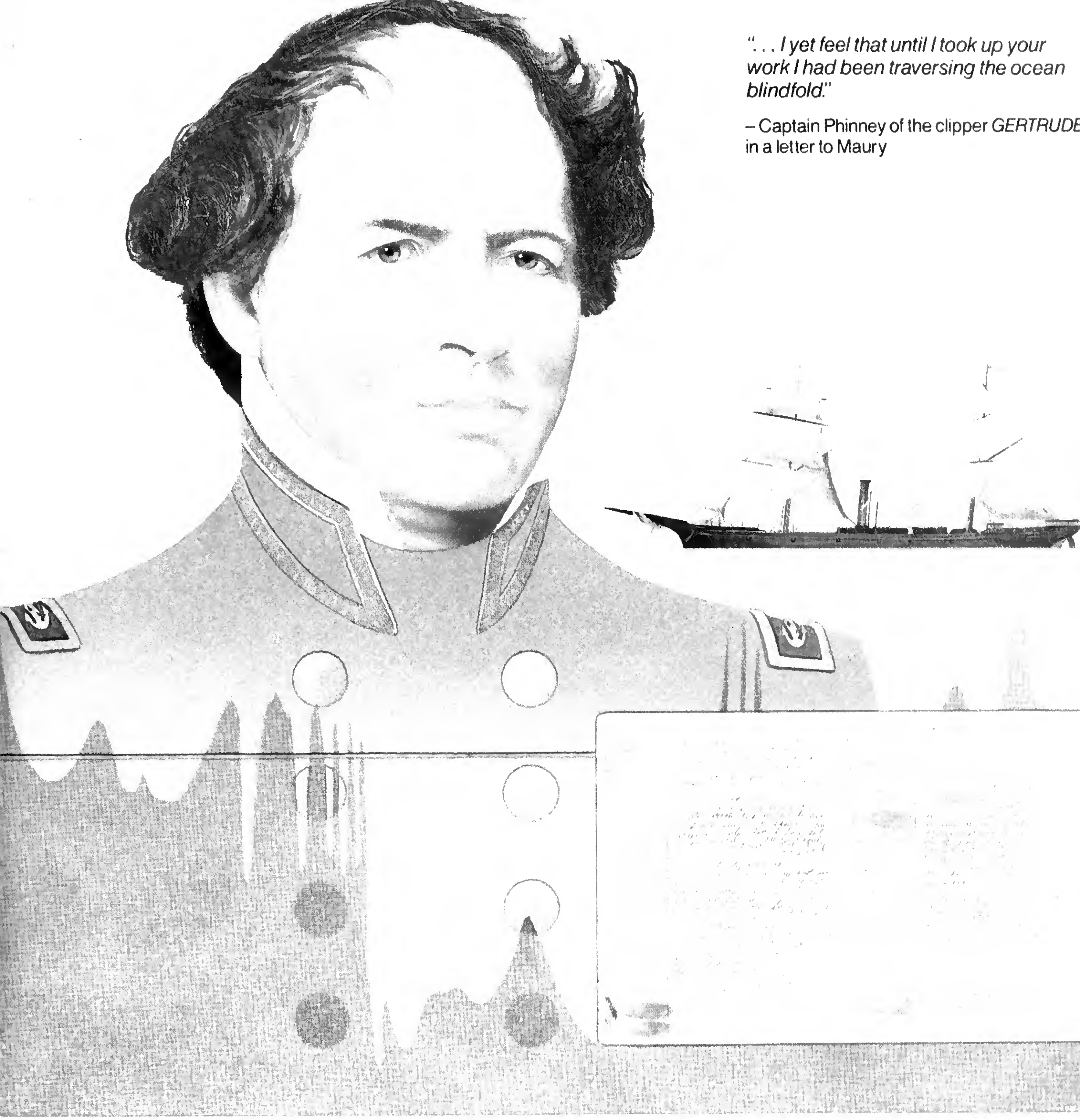
Oceanus magazine
P.O. Box 6419
Syracuse, NY 13217-6419

Mail this completed form and cheque to:

Cambridge University Press
The Edinburgh Building
Shaftesbury Road
Cambridge CB2 2RU
England

"... I yet feel that until I took up your work I had been traversing the ocean blindfold."

– Captain Phinney of the clipper *GERTRUDE*, in a letter to Maury



Matthew Fontaine Maury, "PATHFINDER OF THE SEAS"

LAYING THE FOUNDATION FOR FUTURE OCEANOGRAPHY.

For more than a hundred years, U.S. Government navigational charts carried the following notation: *Founded upon the researches made in the early part of the nineteenth century by Matthew Fontaine Maury, while serving as a lieutenant in the U.S. Navy.* This was a fitting tribute to a true pioneer in physical oceanography.

Maury's lifelong study of oceanography began as the result of an unfortunate accident. As a young Navy lieutenant in 1839, Maury was traveling to New York from his family home in Tennessee when he was thrown from a toppling stagecoach. A broken thigh resulted in a permanent limp, bringing his seagoing career to an abrupt end.

Transferred to shore duty, Maury was appointed superintendent of the Depot of Charts and Instruments in 1842. While there he made an intensive study of all ships' logs maintained by the Navy since its formation. From this mountain of data, he developed a system to predict ocean winds and currents. Maury published his findings, *Wind and Current Charts,* in 1847. This work greatly improved ship navigation and became the basis for all subsequent studies of oceanography.

At Sippican, we design, develop, and manufacture expendable oceanographic instruments and ASW devices for the scientists and navies of the free world. We continue to support the systemized study of the world's oceans, work first begun over 140 years ago by Matthew Fontaine Maury.

Seven Barnabas Road, Marion, MA 02738-1499
(508) 748-1160 Telex 200189 SOSI UR Fax (508) 748-2091

Naval Oceanography Highlights

This list offers excerpts from an extensive timeline assembled by author Nelson. Interested readers may request the complete listing from the editorial offices of *Oceanus*.

1811

• First documented Navy hydrographic survey from which a chart was published, New London harbor, conducted by USS *Constitution* .

1830

• Navy's Depot of Charts and Instruments opened in Washington, D.C.

1837

• New Depot conducted first survey.

• First lithographic press obtained by the Depot and the first nautical chart published by the Navy.

1838

• Congress appropriates $300,000 for "a surveying and exploring expedition to the Pacific Ocean and South Seas," and the U.S. Exploring Expedition, commanded by Lt. Charles Wilkes, USN, sails on a four-year mission of exploration and discovery.

• Secretary of the Navy James K. Paulding requests that the Depot begin meteorological observations every three hours around the clock.

1841

• U.S. Exploring Expedition maps 1,500 miles of coast proving Antarctica is a continent.

1842

• Lt. Matthew F. Maury, USN, assigned to command of Depot.

1844

• First expedition sent to Central America to survey for a possible interocean canal route.

As we study the laws of nature...It is like climbing a mountain: every fact or fresh discovery is a step upward with an enlargement of the view, until the unknown and the mysterious become boundless–self infinitely small; and then the conviction comes upon us with a mighty force, that we know nothing–that human knowledge is only a longing desire.

–From the text of an address given by Lt. Matthew Fountaine Maury to the literary societies of the University of Virginia on June 28, 1855

Naval Oceanography: A Look Back

by Stewart B. Nelson

There is a temptation in doing an historical overview to find a beginning or some key event from which to launch. In the purest sense, oceanography began when man first pushed off from the shore and realized that the winds and currents influenced his movement. As he ventured further, the stars became important in finding his way at sea, and the bigger the craft, the more vital to know how much water was under the keel. Eventually, the study of the sea acquired its own language–first "hydrography," and then the more inclusive "oceanography." The term "Naval Oceanography" means simply the study and knowledge of the oceans applied to Navy interests. Here, we discuss the development of naval oceanography along a path of key events.

The Beginning

The primary concern of any seafarer has always been a safe ocean passage based on decent, trustworthy, navigational information. Yet, over time, thousands of ships foundered in unfamiliar waters. Sailors often depended on waterfront hearsay to determine the best routes from one port to another.

When Benjamin Franklin was Postmaster General of the Colonies, people complained that it took the mail packets coming from England two weeks longer to make the westward crossing of the Atlantic than it took Nantucket whalers. Taking the problem to his cousin, Nantucket sea captain Timothy Folger, Franklin discovered that the whalers had learned to use the Gulf Stream currents to their advantage. Folger told him that the whalers

> "...have sometimes met and spoke with those packets who were in the middle of (the Gulf Stream) and stemming it. We have informed them that they were stemming a current that was against them to the value of three miles an hour and advised them to cross it, but they were too wise to be counseled by simple American fishermen."

1846
- The first "Wind and Current Chart of the North Atlantic" published by the Depot.

1848
- Congress directs "meteorological observations to be conducted under the direction of the Secretary of the Navy,"with responsibility assigned to the Depot of Charts and Instruments.

1852
- U.S. Japan Expedition sails under the command of Commodore Matthew C. Perry, USN. This expedition produced bathymetric charts and other navigational data, as well as Lt. Silas Bent's scientific paper, "The Japanese Gulf Stream."
- Under the direction of Maury, the Navy's Depot issues its first "Whaling Charts of the World."

1854
- Depot redesignated U.S. Naval Observatory and Hydrographical Office.

1866
- Naval Observatory and Hydrographical Office separated; U.S. Hydrographic Office established.
- Comdr. Thomas S. Fillebrown, USN, was detached from the Naval Observatory and appointed "Hydrographer." Hydrographic Office moved into rented quarters in what is known as the "Octagon House" at 18th Street and New York Avenue, NW.

1869
- First "Notice to Mariners" initiated on a continuing basis.
- The first commercial agents for the sale of Hydrographic Office charts and publications were appointed in the cities of New York, Boston, New Orleans, and

San Francisco.
1873
The Naval Observatory installs the largest refracting telescope in the world (26-inch, (still in use today).
1877
• At the Naval Observatory, civilian astronomer Asaph Hall discovers the moons of Mars.
1885
• Hydrographic Office begins collection of data for the preparation of magnetic variation charts. Previously, the Hydrographic Office depended wholly upon such information issued by the British Admiralty.
1897
• Under a specific Congressional appropriation to the War Department, the Hydrographic Office conducts a "necessary survey of entrance to and of Pearl Harbor, Hawaiian Islands, and to enable the Secretary of the Navy to ascertain and report to Congress the amount of land necessary to be acquired in said harbor and the probable cost thereof for a coaling and repair station." At that time the Hawaiian Islands were an independent republic.
1900
• Navy purchases for $150,000 the 53-foot submarine *Holland*—and the ocean's third dimension is added to the Navy's operating domain.
1912
• As a result of Hydrographic Office participation in the *Titanic* investigation, first steps are taken which eventually led to the forming of the International Ice Patrol.
1917
• Assistant Secretary of the Navy Franklin Delano

These "simple American fishermen" and sailors made up our fledging Continental Navy and brought with them their knowledge of the seas, the winds, and the stars. Should *this* be marked as the beginning of Naval Oceanography?

Almost 200 years ago, in 1798, the first three ships of the newly-founded Navy Department, *Constitution*, *United States*, and *Constellation*, put to sea and made the first depth soundings and meteorological observations. Was *this* the start of Naval Oceanography?

Or, in another measure, can Naval Oceanography mark its formal beginning with the creation, in 1830, of the Navy's Depot of Charts and Instruments? It's perhaps as good a launching point as any other event. As the name implies, the first order of "oceanographic" importance for the Navy was a storage facility, to collect and preserve the Navy's log books and navigational instruments.

Prior to 1830, when a Navy ship was put out of commission, its log books, charts, and instruments were tumbled into storerooms at various navy yards. Neglected, they quickly became unfit for further use after such storage. Eventually, the Board of Naval Commissioners became concerned about this state of affairs, and, on November 29, 1829, it recommended to the Secretary of the Navy:

> "That an officer be appointed to take charge of all nautical instruments, books, and charts not on board ship, to keep them in order for use when required. Among other duties, he would be required to attend particularly to the time pieces, or chronometers, to ascertain precisely their character such as their rate of deviation from time to time, whether they are affected by changes of weather, etc., for the information of those who may have to use them at sea. The character of each chronometer thus ascertained shall be delivered to the officer receiving the chronometer itself."

Founding of the Navy's Depot Of Charts and Instruments

On December 6, 1830, a Depot of Charts and Instruments was established in Washington, DC., and the Secretary of the Navy placed Lieutenant L.M. Goldsborough in charge. Lieutenant Goldsborough had, in fact, supported the Board's recommendation and had offered the Secretary some specific suggestions for establishing such a facility. (Actually, matters may have been facilitated by Lieutenant Goldsborough's father, who happened to be the Secretary of the Board of Navy Commissioners!)

Among the functions of the new Depot was the determination of errors and rates of all chronometers sent to vessels being fitted out for sea. This was accomplished by means of sextant and circle observations. Eventually, the Depot obtained a 30-inch focal length transit telescope for this purpose and mounted it in a small circular building near the house rented for the Depot, on what is now G Street, between 17th and 18th Streets, NW, in Washington, DC. This was the first astronomical instrument erected by the Navy.

At the time of the establishment of the Depot, charts and nautical books were purchased from private sources. They were nearly all of

Lt. Charles Wilkes, USN, assumed command of the Depot of Charts and Instruments in 1833 and from 1838 to 1842 commanded the U.S. Exploring Expedition, the country's first scientific seagoing endeavor.

European origin, calculations used unfamiliar meridians, and the sailing directions were often in foreign languages. The Depot was instructed to modify charts to the meridian of Greenwich, England, and to translate the notations and instructions into English. A strong appeal was made by Lieutenant Goldsborough for the purchase of a lithographic press, but this was not authorized until some years later.

In 1833, Lieutenant Goldsborough took leave from the Navy to command mounted volunteers in the Seminole War. He was succeeded at the Depot by Lieutenant Charles Wilkes.

Start Of Hydrographic Surveying And Chart Production

One month after becoming Superintendent, Lieutenant Wilkes began relocating to a house he owned on Capitol Hill. Here, Lieutenant Wilkes had built, at his own expense, a 16-foot square observatory. However, except for the rating of chronometers, it does not appear that any regular series of astronomical observations was made at the time.

In May 1835, the Depot finally installed a lithographic press for chart production. At the same time, the Navy Department began its hydrographic surveys. In the Spring of 1837, Lieutenant Wilkes was relieved from duty at the Depot and assigned to conduct hydrographic surveys on the shoals of Georges Bank. Lieutenant James M. Gilliss, whose

Roosevelt asks Harvard University's Dr. Alexander McAdie to accept a Naval Reserve commission for the purpose of establishing a weather service for the Navy.

•In response to the threat posed by German U-boats, the Naval Consulting Board establishes its Committee on Submarine Detection by Sound.

1924

•At the invitation of Acting Secretary of the Navy Theodore Roosevelt, Jr., the Hydrographic Office hosts the first interagency General Conference on Oceanography, where members agree that "research in oceanography will take a permanent place among the activities of the Navy."

1927

•National Academy of Sciences establishes Committee on Oceanography (NASCO), and NASCO, in its first report, offers among its several recommendations that the Navy become more active in oceanographic research and that a Navy vessel be specially fitted for the work. Other recommendations of the NASCO report lead to a series of grants from the Rockefeller Foundation to establish the Woods Hole Oceanographic Institution, the Oceanographic Laboratory at the University of Washington, and additional facilities at the Scripps Institution of Oceanography.

1931

•Hydrographic Office acquires its first suite of oceanographic equipment for use on the converted hydrographic survey ship *Hannibal.*

1935

•Beginning of develop-

ment of buoy-mounted automatic weather station (first device was available in 1939).
•Sonar echo-ranging system developed.

1940
•First Navy weather central established in D.C.

1943
•U.S. Navy assigned responsibility for supplying oceanographic data to all the military services.
•An Oceanographic Unit is established within the Hydrographic Office.

1946
•President Harry S. Truman signs Public Law 588 establishing the Office of Naval Research (ONR).
•Naval Research Laboratory develops helicopter sonar for anti-submarine warfare.

1949
•Hydrographic Office and Office of Naval Research cosponsor Operation Cabot, the first multi-ship survey of the Gulf Stream. This project clearly showed loops and eddies in the Gulf Stream.

1950
•Navy sponsors first successful numerical weather forecast.

1952
•First long-range Arctic ice forecast issued by the Hydrographic Office.

1954
•Continuous annual Antarctic operations started, later known as Operation Deep Freeze.
•Naval Research Laboratory obtains photograph from rocket launched from White Sands, New Mexico, which provides the first view from space of a major storm cloud formation.
•Joint Numerical Weather Prediction Group formed (Suitland, Maryland), involving the U.S. Navy,

This is a view of the U.S. Capitol Building about 1820. Lt. Charles Wilkes' property, which housed the Navy Depot, the small observatory built by Wilkes in 1834, and Wilkes' family, were located about 1,200 feet north of the Capitol and may be among the houses sketched to the left of the Capitol in this view.

primary interest was astronomy, was placed in charge of the Depot.

In 1837, Naval Oceanography recorded one of its first milestones when the Depot published four engraved charts illustrating hydrographic surveys conducted by American naval officers. The actual engraving was done under contract by private parties.

United States Exploring Expedition (1838-1842)

In 1838, the U.S. Government sent out its first scientific expedition with Charles Wilkes, now a Commander, in charge. The U.S. Exploring Expedition, with a Congressional authorization not to exceed $300,000, was to conduct explorations and surveys of the Pacific Ocean and the South Seas. The objectives were "to determine the existence of doubtful dangers reported in the track of the United States trade, to make astronomical observations for locating shoals, islands, reefs, etc., observations of terrestrial magnetism, variation of the compass, etc., to instruct the natives of the island visited in agriculture and horticulture and to encourage them to increase their output, to discover if possible a shorter route to China via the Sulu Sea." The civilian scientific staff of the Expedition included a philologist, two naturalists, a conchologist, a mineralogist, a botanist, a horticulturist, and two draftsmen. The four-year Expedition, ending in New York City in 1842, covered nearly 90,000 miles, and resulted in the survey of 280 islands, the determination of about 2,000 geographic positions, an atlas containing 106 new nautical charts, and a vast collection of fauna, flora, and cultural artifacts.

A Permanent Depot

As the hydrographic and astronomical work of the Depot increased, new, permanent facilities were needed. The Navy Department petitioned the Congress for an enlarged Depot and an observatory, and the report accompanying the bill specifically mentioned the Depot's activities in the areas of meteorology, magnetism, astronomy, and hydrography.

Concerning hydrography, the report noted:

> "It is particularly desirable that information on this subject be collected from all quarters as well for the navy as for the commercial marine generally; and there is, no doubt, a great mass of such information locked up in the memories of our whalers and Indiamen...Yet from the fact that they know not where to send it, perhaps it never passes beyond the immediate crew.
>
> "The depot of charts and instruments is the proper receptacle of such information, till the organization of an appropriate hydrographic bureau. Let the captains of our merchant ships know they will be thanked for its communication, and receive credit as public benefactors, and there can be no doubt, great pride will be taken in its transmission."

A Congressional act of August 31, 1842, authorized the Secretary of the Navy "to contract for the building of a suitable house for a depot of charts and instruments of the Navy of the United States on a plan not exceeding in cost the sum of $25,000." The site selected, at 23rd and E Streets, NW, is now occupied by the Navy's Bureau of Medicine and Surgery.

A New Era

By late 1844, the new Depot building was ready. Lieutenant Matthew Fontaine Maury, who had relieved Lieutenant Gilliss as Superintendent in July 1842, was inclined more toward hydrography and meteorology than his predecessor, who was, above all, an astronomer. While considerable work had been done in the field of hydrography by Wilkes and others, it was Lieutenant Maury who really laid the foundation for the systematic hydrographic work of the Navy.

Organizing an extensive system of collecting data from Navy and merchant ships in all parts of the world, and using information from the stored Navy ship logs, Maury aggressively went about his work. He was committed to make charts of "the prevailing winds and currents, their general characteristics, and all the physical features of the ocean, including the meteorology, the limits of icebergs, the feeding grounds of whales, and all facts of interest and value to the maritime community."

The charts prepared during Maury's tenure at the Depot (1842-1861) were known as "Wind and Current Charts." They consisted of six series: Track Charts, Trade-Wind Charts, Pilot Charts, Whale Charts, Thermal Charts, and Storm and Rain Charts. Maury's charts also extended to the Pacific and Indian oceans, based largely on the data collected by Commodore Matthew C. Perry's Exploring Expedition (1852-1854) and the

Air Force, and Weather Bureau.

1958

- First bathymetric swath system deployed.
- The USNS *Gibbs*, a converted seaplane tender, was assigned to Hudson Laboratories of Columbia University. Besides being the first assignment of a Navy-owned ship to a civilian university oceanographic laboratory, the USNS *Gibbs* was the first (and only) university-related ship to be operated by the Military Sea Transportation Service (now the Military Sealift Command).
- Navy assigns a converted salvage ship to Woods Hole Oceanographic Institution for oceanographic research, R/V *Chain*.

1959

- Navy assigns converted salvage ship to Scripps Institution of Oceanography for oceanographic research, R/V *Argo*.
- Navy issued its report, *Ten Year Program in Oceanography* (TENOC), calling for a substantial increase in oceanographic programs and ships.

1960

- Funds provided for first ship to be specifically designed and constructed for oceanographic research, R/V *Conrad*. Assigned to and operated by Lamont-Doherty Geological Observatory, Columbia University.
- Under the aegis of the Naval Electronics Laboratory (now the Naval Ocean Systems Center) the bathyscaph *Trieste* makes a record-breaking dive to 35,800 ft. in the Challenger Deep.

1961

- Navy Numerical

Weather Problems (NANWEP) Group aquires its first computer, a CDC 1604, and is redesignated the Fleet Numerical Weather Facility (FNWF).

1962

•Hydrographic Office redesignated U.S. Naval Oceanographic Office.

•The Naval Oceangraphic Data Center is redesignated as the National Oceanographic Data Center (NODC).

•Navy's FLIP (Floating Instrument Platform) completed and assigned to Scripps Institution of Oceanography.

1964

•First Conference on Military Oceanography held at the Naval Oceanographic Office.

•The habitat Sealab 1 completes a 4-man, 11-day mission at a depth of 193 feet off Bermuda's Plantagenet Bank.

•The nation's first research submersible, the Navy's DSV (Deep Submergence Vehicle) *Alvin*, is placed in service at Woods Hole Oceanographic Institution.

•Lost nuclear submarine USS *Thresher* found and photographed by Navy's oceanographic ship USNS *Mizar*.

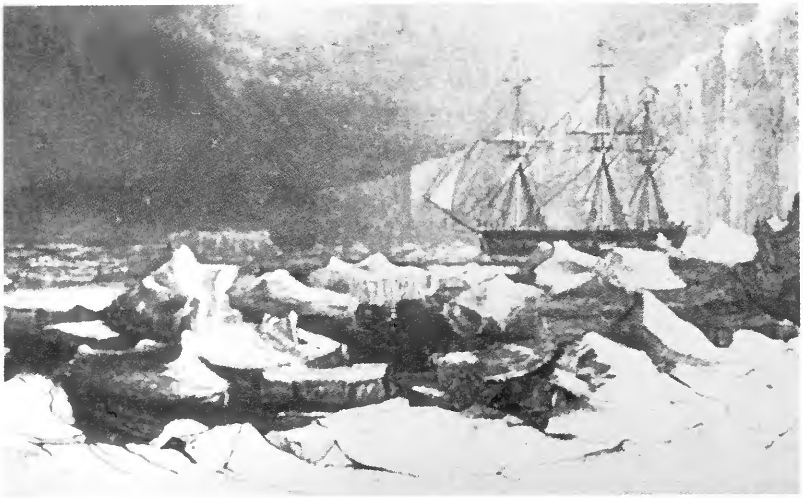
•Deep-towed magnetometer developed by scientists and engineers of the Naval Oceangraphic Office and the Naval Research Laboratory.

1965

•Naval Undersea Research and Develop ment Center develops the first practical remotely-operated vehicle CURV (Cable-controlled Underwater Recovery Vehicle).

1969

•Fleet Numerical Weather Center begins routine and ongoing production of



The U.S. Sloop-of-War Peacock *was built in 1814 by the New York Navy Yard and assigned to Lt. Charles Wilkes's U.S. Exploring Expedition (1838-1842). She is shown here off the Antarctic continent. While attempting to cross the bar at the mouth of the Columbia River in July 1841,* Peacock *grounded, was abandoned by her crew, and pounded herself to pieces.*

Commodore Cadwalader Ringgold/Lieutenant John Rodger North Pacific Surveying Expedition (1853-1859).

Maury saw no limit to the Depot's fields of investigation: "The form and divisions of the marine areas of the globe, with the winds that blow over the surface waters and their agency in minimizing the duration of the passages of ships, the contours of the ocean bed from the sea level down to the greatest depths, the temperature, the circulation, the physical and chemical properties of sea water, the currents, tides, waves, the composition and distribution of marine deposits, the nature and distribution of marine organisms and the modifications brought about in living things by the conditions of their existence, the relation of man to the ocean in the development of fisheries, commerce, civilization, navigation, hydrography, and marine meteorology."

While the word "oceanography" would not enter the English language until 1883, it was apparent that Maury had already defined it in its very broadest terms. Today, Maury is internationally recognized as one of the founders of modern oceanography.

Separation of Astronomy and Hydrography

When Maury cast his lot with the Confederacy, James Gilliss, who favored astronomy, returned for a second time as Superintendent of the Depot. It was only a matter of time before the civilian-dominated field of astronomy would be separated from the Navy officer-dominated field of hydrography.

The separation finally happened in 1866 when Congress established the separate Navy commands of the U.S. Naval Observatory and the

Hydrographic Office. Commander Thomas S. Fillebrown, USN, was detached from the Naval Observatory and appointed "Hydrographer." The Hydrographic Office moved into rented quarters in what is known as the "Octagon House," at 18th Street and New York Avenue, NW. The original personnel of the newly-created Hydrographic Office consisted of a commander (the Hydrographer), two lieutenant commanders, one lieutenant, two ensigns, a professor of mathematics, and seven other civilians.

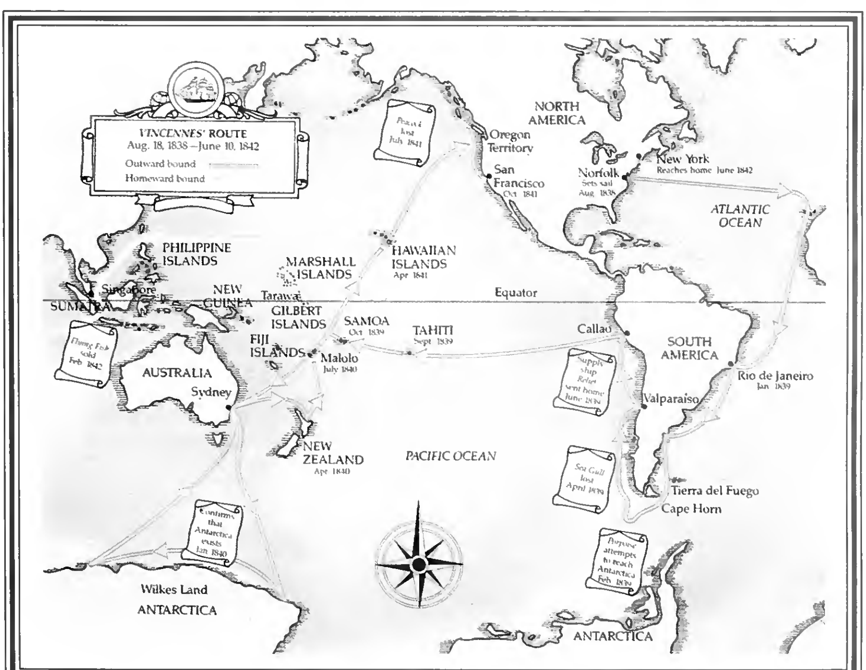
Oceanography Comes of Age

Following the Civil War, the activities of the Hydrographic Office were largely devoted to hydrographic surveys for fleet anchorages and for the laying of commercial telegraph cables. Without the great scientific drive of Maury, the Hydrographic Office endured a long period of fairly standard and repetitive activity. World War I, with the challenge of trying to locate enemy submarines, thrust ocean science into the forefront, followed by peace and another retrenchment.

While federal support did not increase after the war, intellectual curiosity about oceanography continued, and philanthropic funds were used to establish the Woods Hole Oceanographic Institution, the Oceanographic Laboratory at the University of Washington, and additional facilities at the Scripps Institution of Oceanography.

In 1929, the Secretary of the Navy convened a special board to review the Navy's role in future oceanographic programs. The board's

The track of USS Vincennes, *flagship of the U.S. Exploring Expedition, 1838 to 1842. Under the command of Charles Wilkes, the U.S. Exploring Expedition covered nearly 90,000 miles.*



numerical oceanographic and acoustic products in support of ASW operations.

- Nuclear-powered ocean engineering and research submarine, *NR-1*, commissioned.
- Arctic Submarine Laboratory established to study the physical and chemical properties of sea ice.
- Development of the LIght Behind Camera (LIBEC) system for deep ocean search and inspection.

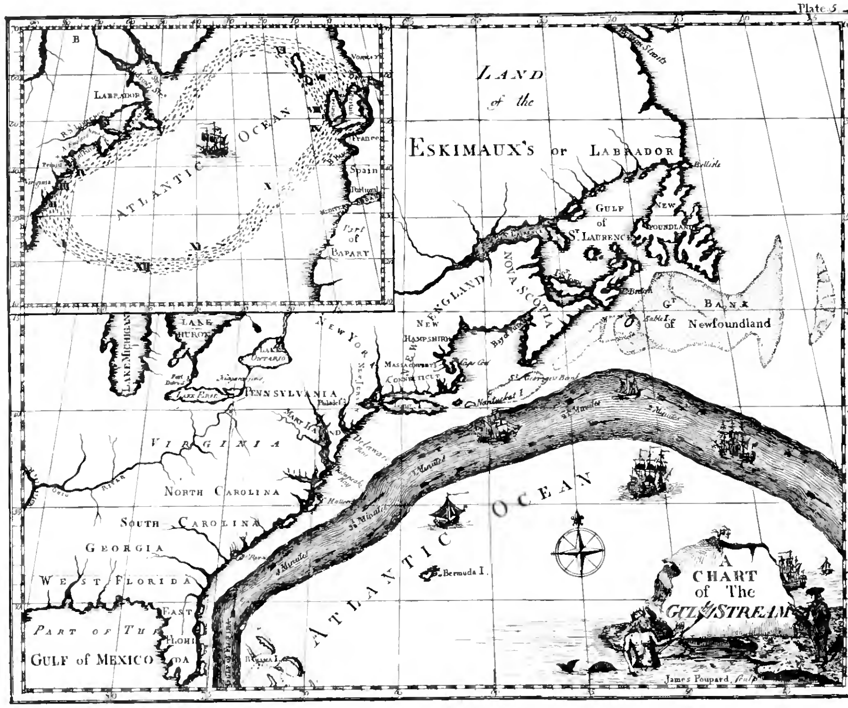
1970

- Naval Experimental Manned Observatory (NEMO), developed by the Naval Civil Engineering Laboratory, is certified as a U.S. Navy submersible. NEMO is the first transparent-hull acrylic plastic submersible approved for manned service.
- Colossus II, the first major research and development effort into shallow water sound propagation, is completed.

1972

- Oceanographic research ship USNS *Eltanin* completes a 10-year, circum-Antarctic survey of 410,000 miles.
- World's first submersible using glass as part of the pressure hull is christened at the Naval Ocean Systems Center. *Deep View*, with a 44-inch diameter glass hemisphere in front, is a two-person submersible used for oceanographic research.
- *Makakai*, a two-person submersible with a six-foot diameter acrylic plastic pressure hull for scientific observation, is christened at the Naval Ocean Systems Center's Hawaii laboratory.

1973
•Navy's first Small Waterplane Area Twin-hulled (SWATH) ship, the Naval Ocean Systems Center's Stable Semi-Submerged Platform (SSP) *Kaimalino* (a Hawaiian word meaning "calm water"), is completed.
•Naval Ocean Systems Center's Cable-controlled Underwater Recovery Vehicle (CURV III) attaches a recovery line that allows the rescue of two men trapped in the *Pisces III* submersible for three days at the bottom of the Irish Sea in 1,500 feet of water.
1974
•Project FAMOUS, the French-American Mid-Ocean Undersea Study, is initiated.
•First spectral ocean wave model becomes operational at Fleet Numerical Weather Center to forecast the occurrence of dangerous sea conditions.
1976
•Naval Oceanographic Office relocated from Washington, D.C., area to Bay St. Louis, MS.
•Naval Ocean Research and Development Activity (NORDA) established at Bay St. Louis, MS.
•Automated Product Request (APR) system becomes operational at Fleet Numerical Weather Center (FNWC) allowing ships at sea to request and receive FNWC products.
1977
•Fleet Numerical Weather Center begins processing and distributing environmental satellite imagery.
1978
•Launch of Seasat, the first multi-sensor active/passive satellite dedicated to oceanographic remote



Benjamin Franklin prepared this chart of the Gulf Stream in 1769 to help speed English mail packets across the Atlantic. It was published in 1786 by the American Philosophical Society and combined, for economy's sake, with Henry Gilpin's herring migration chart at upper left.

recommendations resulted in the establishment of a Section of Oceanography in the Hydrographic Office (1933) and increased cooperation with private and academic oceanographic institutions.

Again, it would take a war, this time World War II, to demonstrate oceanography's importance to naval warfare. The Navy turned to private and academic research institutions for scientific expertise. Among the many significant accomplishments were improved oceanographic instrumentation, bottom sediment charts, studies that improved the maintenance of trim on submarines, long-range weather forecasts, evaluation of beach information for amphibious landings, development of submarine detection equipment, manuals for sonar operators, identification of the deep scattering layer, and underwater sound and explosive phenomena. Through all of this, the Hydrographic Office continued its surveying operations using an astonishing variety of ships. In the peak year of 1944, the Hydrographic Office issued over 43 million charts!

Recognizing the important role played by research, Congress established the Office of Naval Research (ONR) in 1946. Among its activities, ONR continues to provide support for basic ocean research and technology.

The expanded role played by the Hydrographic Office was also recognized, and, in 1962, its name was changed to the Naval Oceanographic Office. Oceanography's significance was further recognized in 1966 when the Navy established the flag position of "Oceanographer of the Navy."

