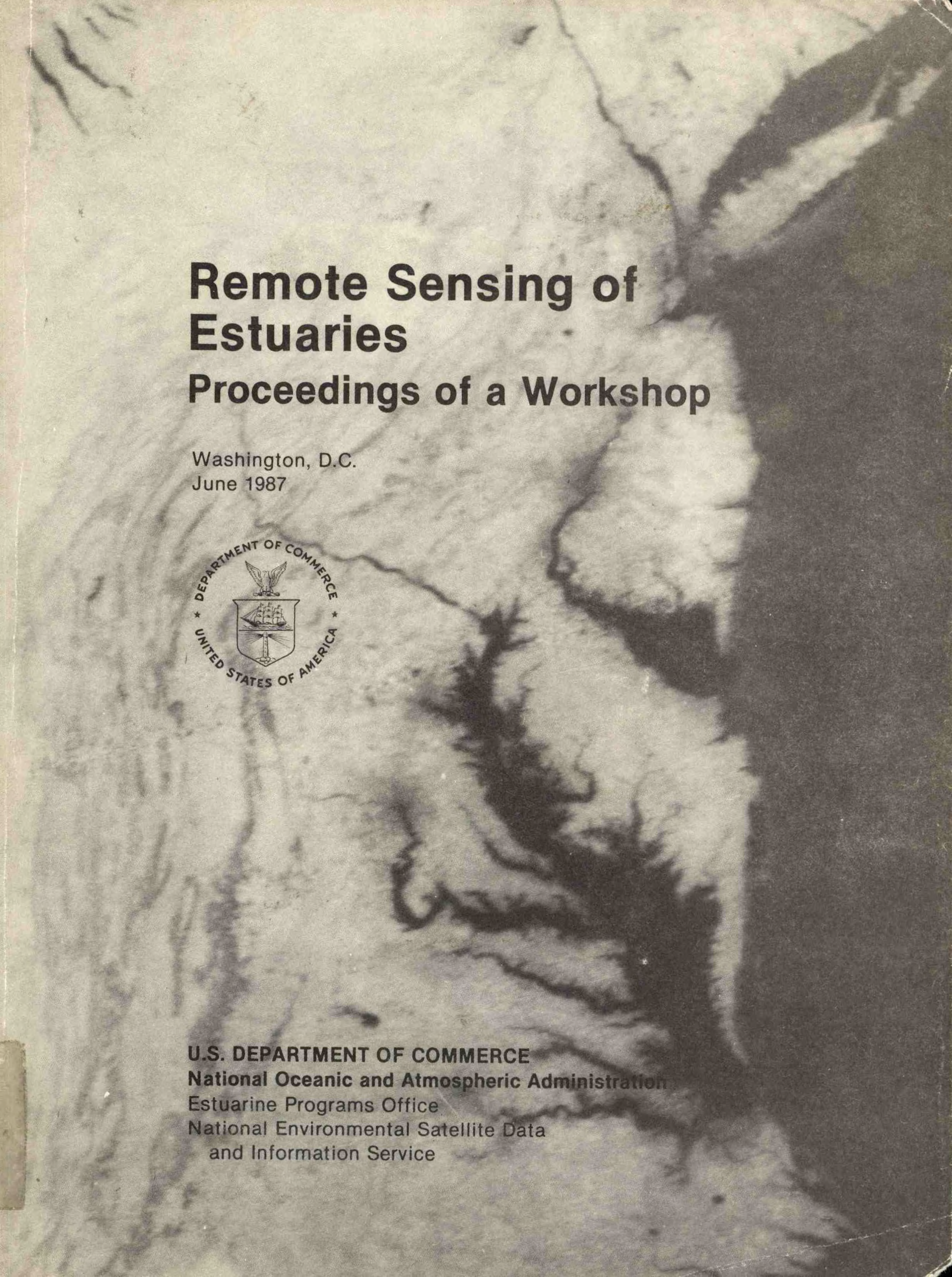

Remote Sensing of Estuaries

Proceedings of a Workshop

Washington, D.C.
June 1987

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Estuarine Programs Office
National Environmental Satellite Data
and Information Service

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Edited by:
Vytautas Klemas
James P. Thomas
James B. Zaitzeff

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

U.S. DEPARTMENT OF COMMERCE
Secretary of Commerce

National Oceanic and Atmospheric Administration
Anthony J. Calio, Under Secretary

Estuarine Programs Office
Virginia K. Tippie

National Environmental Satellite Data
and Information Service
Thomas N. Pyke, Jr.

This publication is the result of a seminar and workshop conducted by the National Oceanic and Atmospheric Administration, Estuarine Programs Office (EPO), the National Environmental Satellite, Data, and Information Service (NESDIS), and the University of Delaware. The transcript was prepared by EPO and the University of Delaware; the workshop and publication costs were covered by EPO and NESDIS. Technical editing and typing of the document was done by Alice Roberson and assisted by Janet Davis of EPO and Heather Froozandeh of the University of Delaware.

PROCEEDINGS OF A SEMINAR AND WORKSHOP ON

REMOTE SENSING OF ESTUARIES

This Seminar and Workshop were conducted in Washington, D.C. on December 3 and 4, 1985, and were sponsored by the NOAA Estuarine Programs Office and the NOAA National Environmental Satellite, Data, and Information Service (NESDIS)

Organized and Edited By:

Dr. V. Klemas
University of Delaware

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NOAA Estuarine Programs Office

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NOAA/NESDIS

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EXECUTIVE SUMMARY

Estuaries are highly productive, producing large quantities of animal and plant biomass each year. They are sites of inshore fisheries and spawning/ nursery grounds for many species of pelagic finfish. They shelter many plants and invertebrates of ecological and economic significance. Estuaries also provide ports, industrial and residential sites, recreational opportunities and tourist attractions. Because of these attractions, estuarine shorelines are usually the first to be populated when agricultural, urban and industrial development occurs. To determine the impact of such development on the "health" of estuarine systems, many studies are being conducted requiring extensive monitoring of a wide range of physical, geological, chemical and biological properties of the water column, the benthos and surrounding wetlands. Most of these studies employ ship and field data and make very little use of remotely sensed data.

Remote sensing offers a unique opportunity to observe and monitor entire estuaries synoptically and compare them to other estuaries. However, due to the tidal influences and small features which need to be detected, estuaries place severe temporal and spatial resolution requirements on sensing systems as compared to open ocean or land applications. Also, most estuarine researchers and managers are not familiar with remote sensing techniques and data availability.

Therefore, the National Oceanic and Atmospheric Administration (NOAA) Estuarine Programs Office, and the National Environmental Satellite, Data and Information Service (NESDIS), with the help of other agencies and the University of Delaware, organized a seminar and workshop with the following objectives:

(1) To evaluate remote sensing techniques as a cost effective means for obtaining useful qualitative and quantitative data for an improved understanding of the physical, biological and geochemical properties of estuaries.

(2) To review data requirements for hydrodynamic water quality and ecological models of estuaries (with emphasis on data obtainable by remote sensors).

(3) To review the wide range of remote sensors and techniques available to users for monitoring the physical, biological and geochemical properties of estuaries and surrounding wetlands and drainage basins.

(4) To produce conclusions and recommendations for future use and development of remote sensing in estuarine studies.

The first day was devoted to reviewing data requirements for estuarine models and presenting an overview of the remote sensing techniques which seem useful for estuarine studies. On the second day, the following four workshop panels prepared requirements, available techniques, and a list of conclusions and recommendations for future use of remote sensing in estuarine studies.

(1) Wetlands and Uplands Panel
(2) Water Column Properties Panel
(3) Physical Processes and Estuarine Dynamics Panel
(4) Benthic Environment Panel

The panels concluded that remote sensing, when used with appropriate models and ground requirements, can indeed provide cost-effective, synoptic information on wetlands and estuaries with improved temporal and spatial resolution. This conclusion is also supported by the scientific papers presented at the seminar and included in the latter part of these proceedings. A summary of the availability and performance of remote sensors for estuarine studies is presented in Table 1. The panels also made many recommendations for further improving the use of remote sensing in estuarine research and monitoring. The panel recommendations can be summarized as follows:

1. <u>Basic Research and Model Development</u>

- The use of remote sensing data should be integrated into models that describe wetlands and estuarine ecosystems and their forcing functions, particularly in those cases where remote sensing measurements offer increased cost-effectiveness, synopticity, and the improved temporal/spatial resolution of required parameters.

- Research should be undertaken to extract the maximum information available about wetlands and estuaries from the integrated use of sensors, both in terms of spectral wavelength components and multistage spatial sampling (e.g. ship/aircraft/satellite).

- Improved physical and statistical models and algorithms should be developed, and additional basic research in hydrologic optics performed, to improve our ability to remotely identify and measure estuarine water constituents (organic/inorganic, particulate/dissolved, nutrients/toxics). This would include development of operational algorithms based on existing CZCS algorithms to allow atmospheric correction, pigment concentrations, and diffuse attenuation coefficients to be calculated in estuarine waters.

Table 1. Performance of Remote Sensors for Estuarine Studies.

Sensor	Plat-form	Veg.& Land Use	Biomass & Veg. Stress	Coast-line Erosion	Bottom Feat. SAV	Depth Profiles	Susp. Sed. Ptrns.	Susp. Sed. Concen.	Chloro-phyll Concen.	Oil Slicks	Surf. Temp.	Water Sal.	Curr. Circ. Ptrns.	Wave Spectra	Surf. Winds
Film Cameras	A	3	2	3	3	2	2	1	1	2	0	0	2	2	1
	S	2	1	2	2	1	2	1	1	1	0	0	2	2	1
Multispectral	A	3	2+	3	3	2	3	2+	2+	3	0	0	2	2	1
Scanners	S	2	1	2	2	2	3	2	2	2	0	0	2	2	1
Thermal IR	A	1	1	1	0	0	1	0	0	3	3	1	2	0	1
Scanners	S	0	0	0	0	0	1	0	0	1	3	0	2	0	1
Laser	A	0	0	1	2	3	1	0	0	1	0	0	0	3	1
Profilers	S	0	0	1	1	1	0	0	0	0	0	0	0	2	0
Laser	A	1	1	0	0	0	2	2	3	3	1	1	1	0	0
Fluorosensors	S	0	0	0	0	0	1	1	1	1	0	0	0	0	0
Microwave	A	1	0	0	0	0	1	1	0	2	3	2	2	1	3
Radiometers	S	0	0	0	0	0	0	0	0	1	2	1	1	0	2
Imaging Radar	A	2	1	3	0	1	1	0	0	3	1	1	2	3	2
(SAR or SLAR)	S	1	0	2	0	1	0	0	0	2	0	0	1	2	1
CODAR (Radar)	G	0	0	0	0	0	0	0	0	0	0	1	3	2	2
RADS(Acoustic)	G	0	0	2	3	3	2	1	0	1	0	0	3	1	0
UW Camera	G	0	0	2	3	2	2	1	1	1	0	0	1	0	0

Rating
3 = Reliable and Available (Operational)
2 = Qualitative and/or Needs Additional Testing
1 = Experimental and/or Not Widely Available
0 = Not Applicable

Platform
A = Aircraft (Medium or Low Altitude)
S = Spacecraft (Satellite)
G = Ground (Boat or Field)

2. New Sensor Development

- For studies of wetlands plant communities as well as other features of land cover in coastal environments, sensors having better spatial (10 m) and spectral resolution (10 nm) need to be developed. Within the visible and infrared region of the spectrum, examples of such sensors include the Jet Propulsion Laboratory's imaging spectrometers which will lead to better characterization of plant internal composition and physiology, thus improving inferences about other environmental parameters such as nutrient limitations and tidal regimes. The National Aeronautics and Space Administration's AMES Research Center Airborne Ocean Color Imager (AOCI) capabilities for measurement of total phytopigment concentration, diffuse attenuation coefficients and total sediment load should be evaluated. In the microwave region, multiple wavelengths, look angles and polarizations are needed to improve discrimination of species of wetlands grasses, shrubs and forests, and provide all-weather capability.

- Development of the following systems should be expedited in order to improve the measurement of water constituents:

(a) High spatial resolution (30m) microwave radiometer for salinity and other measurements. Aircraft instrumentation development for this is recommended.

(b) Narrow band (10nm) multispectral scanner for sensing of estuarine water constituents. Wavelength characteristics should range from .443-.670 µm in visible, and .750 µm and 10.5-12.5 nm in the near and thermal infrared.

(c) Development of laser systems for:

    (a) Temperature in depth
    (b) Bathymetry
    (c) Water constituents (e.g. chlorophyll, suspended sediment, dissolved organics)
    (d) Phytoplankton species composition

(d) Development of <u>in situ</u> horizontal profiling acoustic current meters such as scintillation instruments.

(e) Development of higher resolution and land-based radar systems for discrimination of surface currents and waves (e.g. extend HF radars into VHR band; complete development of two-frequency microwave radar).

- Improved devices need to be developed for collecting subsurface information on estuarine living resources and their habitats. Specifically, acoustic devices such as SONAR, scanning SONAR and Doppler current meters should be further improved for mapping bathymetry and sediment structure, identifying various benthic community types, and measuring near-bottom currents.

3. Sampling and Experiment Design

- There must be a long-term commitment to make satellites available for an improved understanding and management of estuaries. This should include the development of sensors with adequate sampling resolution and frequency in new satellite or aircraft systems, as well as a study for the placement of an OCI-type instrument on GOES. A continuity of data flow is required for trend analysis and assessment of management actions.

- Government agencies (NOAA, EPA, NASA, Corps of Engineers, USGS, etc.) should sponsor an interdisciplinary estuarine remote sensing panel to plan a demonstration project whereby selected remote sensing systems, used in conjunction with boat and field measurements, are used to study an estuarine system. This demonstration project should provide a framework for effective use of remote sensing to study and manage estuarine systems nationwide.

- New sampling systems should be developed for collecting large numbers of field samples and measurements coincident with remote sensing operations. This could include radio-controlled buoy systems which collect surface and subsurface water samples coincident with aircraft or satellite overpasses, or acoustical measurements.

- Aircraft-based techniques should be brought into estuarine data collection programs in a more expeditious and cost-effective way. Joint projects between NOAA, NASA, the Navy, and other agencies should be explored to reduce costs.

- More emphasis should be placed on integrating remote sensing products with conventional analysis products for improved understanding and use by multidisciplinary teams and managers.

4. Data Management

- There should be a lead agency or Center whose responsibility would be to coordinate a database of all estuarine remotely sensed and pertinent *in situ* data and provide users with information on sources, data availability, quality, geographic storage unit, product forms and costs.

- Geographic Information Systems (GIS) should be adopted, to the maximum extent possible, as the standard way to present data for estuarine management.

- When an estuarine project utilizing remote sensors is designed and implemented, data dissemination, standardization and archiving of the remotely sensed information should be given equal priority with details of the design and performance of the collection platform or system. All archived data should be retrieved and re-recorded on up-to-date, high-density hardware for long-term storage with easy access. For instance, most of the AVHRR LAC/HRPT data should be retrieved from IBM tapes and suitably archived.

- Development of inter-calibration techniques to interrelate data from the various sensors is essential to the full utilization of remotely sensed data, and technique descriptions for the production of user products (e.g. techniques for processing CZCS imagery into chlorophyll maps).

- The time between data collection and product dissemination for operational use by researchers and managers should be decreased. For archive retrieval, a timely response is also required (e.g. days/weeks).

- A users guidebook system needs to be prepared which provides information on sensor packages and their capabilities on available software. The guidebook should be upgraded annually.

- Standard unpacking software routines should be written for mainframes, minis and micros.

- Raw and engineering data with digital products, as well as film and paper graphic products, should be made available upon request.

5. <u>Coordination, Training and Information Dissemination</u>

- Better coordination and cooperation among government agencies and other participating institutions is required in the development of a uniform, calibrated database of aircraft and satellite imagery. The NOAA Estuarine Programs Office should set up a working group to examine the needs for generic data/information in the estuaries and how these needs may be addressed through effective coordination aimed at the modification of existing programs and/or the development of new interagency programs that would utilize current remote sensing technology.

- Users should receive timely reports on sensor status and estuarine research projects that are underway or are being planned for the near future.

- Research between government agencies, universities and other institutions within geographic regions should be coordinated.

Development of techniques and remote sensing systems should be closely coordinated with estuarine management needs, including both monitoring and research, to assure effective and efficient use of new systems.

More effective methods for transferring remote sensing technologies to the estuarine, oceanographic, and management communities should be developed. For instance, training should be provided to estuarine scientists and managers in relevant applications of remote sensing techniques.

INTRODUCTION AND OBJECTIVES

Most estuaries behave like semi-enclosed brackish water reservoirs and have physical, chemical, geological, and biological features different from those of the ocean with which they interact, and from the freshwater streams that empty into them. Uncontaminated estuaries are extremely fertile, producing large quantities of animal and plant materials (i.e. total biomass) each year. They are sites of many highly productive and valuable inshore fisheries, and the spawning areas or nursery grounds of many species of pelagic finfish, which range over the waters of the continental shelves of the Earth's oceans. They also shelter many plants and invertebrates of ecological or economic significance (Hargis 1981).

The sheltered waters and extensive tidal shorelines of estuaries also provide ports, industrial and residential sites, recreational opportunities, and tourist attractions. Because of these attractions, estuarine shorelines are usually the first to be populated when agricultural, urban and industrial development occurs. To determine the impact of such development on the "health" of estuarine systems, many studies are being conducted requiring extensive monitoring of a wide range of physical, geological, chemical and biological properties of the water column, the benthos and surrounding wetlands. Most of these studies use ship data and make very little use of remotely sensed data.

For nearly two decades, satellites have been providing useful meteorological information used in weather forecasting, including cloud circulation. Since the launch of LANDSAT in 1972, there has been a similar surge of activity in land-related remote sensing, including geology, agriculture, and forestry. More recently, oceanographers have begun using satellite imagery for open ocean investigations, including studies of current circulation, Gulf Stream rings, chlorophyll distribution, etc.

Why then is remote sensing not being used routinely in estuarine studies? One reason is that estuaries have very stringent technical sensing requirements. For instance, Gulf Stream meanders and ring dynamics can be monitored twice weekly at 1 km resolution, yet tidal effects on estuarine currents and fronts require hourly observations at resolutions of about 20 m. However, there seems to be a more basic reason for the reluctance to use remote sensing, i.e. estuarine researchers and resource managers are not familiar with available remote sensing techniques and systems, and therefore lack confidence in them or find them too expensive and requiring too much sophisticated technology (i.e. the black box syndrome).

Therefore, a seminar and workshop were organized with the following objectives:

(1) To convincingly demonstrate to the user community that remote sensing can offer cost effective means for obtaining useful qualitative and quantitative data for physical, biological, and geochemical studies of estuaries.

(2) To review data requirements for hydrodynamic water quality and ecological models of estuaries (with emphasis on data obtainable by remote sensors).

(3) To review the wide range of remote sensors and techniques available for monitoring the physical, biological, and geochemical properties of estuaries and surrounding wetlands and drainage basins.

(4) To produce conclusions and recommendations for future use of remote sensing in estuarine studies.

The seminar program is shown in the next section. The first day was devoted to reviewing data requirements for estuarine models and presenting an overview of the remote sensing techniques which seem useful for estuarine studies. On the second day, four workshop panels prepared requirements, available techniques, and a list of conclusions and recommendations for future use of remote sensing in estuarine studies. The papers presented by the seminar speakers are included in these proceedings and were used as reference material for discussions, conclusions, and recommendations emanating from the workshop panels conducted on the second day. The four workshop panels of experts were organized as follows:

(1) Wetlands and Uplands Panel
(2) Water Column Properties Panel
(3) Physical Processes and Estuarine Dynamics Panel
(4) Benthic Environment Panel

A list of panel members and seminar attendees is shown in the Appendix A and B respectively.

The NOAA Estuarine Programs Office and the NESDIS Oceanic Sciences Branch were the prime organizers of this seminar and workshop. However, valuable contributions were made by other agencies and their representatives participating in this effort, including the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, the U.S. Geological Survey, the U.S. Army Corps of Engineers, the National Science Foundation, the National Aeronautics and Space Administration, and individuals from universities, industry, and state and local agencies. Dr. Vic Klemas, from the University of Delaware, was invited to organize the technical program and conduct the workshop.

SEMINAR PROGRAM

THE NOAA ESTUARINE PROGRAMS OFFICE,
THE NOAA NATIONAL ENVIRONMENTAL SATELLITE, DATA AND INFORMATION SERVICE
THE U.S. ENVIRONMENTAL PROTECTION AGENCY,
THE U.S. FISH AND WILDLIFE SERVICE

A SEMINAR AND WORKSHOP ON ESTUARINE REMOTE SENSING

DECEMBER 3 AND 4, 1985
U.S. Department of Commerce, Hoover Building
14th and Constitution Avenue, N.W.
Main Auditorium, Washington, D.C.

SEMINAR ON DATA REQUIREMENTS
REMOTE SENSING TECHNIQUES

TUESDAY, DECEMBER 3, 1985

Morning Session

CHAIRMAN:
DR. JAMES THOMAS, NOAA ESTUARINE PROGRAMS OFFICE

WELCOME AND INTRODUCTION Mr. Russell Koffler, NOAA Acting Deputy Administrator for Satellites	8:30
BASIC SCIENTIFIC AND MANAGEMENT ISSUES WHICH NEED TO BE ADDRESSED (USING CHESAPEAKE BAY AS A SPECIFIC EXAMPLE) Dr. T. Davies, U.S. Environmental Protection Agency Dr. J. Thomas, Estuarine Programs Office (NOAA)	8:50
REMOTE SENSING OF ESTUARINE PROPERTIES: AN OVERVIEW Dr. V. Klemas, University of Delaware	9:40
DATA REQUIREMENTS FOR HYDRODYNAMIC MODELS OF ESTUARIES Dr. W. Boicourt, University of Maryland	10:20
DATA REQUIREMENTS FOR WATER QUALITY MODELS OF ESTUARIES Dr. R. Thomann, Manhattan College	10:50
DATA REQUIREMENTS FOR ECOLOGICAL MODELS OF ESTUARIES Dr. W. Boynton, Chesapeake Biological Laboratory	11:20

LUNCH 11:50 - 1:00

Afternoon Session

CHAIRMAN:
DR. JAMES ZAITZEFF, NOAA NATIONAL ENVIRONMENTAL SATELLITE, DATA AND INFORMATION SERVICE (NESDIS)

AIRBORNE MULTISPECTRAL SENSING OF ESTUARINE PROPERTIES Dr. W. Hovis, TS-INFO System, Inc.	1:00
REMOTE SENSING OF WETLANDS Dr. D. Bartlett, NASA Langley Research Center	1:30
SATELLITE REMOTE SENSING OF DISSOLVED AND PARTICULATE SUBSTANCES IN ESTUARIES Dr. R. Stumpf, NOAA/NESDIS	2:00
RADAR MAPPING OF SURFACE CURRENTS (CODAR) Dr. R. Williams, NOAA/National Ocean Service	2:30
REMOTE SENSING OF SUBMERGED AQUATICS Dr. S. Ackleson, University of Delaware	3:00
REMOTE SENSING OF THE BENTHIC ENVIRONMENT Dr. D. Rhoads, Science Applications International Corp.	3:30
REMOTE ACOUSTIC DOPPLER SYSTEM (RADS) Dr. G. Appell, NOAA	4:00
DISCUSSION AND WORKSHOP ANNOUNCEMENTS	4:30

WORKSHOP ON ESTUARINE REMOTE SENSING
WEDNESDAY, DECEMBER 4, 1985

CLOSED SESSION

Attendance at this workshop is limited to invited participants, who will primarily consist of speakers from the previous day's seminar and invited experts. The purpose of the workshop is to prepare an executive summary outlining requirements, available techniques, and future recommendations for estuarine remote sensing.

Morning Session

CHAIRMAN:
DR. V. KLEMAS, UNIVERSITY OF DELAWARE

GENERAL MEETING TO CLARIFY PANEL TASK ASSIGNMENTS AND PROPOSED OUTLINE OF FINAL REPORT	8:00
SEPARATE INTO PANELS OF EXPERTS, INCLUDING USERS AND REMOTE SENSING SPECIALISTS	8:45

(a) Wetlands and Uplands
(b) Water Column Properties
(biological, chemical, geological)
(c) Physical Processes and Estuarine Dynamics
(d) Benthic Environment

DISCUSSION AND DIVISION OF TASKS AMONG PANEL MEMBERS	9:00
PANELS START WRITING ROUGH DRAFTS OF THEIR REPORTS	10:00

LUNCH 12:00 - 1:00

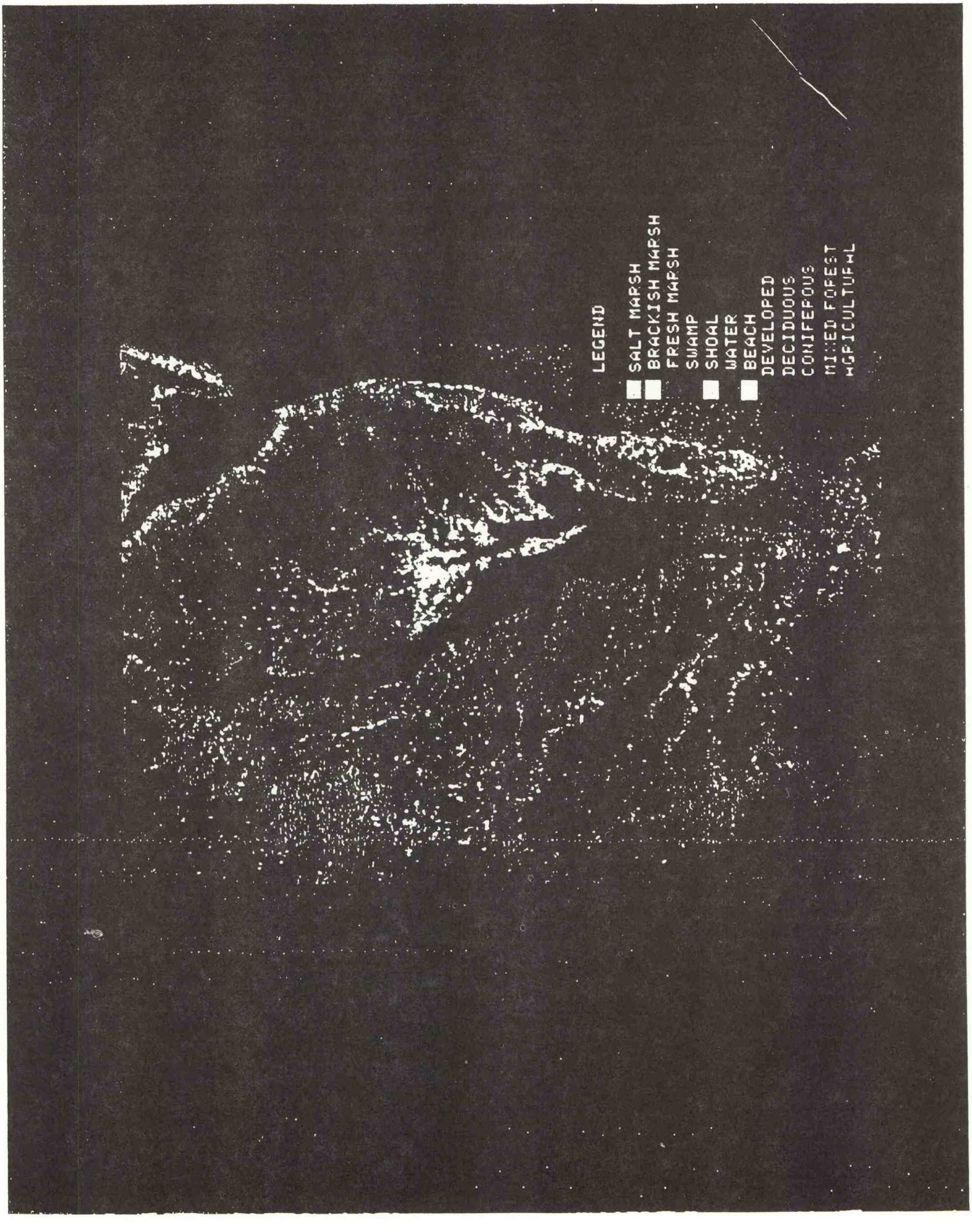
Afternoon Session

PANELS COMPLETE ROUGH DRAFTS OF THEIR REPORTS	1:00
CHAIRMEN INTEGRATE PANEL FINDINGS AND RECOMMENDATIONS	2:00
PRESENTATION OF SUMMARIES OF PANEL FINDINGS AND RECOMMENDATIONS TO ALL WORKSHOP PARTICIPANTS	3:00
ASSIGNMENT OF EDITORIAL TASKS TO PANEL CHAIRMEN, SECRETARIES, AND MEMBERS FOR PREPARATION OF FINAL REPORTS	4:00

LAND COVER IN THE CHESAPEAKE BAY AREA

Land cover classes were determined for four Landsat scenes using a supervised classification algorithm based on maximum log-likelihood decision criteria. Unclassified pixels, clouds and cloud shadows, and discrepancies between certain land cover classes were resolved through a pixel by pixel comparison with LUDA data. The scenes, dated October 24 and 25, 1978, were processed individually then subsampled and combined as a single mosaic for display purposes. The display represents less than 1 percent of the pixels for which land cover data were calculated.

Edward A. Bright, Jerome E. Dobson, Gene M. Silberhorn


LEGEND
SALT MARSH
BRACKISH MARSH
FRESH MARSH
SWAMP
SHOAL
WATER
BEACH
DEVELOPED
DECIDUOUS
CONIFEROUS
MIXED FOREST
AGRICULTURAL

WORKSHOP PANEL REPORTS

1. PANEL ON REMOTE SENSING OF WETLANDS AND UPLANDS

PANEL MEMBERS:

D. Ekberg, Chairperson	M.F. Gross
R.A. Baltzer	K. Haddad
R. Backes	N. May
D.S. Bartlett	H. Mustafa
K. Butera	D.J. Norton
D.R. Dilen	G. Silberhorn
J.E. Dobson	G.W. Thayer
D. Field	R. Tiner, Co-chair person

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1.1 WETLANDS/UPLANDS ISSUES

The major issues facing wetlands and their interfaces with uplands center about human activities. Man's physical alteration of fish and wildlife habitats, alteration of freshwater flow into estuaries, channelization that increases saltwater intrusion into brackish or freshwater areas, the introduction of toxic chemicals and pathogens, and eutrophication confound our knowledge of fish and wildlife habitat relationships. Since our knowledge of these relationships is far from complete, the regulations that have been promulgated to protect wetlands are also less than adequate.

Information Needs

If our ultimate goal is to quantify wetlands, many pieces of information are needed:

1. Wetland/Upland Boundaries
   - (a) Jurisdictional
   - (b) Natural
2. Plant Cover Types (to species level of identification)
3. Wetland/Upland Hydrology
4. Wetland/Upland Changes
   - (a) Natural
   - (b) Man-Induced (legal and illegal)
     - (i) dredge and fill
     - (ii) marinas
     - (iii) impoundments
     - (iv) drainage
     - (v) other
5. Upland Drainage Pattern
6. Wetland/Upland Watershed Boundaries
7. Wetland/Upland Habitat Changes
8. Wetland/Upland Water and Uses
9. Water Quality (pH, D.O., salinity, carbon, organics, inorganics)
10. Topography
11. Nutrient Exchange

Usefulness of Remote Sensing Methods

Table 2 lists the twelve information needs and areas, and ranks various remote sensing methods for obtaining data. The Panel is of the opinion that the technology for obtaining remotely sensed data of wetlands and uplands is quite useful, but feel that some of the data that are available for use could be made more "user friendly." All data should be stored digitally, a standardized land cover/land use classification system should be used, and area coverage should be repeated every one to five years. Interagency coordination on research progress could be improved. Advance notification of projects planned would enhance cost sharing and provide each agency more data for less cost. There is a definite need for "noiseless" data by the user. A clearing house through which coastal research and management interests could screen and require good quality, standardized digital data would greatly facilitate the use of remotely sensed data by all users. The number of users probably would increase if better data were available.

1.2 IMPEDIMENTS TO MONITORING EMERGENT TIDAL WETLANDS

Periodicity of Satellite Passovers

One of the major problems encountered by potential users (wetland scientists/managers) of satellite imagery is the limited time in which the target areas are sensed (time coverage of orbital platforms). Ideal conditions such as low tide, peak standing crop, and little or no cloud cover seldom coincide. On the other hand, utilization of aerial imagery can be controlled more readily.

Cost of Imagery (Scene)

The cost of a particular scene can be prohibitive for many users. A high resolution scene of the Lower Chesapeake Bay (180x180 km), for example, costs about $3,300. Electronic peripherals (hardware and software) range between $35,000 and $150,000. The interpretation process is also demanding of the average minicomputer in a multi-user situation. Late night work is often necessary in order to obtain full use of the program. Dedicated processing systems can greatly reduce this burden.

Resolution

The current resolution of Landsat imagery is useful only in broad to mid-level wetland classification studies. The National Wetlands Classification System and many state systems are generally too detailed for reliable satellite imagery interpretation. Landsat imagery appears to work well for monospecific wetlands such as salt marshes dominated by *Spartina*

Table 2. Performance and Availability of Remote Sensors for Wetlands/Uplands Studies

Sensor	Plat-form	Wet-Land Bound. Extent	Species Compos. of Veg.	Land Use	Species Compos. of Fauna	Produc-tivity/ Biomass	Water Qual.	Hydraul. Tidal/ River	Fresh-/ Salt-Water Dynam.	Envir. Stress	Geol./ Soils	Data Mgt.	Meteorol.
							*1		*2				
Film	A	4	4	4	2	4		Needs det.		4	4	-	0
Cameras	S	3	3	3	0	3		features		3	3	-	0
Multispectral	A	1	1	1	1	1		1		1	1	-	1
Scanners	S	3	3	3	0	-		1		3	3	-	0
Thermal IR	A	1	1	1	0	0		1		2	1	-	2
Scanners	S	1	1	1	0	0		1		1	1	-	2
Laser	A	-	-	-	-	1		1		-	-	-	-
Profilers	S	-	-	-	-	1		1		-	-	-	-
Laser	A	0	1	0	0	0		0		0	0	-	0
Fluorosensors	S	0	0	0	0	0		0		0	0	-	0
Microwave	A	1	1	1	0	0		0		0	1	-	0
Radiometers	S	1	1	1	0	0		0		0	1	-	0
Imaging	A	1	1	1	0	-		1		0	1	-	-
Radar	S	1	1	1	0	-		1		0	1	-	-
CODAR (Radar)	G	-	-	-	-	-		-		-	-	-	-
RADS (Acoustic)	G	-	-	-	-	-		-		-	-	-	-
Video Data	G	1	1	1	1	1		1		1	-	1	-

*1: See Water Column Panel. *2: See Water Column Panel.