Naval Oceanography Today

Ships, planes, buoys, satellites, more than 3,500 men and women, military and civilian, an annual budget topping $500 million—Naval Oceanography, today, is big business. There is yet another way to look at Naval Oceanography and that is the number of organizations that have spun off of that humble little storage facility created almost 200 years ago.

The direct descendent of the Depot was the Hydrographic Office, now the Naval Oceanographic Office. Today's Defense Mapping Agency, Naval Oceanographic Research and Atmospheric Research Laboratory, and the National Oceanographic Data Center also trace their roots to the Depot.

Matthew Fontaine Maury would, I think, be pleased.

Dr. Stewart B. Nelson serves on the staff of the Oceanographer of the Navy. He also served as a staff member on the Presidentially-appointed National Advisory Committee on Oceans and Atmosphere, a Congressional Fellow, and a senior manager at the Naval Oceanographic Office in Bay St. Louis, Mississippi. He is the recipient of the Secretary of the Navy's Distinguished Civilian Service Award and the author of Oceanographic Ships Fore & Aft.

sensing. Data processing support provided by Fleet Numerical Oceanography Center. (Seasat, unfortunately, failed about 100 days after launch).

1980
•Optimum Path Aircraft Routing System (OPARS) becomes operational at Fleet Numerical Oceanography Center in support of naval aviation.

1982
•Space Oceanography Committee established to promote exploitation of space shuttle for ocean research.

1985
•Launch of Navy Geodesy Satellite (Geosat) to provide improved marine geoid and to study mesoscale oceanography.
•The wreck of RMS *Titanic* is found during full system tests of a new ONR sponsored undersea search system called *Argo*.

1989
•Global dynamic ocean circulation model implemented and tested at the Fleet Numerical Oceanography Center as a precursor to implementation of a global eddy-resolving ocean model for enhanced support of ASW operations.

1990
•Advanced Tethered Vehicle, under development at the Naval Ocean Systems Center's Hawaii laboratory, achieves 20,000-foot depth operational capability.
•Polar Orbiting Geomagnetic Survey (POGS) Satellite launched. POGS measures global magnetic field to support World Magnetic Chart Model.
•Navy contracts for Class VII supercomputer, a Cray Y-MP, for the Naval Oceanography center in Bay St. Louis, MS.

Anti-Submarine Warfare and Naval Oceanography

Any nation that intends to exert maritime power beyond its own shores must develop a global anti-submarine warfare capability

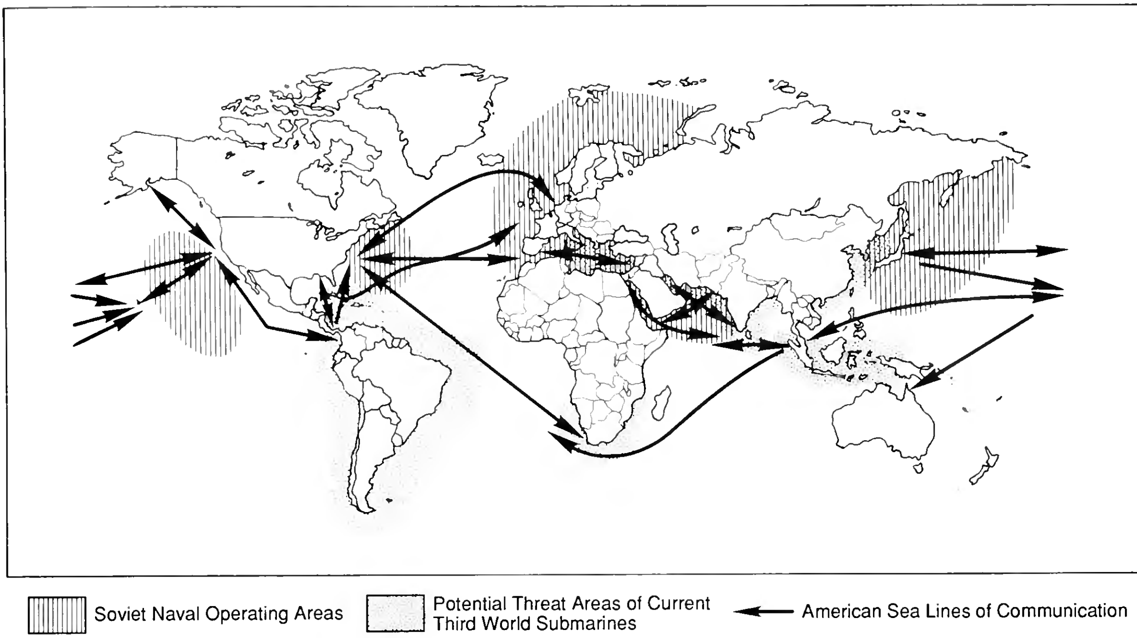
Robert S. Winokur and Craig E. Dorman

The German submarines that nearly tipped the tide of battle in both WWI and WWII could submerge only for short periods of time and were armed with relatively primitive guns and straight-running torpedoes. The modern attack submarine is a stealth threat an order of magnitude more formidable. Longer than a football field, it radiates less noise than a lawnmower, and its submerged endurance is limited only by the amount of food it can store. As armament, it carries modern torpedoes, now wire-guided and computer-controlled, and long range cruise missiles (SLCMs). The nuclear-tipped, land-attack SLCMs carried by U.S. and Soviet submarines blur the distinction between tactical and strategic platforms. Even today's diesel-powered submarines of the Third World–more than 200 are operated by some 25 nations–are extremely quiet and lethal, with submerged endurance measured in days.

Given the capabilities and worldwide distribution of submarines, any nation that intends to exert maritime power beyond its own shores must develop a global anti-submarine warfare (ASW) capability. In recent years, in fact, ASW has been the U.S. Navy's top war-fighting priority.

ASW–extracting small and indistinct bits of information out of a large and noisy ocean–is extremely difficult (barring a lucky break like cracking the German radio command code in WWII). Indeed, if a submarine has no other job than to hide, it is nearly impossible to locate. This is why our ballistic missile submarines (SSBNs) are acknowledged as the most survivable arm of our nuclear defense triad (the triad being air-, sea-, and land-based weapons systems).

Because ASW starts by sorting out signals in the ocean, be they acoustic, optical, chemical, or physical, it is really a form of applied oceanography. As the targets become quieter, our need grows for more knowledge of ocean characteristics and processes. Both in its support of



The global nature of anti-submarine warfare operations shows clearly in this chart. Many sea lines of supply are within reach of Third World nations' submarine forces. Examples of vital choke points are the Suez and Panama canals, the entrance to the Persian Gulf, and the straits of Malacca and Florida.

basic research and in its application of the resulting knowledge, the Navy works closely with the nation's oceanographic community.

Historical Perspective

The idea of underwater weapons dates back to the time of Alexander the Great, who used an early form of diving bell in naval warfare. The first "submerged boat" was constructed in the early 17th century, and the submersible vehicle *Turtle* was used as an offensive weapon in a failed attempt to attach a mine to an English man-of-war during the American Revolutionary War. The first recorded sinking of a warship by a submarine took place during the American Civil War when a Confederate submerged craft, CSS *Hunley*, attacked and sank the Union corvette USS *Housatonic*. Following the Civil War, development of the submarine continued at a rapid pace, motivated by development of the torpedo in 1866. By the turn of the century, the U.S. Navy commissioned its first submarine, *Holland*. Six years later, the Russian Navy bought its first submarine, *Protector*.

By the start of WWI, Germany, with 20 in its fleet, was building the most advanced submarines in the world, though they still functioned basically as submersible surface ships. During 1915 and 1916, they were sinking about 100 ships a month with only nominal losses. In April 1917 alone, German U-Boats sank 444 surface ships, effectively confining the English fleet to its bases.

British efforts to counter the U-Boats started in 1915, with the development of crude hydrophones, to "listen" underwater, and depth charges for attack. The French began experimenting with acoustic echo ranging, and the U.S. established the Naval Consulting Board, under Thomas A. Edison, to support promising work in magnetic detection and underwater sound transmission.

These early efforts made enough progress to reveal that irregularities in acoustic transmission were due to the complexities of the ocean. However, there was insufficient progress to make ASW acoustic systems operationally effective during WWI. Rather, it was the introduction of the convoy system immediately following the huge losses of April 1917–together with gunfire, ramming, and mining–that broke the U-Boat stranglehold. By the end of the war, the Allies had found ways to minimize shipping losses, even though the submarine remained undefeated.

In spite of its failure to yield an operational system, WWI-era ASW research set the direction we have pursued ever since. The key ASW task was to detect the submarine at a distance sufficient to avoid or attack it before it launched its weapons. The only way to do this, then as now, is to exploit water's ability to transmit energy radiated by or bounced off the submarine. Since acoustic (pressure) waves propagate further with less loss underwater than do light or radio signals, sound is the natural choice for an ASW sensor.

ASW exploits water's ability to transmit energy radiated by or bounced off the submarine.

The key is to efficiently receive sound radiated by the submarine (passive sonar) or to produce and direct sound pulses that bounce back from the target (active sonar), and then to display the resulting information in ways that separate signal from noise. This requires hydrophones and transducers, devices that convert sound energy in the water into electric energy on the ship (and vice versa). ASW sonar development since WWI has progressed from crude devices and simple listening systems to hydrophone arrays that are over one mile long and transducer arrays weighing tons.

The British were determined not to repeat the harsh lessons of WWI. By the 1930s, their Anti-submarine Division International Committee (ASDIC) had fielded operational echo-ranging devices on destroyers, and by the end of WWI, they had installed fixed bottom-mounted listening stations cabled ashore around the coast of the United Kingdom. While the U.S. conducted little direct ASW research in the early interwar years, American ocean science developed rapidly, and the Navy's Hydrographic Office served as a link with universities.

Navy's cooperation with academia proved extremely valuable as war again approached. As sonar systems evolved, it was becoming apparent that the ocean itself would be the limiting factor in determining acoustic range and performance. Examples of the contribution of academic research include the discovery that sonar performance is degraded in the late afternoon due to the diurnal heating of the near-surface waters (later called the "afternoon effect"), the invention and subsequent refinement of the bathythermograph to measure temperature variations, and the discovery of the sound channel that allows sound to travel great distances. These developments are the very foundation of today's ASW capabilities.

Discovery and explanation of the afternoon effect came in 1936 when researchers observed that sonar performance degraded severely in the afternoon. The discovery had enormous tactical value, since it defined conditions of safe and dangerous operation, especially important for the relatively short-range sonars of WWII. This effect occurs when afternoon heating of the surface layer of the ocean causes changes in sound speed, which causes sound emitted in this layer to be refracted or bent sharply as it enters the cool water beneath. This results in the creation of a "shadow zone," where sound intensity is very low and sonar performance is poor.

The invention of the bathythermograph (BT), which was rapidly lowered through the water, not only permitted scientists to study the ocean but also, when used from a destroyer, permitted sonar operators to quickly locate surface layers in order to calculate sonar performance. BTs would measure temperature to a depth of 400 feet at ship speeds of

Naval Photographic Center

Over the Pacific Ocean an SH-2F airborne multi-purpose system helicopter (LAMPS) drops a sonobuoy during ASW exercises. Sonobuoys help to locate and track enemy submarines during fleet operations.

15-to-18 knots. Today, expendable BTs are used routinely to locate thermal discontinuities and major oceanic features, such as fronts and eddies.

The sound channel, discovered in the early 1940s, would not be fully exploited during WWII. It results from the natural characteristic sound speed profile of the deep ocean. The ocean acts like a lens, and sound signals emitted in the channel can propagate without hitting the surface or bottom, thereby permitting sound to be heard over distances of thousands of miles. Knowledge of the deep sound channel, often referred to as the "SOFAR channel," for Sound Fixing and Ranging, led to the development of a system used to locate downed airmen. The pilot would drop a small bomb set to explode in the Channel, and his location could be determined from the signals received at three remote listening stations. In the years since WWII, this basic concept has been studied in detail and has evolved into both navigation systems and ASW surveillance systems where towed or bottom-mounted receiving arrays listen for submarine-generated signals that propagate into and along the sound channel.

One final development of the WWII era, though never fully implemented at the time, also helped set the course for postwar submarine activities. Use of air power ensured that "submergible surface ships" would never again be effective. The Germans were aware of this even in the early 1940s. But, in spite of massive efforts, they were unable to develop a true long-endurance, high-speed submarine before their surrender in 1945. Both the U.S. and U.S.S.R. have since developed the technology to a fine art.

Armed with ASDIC "products" and a rapidly increasing knowledge of ocean acoustics, the British caught the German U-Boats unaware at the start of WWII. This advantage did not last long, however, as the Germans countered by shifting their tactics to surfaced night attacks against lightly escorted convoys in acoustically-poor coastal waters. Throughout the rest of the war, submarine operations and ASW responses became a game of strategy and counterstrategy, tactics and countertactics, technology and countertechnology. Radar and aircraft made major contributions to ASW, both by detecting and attacking surfaced submarines and by forcing the Germans away from the coasts and into submerged transit. These and many other Allied techniques that ultimately rendered the German U-Boat ineffective–magnetic anomaly detection, sonobuoys launched from aircraft, radio direction finding, specially designed ASW ships and airplanes–are still in use today.

Another ASW refinement relates to the characteristics of sounds made by submarines. Some of this noise is "broad band," containing a wide range of frequencies with no particularly unique characteristics. Other noise is "transient," like slamming a door, flushing a toilet, or dropping a hammer onto the deck. Both are very difficult to distinguish from things that happen naturally in the ocean. Submarines (at least nuclear submarines), however, have a lot of rotating equipment–motors, pumps, shafts, and propellers–and each of these gives off sounds at a particular frequency. By knowing characteristic frequencies, it is possible to design sonar equipment to increase passive detectability.

Importance of ASW

The history of this century's two world wars has clearly demonstrated that the submarine is the most important threat to a navy's ability to control the seas. The submarines of those wars bear little resemblance to today's nuclear-powered, missile-carrying submarines that can operate anywhere in the world ocean and have almost unlimited endurance. The diesel-powered submarines of WWI and WWII were mainly a menace to ships at sea, whereas today's nuclear-powered submarines pose a threat to any target, at sea or on land.

The history of this century's two world wars has clearly demonstrated that the submarine is the most important threat to a navy's ability to control the seas.

The United States is essentially an island nation and, as such, sea power has been a cornerstone of its maritime heritage. Anti-submarine warfare, in turn, is a centerpiece of the country's ability to maintain maritime superiority, to meet global responsibilities, and to maintain freedom of the seas. To protect its coastlines, to maintain sea lines of communication and supply to allies, to project power whenever required in the world, and to assure freedom of navigation for all peaceful uses of the ocean, the U.S. must maintain control of the seas as necessary in times of peace as well as war.

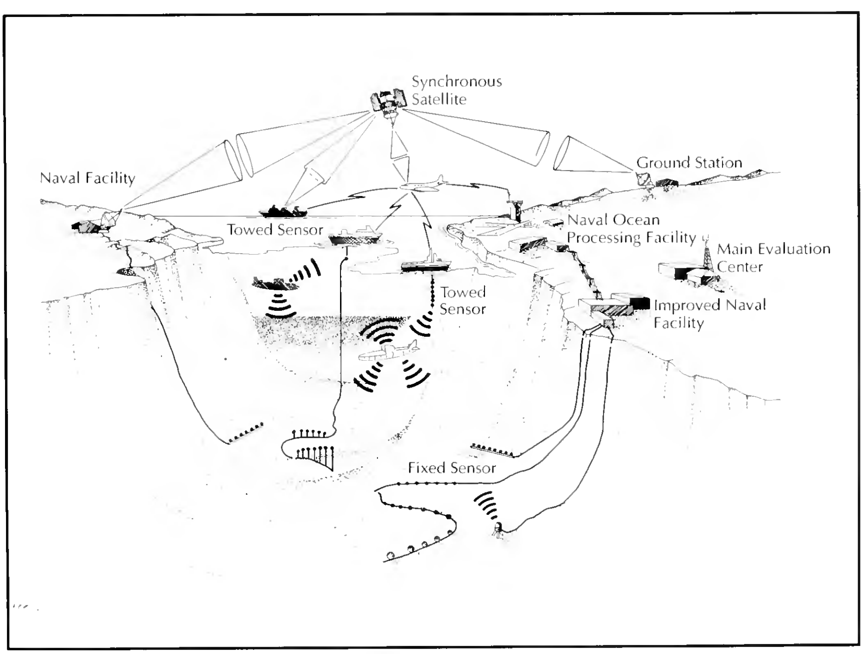
In the decade following WWII, the Soviet Union began the most ambitious peacetime submarine building program ever undertaken. This program continues even today, as the Soviet Union maintains a submarine force of unprecedented peacetime size, diversity, and capability. This fleet, which numbers about 350 nuclear and diesel vessels, includes more than 75 strategic ballistic missile submarines, of which more than 65 carry long-range anti-shipping and land attack cruise missiles. The most modern of these submarines, such as the Akula class launched in 1984, are exceptionally quiet and are capable of operating for extended periods under Arctic ice. In addition, the geography of the Soviet Union is an asset to its strategic missile fleet. Taking a lesson from two world wars, the Soviet Navy has made the submarine its most important weapons system.

Today, we are witnessing a changing world environment and the clear perception of a declining Soviet threat. In spite of this, the Soviet Navy continues to modernize and expand. The Soviets are retiring old 1950s and early-1960s submarines, but they show no clear sign of reducing either warfighting capabilities or new construction. They continue to build submarines at a rate more than triple that of the U.S. Navy. Advances in submarine quieting have had a major impact on the tactical edge the U.S. has enjoyed in ASW, making acoustic detection more difficult and demanding an even greater understanding of the ocean for tactical advantage. While it is probable the Soviet submarine force will be smaller in the future, it will be more operationally capable and technologically advanced.

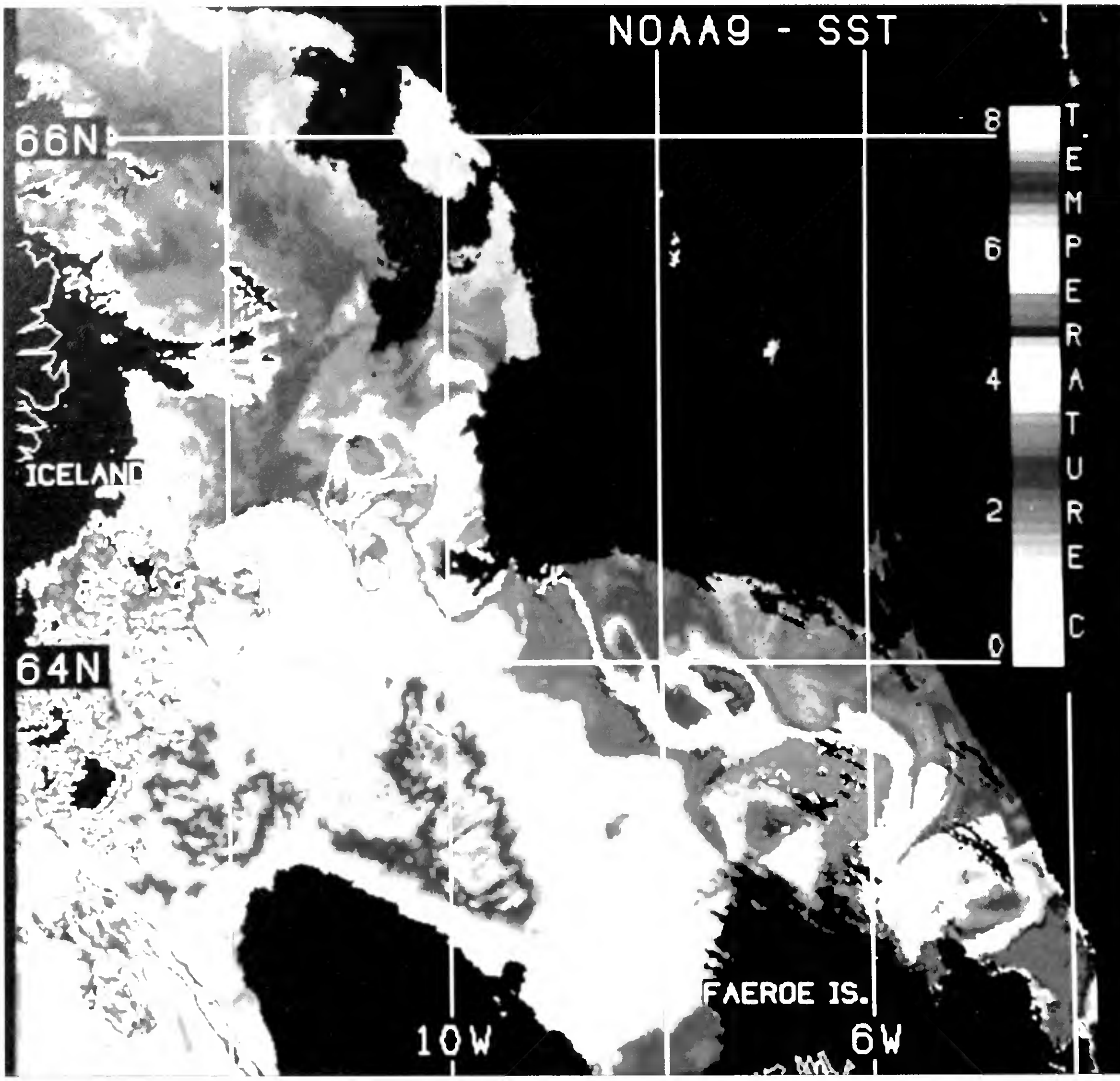
U.S. concern has focused on the Soviet submarine fleet in the post-WWII era. Today, however, we face an increasing challenge in the growing number of sophisticated submarines manufactured by industrialized nations for Third World and nonaligned nations. This growing submarine force spans the globe and includes over 20 nations in the Far East, the Middle East, Africa, Europe, and South America.

The Soviet Union continues to build submarines at a rate more than triple that of the U.S. Navy.

E Paul Oberlander



The U.S. Navy's ocean surveillance system consists of both fixed and towed acoustic sensors that provide submarine detection and cueing to tactical ASW forces.



Naval Oceanographic and Atmospheric Research Laboratory

This satellite infrared image shows the location of the Iceland-Faeroes front and the variability of temperature profiles in the vicinity of the front on May 20, 1987.

The significance of this potential threat was demonstrated during the Falklands War, when an Argentine submarine conducted operations against the British during a patrol that lasted almost seven weeks at distances of 800 nautical miles from a support base. The Argentine submarine *San Luis* did, in fact, get close enough to its target to fire a torpedo. Although it failed to detonate, this incident demonstrates the vulnerability of even a modern ASW force to a Third World submarine. Conversely, the sinking of the Argentine cruiser *Belgrano* by a British submarine is effective evidence of modern submarine lethality.

Since an effective submarine warfare capability exists today worldwide, areas where the U.S. needs ASW capability are limited only by where we want to operate safely at sea. Given our vital sea lines of supply, our concern with regional conflicts in areas such as the Persian Gulf, Caribbean, Mediterranean, and South Asia, and the continuing need to be alert to a Soviet maritime threat, there are few, if any, areas of the world ocean that we can ignore. For the last 30 years, our attention has focused on the Norwegian and Barents Seas, the eastern Arctic, the western Atlantic, and the eastern and western Pacific, as we have positioned ourselves vis-á-vis the Soviet Union. Today, even that broad coverage is not enough. We need to think in global terms, especially in the complex coastal regions of Third World nations and at critical choke points.

Oceanography Support for ASW

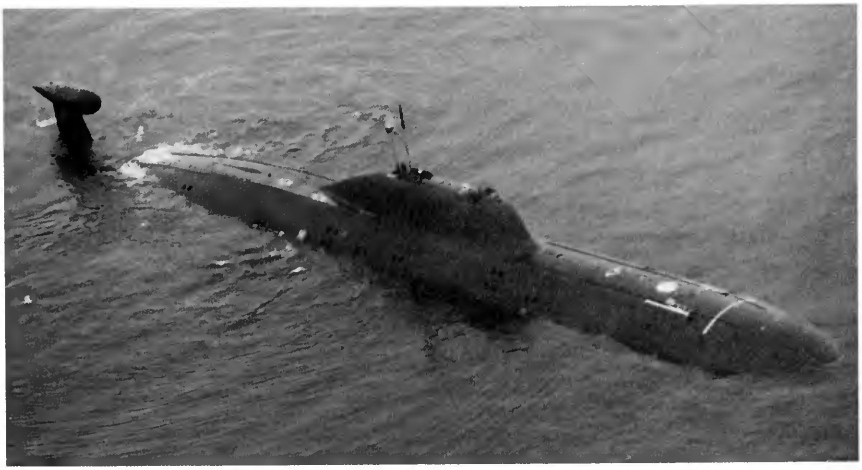
Today, major efforts are underway to characterize the full spectrum of submarine emissions. The goals are to understand the limits imposed by the environment on passive long-range detection, to understand oceanographic factors limiting active sonar systems, and to provide improved prediction and analytical models that help sonar system designers and operators understand ASW system performance. To this end, a new generation of systems is being developed with better low-frequency response.

While ASW has become very high-tech since WWII, oceanography has kept pace, building on the directions established during and after WWII. Quiet submarine targets require technology developments that will make the difference between operational success and failure.

As the Soviets built and deployed a large and powerful submarine force, U.S. ASW became a big and expensive business. At the front end of our ASW strategy is the ocean surveillance system. Acoustic information gleaned from continuously monitoring the ocean basins is merged with data from other intelligence sources to provide a starting point for local searches. Fixed-wing patrol aircraft with sonobuoys, radars, and magnetic anomaly detectors (MAD) are sent to follow-up, identify, and attack surveillance system detections. Submarines are deployed to fill gaps in the surveillance network or to cooperate with the aircraft in target localization and attack.

Surface ships operate in groups. Whether in merchant convoys, surface attack groups, or carrier battle groups, the principle forces–merchant ships, battleships, cruisers, or aircraft carriers–are surrounded

At the front-end of our ASW strategy is the ocean surveillance system.



The newest Soviet nuclear attack submarine, the Akula class, is quiet and fast and is likely to set the standard for Soviet submarine design into the 21st century.

and protected by special ASW units. These include frigates and destroyers, with hull-mounted active sonars and long, towed arrays of passive sensors, and helicopters that can operate either alone, with sonobuoys and MAD, or in cooperation with the surface ships. All of these forces have very sophisticated computerized processing and display systems, and they are interconnected by complex command and communications networks.

The search for ASW improvements focuses on exploiting our understanding of the ocean.

Acoustic models form the basis for predicting the performance of any ASW system. Like today's ASW forces and systems, the models used are sophisticated and complex and take into account the range- and time-varying ocean environment. ASW system performance predictions must be made on the time and space scales of importance to tactical naval operations. Such operations may involve the protection of a transoceanic convoy or a battle group deployed in the Persian Gulf.

The Navy supports a large effort to provide oceanographic information to ASW system operators. It starts with a climatological and geographical data base that includes a high-resolution, four-dimensional (time, depth, latitude, and longitude) digital model of temperature and salinity for most of the world ocean, as well as currents, ambient noise, bottom topography and morphology, and magnetic and ambient acoustic characteristics. This data base is updated and refined continually by Navy and civilian surveys, and it forms the background picture for operations and the baseline for dynamic global and regional models.

Another major element is satellite imagery which provides synoptic data on "ocean weather" and locates, to a first order, the position of features such as fronts, eddies, and ice, which are indicators of acoustic conditions.

The satellite images are combined with "real time" oceanographic data, collected from ships and buoys, and the climatological data base to yield the best available description of the three-dimensional ocean environment. The result is a gridded data field over a large area or a tailored oceanographic description for a local area of operational interest. This, in turn, forms the basic input for the numerical forecasts of oceanographic and acoustic conditions. This process uses a network consisting of the supercomputers of the Fleet Numerical Oceanography Center in Monterey, California, the Operational Oceanography Center of the Naval Oceanographic Office in Bay St. Louis, Mississippi, and fleet oceanography regional centers.

To supplement these products and to provide direct and immediate support to the ASW commander, the forces at sea have, or will soon have, their own environmental support and prediction systems. By using BTs and satellite images received at sea, and by monitoring ambient noise with their ASW systems, they can produce detailed estimates of the detectability of targets in their area and optimize ASW system performance.

Even with all of these modern systems and our increased oceanographic knowledge, ASW is still a challenge. The complexity of the oceans gives the careful, well-designed submarine an inherent advantage. So, unless the ocean becomes "transparent" (which appears highly unlikely), ASW will be largely a matter of restricting the submarine's movement, and carefully sorting through masses of sounds for the few that don't belong.

Building on today's capabilities, the search for ASW improvements focuses on exploiting our understanding of the ocean, searching for improved acoustic and nonacoustic ASW techniques, and using this understanding for tactical advantage. Ocean acoustics research aims to understand the basic limits the ocean imposes on acoustic performance across a very broad range of frequencies. These developments have emphasized the research and characterization of broad ocean areas.

Nonacoustic ASW is not new. However, while there is little likelihood that any other phenomenology will replace acoustics as the primary ASW detection technique, the Navy is investigating supporting methods. For example, bioluminescent organisms–animals and plants that glow when disturbed–are ubiquitous in varying concentrations in the ocean. During WWII, German U-Boat commanders were acutely aware of marine phosphorescence at night as they operated in very shallow waters off the coast of the U.S., realizing that this increased the possibility of visual detection by aircraft or surface ships. Submarines physically push water out of the way and mix it, causing turbulence, vortices, and density changes in the ocean. The resulting hydrodynamic signal can be exploited if distinguished from the natural background. The problem with nonacoustic ASW techniques involving optical or hydrodynamic detection of wakes is that signals are difficult to measure and are attenuated rapidly compared to acoustic signals.

Hydrodynamic signals can be exploited if distinguished from the natural background.

Conclusion

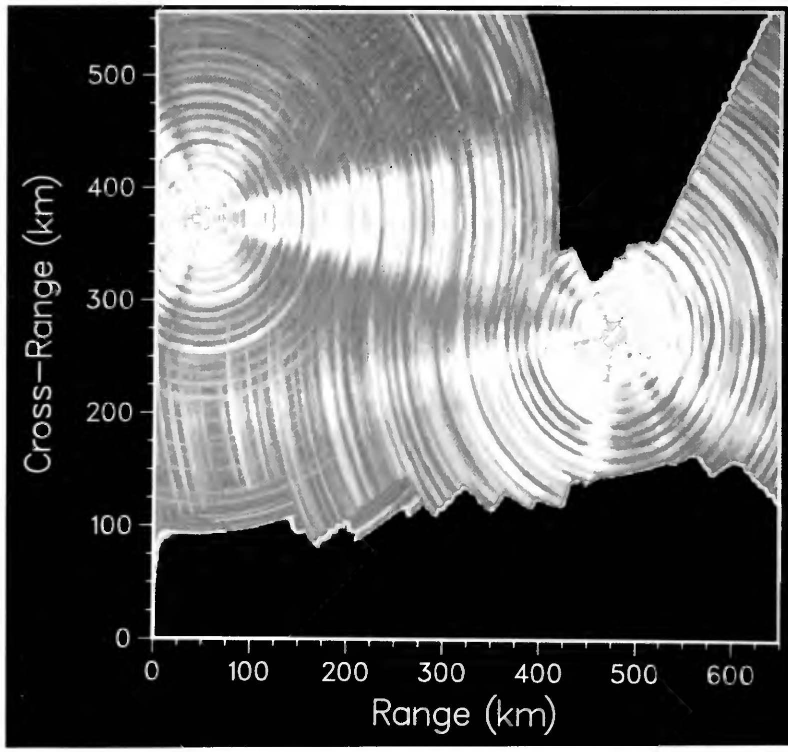
Although mission oriented, naval oceanography since its inception has been a contributor to national peacetime interests. Today, national security concerns are no longer measured in military terms only but also include environmental and economic considerations.

Using ASW alone, many examples of past and future Navy contributions to the national good can be cited. It is especially noteworthy that Navy activities in ocean forecasting, data bases, Arctic exploration, and acoustic tomography contribute directly to our efforts to understand global climate change. The Navy routinely provides oceanographic and weather data to the civilian community. In addition, they make selected Arctic under-ice profile data available for study on variations in ice thickness related to global warming. Navy receiving systems can also be used to monitor earthquake activities, movements of cetaceans, and the eruption of megaplumes associated with plate tectonics.

Finally, the Navy is contributing to multinational measurement programs, such as the World Ocean Circulation Experiment (WOCE), thereby making an important contribution to our understanding of the world ocean.

Under the best of conditions, ASW is a complex process, and, over the last 75 years, oceanography has played an increasingly important role. This area will remain a high priority and an important development area for the foreseeable future, although the Navy is in a transition period in dealing with a modern, more capable threat. The Navy's Tactical Oceanography program is providing the oceanographic infor-

National security concerns are no longer measured in military terms only but also include environmental and economic considerations.



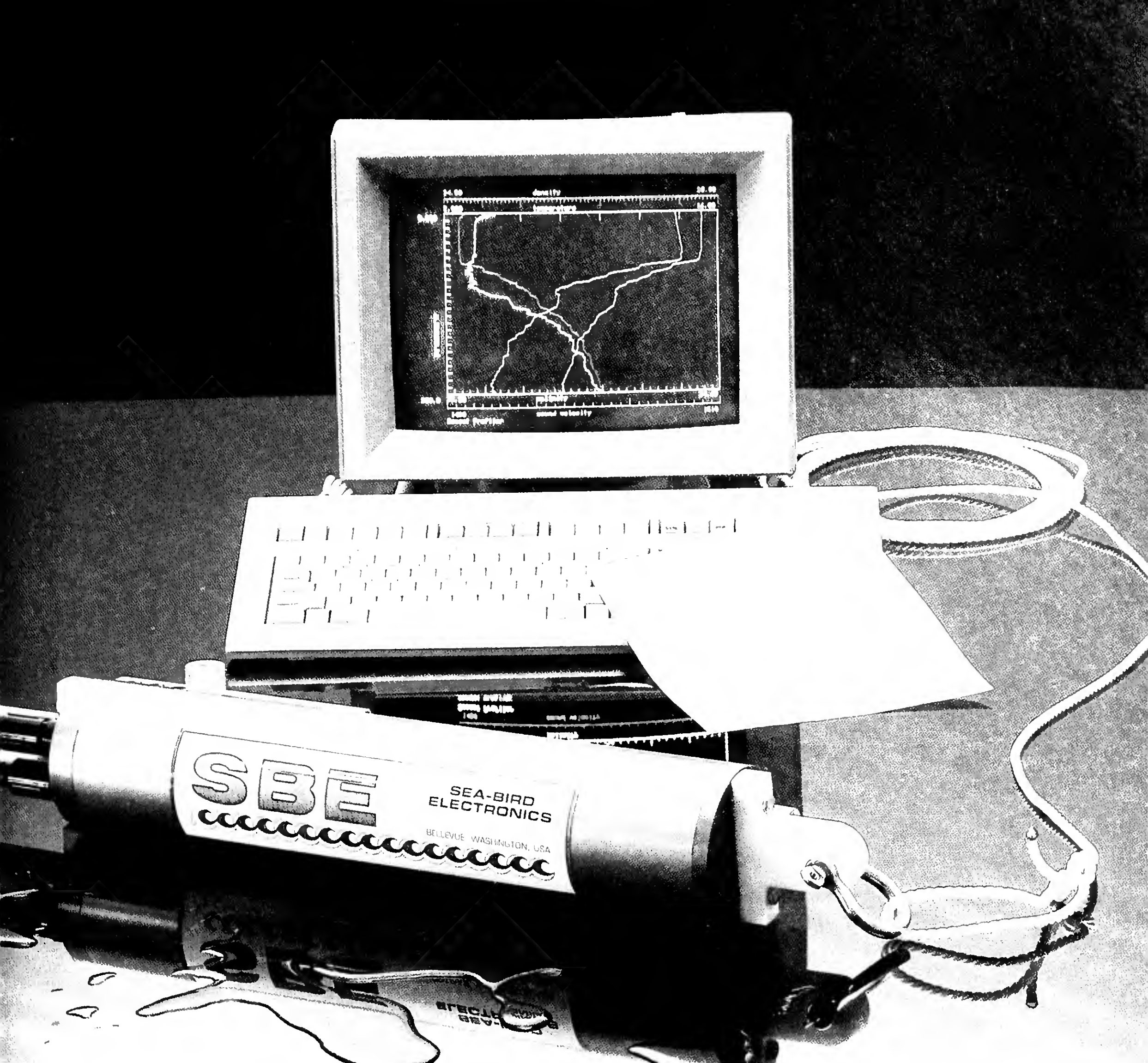
Courtesy of W. Kuperman

Acoustic prediction for two receivers depicts positioning of ASW receivers to optimize performance using a model under development at the Naval Research Laboratory.

mation necessary to support new ASW sensor technology and to provide the real-time support required to efficiently deploy forces and make the right choices on sensor employment. Oceanography will continue to play a vital role in this nation's ASW capability, as well as contribute to national efforts in environmental security.

Acknowledgements: In the preparation of this article, the authors used two key references for background material on ASW and history. They are: "Antisubmarine Warfare - Meeting the Challenge," prepared by the ASW Division of the Office of the Deputy Chief of Naval Operations (Naval Warfare), April 1990, and an informal document, "The Submarine and the Ocean Environment, 1914-1945," by G. E. Weir, Naval Historical Center.

Robert S. Winokur is Technical Director, Office of the Oceanographer of the Navy.
Craig E. Dorman is Director, Woods Hole Oceanographic Institution, and Rear Admiral (Retired), U.S. Navy.


SBE
SEA-BIRD ELECTRONICS
BELLEVUE WASHINGTON, USA

Tactical Oceanography

Richard M. Root,
Jim L. Mitchell,
and Kerry J. Legendre

Knowledge of oceanography is the key to development and application of ASW tactics.

Anti-submarine warfare (ASW) is the Navy's top warfare priority. While the Navy maintains its continuing interest in oceanography for many reasons, the most compelling is that ASW systems must operate in a complex and variable ocean environment. The results of oceanographic research play a significant role in the design, development, and procurement of ASW systems that offer the promise of improved performance. Will the systems live up to those promises when used by the Fleet? Is the Fleet using the systems they now have as best they can? Can the Fleet exploit the ocean environment to offset the quieting of Soviet submarines? The answers often depend on whether or not Navy mission planners and system operators have the necessary oceanographic knowledge and information and can exploit them when they make tactical decisions on where and how to deploy ASW sensors and systems. It has often been said that knowledge is the key to ASW, and knowledge of oceanography is the key to development and application of ASW tactics.

Tactical Oceanography, developing and providing oceanographic information for use by tactical ASW forces, is advancing rapidly. The Naval Oceanographic and Atmospheric Research Laboratory (NOARL), reporting to the Office of Naval Research (ONR) and the Chief of Naval Research, is the principal Navy laboratory performing integrated research, development, testing, and evaluation in ocean science, ocean acoustics, atmospheric science, and related technologies, to improve and support Navy systems and operations. NOARL serves as one of the paths to the Fleet for research sponsored by ONR and conducted by universities.

The Naval Oceanographic Office (NAVOCEANO), reporting to the Commander, Naval Oceanography Command, is responsible for providing operational support to the Fleet in Tactical Oceanography. Many of the fruits of NOARL's research and development efforts are transferred to Fleet operational use by integration into NAVOCEANO on-scene environmental prediction systems, such as the Tactical Environmental Support System (TESS) and the Mobile Oceanography Support System (MOSS). Others come from NOARL to NAVOCEANO's Operational Oceanography Center. The strong ties and close relations between these two commands do much to ensure that the United States has a capability in Tactical Oceanography that is unmatched in the world.

Though new systems for measurement of in situ parameters of the ocean, such as drifting buoys, increase the amount of data available, they will always provide only a few points of information in the vast reaches of the ocean. Remote sensing of the ocean from satellites, however, gives us remarkable new abilities to determine the state of the ocean over large regions in close-to-real time. Coupling this data with the tremendous power of state-of-the-art computers allows new models of the ocean to provide nowcasts (the state of the ocean now) and forecasts (the state of the ocean over the next few weeks) to Naval planners and operators, much as weather forecasts are provided by the Fleet Numerical Oceanography Center (FLENUMOCEANCEN). Satellite communications provide these forecasts to widely spread forces. Finally, the power of desk-top computers, with their ability to provide visual output, has increased so rapidly that at-sea operators now have highly capable Tactical Decision Aids, such as TESS, to assist them in their missions.

Oceanographic information, as used in Tactical Oceanography, includes predicting the propagation of sound in the ocean. Even after many years of research into different methods for detecting submarines, acoustic methods remain the most useful. Acoustic ASW involves either listening for sound generated by an enemy submarine (passive acoustics) or generating sound and listening for an echo from the enemy submarine (active acoustics). In both cases, the sound's speed through the ocean is affected by temperature, salinity, and pressure variations. In addition, the sound is affected by interaction with the bottom or the surface.

The following are definitions of acronyms used in this article, in the order in which they appear:

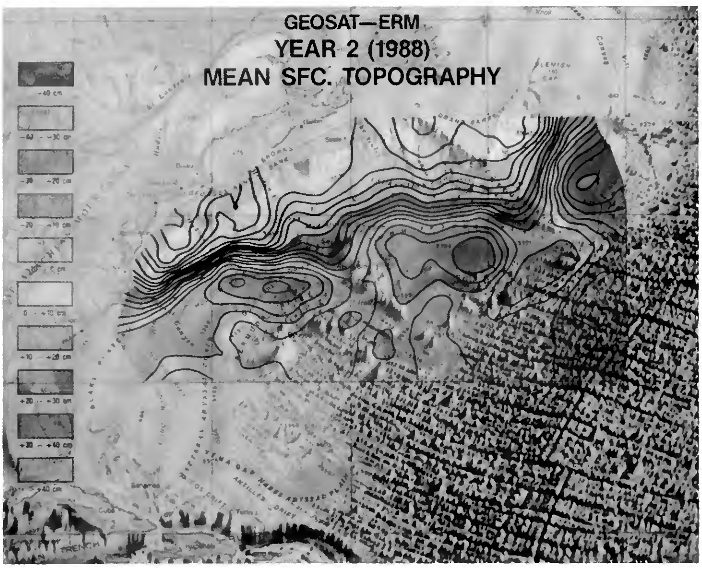
- *ASW - Anti-Submarine Warfare*
- *NOARL - Naval Oceanographic and Atmospheric Research Laboratory*
- *ONR - Office of Naval Research*
- *NAVOCEANO - Naval Oceanographic Office*
- *TESS - Tactical Environmental Support System*
- *MOSS - Mobile Oceanography Support System*
- *FLENUMOCEANCEN - Fleet Numerical Oceanography Center*
- *REX - Regional Energetics Experiment*
- *KERE - Kuroshio Extension Regional Experiment*
- *ICAPS - Integrated Carrier ASW Prediction System*

Passive acoustics techniques are complicated by ambient noise from natural sources (such as waves, rain, or even small earthquakes) and man-made sources (such as ships or oil rigs). In addition to the ambient noise, active acoustics must contend with reverberation from the surface, the seafloor, and sea life. The use of passive systems has been very important over the last 20 years, but the quieting of Soviet submarines has caused renewed interest in active systems. To achieve longer ranges, systems at lower acoustic frequencies and higher powers are under serious consideration. Because this requires development of new information and tactics, these are exciting times with challenges and opportunities for Tactical Oceanography.

Tactical Oceanography is far too broad a subject, and there are too many institutions (both Navy and academic) to cover in one article. However, we can provide an overview of the work at NOARL and NAVOCEANO and the exciting advances that are now being made.

Data Bases for Tactical Oceanography

Some inputs to the Tactical Oceanography process, such as seafloor bathymetry and seafloor geophysical properties, are relatively unchanging. These components can be surveyed, stored in a data base, and made available to modelers or tacticians. Other factors, such as ambient noise, can be measured in a few places for current use, but cannot be accurately predicted. Often we rely on data bases collected over many years to provide a "climatological" or average historical value.



Annual mean sea surface topography of the NW Atlantic Gulf Stream region, overlying seafloor topography, is shown as observed during 1988 with GEOSAT-ERM altimetry. Note the two prominent local recirculation gyres south of the Gulf Stream.

NOARL, as a research and development organization, is responsible for defining the necessary data and developing new data collection techniques. NAVOCEANO, as an operational Command, is responsible for collecting the data, upgrading the standard data bases, and providing the information to the Fleet. To do this, NAVOCEANO uses satellites, drifting buoys, aircraft, and 12 survey ships to collect oceanographic, geophysical, and hydrographic data. These survey efforts provide data to support accurate navigation and effective operation of weapons systems. Data are collected from the entire water column, and geophysical measurements and core samples are taken to describe the seafloor.

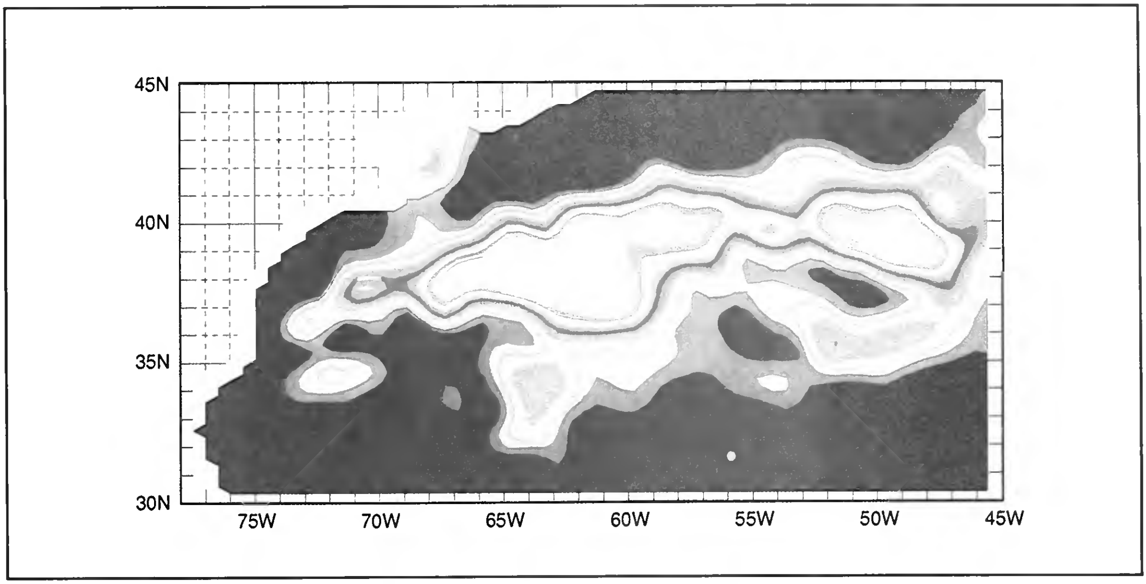
Data that relate directly to anti-submarine warfare include bathymetry, ambient noise, and acoustic bottom loss. Researchers must continually update the data bases to meet the Fleet's changing needs. Surveys are conducted to cover uncharted areas, to increase data density, or to meet the data requirements for new sensors. Special surveys for local ocean areas can be conducted to support specific Fleet operations or exercises. Much of the information collected is used to build data bases resident in environmental prediction systems used by the Fleet.

Ocean Sensing and Modeling

Because remotely-sensed data and modeling are so closely linked, scientists at NOARL emphasize research and development projects that use complementary satellite sensing and numerical model simulations, drawing on university as well as their own work. A prototype for such a multidisciplinary effort is the Northwest Atlantic Regional Energetics Experiment (REX). Now nearing completion, REX has developed several fundamental and novel conclusions regarding the dynamics and energetics of the Gulf Stream. Chief among these are:

- Mesoscale variability of the Gulf Stream is at a maximum along a corridor from just west of the New England seamount chain, eastward over the deep Sohm Abyssal Plain, and ending at the Newfoundland Ridge.

- A two-gyre structure is exhibited in the recirculation of the annual mean Gulf Stream, apparently due to the presence of the seamount chain.
- Monitoring of the energy budget of Gulf Stream variability (both available potential and kinetic) with the Navy's GEOSAT-ERM satellite both verified and expanded historical notions of Gulf Stream energetics estimated from compilations of years of in situ measurements.
- The critical importance of the North Atlantic's Deep Western Boundary Current in the separation and eastward penetration of the Gulf Stream is verified by comparisons of numerical model simulations with satellite and in situ observations.
- The relatively simple vertical structure of ocean density within the Gulf Stream and associated Rings (i.e., REX observations indicate that over 90 percent of the Gulf Stream's mesoscale energy is stored in only two vertical degrees of freedom) allows for the conversion of satellite surface observations, such as surface topography with an altimeter, into inferred vertical profiles of temperature, salinity, or sound speed for use in naval applications.



Upper ocean eddy available potential energy of the Gulf Stream computed at NORDA from surface topographic RMS observed with GEOSAT-ERM altimetry. Minimum potential energy is purple and maximum is pink. Distribution and magnitudes are in excellent agreement with estimates based on hydrographic measurements.

Based on these results, a highly realistic ocean forecast system for the Gulf Stream should become operational within the U.S. Navy in 1991. This is the first system to demonstrate forecast skill for the Gulf Stream significantly better than persistence (i.e., the assumption of no evolution in the mesoscale structure).

Building on the successes of REX, future multidisciplinary research will focus on a comparative study of the mesoscale dynamics and energetics of the Kuroshio Extension and the Gulf Stream as part of the upcoming Kuroshio Extension Regional Experiment (KERE), a joint

NOARL-academic project. Like REX, KERE will be a coordinated project involving the major techniques of satellite sensing, field experiments, and ocean numerical modeling.

Researchers will use the satellite data in both the Kuroshio Extension and Gulf Stream systems, while the collection of supporting in situ data is scheduled for the Kuroshio Extension only. KERE will culminate in a comparison of the dynamics and energetics of the Northern Hemisphere's two major western boundary currents, enhancing our understanding of the fundamental dynamics and energetics of western boundary currents. In the future, this knowledge will provide the Navy with operational models for this important portion of the Pacific Ocean.

KERE will culminate in a comparison of the dynamics and energetics of the Northern Hemisphere's two major western boundary currents

Acoustic Modeling

Once researchers obtain a description of the ocean structure, the next question concerns its impact on the propagation of sound in the ocean. Acoustic models are used to calculate the acoustic energy lost between a source and a receiver. Until very recently, operational acoustic performance prediction models assumed that the ocean was uniform over large areas and that the ocean bottom was flat (range-independence assumptions). While both assumptions are wrong in many, if not most, cases in the real world, they have taught us a great deal about the way acoustic energy propagates through the ocean.

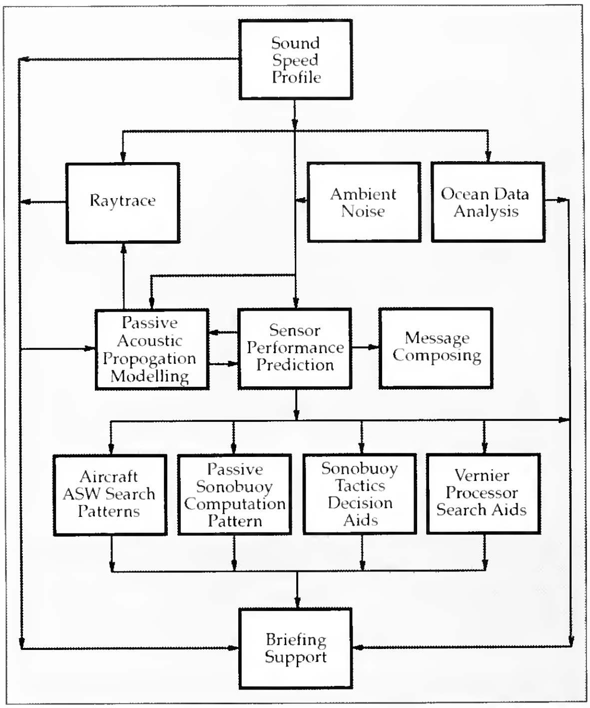
The equations of acoustic propagation in a range-independent case can be solved exactly, and rapid, relatively accurate models can be compared to the exact numerical solutions to ensure confidence in the models. We can also gain confidence by comparison of model outputs to measurements made at sea. Only very special cases of range-dependent acoustic propagation can be solved exactly, but in recent years there have been dramatic increases in the capability of the research community to model range-dependent cases with surprisingly acceptable accuracy. For example, the figure on page 38 shows the use of the Navy standard parabolic equation acoustic model to calculate the loss of acoustic energy in the water column and in the bottom as sound propagates from a source in the presence of a sea-mount. This information, available in TESS and MOSS, is invaluable to a tactical commander who might be attempting to locate a submarine in an ASW scenario.

The presence of these new models in the Fleet has considerably increased the demands for accurate information on bathymetry, bottom type and associated geoacoustic information, and sound-speed profiles as they vary over an area of operational interest. As new ASW systems are developed, it is likely that these demands will continue to increase.

Even with these advances, the range-dependent models calculate the loss only along a single line between two geographic points. A subject of considerable research interest for Tactical Oceanography is the calculation of the entire acoustic field in a fully three-dimensional ocean. For the moment, this cannot be done in a timely fashion. Even state-of-the-art supercomputers are not fast enough to provide solutions of use to a tactical commander. Over the next few years, however, scientists at NOARL believe that advances such as massively parallel computers will offer new ways to attack this problem.

Product Delivery

Once environmental data have been collected and processed, they must be presented to Fleet units to help them perform their respective missions, including ASW. These data are sent either directly to the Fleet or to other Navy activities for more processing before delivery to operational units. Much of the data collected by NAVOCEANO is included in Navy standard data bases, such as the Digital Bathymetric Data Base and Historical Ocean Profiles, that are employed in all of the on-scene environmental prediction systems used by the Fleet. The Operational Oceanography Center at NAVOCEANO receives satellite imagery and provides a near-real-time ocean front and eddy location analysis to regional centers and FLENUMOCEANCEN. The regional centers tailor the location analysis for local areas of interest and provide the information on fronts and eddies to Fleet units.

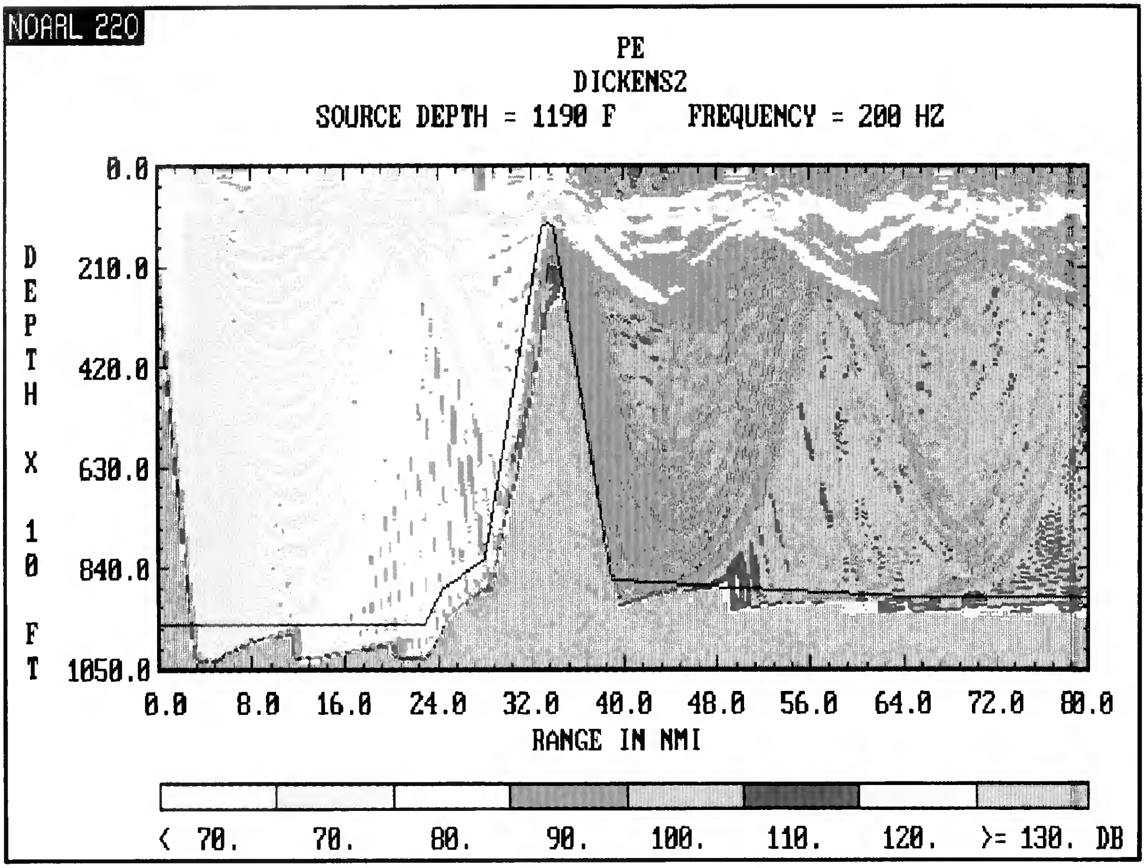


An operator can estimate the range at which particular sensors can detect an enemy submarine by using products such as the Integrated Carrier ASW Prediction System shown in this program flow.

FLENUMOCEANCEN uses the location analysis to initialize its regional scale ocean models, which are then used for acoustic predictions. These products can be sent to Fleet users via radio Teletype. Oceanographic and acoustic information are also available to Fleet users in publications like *Environmental Guides* for standard ocean areas and other special reports. Many of these environmentally-related publications are required in the inventories of ships, submarines, and aircraft involved in ASW. Some data go to the Defense Mapping Agency to produce charts for the Fleet.

Tactical Decision Aids

The Naval Oceanographic Office maintains the Navy's standard data bases for all environmental prediction systems used by Fleet units. These data bases, used with oceanographic and acoustic programs, provide the operator with the tools needed for acoustic range predictions. The operator can take a bathythermograph profile (a vertical temperature



The range-dependent acoustic field produced by a 1,190 foot, 200-hertz source is shown as calculated by the Navy standard parabolic equation propagation model. It demonstrates the dramatic effect Dickens Seamount would have on acoustic propagation, by blocking propagation to deep or shallow receivers (topographic blockage).

profile of the upper portion of the water column), and enter it in the prediction system. The profile is merged with the deep historical profile from the data base to obtain surface-to-bottom temperature and sound-speed profiles. Other products, such as propagation loss curves and acoustic ray traces, can be generated for the water mass of interest. Using these products, the operator can estimate the range at which particular sensors can detect an enemy submarine.

There are also modules such as the Sonobuoy Tactics Decision Aids, resident on the Integrated Carrier ASW Prediction System (ICAPS), that provide guidance on sensor placement. The figure on page 37 shows the modules and the program flow of ICAPS. In addition to the oceanography and acoustic modules used for ASW support, prediction systems such as TESS contain a search-and-rescue program and various atmospheric and electromagnetic propagation modules.

In the future, new ASW systems using Low Frequency Active sources will lead to requirements for new Tactical Decision Aids. NOARL, under the sponsorship of the Oceanographer of the Navy's Advanced Underwater Acoustic Modeling Project, is actively working to produce these new aids. However, many basic questions must be answered before we can confidently and accurately predict the performance of these new systems.

It is an exciting time for Naval Tactical Oceanography. The need for more support to the Fleet is recognized by both the Fleet and the research community. The problems are stimulating, both from a research point of view and from an operational point of view. We are in the midst of a revolutionary increase in our ability to measure, model, and predict the state of the ocean and the performance of ASW systems in the ocean. While there are many challenges left for the future, we have already made significant progress.

Richard M. Root is Associate Technical Director and Director, Operations Research and Strategic Planning at the Naval Oceanographic and Atmospheric Research Laboratory (NOARL), located at Stennis Space Center, Mississippi.
Jim L. Mitchell is an oceanographer in the Ocean Sensing and Prediction Division at NOARL, and he is the Office of Naval Research's principal investigator for the Northwest Atlantic Regional Energetics Experiment (REX) and the upcoming Kuroshio Extension Regional Experiment (KERE).
Kerry Legendre is an oceanographer working for the Tactical Support Group at the U.S. Naval Oceanographic Office at Stennis Space Center, Mississippi.

Numerical Air/Sea Environmental Prediction

The Fleet Numerical Oceanography Center is the Navy's primary numerical processing center for global oceanographic and meteorological analysis and prediction.

by Jack J. Jensen and John Hovermale

Through the ages, weather has been the mariner's greatest ally and most ferocious adversary. Seafarers have always been mindful of the weather, good and bad, and the sailors of the U.S. Navy are no exception. In many ways, the Navy is more sensitive to environmental conditions today than it was a generation ago, even though the platforms and sensors are far more capable than they have ever been. This seeming contradiction results from the advancing nature of the threat the Navy must counter. Today's threat is faster, more lethal, and quieter with respect to the environment. Stealth technology and submarine-quieting efforts complicate efforts to detect an enemy and to protect our own ships, planes, submarines, and people.

The Fleet Numerical Oceanography Center

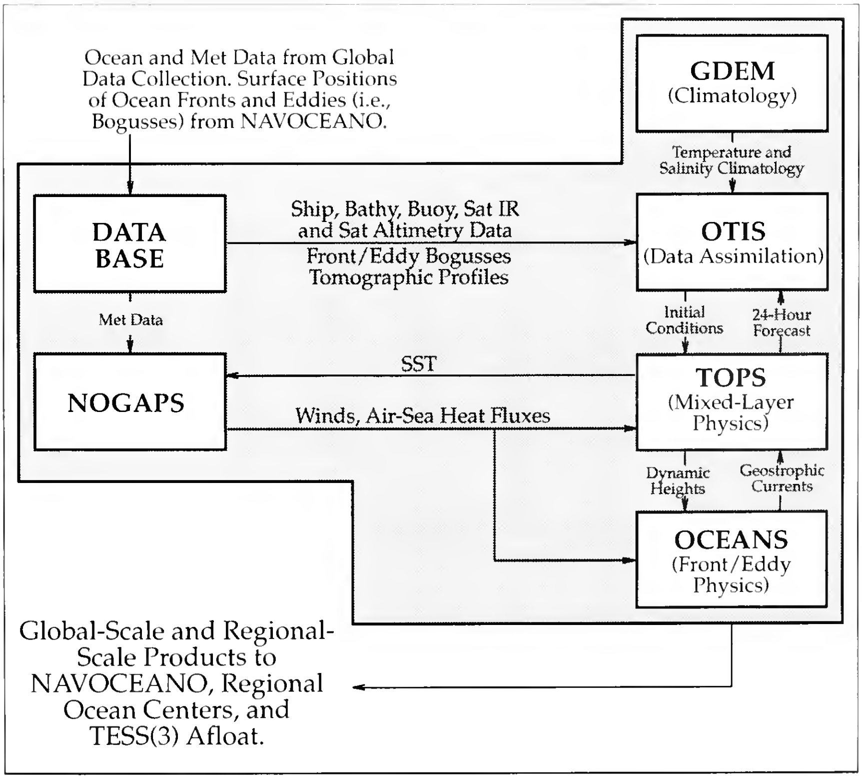
The Fleet Numerical Oceanography Center (FLENUMOCEANCEN) in Monterey, California, is the Navy's primary numerical processing center for global oceanographic and meteorological analysis and prediction. Of the three national weather centers (the others are the National Meteorological Center in Camp Springs, Maryland, and the Air Force Global Weather Central at Offutt Air Force Base in Omaha, Nebraska), it is the only one performing operational global ocean analysis and prediction, and it maintains the largest real-time oceanographic data base in the world.

Reporting to the Navy's agent for environmental support, the Commander of Naval Oceanography Command, Bay St. Louis, Mississippi, the Center is responsible for supporting Navy and Department of Defense (DoD) activities. Although its prime focus is to support one customer, the U.S. Navy, the unique capabilities and many of its 7,000 daily products have also become highly valuable to the civil sector. One important aspect, in this time of environmental awareness and concern, is its ability to define the environment in real time, from the bottom of the ocean to the top of the atmosphere.

The Center's staff numbers nearly 300, approximately half of whom are military. Of the military, one third are officers, mostly specialists in Navy oceanography, and about half of these hold graduate degrees.

Research for and development of the oceanographic models and techniques that are the mainstay of FLENUMOCEANCEN's automated production runs are the responsibility of the Naval Oceanographic and Atmospheric Research Laboratory (NOARL). NOARL's Atmospheric Directorate, also in Monterey, ranks among the world's leaders in understanding and modeling the marine boundary layers and lower atmosphere. The lowest 12,000 feet of the atmosphere are critically important to safe and effective Navy operations. NOARL's Ocean Science Directorate provides comparable world-class expertise in ocean and ice analysis and prediction. In addition, the research and development support does not end once models become operational–NOARL scientists continue to monitor and maintain the quality of operational models in support of the FLENUMOCEANCEN scientific and technical staff. This technical teamwork provides the United States with an unmatched research, development, and operational capability in real-time environmental prediction.

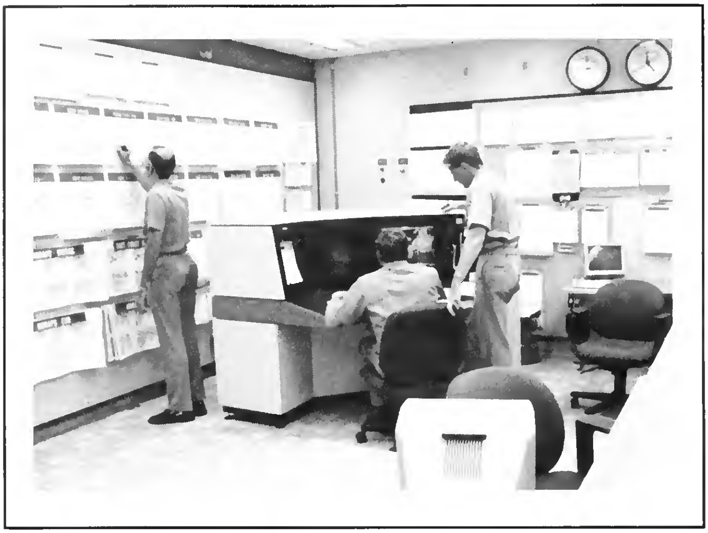
In addition to outstanding technical personnel, four key ingredients combine to produce highly accurate numerical analyses and products: data, the computing power to analyze the data, complex software programs to manage and model the data, and reliable communications to bring in the data and to distribute the products.



This is a representation of the process used by the Fleet Numerical Oceanographic Center (FLENUMOCEANEN) for numerical prediction in the ocean. This system is similar to others used by the Navy for operational weather forecasting.

Numerical Analysis

The initial step in the process of modeling is transforming irregular distributions of environmental observations into the most representative distribution; this is referred to as "assimilation." In today's Navy models, a highly sophisticated ocean thermal assimilation procedure forms the basis for the analysis of present ocean conditions and subsequent forecasting. The NOARL-developed atmospheric model also uses advanced data assimilation techniques to analyze the state of the atmosphere and a sophisticated 18-layer forecast model, reliable seven days out, to "drive" the ocean forecast model.



Quality control staff at FLENUMOCEANCEN in Monterey California, work at the Naval Environmental Display Station.

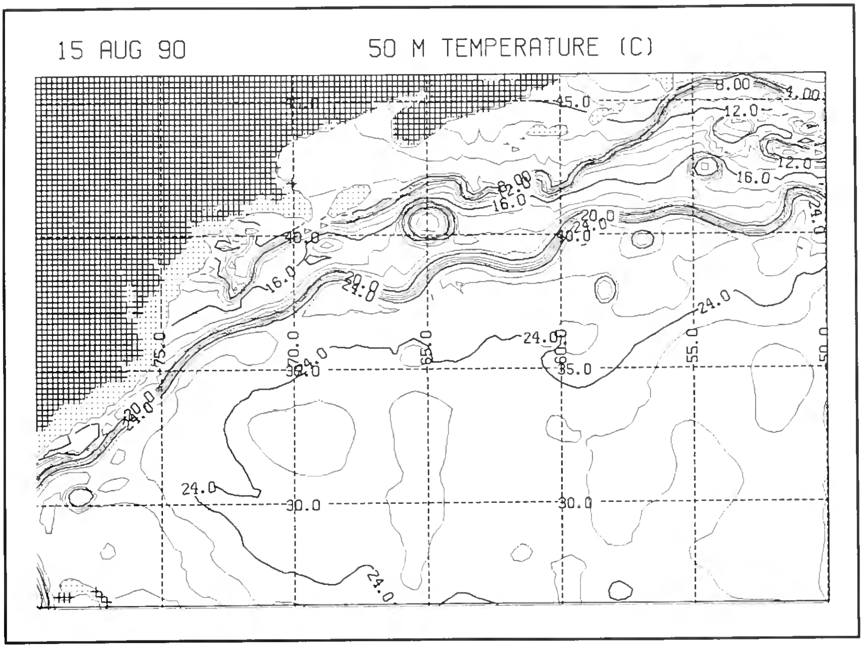
Atmospheric modeling is more advanced than ocean modeling, primarily because mankind has been measuring the environment for hundreds of years, while ocean measurements are a very recent phenomenon. Even now, there are relatively few observations of the ocean each day, despite the fact that it covers more than twice the area of the exposed land masses.