<u>Rating</u>
4 = Reliable and Available for High Resolution/Quantitative Analysis
3 = Useful for Low Resolution/Quantitative Analysis
2 = Limited Use/Qualitative
1 = Experimental and/or Not Widely Available
0 = Not Applicable

<u>Platform</u>
A = Aircraft
S = Spacecraft
G = Ground

<u>Other Considerations For Ranking</u>
Spatial Resolution
Radiometric Range & Sensitivity
Coverage
Cost

alterniflora, but more diversely vegetated wetland areas (tidal freshwater marshes) are much more difficult to interpret. According to the literature, biomass estimates of salt marshes are possible and reasonably accurate using satellite imagery.

Many coastal states have a large number of small marshes (less than one acre) that often occur along tidal tributaries. Virginia, in particular, has numerous secondary and tertiary waterways that eventually connect with major rivers or Chesapeake Bay. Small marshes of various configurations are very seldom detected by satellite imagery, particularly narrow fringing marshes and those shaded by tree canopy. Despite their small size, these marshes are ecologically valuable to the estuarine system. It is important for scientists and wetland resource managers to monitor such wetlands because they often occur in areas of urban development (at least in Virginia).

Despite the problems in using satellite imagery, there has been success in classifying large segments of tidal riverine wetlands in three major categories: (1) oligohaline (dominated by Spartina cynosuroides); (2) tidal freshwater marshes (high diversity of herbaceous wetland vegetation); and (3) tidal freshwater swamps (dominated by trees). Unfortunately, the various plant communities commonly found within these three wetland types can seldom be differentiated using satellite imagery.

Landsat imagery has a real potential as a useful tool in estuarine research; however, resolution needs to be improved in order to attract more users.

Atmospheric Effects

A number of algorithms have been developed to correct Landsat digital images for atmospheric and illumination effects. The algorithms can be grouped into three general categories: (1) corrections based on in situ measurements of atmospheric parameters collected at the time of the overflight (e.g. Bartlett et al. 1977, Rogers et al. 1973); (2) atmospheric models requiring parameters measured from nearby first-order weather stations (e.g. Foster 1984, MacFarlane and Robinson 1984, Otterman and Robinove 1981); and (3) corrections determined empirically from the imagery (e.g. Ahern et al. 1977, Alfoldi and Munday 1978, Lindell et al. 1985, Potter 1984, Potter and Mendolwitz 1975, Switzer et al. 1981). Some coastal areas have a high incidence of cloud cover, making in situ measurements of atmospheric parameters at the time of the Landsat overflight expensive and uncertain. All three types of algorithms are usually global corrections, and therefore assume a spatially uniform atmosphere across the entire area of interest. From the practical standpoint, however, coastal wetlands are sometimes located at appreciable distances from the stations where atmospheric parameters for the model are measured. Thus, the investigator is forced to assume a spatially homogeneous atmosphere when, in reality, atmospheric effects may be markedly different between the study area and station where the data for the correction algorithms were collected. The third type of correction algorithm may offer the most potential since most users rely on imagery retrieved from the archives.

From the user's perspective, there are a bewildering array of atmospheric corrections for Landsat data, with no clear-cut indication as to which algorithms perform adequately for coastal land cover and land use. Users may not have access to atmospheric correction programs or have the resources to evaluate the adequacy of various algorithms for use in coastal wetlands. Thus, some effort needs to be directed towards determining which atmospheric correction algorithms work by assessing the results in a rigorous manner, e.g. using signature extension techniques or change detection over coastal areas where the areal extent and identity of land cover is known.

Image Registration

Image registration is the process of digitally warping an image to fit the coordinate system of another (scene-to-scene registration), or a map projection (scene-to-map registration). Accurate registration is an essential step prior to conducting analyses to inventory and monitor coastal resources through:

- multidate image files for change detection or to enhance classification accuracy
- field operations to collect surface truth information
- incorporating collateral (non-image) data into the analysis to augment the classification process
- temporal change analyses.

Ideally, subpixel registration accuracies are required for some analyses such as quantifying shoreline changes related to erosion or accretion. In practice, however, subpixel accuracies are seldom achieved for change detection problems in coastal areas, and actual changes in the positions of habitat boundaries are confounded with errors of registration. In particular, accurate registration of LANDSAT MSS images is difficult because the 80 m ground resolution of the scanner obscures most fixed landmarks suitable for ground control points. High resolution imaging systems such as Landsat Thematic Mapper and the French SPOT satellite should allow more accurate registration.

Each user seems to handle the registration in his own way, depending on the application, constraints imposed by the time and costs involved, and the computer hardware and software available.

Some effort should be directed toward improving methodologies to register digital images:

- determine the optimum number and spatial distribution of ground control points required to minimize mapping errors and processing costs

- improve techniques for transforming the image coordinates into a map projection

- incorporate better techniques into registration software to allow rapid assessment of registration accuracy

- determine the optimum resampling techniques for digital images of estuarine areas.

Tidal Levels

Tidal fluctuations are a prominent characteristic of estuaries and may complicate the analyses of multi-date LANDSAT digital images by introducing broad-scale spectral variation into some types of coastal land cover. Variation in tidal height can affect analyses of digital images in at least two ways: (1) marked differences in land-water ratios between images made on different dates (Carter and Anderson 1976, Faller 1977); and (2) causing some estuarine land cover (e.g. mud flats and open water) to become spectrally indistinguishable using automated classification techniques (Bartlett et al. 1977).

The effects of tidal level changes on image analysis may vary in relation to several factors:

- ground resolution of the scanner
    - tidal height at the time of the overpass
    - landward distance from the coast
    - species composition and density of emergent marsh vegetation

- size frequency distribution of waterbodies
    - level of convolution in the shoreline.

More work is needed to quantify the effects of tidal fluctuations on the analysis of digital images of estuarine areas.

Radiometric Noise

Radiometric artifacts are present in both LANDSAT MSS and TM digital images:

- Striping Noise: caused by slight differences in gain among the several detectors used for each band, and visually appears as stripes in areas of nearly-uniform radiance, e.g. large expanses of open water.

- Coherent Noise: thought to be the result of electronic or mechanical oscillations onboard the satellite (Bernstein et al. 1985, Anuta et al. 1984) that introduce noise resembling a woodgrain or herringbone pattern in the images.

The presence of radiometric noise in one or more spectral bands may become troublesome to the analyst when image enhancement techniques are used to highlight the various attributes of a given scene. Since noise is seldom correlated between pairs of spectral bands, techniques such as band ratioing will worsen the problem by enhancing the noisy pixels and, thus, markedly detract from the interpretability of the output image. Noise may also have a tendency to lower the accuracies of Thematic maps derived from automated classifications of single or multi-date Landsat data files. Reduced map accuracies may be the result of increased confusion among certain spectral classes, resulting from the additional statistical variability introduced into the image by the noise components. There is some evidence suggesting that even low-level noise can mask some low-contrast features in Landsat TM images of open water areas (Anuta et al. 1984).

1.3 A NEED FOR AN ACCEPTED STANDARD SYSTEM OF WETLAND CLASSIFICATION FOR A NATIONAL PROGRAM

Wetlands is a term generally recognized by statesmen, laypersons and scientists. However, within the environmental and habitat assessment community, there are a multitude of classification schemes that are employed to describe wetlands, and various habitat types that fall under this term. Each is designed with specific needs in mind which, unfortunately, often result in information incompatibility.

NOAA's National Marine Fisheries Service (NMFS) and National Ocean Service (NOS) have begun an inventory of the nation's coastal wetlands by compiling and evaluating existing coastal wetlands acreage information for the contiguous United States. The purpose of the project is to summarize existing data by state and coastal county to form a national database of wetland acreage. This information should be useful at several levels, including coastal management decisions, status and trend studies, and fisheries habitat research. This effort complements ongoing efforts in the USFWS, and NOAA is working closely with this agency.

The data phase of the project has been completed and several problems with the data have become apparent. One of the most severe problems is the variation in wetlands definitions, classification schemes, and between states and inventory techniques. Since 1979, the most widely accepted wetlands classification has been that of Cowardin et al. (1979), developed for the National Wetlands Inventory of the USFWS. However, many of the coastal states conducted their inventories prior to 1979 and used a variety of classification schemes suited to their own needs.

During the initial stages of the project, we decided that the Cowardin system would be the standard for the database and that all data that did not use this scheme would be converted to Cowardin equivalents. However, a problem arose with some states that grouped several wetland types into broad categories which could not be disaggregated. Under these circumstances, conversion to the Cowardin system was not always practical.

The wetlands inventory being conducted by NOAA demonstrates the need of a nationally accepted wetlands classification scheme. While the classification schemes developed by individual states may meet their own needs, they do little for decision-makers or researchers required to make comparisons on a regional or national scale. The growing acceptance and hierarchical design of the Cowardin system makes it the logical candidate for any future inventory effects. Its hierarchical nature allows for classification of fine detail where such data exists or the aggregation of detailed data into more general data sets. This also makes it ideal for future use in digital databases and geographic information systems. Future expansion of the Cowardin system to cover adjacent uplands may further strengthen this method of classifying our nation's wetlands.

1.4 TECHNOLOGY

Aerial Photography

Aerial photography is the traditional remotely-sensed data used for land cover and land use mapping. Today, it is still the most reliable, accurate and cost-effective means of acquiring precise, detailed information on wetlands and uplands. Interpretation of aerial photographs provides the most accurate means of delineating precise wetland boundaries and cover types. A major advantage is that aircraft can be sent up at required periods to collect remotely-sensed data for special purposes. For example, identification of low tide throughout a single large estuary requires a special mission and considerable planning, since some upstream portions are still flooded while downstream areas are experiencing low tide. This is essential to accurate assessment of shoreline changes such as erosion of wetlands.

Aerial photointerpretation techniques are widely used by government agencies, universities, and private consulting firms, and aerial photography is readily available to virtually anyone. The National High-Altitude Photography Program has produced recent aerial photography for most of the country, and the remaining areas are under contract. The country, therefore, should have complete high-altitude photo coverage within the next two to three years. This photography has enormous utility for wetland and upland mapping. Other scales of aerial photography are also widely available to satisfy the varied needs of users.

Satellite Technology

This discussion will focus on some of the important facets of satellite technology which are pertinent for monitoring, mapping and assessing wetlands and uplands. When considering a sensor application and design, the following characteristics are important:

- Orbit and Altitude: governs spatial resolution, sun angle and time and sequence of repeat coverage.

- Spatial Resolution: governed by altitude and telescope optics. As ground resolution increases, the potential for detailed feature extraction occurs, but so does data volume.

- Spectral Resolution: in conjunction with spatial resolution, this is the major factor governing the ability to extract usable information from the data. Prisms, filters and specific wave-sensitive components are used to measure broad to narrow bands of wavelengths. Increased numbers of bands and selective band combinations provide the user with a necessary choice of information for feature extraction (depending on application) but, again, data volume can increase.

- Sensors are characterized as active or passive. An active type of sensor would be radar in which the sensor projects a beam and measures its return. A passive sensor measures spectral emission or reflectance without projecting the source of energy being measured.

These and many other characteristics govern the success or failure of any satellite sensor to meet the needs of a remote sensing application. Beyond the actual sensor technology, certain inherent advantages to using satellite technology are evident. As with certain aircraft data, satellite data are digital, providing easy computer manipulation. Being above the atmosphere and on a passive craft, platform stability allows for utilizing high resolution optics and easy geographic rectification to ground coordinates.

Two currently orbiting sensors, the French SPOT and the Landsat Thematic Mapper (TM), have important applications for wetland/upland assessment, primarily due to spatial and spectral resolution. The SPOT has an advantage in spatial resolution (10 and 20 m versus 30 m), while TM has a spectral advantage (7 bands versus 4 bands).

Future sensors will include higher spatial resolution (spectral resolution up to 256 spectral bands and radar), and rapid data turnaround capabilities. Satellite sensor technology advancements will provide the estuarine researcher and manager with a wealth of information, but only if research and management begin using this type of technology now. As any researcher or manager knows, the complexities of dealing with the estuaries in both a management and research mode precludes the reliance on a single data set or type of data sets. This applies to the remote sensing aspects, where satellite data become only a layer of data in a multi-facet approach. Aircraft and ground data are also integral parts, and one does not necessarily preclude the other.

There has been a general failure by the estuarine researcher and manager to effectively explore the applications of satellite technology (and for that matter, all remote sensing techniques). This reflects the past high costs of utilizing this technology and the lack of federal dollars available to develop the applications of these data, as opposed to determining the engineering specifications. Costs for computing power are being dramatically reduced, while the development of software to effectively process and extract information has and will continue to improve. The instilled perception by the estuarine manager/researcher that this is not a cost-effective nor technologically viable tool is no longer valid. This is particularly true for wetland/upland applications, with the current availability of SPOT and TM data and the ability to multi-layer data into Geographic Information Systems. If the estuarine researcher and managers do not embrace and influence the application and direction this technology takes, the cost to catch up will exceed the ability to generate the resources to do so.

Inventory Costs

Figure 1 represents an effort to incorporate many complex factors into the rather simplistic estimates required to perform comparative cost analysis. The readers of this report should be reminded, however, of the uncertainties involved, and cautioned against the use of this figure as a tool for computing the cost of any specific project. The figure is intended to show general relationships between techniques and to indicate the scales at which each enjoys its most efficient utility. This figure does not include the digitization of information obtained from the interpretation of aerial photography.

1.5 CONCLUSIONS AND RECOMMENDATIONS

Though remote sensing technology has qualified utility for some observations in wetland environments, advancements in the technology are sought to observe additional phenomena, to implement a higher degree of measurement precision for some observations, and to improve geographic coverage and frequency of data acquisition from remote platforms. The desirability of these advancements is unquestioned. The present state-of-the-art supports land cover identification in the wetlands, though with numerous constraints, and the inferences that can be drawn about environmental parameters based on such identification. Even for observations of land cover, let alone more subtle and complex phenomena, application of the technology is limited by the spectral and spatial resolution of existing sensors and their capability to provide desired spatial and temporal coverage. Other limitations and immaturity in the technology are recognized as well. The purpose of this section is to recommend areas of research where initial indications or a prior understanding suggest such research might lead to substantial advancements for what can be learned about coastal environments from remotely sensed data. Advanced sensor development, coastal science, image and data analysis, and data management are summarized below.

Advanced Sensor Development

The justification for advanced sensors to observe coastal phenomena is driven by our knowledge of present measurement requirements and other observations, if accommodated by new technology, that may provide new or additional insight into coastal wetland processes.

Spatial Resolution. Wetland plant communities, as well as other features of land cover in coastal environments, exhibit important variations that should ideally be captured by 10 m spatial resolution. Research to improve sensor spatial resolu-

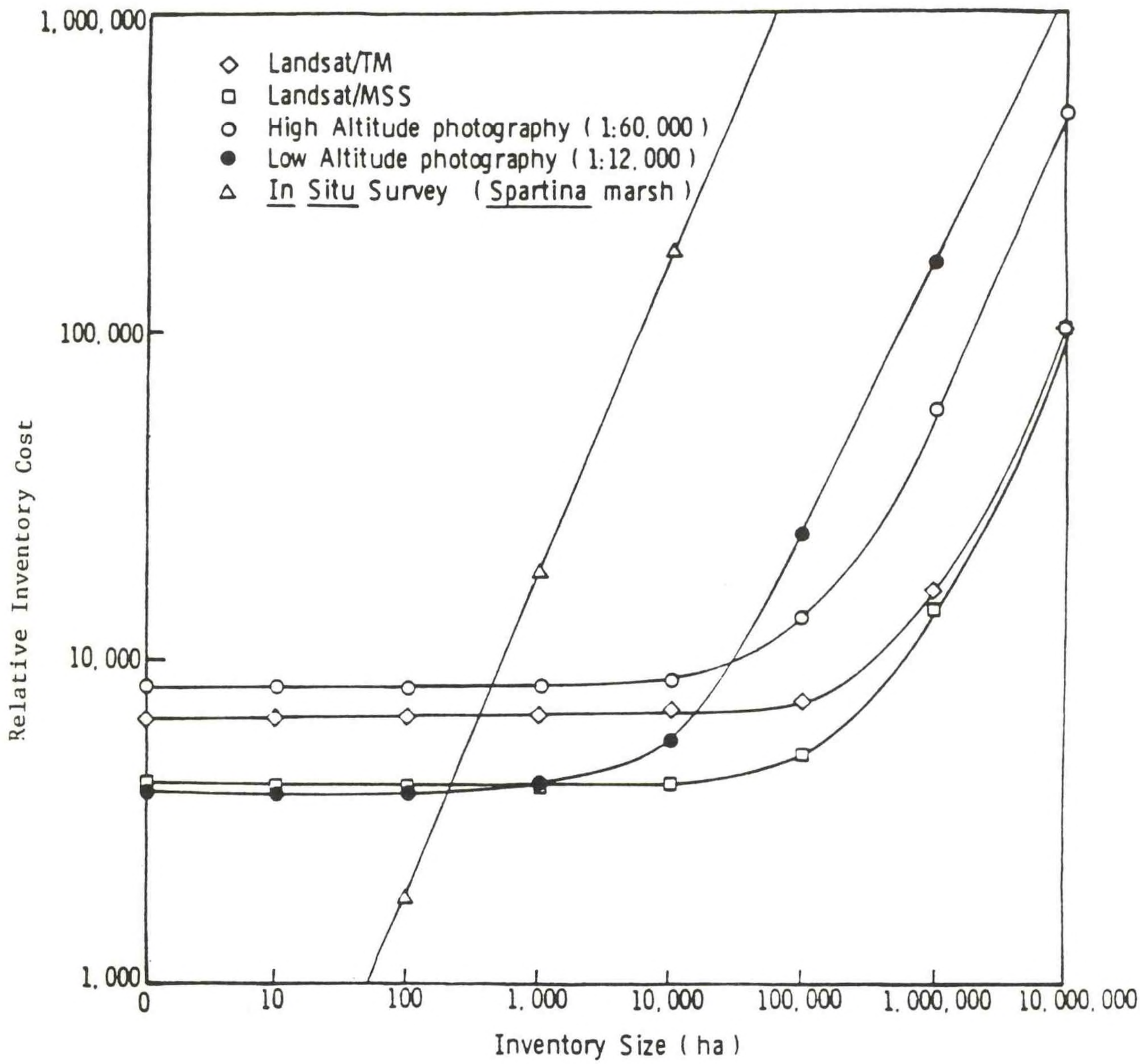
1,000,000
100,000
10,000
1,000
Relative Inventory Cost
Landsat/TM
Landsat/MSS
High Altitude photography (1:60,000)
Low Altitude photography (1:12,000)
In Situ Survey (Spartina marsh)
0
10
100
1,000
10,000
100,000
1,000,000
10,000,000
Inventory Size (ha)

Figure 1

tion to this limit would contribute significantly to the capability to learn more about wetlands from the unique and effective "remote" perspective.

Spectral Resolution. The increased knowledge about wetlands that can be learned from measurements in the full range of the electromagnetic spectrum and/or with increased precision should be an incentive for such advanced sensor development. Initial investigations with microwaves suggest that measurements of this area of the spectrum may lead to improved discrimination of wetland grasses, shrubs and forest, and provide an all-weather capability for data collection, since microwave sensors can be used to penetrate the cloudy atmosphere typical of wetlands. Early results from NASA experiments indicate that the use of multiple wavelengths, look angle and polarizations, as well as the measurement of coherent polarization, may make tremendous contributions to the characterization of wetlands from space. Research is strongly suggested in this area, and the participation of wetland scientists in NASA's planning of its SIR-series of microwave experiments on Space Shuttle missions is strongly urged.

Within the visible and infrared region of the spectrum, the results of early studies indicate that more precise measurements, such as are promised by NASA's proposed imaging spectrometer, may lead to fruitful characterization of plant internal composition and physiology, thus improving inferences about other environmental parameters such as nutrient limitations and tidal regimes. Continued research in this area is strongly recommended and, again, the early participation of wetland scientists is vital to the effective development and application of this new sensor for coastal wetland science.

Operational Capabilities. To fulfill the potential utilization of advanced sensors, operational capabilities must be concommitantly developed. These capabilities encompass the breadth of spatial and temporal coverage required to make remotely sensed data useful in wetland environmental monitoring. The ability to precisely capture tidal and/or flood events that greatly influence the present and future character of a wetlands environment, as well as plant phenology which is a seasonal phenomenon, is highly desirable. Development of geostationary platforms to meet these needs is strongly urged.

The development of real-time command of sensors, particularly pointable sensors, would also greatly benefit studies of wetland environments. Coupled with real-time video coverage of the geographic target, a sensor could be made responsive through instantaneous command from a ground team to specific locations of interest. This could benefit timely collection of both remote data and groundtruth data. Thus, development of real-time command and video display could make a tremendous contribution to both experimental and operational endeavors and is recommended as a research objective.

Coastal Wetland Science

Remote sensing offers a unique source of data achieved by a unique perspective from which to observe coastal wetlands. From an orbital sensor, a wetland environment can be viewed in the entirety of its system--all parts observed in synergism. Remote sensing provides a singular opportunity to understand wetlands as a dynamic ecosystem, the physical and biological components, and the forces of climate and hydrology which control them. It also provides a sound basis for comparative studies of wetlands throughout the world.

To take advantage of the full potential of remote sensing technology, wetland scientific research is recommended in two primary areas. First, models that describe the ecosystem and its forcing functions in a way that maximizes the use of remote sensing measurements to represent state variables should be pursued. Wetland scientists should undertake the development and testing of such models. Second, research should be undertaken to extract the maximum information available about wetlands from the integrated use of multiple sensors, both in terms of spectral wavelength components and multi-stage spatial sampling.

In support of both areas of directed research, it is essential that wetland scientists focus on correlative studies that can contribute to an interpretation of current and potential remote sensing measurements, e.g. given the specifications of an imaging spectrometer, determine which physical or biological phenomena are detectable by the increased capability of the sensor. Advancements in wetland science to incorporate remote sensing measurements are strongly recommended.

Image and Data Analysis

The development of advanced systems can provide new and different information about wetland environments only to the extent to which the meaning of the remotely sensed data is understood. Research is recommended to improve the basic understanding of how incoming radiation interacts with the wetland environment and the ambient atmosphere before its ultimate measurement by a sensor. In particular, surface water reflects energy differently from vegetative components, soil and the debris characteristic of wetlands. The reflection of energy by mixtures of target components can cause significant confusion in interpretation and should be a major focus for research. In addition, improved pattern recognition techniques can provide important new information about wetland features that can be characterized by spatial relationships.

Just as textural information can be gleaned through manual interpretation of images, automated techniques to identify patterns in digital imagery may be the tool to enhance the use of remotely sensed data in a significant way. The identification of ecotones and hydrographic features characteristic of wetlands may be accomplished through such techniques. Research should be pursued in automated pattern recognition and the results applied to wetland imagery.

Data Management

As remote sensing technology generates an ever-increasing volume of data, the community of wetland scientists should join with other Earth scientists in ensuring that improvements in data management are fully supported. System concepts and technology should be developed for the responsible archive and distribution of remotely sensed Earth data, as well as access to important in situ correlative data and measurements. Development of calibration techniques to normalize data acquired from the various sensors is essential to full utilization of remote data. Improvements in data management, standardization and calibration are strongly recommended.

Interagency Coordination

Interagency coordination and cooperation is essential as we strive to achieve effective management of the nation's estuaries, and would result in the availability and development of useful generic products for the estuaries and coastal wetlands. The development of appropriate estuarine databases for the use of managers and scientists, in fact, depends on the expertise and capabilities that reside in a number of agencies and academic institutions. Through effective coordination among themselves and academia, the agencies can assure that existing programs such as National High-Altitude Photography (NHAP) and National Wetlands Inventory (NWI) do meet the data/information needs of those concerned with the estuaries. For example, The NHAP program could include more thorough coverage of the estuaries and coastal wetlands, and the NWI program could begin to implement remote sensing technology specifically for the production of more detailed information needed in connection with periodic monitoring of resources; both programs could increase the frequency of coverage. Coordination and cooperation among agencies could also result in the development of a uniform, calibrated database of satellite imagery for the nation's coastal wetlands, a requirement of federal agencies that could also become a valuable source of data for activities conducted by state and academic institutions. It is recommended that the NOAA Estuarine Programs Office set up a working group to examine the needs for generic data/information in the estuaries and how these needs may be addressed through effective coordination aimed at the modification of existing programs and/or the development of new interagency programs that would utilize current remote sensing technology.

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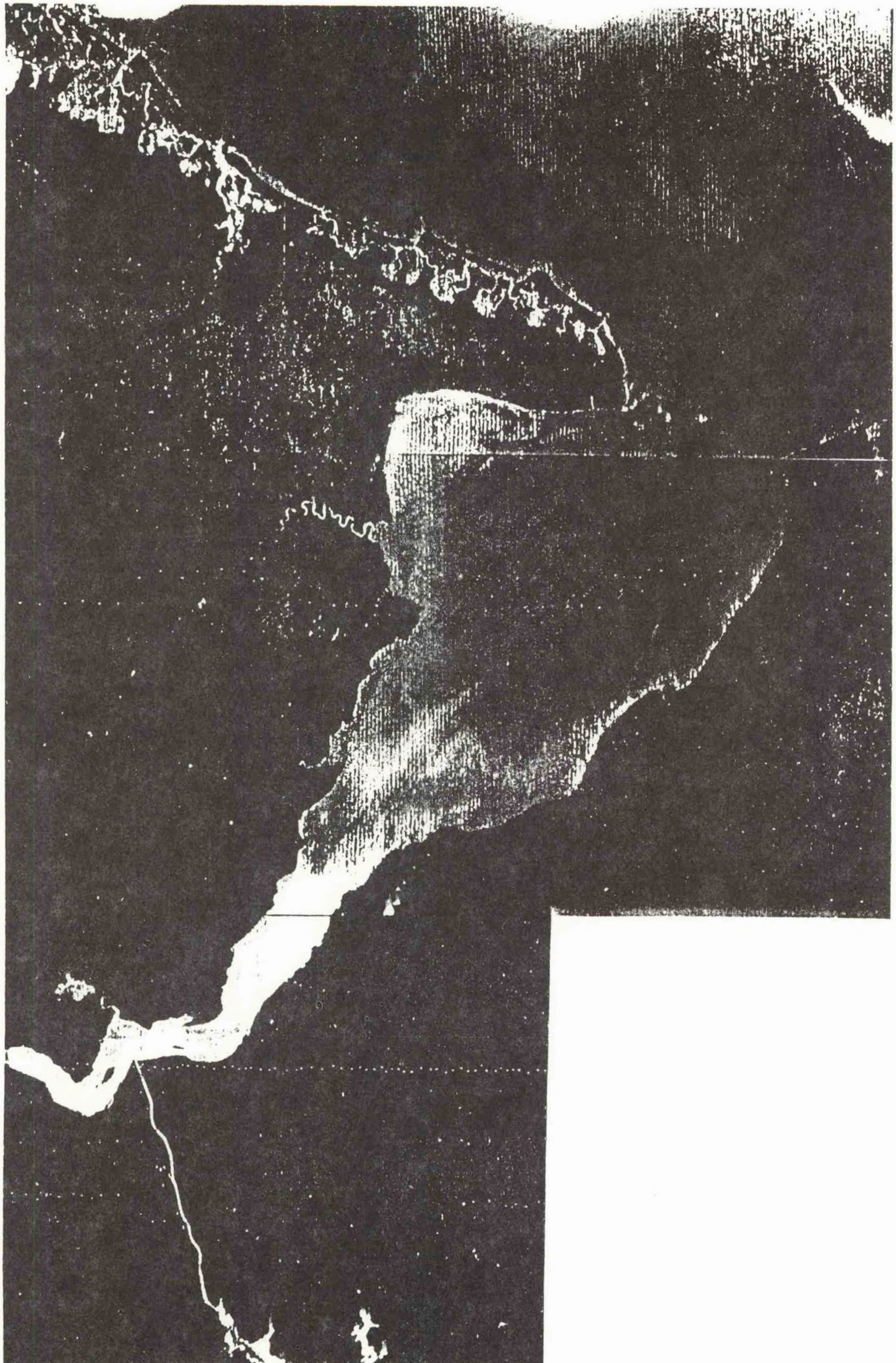
Color enhanced suspended sediment concentration map of Delaware Bay derived from Landsat multispectral scanner (MSS) data. Sediment concentrations are derived from non-linear regression equations. Orange color represents radiance levels corresponding to 211 mg/liter and green 104 mg/liter sediment concentrations.



2. PANEL ON REMOTE SENSING OF WATER COLUMN PROPERTIES

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2.1 ISSUES CONCERNING WATER COLUMN PROPERTIES

There are three major issues concerning estuaries and their management which relate directly to water column properties and which can conceivably be enhanced by information gathered through remote sensing. These issues are (1) water resource management (study and monitoring of estuarine and tributary fresh waters), (2) living resource management, and (3) control of point- and nonpoint-source pollution.

Water resource management involves research and monitoring of the water quality of the estuary. This typically implies a determination of the physical water characteristics as well as the type and quantity of materials found in the water of the estuary and supplied to it through streams and runoff. In this context, the value of remote sensing would be determined by the degree to which it can provide information on the amount, distribution and movement of the various substances in the water or aid in obtaining the needed information.

There are several types of systems which can be of use. Surface temperature distributions are routinely measured with thermal infrared radiometers; surface salinities can be measured with airborne passive microwave radiometers. In both cases observations are limited to the water surface (top few millimeters). The SST measurments are fully operational with RMS errors of 1.0°C. Salinity measurements are functional in research with accuracies of 1 ppt. Neither require surface calibration.

Observations of water column characteristics are accessible only to systems operating in the visible region of the electromagnetic spectrum or to acoustic systems. Ship-based acoustic systems have been used to locate and map the horizontal and vertical distribution of particles in the water column, to locate density discontinuities and to map the distribution of fish. Optical imaging systems on aircraft and satellite have been used to map vertically integrated chlorophyll and sediment distributions. In either case, detection depends on the unique spectral characteristics of the target. Because of the intimate optical interrelation of the sediment, organic detritus and chlorophyll, distinction among these targets is difficult. More promising for chlorophyll and dissolved organic carbon (DOC) is the use of aircraft laser fluorosensing systems which can be "tuned" to the absorption and fluorescence of a specific target. The potential of such systems has been demonstrated and they have been used extensively in research field experiments, but they are not fully operational.

In living resource management, the major concerns at present are eutrophication and habitat degradation. Much of the information required to evaluate habitat conditions is the same as that required for water quality management. One additional parameter which is accessible to remote sensing is an estimate of the depth of the photic zone. This has been estimated using spectral (visible region) data and laser Raman scattering observations.

Early detection and monitoring of eutrophic conditions in an estuarine system requires monitoring of organic and inorganic nutrients. Any ability of remote sensing to identify sources or track the inputs and disposition of nutrients would be of value even if the methods are somewhat indirect. The addition of nutrients to an estuarine system frequently results in intense algal blooms and the production of organic matter. Such organic matter, if it sinks through a pycnocline and into bottom water below the euphotic depth, respires and decomposes utilizing oxygen and producing hypoxia or anoxia in bottom water. Thus the use of remote sensing to locate the source of the bloom (by means of changes in chlorophyll or other indicator), to follow its development, demise and transport would be of use. Such a bloom can develop over a period of only several days, drift, and disappear in several more, making it quite difficult to first find and then follow by ship.

In estuaries, unlike lakes, eutrophic conditions will not necessarily be marked by obvious blooms; subtle changes in nutrient concentrations may be the major indication of eutrophication. Nutrient over-enrichment frequently leads to a change in the algal population or phytoplankton species make-up. Changes in the species and cell size can result in major changes in the food web or to the fisheries themselves. The potential for differentiating among major phytoplankton types and detecting changes in species composition, distribution and abundance has been demonstrated using airborne laser fluorosensing systems.

The third major issue concerning estuaries is control of point- and nonpoint-source pollutants. Discrimination of toxic or pathogenic materials, and identification of their sources, trajectory, dilution, dispersal and fate is desired. In a few cases the pollutant can be detected and identified remotely. Oil, for example, can be identified and tracked by several remote means as long as the oil remains on the water surface. There also exists some possibility of detecting oil and other pollutants in the water column using laser induced fluorescence or Raman scatter if the substance either fluoresces or has a strong Raman signal. Preliminary evidence exists indicating that oil and several priority pollutants (toluene, phenol, o-chlorophenol, p-nitrophenol, 2,4-dinitrophenol, and xylenes) may be detectable using this approach. Such methods would be strong candidates for research.

In most instances, the contribution of remote sensing will be to provide indirect indicators of the pollutant. For example, contaminants frequently associate with suspended particulate material making the remote observation of suspended sediments of some interest. A pollutant may alter the spectral reflectance or fluorescence of naturally occurring substances (chlorophyll, DOC) and this alteration could be useful as an indicator of a problem.

The majority of these estuarine information needs can be served by remote sensing to some extent. The potential that has not yet been realized is to integrate appropriate remote sensing techniques with other sampling activities in the estuaries of concern in order to meet specific information needs.

Table 3 identifies the applicability of remote sensing techniques to the collection of data on water column properties that is necessary to estuarine research and management. An evaluation of the technique's operational level is provided on a scale of one to five with five being operational (functionally dependable instrument with interpretable output of high confidence on continual basis). The evaluation is made assuming that the remote system is used for extrapolation of in situ observations. Each technique is also categorized according to the type of observation. Surface (S) implies a penetration depth of a few centimeters at most. Integrated (I) refers to measurements of subsurface characteristics integrated from the surface to the depth of penetration -- a depth which varies with the technique and the optical properties of the water. Profiling (P) describes instruments which are capable of providing information on the vertical distribution of the target parameter.

2.2 REMOTE SENSING MODES OF OPERATION

For remote sensing to be useful in any application, it should be able to provide information that is unavailable from other sources or to provide data more efficiently than would otherwise be possible. In most cases, remote sensing is only one of several data gathering tools, and it may play a variety of roles in a research or decision making process. For the present purpose, it is useful to specify three characteristic roles that remote sensing plays in a data gathering exercise. These are (1) surveillance, (2) extrapolation and (3) identification and quantification.

In the surveillance mode, remote sensing data is used to monitor changes. The phenomenon observed may only be an indirect indicator of the phenomenon of interest. However, if the remote data is relatively inexpensive compared to more definitive techniques or if it provides coverage that is difficult to obtain by standard sampling methods, then it can be invaluable in designing a sampling scheme that will optimize the available resources. As an example consider a sampling problem that is associated with the development of estuarine fronts. A spotter aircraft in radio contact with a ship can guide the ship to

Table 3. Applicability of Remote Sensing Techniques to Data Collection on Water Column Properties

The evaluation is made on the assumption that the remote system is used to extrapolate from in situ observations.