The complexity of atmospheric models has increased tremendously since their first use in operational "weather" forecasting in the mid-1950s. In fact, for many years, models were used to predict only the mass structure (pressures and temperatures) of the atmosphere, with winds only inferred. In the mid-1960s, with the introduction of "primitive equations," both prediction models and objective analysis systems began to include winds.

"Primitive equations" is a general term for the basic physical laws describing atmospheric processes as a function of space and time. These laws are, in no particular order of importance, the three-dimensional equations of Newton's law of motion, the thermodynamic energy equation, the equations of mass continuity for the well-mixed (dry) atmosphere and the less well mixed water in its various forms, and, finally, the equation of state for atmospheric gases.

The strategy for producing all forecasts begins with analysis, at a given time, of the spatial variation of the basic variables, (e.g., wind, temperature, pressure) that appear in the primitive equations. This leaves only functions of time in the primitive equation, and the equations are "solved" for these terms, which are then used to extrapolate the basic variables over short periods (a few minutes). A slightly new spatial distribution of variables is obtained, and the process is repeated again and again until the desired, ultimate period of the forecast has been reached.

The process is essentially the same for numerical prediction in the ocean, except that the equations are less complex. The overall process is characterized in the chart on page 41. Other physical processes are



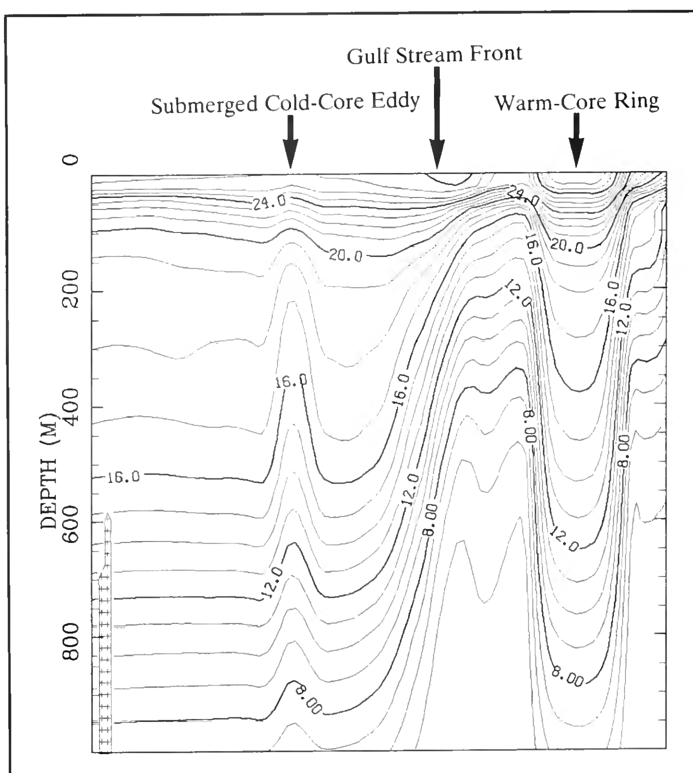
This example of horizontal ocean modeling indicates the temperature at 50 meters depth from the FLENUMOCEANCEN Regional-Scale OTIS 3.0 Analysis for 15 August 1990. The contour interval is 1°C.

included in primitive equation models (e.g., the laws governing solar and terrestrial radiation, the effects of small scales not resolvable on model space grids, and land and sea surface interactions.) With this final addition, the first step toward coupling atmosphere and ocean models is initiated.

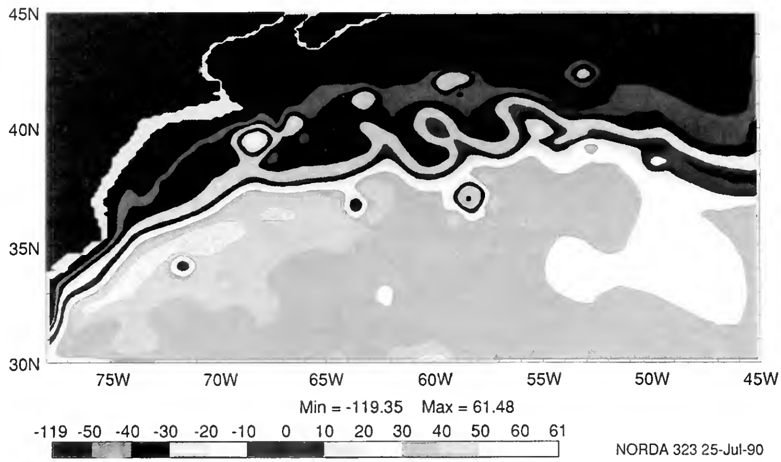
Prediction

The prediction equations, which are essentially "perfect," must be approximated numerically, so modelers must deal with imperfect laws. However, larger computers allow model builders to overcome these numerical imperfections in the physical laws. Note the correlations between increases in forecast accuracy and computer power in the chart on the opposite page. The physical realism of current atmospheric models allows numerical simulation of small-scale weather events, such as typhoons, squall lines, and fronts.

Of particular interest to the Navy is the fact that the next generation of computers will allow the operational inclusion of highly



This temperature cross section from a vertical ocean model indicates temperature variation by depth taken for the same date as the horizontal model above. The contour interval is 1°C.



A horizontal forecast for the week of July 29, 1990, indicates surface temperature variations for the Gulf Stream. This forecast was the result of models in use at FLENUMOCEANCEN.

sophisticated planetary boundary layers in models.

Increased computing power has also extended the time ranges of predictions. Major operational centers can now forecast, with demonstrated skill, discrete weather events seven to eight days in advance. In cases of systematic trends in larger-scale patterns, averages of many forecasts staggered in time provide valuable input for monthly ocean projections. Thus, whereas operational models and long-range forecast/climate models began from quite different points over three decades ago, they are converging rapidly in design and forecast ability. In addition, research advances in each area are increasingly interadaptable.

The Navy Operational Global Atmospheric Prediction System (NOGAPS), developed by NOARL and applied by FLENUMOCEANCEN, is an example of a world-class operational system poised to make the leap to a long-range research prediction system. It will continue to function in dual roles, improving its twice-daily, five-day forecasts of "weather" related to discrete atmospheric events and playing an important role in the Navy's contribution to the nation's Global Climate Change Program.

The historical perspective of numerical environmental prediction provided thus far has emphasized the atmosphere. The application of the same technologies to the oceans has lagged primarily because of the paucity of data. Skillful predictions of distinct ocean currents and eddies were thought impossible for some time because the initial state of the ocean could not be established nearly as well as that of the atmosphere.

As mentioned earlier, the fundamental equations describing the behavior of the ocean are less complicated versions of the atmospheric equations, but in some ways (numerically and computationally) the ocean equations are more difficult to apply. The differences would require text books to explain. However, we will simply note here that the lateral constraints in the oceans (continents) and the relatively small special variations in the oceans create computational challenges more demanding than those in the atmosphere.

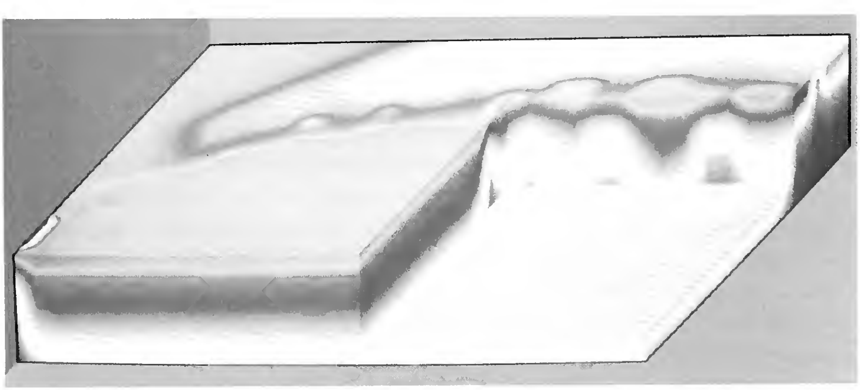
ue to these factors and the data voids, progress in ocean prediction lags at least two decades behind atmospheric prediction. Despite the limitations, ocean prediction has provided valuable operational support for a number of years, particularly where the lower atmosphere plays a major role in determining the outcome (e.g., one to five day prediction of surface waves and upper ocean thermal structure).

Computational power and satellite data coverage are just now becoming adequate for modelers to consider the entire global ocean circulation, extending ocean forecasts from days to months. NOARL is transferring a regional (Gulf Stream) prediction system and a first-generation global ocean prediction system to operations. Rapid upgrades to these systems are planned, as ocean data coverage and computational power increase during the 1990s. In order to extend skillful forecasts to one week and beyond, data coverage must be global. Coverage over a single continent would limit forecast skill to about one day, even with the most sophisticated model imaginable.

Meteorologists have been trying to obtain a better global representation of the atmosphere since the early 1950s when a WWII radiosonde network began to provide upper air pressure, temperature, and moisture measurements over continents. Researchers expected immediate improvements in predictions during the 1960s when the ability to obtain cloud images and vertical temperature and moisture soundings from satellites was demonstrated. The data were of poorer accuracy than originally advertised, however, and there was a major problem related to the three-dimensional analysis system designed to treat conventional observations.

Thus began a move toward "optimal" analysis systems. They are called "optimal" because they logically accept different types of observations and weight them relative to their statistically-derived accuracies. These systems, especially when employed in their "multi-variate" form (analyzing all meteorological variables at one time and taking advantage of their statistical cross correlations), began to show some positive impact on predictions of satellite temperature data. Southern hemispheric analyses, critical to support five-to-seven day predictions, could not be produced today without satellite temperature data.

With the introduction of geostationary satellites, cloud pictures could be taken frequently enough to track individual cloud elements from picture to picture, and the cloud top heights could be estimated knowing their top temperatures. From this information, high level winds in the atmosphere could be inferred. These estimates were found to be



A three-dimensional volume of Gulf Stream ocean temperatures is plotted here from the Daily Synoptic Ocean Analysis of November 14, 1990. Red is warmest water, and blue is coldest. (Land mass is not shown but would be at upper left.)

surprisingly accurate and had high immediate impact on forecast accuracy when ingested through the Multi-Variate Optimal Interpolation (MVOI) system.

Remote sensing of the oceans first concentrated on sea-surface temperature, followed by sea state (i.e., wave action). With the demonstrated ability of satellite-borne radars to determine sea elevation with great accuracy, the strength and direction of ocean circulation systems could be inferred, though it will take time to reach the full potential of these information sources.

The U.S. Navy's Fleet Numerical Oceanography Center processes nearly a quarter of a million observations per day into one comprehensive data base.

New satellite systems, such as NASA's Earth Observing System (EOS), will deliver greater volumes of data and mandate more effort toward the challenge of assimilating satellite data into models. EOS, a superior observing system, will be launched by the late 1990s carrying a suite of more than 20 sensors to provide expanded coverage of sea elevation, sea state, and atmospheric winds at all levels. This will introduce a new level of realism about the environment into air/ocean simulation/prediction systems.

It will also require advances in another critical component of modern environmental analysis/forecast systems–that of data base management and data quality control. Neither MVOI nor the primitive equations are sufficiently robust to handle large variations in observational error levels. Therefore, all data bases must be logically organized for systematic intercomparisons, and there is an emerging role for expert systems and neural networks in this data gatekeeping role of modern environmental prediction.

Products

Virtually all of FLENUMOCEANCEN's principal daily products depend to some extent on global atmospheric analysis and derivative forecasts. Wind forecasts and warnings, isobaric heights, movement of severe storms, flight forecasting and the optimal routing of aircraft, etc., all derive their bases from the global atmospheric forecasts. Ocean analyses and forecasts produce high-seas warnings and thermal profiles, and they allow for the optimal routing of ships and effective search-and-rescue efforts. Anti-Submarine Warfare (ASW) support includes the prediction of ambient noise, acoustic performance, radar coverage, electro-optical and infrared sensor performance, the location of ocean fronts and eddies, and the generation of tailored products and tactical applications for specific platforms, sensors, and weapons systems.

FLENUMOCEANCEN also provides daily support for strategic submarines, research and development, and global sea-ice analyses and forecasts. Two of the FLENUMOCEANCEN products, those for the optimal routing of ships and aircraft, save money in fuel equal to approximately twice the annual operating cost of the Center.

Merely generating analyses and forecasts is not sufficient, however. Effective fleet support is totally dependent on adequate and reliable communication links among widely dispersed activities. Nearly two dozen circuits at FLENUMOCEANCEN, a number operating via satellite, ensure efficient processing of inbound and outbound data. Nearly a quarter of a million observations per day are processed efficiently into one comprehensive data base. Typical data include surface weather observations, buoy reports, upper-air soundings, ocean temperature profiles, and various data received from environmental satellites. Increasingly, satellite data provide abundant, high-quality observations for accurate global analyses and forecasts.

Until the recent proliferation of desktop computing capability, the only effective and efficient way to manage the provision of environmental information was to centralize the processing at FLENUMOCEANCEN. Computers were just too expensive and complex to distribute around the world.

Recently, however, the Navy has embarked on a bold program to place highly capable, but reasonably small, inexpensive, and ruggedized computers on ships and in regional centers and facilities. The cornerstone of the global support architecture of the future, the Tactical Environmental Support System, version 3 or TESS(3), will be fully integrated with in situ sensors and the new high resolution satellite receiver. Key features of TESS(3) are its integral data base and its ability to relieve the operator of the high level of manual intervention previously necessary.

TESS(3) was developed by Lockheed Missiles and Space Corporation, Austin Division, in association with NOARL. The system is architecturally robust and can be expanded or augmented with new components quickly and inexpensively. It is presently undergoing test and evaluation and should be in full operation in 1991.

TESS(3) signals the beginning of a new era in environmental support to the Navy. NOARL's central role in the development of TESS(3) will continue as the evolutionary growth/sophistication of the system proceeds. For the first time, commanders at sea will be able to maintain indigenous, three-dimensional air and ocean data bases, and will not be dependent on the communications links to FLENUMOCEANCEN in order to apply multi-dimensional environmental knowledge to their advantage. This is particularly important when rapid response is essential and when ships are operating in areas of high-environmental variability. The role of FLENUMOCEANCEN cannot be eliminated, however, and this center will continue to provide the boundary conditions for air and ocean, as well as forecasts for various timeframes, to the ships on a regular basis . It will also be the overall guarantor of quality, with its rigorous, consistent, and objective analyses.

The Navy has been a pioneer in the observation and analysis of ocean currents, temperature structures, and maritime storms. Frequently, Navy ship or shore observations are key indicators of deteriorating weather in a region of few, if any, other observations. Navy area warnings are routinely shared freely, and, indeed, are transmitted openly via facsimile to anyone who cares to copy them.

In recent years, as concern for potential changes in global climate has increased, it has become clear that the FLENUMOCEANCEN global atmospheric and ocean observational and analytical data bases are extremely valuable. NOARL's progress in ocean and atmospheric predictions, including coupling of the systems, places the Navy in a prime position to contribute additional understanding. FLENUMOCEANCEN and NOARL have strengthened their ties to the NOAA Center for Ocean Analysis and Prediction, also located in

Frequently, Navy ship or shore observations are key indicators of deteriorating weather in a region of few, if any, other observations.

Monterey, to ensure maximum information flow from FLENUMOCEANCEN to scientists across the nation.

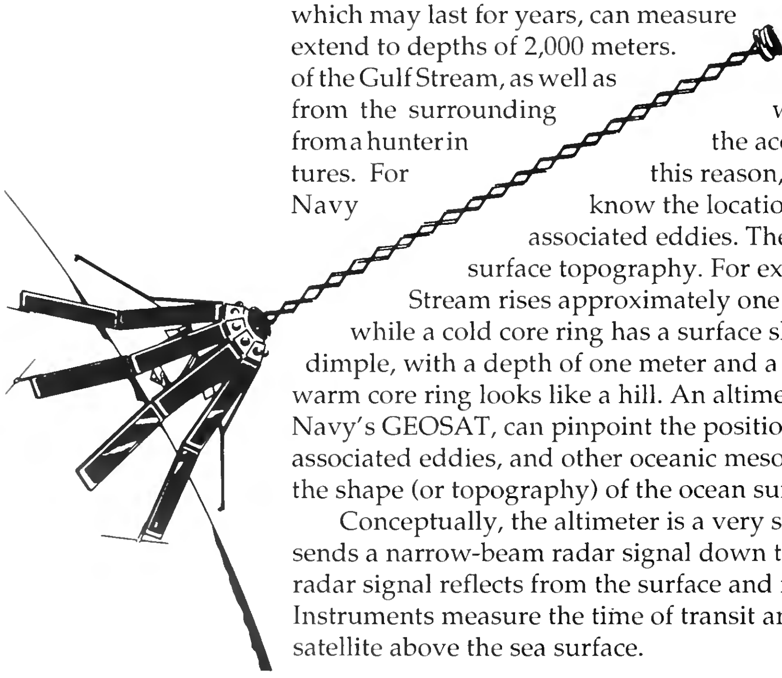
The numerical prediction of the air and sea environment and the application of those environments to the performance of Navy platforms, sensors, and weapons systems is a complex task, dependent on an admixture of skilled people, a highly capable and integrated computer center, millions of lines of complex software code, massive amounts of data, and effective global communication links. Today's skill results from continuous, incremental advancement in research and development and operational implementation over the last 30 years. At the heart of the Navy's system, FLENUMOCEANCEN and NOARL are on the leading edge of the science and are well-suited to provide unique support to the military forces and also to civilian scientists seek important answers to questions involving global ocean-atmosphere environments.

Captain Jack Jensen has been the Commanding Officer of the Fleet Numerical Oceanography Center, Monterey, California, since June 1989. He is a Navy Oceanographer with broad experience in Navy research and development and operational environmental support.
Dr. John Hovermale has been the Technical Director of the Atmospheric Directorate of National Oceanographic and Atmospheric Research Laboratory since 1985.

GEOSAT: A U.S. Navy Spaceborne Altimeter

by David L. Porter, Scott M. Glenn, Ella B. Dobson, and Allan R. Robinson

The warm Gulf Stream current flows northward along the U.S. east coast from Florida to Cape Hatteras, then turns offshore towards the Grand Banks of Newfoundland. Between Cape Hatteras and the Grand Banks, it separates the cold Slope water to the north from the warm Sargasso Sea to the south. In this region, the Gulf Stream meanders like a river. Large southward meanders can separate from the Stream, trapping cold Slope water in the Sargasso Sea and forming a cold core ring. Conversely, large northward meanders can separate and trap warm Sargasso Sea water in the Slope water, forming warm core rings. Once formed, the rings drift west until they are reabsorbed by the Stream. These rings, which may last for years, can measure 100 kilometers across and extend to depths of 2,000 meters. Since the acoustic properties of the Gulf Stream, as well as its rings, differ dramatically from the surrounding water, a submarine could hide from a hunter in the acoustic shadow of these features. For this reason, it is important that the U.S. Navy know the location of the Gulf Stream and its associated eddies. These oceanic features create a sea surface topography. For example, the surface of the Gulf Stream rises approximately one meter in about 80 kilometers, while a cold core ring has a surface shape that looks like a gigantic dimple, with a depth of one meter and a radius of 50 kilometers, and a warm core ring looks like a hill. An altimetric satellite, such as the U.S. Navy's GEOSAT, can pinpoint the position of the Gulf Stream, its associated eddies, and other oceanic mesoscale features, by measuring the shape (or topography) of the ocean surface.

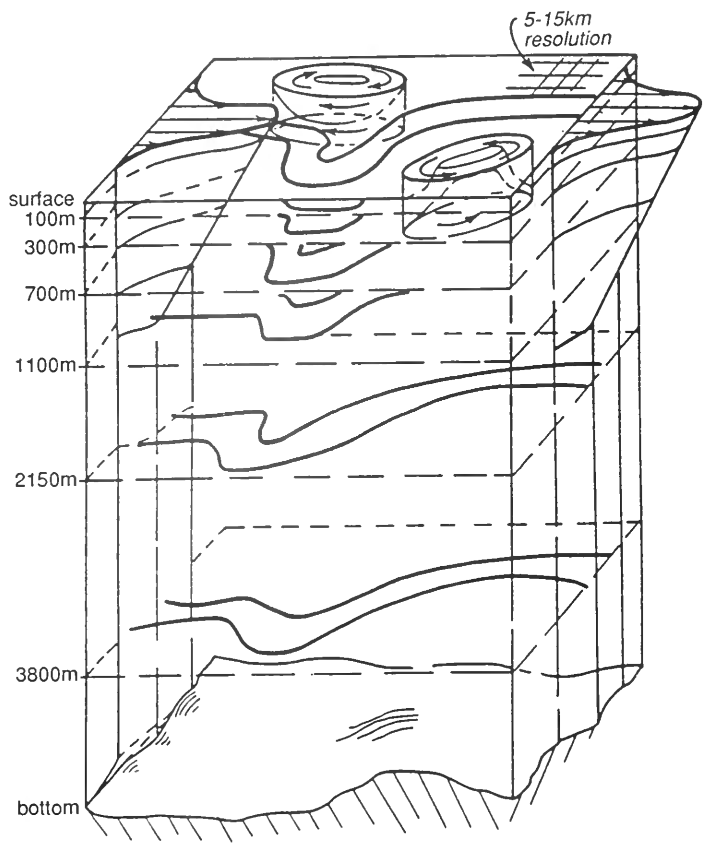


Conceptually, the altimeter is a very simple device. A parabolic dish sends a narrow-beam radar signal down to the surface of the Earth. The radar signal reflects from the surface and is picked up by the satellite. Instruments measure the time of transit and compute the altitude of the satellite above the sea surface.

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) designed and built GEOSAT, the fourth orbiting U.S. altimeter for the U.S. Navy (Skylab, Geos-3, and SEASAT were the other three). It was launched from Vandenburg Air Force Base on March 5, 1985, and yielded four years of data before its altimeter began to fail. Its primary mission, to measure the earth's shape, or geoid, with a high degree of horizontal and vertical accuracy, was accomplished in its first 18 months. Because of the strategic importance of this data, it is classified. However, wind and wave data, which GEOSAT also measured, were released from the classified mission through the National Oceanic and Atmospheric Administration (NOAA).

In September 1986, the classified mission was declared complete and the satellite was maneuvered into an orbit that repeated exactly every 17.05 days–the same orbit that SEASAT occupied in 1978. Since the altimetrically-measured sea surface shape from SEASAT was in the public domain, the GEOSAT altimetric data was not classified as long as its ground track remained within one kilometer of the SEASAT ground track. Under an agreement with the U.S. Navy and JHU/APL, NOAA was responsibile for generating the unclassified data set for the oceanographic community. The raw data was merged with orbit positions (or ephemeris) computed by the U.S. Navy Astronautics Group, and environmental corrections for the ocean and Earth tides, water vapor in the atmosphere, and effects of the ionosphere were added to the satellite data to create the Geophysical Data Records (GDRs).

Schematic of the initial stream function field with stream and ring models.



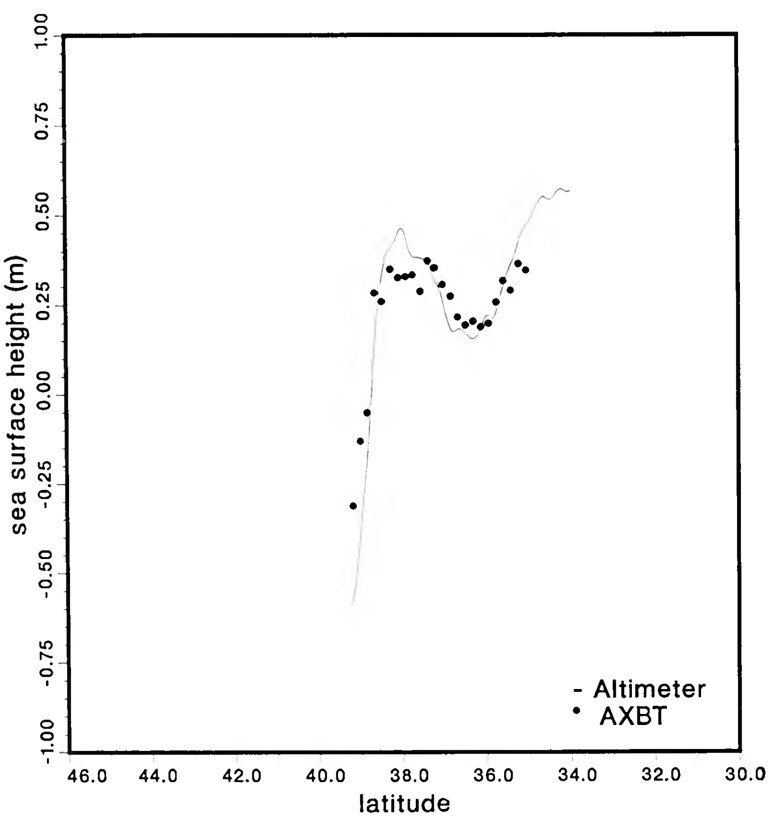
As is the case with most data analyses, "One person's signal is another person's noise." Though some researchers have done well in measuring global tides with GEOSAT, in the case of mesoscale features, such as the Gulf Stream and its rings, the tides are noise that must be removed. Hence, a model of the global tide is used to remove the ocean tide as well as the "solid" Earth tide. Ocean tides have amplitudes of about 50 centimeters in the Atlantic, while the Earth tides have amplitudes on the order of five centimeters.

Ocean surface waves also affected the return of the radar signals, which reflect off the peaks of the wave first and the troughs last. This would not have been a problem if the wave peaks were mirror images of the troughs. Since they were not, this developed an Electromagnetic (EM) bias. The analysis was corrected by adding an empirically-obtained portion of the significant wave height, determined from the altimeter, back into the sea surface height signal.

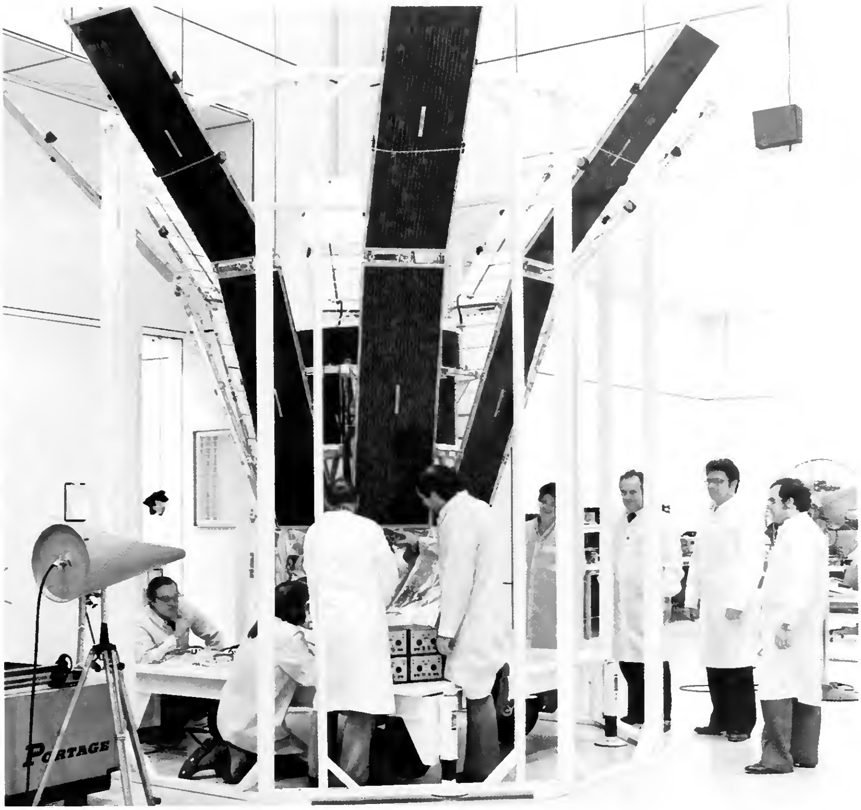
The last and largest correction in the computation of the sea surface height was that due to orbit error (i.e., the difference between where the satellite actually was and its estimated location). The vertical orbit error can be as large as 4 meters, an obvious problem when you are looking for signals no larger than 1.4 meters. However, the 4-meter error has a wavelength associated with the Earth's radius on the order of 6,000 kilometers, and the mesoscale feature signal has a length scale of about 100 kilometers. Therefore, researchers used a quadratic equation to remove the difference in height between a pass and a reference pass. This is essentially a high-pass filter that eliminates the long wavelength orbit error and allows the measurement of smaller mesoscale features.

Researchers computed a one-year average of the altimetric sea surface from which an independent "ocean estimate" was subtracted to obtain the synthetic geoid. When the synthetic geoid is subtracted from an individual altimetric sea surface height, it eliminates the geoid and leaves an estimate of the dynamic topography due to the mesoscale currents (See Box on pages 56 and 57).

An independent average ocean height estimate was calculated by the Harvard University Gulf Stream Forecasting Project. Gulfcast, as the project became known, was sponsored by the U.S. Navy to develop an operational forecasting system for the Gulf Stream region. During the Gulfcast project, seven-day forecasts of daily Gulf Stream and ring locations were generated each week for approximately 18 months. As



This plot shows the sea surface height (solid line) determined from the altimeter for a pass on May 12, 1987. The solid dots are the sea surface height measurements from AXBTs dropped along the pass 19 hours before GEOSAT overflew the ground track.

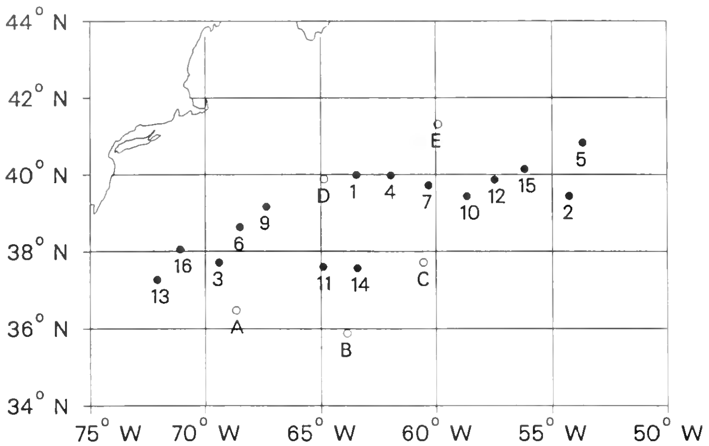


Courtesy of The Johns Hopkins University Applied Physics Laboratory

GEOSAT undergoes testing in the instrument bay at The Johns Hopkins University Applied Physics Laboratory.

with atmospheric weather forecasting systems, Gulfcast relied on a numerical forecast model, an observational network, and a method for melding the model forecasts with the new observations. The figure on page 51 illustrates the numerical model component of the Gulfcast system, the Harvard Open Ocean Model, which is usually configured with a 10 to 15 kilometer horizontal grid and 6 to12 vertical levels. The numerical model is initialized with the most recent estimates of both the Gulf Stream's and rings' three-dimensional velocity fields.

The sea surface heights, as measured by the altimetric system, were then compared with the sea surface heights computed from aircraft-based measurements. The aircraft dropped air expendable bathythermographs (AXBTs) that yielded the vertical structure of the ocean temperature along the satellite tracks. The figure opposite shows the excellent agreement between the altimetric measurement (solid line) and the discrete aircraft measurements (solid dots). A comparison along 16 ground tracks had an average root mean square difference between the altimeter and the ocean measurement of 9.6 centimeters. Thus, the altimetric system for measuring the absolute sea surface height using the synthetic geoid had an accuracy of 9.6 centimeters, an excellent result. With this, researchers can locate exactly the position of the Gulf Stream and the rings, and determine their strength. This is just the information the U.S. Navy needs to locate features that can hide submarines. The figure on page 54 represents 17 days of altimeter data over the Gulf Stream with the numbers on the positions corresponding to the day of the period starting November 2, 1987 (position 1). The open circles



This map shows the position of the Gulf Stream axis (numbered points) determined from the maximum velocity for the 17-day period starting November 2, 1987. Five associated eddies (lettered circles) are also shown.

labeled with letters are the positions of eddies determined from the altimeter. Notice the large meander in the Stream for the points labeled 11 and 14.

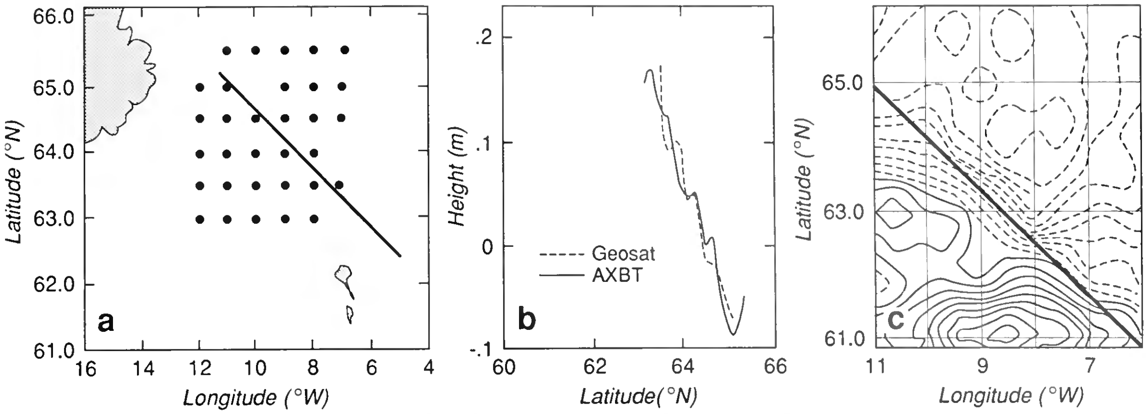
To obtain ocean surface temperature readings, there are two real advantages of the near-real-time altimetric system over satellite infrared. The first is that when eddies "sink" and lose their surface temperature signature, they become invisible to the infrared sensors. However, they still retain a surface shape that the altimeter can measure. The other advantage is that the altimeter can measure the Gulf Stream and its eddies through the cloud cover, which infrared cannot do. This is especially important in tactical areas, such as the Norwegian Sea, where there is a weaker oceanic front than that of the Gulf Stream and where it is cloud-covered most of the year.

The straits between Iceland and the Faroe Islands in the Norwegian Sea, figure A on page 55, are interesting for altimetric application for several reasons: 1) the area has not been as well researched as many other ocean areas; 2) compared to the Gulf Stream region, its sea surface height signal is much smaller (i.e., 10 to 30 centimeters); 3) the bottom topography has a ridge, running from Iceland to Great Britain, which influences the circulation; and 4) it is strategically important to U.S. defense of the Atlantic Ocean. Since the GEOSAT altimeter has a noise level on the order of five centimeters, there was some question whether it could accurately measure this oceanic mesoscale front and the associated eddies in this region.

For a study of the altimetry data in this area, data were collected and corrected for the area from 60° to 68° N latitude and from 15° W to 0° longitude. However, the amount of data available for forming the synthetic geoid in this region was very limited compared to the Gulf Stream. No dynamic model was used, and no infrared data were available on days used in the analysis because of persistent cloudy conditions. Despite these limitations, results were very promising.

The dots in figure A on page 55 represent a grid of AXBT measurements made on the previous day. In order to compare the altimeter measurement of sea surface height and in situ data, a synthetic geoid was computed along this track using the altimeter average and an average derived by interpolating the AXBT data along the same ground track positions from a number of independent surveys.

Once this synthetic geoid was computed, it was subtracted from the altimeter sea surface height for that day to give absolute sea surface height. A comparison of this altimetric sea surface height with AXBT-derived heights is shown in figure B on page 55 where the dotted line is the altimeter and the solid curve is the height computed from the AXBT data. The curve represents the slope of the front as the altimeter moves from 63° to 64.8° N. The position of the front can be seen in figure C, a



a) Map of the Iceland-Faroe region showing GEOSAT ascending ground track and positions of AXBT drops on April 25-26, 1987. b) Sea surface height from GEOSAT (dashed line) and AXBTs (solid line). c) Contour map derived from AXBT's April 25, 1987. Contours are spaced 0.02 meters.

contour map of sea surface height derived from the AXBTs in the region on April 25, 1987. Contours are every 0.02 meters, dotted lines are negative, and solid lines are positive. The heavy line from south to north is the altimeter ground track. The agreement between the in situ data and the altimeter data is very good for this case.

While there were many good comparisons among the 29 cases studied, there were also those that were not very good. In those cases, we believe the differences were due to changes in sea surface height. The measurements from the two systems were not made at the exact same time, and the spatial resolution of the AXBT data was rather sparse. We hope that flights of other altimeters will provide an opportunity to research this area more thoroughly and confirm that an altimeter can accurately measure sea surface height in this small signal region of the ocean. If so, it would prove that the altimeter is a viable instrument for observations from space of oceanic features over a majority of the world's oceans.

David L. Porter is a member of the Space Geophysics Group at the Applied Physics Laboratory of The Johns Hopkins University.
Scott M. Glenn is associate professor at the Institute of Marine and Coastal Sciences, Rutgers University.
Ella B. Dobson is a member of the Principal Professional Staff of the Applied Physics Laboratory of The Johns Hopkins University.
Allan R. Robinson is the Gordon McKay Professor of Geophysical Fluid Dynamics at Harvard University and a member of the Oceanus *Editorial Board.*

Gulfcast Cycle

The observational network and a typical seven-day forecast cycle are illustrated on the opposite page. The observational network consists of: a) satellite infrared imagery, which can be used to locate the surface temperature fronts of the Gulf Stream; b) Air eXpendable BathyThermographs (AXBTs), which are dropped from aircraft to locate the subsurface temperature fronts; and c) the GEOSAT altimeter, which is used to locate change in sea-surface height across the Gulf Stream and the rings. Because the data coverage from all sensors is patchy, their data alone is not sufficient to define the entire Gulf Stream for each numerical model initialization. Instead, the previous week's forecast is adjusted to comply with the new data, thereby allowing the forecast to define the Gulf Stream and ring structure where data gaps exist. The data-updated forecast is then used to initialize the next numerical model of the Gulf Stream. The average of 364 daily Gulfcast estimates from October 7, 1988, to October 4, 1989, were used to compute the ocean estimate and, hence, the synthetic geoid shown in Equation 3.The questions to compute the synthetic geoid are:

SSH = Geoid + Ocean (1)

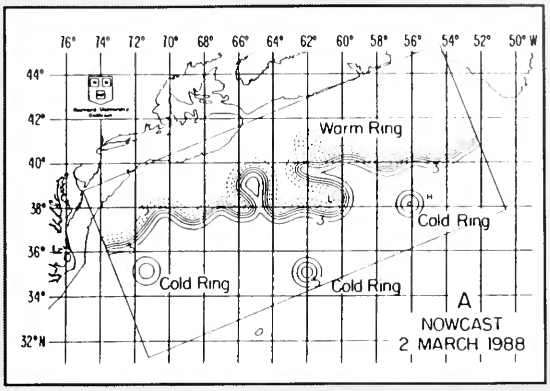
where the "Geoid" is the height of the surface caused by the gravity field of the Earth, the "Ocean" is the sea-surface height induced by the mesoscale currents, and SSH is the sea-surface height. The geoid can still be much larger than the sea-surface height, e.g., on the order of 20 meters compared to the ocean's 1 meter. The problem is to separate the geoid signal from the ocean height signal. Our approach was to calculate an average, ( ), sea-surface height. Thus, Equation 1 becomes:

(SSH) = Geoid + (Ocean) (2)

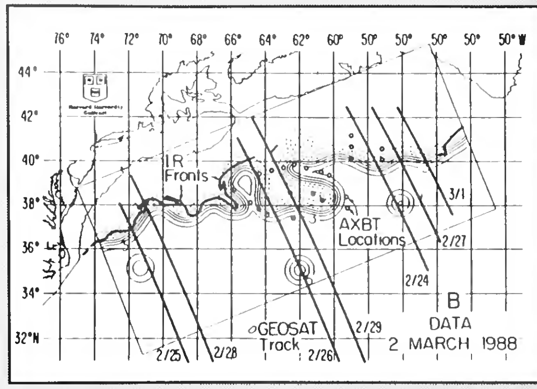
Since the geoid is a constant, the average of the geoid is the geoid. We then subtract an average sea-surface height based on an independent "ocean estimate," such as the Harvard University Open Ocean Model, to obtain the "synthetic geoid," or geoid estimate.

Synthetic Geoid = (SSH) - (Ocean Estimate) (3)

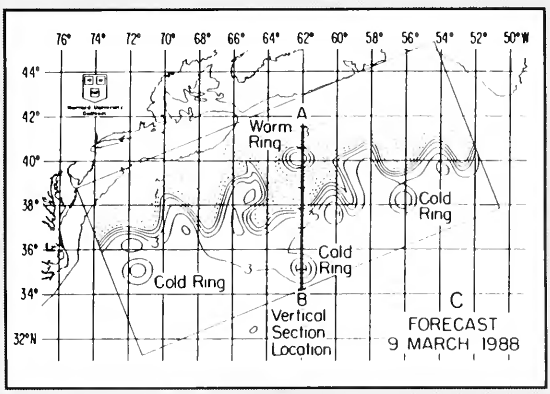
When this synthetic geoid is subtracted from the first equation, it subtracts out the geoid and leaves an estimate of sea-surface height due to mesoscale currents.



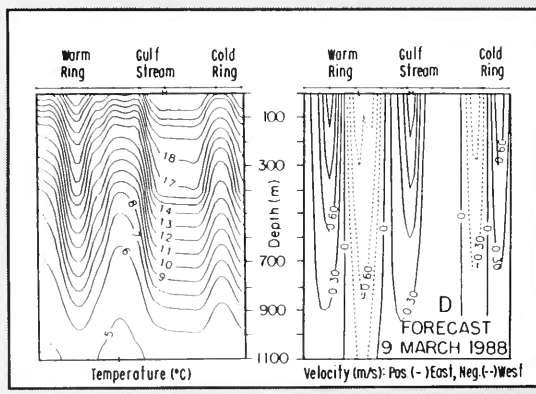
A. Nowcast



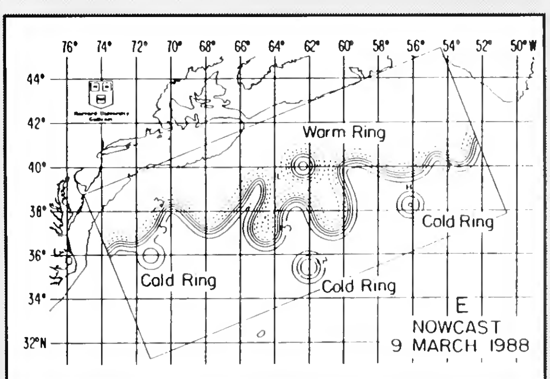
B. Input Data



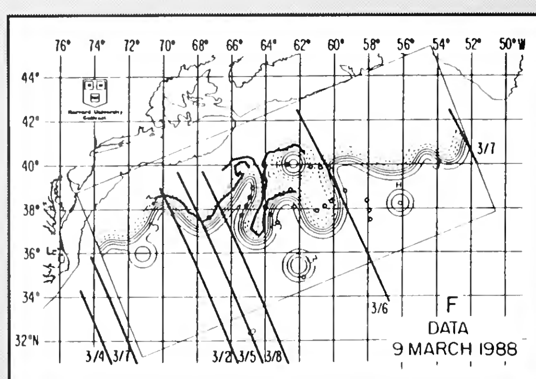
C. Forecast



D. Forecast Vertical Sections



E. New Nowcast



F. New Data

Arctic Oceanography

Thomas B. Curtin,
Norbert Untersteiner,
and Thomas Callaham

Earth's polar regions, the cold reservoirs for the heat engine that determines weather and climate, are critical in the thermal balance of the planet. While the sun is high in the sky during summer at high latitudes, days are long and the surface receives as much heat energy as in the tropics. But with declining solar elevation, days move progressively into perpetual night. During those times, the surface radiates energy to space quickly. Even though the circulation of the atmosphere and ocean imports heat from lower latitudes, this import is insufficient to compensate for the loss, and temperatures drop precipitously.

The Arctic, an ocean, and the Antarctic, a continent, respond much differently to this seasonal cycling. The arctic surface cools in winter to a monthly mean temperature of -35°C in March. Sea ice covers the central Arctic Ocean perennially and expands into its marginal seas in winter. The surface heat budget, and hence the presence or absence of ice on the ocean, is determined by a delicate equilibrium involving horizontal transport and vertical flux in the atmosphere and the ocean. Processes determining vertical fluxes include surface radiation, air-ice-ocean interaction, and deep ocean convection; those affecting horizontal transport include ocean circulation, flow across continental shelves, and river input.

Predicting the location and characteristics of the sea ice cover in the Arctic is of great value in fisheries, resource development, national defense, and transportation. Blockage or opening of ports and channels, the distribution of cracks or leads within the pack ice, changes in the motion, concentration, and thickness of the ice, and conditions at the ice-edge are of interest. Typical ice-strengthened cargo vessels, for instance, can proceed through heavy ice when the ice field is open. However, they encounter difficulties even in thinner ice if the ice is consolidated and under pressure. Under-ice submarine operations may be influenced by lead sizes and orientations.

Today unprecedented technology to better observe high-latitude weather and ice conditions is available. Satellite-borne sensors, high-speed computers capable of calculating weather and climate patterns on

Today unprecedented technology to better observe high-latitude weather and ice conditions is available.

U.S. Navy Photograph

After surfacing through ice several feet thick near the North Pole, USS Billfish *(SSN 676) is inspected by its crew. Operations under the ice greatly reduce or eliminate the effectiveness of anti-submarine aircraft and surface ships, turning antisubmarine warfare into duels between subs.*

a global scale, and communications that can provide real-time data are all operational and being improved. However, the geophysical processes at work in this hostile region over a wide range of space and time scales are not adequately understood for precise forecasting of sea ice, weather, and climate.

Surface Radiation Balance

Incoming solar radiation at the surface is difficult to calculate because it is largely controlled by clouds. In addition, chemical pollutants and particulate matter, known as arctic haze, are transported from industrial centers into the Arctic over long distances. They also affect transmission and reflectance of energy at different wavelengths. Carbon dioxide, methane, and soot carbon in the haze are highly correlated, suggesting a common combustion source. Transport over 8,000-kilometer paths from sources in Europe has been documented.

Ice and snow greatly increase the albedo, or reflectivity, of the surface compared to open ocean or land. Large-scale albedo changes occur during seasonal transitions. Early snow in autumn or late snow in spring can have a significant influence on the annual ice budget by reflecting a large fraction of the incoming radiation.

Air-Ice-Ocean Interaction

The perennial ice cover in the central Arctic Ocean expands and contracts seasonally between 9 and 15 million square kilometers. We know from sedimentary evidence that during climate cycles of the past, for instance during the last glacial maximum 18,000 years ago, sea ice in the Atlantic sector reached far south, possibly as far as the Iberian Peninsula. But in recent decades, notably since reliable sea ice data have been obtained by satellite, the seasonal cycle of sea ice extent has repeated itself with no long-term trend. However, some of the individual processes affecting the surface heat balance have large interannual and decadal variations, and possibly longer-term trends, that should cause a much greater variability of the sea ice cover than observed.

The perennial ice cover in the central Arctic Ocean expands and contracts seasonally between 9 and 15 million square kilometers.

Interactions of ice and snow with the atmosphere and ocean may include negative feedback, which tends to stabilize the system, or positive feedback, which tends to amplify disturbances and make the ice a rapidly and sensitively responding element of the system. Positive feedback is supported by model calculations of the effects of climate change, such as a doubling of the current carbon dioxide content of the atmosphere. Extreme responses include irreversible changes in state: the perennial Arctic sea ice would not return once it was removed, even under the present climatic conditions. The amount of heat stored in the ocean during an ice-free summer would be so great that ice grown in the following winter would melt completely come summer. Negative feedback is supported by the observed bounds in extent of sea ice over the seasonal cycle despite a large range of year-to-year variability in atmospheric conditions. Understanding the feedback mechanisms in air-ice-ocean interaction is an active area of research.

Where ice covers the ocean in summer, sea surface temperatures cannot rise more than fractions of a degree above freezing because the heat supplied by the sun and air is used for melting ice rather than raising the temperature. Thus, mean monthly surface temperatures in the central Arctic are near 0°C in June, July, and August. In addition to serving as a heat sink, the sea ice, which rejects most of the salt upon freezing, acts like a large freshwater pump at the surface, adding salt to the ocean while freezing and diluting the ocean as it melts. Losing and regaining about one-third of its mass in every seasonal cycle, this process leads to the formation of low-salinity water near the surface and, in certain regions, the sinking of denser, high-salinity water into the deep ocean with possible global impact. The ice also greatly alters the direct mechanical effects of the atmosphere on the ocean. Sea ice is an ensemble of randomly- shaped pieces ranging in size from centimeters to kilometers. Kilometer-size "floes" fracture, exposing the ocean to cold air, or are thrust together to form pressure ridges several tens of meters thick.

In summer, this ensemble of floes is loose and mechanically weak and can be modeled as a continuously deformable surface layer of the ocean. Motion is controlled by wind, ocean currents, and the rotation of the earth. Unconstrained, ice moves at roughly one-fiftieth of the wind speed, acting through friction to accelerate the surface layers of the ocean. In winter, the ensemble of floes is rigid and mechanically coupled.

Large sections move as one piece, with shear zones where these pieces slide past one another. Sometimes the ice becomes strong enough to stop, resisting all external forces. Except for very long swells, the Arctic Ocean is unique among oceans in the absence of a local sea state in winter. When constrained in the form of a large plate, the force of the wind applied in one area may be dissipated hundreds of kilometers away in strain and fracture. Study of this kind of discontinuous behavior is particularly difficult since the measurement of forces acting over these scales poses enormous technical difficulties. Nearly a century of effort to understand sea-ice dynamics, beginning with Fridtjof Nansen's pioneering work, has yet to produce a universal formulation applicable to problems on all scales.

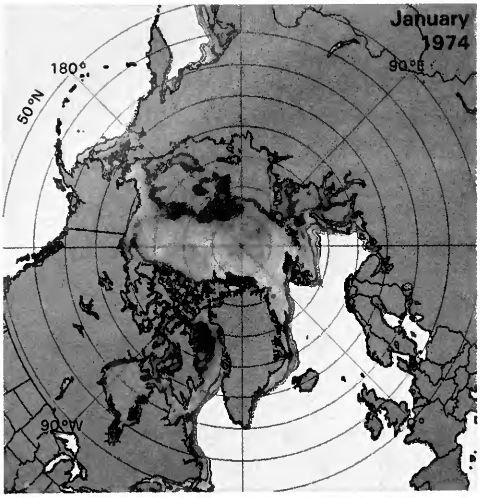
Thermal and mechanical effects are variable within the Arctic basin. For instance, in the Beaufort Sea, where the ice generally drifts in a clockwise gyre, a typical floe lasts about a decade and much of it is near "equilibrium thickness," where the amount of freezing in winter is equal to the amount of melting in summer. In the eastern Arctic basin, which is dominated by the vast Eurasian shelf, the ice generally moves from the region off Eastern Siberia out through the gap between Greenland and Spitsbergen (Fram Strait) in the course of about three years. That region is one of net ice production and export through Fram Strait, implying that the ocean receives more salt each winter than it regains fresh water the following summer. At the same time, however, that region receives a large amount of freshwater runoff from the rivers that drain the northern half of Asia. The total transport of fresh water, including ice across the eastern Arctic, is one of the largest in the world, second only to the Amazon River.

The total transport of fresh water, including ice across the eastern Arctic, is one of the largest in the world, second only to the Amazon River.

Deep Ocean Convection

The hydrologic cycle of the Arctic Ocean may have global impact due to its particular linkage with convective or sinking processes in surrounding marginal seas. In subpolar seas during fall and winter, surface cooling in areas with little vertical density change can result in the unstable sinking of surface waters to great depths. The tendency for the water to be uniform in density with depth is enhanced by the dynamics of the wind-driven circulation gyres in the subpolar seas. Countering this tendency is the freshwater outflow from the Arctic Ocean, which can cap marginal sea waters with a stabilizing layer of less dense water. The net balance at any given time between these competing processes may have far-reaching effects. Sinking surface water in the Greenland, Iceland, Norwegian, and Labrador seas is a source of deep water that ultimately spreads into every ocean basin. This planetary-scale thermohaline circulation redistributes heat, salt, oxygen, and biologically important chemicals.

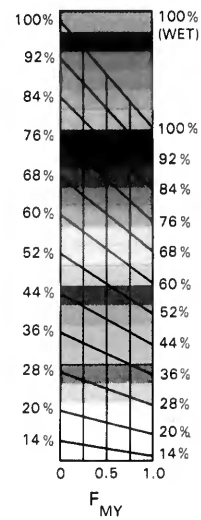
Recent evidence suggests that the thermohaline circulation is variable on time scales from decades to millennia. On time scales of 1 to 50 years, North Atlantic salinity and temperature anomalies may represent the second largest signal, after El Niño, in the ocean-atmosphere system. For example, a North Atlantic salinity anomaly from 1968 through 1972 may be an analog to past climatic regimes in which deep convection was



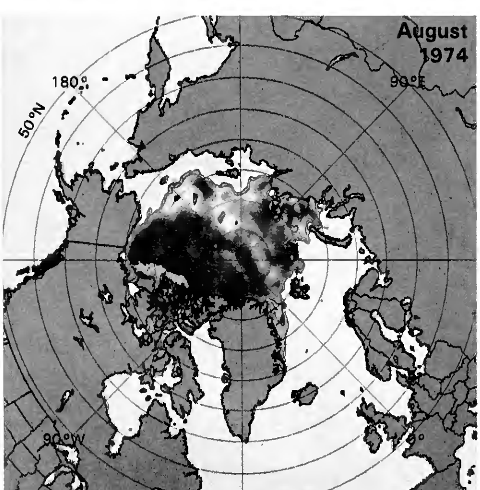
suppressed by freshening of the waters in polar regions. This case was associated with a large positive anomaly in sea ice coverage. Existing data are consistent with a theory that major ocean anomalies in the twentieth century have resulted from periods of enhanced precipitation over northern land areas that feed back to high-latitude precipitation on an interdecadal cycle. The existence of more than one stable climate regime, depending on the occurrence of convection in Atlantic subpolar seas, has been suggested by both paleoclimatic analyses and model experiments. Although the precise preconditioning sequence necessary to trigger such convection is not well understood, exchange through Fram Strait, regulated by the circulation in the central Arctic basin, plays a critical role.

Microwave observations of sea ice made by satellite-borne radiometers in near-polar orbit are shown above and below. Although microwave sensing provides only 20-to-30 kilometer resolution (infrared sensing can resolve one-kilometer features), it is weather and daylight independent. Colors (see right) in these images indicate the fraction of ice in an area that has survived more than one seasonal cycle.

Arctic Basin Circulation



The surface layer (0 to 50 meters) circulation is best known since it can be deduced from ice drift. The main features include clockwise flow in the Beaufort gyre, with occasional summer reversals, and eastward drift across the Eurasian Basin. Wind forcing is dominant. The surface layer is relatively fresh due to river runoff, Pacific inflow, and ice melt. The surface circulation does not usually correlate well with deeper flow. Below the surface layer, circulation has generally been inferred from the distribution of water properties. From 50 to 200 meters, where salinity increases most (the halocline), water resides from 4 to 14 years, based on thermal anomalies and radiochemical tracers. Residence times increase with depth. Data are too sparse to determine flow patterns. From 300 to 500 meters, where relatively warm water of Atlantic origin is found, residence times from 3 to 15 years have been deduced. The lower values are north of the Barents Sea. The intermediate waters of the Eurasian Basin, below the Atlantic layer, have residence times of a few decades, and no corresponding estimates are available from the Canadian Basin. In the deep water below 1,500 meters, water circulates for 200 years in the southern Eurasian Basin, and from 500 to 800 years in the Canadian Basin.



Relatively high salinities in the deep water, particularly the Canadian Basin, have not been explained. The few direct current measurements, as well as models based on tracer data, suggest that the large-scale subsurface circulation is confined in narrow boundary currents, a few tens of kilometers wide, along the margins of the major basins. These boundary flows are counterclockwise in each basin, opposite much of the surface layer motion. Current speed appears to peak at intermediate depth. In the Canadian basin, subsurface mean flow is weak, with comparable energy apparently residing in mesoscale (10 kilometer) eddies possibly generated along the continental margins. In the Eurasian basin, eddy activity seems to be lower. The existing data base, however, is sparse.

Cross-Shelf Flow

The vast, shallow continental shelves of the Arctic Ocean occupy over one-third of its area, but only two percent of its volume. Much of the shelf is ice-free during summer, making it the primary site of melt water in summer and ice production in winter. The shelf is also influenced by river runoff, sedimentation, and biological activity. The permanent ice cover of the central Arctic Ocean limits vertical exchange, thereby magnifying the importance of processes along its edges. For example, the lower halocline appears to be water of Atlantic origin that crosses the Barents and Kara shelves where biological processes impart a particular chemical signature. Similarly, Pacific water entering through the Bering Strait is modified on the Chukchi shelf and spreads throughout the Canadian basin, forming a distinct layer between the surface ice cover and the Atlantic-derived water. Budgets accounting for the observed water property distributions in the Arctic Ocean from known sources on surrounding shelves do not currently balance. However, interannual variability is high, and large areas of shelf bordering the Soviet Union have not been studied. Cross-shelf transport in submarine valleys, such as has been observed in Barrow Canyon, is one of several possible mechanisms to be evaluated in assessing the role of nearshore ice production in maintaining Arctic circulation and water masses.

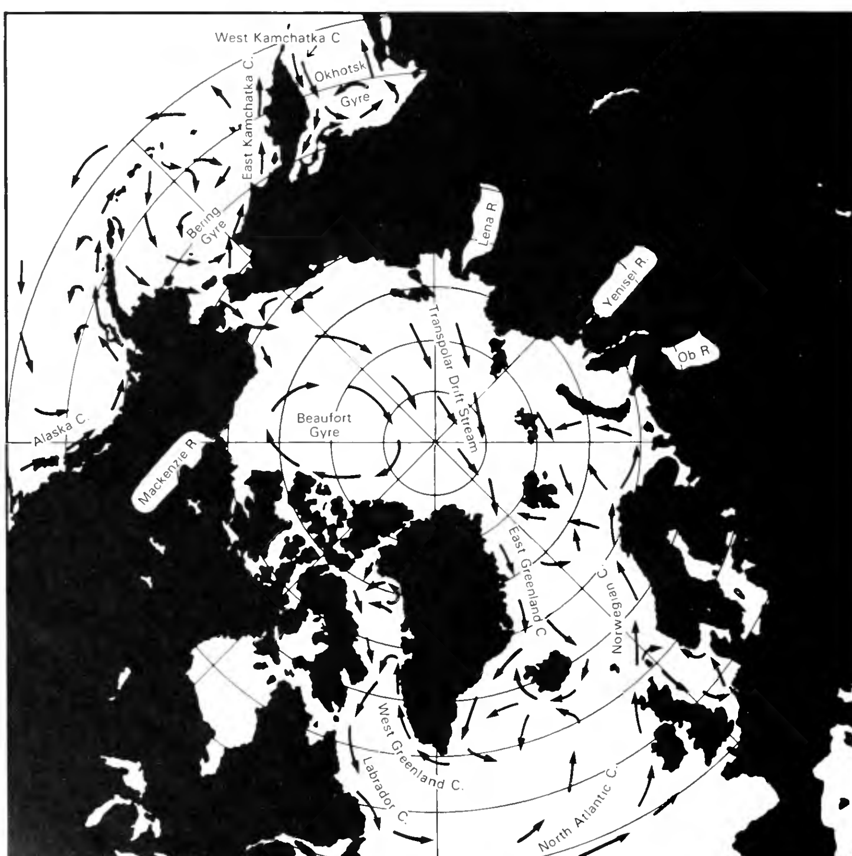
In response to wind and ocean currents, ice floes can crack apart and expose the ocean to the atmosphere in open "leads."

Forecasting

Sea ice and high latitude oceanographic analyses and forecasts are provided by the Naval Polar Oceanography Center (NPOC), part of the Navy/NOAA Joint Ice Center (JIC), in Suitland, Maryland, to a variety of users worldwide. Standard products include expected ice edge location, inner pack concentrations, stages of development, expected port openings/closings, length of navigation season, accumulated freezing degree days, and ice thicknesses at selected ports. Tailored products for specific operations may include open water locations, convergence conditions, and expected drift. Such analyses require the blending of diverse data from satellites, buoys, ships, and aircraft with model forecasts and climatology.

Atmospheric model forecasts come from the Fleet Numerical Oceanography Center, Monterey, California; the National Meteorological Center (NMC), Washington, D.C.; and the European Center for Medium-Range Weather Forecasting, Reading, England. Outputs provide the ice forecaster with information on the movement and intensification of pressure systems, wind fields, and air masses. This information, combined with oceanographic data and the current sea ice analysis, is the basis for short term (24 to 168 hours) ice forecasts. Longer term outlooks (30-day, seasonal) utilize the NMC Climate Analysis Center's 30-day and seasonal meteorological forecasts together with ice climatology.

Due to the inaccessibility of the region, satellite remote sensing is particularly important. Visible, infrared, and microwave imagery are available through receiving stations at Gilmore Creek, Arkansas, and Wallops Island, Virginia. In the visible and infrared (one kilometer resolution), clouds often obscure the surface. The microwave imager, a passive device with 36-kilometer resolution, is the only available all-weather satellite sensor for ice.



This figure shows surface currents in the Arctic region. Arctic Ocean flow has been determined from yearly mean motion of sea ice analyzed from direct observations. The rivers that are the main source of fresh water to the Arctic basin are also shown.

In 1991, the European Space Agency is planning to launch ERS-1, a satellite with a synthetic aperture radar (SAR) capable of providing all-weather, high-resolution (10 meter) imagery. Although areal coverage from ERS-1 will be small, detailed sea ice analyses will be possible in specific regions. In the mid-1990s, Canada's RADARSAT will provide SAR coverage of the complete Arctic Ocean daily. The data rates from these new sensors will be huge. NASA recently completed the Alaskan SAR Facility (ASF) in Fairbanks as a downlink for the western Arctic region. Digital data links between ASF, Canadian facilities, and NPOC are being established. Procedures and algorithms to handle and interpret the unprecedented flow of data are currently under development.

The Arctic Buoy Program, designed to collect surface meteorological data remotely throughout the Arctic, began in 1979 as part of the Global Atmospheric Research Program. ADRAMS buoys are dropped from aircraft onto the drifting sea ice and transmit position, barometric pressure, and air temperature by satellite . SALARGOS buoys are deployed at the surface and sample upper-ocean temperature and salinity, in addition to the atmospheric variables. Other buoys are also used to measure acoustic ambient noise. The meteorological information is linked to the Global Telecommunications System for incorporation into near-real-time global weather analyses. To maintain adequate coverage across the Arctic, more than 50 percent (about 10) of the buoys must be replaced each year due to displacement by ice drift. Ultimately, the buoy array will be networked and integrated with autonomous underwater vehicles to provide comprehensive, three-dimensional air-ice-ocean data. Under a recent multi-agency Memorandum of Understanding, the Joint Ice Center is responsible for coordination of future buoy array deployment and funding, and it will maintain international collaboration, such as in the past with Canada and Norway.

The microwave imager, a passive device with 36 kilometer resolution, is the only available all-weather satellite sensor for ice.

A New Era of Cooperation

This is a new era of interagency and international cooperation in the Arctic. In 1984, Congress passed the Arctic Research and Policy Act to define and coordinate U.S. activities in the north. In 1986, the U.S./ Canada Joint Ice Working Group was established to formalize the exchange of ice information between the two countries for operational and research purposes. In August 1990, the International Arctic Sciences Committee (IASC) was formed to facilitate collaboration in scientific research. The IASC is the first formal body to include the Soviet Union, with its extensive experience in the Arctic. Multinational research expeditions to the North Pole, involving icebreakers from several countries, will begin in 1991. To complete baseline physical, geological, and biological descriptions of the environment, an International Arctic Science Year is being organized for 1993.

Our understanding of the Arctic environment has increased dramatically since the end of the International Geophysical Year in 1958. Over the past 30 years, the Office of Naval Research has been the only agency in the United States to maintain a steady and coherent basic research program in Arctic oceanography, sea ice, and air-ice-ocean interaction. The full value of this work is coming more into focus now as the geo-

Installation (top photo) and final configuration (bottom photo) of a SALARGOS buoy in the central Arctic are shown. The buoy drifts with the ice and telemeters its position and meteorological and oceanographic measurements several times a day through polar orbiting satellites to operational forecast centers. An array of about 20 buoys, of which this is one type, covers the entire Arctic Ocean.

sciences proceed to assemble a picture of the Earth as a system that we are learning to understand and may some day be able to predict.

Dr. Thomas B. Curtin is Program Manager of the Arctic Sciences Program at the Office of Naval Research, Washington, D.C.
Professor Norbert Untersteiner is Chariman of the Department of Atmospheric Sciences at the University of Washington.
Captain Thomas Callaham is the Commanding Officer of the Naval Polar Oceanography Center in Suitland, Maryland.

Developing Oceanographic Products To Support Navy Operations

Michael J. Carron
and Kenneth A. Countryman

NAVOCEANO scientists employ nine ships, three P-3 aircraft, a multitude of satellites, and drifting buoys for survey and real-time Navy support.

As young oceanographers and geophysicists fresh out of graduate school, we reported for work at the Naval Oceanographic Office (NAVOCEANO) feeling somewhat awestruck by its fleet of 12 oceanographic, hydrographic, and research ships, its three specially equipped P-3 aircraft, and their mission to explore and survey the world's oceans from the Arctic to the Indian. While rushing to prepare passport applications and obtain physical examinations, we quickly discovered that scientists from NAVOCEANO and the Naval Oceanographic and Atmospheric Research and Development Laboratory (NOARL), both located at Stennis Space Center on the Mississippi Gulf Coast, can spend much of their lives at sea or preparing to go there.

NAVOCEANO scientists employ nine of these ships, the three P-3 aircraft, a multitude of satellites, and drifting buoys to support the Navy's specific survey and real-time support requirements. Scientists from NOARL and other Navy laboratories carry out basic research and development activities on the other three ships. While considerable coordination is needed to keep NAVOCEANO's ships and aircraft fully staffed and equipped, the main focus of our efforts is a program to process the data gathered on these surveys, as well as information obtained from other U. S. sources, other nations' naval fleets, and the oceanographic, fishing, and shipping communities.

Since NAVOCEANO's inception as the Navy Depot of Charts and Instruments in 1830, the goal has been to provide vital operational products for the U.S. Navy, Department of Defense, and contributing allied naval forces. Commander Matthew Fontaine Maury, superintendent of the Depot, which became the United States Naval Observatory and Hydrographical Office in the 1840s, was the first American to compile oceanographic data on a large scale and develop products to support naval and industrial operations. Maury developed the first series of these, known as Wind and Current Charts, from information contained in ships' logs. For this assemblage of navigation aids, he produced a collection of Pilot Charts that contained statistical information on observed winds for each five-degree square of the world's oceans. Maury's series of Thermal Charts indicated the surface temperature for the Atlantic Ocean. His Storm and Rain Charts represented historical storm tracks for both the Atlantic and Pacific Oceans. He even produced a series of worldwide charts showing statistics of whale sightings.

Sophisticated sensors and computer systems onboard modern naval vessels and aircraft aid in every application from navigation to anti-submarine warfare.

NAVOCEANO has undergone some major changes since those early days, but its officers and scientists continue the tradition of producing high-quality products for fleet operational support.

Early scientists suffered from a dearth of information. The little that was available came from scattered Naval and merchant ship logs and infrequent, but vital, research cruises lead by American and British scientists.