	Salin.	Temp.	Chl.	Sed.	DOC	Opt. Depth	Oil	Nutrients and Toxics	Pycnocl and Fish
Aircraft/Satellite:									
Visible/IR Spectra	-	-	4/I	4/I	2/I	4/I	5/S	-	-
Thermal IR	-	5/S	-	-	-	-	5/S	-	-
Passive U-Wave	4/S	4/S	-	-	-	-	5/S	-	-
Aircraft:									
Laser Fluorosensor	-	-	4/I	4/I	3/I	4/I	4/S	-	-
Laser Raman	2/I,P	2/I,P	-	-	-	-	2/P	2/P	-
Laser Profiler	-	-	1/P	3/P	-	3/P	2/P	-	2/P
Photo/Spotter (qualitative)	-	-	1/I	5/S,I	-	-	5/S,I	-	5/S,I
Video	-	-	1/I	1/I	-	-	5/S	-	-
Shipboard:									
Acoustic Sounder	-	-	-	4/P	-	-	-	-	5/P

S = Surface
I = Integrated Volume
P = Profiling

- Not Applicable
1 Limited Utility
2 Potential Utility, Research Needed
3 Demonstrated Potential, Field Tests Required
4 Functional, Not Yet Operational
5 Operational

appropriate sampling sites and help to insure that the ship's position is adjusted as the frontal system develops. Similarly, a satellite-based imaging system (MSS, TM, AVHRR, CZCS) could possibly be used to monitor changes in chlorophyll or suspended solids in an estuary. Detection of some characteristic change in the indicator target could be used to signal the start of a sampling program and aid in the design of the sampling scheme. Aircraft offer finer spatial and temporal resolutions, while satellites cover larger areas and provide regular coverage that eliminates scheduling problems. It is worth noting that both examples imply real-time or nearly real-time availability of the remote data. This is often a necessary characteristic of the surveillance mode of operation.

A second common mode of operation for remote sensing is to provide data which will allow extrapolation from a few selected "surface truth" data points. This is probably the most common and effective way of using remote data. A good example of this sort of application would be the use of laser fluorosensing to map the horizontal, surface distribution and quantity of chlorophyll or DOC. At present, laser fluorosensing data do not yield absolute concentrations. However, an aircraft laser system can be used to map the relative distribution of either chlorophyll or DOC over an area that is too large to be covered by a boat in a time that is short compared to typical tidal fluctuations. Coupled with relatively few ship-based measurements to provide absolute concentrations, the laser data can be calibrated, with the end result being a concentration distribution map that neither ship nor aircraft could have obtained alone.

The third mode of operation, identification and quantification, is both the most limited in scope and the most difficult. This is particularly true in estuaries where the complex mix of substances in water makes differentiation particularly difficult. For example, remote estimates of chlorophyll distribution and concentration have been made almost routinely in ocean waters using passive spectral data. The same techniques fail in some or many estuarine waters where the increase in suspended sediments makes unambiguous identification and quantification of either chlorophyll or sediment much more difficult.

Laser-induced spectral fluorescence and Raman scattering are the most promising remote sensing techniques for identifying or quantifying specific substances since both techniques rely on physical interactions that are peculiar to the particular molecular species. Both techniques are still experimental for most applications, but are fully functional for several important water column properties (see Table 3).

There are several difficulties associated with the use of remote sensing. Effects of cloud cover and lack of depth penetration are problems often cited as objections to the use of satellite remote sensing. Also cited are the lack of accessibility and expense of remotely sensed data, and the difficulty of obtaining remote data in real-time or even near real-time. An additional factor is the fact that remote sensing is complex and requires a multidisciplinary background. Finally, like any other analytical technique, remote sensing alone does not provide complete answers for studies in marine pollution. In situ sampling is required in many instances for optimal qualitative interpretation of remote data.

In spite of the difficulties mentioned above, remote sensing does add to our ability to understand complex and dynamic estuarine areas primarily by 1) providing synoptic and detailed information for the surface field in which in situ measurements at isolated locations are made and (2) directing surface ships to key areas to maximize sampling ability. It should also be noted that remote sensing technology and data processing is a rapidly advancing field.

2.3 CONCLUSIONS AND RECOMMENDATIONS

Remote sensing for estuarine studies is no panacea; however, incorporating remote sensing into a study or management plan can be both useful and cost effective if the techniques and mode of operation are appropriate. It would appear that properly equipped aircraft could be used immediately to provide data, the cost of data acquisition being the major limitation in many cases. Information from satellites is more widely available, although it is also costly and its utility limited by the design of the existing satellites and the capital costs of new satellites. The primary need, however, is to be able to apply existing remote sensing techniques to specific applications. It is of crucial importance that remote sensing be applied at the appropriate level and integrated into the study plan. While only the more operational of the remote systems can be thoroughly integrated, the more experimental techniques should be included whenever feasible with the goal of encouraging the development of the technique as a practical tool.

Recommendations

(1) Incorporate cost-effective, operational remote sensing techniques as an integral part of existing data collection programs. Emphasis should be given to the ability of remote sensing to optimize sampling strategies and to extrapolate from and interpolate between surface in situ observations.

(2) Include experimental remote sensing techniques in data collection programs whenever possible. Potential users must be involved in the development of new techniques and systems to ensure applicability, assure the collection and availability of the *in situ* data necessary for calibration, and to provide field-testing of the techniques on actual estuarine environmental and scientific problems.

(3) Support research for the more promising remote sensing techniques. Particular attention should be given to developing techniques for:

   a. Improving techniques that collect subsurface information on living resources, water properties and materials,

   b. Detecting and measuring toxics and nutrients,

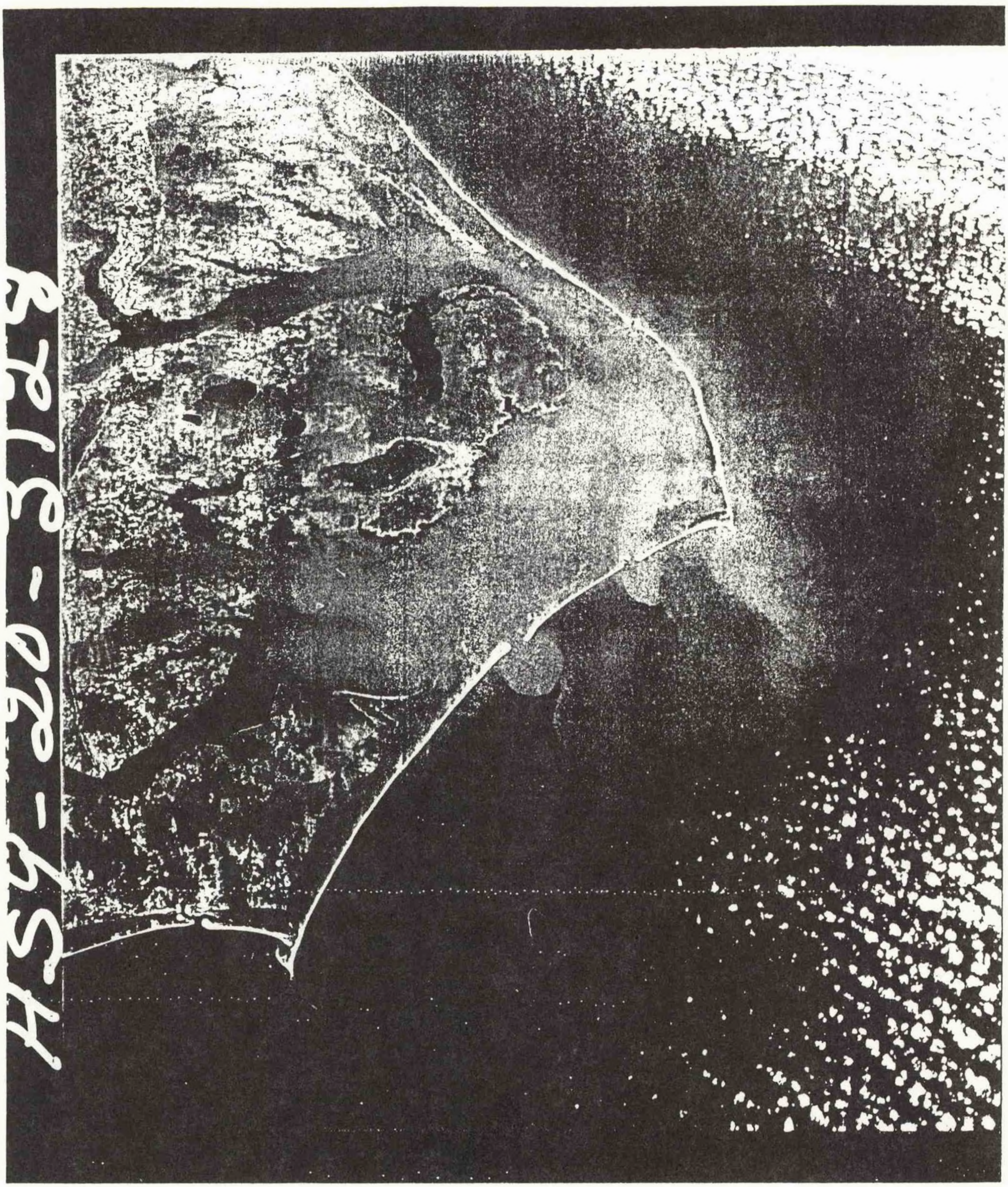
   c. Decreasing ambiguities in observations between water column properties.

(4) Coordinate development of techniques and remote sensing systems with estuarine management needs, including both monitoring and research, in order to assure effective and efficient new systems.

(5) Encourage a long-term commitment to make satellite data available and suitable for estuarine purposes. This will involve incorporating adequate sampling resolution and frequency in new satellite sensors.

(6) Facilitate transfer of remote sensing technologies to the estuarine research and management communities.

Apollo IX color photograph of the North Carolina Coast, taken March 12, 1969. The photograph is significant in showing that satellite imagery can be used to detect water masses, large scale sediment patterns as well as inferring coastal processes. Plumes of discolored water are shown to be emanating from Ocracoke and Hatteras Inlets and are the ebb tide discharges of low density, highly turbid water. The boundary between the Gulf Stream and the turbid continental shelf water is visible further offshore. Watermass variability patterns, shown by color space photographs, in conjunction with pertinent historical and environmental data, plus a concurrent ground truth collection program, can provide valuable synoptic, oceanographic data.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WORKSHOP PANEL REPORTS

3. PANEL ON PHYSICAL PROCESSES AND ESTUARINE DYNAMICS

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3.1 INTRODUCTION: USES OF REMOTE SENSING DATA

The wide range of potential uses of remotely sensed data makes it difficult to prepare a single set of requirements. Agencies such as NOAA, COE, EPA and the Coast Guard have operational needs which can be met in part by remote sensing technology. These needs may be satisfied by data for which the primary consideration is delivery and processing on a real-time or quick turn around time basis. These uses include ship passage and navigation, assessment of shore erosion and bathymetric changes, sediment transport, flooding and storm events, etc. Monitoring programs that seek to identify long-term trends in physical or biological parameters need data which can be generally collected at more widely spaced time scales (e.g. weekly or biweekly), but which must continue over long periods of time. Remote sensing of surface temperature, turbidity, chlorophyll-a (and possibly salinity and organic constituents when technologies are refined) can be integrated with existing ground-based (e.g. shipboard) programs to provide synoptic data over the entire estuary, with the monitoring program providing groundtruth for the remote sensors. Since these data are usually archived, more flexibility is allowable in data reduction and delivery time. Reliance on remote sensing alone (e.g. with little or no ground truth) for monitoring is constrained by accuracy and precision of existing instrumentation, as well as spatial resolution. Physical oceanographers and estuarine modelers require reliable quantitative data, often at very short (i.e. tidal or less) time scales and, in most cases, vertical profiles as well as surface features. The synoptic surface view provided by satellite or high altitude imagery is primarily useful in assisting the interpretation of data obtained from shipboard or ground-based sensors through qualitative delineation of surface features (e.g. fronts, slicks, etc.), and quasi-quantitative estimates of parameters such as turbidity, chlorophyll, salinity and surface current velocities. Spatial resolution of some sensors is currently inappropriate for widespread application in estuarine studies, while temporal coverage of most systems does not approach the resolution necessary to study processes at tidal (or shorter) time scales. Certain systems (e.g. Remote Acoustic Doppler System [RADS]) have utility for supplying velocity profiles over short time periods, albeit at single points in space.

3.2 ESTUARINE SCALES

Estuarine scales can be regarded as resulting from the primary effects of the shape of the basin, and the secondary effects of the hydrodynamics of the coastal circulation, the wind driven circulation and the interactions of these features.

Primary scales are:

a. Width (0.5-20 km)
b. Shape (i.e. shoreline morphology)
c. Bathymetry (0-200 m)

Secondary scales are:

a. Front Width (2 m-2 km)
b. Length (2-30 km)
c. Vertical extent (2-100 m)

<u>Time</u>:

a. The primary energetic time scale for U.S. east coast estuaries is the semi-diurnal tide (12.5 hours); in fact, the energy spectra computed from long-time series of data exhibit a dominant peak at the corresponding frequency in many estuaries. Also of some importance along the east coast, but much more so along the Gulf and West Coasts are the diurnal period tides that may dominate the quasi-periodic circulation, as in the Gulf of Mexico, or appear as a major component of mixed tides, as for the West Coast.

b. Perhaps second to the tidal currents in importance are wind-driven components of circulation responding to atmospheric forcing, typically on the order of 4-8 days in time scale. This behavior is a consequence of the propagation of major storm systems across the U.S. continent.

c. Seasonal cycles are, of course, important to the physical chemical, biological and geological processes of the estuary, and also to the long-term baroclinic component of the circulation. The seasonal march of temperature and salinity, mainly through river discharge, determines the long-time scales of flow on the order of months.

d. These seasonal fluctuations are also responsible for the vertical structure of the water column which, together with the intensity of the circulation, basin shape and short-term atmospheric forcing, determines the time scale of internal waves, e.g. tidal period, internal seiches, short period, Langmuir circulations, as well as the development of turbulence, especially near the surface and bottom and, of course, the microstructure in temperature and salinity, which contributes to the time scales of diffusive mixing.

3.3 PERCEPTIONS OF USER COMMUNITY

Qualitative vs. Quantitative: Users seem to agree that while qualitative information may be helpful, we are ultimately interested in quantitative applications.

Some sensors just don't give useful data products for many and varied applications because of the limited spatial and/or temporal resolution.

Information: There are at present no good seminar or educational courses to teach practicing oceanographers about specific oceanographic applications. Information about imagery (satellite or high-flying aircraft) sources and retrieval, etc., is generally lacking.

Merging data sets: e.g. satellite with *in situ* Geographical Information System capabilities, etc, is an important prerequisite to the widespread application of satellite data in estuarine applications.

Integrated multidisciplinary teams, i.e. remote sensing experts with biologists and physicists are required to obtain maximum utilization of satellite or any remotely sensed data.

Many systems are really not operational for users because of limited accessibility to either data or image analysis systems. Data quantity and data formats may preclude useful application of these data.

3.4 IMPORTANT VARIABLES

The important variables delineating the dynamics of estuaries, which are amenable to remote sensing are:

Velocity
Temperature
Salinity
Waves and Tides
Wind Velocity
Sediment
Transparency
Chlorophyll and Other Biological Tracers and Integrators

The necessary characteristics of remote sensing systems in measuring those variables are described in the paragraphs below.

3.5. COMMENTS ON DATA UTILITY

Accuracy and Precision

Accuracy is a function of the groundtruth system and data analysis noise, and also affects the accuracy and the calibration process necessary to assure the quality of the data. Systems that require extensive groundtruth collection or difficult calibration procedures are not preferred.

Precision reflects the sensitivity and reliability of the instrumentation. Some existing instruments have been designed for land or open ocean systems and thus have lower capabilities to discriminate features of relatively turbid estuaries or nearshore environments.

Qualitative vs. Quantitative

Qualitative information can be used by quick-response operational programs in support of long-term monitoring programs, for the interpretation of hydrodynamic features, and for real-time data for navigation.

Quantitative information is required for hydrodynamic and other types of modeling and monitoring. Most of the remote sensing techniques currently available are not capable of providing data at the appropriate spatial and temporal scales for such purposes. The only systems that provide such information at this time appear to be RADS and CODAR.

Spatial Resolution and Dimension

Depending on the complexity of the investigation, 2- or 3-dimensional data may be required. Satellite and high altitude systems can provide valuable synoptic surface information over a large area, but the data are not quantitative without extensive groundtruthing for single views. With the exception of Landsat, SPOT and MOS-1, the satellite spatial resolutions are currently too coarse for studying the majority of estuaries. Landsat also has the problem of near coastal area resolution. The greatest limitation of most remote sensing data is its lack of vertical information. RADS appears to be the only system that will provide vertical profile data.

Record Length

Data of historical interest must be archived, and those agencies responsible for storing the data should coordinate closely with user groups to establish and ensure a workable format and means of access to products.

Swath Width

The footprint (or ground area coverage) of the instantaneous field of view (IFOV; spatial resolution) must be small enough to portray features of estuaries, which are relatively narrow waterbodies. However, a wide swath (scene width) often sacrifices spatial resolution because of scanner and data-handling limitations. On the other hand, narrow swath widths may require multiple fly-overs and increase the cost and time of full area coverage. A wide track may not provide adequate spatial resolution.

Lifetime

A major constraint to the usefulness of remote sensing has been the vulnerability of technology-transfer programs to reductions in funding or political support. If a program is terminated, the data should still remain archived and available to users.

The life of a remote sensing system is a design consideration which will determine the cost of data collection and the data collection period.

Time and Space Coverage of Platform

In most cases, spatial detail decreases as synopticity increases. Satellite techniques provide good synoptic coverage, but often not enough spatial detail. Low altitude techniques provide good spatial detail but less synoptic information because longer times are required to cover an entire area. Satellite Synthetic Aperature Radar (SAR) is one of the few exceptions where a higher-resolution image can be obtained faster by lower-altitude aircraft systems.

Image Vs. Line Sensor

Same problems as discussed above.

Interference from Weather

If cloud coverage obscures a study site, the technique has less utility than a technique which is not affected by the weather.

Mission Accessibility

The availability of a remote sensing system is a problem. The satellite or high altitude techniques are out of the control of the users, but are always producing data as long as the program is funded. The low altitude ship or ground sensors must be paid for by the user and are less accessible due to the costs of purchasing and/or operating the equipment, or a lack of sources from which to gain access to the equipment.

Mission Flexibility

Availability of imagery from spacecraft is constrained by operating schedules outside the control of the user, and sometimes influenced by weather. The quality of the image may depend on other factors outside user control.

3.6 ACCESS TO DATA

Problem

Types, availability and source of remotely sensed data are not widely published and standardized.

Recommendation

There should be a lead agency (group) whose responsibility would be to coordinate a database of all remotely sensed data and provide users with the capability of identifying source, available quality geographic storage units, product forms and costs of data via a variety of search services, i.e. geographic regional names, specific latitude-longitude or UTM coordinates, point or groups of points (polygons) which differ from the area of interest, and date and time of collection. The user should learn: (1) source--agency who archives the data; (2) availability--time required from request until user has the data inhouse; (3) quality--percent cloud cover and whether data is calibrated; (4) product form--digital or film product and whether the data is in a raw or preprocessed form; and (5) costs--itemized for each product. Preview capability of imagery versus microfiche at no cost or minimal cost. This entire system should be accessible through dial-up from user terminal.

Problem

There is a diversity of formats for the storage and analysis of remotely sensed data (for example: 8- and 10-bit AVHRR data, 8-bit CZCS and Landsat data). Computer Compatible Tape (CCT) files of Landsat data can be recorded band sequential or band interleaved by line.

Recommendation

Formats for remotely sensed data should be standardized similar to those of NODC and EPA standard data formats for currents, winds, etc., which make remotely sensed data more readily and economically usable. Record lengths should be of manageable size.

Problem

Making sure that data is archived for the entire community and keeping this data for extended periods of time, e.g.

preservation of the AVHRR/LAC and HRPT archive. Without this archive, long-term scenes and climatological studies are not possible.

Recommendation

When a project sensor is designed and implemented, data dissemination, standardization and archiving should be given equal priority with details of the collection platform or system. All archived data should be retrieved and re-recorded on up-to-date hardware, i.e. move away from tape storage. Most of the AVHRR LAC/HRPT data should be retrieved from IBM tapes and suitably archived. Much of this data is already lost -- only the low resolution data has been saved. The remaining is an invaluable resource for high resolution climatology studies. An attempt should be made to recover the lost high resolution data.

Problem

Lack of timeliness for data delivery to the user from operational data ingest or retrieval from archives.

Recommendation

The time between data ingest and product dissemination for operational use by researchers and managers should be minimized. For archive-retrieval, a more timely response--days/weeks as opposed to months is required.

Problem

Lack of timely information concerning operational sensors and projected programs.

Recommendation

Users should receive timely reports on sensor status and estuarine research projects that are being planned for the near future. Research activities of Federal and state agencies and universities within geographic regions should be coordinated.

Problem

Software development is required for each new remote sensing data type. There is a lack of standardized quality control, documentation of programs and use of computer languages (e.g. Fortran) used.

Recommendation

Standard unpacking software routines written for main-frames, minis and micros should be available and documented, and user guides available for all users. Standardized, transport-able (public domain) software package for unpacking remote sensing data should be made available.

Problem

Lack of knowledge of what remote sensor packages are available and what types of measurement can be derived from the data collected.

Recommendation

Terminal users database that is periodically updated and that specifies all sensor packages, capabilities and availability of these sensor packages should be implemented.

Problem

How to incorporate several remotely sensed data sets with additional data sets into a single, working GIS-type database.

Recommendations

Perform a survey of available software. Develop software standards/requirements for GIS systems for the oceanographic community.

Problem

What form of the data should be provided.

Recommendation

Raw and engineering data with digital products, as well as film and paper graphic products, should be made available.

Problem

What software/techniques for processing raw data into finished engineering products should be provided?

Recommendation

A software library, user guide and technique descriptions for the production of engineering products are required. These manuals and software should be available in a timely manner after operational products are produced, e.g. techniques for processing CZCS imagery into maps of chlorophyll and diffuse attenuation coefficients are only now being written in technical manual form.

3.7 GROUNDBASE SYSTEM EVALUATIONS

(Awivatt, CODAR, Tomography, RADS, Acoustic Backscatter, Scintillation)

Other Remote Techniques

Depending on the nature of the question addressed, possible budgetary constraints, etc., other remote techniques can also be used alone and in conjunction with shore methods. Conventional current meters and moorings, despite their lack of vertical resolution, will always have their place in estuarine oceanography. Likewise, over-the-side measurements performed from a ship or small boat (current meter profiler such as a Neil

Brown acoustic instrument, CTD and hydrographic sensor systems) are very valuable when studying features such as coastal or turbid/clearwater fronts. Measurements performed from aircraft equipped with remote sensors (e.g. mounted radiometers and expendable air-dropped probes [AXBT, AXSTD]) enable users to characterize a relatively large area in a near-synoptic fashion. Aircraft can also track a large number of Lagrangian drifters, either air-deployed or emplaced from small surface craft. Drogues can also be remotely tracked from the nearby coastline or via satellite (ARGOS).

In summary, when planning an experiment in an estuary, due consideration should be given to the time and spatial scales of the phenomena being addressed, the flexibility of the principal investigator in scheduling (which may constrain the experimental designs due to difficulties in acquiring instruments or platforms simultaneously), the budgetary constraints, etc. The experiment can then best be designed by using a judicious mix integration of the instruments or techniques referred to above, as well as useful remote sensing imagery from satellites. Physical oceanographic measurements should, to the extent possible, also be supplemented by biological and chemical sampling (e.g. for chlorophyll, nutrients, etc.) which help in identifying water masses or parcels.

Remote Measurement Systems

Groundbased systems currently offer the most dependable means of obtaining quantitative measurements over the proper time and space scales required for depicting estuarine physical processes.

RADS--Remote Acoustic Doppler System. Provides profiles of currents in ranges of from 10 m to 350 m depending on instrument frequency with a resolution of up to 1 m for the highest frequency units. Possesses the potential to measure fine structures, including turbulence, using coherent processing techniques, which are now under development.

RADAR Techniques. Surface imaging radar operating at various frequencies can obtain surface current maps of various spatial resolutions. Most of the recent remote sensing applications in recent years have utilized high frequency (HF) radars. The HF radars that are commercially available (i.e. CODAR, having a spatial resolution in the order of 1.5 km) are appropriate to the large estuaries. Microwave systems offer the most promise for imaging over the desirable spatial scales of small estuaries, but applications require further development.

Other Techniques

There are various other promising techniques which are presently in various stages of development, such as acoustic tomography, acoustic reciprocal transmission, acoustic scintillation, laser technology, acoustic time of travel, electromagnetic cables. These techniques require further research to determine their specific capability to measure estuarine physical processes.

3.8 RECOMMENDATIONS

Training should be available to practicing oceanographers in specific applications of remote sensing techniques. The training should be directed toward the mastery of techniques required for these specific applications and problem areas.

More emphasis should be placed on integrating remote sensing products with conventional analysis products.

Remote sensing systems need to be responsive to the fine temporal and spatial scales peculiar to estuaries.

RADS techniques can presently be operationally employed for current velocity profile measurements in estuaries. HF radars such as CODAR can also be employed for synoptic measurements of surface currents in the larger estuaries, and show great promise for the near future.

There should be a lead agency whose responsibility would be to coordinate a database of all remotely sensed and pertinent *in situ* data and provide users with information on sources, data availability, quality, geographic storage unit, product forms and costs.

There should be storage of remotely sensed data in a permanent archive for retrieval in most of the time series or climatological studies, especially most of the AVHRR, LAC/HRPT data prior to April 1985.

Development of the following systems should be expedited:

1. High resolution microwave radiometer.

2. Narrow band (10 nm) multispectral scanner for sensing of water quality parameters.

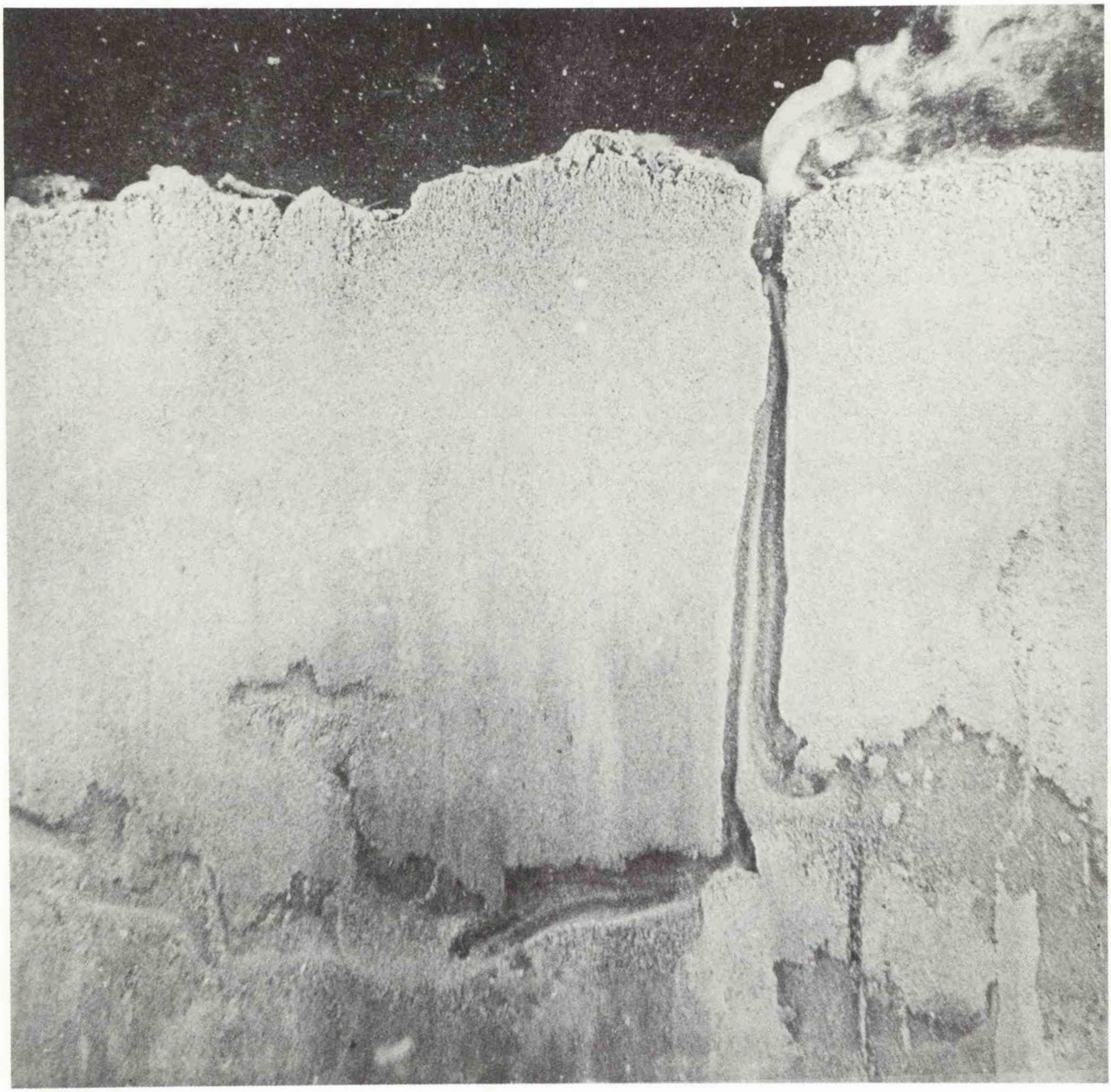
3. Development of laser systems for:

    a. Temperature in depth (Raman backscatter)
    b. Bathymetry
    c. Water quality parameters.

4. Development of *in situ* horizontal profiling acoustic current meters such as scintillation instruments.

5. Development of higher resolution and land-based radar systems for discrimination of surface currents and waves, e.g. extend HF radars into VHF band; complete development of two-frequency microwave radar.

Sediment-profile photograph taken with the Rhoads-Cande sediment profile camera. This optical instrument is used to obtain high resolution information about structures and processes in the upper 20 cm of the seafloor. This image was taken south of the Rappahannock River mouth on the western side of the lower Chesapeake Bay. Large areas of the seafloor were mapped with this system showing structures present in this typical image. The dark area at the top of the image is the water overlying the bottom. The surface boundary roughness is ca. 1 cm. The water-filled excavations at 10 to 15 cm below the sediment surface were produced by maldanid polychaetes which feed head-down and pass sediment upward to the surface. The high reflectance of the image indicates that the sediment (muddy fine to medium sand) is low in sedimentary sulphides. A vertical burrow structure is seen to the right. Increased pore-water pressure from the penetrating optical prism is forcing water and fine-grained sediment out of the burrow (plume). These images can be obtained at a rate of one per 40 seconds. Computer image analysis allows measuring about 20 parameters from negatives within 4 minutes. This mapping system is unaffected by ambient water turbidity and is routinely used to map benthic processes in coastal environments. The system can also be instrumented to obtain measurements (e.g. dissolved oxygen or penetrometers to measure sediment bearing strength) at the time of imaging. This system is often used to document structures imaged by sidescan sonar.



4. PANEL ON REMOTE SENSING OF THE BENTHIC ENVIRONMENT

PANEL MEMBERS:

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M. Lockwood, Rapporteur
R. Orth
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4.1 METHODOLOGY

The panel began by defining the properties of the benthic estuarine environment that are important to the multidisciplinary problem of estuarine management. Next, remote sensing techniques for studying each property were identified. These techniques fell within one of two categories: those that are presently being used operationally; and those that show promise in the not-too-distant future, but require additional research and development to perfect. Each technique was then ranked in its ability to gather information pertaining to benthic properties (Tables 4 and 5). This ranking ranged from 0 to 3, where

- 0 = not applicable,
- 1 = limited value and likely to remain so,
- 1+ = presently of limited value, but shows high future potential,
- 2 = moderate value but needs additional development,
- 3 = high value, may be used operationally.

Finally, because these rankings say little about the availability of each data type or the ease with which a technique may be applied, a second status ranking was applied (Table 6), where

- 1 = presently unavailable,
- 2 = limited availability,
- 3 = readily available.

4.2 RESULTS

The remote sensing techniques identified may be further divided into two groups, classical and non-classical. Classical remote sensing techniques are defined as those requiring an aircraft or satellite platform (Table 4), whereas non-classical remote sensing techniques require sensors deployed from a floating platform that are either positioned within the water column or imbedded within the bottom substrate (Table 5). In benthic surveys, classical remote sensing techniques are limited to optically shallow waters, where the above-water signal is affected by the reflectance characteristics of the bottom. Non-classical techniques, because the sensor may be lowered to any depth, are not limited to optically shallow water.

As a group, the usefulness of any remote sensing technique is related to the kind of benthic parameter of interest. Classical remote sensing techniques are applicable to parameters associated with the surface of the substrate such as submerged aquatic vegetation (SAV), communities of macro- and micro-algae, and bathymetry. Non-classical remote sensing techniques may address both surface- and within-substrate parameters such as sediment morphology and chemical composition.

Table 4.

Applications of Classical Remote Sensing Techniques to Selected Benthic Estuarine Problems

Sensor	SAV	Macro Algal	Micro Algal	Sed. G.S.	Macro Topo.	Micro Topo.	Comm. Type	Trace Met.	Geo-Tech. Prop.
Lan. MSS	1-3	1-3	1-3	1	1	1	1	0	0
Lan. TM	1-3	1-3	1-3	1	1	1	1	0	0
SPOT HRV	1-3	1-3	1-3	1	1	1	1	0	0
Air. MSS	2-3	2-3	2-3	1	2	2	2	0	0
Scan. Spec.	1+	1+	1+	1+	1+	1+	1+	0	0
LIDAR	1+	1+	1+	1+	2-3	2-3	1+	0	2-3
Aerial Photo.	3	3	3	1-2	2-3	2	2	0	0

Rating Key:
0 = Not applicable
1 = Limited usefulness
1+ = Future potential; more research needed
2 = Useful, but requires additional field testing
3 = Operational or successfully field tested.

Table 5.

Applications of Non-Classical Remote Sensing Techniques to Selected Benthic Estuarine Problems

Sensor	SAV	Macro Algal	Micro Algal	Sed. G.S.	Macro Topo.	Micro Topo.	Comm. Type	Trace Met.	Geo-Tech. Prop.
SONAR	1	1-2	1	3	3	3	1-3	0	1+
Scan. SONAR	3	1+	1	3	3	3	1-3	0	3
REMOTS	1	1	2	3	0	3	3	1	2-3
UW Photo.	3	3	3	3	3	3	3	0	1
Ultra-Sound	0	0	1	1+	0	1+	1+	0	1+
Gamma-Probe	0	0	0	3	0	3	3	0	3
X-Ray Image	0	0	0	1+	0	1+	1+	0	1+

Rating Key:
0 = Not applicable
1 = Limited usefulness
1+ = Future potential; more research needed
2 = Useful, but requires additional field testing
3 = Operational or successfully field tested.