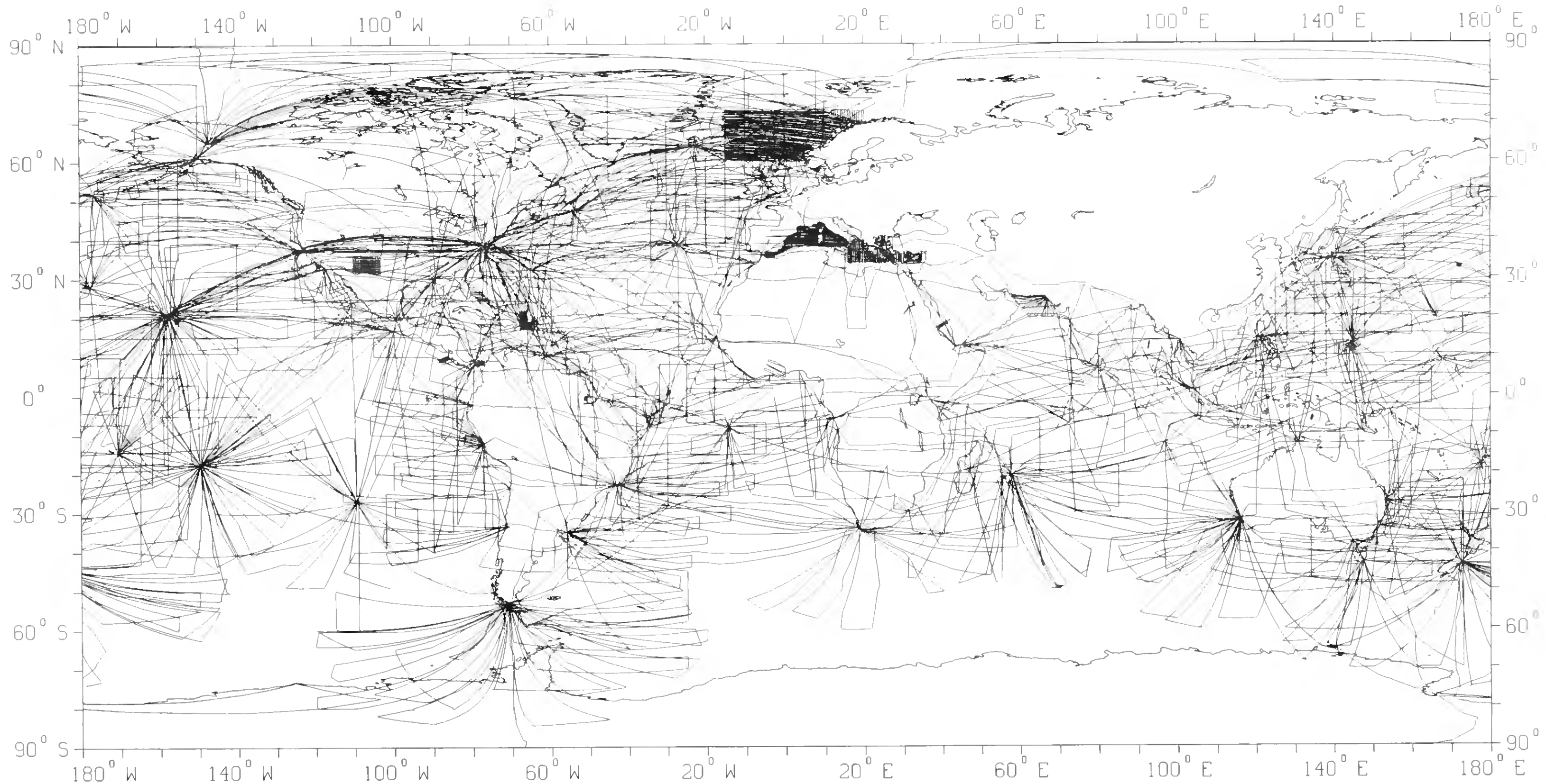
Although today's NAVOCEANO scientists manage and draw from huge data bases, most of the world's ocean areas remain surprisingly undersampled. To support the United States Navy's global responsibilities, Naval Oceanography Command scientists continuously gather and compile the world's most comprehensive collection of geophysical and oceanographic data. This information is then developed into products for operational use by the Navy and Department of Defense. The data products generally fall into four categories: water depth, oceanographic properties of the water column, the gravity and magnetic fields of the Earth, and geoacoustical properties of the oceans. Cartographers use perhaps the best-known NAVOCEANO product, the World Magnetic Field Model, to create the magnetic variation compass roses found on most of the world's navigation charts. Variation is the angular difference between true and magnetic north. The magnetic compass rose allows the navigator to estimate the direction of true north by using a magnetic compass. NAVOCEANO maintains the World Geomagnetic Data Library and produces the World Magnetic Field Model.

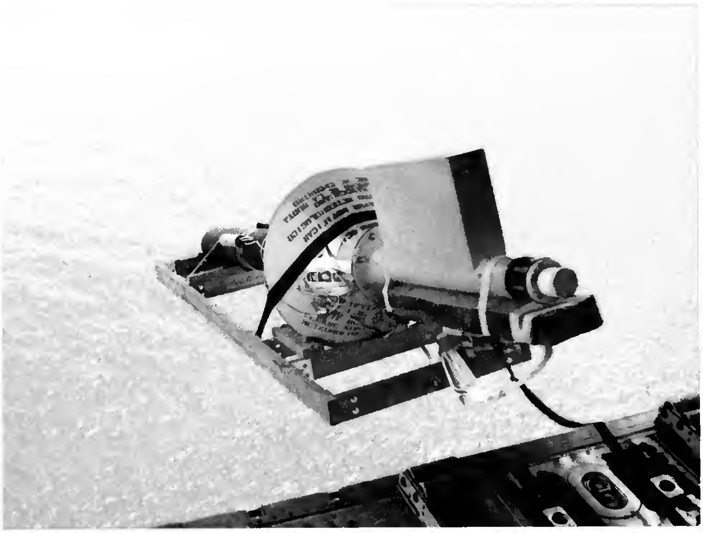
The Earth's magnetic field is constantly changing. Therefore, NAVOCEANO personnel, in collaboration with the British Geological Survey, use both aircraft and satellite resources, in combination with data from an international magnetic observatory network, to map the Earth's magnetic field and gauge how it is changing.

Opposite page: NAVOCEANO scientists have literally covered the world's oceans collecting magnetic data to update the World Magnetic Field Model. This chart shows tracks of Project Magnet aircraft from 1950-1989

Generally, the fleet support products concentrate on the operational capabilities of the Navy's air, surface, and submarine forces. Sophisticated sensors and computer systems onboard modern naval vessels and aircraft aid in every application from navigation to anti-submarine warfare. Today's naval commander can afford no delay following detection of a potentially hostile vessel by sonar or radar. Vital decisions must be made in a matter of seconds. To aid in this process, onboard computer systems constantly update all pertinent environmental data relating to the ship's location and how its weapons and sensors are responding to the environment. NAVOCEANO scientists maintain and

PROJECT MAGNET
SURVEYS (1950-1989)





NAVOCEANO deployed more than 250 satellite-linked drifting buoys during 1990. This buoy, which measures the wind speed and direction, wave height, temperature of the air and water, and barometric pressure, is being deployed from an Air National Guard C-130 in the western Pacific Ocean.

NAVOCEANO's Oceanographic Operations Center processes environmental satellite data from a multitude of spacecraft. Information from these satellites is used to determine the position of oceanographic features of tactical interest to our naval forces.

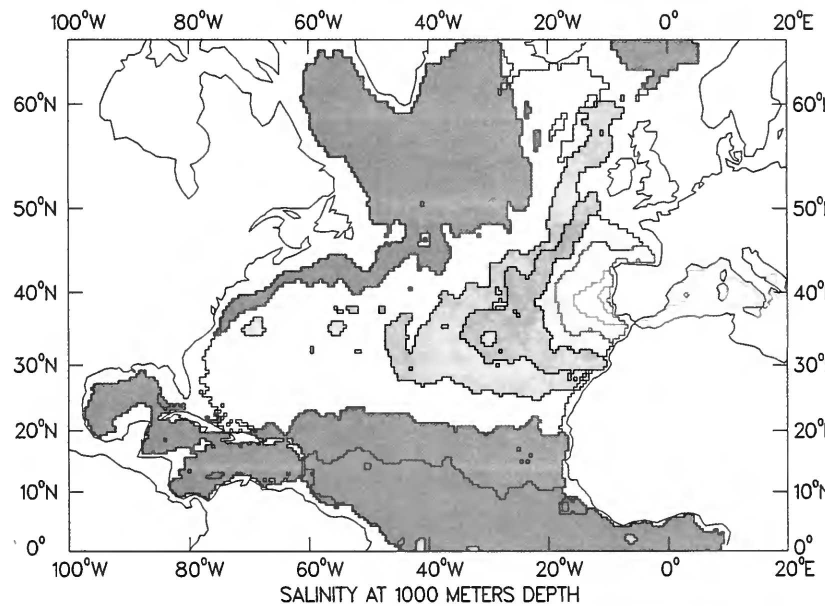
ensure the accuracy of much of the computer's environmental information.

In Matthew Maury's days, the sheer volume of historical information would have overwhelmed ships' officers, even if they had been trained to interpret it. In his charts, Maury attempted to condense and summarize the information gleaned from the observations made by past ship masters in an easy-to-follow, decision-making tool. The Naval officer of old was faced with information problems limited in scope. His best available information was limited to that contained on charts, in books, and, often, only on his own experience. Today, problems are much more complex. However, through modern technology and advanced education, naval commanders are better able to address them.

The Naval Oceanographic's vast data holdings, and the need to store them in a highly-efficient, readily-available, computer-compatible format, makes the problem of data condensation and summarization even more critical than during Maury's days. Of the long list of products, several striking examples demonstrate how NAVOCEANO scientists are reducing the mountains of data into tools that a naval commander can use with relative ease. One example is temperature distribution in the oceans.

Temperature, salinity, and pressure are primary factors affecting the speed of sound in water. Armed with knowledge of how sound travels in the ocean, one can determine the distance at which a vessel or aircraft with underwater sensors can detect another ship or submarine. For the last 100 years, naval, scientific, and commercial vessels and aircraft have measured the temperature, and sometimes the salinity, of the water. Most of these measurements are limited to a depth of 400 meters. Some oceanographic institutions, NAVOCEANO among them, often make measurements to depths exceeding 5,000 meters. Working closely with the National Ocean Data Center, a part of the National Oceanic and Atmospheric Administration, NAVOCEANO has assembled an immense collection of data from U.S. and foreign naval forces, universities, research institutions, and industrial sources into what is now called the Master Oceanographic Observation Data Set (MOODS). This data set contains nearly four million vertical profiles of temperature, salinity, and other oceanographic parameters that vary widely in space and in quality.

Obviously, a naval commander cannot use all of these data to make decisions about sensor and weapon deployments. In the late 1970s, scientists at NAVOCEANO began constructing a worldwide gridded climatology MOODS holding. Using sophisticated mathematical techniques, they computed synthetic temperature and salinity profiles from the surface to the ocean bottom for all seasons and for every 30 minutes of latitude (30 nautical miles) and 30 minutes of longitude (22 nautical miles at the latitude of Woods Hole). This climatological model, called the Generalized Digital Environmental Model, has become the Navy's standard ocean temperature, salinity, and sound speed model. The master model, or subsets of it, resides on the computers of all U.S. Naval surface ships, submarines, and aircraft performing antisubmarine warfare missions. Naval Oceanography Command Centers and Facilities worldwide also use this data to assist in real-time support of U.S. and allied Naval forces.



NAVOCEANO's Generalized Digital Environmental Models of the world ocean temperature and salinity are mathematically constructed from the Master Oceanographic Observation Set. The high-salinity water (red) that spills from the Mediterranean plays an important role in the propagation of sound in the eastern Atlantic.

The model was designed to allow easy access to graphic representations of nearly any temperature- and salinity-related ocean parameter. For example, a graphic representation of salinity at a depth of 1,000 meters in the Atlantic Ocean shows a large saline plume, the result of warm, salty water flowing from the Mediterranean Sea. Since temperature and salinity greatly affect sound speed, this warm, salty water significantly impacts the way sound travels in the ocean and the resulting performance of sonar systems.

Likewise, by representing the temperature of the Pacific Ocean as a section running from south to north, one can visualize temperature change and, thus, the potential change in the sound speed along this section. Using this gridded climatology of ocean temperature and salinity, along with the variability of these parameters, NAVOCEANO scientists can respond quickly to requests for information concerning the sound speed structure at any location in the world's oceans.

Researchers continue to develop and test new methods for modeling the ocean.

Researchers continue to develop and test new methods for modeling the ocean. Today, using satellite imagery, analysts can locate features such as the Gulf Stream Current off the east coast of the United States and the Kuroshio Current off Japan. This real-time information is merged with our climatological temperature fields to present an improved estimate of ocean conditions at any given moment. Methods developed principally at the Naval Oceanography and Atmospheric Research Laboratory and at Harvard University are used to predict how these ocean temperature fields will change over time. NAVOCEANO's analysts and acousticians use this information to assist fleet commanders in positioning their aircraft, submarine, and surface sensors.

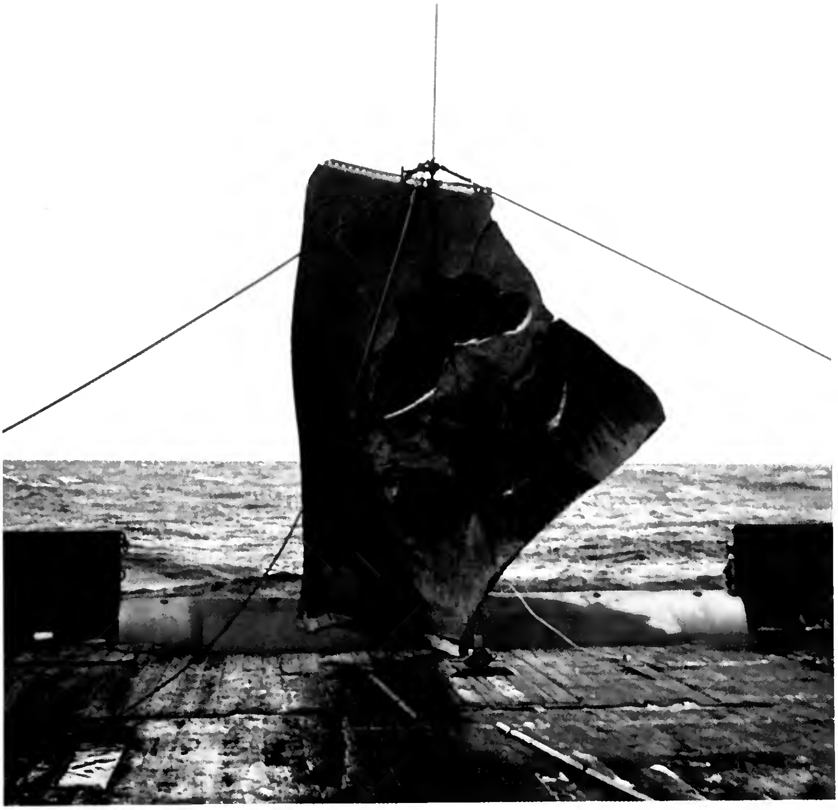
Another example of NAVOCEANO's fleet operational support is the digital bathymetry (depth of the ocean) data bases. The first of these was a model of the depth of all of the world's oceans deeper than 200 meters. This data base, now in the public domain, is distributed by the National Ocean Data Center. Naval antisubmarine forces use digital bathymetry data bases as a major parameter in predicting sensor performance.

As an offshoot of the deep-water bathymetry program, NAVOCEANO scientists use data collected by the Navy's GEOSAT altimetric satellite to search for uncharted seamounts and other potential hazards to submarine navigation. Altimetric satellites measure minute changes in the ocean surface's shape that are caused by submerged masses, such as underwater mountains or large shoals. Over 450 suspected sites, many of them very near the surface, have been identified. NAVOCEANO intends to survey as many of these suspected hazards to navigation as possible and provide information to correct submarine navigation charts and bathymetry data bases.

As long as the Navy deploys submarines, ships, and aircraft with highly sophisticated sensors and weapons systems, scientists of the Naval Oceanography Command will continue to explore the oceans. The object of this never-ending quest is to give the fleet the highest quality operational support products possible.

Michael J. Carron was the NAVOCEANO representative to the Commander of the Mediterranean Fleet from 1982 to 1985 and Head of the Physical Oceanography Branch from 1986 to 1988. He is presently Director of the Advanced Technology Staff.

Kenneth A. Countryman has led oceanographic surveys in the Arctic, Antarctic, Atlantic, and Pacific oceans. In the late 1970s, he began construction of the worldwide Generalized Digital Environmental Model of temperature and salinity. Since 1989, he has been Head of the Models Section of NAVOCEANO's Physical Oceanography Division.



Wreckage from the Space Shuttle Challenger *is recovered off the coast of Florida during the salvage operation that followed the 1986 disaster.*

The Ocean Versus Deep-Water Salvage

Charles "Black Bart" Bartholomew and Craig Mullen

On January 28,1986, in full view of the world, America's manned space flight program experienced its worst accident with the catastrophic loss of the Space Shuttle *Challenger*. The wreckage of this once-proud technological marvel was scattered over a 150 square mile area, much of it in the path of the Gulf Stream. A massive search-and-recovery effort, the largest effort of its type in history, was mounted to help investigators determine the exact cause of the failure. Driven by a presidentiallymandated deadline, salvors worked around the clock to meet the objective—RECOVER THE EVIDENCE!

Mother Nature was to play a significant and starring role in determining the outcome of the effort. Always hampered by the swiftly flowing Gulf Stream, which often moved at five to seven knots, salvors were forced to contend with strong currents, poor visibility, and marginal weather in this exposed area off the Florida coast. Searchers were forced to tow sonars against the current because moving with it substantially exceeded the low speed required for effective use of the equipment. Recovery techniques required modification, and it took several weeks to develop the right approach to attaching lift-lines to heavy pieces of the solid rocket boosters (SRBs), the units that help propel the Shuttle into space. An effective use of manned submersibles, unmanned vehicles (ROVs), and the Nuclear Research Submarine *NR-l*, finally overcame the power of the Gulf Stream.

Salvors were forced to contend with strong currents, poor visibility, and marginal weather in an exposed area off the Florida coast.

Predicting on-site weather and forecasting location and speed of the Gulf Stream also proved difficult. They appeared to have a mind of their own and often defied forecasters' predictions.

The Challenger Project was not the first time in recent years that salvors were faced with a major recovery effort from deep waters off the Florida coast. It was a combination of two Space Shuttle-related jobs that initiated a renewed look at the effect of oceanographic conditions on deep-water search and salvage projects.

In July 1982, a little less than four years before the loss of *Challenger*, salvors were confronted with an earlier Shuttle incident involving the two solid rocket boosters. On the fourth Space Shuttle flight, the main parachutes, designed to gently lower the reusable rockets to the ocean surface for recovery, failed to deploy properly, and the SRBs plummeted into the sea from a height of 150,000 feet. What happened? What went wrong? What needed fixing? Shuttle program managers needed answers, and fast.

Although salvors quickly located the wreckage, an unpredicted eddy of the Gulf Stream moved into the area and made ROV operations at 3,300 feet almost impossible. Confronted by poor environmental conditions at the site and the need to recover pieces of wreckage weighing up to 20 tons, salvors breathed a sigh of relief when close-in photography and videotape of the wreckage proved sufficient to solve the mystery. The explosive bolts holding one leg of each main parachute had released prematurely.

Events such as the fiery loss of *Challenger* and the earlier SRB sinking forced salvors to contend with environmental factors that test the limits of people and equipment. Understanding and quantifying how extreme environmental influences affect the outcome of a marine salvage project were the prime movers in the development of a new generation search-and-recovery system.

Environmental considerations have always played an important role in determining the outcome of deep ocean salvage projects. From their earliest efforts, when men held their breath or stuck their heads in buckets of air, the ocean's depths have forced salvors to invest in increasingly sophisticated and costly devices in order to overcome this hostile environment. Since events leading to a salvage project are generally unplanned, salvors are stuck with whatever the conditions happen to be at the site. Strong currents, extreme depths, bad visibility, poor surface weather, and unpredictable bottom topography are among the many factors that face salvors. If the bottom is smooth and firm, except in one location where there are mountains and rifts, the plane wreckage will surely come to rest there.

As for the hardware, economics generally dictate compromise in the capability of salvage equipment. The cost of equipment that enables salvors to respond to 85 percent of the requirements is relatively modest when compared with the costs necessary to address the last 15 percent.

Salvors, often have to generate their own oceanographic data. For example, in 1987, Navy salvors were trying to locate a commercial Boeing 747 in over 14,000 feet of water near the island nation of Mauritius in the Indian Ocean. While there were no detailed hydrographic charts of the area, the Navy knew that the bottom was mountainous. An oceanographic research vessel with a Sea Beam sonar system happened to be operating in the general vicinity. It was hired, accurate oceanographic charts were developed, and the search commenced. Without this type of vital data, search plans cannot be optimized, and the probability of impacting the bottom with a towed search system is substantially increased.

Salvors often have to generate their own oceanographic data

Because of the severe impact high currents have on salvage operations, the Navy Supervisor of Salvage funded NORDA's Ocean Technology Division to develop an Automated Current Profiling System (ACUPS) to provide near-real-time data on current speed and direction versus depth. A recently developed electromagnetic current sensor that is insensitive to vertical flow takes a current profile as it is lowered from the surface. Data are taken by the current sensor and stored internally until retrieved by a portable computer after the sensor is recovered. ACUPS was used operationally for the first time in February 1986 in a support role on the *Challenger* salvage.

In late 1986, confronting salvage projects around the world whose outcome was affected by strong currents or extreme depths, the Navy took a long look at design goals for a Remotely Operated Vehicle (ROV) system capable of heavy work in strong currents and at substantial depths. Before developing the specifications for a deep-diving ROV system for use in Navy salvage projects, the Navy and Eastport International undertook a comprehensive study to quantify the extremes of current conditions on a worldwide basis.

The first parameter was the depth rating of the system. A review of past requirements indicated that equipment which could operate at depths of 20,000 feet would have covered 100 percent of historic requirements. World bathymetric charts were consulted to ensure that depths in key areas of interest did not exceed this rating. Although a sizable area of ocean floor lies deeper than 20,000 feet, it is generally in areas remote to prime Navy operating concern, and a sizable investment in research would be necessary to achieve what was viewed as a relatively small increase in coverage.

Experience showed that, after depth, the next major factor influencing design criteria is the strength of ocean currents. Since an ROV is connected to its surface support platform via cable, and drag is created on the vehicle and umbilical as water flows against them, it was obvious that researching ocean current profiles (i.e., current strength versus depth) would be necessary.

Published oceanographic reference material was studied, Government and civilian scientific centers of oceanographic study were contacted, and reams of data were collected. The limited availability of current profile data from the surface down to 20,000 feet was immediately apparent. Although some areas of the world have been extensively studied, such as the Gulf Stream and the Japan current, and current profiles developed, few deep-water current profiles that include readings at the surface, intermediate depths, and bottom are available for the balance of the world. Researchers were forced to develop composite deep-water current profiles, often from widely spaced individual readings at various depths. This data was critical to understanding the potential environment in which the ROV was to work. Drag forces against the vehicle and umbilical directly affect the horsepower necessary to maneuver in strong ocean currents and to carry out the necessary work once on site. As the current profile worsens, system drag increases. Higher drag requires more horsepower to maneuver. As the drag and horsepower increase, the umbilical grows to accommodate the strength and horsepower demands, which, in turn, increase drag—it becomes a vicious circle.

Surface weather conditions also play a major role in defining support equipment specifications. Here, again, much information is available on surface weather patterns and seasonal variations. Utilizing historic data, engineers analyzed the effect of various weather conditions on probable support vessels. Sea conditions have a direct impact on the ability of a vessel to stay on station and operate its salvage equipment. The dynamics of ship movement may, in turn, dictate the use of motion compensation equipment to facilitate operations over a broad range of weather conditions or vessel sizes. Having dropped important salvage objects in the past due to the dynamics of ship motion (an F-14 off Scotland and others), this point was not lost on salvors.

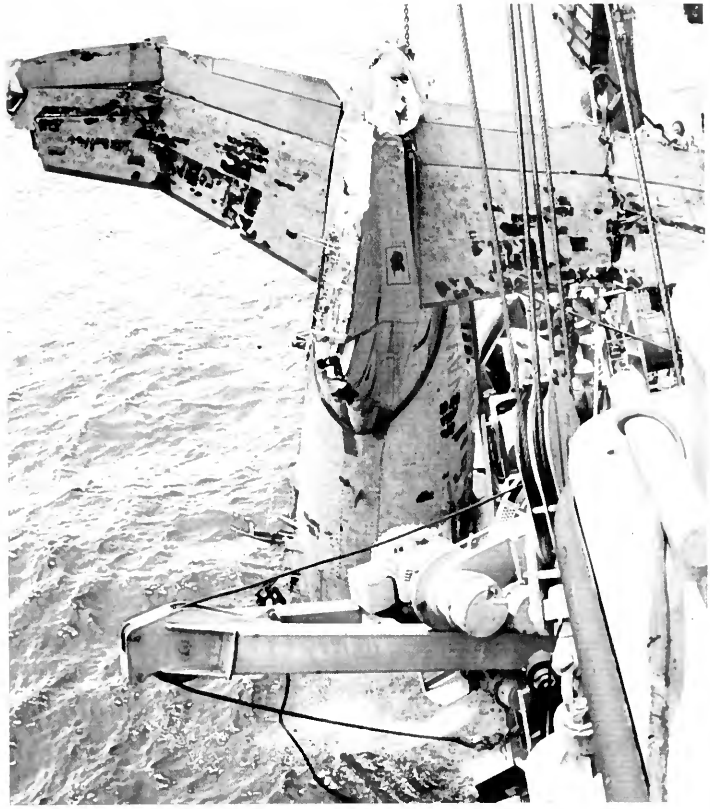
After completing this comprehensive study, the Navy, with the assistance of Eastport International, built a salvage ROV system called CURV (Cable-controlled Underwater Recovery Vehicle), which can operate over a wide range of current conditions and to depths of 20,000 feet.

The U.S. Navy's CURV (Cable-controlled Underwater Recovery Vehicle) can operate over a wide range of current conditions and to depths of 20,000 feet.

During sea trials in March and April of 1990, CURV exceeded its 20,000 foot design depth limit with a dive to 20,105 feet, a world ROV first. It had made it to its design depth, but could it work the strong currents of the Gulf Stream, one of the prime reasons for building it? Although few strong currents had been encountered during sea trials, events were to give CURV a quick chance to prove itself.

In October 1989, a U.S. Navy carrier-based aircraft (an S3, in Navy parlance) crashed during takeoff from USS *John F. Kennedy*. The site happened to be 120 miles off Cape Hatteras, North Carolina, in the middle of—you guessed it—the Gulf Stream. The water was 10,300 feet deep, and accident investigators wanted the majority of the plane back to determine why it had crashed.

Again, searching into the current only, the Navy located the plane with its ORION search system and established the wreckage position. CURV was readied for action, the first real test.



The CURV System's first real test was recovery of an aircraft that had crashed during takeoff from USS John F. Kennedy *off Cape Hatteras, North Carolina.*

The Navy directed Eastport to mobilize the CURV System aboard USS *Grasp*, one of the newest salvage ships in the Navy fleet. Since the Gulf Stream currents were to be a major factor, the deployment system was reoriented to operate over the stern, rather than from its usual position over the side, allowing CURV's umbilical to stream well aft of the ship's propellers. Eastport's lift-line spooler, developed especially for deep water/high current situations, was also readied for use. Like a giant fishing reel, the unit would allow salvors to attach a recovery line to the S3 aircraft without danger of becoming entangled with the line and fouled to the wreck.

Since the Gulf Stream current was the major factor in determining the outcome of the project, much research was done from available information on the location and speed of the current. From historic records, salvors estimated that the current would flow at 5.5 knots on the surface, tapering off to 3 knots at 3,500 feet, and to 1.25 knots at the bottom. Salvors used the Navy's oceanographic unit at Norfolk, Virginia, to help predict the weather as well as the location and speed of the Gulf Stream at the site.

Predictions from the beach proved reasonably accurate. The Gulf Stream, on many days, boiled past the ship and streamed the cable and vehicle well away from the ship's propeller. Often working 3,300 feet or more behind the ship, due to the effect of the strong current, CURV took a series of important 35-mm photographs and several hours of high-quality videotape. Then the vehicle attached a strong Kevlar lift-line to the 15-ton aircraft, which was ultimately recovered to the deck of *Grasp*.

In the six short years since the loss of the SRBs from America's fourth Space Shuttle flight and the *Challenger* disaster, salvors have concentrated on understanding the effect of oceanographic factors on deep-water salvage and equipment capabilities necessary for successful deep-water salvage. CURV's success on the S3 Project clearly shows that solid engineering, when coupled with a thorough understanding of the oceanographic variables, can overcome one of Mother Nature's strongest forces, the Gulf Stream.

Captain Charles ("Black Bart") Bartholomew was the Director of Engineering/Supervisor of Salvage and Diving with the Naval Sea Systems Command. During the course of his 22 years as a Navy diver and salvor, he participated in or supervised the salvage of 18 ships, numerous aircraft, and one Space Shuttle.

Craig T. Mullen is the President and Chief Executive Officer of Eastport International, Inc., and has been involved in deep ocean salvage and search-and-recovery engineering projects since 1968.

In Memory of "Black Bart"

On November 15, 1990, Captain "Black Bart" Bartholomew died while diving off the coast of Panama City, Florida. He was my friend, and I will miss him. Black Bart, as he was known to many of us in the Diving and Ocean Engineering world, was full of life and energy. He loved the sea and when death came, Bart was doing what he enjoyed most in life–diving with the Navy. His family, the Navy, his friends and the Ocean Community, as a whole, have lost a friend. Perhaps, just perhaps, when we look into the night-time sky, there will be one more bright light helping us navigate our way...Smooth sailing, shipmate.

—C.T.M.

Project Marco Polo

Kathy Sharp Frisbee

I never pictured myself going to Indonesia, " mused 14-year-old Kate Baird, "but I'm certainly glad I did." Culture, geography, and science, were more than textbook terms to two high school students and two teachers this past summer–they were reality. As participants in a pilot program called Project Marco Polo, the students and teachers explored exotic Indonesia, sailed amidst the country's nearly 14,000 scattered islands that extend along the Equator from Southeast Asia to Australia, and conducted hydrographic surveys for the U.S. Navy in the tropical waters of the country's Macan Archipelago, south of Sulawesi, west of Borneo, and northeast of Bali and Java.

Project Marco Polo was created to rekindle young people's interest in geography, culture, and science through firsthand experiences.

A team effort by the National Geographic Society (NGS) and the U.S. Navy, Project Marco Polo was created to rekindle young people's interest in geography, culture, and science through firsthand experiences. The program is named for world-renowned adventurer Marco Polo, who traveled through Indonesia 700 years ago, returning to his homeland with new knowledge of the land, seas, and oceans and relating stories of newly discovered cultures that defied belief.

The project intends to stir that same wonder and curiosity by taking American students and teachers on journeys to worldwide destinations, to experience the unconsidered and unfamiliar, then return home and tell their travel tales to students and adults alike. Working together on the project's goal of turning the tide on American youths' ho-hum attitude and lagging literacy about the peoples and places of the world were Dr. Gail Ludwig, Geographer in Residence for NGS's Geography Education Program; Pat Lanza, renowned NGS free-lance photographer; RADM Richard F. Pittenger, recently-retired Oceanographer of the Navy, now Arctic Coordinator for the Woods Hole Oceanographic Institution; Gail S. Cleere, Public Information Officer for the Oceanographer of the Navy; and Penny Dunn, Hydrographic Programs Manager, Naval Oceanographic Office.

© Patricia Lanza

Working at the Nav Aids site on Pasi Teloe Island, Indonesia, Project Marco Polo students Kate Baird and Ryan Berger establish location points with the offshore survey launch.

Chosen by NGS and the Navy to make the trip of their lives along with Kate Baird were Joyce Munden, Baird's social studies and curriculum supervisor at Springfield Public Schools in Springfield, Missouri, Ryan Berger, age 16, from Thousand Oaks High School in Ventura County, California, and Berger's geography and history teacher at Thousand Oaks, Greg Barker.

"One of my friends told me before I left that she thought the inflight movie would be the highlight of my trip," said Baird, "but when I came back, they were all very interested."

Project Marco Polo began in mid-August 1990, when the participants and planners met in Pearl Harbor, Hawaii. Next they flew to Guam, then to Denpasar, Bali, and then to the port of Ujung Pandang, Sulawesi. There they boarded the 393-foot coastal survey ship USNS *Harkness*, where they would live and work with the 150-member crew for six days.

Harkness crew and guests sailed to the Macan archipelago to conduct hydrographic survey work, that is, the surveying and mapping of subsea terrain, a cooperative effort the Navy undertakes in the waters of many countries to ensure safe navigation for world mariners. Here the participants learned how today's methods of surveying compare to the antiquated dropped lead-line method, which was used in Marco Polo's time and continued until the 20th century. One participant's entry in a daily journal, which they were each required to keep, read:

"Ocean and coastal charts were rare, and those that did exist were often unreliable. Current nautical charts of this area are based on data at least a century old, and the survey we are on will update these."

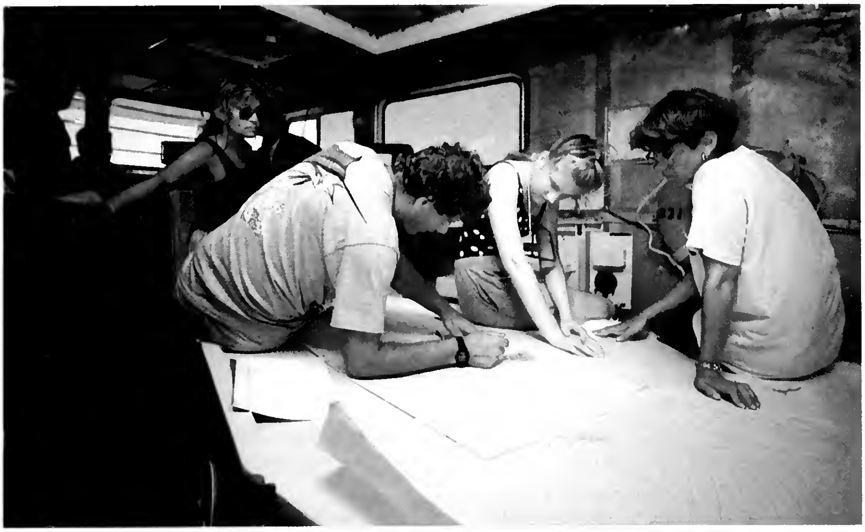
Baird said she had never realized the Navy was involved in oceanography, nor could she have imagined the extent of that involvement worldwide, and she was particularly impressed with the sophisticated equipment used.

"They took us out on launches and taught us how to take readings with a depth meter and computer-record various depths," said Baird. "Then we returned to the ship where they computer-processed the data and printed out a map on posterboard to show us what we had done."

© Patricia Lanza

Mike Smith, civilan physical scientist with Project Marco Polo, explains the complex survey process to Kate and Ryan, and a young islander, who had never seen foreigners before, listens.

© Patricia Lanza



Aboard the Harkness *survey launch, Kate Baird, teacher Joyce Munden, Mike Smith, public information officer Gail Cleere, and Navy personnel plot and prepare to measure subsea depth points.*

Trips were also made to land sites, such as Pasi Teloe, a small island with "perhaps 100 residents, an assortment of cats, chickens, and goats, and a jumble of thatched bungalows built on stilts along the beachfront," according to one participant's journal entry. They approached the island in rubber dinghies, and disembarked half a mile from shore onto a reef, then waded to the beach toting their gear atop their heads. After becoming acquainted with the friendly islanders, who curiously inspected the new arrivals, the participants walked to their campsite on the island's tip, where a temporary Navy outpost was manned by some of the ship's personnel to take navigational fixes for survey operations.

"It never occurred to me that people lived without electricity and a lot of things we take for granted," said Baird, "and yet they're happy and very nice. They don't miss what they don't have. For me, it was a lesson that you don't have to have material things to be happy."

In summing up her experience, Baird said, "If I hadn't gone, I would never have seen the kind of things I did see, and it wouldn't have interested me very much either. Because we do have so much, we just can't imagine what it would be like if we didn't. Seeing the way these people live touches you personally."

Since her return, Baird has given six presentations about her experience with Project Marco Polo to students and teachers, and she plans to give more. Already, she says, the Navy and National Geographic Society are planning for next year's project with the destination yet to be determined.

For further details about Project Marco Polo, contact Gail S. Cleere, Public Information Officer, Office of the Oceanographer of the Navy, U.S. Naval Observatory, 34th Street and Massachusetts Avenue, N.W., Washington, D.C. 20392-1800.

Kathy Sharp Frisbee is the Editorial Assistant for Oceanus *magazine.*

The United States Navy's Role in Navigation and Charting

Accurate and current large-scale charts are essential to the safe passage of both military and commercial shipping

James E. Koehr

The nautical chart, an essential navigational instrument, is a work sheet for plotting courses and determining positions. It shows the depth of the water, the shoreline of adjacent land, topographic features that may serve as landmarks, fixed and floating aids and hazards to navigation, and other information to aid the navigator. The world ocean covers about 70 percent of the earth's surface. Not surprisingly, ships carry about the same percentage of the world's trade, and no country is entirely independent of the materials that sea-borne trade represents. Accurate and current large-scale charts are essential to the safe passage of both military and commercial shipping.

The following departments and agencies share the United States government's responsibility for hydrography. The Department of Commerce, through the National Oceanic and Atmospheric Administration and the National Ocean Service, is responsible for surveying and charting the jurisdictional waters of the United States. The Department of Defense, through the Army Corps of Engineers, is responsible for surveys of the inland waterways, navigable rivers, and canals of the United States. The Department of Defense, through the Defense Mapping Agency (DMA) and the Navy, is responsible for surveying and charting areas outside the jurisdictional waters of the United States.

Within the DMA/Navy partnership, DMA compiles, produces, prints, and distributes the charts, and the Navy conducts surveys. If DMA determines that the data for a given chart is deficient for some reason, they request that the Navy survey the area.

In 1978, the Chief of Naval Operations established the Naval Oceanography Command to centralize responsibility for several aspects of the Naval Oceanography Program. The Command employs some 3,000 officer, enlisted, and civilian personnel, with the largest single element of the Command being the Naval Oceanographic Office (NAVOCEANO). The Command oversees 12 survey ships, three survey aircraft, two major production centers, three regional centers, two area oceanography centers, and several facilities, detachments, and units ashore.

The Navy is also involved in several research and development efforts related to navigation and charting. The Navy's lead lab for mapping, charting, and geodesy is the Naval Oceanographic and Atmospheric Research Laboratory (NOARL). Over the past several years, NOARL has been very active in applying remote sensing technology to hydrographic applications and in the use of digital data to support Navy requirements.

Hydrography

Hydrography is the branch of physical oceanography concerned with the measurement, description, and mapping of the surface waters of the earth and their surrounding land masses, especially for navigation. The data collected during a hydrographic survey include water depths, the positions and descriptions of floating and nonfloating aids and hazards to navigation, bottom composition, water clarity and color, sound velocity, tidal behavior, and information on surface and near-surface currents.

The Global Positioning System will provide highly accurate, 24-hour-a-day position information nearly anywhere on or near the surface of the Earth.

Global Positioning System

The Global Positioning System (GPS) replaces shore-based transmitter sites. When fully operational, it will consist of a constellation of 21 satellites, plus three active spares. The system will provide highly-accurate, 24-hour-a-day position information nearly anywhere on or near the surface of the Earth. GPS will be capable of accuracies to satisfy small scale (1:50,000 and smaller) survey requirements, and Differential GPS will achieve accuracies to satisfy all but the largest scale (1:5,000 and larger) requirements.

Hydrographic Cooperation Program

The Navy is deeply committed to cooperative surveys with other nations and has provided hydrographic assistance to other nations on specific request. More formally, the Navy established the Harbor Survey Assistance Program in 1964 to help various South American and Central American countries survey their ports and harbors. With the program broadened to include offshore areas, it was renamed the Hydrographic Survey Assistance Program. Then, in 1985, the Oceanographer of the Navy changed the name to the Hydrographic Cooperation (HYCOOP) Program, a true cooperative venture where each country contributes and each country then shares the products.

Sixteen countries currently participate in the program, and the Navy intends to expand the program to a total of 24 in the next few years. In 1984, there was only one Hydrographic Cooperation Program office, which served Latin America. Now there are regional offices covering the Caribbean, the Middle East, Europe, Africa, and the Far East.

Hydrographic Training Program

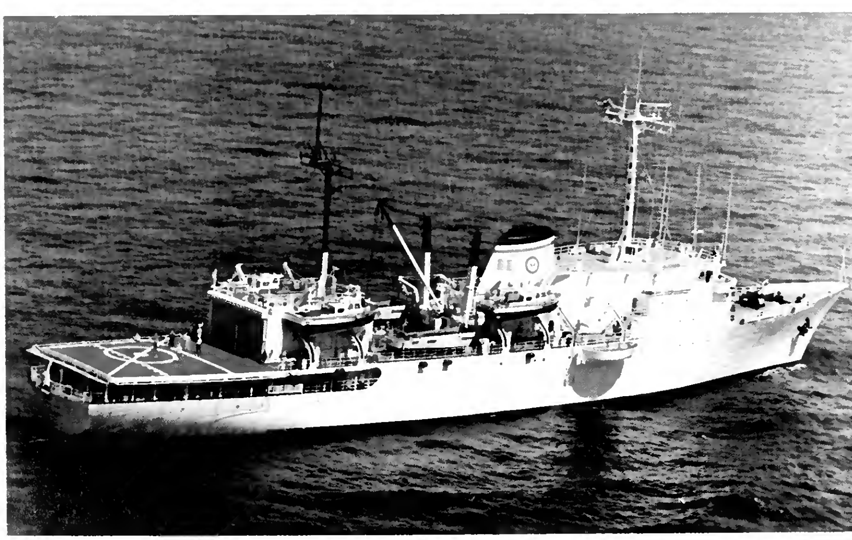
Hydrographic training has always played a major role at NAVOCEANO and elsewhere within the Navy. One of the services the HYCOOP Program provides is a six-month intensive course in practical hydrography for officers and civilians of most interested nations. The course, offered annually from April to October at NAVOCEANO in Mississippi, consists of modules in mathematics, geodesy, hydrography, oceanography, nautical science, cartography, and law of the sea. This is a shortened version of a one-year course taught by NAVOCEANO from 1952 through 1981. The new course began in 1986 and received a Category "B" certification from the International Hydrographic Organization and the International Federation of Surveyors in 1989. Since 1952, more than 400 students from 45 different countries have graduated, and many of have achieved prominent positions in their own nation's hydrographic or mapping services.

Geomagnetics

Another aspect of the Navy's support to navigation and charting is its geomagnetic program. The origin of the compass rose on nautical charts is a world magnetic chart model developed by the Naval Oceanographic Office in cooperation with the United Kingdom's British Geological Service.

Because the Earth's magnetic field is neither stationary nor constant in physical configuration, it requires measurements on a continuing basis. NAVOCEANO is the only organization in the world that collects worldwide airborne magnetic data directed at complete definition of the geomagnetic field. Since its beginning in the early 1950s, several airplanes have served as the platform for this data collection effort. The current Project MAGNET airplane is a specially-configured RP-3D.

On April 11, 1990, the United States launched the Navy's Polar Orbiting Geomagnetic Survey (POGS) satellite from Vandenburg Air Force Base. Control of the satellite will be at NAVOCEANO's Mississippi



USNS Chauvenet *and USNS* Harkness *(pictured) will be replaced by the smaller and more efficient* McDonnell *and* Littlehales *now being constructed.*

In the future, satellites will do much of the geomagnetic survey work performed by the Project MAGNET airplane.

ground station. Two remote tracking stations, one in Fairbanks, Alaska, and another to be installed in Edinburgh, Scotland, will complete the ground segment of the POGS experiment. Data from this satellite will replace much of the data that has been collected in the past at a significantly higher cost by the Project MAGNET airplane.

Satellite Altimetry

POGS isn't the Navy's first use of satellites for hydrography and will not be its last. Another spaceborne sensor that is already paying off is the satellite radar altimeter. The Geodetic/Geophysical Satellite, or GEOSAT, was built by the Applied Physics Laboratory of Johns Hopkins University and launched in March 1985. The satellite carried a single frequency (13.5 gigahertz) radar altimeter designed to provide 3.5 centimeters precision at 2 meters significant wave height. By looking at the topography of the surface of the ocean, it is possible to detect deflections in the surface that suggest a large mass, such as a seamount, beneath the surface. Using that information, conventional hydrography can determine its least depth and exact position. The result is more efficient use of ship time.

As with most other remote sensors, satellite altimetry also has oceanographic applications. NAVOCEANO has also used GEOSAT data in the detection of fronts and eddies, ice edges, wind speed, and wave height. GEOSAT had a design service life of about three and a half years. At the time of its failure earlier this year, it had been operating for almost five years.

Airborne Laser Sounders

Since the 1960s, the Navy and other organizations have been attempting to develop an operational airborne laser echo sounder. Such a system determines depth from the elapsed time between the transmission of a pulse of laser light and the receipt of reflections, from both the

NAVOCEANO's Hydrographic Survey Ships

NAVOCEANO relies on several vessels to perform coastal hydrographic surveys. Since 1971, USNS Chauvenet *has surveyed in the Republic of Korea, the Philippines, the Bashi Channel, the Caroline Islands, Panama, Indonesia, Somalia, Kenya, and Djibouti. USNS* Harkness *has surveyed in Greece, the Mona Passage, the Dominican Republic, Haiti, Egypt, the Yucatan Channel, Somalia, Oman, and Indonesia.*

At 393 feet, Chauvenet *and* Harkness *are bigger than most modern hydrographic survey ships. Each has a beam of 54 feet and a draft of 18 feet. They displace some 4,800 tons, and each ship carries about 150 people, 70 in the contractor crew and 80 in the hydrographic detachment. The ships operate at a speed of 13 knots, have a range of about 12,000 nautical miles, carry four 36-foot hydrographic survey launches, two LCVP landing craft, and, up until this year, a helicopter, its crew, and maintenance team. Both ships have 12 kilohertz wide-beam echo sounders, and both the ships and launches use dual-frequency, shallow-water depth sounders, medium-range and short-range positioning systems, side-scanning sonar systems, Global Positioning System (GPS) receivers, and automated data collection and processing systems. The two ships are also capable of producing nautical charts on board for immediate use by an operational commander.*

In 1988, the Navy signed a contract with Halter-Marine of Moss Point, Mississippi, for the construction of two new coastal survey ships. USNS McDonnell *and USNS* Littlehales *at 208 feet each will be about half the length of the* Chauvenet*-class ships. They will have a beam of 45 feet and a draft of only 14 feet, and survey speed and endurance will be about the same as for* Chauvenet *and* Harkness. *The ships will carry 34 people including a contracted crew of 24 and a hydrographic detachment of 10 NAVOCEANO military and civilian hydrographers and electronics personnel.*

McDonnell *and* Littlehales *will carry only two 34-foot survey launches. The ships and launches will operate almost exclusively with GPS receivers. They will carry microwave positioning systems for use in large-scale port and harbor surveys. Both ships will still be able to deploy tide gauges at sea, but the big landing craft will be gone.*

Although smaller than Chauvenet *and* Harkness, McDonnell *and* Littlehales *will be able to do more than the two older ships, primarily due to the capabilities of the GPS and the increased capability provided by a modern multibeam, shallow-water sonar system, the SIMRAD EM100. The EM100, complete with on-board, post-processing hardware and software, will map the seabed in coastal areas and on the continental shelf in water to 600 meters deep.*

Except when in port, McDonnell *and* Littlehales *will operate 24 hours a day, seven days a week. With the EM100, the ships will be collecting many more soundings per mile than the older ships. At the same time, the hydrographic detachment will go from 80 people to about 10. To handle the flood of data with fewer people,* McDonnell *and* Littlehales *will be equipped with state-of-the-art computer hardware and software for ship and launch conning, data logging, processing, editing, and display.*

—JEK

surface of the water and from the seabed. A scanner distributes the light pulses and, thus, the depth measurements over a swath under the airplane.

The Navy ended its laser sounder development effort in 1989. When it began in the mid-1970s, the technology needed to produce an operational system did not exist. Later, with other organizations actively involved in laser sounder development, it did not make good economic sense to start over with new lasers and other hardware. The Army Corps of Engineers is developing a laser sounder system for harbor surveys, and it is likely that an operational system will be commercially available in the next few years.

Airborne Multispectral Scanners

At the laser pulse repetition rates available today, there will be gaps between depth measurements, especially in shallow water. A multispectral scanner can examine the spaces between soundings to ensure that the laser sounder hasn't missed anything that could be hazardous to shipping.

The sun's energy is the basis of a multispectral scanner's measurements. Portions of the light spectrum are progressively absorbed as sunlight passes deeper into the water column. Eventually, if the water is neither too turbid nor too deep, light will strike the bottom and be reflected back. A receiver on an airplane scans a swath of water, and the system measures and stores the unabsorbed spectrum (the more complete the spectrum, the shallower the water) from each resolution cell. A computer then examines the picture made up from all the resolution cells (pixels) to locate possible hazards.

While several satellites have flown with multispectral scanners, the accuracy and resolution of their depth measurements do not yet meet international standards. However, DMA has already used satellite scanner data to identify underwater hazards and to reposition inaccurately-charted land masses, and the Navy has used DMA multispectral scanner data in reconnaissance for its hydrographic surveys.

An airborne electromagnetic sounder is independent of water clarity, bottom reflectivity, and time of day.

Airborne Electromagnetic Bathymetry

The optical sensors of airborne laser sounders and the airborne multispectral scanners are of limited value where light cannot penetrate. Also, the passive multispectral scanner cannot work at night. An airborne electromagnetic (EM) sounder does not depend on the clarity of the water or on bottom reflectivity or on the time of day to make its measurement.

In an EM sounder, a primary coil generates an electromagnetic field as the system is flown over the water. This field causes electric currents to flow in the conductors (bottom sediments, water, and, perhaps, ice layer) below the aircraft, and those currents generate secondary electromagnetic fields. A secondary coil towed behind the aircraft senses these secondary fields, and the water depth can be determined by studying the amplitude and phase shift of the secondary field.

EM sounders hold great promise for hydrography because of their

A team of hydrographers installs a tide gauge on Navassa Island. Tide corrections are required to adjust all of the depths measured on a survey to a common datum.

ability to sound to greater depths and their immunity to water clarity problems. However, they have a significant, unresolved problem: the system's low resolution tends to smooth out the bottom features. Of course, smoothing out a bottom hazard is unacceptable in hydrography. NOARL researchers have built a prototype rigid boom EM sounder system, and they are attempting to overcome this resolution problem through improved processing algorithms.

Besides hydrography, EM techniques have other applications. Because of their ability to pick out conductivity discontinuities, they have been used for years in mineral exploration and for airborne geophysical mapping over land. The system also has possible application in determining sea-ice thickness and in mine warfare.

The United States Navy continues to put an appropriate emphasis on its navigation and charting support responsibilities. International trade and commerce and national defense depend on good, up-to-date, modern charts. As more ships begin to operate with global positioning satellite system receivers, it is essential that the positional accuracy of DMA's charts keep pace. The maritime infrastructure in many coastal waters has grown in complexity with large increases in the numbers and types of fixed and floating aids to navigation and in new port facilities. Highly regulated coastal traffic procedures also put more demands on the navigator, and the electronic chart will impose new requirements for digital data.

In an environment of shrinking budgets and varying national priorities, Navy support to navigation and charting is holding its own. New ships with improved capabilities and continued growth in cooperative ventures with other nations will increase the quantity and quality of the data collected. New survey techniques, including increased automation and the use of satellites and remote sensing from aircraft, are just over the horizon. There is little doubt that the future will see fewer dollars. The Navy's task will be to use those dollars wisely.

RADM James E. Koehr, USN, is the Commander, Naval Oceanography Command, Stennis Space Center, Mississippi.

Astrometry and Precise Time

Gart Westerhout and Gernot M. R. Winkler

Everything from the edge of the Earth's atmosphere to the distant mysterious quasars is in the province of the U. S. Naval Observatory (USNO), one of the two second-echelon commands reporting to the Oceanographer of the Navy. The Observatory is charged with providing astronomical data and precise time to users in the Department of Defense, many civilian agencies, and the general public for use in navigation, command, control, communications, and intelligence.

The U.S. Naval Observatory's province extends from the edge of Earth's atmosphere to the distant mysterious quasars.

In this article, we divide the work of the Observatory into two parts. The first describes astrometry, the measuring and predicting of positions and motions of the Sun, Moon, planets, and stars, and calibrating all navigation, guidance, and positioning systems. The second describes the role of the USNO as the operational time reference for the electronic navigation and communication systems of the government.

Astrometry

Positioning on the surface of the Earth, guidance in space, satellite navigation, and travel to other planets all depend on a precise knowledge of the celestial reference frame. From the determination of your lot line by a surveyor to the mid-course correction of a missile or of a spacecraft on its way to Jupiter, knowing the precise positions of stars is indispensable. As the technology in modern systems becomes more sophisticated, so does the requirement for ever-greater accuracy in USNO products. Modern mine warfare technology, the movement of tanks in the desert, oil drilling platforms, and a myriad of other systems rely on satellite navigation systems that are ultimately calibrated against the stars.

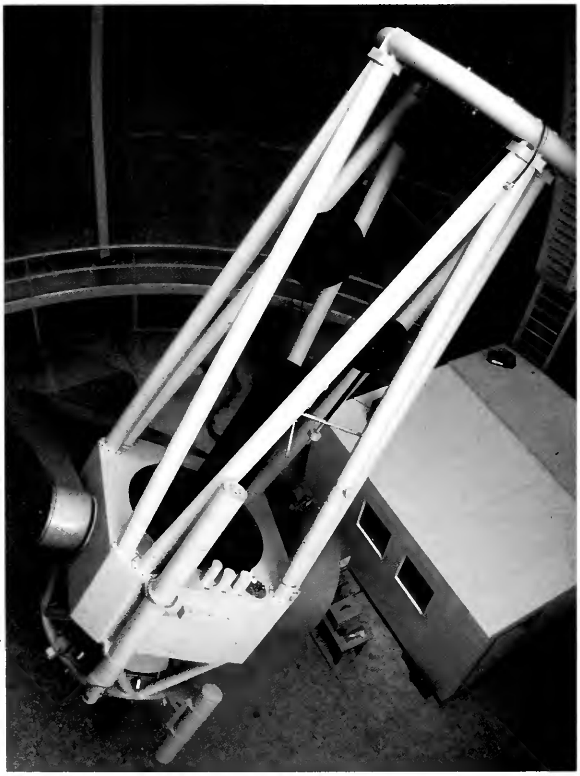
Astrometry is fundamental not only to the Navy, but to the entire field of astronomy. Our most basic information about the nature of the universe and our place within it is the direct result of astrometric measurements. As a spinoff of their mission, astronomers at the USNO determine the fundamental distances to the stars, their masses, the stellar motions in the spiral arms in our Milky Way Galaxy, and motions of solar system objects essential for understanding gravitational and relativistic theories. Their work opens the possibility of finding evidence of other nearby planetary systems.

Astrometry took on new currency when astronomers discovered that quasars, copious sources of radio waves, are billions of light-years away. Such beacons could be extremely stable reference points for motions of other objects. Using radio telescopes in a technique called Very Long Baseline Interferometry (VLBI), their positions can be determined with accuracies of one or two milliarcseconds (a milliarcsecond translates to seven inches on the ground, as seen from a satellite orbiting at 22,300 miles), surpassing comparable measurements by ground-based optical telescopes by factors of 20 to 50. VLBI synthesizes telescope apertures nearly as wide as the Earth itself by the simultaneous use of large radio telescopes separated by intercontinental distances. Since the resolution of a telescope and the precision with which it can measure positions increase with the size of the aperture, these enormous baselines allow for terrific precision.

Unfortunately, only a few hundred quasars can be measured well enough to form a reference frame, and they are extremely faint at optical wavelengths. Therefore, for regular use in both civilian and military systems, the stars remain the only reference objects available. Over many years, USNO scientists have painstakingly measured the positions of tens of thousands of stars using transit circle telescopes. By comparing these positions with those measured in earlier years, they have developed a system of benchmarks that form a nearly-inertial reference frame against which all other systems must be calibrated.

In this reference frame, positions and motions are referred to the plane of the ecliptic through observations of solar system bodies. This dynamic reference system could be compared with a gigantic gyro, effectively invariant over periods of time that are long compared to the time it takes to measure the motions. From 100 years of observations, a fundamental reference frame with an accuracy of 0.1 arcsec or better has been established. The success of radio interferometry, particularly using very long baselines, has spurred similar work in optical and infrared wavelengths.

The USNO astrometric reflector with a 61-inch mirror is located in Flagstaff, Arizona, and is the most precise astrometric instrument in existence.



U.S. Naval Observatory

In an optical interferometer, starlight from two different telescopes is caused to interfere,

U S. Naval Observatory

A star field shows the galaxy NGC 6946 as photographed by the U. S. Naval Observatory.

resulting in a moving fringe pattern, the rate of which is proportional to the motion of the star (due to the Earth's rotation) and the baseline of the instrument, and inversely proportional to the wavelength of the light. For radio waves, which have wavelengths between a few centimeters and a meter, baselines need to be known only to within a few centimeters, a fraction of the wavelength used. In the optical domain, however, wavelengths are on the order of 0.5 micron, and the baselines have to be measurable to a small fraction of a micron.

This has been achieved in an experimental instrument with a 12-meter baseline, constructed with Navy funding at Mount Wilson, California, by a consortium consisting of the U. S. Naval Observatory, the Naval Research Laboratory, the Smithsonian Astrophysical Observatory, and the Massachusetts Institute of Technology (MIT). USNO is now building an optical interferometer scheduled for operation in 1995, which will reach accuracies of five milliarcseconds in absolute position, providing a much-needed improvement in our optical stellar reference frame.

In differential (small-field) astrometry, new high-quantum-efficiency, charge-coupled devices (CCDs) have boosted precision by factors of 5 to 10 compared to traditional photographic methods. These devices, similar to those used in the focal plane of modern video cameras (but much more sophisticated and used at liquid-air temperatures), translate starlight into electrical charges, allowing electronic measurements of star positions. Typical CCD arrays used in astrometry are 500 to 800 pixels square, with pixel sizes in the 15 to 20 micron range. In the development of this technology for precise positioning, the USNO Flagstaff station in Arizona is the world leader.

An evaluation is underway on an array of six CCDs attached to a blank silicon wafer, the same material from which the CCD is made. Data from each CCD can be read out at a different rate so that one array can record faint stars by long integration while, at the same time, another on the same substrate can record very bright stars by many short integrations. With this device, astronomers will be able, for the first time, to measure positions and motions of bright objects, such as satellites and stars, with respect to a background of faint objects and with accuracies far greater than hitherto possible.

CCDs allow astronomers to follow a rapidly moving object without moving the telescope. With this, USNO is developing the technology to improve the orbit determination of Earth satellites using the stellar background as the reference.

Over many years, USNO scientists have painstakingly measured the positions of tens of thousands of stars using transit circle telescopes.

Instruments discussed so far measure a very limited number of stars–enough for the needs of navigation, guidance, and positioning, where the user can make a choice, but not nearly enough for the user interested in satellite tracking. Observing satellites moving against a background of faint stars requires the availability of star catalogs containing many stars per square degree. These star catalogs are also the responsibility of the USNO. They are currently measured with specialized telescopes and photographic plates, but CCDs will soon dominate. In this field, the USNO is developing a different approach. A linear array of CCDs placed in the focal plane of a stationary telescope lets the sky drift by, eliminating or reducing to manageable size distortions introduced by moving telescopes.

At the same time, a joint project with the Mount Palomar Schmidt telescope involves a large USNO measuring machine that plots the positions of stars on photographs at speeds up to 100 stars per second. The purpose of this project is to compare modern images to the images of hundreds of millions of stars observed 30 years ago in order to extract stellar motions and positions, again to serve satellite tracking needs.

The USNO is a unique institution. Some universities occasionally teach a course or two in astrometry and conduct individual limited research projects, but the major astrometry expertise in the U. S. and, for that matter, in the world rests in the USNO. Over the years, the scientific community has come to realize the importance of astrometry, something the Navy realized 160 years ago.

Operational Precise Time Reference

The precise measure of time and frequency is important to modern electronic systems. They can take advantage of the time discipline for improvements in operational flexibility, jamming resistance, speed of access, spectrum utilization, and independence of operations. In addition, electronic navigation, if based on accurate timing, allows for better position determination due to the improved geometry, if times of arrival instead of time differences or directions are used as the basic measurement (a time difference of 100 nanoseconds corresponds to 30 meters in distance).

A second class of applications of modern timing technology arises from the need for space systems to "know" the orientation of the Earth with respect to inertial space. This orientation, of course, is given by sidereal time (or in reference to the apparent position of the Sun), in addition to the momentary position of the terrestrial pole (since the Earth does not rotate with uniform speed, and the position of the pole is constantly changing). While the first class of applications requires a time reference based on the long-term operation of atomic clocks, the second class requires astronomical observations.

Clock Time And Its Uses

Atomic clocks are based on the postulate that the frequency of atomic resonance phenomena is an invariable constant of nature when kept isolated from environmental disturbances, particularly variations in temperature, humidity, and magnetic fields.

At the U. S. Naval Observatory, the Master Clock (MC) operation is based on two different types of clocks. Hydrogen masers exhibit the best performance over shorter periods of time, seconds to several days, whereas cesium atomic beam clocks have excellent long-term performance. Using both types, distributed among ten different clock vaults or laboratories to avoid common problems, ensures the very best performance of the MC, which serves as the operational reference for the electronic systems of the government. It assures that all of these systems have at least one common interface, the standard electronic timing signals. As an example, the electronic navigation system LORAN C is accurately synchronized, not only within each chain but also among chains, to nominally 100 nanoseconds.

The Master Clock serves as the operational reference for electronic systems of the government.

Such a timed navigation system can also serve as a secondary reference for time and time interval (frequency) for other electronic systems. Because it uses the same external reference, the system has, within narrow tolerances, the same time reference as other electronic navigation and communication systems including Omega, Transit, and the Defense Satellite Communication System (DSCS).

The USNO Master Clock

The operation of a clock set, as it is used for the MC, creates an interesting problem: How do we determine a best time? Due to the ever-present random disturbances, in addition to changes of a systematic nature, such as temperature, any two clocks will always diverge with a dispersion at least as large as a random-walk-in-time difference. That is so because the rate of each clock cannot be measured with infinite precision, since the measurements are subject to noise. If this noise is uncorrelated (for example, if it is spectrally white), the summation of the time intervals leads to a small random-walk-in-time. This is usually overshadowed by the much larger systematic effects that last for extended periods of time. This is the reason clocks require the best environmental shielding possible.

In a clock set, it is possible to simply average the readings of all clocks. However, we can do much better. It is the purpose of time scale algorithms to sort out the nonrandom disturbances so that the final estimate of the reference time produces small and randomly-distributed residuals. Several different methods are used by the various timekeeping establishments around the world, but none of these methods are clearly superior. Therefore, research continues. A superior time scale algorithm also would be important from the point of view of the reliability and robustness of the computed reference time. However, because even the best algorithm cannot replace a truly superior clock performance, the search continues for clock improvements.

The Master Clock is backed up by other smaller clock sets at the USNO Time Service Substation in southern Florida and at the Consolidated Space Operations Center (CSOC) in Colorado Springs, Colorado. Access to the Master Clock is possible through any of the previously mentioned electronic systems. For the greatest precision (less than one nanosecond), the USNO is in the process of setting up a network of two-way satellite time transfers.

Since 1967, the USNO clocks have kept time on the basis of cesium atomic resonance that defines the unit of time–the second.

Precise Time And The GPS

The Global Positioning System (GPS) depends on precise timing in several ways. The basic measurement that the user set performs is the measurement of the time of arrival of signals from four satellites simultaneously in view. This places the user on the intersection of three spheres and, in addition, sets the user clock to system time. The system has demonstrated a high degree of accuracy in both positioning and timing. The limit for stationary geodetic applications is on the order of a few centimeters and timing to a few nanoseconds. The worldwide coverage makes the system ideal for a very wide variety of applications in addition to its primary purpose of navigation. However, in many of the contemplated applications, there is concern about the reliability of accuracy due to the problem of system integrity.

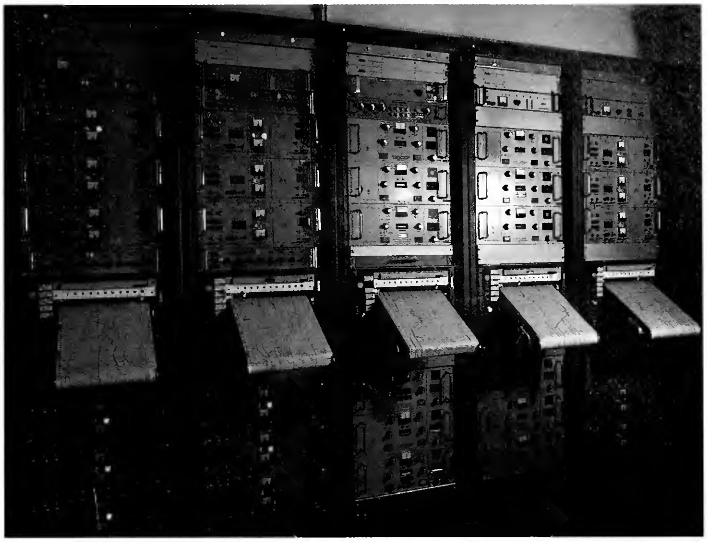
Indeed it is possible that, for short periods, large errors in the signals from an individual satellite can occur, albeit very rarely. This is mainly due to the susceptibility of the electronics in the satellite to cosmic ray hits. Many complicated and costly schemes have been proposed to provide the user with warnings of malfunctions on very short notice. However, if all the data in the user set are used to the fullest, the GPS itself can provide the user with an instantaneous failure indication of an individual satellite on the basis of signal timing redundancy and temporal consistency.

In the absence of Selective Availability, the timing information in its temporal evolution can easily be used for the immediate rejection of a satellite if the information derived from it becomes inconsistent with the rest of the system. This does require a somewhat better user-set clock than usually specified (a simple rubidium standard would suffice), but the use of a better clock provides for additional benefits regarding coverage and ambiguity avoidance.

Astronomical Time, Universal Time, and Polar Motion

The need to determine time authoritatively was the reason for establishing the USNO in the first place. Time and navigation have always been closely connected. Today this relationship has changed, but it has not been eliminated.

Since 1967, USNO clocks have kept time on the basis of the cesium atomic resonance that defines the unit of time–the second. However, clock time and the time of the stars are still coordinated. The present system of Coordinated Universal Time (UTC) provides for an adjustment of exactly one second (the Leap Second) in such a way that the difference between atomic time and astronomically determined time (Universal Time, or UT) is kept to within one second. For high-accuracy requirements, this means that the exact difference must be communicated to the user, which the USNO does through bulletins and direct computer access. The UT values are derived from Very Long Baseline Radio Interferometry (VLBI) observations and from satellite ranging (Doppler observations, LAGEOS, and Lunar LASER echoes). The VLBI technique uses the deep sky directional reference of radio sources at cosmological distances. Presumably, these sources have lateral apparent motions that are imperceptibly small (in contrast to the considerable proper motions of the stars), and they can serve as an invariable directional reference. The USNO has established a network of observing sites (NAVNET) and operates a VLBI correlator facility for the prompt reduction of the observations. The USNO uses all available data for the production of long-term predictions that allow systems such as GPS to upload the information ahead of time. But this is not yet sufficient. The terrestrial pole is not fixed within the Earth, but is subject to a slow irregular motion within an area approximately 10 meters in diameter. Of course, this affects all terrestrial astronomical coordinates. In particular, it affects the momentary direction of North. While the effect is small and can be predicted quite well, it is not negligible for many precision applications. Polar motion is, therefore, also a necessary datum that is included in the predictions provided by the USNO.



The old Master Clock (pictured here) was a wall of knobs and paper printouts. Modern innovations have replaced it with computer screens and keyboards.

The USNO fulfills an essential role as a scientific data service for military and civilian applications. The Observatory's star positions are ultimately the basis upon which all position determination and direction-finding is based on the surface of the Earth and in space. For an increasing number of commercial and military applications, the Master Clock serves as the time reference for electronic navigation and communication systems. The USNO, as provider of the standard data for these applications, is always responding to new and greater accuracy requirements.