Table 5. (cont'd)

Applications of Non-Classical Remote Sensing Techniques to Selected Benthic Estuarine Problems

Sensor	Petroleum Hydrocarbons	Nutrients (P,N,Si,So)	Metabolites (Ch,CO,HS)	Sediment Redox
SONAR	0	0	0	0
Scan. SONAR	0	0	1-3	0
REMOTS	1+	1	3	3
UW Photo.	1	1	0	0
Ultra-Sound	0	0	0	0
Gamma-Probe	0	0	3	0
X-Ray Image	0	0	1+	0

Rating Key:
- 0 = Not applicable
- 1 = Limited usefulness
- 1+ = Future potential; more research needed
- 2 = Useful, but requires additional field testing
- 3 = Operational or successfully field tested.

However, the greatest potential for future classical remote sensing techniques lies in the development of imaging spectrometers and LIDAR. It is possible that, within the very near future, both of these techniques may be combined to detect benthic communities such as SAV and oyster beds, estimate surface biomass and identify plant species.

Of the non-classical remote sensing techniques, acoustic devices such as SONAR, scanning SONAR, and Doppler current meters appear to be of greatest utility. Presently, acoustic devices may be used to map bathymetry and sediment structure, identify various benthic community types, and measure near-bottom currents. Also, it is possible that within the near future, acoustic techniques may offer a nondestructive means of measuring SAV canopy structure.

In terms of availability (Table 6), highest rankings were assigned to Landsat MSS and TM data, aerial and underwater photographs and acoustic data. LIDAR systems which were rated with high potential exist, but are few in number. Imaging spectrometers, also rated high in future potential, have been tested experimentally but have not yet been developed into operational systems.

4.3 CONCLUSIONS

In the management of estuaries, it is important to understand the estuarine system, rather than its individual components. For example, the ability to detect and map submerged aquatic vegetation (SAV) is useful, but an understanding of the factors affecting SAV distribution, combined with distribution data, provides a much more powerful analytical capability. To study an estuarine system, combinations of remote sensing techniques must be applied in order to synoptically measure as many water surface, water column and benthic properties as possible. Also, these combinations must be employed simultaneously, as opposed to sequentially, to give a complete synoptic view of the estuarine system.

Reliable field measurements must be collected coincident with the remote measurements. In many cases, such field data is necessary to calibrate remote sensing techniques and, in all cases, is required as a confirmation of the remote observations.

4.4 RECOMMENDATIONS

It is strongly recommended that government agencies such as NOAA and EPA sponsor an interdisciplinary estuarine remote sensing demonstration whereby selected remote sensing tools, used in conjunction with conventional technologies for measuring

Table 6.

Specifications and Status of Benthic-Related Sensors

Sensor	Platform*	Instrument IFOV (m)	Operational Resolution (m)	Status**
Landsat MSS	S	80	160-240	3
Landsat TM	S	30	60-90	3
SPOT	S	10/20	50	1
Airborne MSS	A	1-10	1-10	2
Scanning Spec.	A/S	1-20	1-20	1
Aerial Photo.	A	<1	<1	3
LIDAR	A	1	1	2
SONAR	B	X1 Y1 Z1%	X1 Y1 Z1%	3
Side Scanning Sonar	B	X1 Y1	X1 Y1	3
UW Photo.	B	.01	.01	3
REMOTS	B	10^{-}	10^{-}	3
Ultra-Sound	B	10^{-}	10^{-}	1
Gamma-Probe	B	10^{-}	10^{-}	1
X-Ray Imaging	B	10^{-}	10^{-}	1

A = Aircraft
B = Boat
S = Spacecraft

1 = Not available
2 = Limited access
3 = Readily available

sea truth, be used to study an estuarine system. The study area should encompass a wide variety of estuarine environments, including wetlands, submerged aquatics and water mass boundaries. Such a program should have the following objectives:

(a) to provide a framework for effectively using remote sensing to study and manage estuarine systems,

(b) to develop a prototype estuarine geographical information system (EGIS) designed for resource management.

The demonstration results, products and experimental design should be well-documented and distributed among the estuarine research community. The project should conclude with a widely-publicized symposium.

Classical remote sensing is shifting from the development of multispectral scanners having a limited number of relatively broad bands to concepts involving imaging spectrometers, where large portions of the visible and near infrared spectrum are sampled in many spectrally-narrow bands. Unfortunately, our knowledge of the detailed optical nature of many estuarine water constituents (e.g. phaeo-pigments, wetlands- and marine-derived detritus and inorganic materials) has not advanced sufficiently to make full use of this new technology. Therefore, additional remote sensing research should include basic research in the areas of hydrologic optics (scattering, absorption and fluorescence).

In estuarine, coastal and oceanographic applications of remote sensing, the weak link has been and remains the collection of reliable, simultaneous field measurements. It is recommended that new sampling systems be developed to collect large numbers of field samples and/or measurements coincident with remote sensing operations. For example, radio-controlled buoy systems that would collect surface and subsurface water samples coincident with aircraft or satellite overpasses, or acoustical measurements.

5. SUMMARY OF RECOMMENDATIONS

5.1 Basic Research and Model Development

The use of remote sensing data should be encouraged in models that describe wetlands and estuarine ecosystems and their forcing functions, particularly in those cases where remote sensing measurements offer increased cost-effectiveness, synopticity, and temporal/spatial resolution.

Research should be undertaken to extract the maximum information available about welands and estuaries from the integrated use of sensors, both in terms of spectral wavelength components and multistage spatial sampling (e.g. ship/aircraft/ satellite).

Improved physical and statistical models and algorithms should be developed, and additional basic research in hydrologic optics performed, to improve our ability to remotely identify and measure estuarine water constituents (organic/inorganic, particulate/dissolved, nutrients/toxics).

Improved pattern recognition techniques should be developed for providing new information on wetland features which can be characterized by spatial relationships.

5.2 New Sensor Development

For studies of wetlands plant communities as well as other features of land cover in coastal environments, sensors having better spatial (10 m) and spectral resolution (10 nm) need to be developed. Within the visible and infrared region of the spectrum, examples of such sensors include the Jet Propulsion Laboratory's imaging spectrometers which will lead to better characterization of plant internal composition and physiology, thus improving inferences about other environmental parameters such as nutrient limitations and tidal regimes. In addition, the NASA Ames AOCI may provide a capability for assessing phytoplankton and seston characteristics of estuarine systems. In the microwave region, multiple wavelenghts, look angles and polarizations are needed to improve discrimination of species of wetlands grasses, shrubs and forests, and provide all-weather capability.

Development of the following systems should be expedited in order to improve the measurement of water constituents:

(a) High spatial resolution (30 m) microwave radiometer for salinity and other measurements.

(b) Narrow band (10 nm) multispectral scanner for sensing of estuarine water constituents.

(c) Development of laser systems for:
   (a) Temperature in depth
   (b) Bathymetry
   (c) Water constituents (e.g. chlorophyll, suspended sediment, dissolved organics)
   (d) phytoplankton species composition

(d) Development of <u>in situ</u> horizontal profiling acoustic current meters such as scintillation instruments.

(e) Development of higher resolution and land-based radar systems for discrimination of surface currents and waves (e.g. extend HF radars into VHF band; complete development of two-frequency microwave radar).

Improved devices need to be developed for collecting subsurface information on estuarine living resources and their habitats. Specifically, acoustic devices such as SONAR, scanning SONAR and Doppler current meters should be further improved for mapping bathymetry and sediment structure, identifying various benthic community types, and measuring near-bottom currents.

The development of real-time command of sensors, particularly pointable sensors, would also greatly benefit studies of wetland environments. Coupled with real-time video coverage of the geographic target, a sensor could be made responsive through instantaneous command from a ground team to specific locations of interest. This could benefit timely collection of both remote data and groundtruth data. Thus, development of real-time command and video display could make a major contribution to both experimental and operational endeavors.

5.3 Sampling and Experiment Design

There must be a long-term commitment to make satellites available for an improved understanding and management of estuaries. This should include the development of sensors with adequate sampling resolution and frequency in new satellite or aircraft systems. A continuity of data flow is required for trend analysis and assessment of management actions.

Government agencies (NOAA, EPA, NASA, Corps of Engineers, USGS, etc.) should sponsor an interdisciplinary estuarine remote sensing panel to plan a demonstration project whereby selected remote sensing systems, used in conjunction with boat and field measurements, are used to study an estuarine system. This demonstration project should provide a framework for effective use of remote sensing to study and manage estuarine systems.

New sampling systems should be developed for collecting large numbers of field samples and measurements coincident with remote sensing operations. This could include radio-controlled buoy systems which collect surface and subsurface water samples coincident with aircraft or satellite overpasses, or acoustical measurements.

Aircraft-based techniques should be brought into estuarine data collection programs in a more expeditious and cost-effective way.

More emphasis should be placed on integrating remote sensing products with conventional analysis products for improved understanding and use by multidisciplinary teams and managers.

Potential users must be involved in the devlopment of new techniques and systems to ensure applicabililty, assure the collection and availability of in situ data necessary for calibration, and to provide field-testing of the techniques on actual estuarine scientific and management problems.

5.4 Data Management

There should be a lead agency or Center whose responsibility would be to coordinate a database of all estuarine remotely sensed and pertinent in situ data and provide users with information on sources, data availability, quality, geographic storage unit, product forms and costs.

Geographic Information Systems (GIS) should be adopted, to the maximum extent possible, as the standard way to present data for estuarine management.

When an estuarine project requiring remote sensors is designed and implemented, dissemination, standardization and archiving of the remotely sensed information should be given equal priority with details of the design and performance of the collection platform or system. All archived data should be retrieved and re-recorded on up-to-date, high-density hardware for long-term storage with easy access. For instance, most of the AVHRR LAC/HRPT data should be retrieved from IBM tapes and suitably archived.

Development of inter-calibration techniques to interrelate data from the various sensors is essential to full utilization of remotely sensed data, as well as technique descriptions for the production of user products (e.g. techniques for processing CZCS imagery into chlorophyll maps).

The time between data collection and product dissemination for operational use by researchers and managers should be decreased. For archive retrieval, a timely response is required (e.g. days/weeks).

A users guidebook/system needs to be prepared which provides information on sensor packages and their capabilities on available software.

There should be standardized formats for remotely sensed data similar to those of NODC and EPA standard data formats for currents, winds, etc., which make remotely sensed data more readily and economically usable. Record lengths should be of manageable size.

Standard unpacking software routines written for mainframes, minis and micros should be made available and documented, including user guides for all users. A standardized, transportable (public domain) software package for unpacking remote sensing data should also be made available.

A terminal users database which is periodically updated and specifies all sensor packages, capabilities and availability of the sensor packages should be implemented.

A survey of available software should be performed. Software standards/requirements for GIS systems for the estuarine community should be developed.

Raw and engineering data with digital products, as well as film and paper graphic products, should be made available.

A software library, user guide and technique discriptions for the production of engineering products are required. These manuals and software should be available in a timely manner after operational products are produced, e.g. techniques for processing CZCS imagery into maps of chlorophyll and diffuse attenuation coefficients are only now being written in technical manual form.

Storage of remotely sensed data in a permanent archive for retrieval in most of the time series of climatological studies is required, especially most of the AVHRR, LAC/HRPT data prior to April 1985.

5.5 Coordination, Training and Information Dissemination

Better coordination and cooperation among government agencies and other participating institutions is required in the development of a uniform, calibrated database of aircraft and satellite imagery. The NOAA Estuarine Programs Office should set up a working group to examine the needs for generic data/information in the estuaries and how these needs may be addressed through effective coordination aimed at the modification of existing programs and/or the development of new interagency programs that would utilize current remote sensing technology.

Users should receive timely reports on sensor status and estuarine research projects that are underway or are being planned for the near future.

Research between government agencies, universities and other institutions within geographic regions should be coordinated.

Development of techniques and remote sensing systems should be closely coordinated with estuarine management needs, including both monitoring and research, to assure effective and efficient use of new systems.

More effective methods for transferring remote sensing technologies to the estuarine, oceanographic and management communities should be developed. For instance, training should be provided to estuarine scientists and managers in relevant applications of remote sensing techniques.

CHALLENGES AND ISSUES FOR ESTUARINE REMOTE SENSING

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NOAA's interests in estuaries range from weather forecasts and warnings (precipitation, runoff, winds, waves), through safe navigation (tides, currents, depth and surface obstructions), to basic research to understand the structure and function of estuarine systems. NOAA's interests also include collection, archival, and portrayal of data; protection, restoration, and enhancement of living marine resources and their habitats; and assessments of impacts which affect the living marine resources.

Man's overall goal in the Nation's estuaries is the effective management of estuarine activities so that any particular use does not needlessly or unknowingly limit or preclude any other use. In other words we want to sustain the long-term economic productivity of the systems and their resources. In this context and with regard to NOAA's interests, four principal environmental, estuarine issues have been identified by NOAA. These same four issues also have been identified by the National Academy of Science and the International Council for the Exploration of the Sea. They are eutrophication or nutrient over-enrichment, toxic materials, pathogens to the living marine resources (LMR), and physical alterations of the habitat. All of these issues affect the use of estuaries by mankind.

I'd like to begin by concentrating on the four major estuarine issues, which we must recognize are the result of increasing human presence and activity on land, as well as the multiple uses to which mankind subjects the estuary proper. Application of RS to monitor human activities and uses of the estuary and the integration of this information in a common data base (e.g. a Geographical Information System) for comparison with other data is of value.

The first of these issues is eutrophication or nutrient over-enrichment of the estuary. Eutrophication occurs from both point source (e.g. sewage treatment plants) and non-point source loading (e.g. land runoff) of the estuarine system by organic and inorganic nutrients, including carbon, nitrogen, and phosphorus. Any ability of RS to identify sources or track the inputs and disposition of nutrients would be of value.

The addition of nutrients to an estuarine system frequently results in intense algal blooms and the production of organic matter. Organic matter, if it sinks through a pycnocline and into bottom water below the euphotic depth, respires and decomposes utilizing oxygen to produce hypoxia or anoxia in bottom water. Thus, the use of RS to locate the source of the bloom, to follow its development, demise, and transport would be of use. A bloom can develop over a few days, drift and disappear in several more -- thus, making it quite difficult to first find and then follow by boat. A more perspective and rapid censusing would help. The ability of RS to assist in determining stratification of the water column, perhaps by airborne expendable bathythermographs (XBTs) or other means or depth of light penetration would be of immense value. Such determination would be helpful in monitoring and understanding the development and geographical extent of hypoxic waters and the frequency of pynoclinal tilting with concurrent lateral movement of hypoxic/anoxic bottom water from side-to-side as occurs in the Chesapeake Bay.

Nutrient over-enrichment frequently leads to a change in the algal population or phytoplankton species make-up. Changes in species and cell size can result in major changes in the food web or to the fisheries themselves. The ability to determine via RS major phytoplankton types, changes in species composition, distribution, and abundance would be a major help in tying eutrophication to a changing food web and effects on fisheries. An extension of this idea would be to follow the growth, distribution, and demise of toxic algal blooms in order to open and close fisheries to protect human health.

The second issue occurring in estuaries is toxic materials (their identity, source, trajectory, dilution or dispersal, and fate) and their affects on the living populations in the system. It would be desirable to follow catastrophic spills of toxic materials. It would be even more desirable to be able to follow less than catastrophic inputs of toxic materials. Contaminants are frequently associated with suspended particulate material. Could RS be used to follow toxic materials directly or indirectly by monitoring the distribution of suspended sediment? What about specific compounds of interest? Could RS be developed to monitor specific compounds? Would this be a worthy area for research for the future or is it not practical? Would it be better to have RS determine the overall circulation and combine that information with in situ shipboard measurements of specific compounds? Ideally one would like to relate the distribution and abundance of toxic materials to the distribution and magnitude of problems in the LMR. Can RS help?

The third major issue in estuaries is the presence of pathogens which affect the LMR. As with toxic materials we would like to known the source or origin of a pathogen, how it is transmitted, what its distribution and prevalence is, and what controls or regulates it. Sources might be from river or sewage treatment plant discharges, or from land runoff. The pathogen might be brought in by transplanted or migratory species. Could RS of circulation patterns help if such information were combined with in situ data on the behavior of a particular pathogen?

The fourth major estuarine issue is the physical alteration of the habitat. This issue includes changes in wetlands and freshwater flow, as well as the placement or removal of physical obstacles on the seabed or in the water column. It includes the destruction or alteration of wetlands and submerged aquatic vegetation beds or the restoration and enhancement of these lands or beds by a whole series of natural or man-induced activities. We would like to be able to monitor, over the long-term, changes in wetlands, adjacent uplands, and submerged aquatic vegetation beds. At present it is labor intensive and time consuming to inventory wetlands. In many cases these lands are changing faster than they can be inventoried by traditional methods. We would like to be able to document change (both quantitative and qualitative) over time and relate these changes to the LMR. Once understood, it would allow for improved management of wetlands for the protection and restoration of living resources. Can RS contribute by rapidly inventorying and quantifying change in wetlands? Does it have adequate spatial resolution and discriminatory powers to separate vegetation types? Can RS of wetlands and adjacent uplands be used to monitor the enforcement of regulations, to improve the permitting process, to establish zoning (i.e. buffer strips), and to monitor the placement and effects of best management practices on these lands? Can RS be used to monitor mitigation or restoration and enhancement projects to determine their ultimate outcome?

Freshwater flow is another physical alteration of the habitat that can affect the LMR. Too much freshwater can lower salinity enough to close nursery areas or kill certain species (e.g. oyster). Too little freshwater can decrease flushing, increase contaminant concentrations and lead to bioaccumulation, physiological or reproductive dysfunction, mortality and/or the contamination of fishery products. Can RS monitor the effects of freshwater flow by following salinity concentrations in estuaries?

Because the clean-up of estuarine habitats is directed toward the restoration of the LMR, I'd like to raise several resource issues for consideration. Can RS provide us with any additional information and benefit regarding the timing of events (e.g. spawning and migration), or the distribution and abundance of eggs, larvae, or adults in relationship to the temporal or spatial distribution of any of the four previously mentioned estuarine habitat issues? Could RS be used to assess nursery habitats? Could RS be used to predict future stocks, or to assist hatchery activities?

Finally, I would like to raise the issues of habitat variability and heterogeneity. Both temporal and spatial variability hamper our efforts to understand what is happening in highly dynamic estuaries. We would like to know where to place our stations (direct our ships) and determine how many stations are needed for a representative monitoring program. We would like to know the time scale of events to know how frequently we should sample, and we would like to be able to sample synoptically so that we could improve our ability to understand what was happening in different geographical areas (e.g. parts of the same estuary, or shelf versus estuary) at the same time.

In summary, I have presented four major environmental issues that we would like to manage. These are eutrophication, toxic materials, pathogens, and physical alterations of the habitat. Additionally, I mentioned several fishery management issues and something about temporal and spatial variability and heterogeneity in estuaries. Can RS, in concert with _in situ_ sampling, assist us in understanding and managing these issues? Can RS provide faster, more synoptic, and more dependable information than certain conventional sampling methods? Can RS respond to the needs of managers who must act now? These are the challenges for RS. As the seminar and workshop proceed we will see how these issues are met.

A CASE FOR REMOTE SENSING IN ESTUARINE AND COASTAL POLLUTION AND HABITAT DEGRADATION STUDIES

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ABSTRACT

This paper reviews some of the uses of remote sensing in estuarine pollution and wetlands habitat degradation studies and presents an argument for the use of remote sensing as a tool additional to in situ studies. Such issues include the identification of dumped material, surface oil, plumes and outfalls, fronts in which pollutants concentrate, phytoplankton as a non-point source biological oxygen demand (BOD) load, areas of potential hypoxia, and the degradation or disappearance of coastal wetlands, all affecting living marine resources. Remote sensing can also be used to follow the movement of surface water containing contaminants and in some cases, predict, identify, and follow the development and demise of red tides. Remote sensing even has use in the regulation or management of waste disposal through ecological zoning.

Counter arguments against the use of remote sensing in marine pollution studies say that because hazardous pollutants are not measured directly, its utility is limited. However, even here, remote sensing does add to our ability to understand complex and dynamic areas by 1) providing synoptic and detailed information (spatial and temporal) for the surface field in which in situ measurements at isolated locations are made, and 2) directing in situ sampling to key areas to maximize sampling capabilities.

INTRODUCTION

The use of remote sensing by managers and other persons to respond to environmental problems, is relatively new. As a consequence, some may be unfamiliar with the potential advantages offered by remote sensing. Typically, estuarine pollution and habitat degradation problems can range from an obviously acute and substantial release of visually definable toxic material, such as oil, to the affects on living marine resources caused by less obvious impacts from non-point sources or alterations in our coastal wetlands and adjacent uplands. This paper presents some of the advantages and limitations of using remote sensing in responding to environmental issues.

Remote sensing is the collection of information from a distance, typically through the use of radiant energy emitted from various parts of the electromagnetic spectrum. It also can include acoustics or the collection of information through the use of sound waves.

Remote sensing enhances our ability to understand our environment. Through the use of remote sensing, we are able to make fuller use of the electromagnetic spectrum at wave lengths, both shorter and longer than those in the visible portion of the spectrum, 400-700 nanometers. The very short wave lengths in the ultra-violet range have been used to excite and identify the accessory pigments contained in phytoplankton, and therefore, used to make crude identification of phytoplankton color groups. The ultra-violet portion of the spectrum has also been used to identify oil slicks. The visible portion of the electromagnetic spectrum has been used to identify suspended particulate material and other particles in the water column, chlorophyll concentrations, distributions of surface feeding fish, the identification of different vegetation types in wetlands and adjacent uplands, and identification of water masses and color. Typically, the infrared portion of the spectrum has been used to examine sea surface temperatures and plant material containing chlorophyll. The microwave portion of the spectrum has been used to determine sea-surface salinity, sea-surface topography, wind velocity and direction, sea state, sea ice, and oil slicks. The use of acoustic remote sensors have been used to locate and map the distribution of particles in the water column, to determine bathymetry, thermal or salinity discontinuities, and the distribution of fish.

Most marine pollution studies occur in highly dynamic estuarine and coastal waters where spatial and temporal scales are important. In these waters, our ability to understand surface distributions of specific variables, has been hindered by our inability to 1) assess surface conditions over broad areas synoptically, 2) define critical surface parameters with sufficient longitudinal or aerial definition (spatial resolution), and 3) provide temporal frequency appropriate for the phenomena being examined. Remote sensing assists in overcoming, not only these kinds of difficulties, but also offers the possibility of concurrent and coincident measurements, thereby making synoptic intercomparisons of such variables as temperature, salinity, phytoplankton pigment, and suspended sediments possible.

Remote sensing is best applied in conjunction with traditional _in situ_ measurements. Such application not only provides sea truth information, but also provides information on the vertical structure of the water column and on additional variables not measurable by remote sensing. This enhances the interpretability of the remotely sensed data. At the same time, the use of remote sensing enhances the utility of _in situ_ measurements by overcoming some of the limitations inherent to in situ measurement techniques (e.g., synopticity, temporal and spatial resolution).

Remotely sensed data can be collected via satellites, aircraft, or land-based systems such as the Coastal Dynamics Application Radar (CODAR). Satellites offer the advantage of regular fly-overs without additional cost and provide broad regional coverage. Aircraft offer the advantage of greater spatial resolution, the ability to fly as frequently as required (temporal resolution), the ability to fly under clouds (unless very low), and the ability to offer flexibility in instrumentation mix (e.g., pigment concentration and differentiation, temperature, salinity, and turbidity) on a single aircraft. Land-based systems (e.g., CODAR) offer the advantage of synoptic, high spatial resolution on a continuous basis.

EXAMPLES

Remote sensing, both acoustic and electromagnetic, has been used to examine specific variables (e.g., temperature, salinity, color) and issues (e.g., dumping, eutrophication, physical degradation of the habitat) as well as to provide a broad-scale perspective within which to couch estuarine and coastal pollution studies. These may be examined by aircraft and satellite remote sensors.

One of the issues for which remote sensing has been used is the dumping of sewage sludge and acid waste materials. In the New York Bight apex, Johnson et al. (1979) used remotely sensed information to locate, identify, and study the temporal dispersion of plumes resulting from the dumping of sewage sludge. The remotely sensed data were collected by a multispectral scanner and camera carried by a NASA aircraft. Multiple flights were made over the sewage sludge plume at about 15 minute intervals for about two hours after the dump and the dispersion characteristics of the plume were determined based on the distributional differences at each time interval. Proni et al. (1976) at the same time as the aircraft overflights, examined the in situ vertical distribution of particulate material from the sludge dump by means of acoustic tracking. Additional to the qualitative distribution of these plumes based on remote sensing alone, a quantitative analysis was accomplished by regressing in situ sampled quantities of sewage sludge against remotely sensed data (spectral radiance). Johnson (1980) used photographic and multispectral scanner data to distinguish sewage sludge from acid waste plumes based on the distinctive spectral characteristics of each.

Remote sensing has been used to locate and follow the trajectory of estuarine plumes and outfalls. To locate and follow the trajectory of such estuarine plumes and outfalls is important because they carry biostimulants and contaminants which ultimately affect estuarine and coastal fisheries.

Johnson et al. (1981) making use of infrared remote sensing, were able to define the thermal plume eminating from Lower New York Bay during the summer of 1977. Klemas et al. (1974) used LANDSAT to locate and trace suspended sediment plumes off the mouth of the Delaware Bay.

Munday (1981) made use of approximately ten years of LANDSAT information to examine the distribution and behavior of the Chesapeake Bay plume. From the 81 LANDSAT images used, he was able to describe the general movement of the Chesapeake plume with a greater degree of assurity than is possible from many non-synoptic cruises. Since that time, Fedosh and Munday (1982) have also examined the plumes emanating from the Delaware and the Hudson-Raritan estuaries. The data have been plotted to show plume trajectories for flood and ebb tides and different wind conditions. Because the data come from all times of the year, over a ten year period, the data are not only historical but represent a long-term average. This becomes extremely valuable to managers and researchers attempting to define the continental shelf area directly influenced by estuarine plumes, particularly with regard to affects on living marine resources.

During Superflux (Campbell and Thomas, 1981) the Chesapeake Bay plume was monitored by seven different sensors flown by aircraft. Of particular interest was the comparison of in situ salinity data collected over a period of several days and remotely sensed salinity data collected over a period of approximately two hours. The in situ data when plotted, exhibited a smoothly contoured, discrete tongue of water emanating from the mouth of the Chesapeake Bay. However, the remotely sensed data collected over a period of approximately two hours did not exhibit the same smoothly contoured, discrete tongue of water emanating from the Bay mouth. Rather, isolated pockets of higher or lower salinity were exhibited by the remotely sensed data. This so-called pocketing and added detail in contouring, were not in evidence in the more generalized in situ data. From data collected on a successive overflight of the plume two days later, it became apparent that the plume was far more dynamic than the in situ data suggested. Thus, from remote sensing new information was gained in terms of understanding the dynamics of an estuarine plume; and collection of this kind of synoptic and detailed information is not possible using a single surface ship.

Kuo and Talay (1979) making use of remote sensing, studied the thermal plume emanating from the Surry Nuclear Power Station on the tidal James River, Virginia. Munday et al. (1978) used dye marker buoys to determine circulation in an estuary where a sewage outfall was proposed. The dye buoys were placed in the water just before high and low tides and the traces emanating from the buoys were followed by photography from a light aircraft. The flood current was found to divide with one half of the current passing over shellfish beds. As a consequence of this information, the sewage outfall was placed so that the effluent went into the half of the flood current which did not flow over the shellfish beds. Remote sensing can elucidate turbidity, temperature, salinity, and chlorophyll as well as dye plumes emanating from estuaries and outfalls and do it in greater detail and more synoptically than in situ sampling of surface water.

Remote sensors mounted on aircraft or satellites are capable of providing synoptic views of frontal systems in estuarine waters (Klemas, 1980). Estuarine fronts represent areas of extremely high gradients or discontinuities in selected variables such as turbidity, temperature, or salinity from one side of the front to the other.

Inside the entrance of Delaware Bay is an oil lightering area. Large tankers entering the mouth of the Bay proceed to the lightering area where they are partially off-loaded prior to going upstream at shallower draft to oil terminals. Because of the lightering activities, environmental managers were interested in predicting the trajectory of oil in the event of an accident. As part of the predicting and modeling of the trajectory of an oil spill, it became necessary to take into consideration estuarine fronts which form during a particular phase of the tide. These were best studied making use of LANDSAT imagery and aircraft photographic data used for locating and describing frontal areas over time. From shipboard sampling, it was found that oil and other surface pollutants were highly concentrated in these estuarine fronts. Based on aircraft and satellite identification of these estuarine fronts, improved modeling and prediction capabilities occurred.

The identification of areas of non-point source contaminant or pollutant loading is another area in which remote sensing is helpful. Non-point source loading of nutrients to estuarine waters can result in eutrophication and excessive biomass of phytoplankton. When the algal biomass sinks below a pycnocline and decomposes due to lack of sun light, the result is a lowering of ambient oxygen concentrations in those bottom waters. Such lowering of bottom water oxygen concentrations can have dramatic impacts on benthic and demersal estuarine and coastal fisheries.

Leming and Stuntz (1984) in studying an important shrimp harvesting area southwest of the Mississippi delta which had recurrent low dissolved oxygen concentrations (hypoxia) found that shrimp and finfish were absent in these areas. Because shrimp, the most valuable fishery in the U.S., were affected, considerable interest was generated to define the area of hypoxia. Shipboard surveys attempted to do this, but were not as successful as the combined use of two remote sensors. These were the Coastal Zone Color Scanner (CZCS) and the Advanced Very High Resolution Radiometer (AVHRR). The combination of in situ dissolved oxygen data, a cluster analysis of pigment data from the CZCS, and thermal data from the AVHRR suggested that hypoxia should be present in areas with both high temperature and high pigment concentrations. This distribution of hypoxia was in fact verified by in situ shipboard sampling. Additionally, the satellite remote sensing data suggested areas of potential hypoxia which the shipboard surveys had missed and therefore, allowed for a better estimate of the potential impact of hypoxia on the shrimp fishery.

A second effect of non-point source nutrient loading is to cause a shift in phytoplankton species. Again, remote sensing has demonstrated a relationship between a gradient of eutrophic to less eutrophic waters and a change in phytoplankton composition within Narragansett Bay, R.I. (Farmer et al., 1980). Such changes in phytoplankton composition can have dramatic effects on fisheries (Ryther, 1954).

Zubkoff et al. (1979) examined the development, movement and demise of a large phytoplankton bloom in the York River, Virginia. They used a combination of small boats for in situ sampling, and an aircraft for taking aerial photography of the phytoplankton bloom. The in situ sampling was used to identify the phytoplankton organism and to quantify the bloom. The remote sensing was used to follow the development, extent, and demise of the bloom over time. Such phytoplankton blooms or red tides, become of major interest to managers when these blooms are toxic. Environmental managers would like to follow the course of such a toxic red tide in order to protect human health.

Non-point source pollution can also emanate from the physical degradation of wetlands and uplands adjacent to estuarine and coastal waters. This may well be the most important issue to which remote sensing can respond. Taylor and Saloman (1968) were able to determine the effects of hydraulic dredging and coastal development in Boca Ciega Bay, Florida, by making use of historical aerial photography. They estimated the loss of 1.4 million dollars annually because of the fill-in of portions of the Bay. The aerial photography (remotely sensed data) was instrumental in determining this annual loss. Today the Northeast and Southeast Fisheries Centers of NOAA's National Marine Fisheries Service (NMFS) are studying coastal and estuarine wetland loss via the LANDSAT Multispectral scanner and the new Thematic Mapper.

Changes in wetlands and uplands adjacent to estuarine and coastal waters are now of major interest to a number of Federal and state agencies. These include: the U.S. Environmental Protection Agency (EPA), the Fish and Wildlife Service (FWS), the U.S. Army Corps of Engineers (COE), the National Marine Fisheries Service (NMFS), and the U.S. Geological Survey (USGS). All are studying wetlands and adjacent uplands changes to understand impacts on estuarine and coastal ecosystems -- whether it is interest by the EPA in source loading and resulting water quality or by NMFS and the FWS in impacts on the living resources or by the COE in the impacts of dredged material, coastal erosion or flooding on the entire estuarine and coastal system.

At present, a debate is underway regarding the potential use of remote sensing in estuarine and coastal pollution and habitat degradation studies. White (1981) believes that remote sensing has failed to emerge as a potent approach regarding marine pollution studies because the remote sensors fail to identify pollutants and contaminants both absorbed and dissolved within the water column.

Invoking the use of remote sensing in estuarine and coastal pollution studies is no panacea. Cloud cover and lack of depth penetration are problems often cited as objections to the use of remote sensing. Others cite lack of accessibility to remotely sensed data or its expense as major objections. An additional problem that may occur and often does, is the fact that remote sensing is complex and requires a multidisciplinary background. Such backgrounds can and should be provided by multidisciplinary teams of _in situ_ investigators examing wetlands, fisheries, ecology, etc., combined with remote sensing specialists. Finally, remote sensing alone does not provide adequate answers. _In situ_ sampling is required in almost all instances, even for qualitative analyses of the imagery.

In spite of the difficulties mentioned above, remote sensing does add to our ability to understand complex and dynamic estuarine areas by 1) providing synoptic and detailed information for the surface field in which _in situ_ measurements at isolated locations are made, and 2) directing surface ships to key areas to maximize sampling ability. Such direction of sampling or experimental design may be derived from the identification of water masses and the zoning of ecological areas within estuarine waters. Zoning can be accomplished by both aircraft and satellite remote sensing.

Remote sensing is also useful in determining trajectories of surface waters. A particularly good example is that of CODAR which has been used to project surface flow and velocity of waters in coastal areas of interest (Barrick et al., 1977). Such a study was undertaken in Prince William Sound, Alaska, in order to project the trajectory of an oil spill from a tanker loading facility located there. Thus, while remote sensors do not identify pollutant compounds _per se_, the remote sensors do provide data describing the surface field within which contaminants or pollutants move. In this way remote sensors and the data they produce become of inestimable value to environmental managers interested in the distribution and movement of pollutant materials.

In recent years, environmental managers have identified particular issues regarding the environment. These issues include: 1) eutrophication, 2) toxic materials, 3) physical degradation of the habitat and, 4) pathogens. Of these, remote sensing can be of assistance with regard to 1) elucidating eutrophication; 2) monitoring toxic materials (if these materials are relatable to some variable which the sensors can perceive); and 3) determining physical degradation of the habitat (particularly with regard to wetlands and uplands degradation). Pathogens, like toxic materials, are not viewed directly by remote sensors. Thus, the study of pathogens may be assisted by remote sensors only if pathogens can be related to something that the sensors can measure. However, both toxic materials and pathogens move with water currents and sediments. Thus, even here, remote sensing can be an added tool to in situ studies.

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THE POTENTIAL USES OF REMOTE SENSING IN ESTUARINE PROGRAM

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The broad goal of the National Estuarine Program is to maintain, protect, and restore water and sediment quality and living resources in the Nation's estuaries. The general process by which this is accomplished is through funding to U.S. Environmental Protection Agency (EPA) Regions and cooperation with state and local agencies. The national office provides guidance, oversight, and information transfer among estuaries, both technical and management. We can therefore serve as a focal point for coordinated efforts in remote sensing (RS) for estuaries.

The philosophy behind the program is to involve key program participants in a management structure that will identify priority environmental pollution problems first, and conduct a comprehensive, basin-wide characterization of the status and trends in pollution and living resources and suggest management alternatives to deal with the problems. Once this is done, management plans are developed and implemented to control point and non-point sources (including land-use planning), manage living resources, protect habitat, and manage freshwater inflow. Comprehensive environmental monitoring must be conducted on a continuing basis. Remote sensing may be of use to estuary programs in characterizing trends, identifying problems, identifying pollution sources, and assisting in monitoring. However, we are primarily interested in practical application of RS technology. Our primary interest in RS is to supplement and/or obtain synoptic information that is not available through conventional sampling, and also to explore alternatives for reducing costs of monitoring. The following are the specific ways in which RS may be of use to estuary programs (we are open to suggestion for other applications):

<u>Non-point Sources</u>

1. Assess agricultural land uses and practices, to estimate loads of sediment and associated nutrients and pesticides likely to be derived from portions of watershed.

2. Observe elevated sediment concentrations in rivers and streams, or plumes in open water bodies. To identify, or verify predictions of, sediment loading from particular land sources.

3. Observe storm water plumes from drains and Combined Sewer Overflow (CSOs) to determine transport distances and directions, and dilution rates.

Point Sources

4. Observe effluent plumes to determine transport distances and directions, and dilution rates for suspended solids, thermal signals, and perhaps salinity signals.

Diffuse Environmental Impacts

5. Observe chlorophyll concentrations to identify potential eutrophication areas. Ground truth data are needed to determine depth of algal blooms, and whether or not they are causing oxygen depletion.

6. Assess extent and quality of wetlands and their vegetation. "Quality" includes: water clarity, chlorophyll enrichment, vegetation type, and health of vegetation.

7. Assess extent and quality of Submerged Aquatic Vegetation (SAV) including grasses or kelps.

8. Observe major disturbances or threats to sanctuaries or refuges. Examples are: encroachment of non-point sources (NPS), riverine or CSO plumes following heavy rains, and plumes from accidental spills.

Water Resources

9. Observe changes in estuarine circulation, stratification, turbidity, erosion, or water levels following water diversion. (Imagery obtained during drought years can provide good indication of some of the short-term effects to be expected from diversion.)

We feel RS has many potential applications in estuaries. These applications must be reasonable in cost, operational-in-nature and have synoptic coverage. Our challenge is to demonstrate this RS application for specific geographic regions such as estuaries.

REMOTE SENSING OF ESTUARIES: AN OVERVIEW

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ABSTRACT

Estuarine applications of remote sensing require a wide assortment of sensors, including aerial film cameras for beach erosion and vegetation mapping, multispectral scanners for wetlands biomass and estuarine water property studies, thermal and infrared scanners for mapping surface water temperatures and currents, microwave devices for salinity or wave measurements, and underwater cameras and acoustic systems for benthic observations. The recent appearance of low-cost microcomputers with user-friendly software for analyzing satellite imagery is enabling more estuarine investigators to use satellite data. The availability of high resolution Thematic Mapper and SPOT (Systeme Probatoire d'Observation de la Terre) imagery is also important to estuarine investigations. However, to meet <u>both</u> spatial and temporal resolution requirements, data from several satellites will have to be combined with aircraft and ship data in a cost-effective way. In this paper, we attempt to summarize the state-of-the-art of remote sensing of estuarine and coastal properties and to point out improvements needed for meeting user requirements.

INTRODUCTION

The inherent values of tidal wetlands and estuaries in terms of carbon fixation, fisheries habitat, nutrient assimilation, global elemental cycling water storage, and sediment stabilization have been established (Odum, 1983). These natural contributions of wetlands to coastal ecosystems, as well as the less tangible values related to aesthetics, education, and recreation for mankind (Reimold and Hardisky, 1979), suggest that coastal wetlands are extremely important systems for the maintenance of the quality of coastal environments. Even though estuarine ecosystems are among the most productive ecosystems on earth, relatively little information is available on the seasonal and annual variability of the growth and net primary productivity of tidal marshes and estuaries. Ecosystem level study is difficult in estuaries primarily because of the size of the system. Input data for ecosystem studies are normally extrapolations from relatively small samples taken at representative points within the system. The advent of the LANDSAT and NOAA satellite series has provided data-gathering systems capable of collecting data for entire ecosystems.

Compared to the open ocean, wetlands and estuaries are very small and undergo rapid changes due to tidal effects. Therefore, observation requirements for coastal features differ significantly from requirements for open ocean investigations. Spatial and temporal resolution become more severe as one moves closer to the coast. This is illustrated in Figure 1, which compares spatial and temporal resolution requirements for various coastal and open ocean applications. For instance, Gulf Stream meanders and warm core rings beyond the shelf can be sufficiently mapped twice weekly with 1 km resolution; fronts and ocean-dumped waste plumes on the continental shelf can be tracked about every four hours with 50 meter resolution, while observation of tidal-induced estuarine fronts requires one-half hourly observations at about 10 meter resolution.

MAPPING COASTAL VEGETATION AND LAND USE

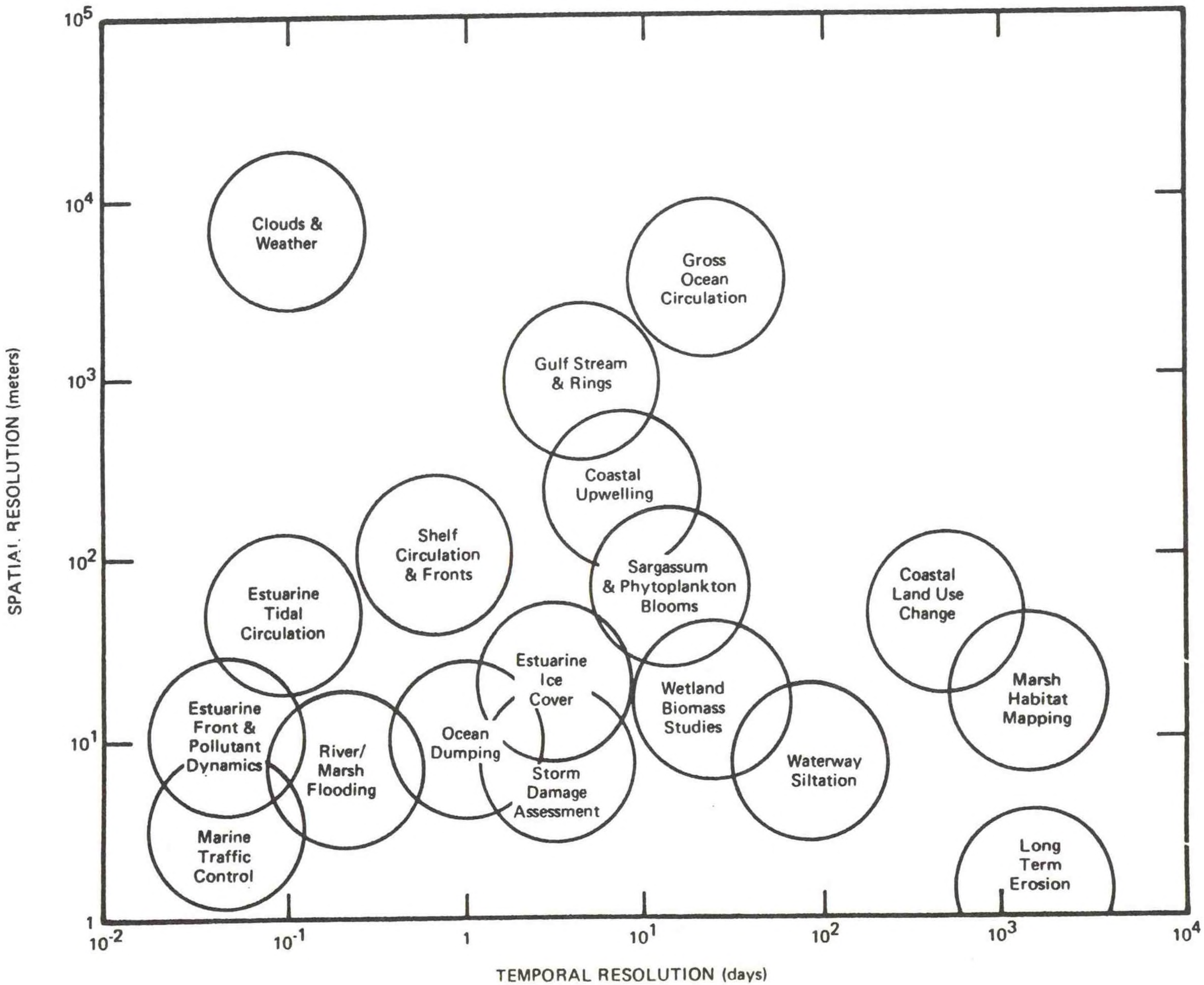
An awareness that wetlands might possess value in their natural unaltered state began in the 1930s, but did not surface as a national policy until the late 1960s. The first major manifestation of national concern for natural systems was the passage of the National Environmental Policy Act of 1969 (Darnell, 1978). This action was reinforced in 1972 with the passage of the Coastal Zone Management Act, which focused directly on the coast and its wetlands. Coastal states, in some cases, had already enacted legislation or followed the Federal lead by enacting legislation protecting and/or regulating activities within wetlands (Haueisen, 1973). The inherent values of wetlands to society for natural waste treatment and aesthetically-pleasing environments (Reimold and Hardisky, 1979) were rapidly becoming apparent.

The result of these events has been close scrutiny of changes in wetlands acreage over time. The primary means of monitoring changes in areal extent of marshes has been through aerial photographic surveys and, recently, more advanced remote sensing techniques (Carter, 1978). The low cost per acre and speedy analysis available by remote sensing (RS) techniques has recommended its use to monitor the effects of man's activities upon marshes (Figure 2). A major thrust of RS activities has been delineation and computation of marsh acreage lost. This, in itself, represents only a part of the impact upon marshes originating from man's activities.

RS as a tool for evaluating vegetative communities began with the aerial camera. With advances in the knowledge of the physics of remote reconnaissance (Colwell, 1963) and with advances in sensor technology, RS instrumentation was developed to probe areas of the electromagnetic spectrum invisible to panchromatic and infrared films (Colwell, 1968). Even as new areas of RS were developing, the usefulness of film media for investigating ecological conditions in natural vegetation

Figure 1.

SPATIAL AND TEMPORAL RESOLUTION REQUIREMENTS FOR COASTAL STUDIES



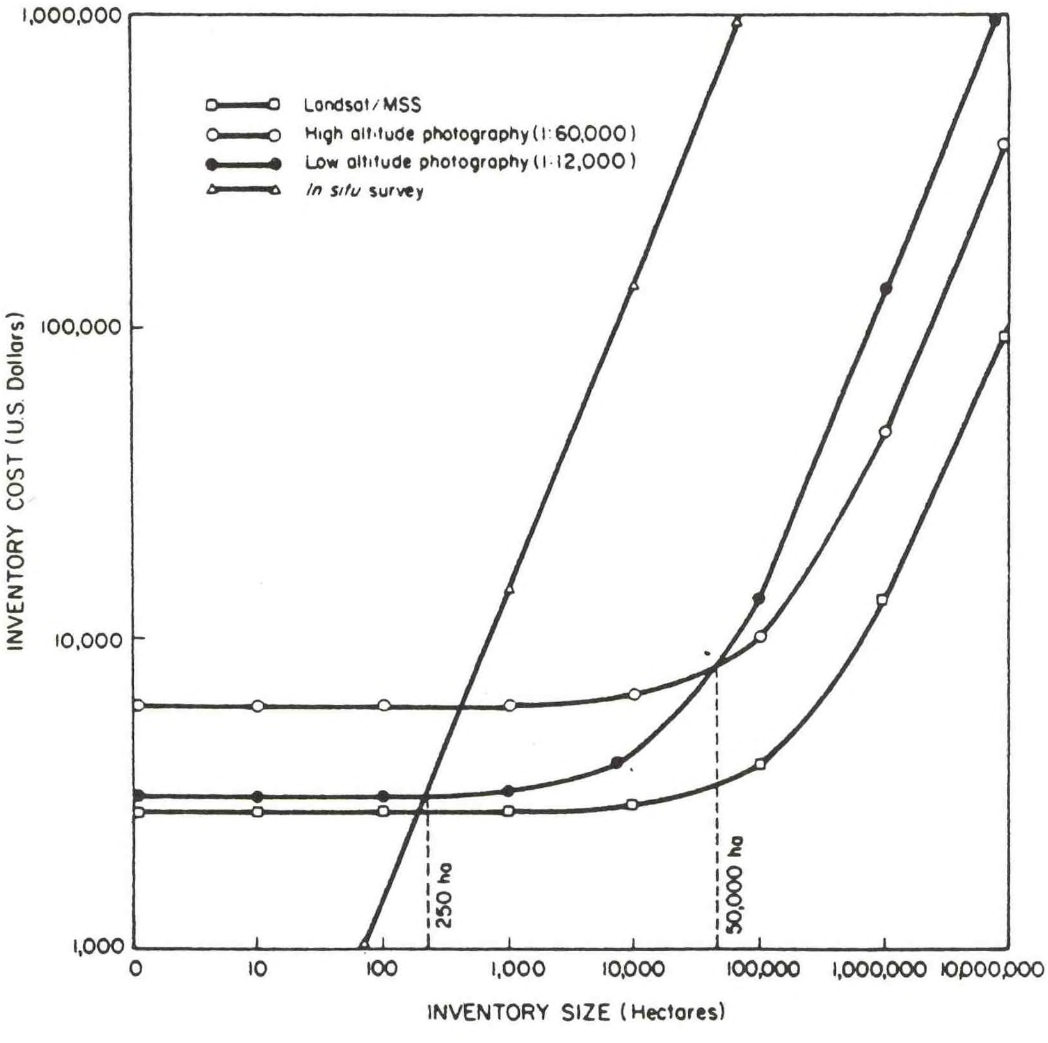


Figure 2. Cost comparison of remote sensing techniques for wetland mapping surveys.

(Colwell, 1967) and agricultural vegetation (Shay, 1976) was being realized. Early reports using aerial photography for seaweed surveys in Nova Scotia (Cameron, 1950) and forest vegetation surveys near Quebec (Schulte, 1951) demonstrated the utility of this RS technique.

Inventories of wetlands using primarily color infrared aerial photography began in the late 1960s as legislation protecting coastal wetlands was being formulated. Stroud and Cooper (1968) used color infrared photography and appropriate ground calibration to estimate the net primary productivity in North Carolina salt marshes. A similar study by Reimold et al. (1973) in Georgia salt marshes reaffirmed the association between color tones on color infrared photography and different quantities of Spartina alterniflora net primary productivity. Microdensitometry and multispectral photographs were used to delineate vegetation types in California (Pestrong, 1969), South Carolina (Guss, 1972), New Jersey (Russell and Wobber, 1972; Anderson and Wobber, 1973), Delaware (Klemas et al., 1974), Wisconsin (Scarpace et al., 1975), and Vermont (Howland, 1980). These efforts at quantification of pigment density from photographs or transparencies and the combination of multiband photography for species discrimination were generally successful.

Additional reports dealing primarily with mapping, wetland inventories and comparisons of RS media for accomplishing the inventories included Egan and Hair (1971) for Maryland wetlands, Gallagher et al. (1972a, b), Reimold et al. (1972), Gallagher and Reimold (1973), and Gallagher (1974) for Georgia salt marshes, Anderson and Wobber (1973) for New Jersey wetlands, and Benton et al. (1977) for coastal Texas marshes. Aerial photography was also useful for delineation and discrimination of types of freshwater marshes. Successful inventories using aerial photography in freshwater marshes included studies of the Florida Everglades (Schneider, 1966, 1968), Nevada marshlands (Seher and Tueller, 1973), Lake Erie fringe marshes (Enslin and Sullivan, 1974), wetlands in glaciated regions of Minnesota (Cowardin and Myers, 1974), freshwater tidal wetlands of Maryland (Shima et al., 1976), forested and nonforested wetlands of Tennessee (Carter et al., 1979), and non-tidal inland wetlands in Florida (Stewart et al., 1980). Seasonal aerial photographs contained the necessary information for determination of evergreen/deciduous boundaries and separation of deciduous canopy classes in the Great Dismal Swamp (Gammon and Carter, 1979).

With the launching of the LANDSAT series of satellites in the early 1970s, Multispectral Scanner (MSS) data became available. The coarse resolution of the data (57 m x 79 m pixels) limited surveys using MSS data to relatively large tracts of wetlands, and the MSS data was usually supplemented with high resolution aerial photography. Mapping and classification of marshlands using MSS data were done in coastal South Carolina and Georgia marshes (Anderson et al,. 1973), in Virginia coastal marshes (Carter and Schubert, 1974), in Delaware coastal marshes (Klemas et al., 1975), in Louisiana marshes (Butera, 1978), in lacustrine, palustrine and riverine wetlands of Michigan (Lyon, 1979a), in the Columbia River wetlands of Oregon (Lyon, 1979b), and in prairie wetlands of North Dakota (Gilmer et at., 1980). The combination of MSS data and aerial photography was also used to develop vegetation maps for forested wetlands like the Great Dismal Swamp (Garrett and Carter, 1977; Carter et al., 1977).

Thompson et al. (1973) discuss many of the operational and photogrammetric considerations necessary to convert RS data in wetlands to reliable vegetation maps. Additional mapping considerations and problems unique to coastal mapping are enumerated by McEwen et al. (1976) and Masry and MacRitchie (1980). The massive effort to inventory and classify wetlands in a format that was useful to wetlands management personnel was difficult. Penney and Gordon (1975) provide an interesting discussion of this problem from the manager's point of view.

The advent of digital spectral data in specific spectral wavebands from the LANDSAT MSS sparked a new era in RS. Data no longer had to be extracted from photographs. Instead, data were already in digital form, allowing direct, quantitative treatment of the radiance data. Ground-gathered spectral reflectance data had been collected for many agricultural crops (Thomas et al., 1967; Gausman et al., 1969; Sinclair et al., 1971; Gausman, 1974). Similar data were also necessary for interpreting spectral signatures from wetland plants. Carter and Anderson (1972) and Pfeiffer et al. (1973) provided in situ spectral reflectance data for a number of wetland plant species. This spectroradiometric data constituted a basis for interpretation of satellite imagery, and also represented useful data for evaluating vegetative canopies from the ground.

The curves in Figure 3, obtained from Bartlett and Klemas (1979), compare the cost of mapping coastal vegetation using ground surveys, aircraft and satellites. The cost of LANDSAT data has more than tripled since Figure 2 was prepared. Figure 3 suggests that for simple vegetation inventories of small test sites, aerial photography should be seriously considered. However, for repetitive observations of vegetative changes, biomass and water properties of areas larger than 10,000 hectares, use of LANDSAT MSS or the Thematic Mapper (TM) data may provide considerable cost savings and speed up the work considerably. TM's spectral bands and 30-meter resolution seem to be particularly well-suited for mapping narrow coastal features, such as tidal marshes and submerged aquatic vegetation beds (Klemas and Ackleson, 1983).

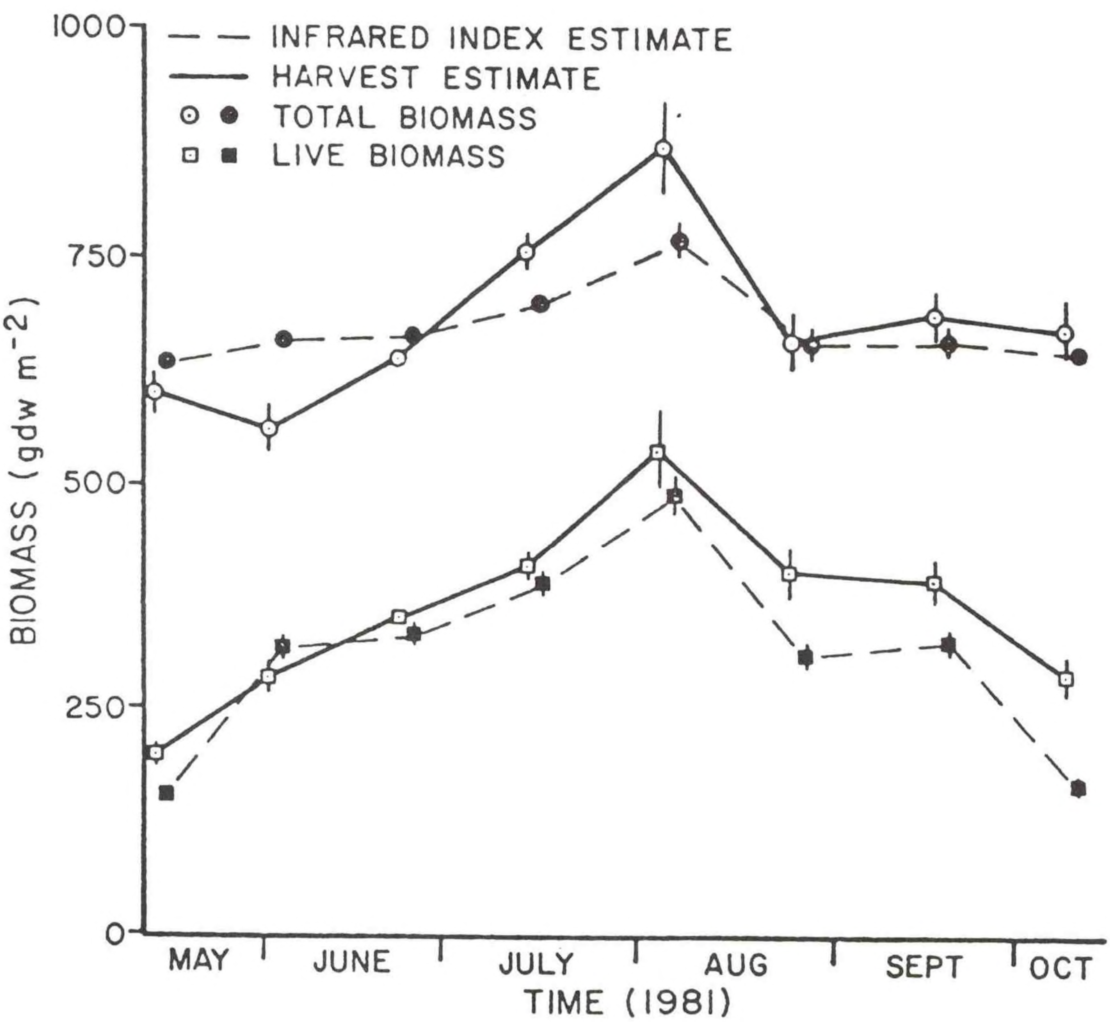


Figure 3. Comparison of remotely sensed and ground-harvested biomass. The Infrared Index is defined as the difference of TM bands 4 and 5 divided by their sum.

ASSESSMENT OF WETLANDS BIOMASS AND PRODUCTIVITY

Ground-based spectral data were found to be highly correlated with the leaf area index of a tropical forest (Jordan, 1969). Marshall (1970) attempted optical density measurements in S. alterniflora salt marshes as a rapid means of biomass comparison. However, his limited data were inconclusive. By the mid-1970s, ground-gathered spectral radiance data in the red region and in the near infrared region were being successfully related to above-ground biomass of a variety of vegetation types. The first group to report success in relating spectral data to gramineous biomass was Tucker et al. (1973) and Pearson et al. (1976). They presented data indicating a very strong relationship between biomass of blue grama grass and spectral radiance ratios. Similar research in wetlands showed much the same results for gramineous wetlands species (Bartlett, 1976), but some difficulty was encountered when working with the broadleaf shrub, Iva frutescens (Drake, 1976).

Subsequent work with the hand-held radiometers in Delaware wetlands (Bartlett, 1979; Bartlett and Klemas, 1979, 1980, 1981), in marshes typical of the Danish Wadden-Sea area in Denmark (Jensen, 1980), and in English bogs and marshes (Curran, 1980, 1982) confirmed the correlation of spectral radiance data with selected canopy characteristcs of wetland plant communities. One of the most important canopy parameters consistently related to spectral data was biomass. Other studies concerned primarily with species discrimination using hand-held radiometers included Best et al. (1981) for hydrophytes occupying the glaciated wetlands of the Prairie pothole region of South Dakota, Ernst-Dottavio et al. (1981) for freshwater wetlands in northeastern Indiana, and Budd and Milton (1982) for a variety of salt marsh plants common to Southern England marshes.

Early work by Bartlett (1976, 1979) determined green biomass, percent live biomass, tidal biomass, and canopy height to be signficantly correlated with spectral reflectance of S. alterniflora and salt hay (Distichlis spicata/Spartina patens mixture) communities found in Delaware salt marshes. These results were obtained using a radiometer configured to the four spectral bands found on the LANDSAT MSS. The most useful spectral waveband combination was the red band (600-700 nm) and a near infrared band (800-1100 nm).

A database of spectral and biomass information was compiled for the dominant salt marsh plant S. alterniflora by Hardisky et al. (1983a), who monitored short and tall swards of S. alterniflora over entire growing seasons. Spectral data were collected with a hand-held GSFC Mark-II radiometer. The radiometer was configured with three spectral bands corresponding to bands 3, 4, and 5, respectively, of the TM. A red band (630-690 nm) sensitive to chlorophyll density, a near infrared band (760-900 nm) sensitive to tissue structure or biomass, and a middle infrared band (1550-1750 nm) sensitive to leaf moisture were used. Spectral radiance data were collected over designated plots and the biomass of each plot was determined by harvesting. Biomass and spectral data were regressed over the growing season, yielding models which included seasonal canopy changes and seasonal variations in solar irradiance. The models were suitable for biomass predictions throughout the growing season. As shown in Figure 3, the spectral data were found to be highly correlated with live S. alterniflora biomass throughout the growing season. In Figure 3, the spectral radiance data are expressed in terms of the Infrared Index, which is defined as the difference of TM bands 4 and 5 divided by their sum.

Supporting studies included an assessment of negative biomass response for S. alterniflora to increases in soil salinity (Hardisky et al. 1983b) and an assessment of positive biomass response for S. alterniflora to irrigations of sewage effluent (nitrogen addition) and freshwater (soil salinity dilution). Changes in canopy moisture in response to changes in soil salinity were negatively correlated to changes in spectral radiance indices, and enhanced biomass production resulting from freshwater or sewage effluent irrigations were positively correlated with increases in measured spectral radiance indices (Hardisky et al. 1983d). An additional study determined that canopy changes resulting from amending an S. alterniflora marsh with heavy metals (copper or zinc) could be detected spectrally (Hardisky et al., 1983d) Live and dead biomass amounts were shown to be significantly higher in copper amended areas than in control areas. This difference in canopy biomass components (proportion of live and dead biomass) was successfully detected with spectral data. From these studies, spectral discrimination of small biomass changes (on the order of 40 gdw m^2) was shown to be feasible and the database for future biomass estimation using spectral data was established.

REMOTE SENSING OF ESTUARINE CURRENTS AND WATER PROPERTIES

Passive RS systems sense either reflected solar radiation or radiated thermal infrared/microwave energy. The solar radiation wavelengths are attenuated exponentially by water, whereas the thermal infrared ones are limited to a very thin surface layer of water. Only the surface layers are sensed as the sensor "looks" at deeper layers of the water column. The signal-to-noise ratio decreased in an exponential manner. In the open ocean, where scattering and absorption effects are of the same order of magnitude, the penetration depth of detectable visible light may exceed 50 meters. Coastal and estuarine waters are more turbid and contain complicated mixtures of dissolved and particulate organic and inorganic substances. As shown in Figure 4, the increased scattering by suspended matter results in Secchi depths of less than one meter in many of the world's bays and estuaries. As one moves from the open ocean into coastal waters, the light attenuation in the water column increases and the wave-length of optimum penetration shifts from blue-green to green and, eventually to red as one enters Chesapeake Bay. While the high turbidity makes the discrimination of specific substances in the water more difficult, turbidity patterns reflect more light and can be detected by LANDSAT MSS bands despite their low radiometeric sensitivity.

The dynamic range of water radiance is about an order of magnitude smaller than that of land targets. Furthermore, in coastal studies one frequently needs to distinguish water masses having only small differences in particulate or dissolved content and, therefore, small difference in the spectra of back-scattered light. As a result, more radiometric sensitivity is required for coastal water studies than those of land. One solution is to increase the number of quantization levels, such as going from 64 on MSS to 256 on TM, a Very High Resolution Radiometer (AVHRR) database and the Coastal Zone Color Scanner (CZCS). Another approach is to decrease the dynamic range of the sensors and to match them more closely to the reflectance extremes of the known water types around the globe. The dynamic ranges of MSS, AVHRR and CZCS are compared in Table 1. Obviously, AVHRR and CZCS are designed to be more sensitive to small radiance variations from different water types than LANDSAT MSS.

Using digital enhancement techniques, LANDSAT MSS, NOAA/AVHRR and Nimbus/CZCS have been used effectively to study sediment patterns, estuarine circulation, frontal dynamics, and ocean-dumped waste dispersion (Klemas, 1980; Klemas and Philpot, 1981). The suspended sediments and wastes frequently act as natural tracers, enabling even LANDSAT MSS to detect the patterns. To improve the contrast of water features, contrast stretching is frequently applied to satellite imagery (Maul and Gordon, 1975). Good examples of multi-level observations of estuarine circulation properties are offered by Klemas et al. (1977) in Delaware Bay, and by Gagliardini et al. (1984) and Karszenbaum et al. (1983) in the La Plata River estuary. Aircraft and ground-based radar techniques are being developed for measuring currents (Schuchman et al., 1979). Of particular interest to estuarine studies is the CODAR (Coastal Dynamics Application Radar) system, a mobile coastal radar unit which can map variable surface currents in real time to 70 kilometers using water wave scatter (Barrick et al., 1977). Currents can also be measured using dyes and drogues tracked from shore or from aircraft (Klemas et al., 1974; Klemas et al., 1977). There

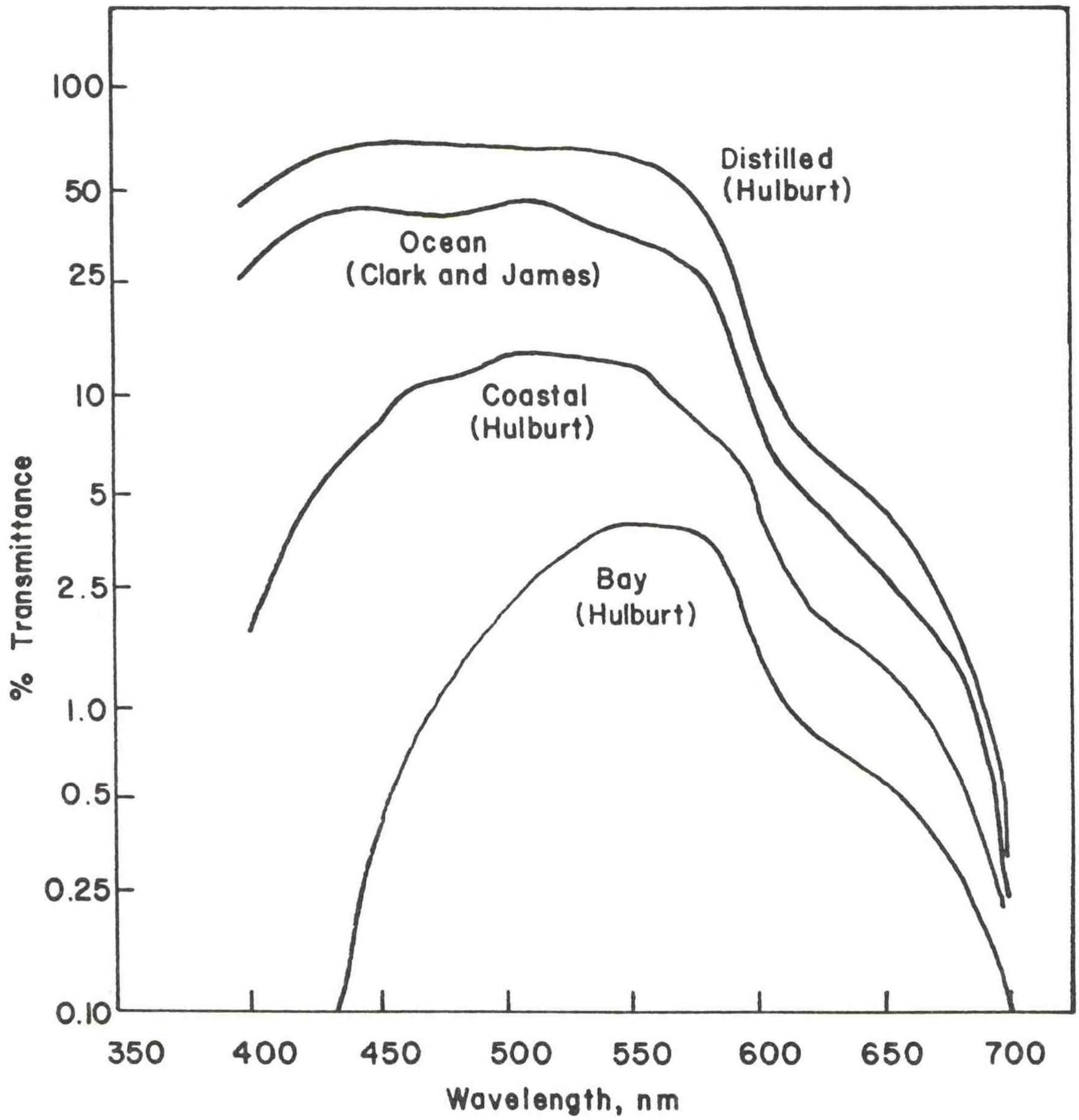


Figure 4. Spectral transmittance for ten meters of various water types.

are also photogrammetric methods for surveying tidal currents (Keller, 1963).

Coastal erosion and coastal geomorphology have been studied successfully using aircraft film cameras and LANDSAT (Dolan, 1973; Dolan et al., 1977; Stafford and Langfelder, 1971). The advantage of aircraft photography is that it provides the high resolution required for accurate measurement of beach erosion and accretion. LANDSAT MSS, however, can provide a geologic overview of an entire coastline, including underwater features. Bathymetric maps have been successfully prepared by extracting water attenuation and bottom reflectance from digitally processed LANDSAT MSS data (Rogers et al., 1982; Lyzenga, 1978, 1979). The water depth algorithm used calculates water depth from LANDSAT MSS 4 (green light) and MSS 5 (red light) data values for LANDSAT pixels that are judged by a threshold test to be water. The threshold test is performed on MSS 7 (near infrared). Pixels whose MSS 7 data values are less than the threshold are judged to be water. The bathymetry software calculates depth values using two algorithms, one for deep water and another for shallow water. In deep water, signals from MSS 4 only are used. In shallow water, signals from MSS 4 and 5 can be used in a ratio algorithm to calculate depth, minimizing the effects of changing bottom reflectance. Following depth processing, depths are aggregated into intervals (generally two meters) and assigned arbitrary colors for filming. Typically, seven to ten intervals are filmed depending on the maximum depth of penetration. LANDSAT TM bands 1 and 2 have further improved bathymetric results.