Dr. Gart Westerhout is Scientific Director at the U.S. Naval Observatory, and he was head of the Astronomy Program at the University of Maryland from1962 to 1977, when he was appointed to his current position.
Dr. Gernot M.R. Winkler is Director of the Time Service Department at the U.S. Naval Observatory USNO. He is responsible for building up the DoD Master Clock at the USNO to its current unprecedented accuracy and is often referred to as "Mr. Time, USA."

Trends in Ocean Science

by Eric O. Hartwig

Advances in ocean science are made by understanding the system as a whole rather than by understanding any particular component in isolation.

Ocean science is more than what is classically called oceanography. It is, rather, composed of a wide range of subdisciplines. Taken together, they seek understanding of the processes and phenomena that occur above, on, within, and below the ocean and that affect the nature and properties of these environments. It is an area of science where greater advances are made by understanding the system as a whole than by understanding any particular component in isolation.

In this article, reference to the "ocean science community" includes the scientists, engineers, students, and technicians who study the ocean as well as the institutions, industries, and agencies supporting them. All are closely interconnected, and action of one part directly impacts the other parts.

As field scientists, ocean researchers face a two-part challenge not found in traditional laboratory sciences. The first part of the challenge is to isolate, identify, and study the dominant processes occurring in the complex environmental system. The second and larger part of the challenge is to verify that the processes or phenomena studied in the laboratory actually occur in the marine environment. If that proof is not possible, the researcher is left with only an assumption, a nonverifiable hypothesis risky to build upon. The future of ocean science requires that the community keep both parts of this challenge in focus.

As we move toward the 21st century, the direction of ocean science is being internally and externally forced to expand beyond its present boundaries of discipline, tradition, and geography by the following trends:

1) field and numerical experimentation,
2) interdisciplinary strength,
3) "hybrid vigor,"
4) environmental security, and
5) increasing importance of the social sciences.

Field and Numerical Experimentation

Ocean science has been exploratory science. It has built a storehouse of observations from which the community could not only test its ideas and concepts but also develop new theories and understanding of ocean processes. As we improved understanding of the processes, we incorporated them into numerical models of the ocean system.

However, as ocean science has matured, the trend has been to mount major field efforts to collect data specific to proving/disproving our ideas, concepts, and theories of marine processes and phenomena. Although this advances understanding rapidly, it places a greater burden upon the community. Before mounting such a field experiment, we must have supporting laboratory, numerical, analytical, and observational proof on the processes/phenomena (generally where other sciences stop). In addition, we must frame the question in a manner that is testable in the ocean environment, and we must have enough information to select a site where the environment is most likely to behave in a manner consistent with the question asked–that is, we attempt to do a "controlled" laboratory experiment in an uncontrollable environment.

This puts severe restrictions on both the choice of location and on the array of instruments and observations required to assure the scientists they have properly documented the conditions they are attempting to understand. As we verify the easier environmental hypotheses, the platforms, instruments, and observational documentation needed become more complex,costly, and require enhanced planning and management.

As we verify environmental hypotheses, the platforms, instruments, and observational documentation needed become more complex and costly.

A peril of this trend is the tendency to miss opportunities. In the early days of ocean science research, many outstanding observations were made as a result of having an extremely broad goal for a particular field effort. The program could afford the luxury of discovery and diversion. However, the high costs of field research today reduce the community's capability to pursue previously unforeseen opportunities in the course of a research program.

As the experiments verify the dynamics of the ocean system, the numerical models become more rigorous and useful. However, the output of these large numerical experiments is rapidly outpacing our ability to supply the scientists and tools needed for analysis. Nevertheless, the trend is toward more numerical experiments, and this trend accelerates as our understanding of ocean processes increases.

Interdisciplinary Strength

The marine environment is a system with many feedback mechanisms that we are only now beginning to recognize. The questions researchers can answer about the marine environment benefit scientifically from, or require, interdisciplinary planning and execution of experiments. (Multidisciplinary science, on the other hand, does not require joint planning nor is there necessarily any anticipated scientific advantage; usually fiscal, political, or other advantages result from the project.) For example, understanding the optical and biological dynamics of the ocean has required optical and biological oceanographers to plan and execute their research jointly.

Formulation and execution of interdisciplinary ocean science programs put large, initial burdens on the community and require looking at old questions in new ways. Increased community interaction dictates that sampling strategies and methods be standardized to meet the needs of all. Both increased interaction and standardization result in significant long-term benefits to the community.

A potential pitfall of increased interdisciplinary cooperation in marine research is the dilution of goals. A broad approach may address all of the influential disciplines, but the depth of the approach may not be sufficient to resolve the questions addressed. The planning, execution, analysis, and publication requirements of interdisciplinary research lead to longer times before scientific rewards are achieved. However, as they result in a greater understanding of the ocean system, the trend is toward more interdisciplinary research programs.

The questions researchers can answer about the marine environment benefit scientifically from, or require, interdisciplinary planning and execution of experiments.

"Hybrid Vigor"

"Hybrid vigor" refers to a mixing of genes that enhances the vitality of offspring and reduces the effects of inbreeding. Only recently have ocean scientists *trained* in ocean sciences. Historically, ocean scientists were trained as physicists, chemists, geologists, engineers, or biologists, and then entered ocean sciences because of their interest in marine processes and phenomena. This trend parallels the previous one, but with an important distinction. Interdisciplinary science draws immediately on strengths existing within the community, while hybrid vigor draws on strengths derived from outside the community over time.

As a trend, hybrid vigor means that the community will work more closely with the parent disciplines in research and in graduate education. The closer coupling of the disciplines will enhance them all, producing new insights among the sciences involved. As a result, ocean science should develop rapidly with interest from other fields due to the expanded opportunities available and increased visibility and faculty positions in academic programs. (This does not mean there will be an increase in the production of, or the need for, more ocean science undergraduates. The nature of the science requires that most of the ocean scientists' training remain at the graduate level.)

As examples, consider biological oceanography and physical oceanography. Biological oceanography has advanced to the point where one limitation to understanding organism distribution is lack of knowledge about internal control and regulation mechanisms. As a result, molecular, biochemical, and other approaches are being developed toward understanding organism distribution. The field gains enormously through this, and a new generation of biological oceanographers is being trained. The participating disciplines are likewise rewarded with new ecosystems and organisms, whose study may reveal novel moleculor structure and function. In physical oceanography, significant advances are being made through the involvement of mathematicians, physicists, and scientists from a host of other disciplines, and their studies of physical ocean processes stimulate new work in mathematics, statistics, physics, and computer science. The hybrid vigor will result from the joint training of graduate and post-graduate students proficient across discipline boundaries.

These mutually beneficial interactions will provide a great deal of the excitement, enthusiasm, and new positions for ocean science in the 21st century.

Environmental Security

Ocean science is important to our "environmental security," a term which defines our confidence in understanding the environment sufficiently to make useful and wise decisions regarding its exploitation by society. Environmental security means we have sufficient understanding to plan for changing environmental conditions globally and regionally. Natural disasters, such as droughts and floods, impact the global economy, infrastructure, and political stability. Therefore, forewarning to avert or mitigate potential regional environmental disasters benefits us all.

> ***"Hybrid vigor" will result from the joint training of graduate and post-graduate students proficient across the discipline boundaries.***

A major goal of ocean science is to develop sets of unifying concepts and theories to help society understand the ocean as a system. Therefore, although a researcher must perform a particular experiment at a specific location in order to constrain it as much as possible, the hope is to project the results globally as process components of dynamical models. Through the synthesis of local and regional processes, global environmental security can be enhanced.

The U.S. Global Change Research Program (USGCRP) is a manifestation of the science and policy issues affected by our understanding of the ocean. The USGCRP requires a global perspective and multinational participation to address the issues successfully. As local scientists tend to understand their own "backyard" best, and specific experimental sites often occur in other nations' waters, increased international cooperation is a must.

Industry, by and large, has not been a significant player in ocean science. Since industry must make a profit, this indicates that there is a low profit potential in this field. Almost exclusively, it has been the Navy and the oil industry for whom benefits have outweighed costs. Historically, this market is dominated not by the Fortune 500 companies, but by small businesses that thrive on close interaction with the research community. Government research support will continue to foster this cooperation, and an increase in the funding for basic research will increase both the international competitiveness and the number of these smaller, entrepreneurial companies. The private sector has much to offer, and the increasing interest in environmental security and the larger global marketplace should create new industrial opportunities.

Emergence of the Social Sciences and Their Impact

Ocean science has been on the "back burner" for national policy makers and the public (beyond interest in sharks, aquaculture, treasure hunting, diving, and so on). That is changing as the United States' health, welfare, and national security become increasingly connected with understanding of the seas. Ocean science is now front-page news and will be called on to address scientific and technical issues facing the nation and the world. With this, the community becomes increasingly acountable for the decisions it makes and the funds it receives.

The social sciences, such as political science, economics, marine policy, and journalism, become more important as environmental security issues increase. Interest from these fields is important to the long-term vitality of ocean science at the national and international level. They provide us with new insights for ocean science opportunities that benefit the public at large. We are accountable, and the social science areas help us understand our strengths and weaknesses in meeting public policy needs.

A major goal of ocean science is to develop sets of unifying concepts and theories to help society understand the ocean as a system.

A potential problem for ocean science is to remain a single community. A century ago, the community of scientists that worked on "Earth systems" was categorized as "natural scientists." As time progressed, they became more diverse, specializing in meteorology, ornithology, geology, and so forth. Their ties to each other were diminished or severed, resulting in diverging goals and objectives. Maximum benefit to ocean science will be found in its relationship with the social sciences, if ocean science builds consensus and remains a single, interactive community with common goals and objectives.

The social sciences will have their own motivation to be involved with the ocean science community, and this involvement will be a major factor in generating support for the field as a whole.

In summary, ocean science is poised to enhance global environmental security. The people, directions, interactions, theories, and new ideas are present, and exponential advancement of our understanding of the environment is now possible, with a more linear enhancement of resources available to the community. Ten years ago, when the community was in an exploratory mode, this would not have been the case.

Dr. Eric O. Hartwig is the Director of Ocean Sciences in the Office of Naval Research.

Naval Science Awards Program

by Kathy Sharp Frisbee

Naval National Science Awards honor excellence in science fair projects.

Three years ago, East Braintree, Massachusetts, was chosen as the proposed site for a new toxic waste incinerator to be built and operated by a company called Clean Harbors, Inc. That set a 14-year-old girl to wondering what effect the facility's pollution output, combined with her community's abundance of existing industrial pollution output, would have on the health of surrounding citizens.

Over the next three years, she conducted her own investigation of area health and environmental conditions, compiling data collected from a house-to-house survey of 400 residents, and analyzing numerous air, water, and soil samples for excessive levels of pollutants. Always interested in science and the medical field, and considering an idea for an ongoing high school science project, she decided to dovetail her epidemiological investigation into one three-year project.

This past summer, nervous, but confident of her research, she presented her findings before a body of officials from the Department of Public Health, the Massachusetts Environmental Protection Agency, and town leaders. As a result of her conclusions from extensive data profiles combined with additional data the state had collected, approval for the proposed toxic incinerator was declined. It was estimated that the incinerator would have burned 45,000 tons of additional toxic waste a year and, thus, would have severely overburdened the community with hazardous pollutants.

"I learned the result in September while in school, and I was totally ecstatic," said Boyle. "Science is an opportunity for you to do things that have never been done before and that in itself, to me, is an incredible thing. Knowing there are tons of things out there that no one has ever done before," said Boyle, "it just gives you enough ambition to go out and do it."

Boyle received a lot of support and encouragement from her classmates and especially from her mother, who is a teacher.

"I don't think I would have done any of this if it weren't for my mother," said Boyle. "She was my first teacher, she put the time in with me, and I think that's a key to academic success, that support from parents and family."

Boyle also received recognition from the U.S. Navy and the Marine Corps through the Naval National Science Awards Program Competition (NNSAPC) for excellence in science fair projects. She was awarded the John Quincy Adams $3,000 Scholarship and a two-week visit this past summer to Navy and Marine Corps research activities in San Diego, California, to "observe the practical application of science and technology."

Boyle's award was one of 23 NNSAPC honors presented in 1990 to high school students. The competition is part of the Naval Science Awards Program, which is administered by the Office of the Chief of Naval Research. Established in 1958, the program's aim is "to encourage the Nation's youth to develop their interests in the sciences and engineering and to pursue scientific or technical careers."

The annual scientific and engineering awards and certificates presented by the Navy and Marine Corps recognize students "whose projects are considered to demonstrate excellence in any field of endeavor, not necessarily military or nautical," according to information received from NSAP project officer, Barbara M. Thurman. It is also requested that the scholarships be applied toward "courses and related academic fees leading to a major undergraduate degree in one of the sciences or engineering."

The annual competition is open to all high school sophomores, juniors, and seniors, who display their projects at regional and state science and engineering fairs. From the Navy and Marine Corps perspective, the challenges facing high school students are limited only by their imagination.

Boyle would agree. "I believe everybody is born with potential," she said, "and it is only when you test your limit, your own capabilities, that you go somewhere. The temptation to distractions will always be there, no matter what your age, but sometimes you have to put blinders on and set goals for yourself. It took me a while to realize it, but hard work does pay off."

Of her trip to San Diego this past summer, Boyle said she was impressed with the Navy's dedication to research. She boarded an aircraft carrier that, to her, looked like a "floating city." She also observed daily research activities, worked with flight and submarine simulators used for training, and, of course, she went to the beach.

"Whenever I thought of the Navy previously, I always thought just of military power, " said Boyle. "I knew different disciplines in the Navy conducted research, but I had no idea of the capacity and power of

Karen Boyle is flanked by Comdr. Mark Gugisberg, USNR, and Comdr. Hanes A. Burkart, MSC, USNR, at the International Science and Engineering Fair in Tulsa, Oklahoma.

research it has and uses to its benefit and to the benefit of society."

Boyle said she has in the past had aspirations to be a pediatric surgeon, but since completing her project and taking part in the public forum, she has seen the critical value of communications between the science world and the legal world, and of having competent environmental lawyers. Now she wants to major in either biology or environmental science.

For more details on the Navy and Marine Corps annual awards and certificates in science and engineering, contact Barbara M. Thurman, Project Officer, Naval Science Awards Program, Office of The Chief of Naval Research, ATTN: 11SPSA, Arlington, Virginia, 22217-5000.

Kathy Sharp Frisbee is the Editorial Assistant for Oceanus *magazine.*

To the Editor:

Regarding your fall issue devoted to Marine Education, I would like to call your attention to the University of Rhode Island's International Coastal Resources Management Project (CRMP). It is a cooperative effort among the Coastal Resource Center (URI), the United States Agency for International Development (USAID), and the governments of Thailand, Ecuador, and Sri Lanka. For CRMP initiatives to succeed, they must not only be technically sound, but they must also be acepted by the public as necessary. An integrated and ongoing public education element is an essential component of CRMP.

Phuket, a tropical island in the Andaman Sea off the western coast of Thailand, is one target area of the Thailand CRMP. Because of its beautiful beaches, warm climate and abundant natural resources, Phuket has grown from a few tourist bungalows to a first class resort in 10 years. The rapid pace of coastal development has resulted in a host of resource-related problems requiring urgent attention, such as degraded water quality; declines in fisheries, destruction of critically important ecosystems, such as mangroves, coral reefs, sand dunes, and wetlands; and increased erosion.

As a part of the ongoing and integrated public education element, CRMP sponsored a three-day training course for tour boat operators alerting them to the fragility of coral reefs. Tour boat operators, dive shops, and diving clubs also participated in a ten-day training course to teach and certify local divers in mooring buoy installation. Since the training course, certified local divers have installed over 200 mooring buoys along the coasts of Thailand. In addition, coral conservation posters in Thai and English are seen on tour boats and in dive shops. Recently, a brochure was designed especially for foreign tourists on coral reef protection. It is distributed through dive shops and hotels.

CRMP Notes are designed for the general public. Environmental issues are presented in a clear, concise and artistic manner. CRMP Notes cover natural resources, such as coral reefs, esturaries, sand dunes, mangroves, and forests. CRMP Notes on land-use management include stormwater, sewage treatment, solid waste, water pollution, and soil erosion. They have been distributed to schools, government officials, hotel owners, and businesses in Phuket. The Phuket Teachers' College is working on a marine science curriculum for elementary schools. And the Phuket Aquarium is building a special coral reef exhibit, which will show the importance of coral reef conservation.

These are just a small part of a continuing education component of the CRMP. Through public education, the people of Phuket are beginning to understand that a booming tourism industry depends on protecting the natural assets that make Phuket an international destination of choice.

Dr. William V. Branan and this writer, from URI, have lived and worked in Thailand for the last two years. Dr. Branan is technical coordinator for the Thailand CRMP, and I am an artist and writer for the project.

Laura Nell Branan
Wakefield, Rhode Island

To the Editor:

Forty four years after World War II, the merchant seamen who carried war supplies to the armed forces through hazardous submarine infested waters, and also manned the ship's guns, were finally granted Veterans Status by the Department of Defense.

It is interesting to note that their death rate was similar to that of the United States Marine Corps.

The problem at this time is: there is no list of surviving seafarers anywhere!

May I ask for your help to find some of these men by running a small notice in your magazine headlined, "*Searching For Merchant Seamen of WW II*".

The story should indicate that they have been granted Veterans Status by the D.O.D. because of a campaign by the Combat Merchant Mariners WW II and that benefits await them.

They may contact the foregoing organization at:

Combat Merchant Mariners WW II
14 Castle Drive
Spring Valley, New York 10977
(914) 623-8484

With many thanks for your cooperation, I remain

Kermit Haber
Executive Officer
Combat Merchant Mariners World War II
Chestnut Ridge, New York

***Water Baby, The Story of* Alvin by Victoria Kaharl. 1990. Oxford University Press, New York, N.Y.. 343 pp. – $21.95.**

Water Baby deserves to be a best-seller. A 25 year history of a research submarine could easily make for a history that only a scientist could like. But in Kaharl's hands, *Alvin's* biography is a gripping saga of first encounters in the deep ocean. It is also a story of risks, the risks of not only riding in a prototype device to the deep ocean floor, but also scientific risks, and risks of building and taking on the responsibility to operate *Alvin*. *Alvin* was commissioned in Woods Hole in 1964, according to Kaharl, because nobody else but the Woods Hole Oceanographic Institution (WHOI) would have it.

Adventure, remarkable characters, natural history and more, it's all here, interwoven into a single story, a story I could not put down once I started to read it. Having been very close to the events associated with *Alvin* for the last 20 years, I know that one of the primary difficulties of writing such a book is that there were too many stories. But, in the tradition of *Alvin's* history, Kaharl has done the improbable by making this a single, rapid-paced tale of discovery.

This book speaks with authority, and without jargon, about deep submergence technology and ocean science. It is not only a history of a submarine, but also a history of deep-sea oceanography. And it's a story of a small band of people, the scientists and crew who have been associated with *Alvin* and its two motherships, especially *Lulu*, which "looked like a piece of the dock that had ripped off," Kaharl writes.

"She wasn't really a catamaran because her pontoons were almost entirely submerged. By now (1968) WHOI knew the consequences of making the forward arch lower than the rear arch . . . In heavy seas, water slapped against the lower arch and the entire ship would tremble and stop or just go backward."

Many readers may be surprised to learn that dealings among scientists are not always harmonious, especially when years of work rides on a few dives. The shocking conditions encountered by *Lulu's* first women scientists, and particularly the chief scientists add another unhappy part of the story.

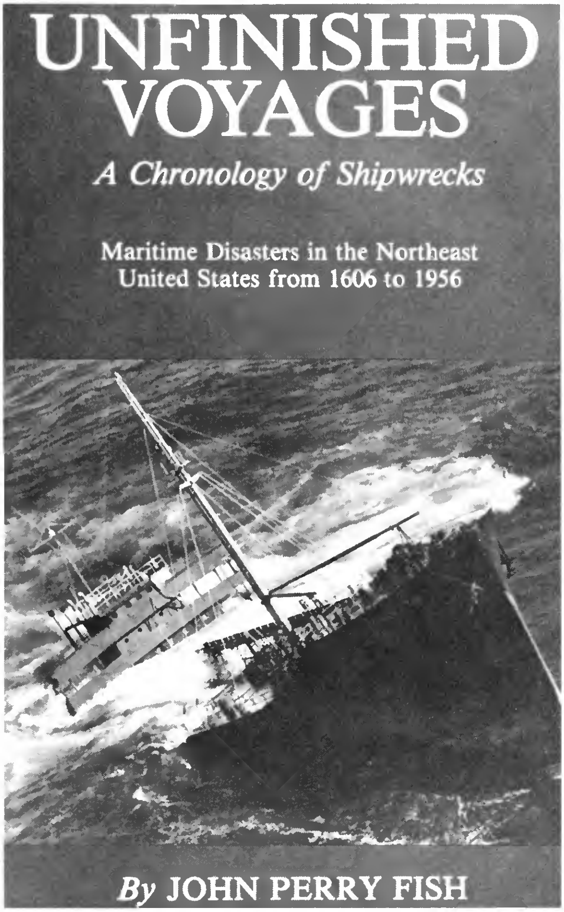
Some of the events in *Water Baby* may be remembered differently by different people, but nobody can argue with this author's attention to detail and concern with accuracy. *Water Baby* is an excellent piece of journalism from a journalist with a gift for making science come alive. Kaharl manages to capture some of the excitement felt by scientists in poorly-understood disciplines.

"The geophysicists are the poets of oceanography. Their lot is not to pry off chunks of earth but to measure the invisible and infer characteristics, eventually to arrive at some elusive truth of what is happening beneath the seafloor. If they can learn what happened a year or a million years before, they can better predict what will happen in the future. Their measurements of magnetism, gravity . . . speak the language of squiggles, blotches and stripes, which they translate into characteristics of the planet — how elastic, porous and dense it is."

Kaharl has managed to capture the essence of being there and being with an extraordinary collection of characters. I particularly liked the parts of the story told about the critical role of crew chief George "Brody" Broderson on *Lulu*. He was "the resident papa-san and patriarch," she writes. "He had no patience for a seaman who couldn't splice line or a scientist who put grimy hands on his clean white submarine."

"There was Chicken Man, the Weasel, Bubble Butt, and Saniflush . . . Charlie Tuna, El Kabong, and Captain Crunch were skippers . . . Baby Duck was pigeon-toed. He was also six-foot-four, had a schooner etched in a front tooth, an anchor tattooed on one cheek, a pony tail, and a long beard that separated into two strands" . . . I strongly recommend this book to all readers.

—Frederick Grassle, Director
Institute of Marine and Coastal Sciences
Rutgers University—New Brunswick, New Jersey



***Unfinished Voyages: Shipwrecks of the Northeast* by John Perry Fish, 1989. Lower Cape Publishing Co., Orleans, MA. 299pp.–$35.00.**

An important part of the heritage of the northeastern United States lies hidden beneath the green waters of coastal New England and New York. Maritime disasters have been part of life in these busy but treacherous waterways from pre-colonial times until the recent advent of sophisticated navigational equipment. Marine historian John Perry Fish, an expert in sonar technology and diving, is also a consummate story teller, providing the reader of *Unfinished Voyages* with a fascinating narrative of shipwrecks and the modern techniques used to locate these drowned time capsules. It is sometimes easy to forget that history is much more than simply names and dates. Divers, also, may forget while rummaging through the silent remains of a wreck, that what now is rubble once was a proud vessel, and, at the end, was perhaps the scene of an intense struggle for survival. John Fish has woven the tales of the last voyages of selected ships and daring rescues to portray the development of American maritime commerce and the evolution of the lifesaving service into the modern Coast Guard.

John's intuitive sense of history carries over to the modern search for wrecks. Of particular interest to this reviewer is the story of the discovery of the remains of the Vineyard Lightship in 1963 by Harold "Doc" Edgerton and Bradford Luther. "Doc" Edgerton, who recently died at the age of 86, was primarily responsible for the development of sidescanning sonar and the electronic flash, or "strobe light," among other scientific accomplishments too numerous to mention here. Captain Luther, a true pioneer of scuba diving in New England, compiled much of the New England wreck data through old newspaper and lifesaving accounts (a copy of his long out-of-print book *Ten Years at Ten Fathoms* is a treasured part of our diving program's library). Lightships have now passed from the scene, but for more than 150 years they bravely served lonely, often hazardous duty as beacons to warn ships of dangerous offshore shoals. More than a few ended up at the bottom from wild storms or from collisions with passing ships. The Vineyard Lightship was lost with all hands during a hurricane in September 1944, but the exact location and cause of her sinking remained a mystery for nearly 20 years. The location of this wreck was also a milestone in that it was the first lost vessel located by "Doc's" new invention, the sidescan sonar.

This reviewer was privileged to have had the opportunity to dive with Brad Luther from his "Wreck Master" more than 20 years ago and more recently with several other divers mentioned in this book, such as Arnie Carr and Pete Sachs.

Unfinished Voyages also provides practical information for modern wreck-seekers. The chapter "Locating Lost Ships" is an excellent, concise discussion of the "high tech" methods of discovering the resting sites of old ships. The appendices, which span more than half the length of this well-illustrated book, definitively list regional newspaper research sources, northeastern life saving stations, and a chronology of over 5,000 vessels lost off the northeastern United States in nearly 400 years of maritime history. *Unfinished Voyages* is an exceptionally well-crafted work that will be of interest to anyone who has an interest in maritime history as well as to the adventurers who dive to the wreck sites.

—Terrence M. Rioux
Diving Safety Officer
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

BOOKS RECEIVED

BIOLOGY

Advances in Marine Biology: Volume 26 edited by J.H.S. Blaxter and A.J. Southward; 1990; Academic Press, New York, NY; 285 pp. - $42.50

Biomanipulation: Tool for Water Management edited by R.D. Gulati, E.H.R.R. Lammens, M.L. Meyer, and E. van Donk; 1990; Kluwer Academic Publishers, Dordrecht, The Netherlands; 648 pp. - $162.50

Invertebrates by Richard C. Brusca and Gary J. Brusca; 1990; Sinauer Associates, Sunderland, MA.; 922 pages - $47.50

Light and Life in the Sea edited by Peter J. Herring, Anthony K. Campbell, Michael Whitfield, and Linda Maddock; 1990; Cambridge University Press, NY, NY; 298 pp. + xviii - $59.50

Penguin Biology edited by Lloyd S. Davis and John T. Darby; 1990; Academic Press, Inc., Boston, MA.; 443 pp. - $79.95

Seabirds of the Farallon Islands: Ecology, Dynamics, and Structure of an Upwelling-System Community edited by David G. Ainley and Robert J. Boekelheide; 1990; Stanford University Press, Stanford, CA.; 380 pp. - $60.00

Sea Mammals and Oil; Confronting the Risks edited by Joseph R. Geraci and David J. St. Aubin; 1990; Academic Press, Inc., San Diego, CA.; 256 pp. - $59.95

ENVIRONMENT

Atmospheric Sciences in Antarctica: Selections from Reviews of Geophysics edited by John W. Meriwether, Jr.; 1990; American Geophysical Union, Washington, DC; 619 pp. - $22.00

Climate Change: The Intergovernmental Panel on Climate Change, Scientific Assessment prepared for IPCC by Working Group 1, edited by J.T. Houghton, G.J. Jenkins, and J.J. Ephraums; 1990; University Press, Cambridge, Great Britain; 365 pages - n/p

Ecology of Sandy Shores by A.C. Brown and A. McLachlan; 1990; Elsevier Science Publishers, Amsterdam, The Netherlands; 340 pp. - $97.50

The Fate of The Forest: Developers, Destroyers and Defenders of the Amazon, by Susanna Hecht and Alexander Cockburn; 1990; Harper & Row, New York, NY; 318 pp. - $9.95

The Global Ecology Handbook: What You Can Do About The Environmental Crisis by The Global Tomorrow Coalition; 1990; Beacon Press, Boston, MA.; 360 pp. - $16.95

The International Geosphere-Biosphere Programme: A Study of Global Change, The Initial Core Projects (Report No. 12, 1990), International Council of Scientific Unions; 1990; Graphic Systems AB, Stockholm, Sweden; 200 pp. + xx - n/p.

Large Marine Ecosystems: Patterns, Processes, and Yields edited by Kenneth Sherman, Lewis Alexander, and Barry Gold; 1990; American Association for the Advancement of Science, Washington, D.C.; 300 pp. - $39.95.

Monitoring Southern California's Coastal Waters compiled by Marine Board, National Research Council; 1990, National Academy Press, Washington, D.C.; 144 pp. - $17.00

The Ocean of Truth: A Personal History of Global Tectonics by H.W. Menard; 1986; Princeton University Press, Lawrenceville, N.J.; 367 pp. - $39.50

Our Common Seas; Coasts in Crisis by Don Hinrichsen; 1990; Earthscan Publications Ltd., London, England; 224 pp. - $13.95

Southern Exposure: Deciding Antarctica's Future by Lee A. Kimball; 1990; a World Resources Institute publication, WRI Publications, Baltimore, MD., 39 pp. - $9.00.

Wild Ice: Antarctic Journeys by Ron Naveen, Colin Monteath, Tui De Roy, and Mark Jones; 1990; Smithsonian Institution Press, Washington, D.C.; 221 pp. - $29.95

FISHERIES

Aquaculture in America, The Role of Science, Government, and the Entrepreneur by Art Tiddens; 1990; Westview Press, Boulder, CO.; 181 pp. + vii - $35.00

Estuarine Ecology by John W. Day,Jr., Charles A.S. Hall, W. Michael Kemp, and Alejandro Yanez-Arancibia; 1989; John Wiley & Sons Publishers; NY, NY; 538 pp. - $54.95

Fishdecks: Seafarers of the North Atlantic by William McCloskey; 1990; Paragon House, New York, NY; 307 pp. - $22.95

Save The Dolphins by Michael Donoghue and Annie Wheeler, 1990; Sheridan House Inc., Dobbs Ferry, NY; 111 pp. - $24.95

MARINE POLICY

Intertidal Flats: Their Value and Legal Status compiled and published by The Sounds Conservancy, Inc.; 1990; 40 pp. - $6.00

OCEANOGRAPHY

Antarctic Science edited by D.W.H. Walton; 1987; Cambridge University Press, New York, NY; 280 pp. - $42.50

Arctic Research of the United States, compiled by the Interagency Arctic Research Policy Committee and the Arctic Research Commission; 1990; published by the National Science Foundation, Washington, D.C.; 120 pp. - n/p.

Journal of Marine Systems: Coupled Ocean - Atmosphere Modeling edited by J.C.J. Nihoul and B. Jamart, Journal of the European Association of Marine Sciences and Techniques; 1990; Elsevier Science Publisher B.V., The Netherlands; 209 pp. - $38.50 (quarterly)

Mud, Muscle, and Miracles; Marine Salvage in the United States Navy by Captain C.A. Bartholomew, USN; 1990; Superintendent of Documents, Government Printing Office, Washington, DC - $32.00

Oceanographic Ships Fore & Aft by Dr. Stewart B. Nelson; reprinted 1982; U.S. Government Printing Office, Washington, D.C.; 240 pp. - $7.95.

Oceanography from the Space Shuttle, a joint project of the University Corporation for Atmospheric Research and the Office of Naval Research, United States Navy; 1989; Office of Naval Research, Washington, D.C.; 200 pp. - free.

Polar Oceanography: Part A, Physical Science edited by Walker O. Smith, Jr.; 1990; Academic Press, Inc., San Diego, CA.; 384 pp - $69.50

Sea-Level Change, prepared by Geophysics Study Committee, Commission on Physical Sciences, Mathematics, and Resources, National Research Council, Washington, D.C.; 1990; 205 pp. - $29.95

Volcanoes of the Antarctic Plate and Southern Oceans: Antarctic Research Series edited by W.E. LeMasurier and J.W. Thomson; 1990; American Geophysical Union, Washington, D.C.; 479 pp. + vi - $55.00

REFERENCE

Black Sea '90 Proceedings: International ocean and marine exhibition and technical conference, September, 1990, Varna, Bulgaria compiled by Center of Ocean Engineering, Varna, Bulgaria, and West Star Productions, Spring Valley, CA.; - $75.00

Everybody Counts: A Report to the Nation on the Future of Mathematics Education compiled by the National Research

Council; 1990; National Academy Press, Washington, D.C.; 114 pp. - $7.95

For The Common Good: Redirecting the Economy Toward Community, the Environment, and a Sustainable Future by Herman E. Daly and John B. Cobb, Jr.; 1990; Beacon Press, Boston, MA.; 482 pp. + xx - $24.95

New England Harbors, photography and introduction by Clyde H. Smith; 1990; Mystic Seaport Museum Stores, Inc., Mystic, CT.; 128 pp. - $35.00

Our Kind: Who We Are, Where We Came From & Where We Are Going, The Evolution of Human Life & Culture by Marvin Harris; 1990; HarperCollins, Publishers, New York, NY; 502 pp - $10.95

Science and Engineering Indicators - 1989 compiled by the National Science Board; 1989; U.S. Government Printing Office, Washington, D.C.; 404 pp. - $26.00

SHIPS & SAILING

Ocean Traders: From the Portuguese discoveries to the present day, by Dr. Michael Marshall; 1990; Facts on File, Inc., NY, NY; 183 pp. - $24.95

Tropical Shipwrecks: A Vacationing Diver's Guide to the Bahamas and Caribbean by Daniel and Denise Berg; 1989; Aqua Explorers, Inc., East Rockaway, NY; 144 pp. - $9.95

Valley, Volume II: A Record of Shipwrecks Off Long Island's South Shore and New Jersey by Daniel Berg; 1990; Aqua Explorers, Inc., East Rockaway, NY; 181 pp. - $18.95

YOUNG PEOPLE

Amazing Science, Tidal Waves and Other Ocean Wonders by Q.L. Pearce; 1989; Simon and Schuster, Englewood Cliffs, N.J.; 62 pp. - $5.95

I Can Be An Oceanographer by Paul P. Sipiera; 1987; Children's Press, Chicago, Ill.; 29 pp. - $3.95

Kelp Forests compiled by Monterey Bay Aquarium Foundation; 1989; Monterey Bay Aquarium Foundation, Monterey, CA.; 63 pp. - $8.95

Nature Hide and Seek-Oceans by John Norris Wood; 1985; Alfred A. Knopf, Inc., NY., NY.; 20 pp. - $9.95

Spilhaus Geoglyph: A jigsaw style map of the continents and oceans for manipulative entertainment and education by Dr. Athelstan Spilhaus; 1989; GeoLearning, Sheriden, Wyoming - $24.95

INDEX, VOLUME 33 (1990)