Water depth can also be measured by the time difference between laser pulses from the water surface and the bottom. Such laser profiles use green wavelengths which penetrate reasonably clear waters (Hoge et al., 1980). A major limitation of laser depth profiling systems is their inability to penetrate turbid water. Most of the laser systems in use perform satisfactorily when the products (a x h) of the beam attenuation coefficient (a) and the depth (h) are from 6 to 10. Since the total attenuation coefficient (a) of the optical beam in the ocean and coastal water varies from 0.5 to 5.0, attainable depths should range from 20 to 2 meters, depending on the turbidity of the water. The Airborne Oceanographic Lidar (AOL) system has shown that a single instrument package can be developed for a wide range of applications and turbidity conditions (Link et al., 1982; Hoge et al., 1980).

Visible images from aircraft or satellites can help provide relative depth profiles which may then be calibrated with airborne laser profilers. Even though powerful laser pulses penetrate the water column to several Secchi depths, a major limitation is their inability to reach bottom in turbid coastal waters. For instance, the turbidities of Chesapeake and

Table 1.

Comparison of radiometric sensitivity (mW/cm²·sr·μm per count) of MSS, AVHRR and CZCS.

Band	MSS(Landsat 1)	AVHRR(NOAA 7)	CZCS(Gain 3)
1		0.052(0.58 -0.68μm)	0.021(0.433-0.453μm)
2		0.034(0.725-1.1 μm)	0.014(0.501-0.530μm)
3			0.011(0.540-0.560μm)
4	0.185(0.5-0.6μm)		0.005(0.660-0.680μm)
5	0.166(0.6-0.7μm)		0.093(0.700-0.800μm)
6	0.126(0.7-0.8μm)		
7	0.40 (0.8-1.1μm)		

Delaware Bays are such that less than half the total area could be mapped with the most powerful laser profiler available.

Since most wavelengths do not penetrate to the bottom of turbid estuaries, to map bottom features reliably, one frequently must turn to underwater television cameras, film cameras, or sonar systems operated from boats. Television and film cameras have been used successfully to study ripple formation, current-induced sediment movement, submerged aquatic vegetation and other features, including wrecked ships (Smith, 1984). Echo sounders and sidescan sonar have been deployed to study bottom geologic features, search for lost equipment, and track schools of fish, and ocean-dumped waste penetration of the thermocline (Proni et al., 1976; Wirts and Acker, 1979).

Suspended sediment concentrations are of interest to marine geologists and biologists since sediment relates to coastal erosion/siltation, and effects sunlight penetration and marine productivity. As shown in Figure 5, with appropriate ground data, suspended sediment concentrations have been mapped from aircraft and satellites (Johnson, 1975; Moore, 1978; Munday and Alfoldi, 1979; Maul et al., 1974; Klemas et al., 1977). One of the major problems in calculating suspended sediment concentration from a measured flux is the difference in absorption and scattering of light in the atmosphere from one time to another. Because of many variables, it may not be practical to determine an atmospheric correction directly, but a combination of dark object subtraction and band ratios may provide an adequate correction. The other major problem is that a backscattered flux may represent a mix of water color, bottom reference, turbidity produced by plankton, and turbidity caused by suspended sediment. In many cases, however, a change in flux is caused simply by a change in the concentration of one constituent.

An optical measure of water color and turbidity can be obtained with RS. Pollutants must affect color or turbidity to be detectable, although dissolved luminescent constituents can be detected by Fraunhofer line discrimination techniques. Dissolved color materials increase the absorption of light in water and decrease the remote signal. Suspended materials increase the backscatter of light and increase the remote signal.

Most studies which obtained good correlation between remotely sensed radiance and concentration data from ships included a calibration of the radiance values based on water sample analyses for sediment concentration, size distribution and composition (Munday and Alfoldi, 1979; Klemas et al., 1974; Johnson, 1975; Ritchie et al., 1976; McKim et al., 1980, 1984). Since sediment concentration is not uniquely related to backscattered radiance, a prior knowledge of grain size, composition and layering is required before radiance maps can be converted

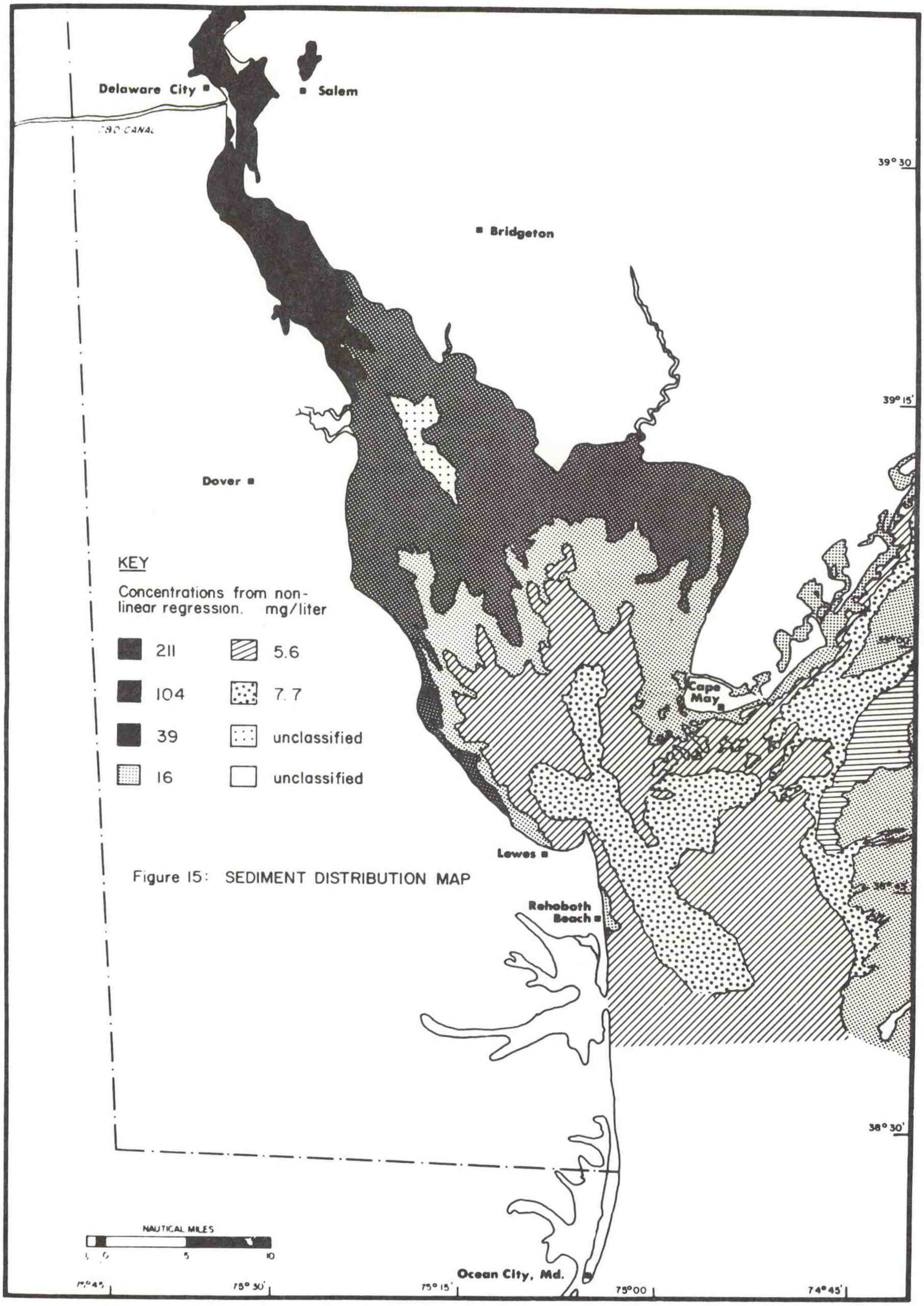


Figure 5. Suspended sediment concentration of Delaware Bay derived from LANDSAT MSS data.

Table 2. Performance of Remote Sensors for Estuarine Studies.

Sensor	Plat-form	Veg.& Land Use	Biomass & Veg. Stress	Coast-line Erosion	Bottom Feat. SAV	Depth Profiles	Susp. Sed. Ptrns.	Susp. Sed. Concen.	Chloro-phyll Concen.	Oil Slicks	Surf. Temp.	Water Sal.	Curr. Circ. Ptrns.	Wave Spectra	Surf. Winds
Film Cameras	A	3	1	3	3	2	2	1	1	2	0	0	2	2	1
	S	2	1	2	2	1	2	1	1	1	0	0	2	2	1
Multispectral Scanners	A	3	2+	3	3	2	3	2	2+	3	0	0	2	2	1
	S	2	2	2	2	2	3	2	2	2	0	0	2	2	1
Thermal IR Scanners	A	1	1	1	0	0	1	0	0	3	3	1	2	0	1
	S	0	0	0	0	0	1	0	0	1	3	0	2	0	1
Laser Profilers	A	0	0	1	3	3	1	0	0	1	0	0	0	3	1
	S	0	0	1	1	1	0	0	0	0	0	0	0	2	0
Laser Fluorosensors	A	1	0	1	0	1	1	2	3	3	1	1	1	0	0
	S	0	0	0	0	0	0	1	1	1	0	0	0	0	0
Microwave Radiometers	A	1	0	1	0	0	1	1	1	3	3	2	2	1	3
	S	0	0	0	0	0	0	0	0	1	2	1	1	0	2
Imaging Radar (SAR or SLAR)	A	2	1	3	0	1	1	0	0	3	1	1	2	3	2
	S	1	0	2	0	1	0	0	0	2	0	0	1	2	1
CODAR (Radar)	G	0	0	0	0	0	0	0	0	0	0	1	3	2	2
RADS(Acoustic)	G	0	0	2	3	2	2	1	0	1	0	0	2	1	0
UW Camera	G	0	0	2	3	2	2	1	1	1	0	0	1	0	0

Rating
3 = Reliable (Operational)
2 = Needs Additional Field Testing
1 = Limited Value (Future Potential)
0 = Not Applicable

Platform
A = Aircraft (Medium or Low Altitude)
S = Spacecraft (Satellite)
G = Ground (Boat or Field)

into suspended sediment concentration maps (Amos and Alfoldi, 1979; Whitlock et al., 1982; Moore, 1978). Considerable progress is being made in the development of optical models of the water column to discriminate organic from inorganic suspended matter, to map substances having varying concentrations (layers) as a function of depth, to eliminate bottom reflections, and to improve atmospheric corrections (Philpot and Ackleson, 1981; Wilson and Austin, 1978). The same discussion applies to mapping pollutant concentrations in coastal waters (Whitlock et al, 1981). To map pollutant concentrations, good ground measurements are required and fairly sophisticated data analysis techniques may have to be used with multispectral scanner data (Philpot and Ackelson, 1981; Klemas and Philpot, 1981).

Chlorophyll concentration strongly influences ocean color and is a good indicator of coastal productivity (Wilson and Austin, 1978). The Coastal Zone Color Scanner (CZCS) on Nimbus 7 has been used with considerable success to map ocean color and chlorophyll-a concentrations over open ocean areas (Hovis, 1977). Despite difficult atmospheric corrections, chlorophyll-a concentrations have been mapped with considerable accuracy (Gordon and Clark, 1980). In turbid coastal waters, it is more difficult to map chlorophyll concentrations using passive techniques. Water masses dominated by dissolved carbon, particulate carbon, and organic sediment have been differentiated with aircraft multispectral scanners (Klemas et al., 1981). Principal component analysis techniques have been particularly effective for identifying estuarine water types (Stumpf, 1984).

Chlorophyll and other pigments have been detected in turbid coastal waters using laser fluorosensing techniques. Cholorophyll concentrations and dispersed oil can be determined using low-altitude airborne lasers operating in the fluorosensing mode (Jarrett et al., 1979; O'Neill et al., 1980). Oil slicks which have not been emulsified and mixed in the water column can be mapped with film cameras, multispectral scanners, and thermal infrared and microwave (Catoe, 1972). In the visible region, oil has a higher index of refraction than background water; in the thermal infrared and microwave bands, its emissivity differs from that of water. Radar can detect it, primarily because oil slicks dampen small surface waves. However, only microwave devices and laser fluorosensors offer hope for measuring oil slick thickness.

Thermal infrared scanners have been very effective for mapping ocean surface temperatures with about $\pm$ $1^{o}C$ accuracy and for studying coastal surface currents (Legeckis, 1975, 1978). Thermal infrared scanners on NOAA satellites, together with multispectral scanners such as the AVHRR and CZCS, have been used to study coastal upwelling and estuarine properties (Gagliardini et al., 1984; Karszenbaum et al., 1983). Productive coastal upwelling events are accompanied by drops in temperature and chlorophyll induced color changes detectable by AVHRR and CZCS.

Large area measurements of ocean salinity are of considerable value to oceanographers investigating the coastal zone. Such data are useful in determining the estuarine impact of river flooding for shellfish bed health monitoring and in detecting coastal water masses where mixing of different bodies of water occur that could affect fish distribution. Changes in salinity and temperature patterns can identify the presence of large-scale turbulence and currents. The data are also useful in refining circulation and pollution models in bay areas. However, salinity is one of the most difficult properties to sense remotely. L-band microwave radiometers employed from land-altitude aircraft have been able to map salinity with an accuracy of less than one part per thousand at 25°C. Such accuracy is useful for estuarine studies where large salinity gradients can be found. Open-ocean salinity sensing requirements are more stringent by at least one order of magnitude. One of the principal needs relates to the measurement of mass density, as inferred from simultaneous temperature and salinity measurements. Such data identify regions of upwelling and circulation patterns.

Coastal wave conditions and wave spectra are best obtained using laser profilers from aircraft, radar mappers (SAR) and radar altimeters (Panicker, 1974; Ross et al., 1970; Born et al., 1979; Schule et al., 1971). Imagers such as synthetic aperture radar or film cameras are particularly effective for wave studies if the data is analyzed using Fourier analysis techniques (Stilwell, 1969). Since surface winds induce capillary waves that influence microwave emission and reflectance, microwave sensors, particularly radar scatterometers such as the one on SEASAT, have been tested for surface wind determinations (Born et al., 1979). SEASAT sensors were specifically designed for measuring and mapping ocean waves, surface winds, currents and other features (American Geophysical Union, 1983). The accuracies of the measurements are remarkable, considering they were made from satellite altitudes.

CONCLUSIONS AND FUTURE NEEDS

As shown in Table 2, remote sensors on satellites and aircraft are capable of measuring many properties of coastal waters, tidal wetlands, and estuaries. LANDSAT MSS and TM, NOAA/AVHRR, Nimbus CZCS, and SEASAT have made major contributions to coastal investigations.

As low-cost microcomputers with user-friendly software become available for analyzing imagery, data from these satellites are being more widely used in coastal and estuarine projects throughout the world. However, many improvements are needed if user requirements are to be fully satisfied in the future. The following are some obvious areas for improvement:

(1) None of the available satellite systems have <u>both</u> the required spatial and temporal resolution for observing tidal-induced processes in estuaries and coastal waters. Synchronous orbit satellites have sufficient temporal resolution, while LANDSAT sensors have enough spatial resolution. Only aircraft can provide both at the present time.

(2) Electromagnetic (EM) sensors have insufficient depth penetration, particularly in turbid coastal waters, for bathymetric or other studies. Although powerful laser profilers can penetrate to several Secchi depths, shipborne sonar profilers must still frequently be used to supplement EM wave techniques.

(3) Chlorophyll and suspended sediment techniques need to be further developed to improve their accuracy to better than the factor two available at present. Multispectral techniques for differentiating dissolved organics, particulate organics, and inorganic sediment in estuaries need to be further refined. A dedicated aircraft with a multispectral scanner having bands similar to the CZCS is required.

(4) Water salinity is one of the most important parameters to be measured in estuaries. Microwave radiometers are capable of resolving salinity down to one part per thousand, which is useful but not sufficient. For estuaries and coastal studies, accuracies down to one-tenth part per thousand are sought.

(5) SEASAT's microwave sensors provided large amounts of valuable data on coastal waves, currents, surface winds, and other properties. However, SEASAT survived only for three months. An aircraft or a similar satellite with higher resolution sensors is needed to provide data for estuarine and coastal investigations of surface winds, currents, and wave spectra.

(6) Underwater cameras and sonar systems have been successfully deployed to map bottom features, submerged aquatics, fish schools, waste dispersion, thermoclines, and fronts in relatively clear lake or shelf waters. These devices must be modified to be usable in turbid estuaries exhibiting more bottom variability, current fluctuations, and stronger gradients in the water column.

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DATA REQUIREMENTS FOR HYDRODYNAMIC MODELS OF ESTUARIES

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The techniques of observation and numerical modeling of estuarine circulations have advanced to that exciting, yet awkward, stage of development where we are ready to examine the process of comparing the two different descriptions of the water motion. To say this may seem to deliberately ignore years of "calibration and verification" of numerical models. In these years, however, the tendency has been to regard the observational data as sacred, inviolate numbers that the models should strive to "match." With the advent of the increased accuracy and resolution that new observational techniques such as remote sensing afford, we now understand that both models and observations have provided incomplete descriptions of these inherently three-dimensional circulations. We must now recognize at the outset of the comparison process, that our traditional measures of estuarine circulation offer only glimpses of the "real" water motion. Comparison then, requires the careful design of appropriate tests of the skill and accuracy of numerical models. Otherwise, the models may be adjusted to the wrong observational measures, apparent agreement between models and observations may arise from artifacts, or good models may be unfairly discounted.

Part of the reason that our improved understanding allows us to address the comparison process directly, with increased insight, is that there has been a convergence in the style of numerical models. In the Dark Ages, there was a tendency toward two styles which can inaccurately be referred to as the "research" approach and the "applied" approach. In the research models, the equations of motion were written for a simplified geometry, and the driving inputs and boundary conditions were structured and simplified to enhance our ability to decipher the controlling physics. This insight was often at the expense of direct comparison of model runs with observations. The applied approach consisted of tuning the equations of motion to the specific water body of interest, and attempting to represent the full geometry and include all the relevant driving forces to achieve a realistic simulation of the circulation, one which we could easily compare with observations. With the improvement in our modeling skills (especially with the advent of the three-dimensional, primitive-equation models) has come not only a convergence in modeling style, but also a substantial additional bonus -- the optimization of a field observational program via guidance from the numerical models. An example of this process is the modification of the moored array design for the third experiment in our study of the Chesapeake Bay estuarine plume on the continental shelf. The three-dimensional numerical model (Chao and Boicourt, 1986) suggested a transition region between the initial, broad turning zone of the estuarine outflow, and the swift and narrow coastal jet in the far field of the plume. In light of this prediction, the positions of the moorings containing the current meters and the temperature-salinity recorders were adjusted to delineate this transition region and to examine the dynamics of the flow and its variability.

The obvious benefits of remote sensing to the measurement and modeling of estuarine circulation are resolution and synopticity. Although the presently available satellite information has been of only limited utility (as the result of limited temporal coverage or inadequate spatial resolution on estuarine scales, or limited availability of imagery), there has been sufficient experience with the satellite sensors to show that present sensors can be used to advantage, and that future sensors will prove of substantial value in delineating the physics and in constructing and testing three-dimensional numerical models. The synthetic-aperture radar on SEASAT provided remarkably well-resolved views of estuarine fronts in the Chesapeake Bay and in its outflow plume on the continental shelf. The Coastal Zone Color Scanner has presented tantalizing views of distributions of tracers such as color, turbidity, and chlorophyll-a. Although there has been some difficulty in developing a correction algorithm that works well in inshore and estuarine waters, the imagery has proved valuable in delineating water mass structures in these regions. The most widely used operational imagery has been the thermal pictures from the Advanced Very High Resolution Radiometers on the NOAA satellites. At present, the spatial resolution is at or below the limit where temperature structure can be developed for small to mid-sized estuaries, but, even in these cases, the outflow plumes can be detected during the transition seasons when the estuary warms or cools faster than the adjacent continental shelf.

DATA REQUIREMENTS FOR WATER QUALITY MODELS OF ESTUARIES

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ABSTRACT

The basic data requirements for the development and application of water quality models in estuaries are presented in the light of the modeling framework for two illustrative problem contexts: eutrophication and toxic substances. Experience has indicated that the modeling framework assists in the justification for data collection but that a rigorous rationale for all variables that can be measured need not always be available. It is indicated that remote sensing can be of significant value to estuarine water quality modeling if quantitative data on chlorophyll-a and suspended solids were available.

INTRODUCTION

The purpose of this paper is to provide some brief comments on the data that are required for the development and application of water quality models of estuaries with some specific recognition of the possible role that remote sensing can fill in estuarine water quality modeling. In general, the fundamental requirements for estuarine water quality modeling are dictated by the nature of the question that is to be addressed. Thus, three issues of concern, among many, are:

1. Is the model to represent a first screening of the impacts of point and non-point sources of wastes or is the model to address detailed consideration of various water quality control alternatives?

2. Is the model to be on a local scale (e.g., a local estuarine embayment on a spatial scale of 1-10 km), an estuary-wide scale (including one, two or three dimensional representations), or on a basin-wide scale (e.g. Chesapeake Bay system)?

3. Does the environmental control question include a temporal dimension, i.e., how long will it take to reach a specified water quality objective or is a steady state approach feasible?

Figure 1 illustrates the latter two questions for the Potomac estuary. These issues, among others (e.g., time and

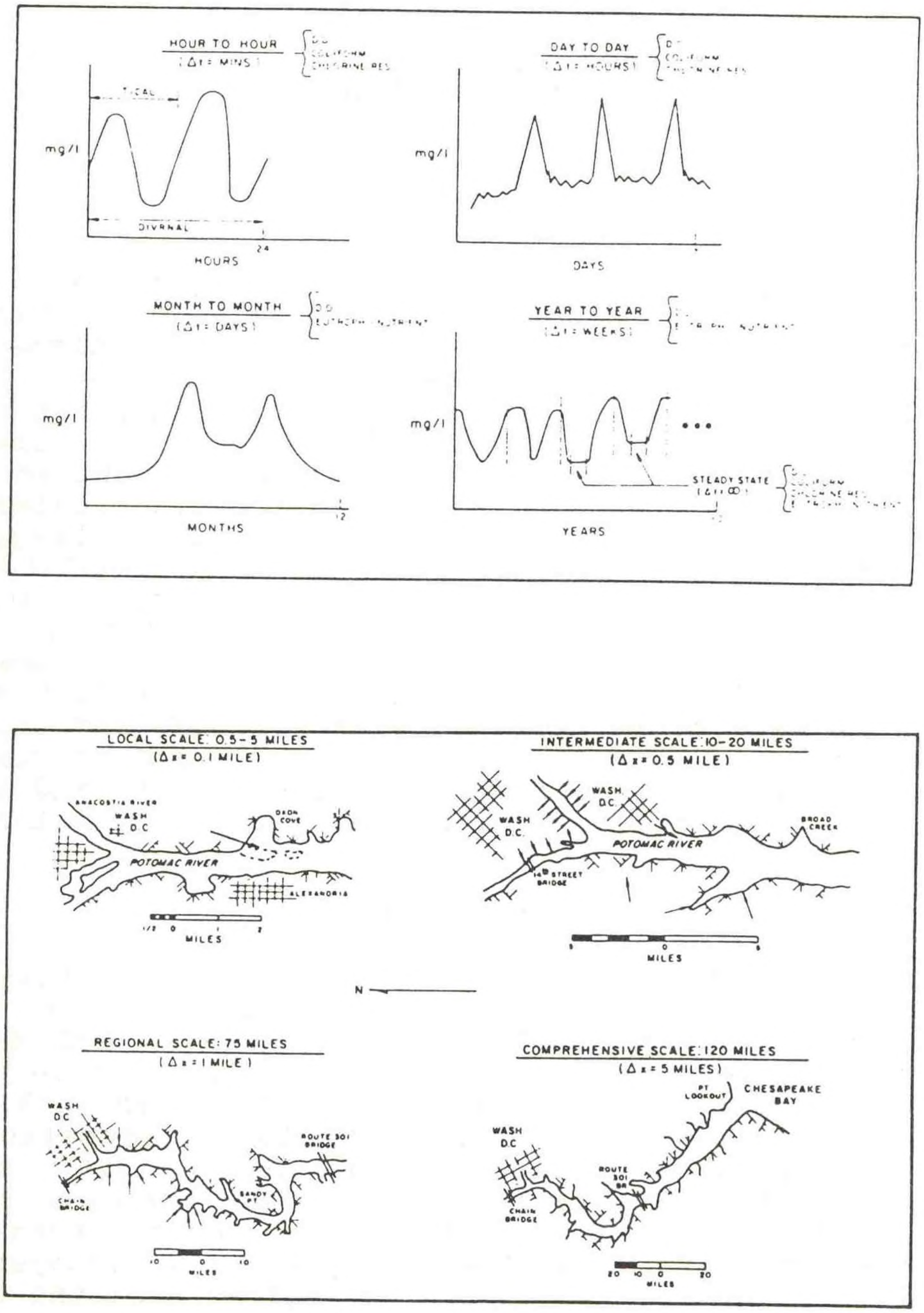


Figure 1 (a) Temporal scales and (b) spatial scales of importance in the Potomac estuary (Thomann and Fitzpatrick, 1982) budget constraints that are imposed on the model development and application) determine the basic model structure given by:

1. The state variables and their kinetic interactions,

2. The spatial scale and dimensionality of the estuaries, model, and

3. The temporal scale (e.g., hour-to-hour, seasonal, or year-to-year) or steady state.

In order to illustrate these concepts within the framework of remote sensing possibilities, two estuarine problem contexts are examined:

1. Eutrophication, i.e., the excessive stimulation of nuisance aquatic plants due to the discharge of nutrients from point and non-point sources, and

2. The fate of chemicals in the estuarine system which may accumulate in certain compartments (e.g. fish, sediment, water column) so as to constitute a toxic effect, in some sense.

The approach herein to describing the data requirements is to first describe the basic structure of the principal equations describing either eutrophication or toxic substance fate and then to indicate the input data that are necessary for development and application of the estuarine water quality model.

Throughout the discussion, recognition should be given to the necessity of data for:

1. Model calibration, i.e., the first tuning of the model to a set of data on the state variables,

2. Model verification, i.e., the subsequent use of the calibrated model to attempt to reproduce observed data under a different set of environmental conditions of freshwater inflow or external loading condition,

3. Post-audit of a model forecast or projection, i.e., the subsequent determination of the credibility of the estuarine model in adequately forecasting the estuarine response to an environmental control action.

Figure 2 schematically shows the basic components of any water quality model. As shown, data for the inputs of the chemical or nutrient from point and non-point sources must be available. Some representation of the hydrodynamic transport and any associated transport structure must be included with associated data on current fields and dispersive properties

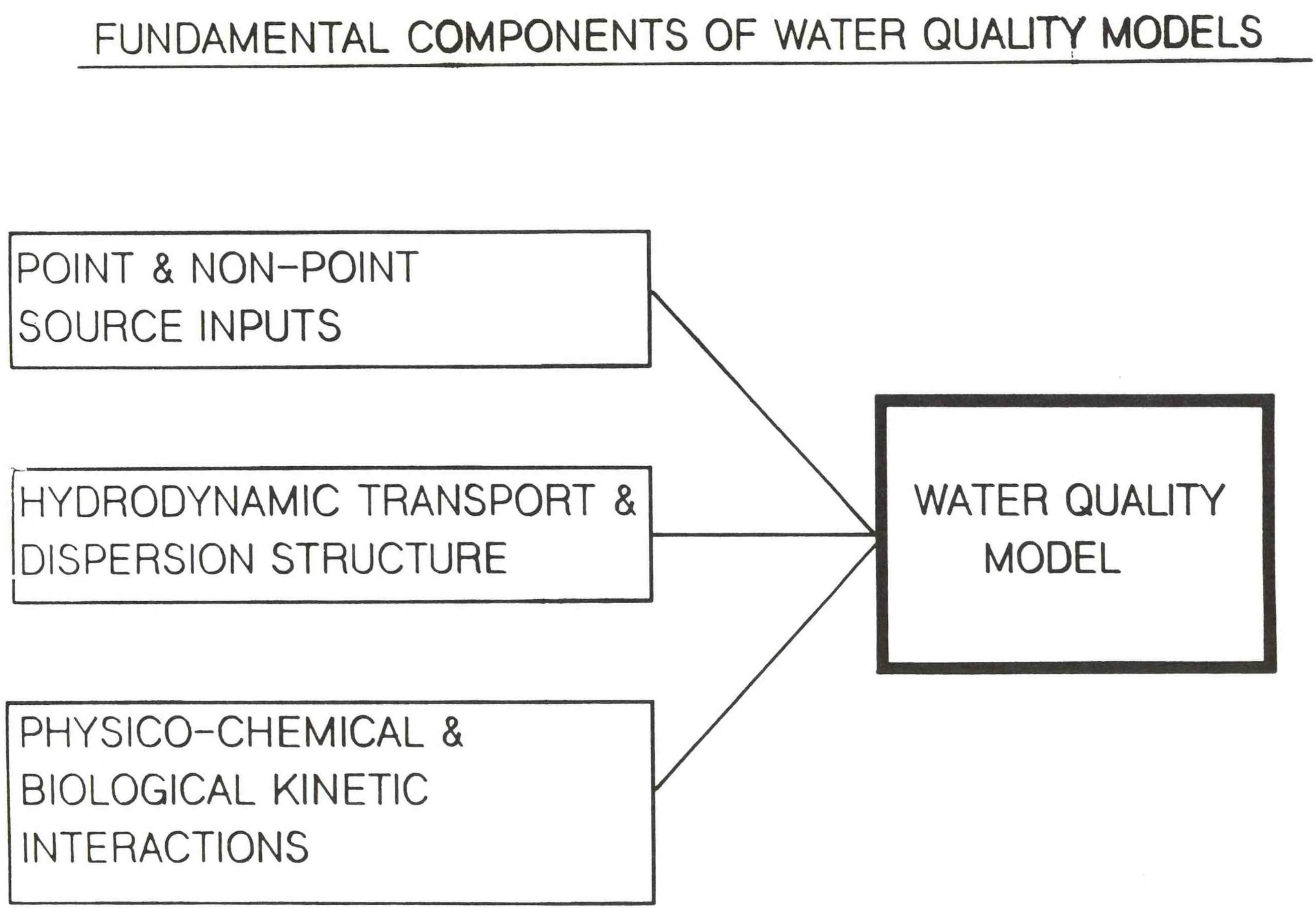


Figure 2. Schematic of water quality model framework

appropriate to the scale of the problem. Finally, the physico-chemical and biological kinetic interactions must be included and data are needed for the state variables and any process rates or fluxes.

DATA REQUIREMENTS FOR EUTROPHICATION MODELS OF ESTUARIES

Specific applications of eutrophication models require utilization of numerical approximations to the basic partial differential equation representing the distribution of a variable in space and time. In order to focus in on the data requirements, it can be shown that a backward difference approximation to a mean tide representation of phytoplankton chlorophyll (a useful measure of eutrophication) is given for segment i of the finite difference grid by:

$$V_i \frac{dP_i}{dt} = \sum_j (Q_{ji}P_j - Q_{ij}P_i) + \sum_j E'_{ji}(P_j - P_i) \qquad \begin{matrix} i=1,2..n \\ j=1,2..n \\ j \neq i \end{matrix} \qquad (1)$$

$$+ (G_i - D_i)V_iP_i - v_iA_iP_i$$

where P_i = the chlor a concentration in segment i

V_i = volume of segment i

Q_{ji} = net advective flow from segments j to i; $Q_{ji} = - Q_{ij}$

E'_{ji} = bulk dispersion from j to i

G_i = phytoplankton growth rate in i

D_i = phytoplankton death rate in i

v_i = net phytoplankton settling rate from segment i

A = interfacial area across which net settling occurs

The growth rate in this equation assumes particular importance because of its interaction with the available nutrient pool. One expression for the growth rate of the phytoplankton is given by

$$G_i = \{G_{max}\theta^{T-20}\}\{\frac{fe}{K_eH}(\exp(\frac{I_a}{I}\exp(-K_eH)) - \exp(\frac{-I_a}{I_s}))\} \qquad (2)$$

$$\{Min(\frac{N_1}{K_{MN_1} + N_1}; \frac{N_2}{K_{MN_2} + N_2}; \frac{N_3}{K_{MN_3} + N_3}; \ldots\}$$

where:

I = solar radiation

f = photo period

T = water temperature

K_e = light extinction coefficient = $f(P,m)$ for m as the suspended inorganic and non-phytoplankton particulates

N_1 = nutrient #1, e.g. available phosphorus

N_2 = nutrient #2, e.g. available nitrogen

N_3 = nutrient #3, e.g. available silica

e = base of Naperian logarithms

This equation indicates the interaction of the nutrient state variables in the parametric forcing of the phytoplankton. Thus separate equations must be written for the nutrient species. For example, for phosphorus, a simple coupled pair of equations for the available and unavailable forms is given by

$$V_i \frac{dN_{ui}}{dt} = \sum_j (Q_{ji}N_{uj} - Q_{ij}N_{ui}) + \sum_j E'_{ji}(N_{uj} - N_{ui}) + v_{ri}A_iN_{si} - v_{si}A_iN_{ui} - K_{uai}V_iN_{ui} + D_iV_ia_pP_i + W_{ui} \quad (3)$$

$$V_i \frac{dN_{ai}}{dt} = \sum_j (Q_{ji}N_{uj} - Q_{ij}N_{ui}) + \Sigma E'_{ji}(N_{uj} - N_{ui}) + K_{uai}V_iN_{ui} - G_iV_ia_pP_i + K_{pi}A_i(N_{di} - N_{ai}) + W_{ai} \quad (4)$$

where (for all segments i):

N_u = unavailable phosphorus (e.g. inorganic particulate, complex organic forms)

N_a = available phosphorus

a_p = stoichiometric phosphorus/chlorophyll ratio

v_p = settling velocity of particulate phosphorus

v_r = resuspension velocity of particulate phosphorus

K_{ua} = hydrolysis and biotransformation rate of unavailable phosphorus to available phosphorus

K_p = sediment diffusive exchange

N_s = sediment particulate phosphorus

N_d = sediment interstitial phosphorus

W_a = mass inputs of available phosphorus

W_u = mass inputs of unavailable phosphorus

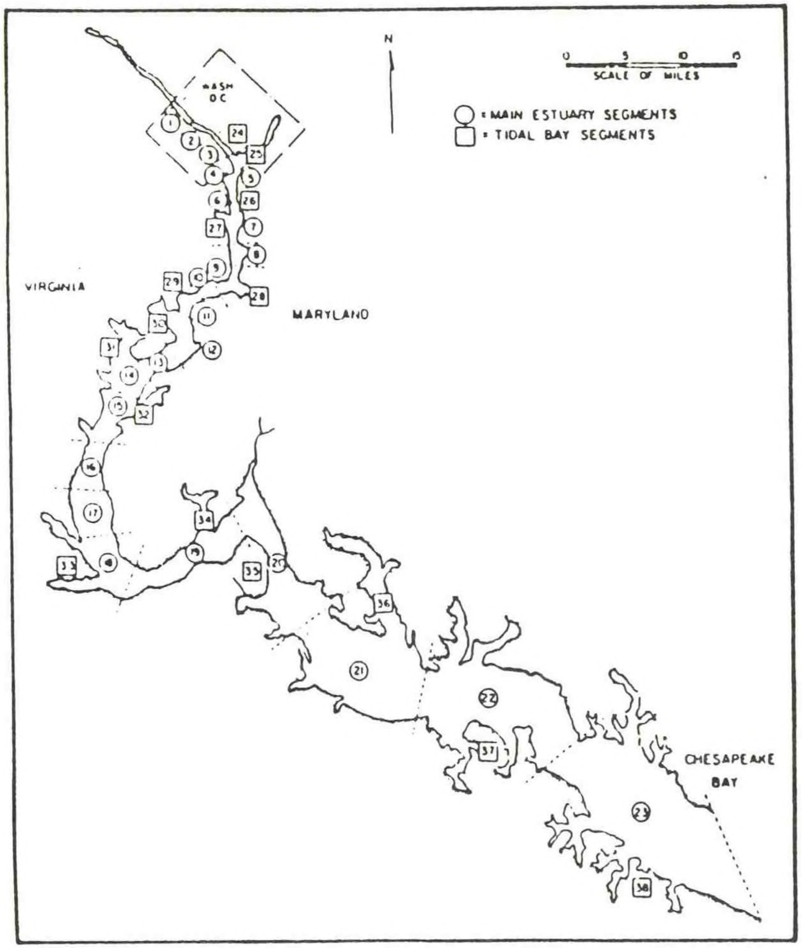
Figure 3 shows a more complete set of kinetic interactions used in a model of eutrophication of the Potomac estuary, the Potomac Eutrophication Model (PEM), and the spatial grid used in that calculation. Equations 1-4 indicate the data needs for a model of this type. Clearly, information on state variables is needed, such variables including phytoplankton chlorophyll and the various nutrient forms.

Application of this model framework to the Potomac estuary has indicated the need to obtain data on other physical and chemical properties as well. For example, the algal bloom of 1983 prompted a detailed field and modeling investigation which indicated the need to examine the p^H-alkalinity and sediment phosphorus release as a likely contributing factor for the bloom. The vertical two-dimensional circulation of the Potomac also appeared to be important and therefore required examination of the suspended solids profiles. For data needs, a conclusion of the Potomac experience is that the standard "laundry list" of variables can be quite important as knowledge increases. Data on such variables as alkalinity which were collected for no immediate apparent reason became significant in later years (see Thomann et al., 1985; Freudberg, 1985).

ROLE OF REMOTE SENSING IN EUTROPHICATION MODELS

From a remote sensing point of view, the most likely candidates for data input into the modeling framework are the surface chlorophyll and the suspended solids concentration. In addition, remote sensing can of course provide some input into the construction of the hydrodynamic transport structure.

Reasonably accurate temporal and spatial mapping of the chlorophyll and suspended solids concentration would be of significant value in the calibration, verification, and post-audit of eutrophication models. Detailed investigations of the potential of remote sensing for these variables has been conducted by Bukata et al (1985) for lakes. Their work, including the remote measurement of the dissolved organic carbon concluded that there were some significant difficulties in accurately sensing the low level chlorophyll concentration in lakes from optical parameters but that the ability to sense suspended mineral material and the dissolved organic carbon appeared promising.



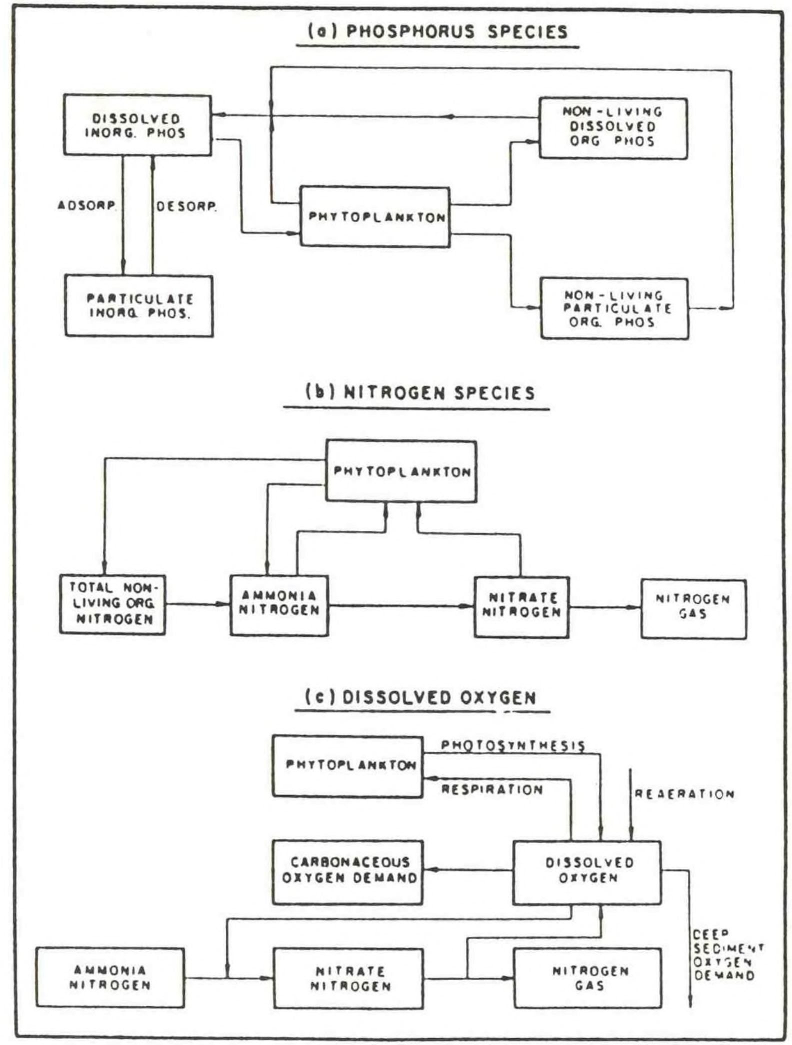


Figure 3. (Left), Segmentation for the Potomac Eutrophication Model (PEM); (Right), State variables and interactions in PEM; from Thomann and Fitzpatrick (1982).

Tanis (1980) describes the use of airborne multispectral data to estimating the areal extent and quantitative mass density of Cladophora Glomerata, a filamentous alga. This benthic alga grows on hard and rocky substrates and can grow to nuisance densities. Tanis (1980) concluded that the airborne collection of data is a practical method for describing the distribution and density of this attached algae.

However, it should be recognized that remote sensing will apparently provide data to only a limited portion of the model as described above. The interaction of the nutrients and the phytoplankton is crucial to the prediction of the effectiveness of the control program. Also, the apparent present inability of remote sensing techniques to provide useful information on the depth structure of key variables will limit its use in water quality model development and application.

Nevertheless, in the fully time variable multi-dimensional phytoplankton models (or similar models for attached forms), the routine availability of chlorophyll measurements would prove particularly useful in monitoring the results of a nutrient reduction program. An example is the reduction program in place for the Potomac estuary and the need for continued study, modeling effort, and monitoring in that estuary.

MODELS OF FATE OF CHEMICALS IN ESTUARINE SYSTEMS

The second major modeling framework that can be used as an illustration of the data needs for estuary water quality models is that of the distribution in space and time of chemicals that may be potentially toxic. The principal difference of this model context from the more traditional estuary water quality models is the tendency for a variety of potentially toxic chemicals to partition on to the particulate matter in the estuary. Thus, the suspended particulate and the sediment water interface, bed load, and the fixed bed sediment become important reservoirs for the chemical. Such interaction of the chemical with the solids dynamics of the estuary must be incorporated into the modeling framework.

The basic equations can be described as follows: For any segment of the water column, designated 1 and for the active sediment segment underlying the water column, designated 2, the equations are:

$$V_1 \frac{dc_{T1}}{dt} = (\text{Transport} + \text{Dispersion}) + K_f A((f_d c_T)_2 - (f_d c_T)_1)$$

$$- (K_{d1} f_{d1}) V_1 c_{T1} + k_\ell A(c_g/H_e - f_{d1} c_{T1})$$

$$- v_s A f_{p1} c_{T1} + v_u A f_{p2} c_{T2} + W_{T1} \qquad (5)$$

$$V_2 \frac{dc_{T2}}{dt} = - K_f A((f_d c_T)_2 - (f_d c_T)_1) - (K_{d2} f_{d2}) V_2 c_{T2}$$

$$+ v_s A f_{p1} c_{T1} - v_u A f_{p2} c_{T2} - v_d A f_{p2} c_{T2} \qquad (6)$$

where c_{T1}, c_{T2} = total toxicant in water column and sediment

f_d, f_p = fraction dissolved and particulate
= f(¶, m)

for

¶ = partition coefficient of chemical on solids

K_f = sediment diffusive exchange transfer coefficient

k_ℓ = air-water chemical exchange transfer coefficient

cg = vapor phase concentration of chemical

He = Henry's constant for chemical

v_d = net sedimentation velocity

$K_{d1,d2}$ = decay rate of chemical

W_{T1} = input of total chemical to water column

Again, inspection of these equations indicates the input load, state variables, and process rates that must be collected in order to construct a field validated model. The chemical in both dissolved and particulate forms in the water column and sediment is central to the required data. Inputs of the chemical from point and non-point sources, including atmospheric input is also necessary. The interaction of the suspended particulate concentration and the bed sediment is also seen.

REMOTE SENSING ROLE

Thus, information on the suspended solids distribution including the location and dynamics of the "turbidity maximum" would be important data for model construction. Remote sensing again could provide spatial and temporal mapping of the suspended solids concentrations to a reasonable degree of accuracy say several mg/l. Such solids data could then be used to calibrate a suspended solids and sediment model of particulate transport for integration into the toxic model as indicated in the preceding equation.

CONCLUSION

Data needs for estuarine water quality models can be obtained by evaluation of the kinetic and transport equations of the model. For eutrophication and toxic substances modeling framework, such equations indicate data needs for the stated variables of nutrients, dissolved and particulate forms of chemicals, among others. Data variables collected should be as complete as possible, supplemented by laboratory data. Detailed justification need not exist however for every variable that is measured since such justification may not be apparent until a later time. Remote sensing possibilities for these problem frameworks appear to be limited at the present time to measurement of surface chlorophyll and suspended solids concentrations. If remote sensing data for these two variables were available in a readily obtainable and usable form, then such data (which would have to be quantitative in nature) could form a useful and important input into the water quality models of estuaries.

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DATA REQUIREMENTS FOR ECOLOGICAL MODELS OF ESTUARIES

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INTRODUCTION

The purpose of this paper is to describe the characteristics, uses, and typical data requirements associated with ecological models of estuarine systems. I have chosen two types of models commonly used (box model and simulation model) for illustrative purposes and to provide examples for those not familiar with ecological models. It appears that many researchers involved in ecological modeling efforts are not sufficiently aware of the utility of remote sensing techniques and, conversely, that the remote sensing community may not be aware of the types of information most needed in developing these models. My hope is that a general discussion of the data requirements of estuarine ecological models will stimulate discussion leading to increased use of remote sensing techniques.

USE OF ECOLOGICAL MODELS

The uses of ecological models of estuarine systems are quite varied. To further promote discussion concerning the application of remote sensing techniques to modeling efforts, I have listed below a summary of these uses with examples of each.

1. Developing conceptual frameworks: This is perhaps the most frequently used application of ecological models and in some ways the most useful. Essentially, a model or picture of the system of interest is drawn up using whatever symbolic language is convenient. An example of several models is given in Figure 1. While such models are characteristic of real systems, the explicit nature of the diagrams allows for objective discussion among researchers. Is this a reasonable view of this system? Have we neglected important pieces in our thinking? Does the model address central research issues?

2. Organizing and prioritizing research activities: Once a conceptual model has been developed, it is quite possible to review the components and processes and come to some conclusions relative to the need for basic experimental studies, field monitoring, and the like. In many instances, it becomes reasonably clear that certain mechanistic relationships in a model have already been well described in the literature and hence need

not be high priority items in a research program. More importantly, needed research items can be identified at an early stage and these can be properly addressed.

3. Developing hypothesis: If ecological models can be simulated at an early stage of a research program they often serve to stimulate improved views of how the system works. This result often occurs because the model initially does not fit the observed facts or produces counter intuitive results (Pielou, 1981). The model can then serve as a framework for developing new or different ideas concerning system function.

4. Forecasting: This use of ecological models is perhaps the best known of all uses although, at present accurate forecasting with such models leaves much to be desired. In general, it appears that reasonably good forecasts can be made with "simple" or "aggregate" models. The problem here is that only aggregated properties of the system can be forecasted and often it is the specific (e.g. which finfish species will increase or decrease given this change in environment?) changes which are of most interest.

TYPES OF ECOLOGICAL MODELS

My goal here is not to provide a review of the various types of ecological models used to date in estuarine systems but rather to provide a sense of several classes of models which are commonly used and which will provide specifics as to the types of data needed for their development. In Figure 1, I have shown two distinctively different types of estuarine models. The first is a model of nitrogen storages and fluxes occurring at the sediment-water interface in an estuarine ecosystem. This type of model is commonly referred to as a "box model" because the important stages are simply indicated as boxes and the emphasis is on the inputs and outputs to and from the boxes. There are several important characteristics that differentiate these from other types of models. First, the stocks or storages and the inputs and outputs are evaluated over only one time interval (e.g. hour, week, year). This class of model is generally not simulated continuously through time. Rather, they represent "snapshots" of the system condition. Secondly, there is no indication of the functional relationships regulating the transfers between the boxes. Thus, in these types of models the question of "why" a flux is large or small is not addressed but rather the rate is simply measured over an appropriate time interval.

The second general type of ecosystem model is shown in Figure 1B and is commonly referred to as a simulation model. The major distinguishing features here are that the model is run through time to observe its behavior and that all of the features regulating exchanges between the components must be specified. Notice that in the nekton model (Figure 1B) there are many specific routines regulating exchanges (e.g. migration program related to ambient temperature, temperature dependent respiration rates, a refuge feature based on seagrass abundance, etc.). Clearly, the data needs for this type of ecosystem model are much more extensive, although similar to those required for box models.

DATA REQUIREMENTS FOR ECOLOGICAL MODELS

At this point it is probably clear that there are large data requirements necessary for the development of estuarine ecological models. While these requirements are large they tend to fall into one of four categories, some of which appear to be amenable to remote sensing techniques.

In brief, general data requirements include the need for information concerning: (a) inputs and losses to and from the system; (b) the mass or number of individuals in each component (i.e. the size of the state variables); (c) the time-dependent magnitude of all exchanges between state variables; and (d) mechanistic understanding of the variables that regulate exchanges among the system components and external features of the model. Documentation of the above is necessary for calibration (i.e. data needed to start an initial exploration of a simulation model), and continuous measurements over appropriate time intervals in similar systems or during different time periods in the same system are needed for purposes of model verification (i.e. verification is a procedure that builds confidence that the model has captured a sense of real system properties; that the model can reproduce another data base which was similar but not the same as the original.)

In most cases, the first two data requirements (inputs/outputs and stock sizes) are satisfied using data developed from field measurements or from monitoring stations. It seems that in these cases there could be some real value in attempting to use standard remote sensing procedures. The need for data describing the time-dependent magnitude of exchanges between model variables present a more substantial problem. Typically, rate measurements are difficult to make, but are essential in model development. The final class of data requirements involves determination of mechanistic relationships between model variables. This need is generally met via laboratory experiments wherein all but one variable is held constant and the response of the target variable is noted relative to controlled changes. These are the most difficult and expensive types of data needed for development of simulation models of ecological systems.

APPLICATION OF REMOTE SENSING TECHNIQUES

I list below the uses we presently envision for remote sensing techniques in the field of ecological modeling. Since I am not familiar with all the potentialities of remote sensing, this list should be viewed as tentative and probably incomplete.

1. System Size: Clearly there have been some impressive accomplishments in this area as evidenced by the data obtained of phytoplankton distributions in the western North Atlantic by the NIMBUS-7 flights. Similarly, the overflight photographs of seagrass distributions in Chesapeake Bay have been useful both in determining system size and in locating sampling stations. If appropriate sensors are available, other system characteristics might also be routinely monitored in estuarine systems (e.g. extent of turbidity maximum zone, phytoplankton bloom areas, zone of upwelling). All of these would be helpful to estuarine ecosystem modelers in that the relative size of these systems could be better determined (and hence provide some clues as to the necessity of adding additional component sub-systems to models) and sampling stations could be more appropriately located.

2. Temporal changes in system characteristics: The variability typical of estuarine systems is often large. Important variables change on time scales of hours to weeks and it would be most useful to have some indications of the magnitude of such changes. For example, Malone et al. (1986) have recently found that in the middle reaches of Chesapeake Bay there is a periodic upwelling of deep waters which results in phytoplankton blooms in the euphotic zone and temporary re-oxygenation of hypoxic bottom waters. Regular imagery of such phenomena would be useful in structuring and calibrating models.

3. Stocks and rates: As I indicated earlier, the measurement of stock sizes, rates of transfer between stocks, and the functional relationships governing these transfers are essential in developing models. It appears that current remote sensing techniques are least able to deal with this type of data need. For example, in fishery models, such as the one shown in Figure 1, there is the need to document the diel and seasonal migration of fish stocks into and out of a litoral zone environment. Inspection of this diagram indicates many other such needs. In these typically turbid environments it may not be possible to use even state-of-the-art technologies (orbital sensors). I suggest here that perhaps in situ sensors would be more appropriate and useful for obtaining data concerning stock sizes and transfer rates needed for ecological models. For example, it would be quite useful to have arrays of sensors in the mid-region of Chesapeake Bay for purposes of measuring short-term changes in salinity, oxygen, and chlorophyll field changes

that have only recently been recorded and that have a major influence on estuarine water quality and habitat conditions. In a similar fashion, it would be most useful to have sensing devices placed in situ capable of monitoring the number and size-class of commercially important finfish species as they move into the spawning grounds in the upper reaches of tributary rivers. In a related fashion, in situ sensors capable of recording the frequency occurrence of particles in the size range of microns to millimeters would be useful in describing the planktonic community and coupled with allometric concepts could provide estimates of much needed fluxes.

CONCLUSIONS

It appears that remote sensing techniques can play a useful role in the development of estuarine ecosystem models. There seems to be uses both from the truly "remote" perspective as well as the more local viewpoint (i.e. in situ sensors) and each can play an important role in the development of needed data sets.

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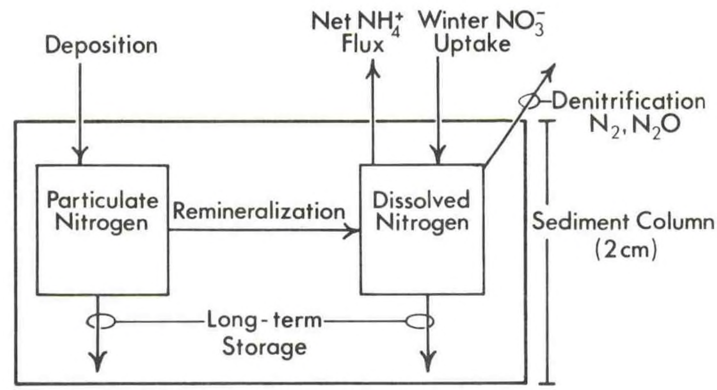
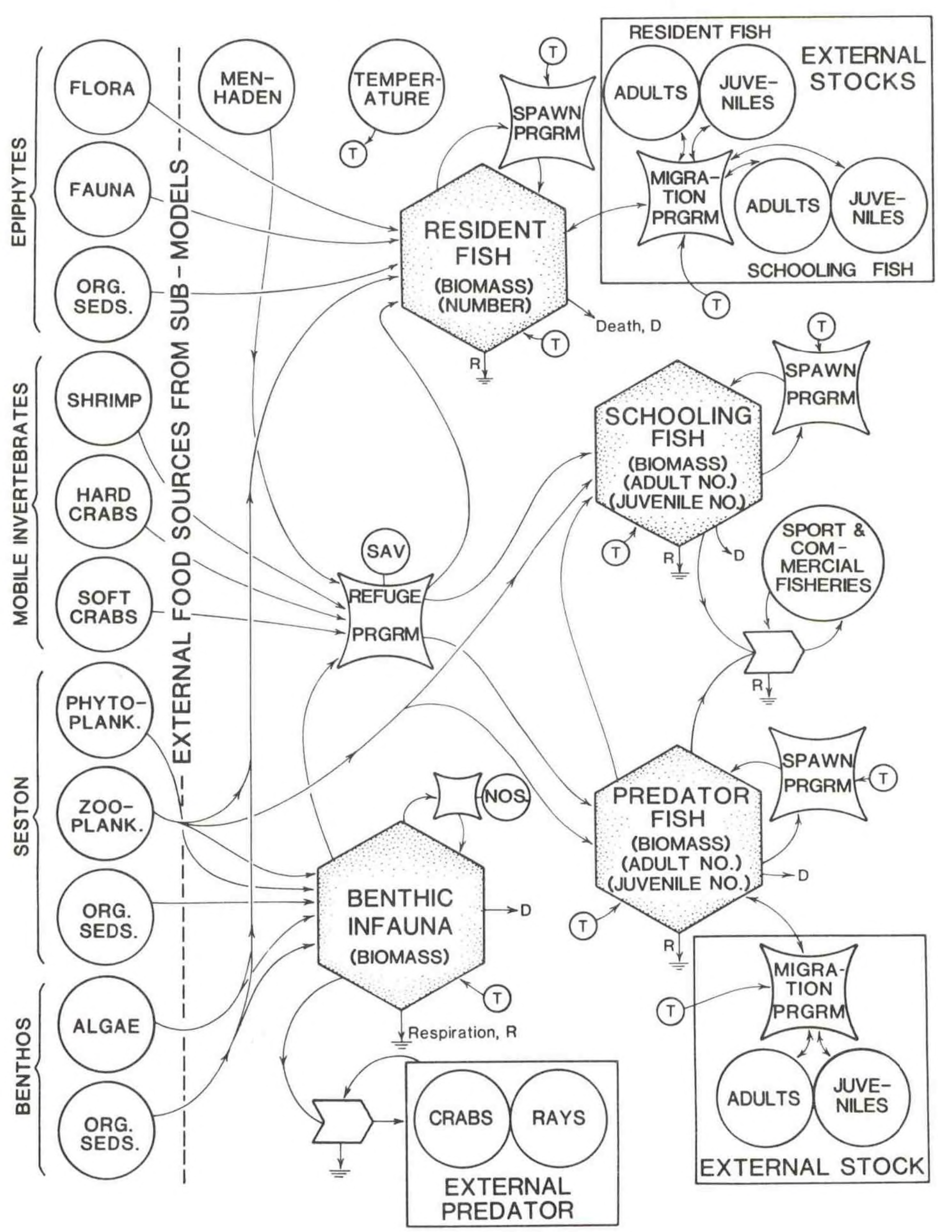
Figure 1.: Examples of two types of estuarine ecological models. The first (A) is "box" model of nitrogen exchanges at the sediment-water interface. Note that there are no indications of factors regulating the magnitude of the exchanges, typical of this class of model. The second model (B) represents the fish or nekton community associated with submersed aquatic macrophytes. This model is intended for simulation and has many indications of functional relationships among state variables (e.g. spawn group, migration program, etc.).

A. BOX MODEL of ESTUARINE NITROGEN EXCHANGES



B. SIMULATION MODEL of ESTUARINE FISH COMMUNITY



DESCRIPTION OF THE NASA OCEAN COLOR IMAGER

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The NASA Ames Research Center, Moffett Field, California is developing a new Ocean Color Imager for flight on the U2 or ER2 aircraft. The imager is a modification of the Thematic Mapper (TM) Simulator, developed earlier, and is specifically tailored to ocean sensing. It has ten spectral bands, selected for ocean color work. Nine of the bands sense reflected sunlight from 430 to 1085 nanometers (nm). See Table 1 for detailed spectral coverage. The tenth band senses thermal emission from 10.5 to 12.5 micrometers.

The sensors will operate at approximately 20 km altitude and scan an angle of 86 degrees, 43 either side of nadir. The Instantaneous Field of View (IFOV) will be 2.5 milliradians for a spatial resolution of 50 meters at nadir. This is somewhat larger than the TM IFOV, 30 meters, but is necessary because of the smaller spectral bandwidth necessary and the high signal to noise ratio needed over oceanic targets.

The data will be digitized on board, to ten bits and the tapes will be of the same format as the TM Simulator tapes except for the ten bit digitization. The aircraft fly at close to 400 knots and operate at altitudes that are usually free of other traffic so flight planning, even over congested areas, is usually possible. The aircraft are based at Ames Research Center and have satellite bases at NASA Wallops Flight Center on the Eastern Shore of Virginia and at Tulsa, Oklahoma.

One or more of the aircraft is normally based at Wallops several times during each year. During those times flights can be made to cover most of the eastern seaboard and the Gulf of Mexico. Information and requests for flights should be addressed to John Arvesen, NASA, Ames Research Center, Code STP, MS 234-1, Moffett Field, CA 94035.

The sensor is scheduled to be ready about September 1986. In the interim data from the TM Simulator was examined from flights over San Francisco Bay. From the data it was seen that the assumption that all of the radiance observed in the long wavelength reflected band would be backscattered from the atmosphere was incorrect. Water mass boundaries and a pattern seen in water flowing under the San Rafel Bridge were clearly visible in the 1035 to 1085 nm band. This means that the atmospheric algorithm, such as used with the Coastal Zone Color

Scanner (CZCS) over open oceans, would not work for such turbid water, even with the extended coverage into the near infrared. The CZCS algorithm requires a spectral band where all, or virtually all, of the radiance is from atmospheric backscatter. The band to resolve this problem has not yet been selected. Possibilities include using the 430 to 450 nm band over water with high chlorophyll where the blue absorption is intensive. This will, obviously, not work when there is a mixture of high and low chlorophyll water in the same scene. Research into an atmospheric correction scheme for this type of water is urgently needed.

TABLE 1

Operating Wavelengths

Channel	Wavelength (nm)	Calculated SNR (note 1)	Input Radiance (note 3)
1	430-450	320	4.2
2	480-500	495	4.0
3	510-530	490	3.0
4	550-570	425	2.0
5	580-600	370	1.5
6	660-680	355	1.0
7	740-790	465	0.5
8	840-890	345	0.3
9	1035-1085	95	0.3
10	10.5um-12.5um	0.10 degrees (note 2)	

Notes

1 AT 20 km altitude, ocean background
2 NETD @ 25 degrees C using internal references
3 Milliwatts/sq.cm-um-sr

Digitized field of view 86 degrees
Instantaneous field of view 0.0025 radians
Scan rate 6.25 scans/second

REMOTE SENSING OF TIDAL WETLANDS

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ABSTRACT

Remote sensing, primarily using aerial photographs, is a widely established and accepted method in mapping and inventorying of tidal wetlands. Wetland habitats are recognized and the boundaries with non-wetlands are drawn primarily on the basis of interpreted vegetative cover as well as on identification of open water, beach, rocky shores, etc. Mapping by remote detection enjoys considerable advantages in speed, flexibility, and cost per area mapped over conventional techniques.

With mapping and inventorying applications well established, research is focusing more and more on effective sensing of functional processes within the wetlands environment. The accurate measurement of radiometric characteristics made possible by hand-held field radiometers and by aerial and orbital multispectral scanners has produced increased efforts in quantitatively relating remote measurements to environmental parameters. Because of the expense of field measurements of functional variables, use of remote sensing technology, particularly orbital sensors, would be extremely cost-effective relative to conventional methods in these applications.

INTRODUCTION

The history of remote sensing of tidal wetlands has corresponded closely with 20 years of growing efforts in management of this vulnerable habitat. It has long been recognized that for those plants and animals adapted to intermittent inundation by saline waters, tidal wetlands constitute an extremely favorable environment, supporting enormous biological activity and production (Odum, 1959). In the early 1960s ecological research began to suggest that tidal wetlands played a valuable role in supporting the high biological productivity of the adjacent estuaries (for example - Odum, 1961; Teal, 1962). It also became clear that because of their occupation of prime coastal dumping and building sites, natural wetlands were being lost at an alarming rate. In 1963, Massachusetts began regulating the use of wetlands through legislation which established conditions for alteration of natural coastal habitat. There followed a burgeoning of state regulatory efforts including further legislation in Massachusetts (1965), Rhode Island (1965), Maine (1967), New Hampshire (1967), Connecticut (1969), and New Jersey (1970)

(Lagna, 1975). Beginning with Connecticut's in 1969, wetlands legislation generally mandated statewide inventories so that the boundaries of the regulated resource could be more clearly defined. The Federal "Coastal Zone Management Act" of 1972 gave further impetus to state management and inventory efforts, and by 1976, every state having ocean or estuary coastlines had initiated some form of wetland inventory (U.S. Fish and Wildlife Service, 1976).

While the intent of all of these efforts was substantially clear, implementation often proved to be a problem. Definitions of "wetlands" varied considerably from state to state. Many were originally defined by their relationship to mean high water (MHW) because of the historic importance of this datum in determination of public versus private ownership. It was soon apparent, however, that this legal boundary often bore little relationship to the functional boundaries of the ecosystem that the statutes were intended to protect (Lagna, 1975). Further, the MHW datum, or any other line of constant elevation relative to sea level, is enormously difficult to identify, map, and update on the flat, soft, vegetated surface of the tidal marsh (Hawkes, 1966; Fornes and Reimold, 1973). Even small errors in vertical positioning can cause changes in the designation of very large areas on the gently sloping marsh surface (Garretson, 1968). The result is that when applied over large areas, conventional ground surveys of wetland boundaries are time-consuming and expensive to conduct, especially as any inventory requires frequent repetition (every 5 to 10 years) to monitor the effects of erosion, accretion, alteration, and other dynamics of wetland physiography. What was needed was a fast, economical, and accurate technique for mapping and inventorying large expanses of wetland.

The obvious alterative to ground surveys was use of remote sensing technology. Problems of difficult access in wetlands were overcome and inventories could be conducted quickly and for a fraction of the cost of conventional surveys. Most state and Federal inventories use some form of remote sensing data, usually aerial photographs, and the majority rely on remote sensing as the primary information source (Carter, 1978).

Having reached an operational phase for mapping and inventorying, development of new remote sensing applications in tidal wetlands continues to parallel developments in management priorities and in ecological research. Pressure for development requires managers to make judgments of relative value in different wetland areas. At the same time, earlier assumptions concerning ecological values of wetland are being subjected to increasingly critical examination by the scientific community. The hypothesized subsidy of estuarine production by "outwelling" of wetland deritus, for example, is the subject of some controversy and, at the least, appears to be highly variable from site to site (e.g. Haines, 1977; Nixon 1980). Information on functional wetland processes is thus required in addition to the data provided by boundary mapping programs. In this area, too, remote sensing has major contributions to make, although the sensing and interpretation techniques used will be substantially different from mapping methods and will require further development.

REMOTE SENSING FOR WETLAND MAPPING AND INVENTORYING

Operational inventories of wetland boundaries rely primarily on identification of plant species or associations. It is usually assumed that designated "wetland" vegetation will not be found to any significant degree outside the tidally inundated zone, and therefore that their presence is indicative of an intertidal wetland. In some states, the transition from one species or growth form to another is identified with a particular tidal datum -- MHW for instance. However, although tidal inundation certainly is a controlling factor in marsh plant zonation, attempts to correlate particular species unambiguously with a specific tidal plane have usually been unsuccessful. Species and associations of plants retain their relative vertical relationships from place to place, but their exact position with regard to a tidal datum is highly site specific (Fornes and Reimold, 1973; Lagna, 1975). Nevertheless, in practice, it is vegetation which is usually used to delinate wetlands because of the difficulties inherent in applying elevation criteria. Some discrepancies with legal definitions of public vs. private jurisdiction may have to be resolved with on-site investigations, but, as it is the wetland ecosystem which is being managed, biological criteria ultimately seem less arbitrary than those based solely on elevation.

Most wetland inventories in the United States are based on aerial photography supplemented by field work and other data sources (Carter, 1978). The identification and mapping of vegetation have been among the most persistent and well-developed applications of remote sensing for many years. For the most part, vegetation is easily distinguished from other types of cover on the basis of its unique spectral reflectance characteristics. The importance of pigments in photosynthetic function results in visible color being a useful diagnostic characteristic of the condition of vegetation as well as discriminating it from non-vegetated surfaces. In addition, reflectance in the near-infrared portion of the spectrum can be related to indicators of the physiological status of vegetation as well as aiding in discriminating of plant species and associations.

It appears that most common film and filter combinations, including panchromatic, can be used to delineate wetlands from uplands as the distinction is often based on obvious textural and topographic differences between wetland plants and upland trees, shrubs, crops, or fill. Stereoscopic viewing is frequently used to discriminate breaks in slope and sharp changes in elevation or canopy height occurring at wetland boundaries (Garvin and Wheeler, 1973). The presence of more subtle boundaries and the desire to differentiate species associations within the wetlands have led to a general preference for the high spectral information content of color-infrared photography (Carter, 1978; Brown, 1978; McEwen and Schoonmaker, 1975). Sensing in the infrared regions of the spectrum also aids in the delineation of the wetland/water boundary due to high contrast between vegetation and highly absorptive water. Atmospheric haze effects encountered at shorter visible wavelengths are also reduced. As with any other remote sensing application, no realistic inventory can be performed without field work for establishing interpretation criteria and validating final results. Direct identification of plant species is, of course, possible only in situ -- interpretation of photographs can only extrapolate the investigator's personal knowledge of the species present and their patterns of occurrence.

An extensive commercial capability for aerial mapping is present in the United States and many other parts of the world. The scale of photography is easily adjusted to the scale, format, cost, and accuracy requirements of particular mapping tasks. When wetland boundaries must be related to holdings of individual property owners, a large mapping scale of 1:2400 has been used (Anderson and Wobber, 1973; Bartlett et al., 1976). Smaller scales ranging from 1:200,000 to 1:500,000 have also been employed in state inventories (Carter, 1978). Planimetric precision of the final product can be selected based on inventory requirements. Boundaries can be interpreted and displayed on the original aerial photography -- an efficient method when map accuracy is not necessary (Bartlett et al., 1976). When conformance with National Map Accuracy Standards is required, photo-interpreted boundaries can be plotted on a standard cartographic base, or photogrammatic techniques can be used to correct for photographic distortions and the boundaries are drawn on the photos themselves (Anderson and Wobber, 1973). Use of the photographs as a representational base has several advantages whether or not map accuracy is desired. The photos often show relationships of buildings, vegetation, and other landmarks that may not be present on standard maps. In many cases, the interpretive criteria applied for positioning a particular boundary are obvious from the photograph, simplifying resolution of disputed designations. The positions of changing shorelines are usually more up-to-date on recent photography than on available maps. Perhaps most important, a photograph has a compelling and easily grasped impact as evidence, particularly for the layman, even when a map might depict the same relationships. As a result, several inventory programs have used a photo-based final product (Brown, 1978; Garvin and Wheeler, 1973; Bartlett et al., 1976).

The same advantages enjoyed by remote sensing in compiling an inventory also apply to periodically updating that inventory. The State of Delaware updated its 1976 inventory (which was based on 1973 aerial photography) in 1979 (Hardisky and Klemas, 1983). The update identified numerous changes in the intervening 6-year period, including violations of the management statute resulting in alteration of approximately 43 hectares of wetland. The update documented that this rate of loss (~7 ha/yr) represented a drastic reduction from the pre-statute rate of ~180 ha/yr from 1954 to 1971 (Hardisky and Klemas, 1983).

Inventories of tidal wetlands are often of interest for reasons other than statutory boundary delineation. The magnitudes of many important wetland functions are directly related to the local extent of the tide marsh ecosystem. As a result, many inventories of wetlands have been performed as a guide to the extent and character of the resource and its impact on adjacent estuarine waters. In most cases, requirements for planimetric accuracy are not as stringent as when statutory boundaries are desired. The result is that the investigator has greater freedom in choosing the scale of the final product and thus may use imaging systems at higher altitudes or with less spatial resolution, with accompanying reductions in cost. The "National Wetlands Inventory" conducted by the U.S. Fish and Wildlife Service is based on aerial photography, producing both a digital data base and maps at 1:100,000 (Montanari and Townsend, 1977). This inventory also identifies shallow open water habitats by bottom type and geomorphic setting (e.g., estuarine, riverine lacustrine, etc.).

Data from the LANDSAT Multispectral Scanner (MSS) have been used for inventorying wetlands at a variety of scales (Anderson et al., 1974; Carter and Schubert, 1974; Klemas et al., 1975; Butera, 1983). LANDSAT inventories have generally been experimental in nature, and while large wetland areas have been successfully identified and classified into dominant vegetation categories, the spatial resolution of the scanner data has restricted its application for operational inventories (Carter, 1978). Nominal ground pixel size for the LANDSAT-MSS is 0.45 ha, making boundary location difficult, particularly for small or narrow marshes. Carter (1978) suggests that a pixel size less than approximately 0.25 ha is required for effective interface of orbital data with operational inventories. The current state-of-the-art orbital scanners, the LANDSAT TM and European SPOT instruments achieve a nominal pixel size of approximately 0.05-0.1 ha, enhancing the potential utility of orbital data. Orbital scanner data suffer from a further disadvantage relative to aerial photography in that less textural information is available to aid in interpretation of cover types. Interpretation relies primarily on spectral criteria because the resolution of the scanner data does not depict the fine differences in texture produced by different canopy structures. Accuracy of classifications of MSS data into wetland vegetation units has been reported to range from 75% to 95% (Butera, 1983; Klemas et al., 1975). Reliance on spectral interpretation criteria does have advantages, primarily in that semi-automated digital interpretation can be employed. For inventories of large areas, this can produce very large reductions in cost.

Cost is normally the overriding consideration in choosing an inventory methodology once minimum standards of scale and accuracy have been established. In fact, inventory standards are rarely determined _a priori_, but are "traded-off" with cost considerations in planning the inventory process. In many states, for example, the MHW line or some datum referenced to MHW would be the preferred boundary for wetlands mapping. The expense associated with mapping this datum, however, has led to alternative definitions based on vegetation -- definitions compatible with less costly remote sensing methods.

Comparative costs for inventory techniques are difficult to obtain for a general case. A general idea of relative costs can be gained from figures cited in the literature [Note: All dollar figures are discounted to 1985 dollars assuming an annual inflation rate of 5% from the date of the referenced study]. The EPA has estimated its costs for an in-the-field inventory of a cordgrass marsh at $26.90/ha (Butera, 1983). A large-scale (1:2400) wetlands inventory based on 1:12,000 color and color-infrared photography was conducted in Delaware for $3.40/ha (Bartlett et al., 1976). Smaller-scale vegetation inventories (not wetlands) in the Midwest used high altitude aerial photography to produce 1:24,000 and 1:250,000 scale maps for $0.41/ha and $0.04/ha, respectively (Eastwood et al., 1977). Butera (1983) computed costs of $0.05/ha for a LANDSAT-MSS inventory of 3900 km^2 of wetlands in Florida. Imagery was interpreted through digital processing of the MSS data. The efficiency of semiautomated interpretation is such that as larger areas are inventoried, incremental LANDSAT-MSS costs fall to $0.01/ha or less (Eastwood et al., 1977; Gaydos, 1978). Figures for specific projects will, of course, vary from those cited, and these figures should be used for comparative purposes only.

The most precipitous drop in unit cost occurs in the transition from conventional field surveys to large-scale (i.e. low altitude) remote mapping. There are also large reductions in cost related to decreasing the scale of a remote sensing inventory. Use of LANDSAT data becomes cost-advantageous for inventories of large areas (>10,000 km^2) if the loss of spatial resolution and classification accuracy can be tolerated.

There can be little doubt about the reliability and cost-effectiveness of aerial photographic wetland inventories. Savings of an order of magnitude or more in time and expense over conventional surveys can be achieved without significant loss of accuracy. The utility of orbital sensors is restricted, primarily by spatial resolution, to inventories of large areas at small scales or, perhaps, to rapid updating of existing maps. As we shall see, however, orbital data have advantages which make it well-suited to other data-gathering applications in wetlands.

REMOTE SENSING OF FUNCTIONAL VARIABLES IN TIDAL WETLANDS

Information other than the location of boundaries and distribution of wetlands is required for effective management. This has become especially clear as early models of wetland functions and values are replaced by more complex ones in which important processes are recognized as extremely variable in time and space (see, for example, Nixon, 1980). The mere presence of a wetland no longer suffices as evidence of high ecological value (although this may be sufficient for other types of value). Criteria for judgment of relative value are available based on local variation in factors such as hydrography and primary production (Silberhorn et al., 1974). We might call such variables "functional" as they relate to the functions of the ecosystem. Generalized assumptions concerning these factors can sometimes be based on knowledge of species distributions and extent (Ibid.), but significant intraspecific variation is common. Further, there are large variations from place to place and seasonally in the characteristics of a particular species. Collection of functional data is sometimes carried out in the field, but such studies can be even more time consuming and expensive than a field boundary inventory. Thus, if remote sensing can be applied to such measurements, large benefits could be obtained.

Recent developments in ecology have provided further motivation for applying remote sensing to assessment of wetland processes. Growing interest in global biogeochemical cycles, particularly that of carbon, has led to recognition of the Earth's vegetation as a major source/sink/transport term in material budgets (Bolin et al., 1979). Wetlands constitute a potentially important, but largely unevaluated, sink for atmospheric carbon because of their high primary productivity and accumulation of organic soils (Rambler, 1983). They are also large potential sources of biogenic gases such as methane and hydrogen sulfide (Bartlett, 1984). Remote sensing offers the only effective means of assessing wetland processes on the scale required for research on global biogeochemical cycles.

An example of an important wetlands process for both management and research interests is primary production. Primary production in tidal wetlands is commonly assessed through periodic measurement of biomass, usually by harvesting of measured quadrats of vegetation (e.g., Smalley, 1959). Typically, vegetation within a 0.25 to 1.0 m^2 quadrat is harvested and returned to the laboratory for sorting into live and dead fractions, drying, and weighing. This process requires significant manpower in the field and lab. Hardisky et al. (unpublished manuscript) estimate 0.33 man-days per sample was required for travel, sampling, and lab work during an assessment in Delaware marshes. As a result, productivity measurements tend to be available only intermittently for local management purposes, and not at all for regional and global scale assessment.

Several studies have indicated that biomass information can be acquired through remote sensor measurements. The most promising technique uses a difference or ratio of upwelled radiance measurements in two spectral bands (one infrared, the other in the "red" wavelength region) as an indicator of the amount of live vegetation present in the canopy (Tucker, 1979). The method is based on the high contrast in reflectance between vegetation and soil in the infrared and between live (i.e. green) and dead vegetation in the "red".

Bartlett and Klemas (1980, 1981) found high correlation ($r = 0.90$) between the LANDSAT-MSS Band 7/Band 5 reflectance ratio and green biomass for the common wetland cordgrass, *Spartina alterniflora*. Hardisky et al. (1983) obtained similar results using spectral wavebands identical to those that are available from the TM instrument. Both studies were conducted in the field using hand-held radiometers.

The requirements of this technique for accurate measurement of spectral radiance effectively excludes aerial photography as a quantitative tool, but is well suited to existing multispectral scanners. The processing steps for digital analysis of multispectral scanner data are essentially the same, whether it is an inventory of cover types or a spectroradiometric estimate of biomass which is desired. Thus, costs for biomass assessment would add only a small amount to resources required for wetland inventories using scanner data. Field or photographic boundary inventories combined with field measurements of biomass, on the other hand, require two separate methodologies adding greatly to the time and resources required. Remote assessment of biomass would therefore be extremely cost-effective relative to alternatives. Aerial scanners could be applied, as could field radiometers, for assessment of relatively small areas with significant savings in the manpower required. However, I believe that it is with orbital sensors that the future of remote biomass detection lies. Fine spatial resolution is not as important for biomass estimates since it is the magnitude and extent of biomass units and not their precise boundaries that is of greatest concern. For research in global wetland biomass and production, of course, the coverage characteristics of orbital sensors are a virtual requirement. Further, as periodic measurements during the growing season are required for production calculations, orbital sensors have a large advantage in efficiency over aerial or field missions which incur significant start-up costs for each repetition of the data collection process.

Research and development in the use of remote sensors for process-oriented measurements, including biomass, must continue before widespread acceptance is achieved. The effects of different plant species, climatic and tidal conditions, and atmospheric perturbations on the interpretation algorithms already developed need to be assessed. Biomass estimates might be used for purposes other than calculation of primary production. For example, biomass of S. alterniflora is influenced by anaerobic conditions in the marsh soil (Howes et al., 1981). Measurements of relative biomass of this species may, therefore, be related to potential for production of biogenic gases by obligate anaerobes living in highly reduced soils. Potential for incorporation of other important variables such as composition of intertidal waters has yet to be explored. There can be no doubt, however, that as requirements for more ecological data over larger and larger areas of the Earth grow, so too will the application of orbital remote sensing technology to measurements of functional variables.

CONCLUSIONS

Approximately 15 years of operational experience has resulted in routine reliance on aerial photographic remote sensing for inventorying and mapping of tidal wetlands. Current requirements for functional wetlands data such as plant biomass and productivity by both management and research interests have produced recent developments in remote sensing measurement technology. Advantages in radiometric accuracy, speed, and efficiency for large areas and for frequent repetitive measurements argue strongly for use of orbital multispectral scanners in applications of this kind.

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GEOGRAPHIC ANALYSIS FOR WETLANDS CHANGE DETECTION

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Among estuarine and other wetlands resource managers, the most pressing need is for better resource information to support management and policy decisions. Often the impacts of policies and policy changes are evident in patterns of wetlands change. Many wetlands resource managers would like to have the ability to monitor large areas using high resolution data for policy analysis and extremely high resolution data for regulatory enforcement. Because of recent advances in geographic information and analysis systems and the development of numerous resource data bases by various Federal and state agencies, it now seems feasible to address the policy analysis needs of these managers. The principal need is to improve land cover identification and change detection in coastal wetlands and to examine the distribution, areal coverage, status (health), and trends in coastal wetlands and adjacent lands. The ultimate goal is to understand the relationships between changes in coastal wetlands and changes in fisheries directly and indirectly dependent on these wetlands.

In contrast, regulatory analysis and enforcement will continue to be handled on a case-by-case basis for the immediate future because general coverage for large areas at such high spatial resolution would not be cost effective at the current state-of-the-art in geographic information systems and data bases.

To accomplish the policy analysis goals it will be necessary to investigate the potential of satellite data to aid in identifying landscape elements which may influence fisheries. Digital remote sensing from satellites offers the advantages of synoptic, large-area coverage and frequent, repetitive observations. In addition the spatial resolution of LANDSAT is substantially more precise than that available on most analog maps available for large areas of the United States. Multispectral Scanner (MSS) data provide a spatial resolution of 79 by 56 meters; each single data point represents spectral data collected from an area of this size on the ground. These picture elements are called pixels. Thematic Mapper (TM) data are collected for pixels of 30 meters by 30 meters. TM offers a greater spectral range (seven intermittent bands from .45 to 12.5 micrometers) than MSS (four contiguous bands from .5 to 1.1 micrometers).

It has been found that the most important factor in comparing the classified images from MSS and TM data is the quality of the scene determined by the natural conditions present at the time of the scene; the tidal stage at the time of the image is crucial for identification and classification of coastal wetlands. With a good scene, both the MSS data and the TM data seem capable of providing classified results with at least 80% or perhaps 85% accuracy. There is little difference between the ability of the TM data and the MSS data in their discrimination of different wetland types. However, the TM data are better able to distinguish small land cover features. Results in both wetlands and uplands emphasize the importance of establishing validation procedures as an integral component of the protocol. Unsupervised techniques may work just as well as supervised techniques provided that validation procedures are explicitly included in the protocol.

The finer resolution and greater spectral discrimination of TM are valuable characteristics, but they come at a higher cost ($3,300 versus $660 per full scene) and involve considerably greater data processing and storage. Unfortunately satellite observations go back only to 1972; further historical analysis requires additional information from sources such as wetlands inventories, maps, aerial photographs, and written documents. The analysis should employ several different classification techniques, field verification, comparison with wetlands inventories, and rectified mapping of land cover based on coincident MSS scene and/or TM scenes for different dates.

It should be noted that other types of land cover data are available for wetlands areas. The National Wetlands Inventory (NWI) is a major national effort to map coastal and interior wetlands by type of land cover, and the Land Use Data Analysis Program (LUDA) is an effort to map all land use (sometimes characterized by land cover) for the entire United States. Both of these programs are labor intensive efforts that are not yet complete for the entire United States and that cannot be repeated on a frequent basis. LUDA has an additional problem in that its spatial resolution (4 ha for some classes and 16 ha for others) is not precise enough to use in monitoring wetlands change. Nevertheless, both of these programs offer data that may be useful for large-area verification of LANDSAT classification. NWI maps at 1:24,000 and 1:100,000 scale can be used for verification of land cover in many areas. Often the best published source of data for verification of LANDSAT data is a series of county or other local tidal marsh inventories such as those done for the Chesapeake Bay area by the Virginia Institute of Marine Science (VIMS). All classifications should be validated through field work in the study area for training sample identification and for verification of classification results.

Interpretation of analog aerial photographs is a subjective art or science depending on individual specialists with considerable experience and natural faculties for pattern recognition. Interpretation and analysis of digital spectral data can be done in an objective, replicable fashion, but the science has not advanced to the point that reliable results can be obtained automatically. Experience and a knack for pattern recognition are still essential. The advantage is that digital remote sensing specialists, using commercial software and equipment, can understand and communicate far more information about much larger areas with finer detail than ever before. If the remote sensing results are then combined with other earth-based data and processed in comprehensive geographic analysis systems, they can be helpful in policy analysis and resource management. At the current state-of-the-art, processing of LANDSAT data is reasonably straight forward as long as the application does not involve more than a single scene. Most interactive image processing systems can easily process data for areas covering 91 square miles or less on TM and 448 square miles or less on MSS using a single image on a 512 by 512 resolution color CRT screen. Some interactive systems offer 1024 by 1024 or similar resolution and thus can process four times as much area on a single screen. It is possible to reapply some of the statistics characterizing land cover to other areas on the same scene (a scene is approximately 115 miles by 105 miles or 12,075 square miles). For scattered small areas this would be done interactively screen-by-screen. Large portions of a LANDSAT scene, whole scenes, and multiple scenes likely would be processed in batch mode.

Most of the policy analysis objectives of wetlands resource managers can be met with current technology and expertise. The only objective requiring substantial new development is that of large-area coverage (areas requiring more than a few scenes). This implies a fairly large volume of data processing, but not an unreasonable undertaking for mainframe computers and large minicomputers. The problem is in maintaining consistency and quality control over the wide range of land covers and spectral conditions represented on so many scenes. In the first place there is considerable latitudinal variation in vegetation and in the form of wetlands from the northernmost to the southermost extremities of the United States. For each local area numerous spectral signatures must be identified in order to distinguish important vegetative types. Care must be taken in extending these signatures to other scenes because of the spectral variation among scenes that can result from differences in atmospheric and vegetative conditions. Because of the orbital path and 16-day coverage cycle on LANDSAT 4 and 5, adjacent east-west scenes have a minimum of one day separation and this is sufficient to encounter significant differences in tide, moisture, cloud cover, and other factors that influence reflectance. Cloud cover often precludes use of the closest time period between adjacent scenes. In wetlands detection, tides are an important factor, and tide stages vary not only among scenes but within scenes as well. Furthermore, there is considerable variation in the distribution of vegetational species and in physical characteristics of each given species from north to south.

A major objective of the effort should be to develop a protocol that assures equally reliable results over large areas. This protocol is likely to include guidelines and minimum standards for:

1. selecting appropriate satellite data
2. acquiring high quality image data
3. training sample and signature identification
4. field work and field verification
5. corroboration with other wetlands and uplands data
6. combining interactive and batch mode processing
7. calibration among scenes using areas of scene overlap
8. spatial rectification
9. geographic information processing and analysis

Ultimately it will be necessary to develop a geographical information and analysis system tailored to the mission of wetlands resource managers in regard to their responsibilities for monitoring coastal wetlands change and for managing wetlands through the permitting process for construction and reclamation projects. From the analyst's standpoint geographical information is far more complex than other forms of tabular data. In the first place the quantity of data is proportional to the number of data points used to represent the distribution of each phenomenon on a continuous earth surface. Additional data are required to locate each point in a spatial coordinate system (e.g. latitude/longitude) and in many cases temporal data are needed as well. If the data are obtained from different maps and other data sources, they cannot be integrated without careful transformation and conversion to account for differences in scale, projection, resolution, data structure, and coordinate system.

Traditionally, maps have been used as the primary mechanism for displaying geographical information because the human brain can visually assimilate these huge volumes of data more easily than it can comprehend the columns of numbers that each image represents. Even so the potential for geographical analysis has been severly constrained by the cartographer's limited capacity for manual computation of such complex data conversions. Wetlands resource management will require a robust geographic information and analysis system with state-of-the-art capabilities for:

1. data capture including data conversion, digitization, editing, and image processing
2. data storage, retrieval, and management
3. data integration

4. mensuration and statistical summarization
5. data manipulation and analysis
6. modeling
7. linking to other models and systems
8. graphical output and display

Subject to cost and technology constraints, telecommunications and device-independent software should permit data transmission and analytical exchange among a variety of sources and users. The system should have ready access to cartographic base files and certain fundamental geographic data bases. The cartographic base file should be in geodetic coordinates, should adopt the standards set by the National Committee for Digital Cartographic Data Standards (NCDCDS) and the Federal Interagency Coordinating Committee on Digital Cartography (FICCDC), and should not be sheet bound. The structure should be amenable to utilization of the 1:24,000 Digital Line Graph and Digital Elevation Model and 1:100,000 Digital Line Graph data bases currently being digitized by the United States Geological Survey and to graphic output compatible with the video disk standards established by the Geographical Information Systems Subcommittee of the Intelligence Information Handling Committee, Director of Central Intelligence.

SATELLITE REMOTE SENSING OF DISSOLVED AND PARTICULATE SUBSTANCES IN ESTUARIES

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ABSTRACT

Satellite sensors, while not designed for estuarine research, can provide data on materials found in estuaries. Vector analysis and physical models based on radiative transfer theory produce insights into seston and pigments where statistical models are unsuccessful. Vector analysis equates changes in orientation of a multispectral vector determined by the data with variations in pigment quality. The vector magnitude depends on the quantity of sediment. The best analyses include one band in the near-infrared in order to correct for sediment. Other bands should encompass regions of maximum pigment absorption. The vector model is particularly useful because it is general in form and can apply to a variety of sensors.

Serious comparative analysis of radiance data over water requires correction for atmospheric path radiance and sun angle. This correction makes possible direct comparisons of images taken on different days. It also improves the ability to determine calibration coefficients.

LANDSAT, Advanced Very High Resolution Radiometer (AVHRR), and Coastal Zone Color Scanner (CZCS) data all can provide information on pigments and seston using this method. Preference for one sensor over another will depend on the spatial and temporal resolution needed for the application.

INTRODUCTION

Cholorophyll content and turbidity are important indicators of water quality in estuaries. Algal blooms may indicate threats to fisheries. Sediment indicates runoff sources and can help trace pollutants. The use of remotely sensed data to detect and measure these materials with minimal calibration using shipboard data, would be an asset in the study and management of estuaries.

Although techniques using aircraft, particularly laser fluorosensing, have had exceptional success in determining the concentrations of pigments and sediments, satellite remote sensing has several advantages. The use of aircraft is rarely routine and aerial remote sensing does not offer synoptic coverage except of small areas. Aerial data collection, like surface data collection tends to be expensive, making the use of satellites an attractive approach.

Recent advances in satellite remote sensing have greatly enhanced the ability to collect biological oceanographic data. The CZCS on the Nimbus-7 satellite has been shown capable of providing estimates of shelf and open ocean cholorophyll (+phaeophytin) concentrations and diffuse attenuation coefficients within a factor of 2 (Gordon et al., 1983). The AVHRR on the NOAA polar-orbiting satellites can provide estimates of sea surface temperature within 1^{o}C.

The CZCS and the AVHRR have rarely been used in estuaries. CZCS and AVHRR sample frequently, 3-6 days and every day respectively, but they have a 1 kilometer resolution that is suitable mostly for large estuaries. The CZCS was specifically designed for use in clearer offshore waters; hence, extremely turbid water will completely saturate some of the visible channels. Most researchers using the CZCS have concentrated on developing algorithms to estimate material concentrations in clear water. The atmospheric correction used in the CZCS chlorophyll algorithm requires negligible detectable radiance in band 4 (670 nm). This requirement does not hold for any moderately turbid water. Even on the inner shelf, the band frequently obtains 10-15 count values (0.1 mW/cm^2-sr-um) brighter than clear water. The AVHRR has the dynamic range for turbid water, but it has only two broad visible bands, which have appeared inadequate for oceanic research.

LANDSAT has had some use in mapping turbidity plumes and in estimating suspended sediment concentrations (Munday and Alfordi, 1979; Munday and Fedosh, 1981), and in mapping variations in water color and sediments (Stumpf, 1984). Nevertheless, researchers have had little success at correlating concentrations of other materials, such as chlorophyll and dissolved pigments, with the satellite radiance data (Bowker et al., 1975; Munday et al., 1979). This difficulty is not necessarily a limitation of the satellites; chlorophyll variations have been noted in clear lakes (Rogers et al., 1975). In turbid water variations in seston or turbidity have usually foiled attempts to isolate various materials with standard statistical techniques.

VECTOR ANALYSIS

In coastal water, Philpot and Klemas (1979) have distinguished different substances in water -- sewage, sludge, sediment, acid waste -- using a form of principal component (vector) analysis. Using this technique, the LANDSAT data could provide an estimate of the age of acid waste by detecting differences in the waste's apparent color, i.e., spectrum, when the waste settled through the water column. Their results demonstrate that satellite data have more use along the coast than suggested by regression techniques.

Stumpf (1984, 1985) has further developed the techniques of using vector forms of satellite spectral radiance data to look at water color in turbid water. (Turbid water is here considered water having a diffuse attenuation coefficient (k) in excess of 0.5 m^{-1}, or suspended sediment concentration (n_s) above 3 mg/l). Because pigments determine water color, viewing and quantifying water color can indicate the distribution and even the quantity of pigments.

This technique may be explained as follows. One can define a coordinate system, or "color" space, using the radiance in different bands as the axes. A vector may extend from an origin that is defined by clear water radiance to a coordinate determined by the spectral radiance measured for any pixel in the scene. The vector orientation will then depend primarily on the quantity of pigments and the vector magnitude will vary with the suspended sediment concentration. A two dimensional example appears in Figure 1, with n_p denoting pigment concentration. In multiple dimensions, this approach lends itself to eigenvector analyses.

To determine the effect of pigments on the orientation, one can use a basic reflectance model (Gordon et al., 1975).

$$1. \quad R = Y\, b_b/(a+b_b)$$

where R = irradiant reflectance, i.e., the ratio of irradiance leaving the water to that entering; Y = a constant, ca. 1/3; b_b = backscatter coefficient; and a = absorption coefficient.

One can make an approximation of eq. 1 for use in turbid water by assuming that all backscatter is caused by sediment, and that pigment and sediment absorption can be separated (Stumpf, 1985). This leads to:

$$2. \quad R = Y\, b_{bs}'/(S' + a_x/n_s)$$

where b_{bs}' = specific backscatter coefficient for sediment and S' = specific attenuation ($b_{bs}' + a_s'$) for sediment. The absorption coefficient for water and pigments, a_x, is expressed as

$$3. \quad a_x = a_w + a_d'n_d + a_c'n_c$$

where n = concentration, a' = specific absorption coefficient, subscripts w, d, and c denote water, dissolved pigments, and chlorophyll-like pigments, respectively.

The orientation of a vector in bands i and j depends on the variation in R. R, in turn, varies with (a_x/n_s). The relationship between the orientation, c_{ji}, at a point and R is

$$4. \quad \frac{dR_i/d(a_{xi}/n_s)}{dR_j/d(a_{xj}/n_s)} = c_{ji}$$

From equation 4, Stumpf obtained

$$5. \quad a_{xi}/a_{xj} = G_s \, C_{ji}^{1/2}$$

C_{ji} is the vector orientation to the data point, i.e., a mean "slope." G_s is a coefficient that accounts for sediment type. It is less than 1 and appears to have a value between 0.6 and 0.8 in the Chesapeake and Delaware Bays.

In two dimensions, C_{ji} is simply the slope of the vector, or the ratio of the two bands. If band j lies in a region of the spectrum where pigments have no influence, such as the near-IR (0.7-1.0nm) and band i lies in a region having pigment absorption, then equation 5 says that the slope should indicate directly the presence of pigments. Large quantities of pigments will increase a_{xi}, thereby increasing C_{ji} (Figure 1). Small quantities of pigments will result in low values of C_{ji}, i.e., low slopes. Knowing the absorption coefficients, one could use equation 3 to estimate the absolute quantity of pigment. Alternatively, one can use concurrent <u>in</u> <u>situ</u> data to calibrate C_{ji}.

Dissolved and particulate pigments have different absorption curves. Dissolved pigments have increased absorbance with shorter wavelengths. Particulate pigments, e.g., chlorophyll and phaeophytin, have strong absorption at 420-480 nm and about 670 nm. Thus, multispectral scanner data, when used with equation 3 have the potential to distinguish between dissolved pigments and chlorophyll-related pigments.

Because equation 4 leads to a non-linearity, where C_{ji} is partially dependent on ns, comparisons of C_{ji} are best made between areas having comparable R (or radiance) or ns; preferably R should differ less than a factor of 4 for comparison. Nonetheless, it is important to realize that this model is general in form and the relation in equation 5 is not limited to a particular sensor.

Suspended material may be estimated using the vector magnitude, or alternatively the magnitude of a single band -- preferably in the region from 500-600 nm or 700-800 nm because

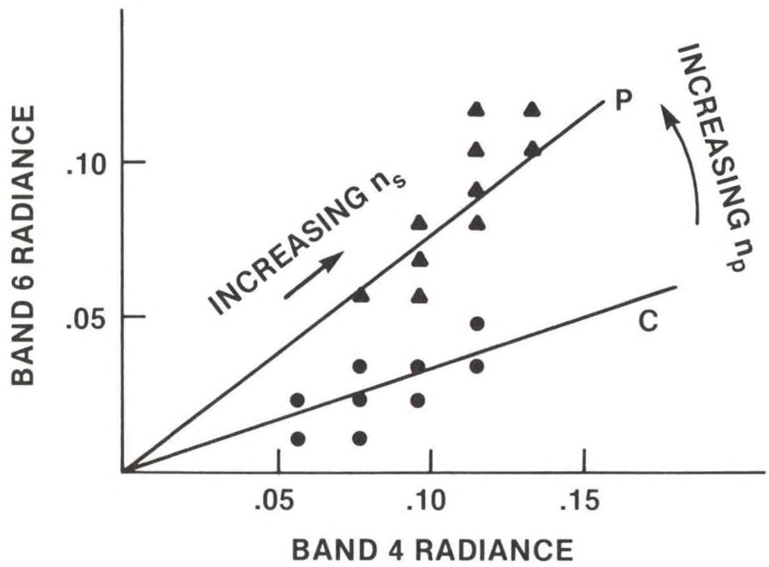

Figure 1: Effects of suspended materials (n_s) and pigments (n_p) on radiance vectors in 2-dimensions with Landsat MSS bands 6 (700–800nm) and 4 (500–600nm). Data from Delaware Bay 17 March 79 (Stumpf 1984) P = platform-shore, C = central bay.

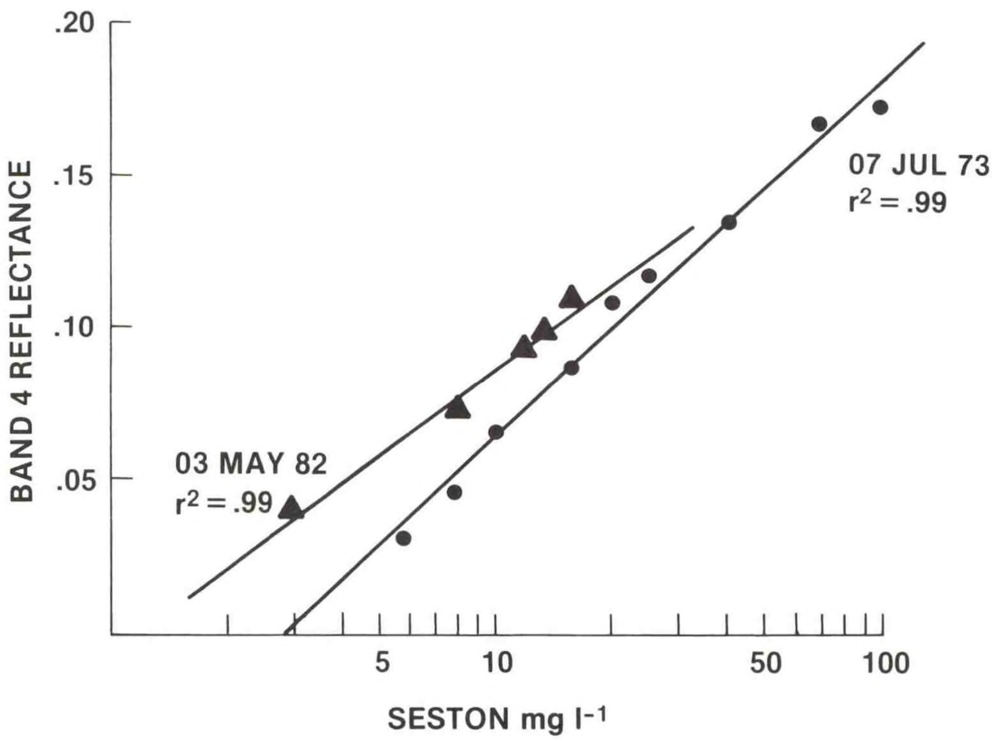

Figure 2: Relation between total seston and reflectance using Landsat band 4 (from Stumpf, 1985; cf. Klemas et al, 1973)

of the reduced or negligible absorption by pigments. The empirical relationship

$$6. \quad R = m \ln(n_s) + b$$

provides the simplest means of relating sediment (or suspended solids) concentration to reflectance (Klemas et al., 1973; Munday and Alfoldi, 1979). The coefficients of equation 6 may vary somewhat with changes in size and composition of the sediment, however in a given estuary, these changes may be slight as shown in Figure 2.

RADIOMETRIC CORRECTION

In order to use equations 5 and 6 to compare different scenes, one must correct the data for the atmosphere and for radiometric (i.e., sun angle) variations. These corrections will make simpler the task of calibrating data sets and will allow one to make more accurate and valid comparisons of data collected at different times.

At present, satellite data of estuaries can be corrected for atmospheric path radiance by subtracting from all pixels the radiance observed at the darkest pixel on the adjacent shelf (Sturm, 1981; Stumpf, 1984). This subtraction also removes the clear water radiance. As a clear water subtraction technique assumes a laterally homogeneous atmosphere, it is best used over small areas (less than 200-300 km^2). Also the subtraction limits the study area to sections of the image that are near nadir. The increase in path radiance with large viewing angles makes the correction more uncertain. The full correction in a band appears as

$$7. \quad R = Q\, L_u/(T\, E_{td})$$

$$\text{with } L_u = L^* - L_a$$

where L_u is the upwelling radiance at the water's surface; L^* is the radiance detected by the satellite; L_a is the path radiance (atmosphere); T is the transmittance; E_{td} is the downwelling irradiance at the water's surface, approximated by the solar constant multipled by the cosine of the solar zenith angle; T is the transmittance; $Q = E_u/L_u$, the ratio of upwelling irradiance to upwelling radiance at the surface. For purposes of detecting relative differences in pigment quantity within a scene, one can use C_{ji}^*, which equals the ratio E_{uj}/L_{ui}, and not make any additional corrections. Because equation 5 uses the ratio of reflectances between bands, it further reduces errors that may result from local changes in atmospheric effects. The most critical corrections are those or path radiance L_a and solar irradiance E_{td}. At present, for lack of better data, Q can be assigned a value of 4-5 and T varies inversely with L_a.

APPLICATIONS

For applications of equation 5, one can use three LANDSAT MSS bands (4, 5, and 6) or also AVHRR bands 1 and 2 or the CZCS bands 4 and 5 (Table 1). Although CZCS band 5 has poor radiometric resolution (about 1/8th of band 4), it was chosen because it is the only CZCS band that lies outside the range of pigment influence. Because of its relatively low sensitivity, band 5 will not respond as rapidly as band 4 to changes in turbidity. Therefore, one may obtain subtle, but non-real changes in vector orientation, and therefore in concentration. Band 5 will also not respond well in clear water, but that is outside our area of interest. The band does show over 20 levels of variation in the Bay (comparable to LANDSAT MSS band 6), making it quite usable. CZCS band 4 lies at an absorption peak for chlorophyll-a making it ideal for estimating concentrations of chlorophyll-a.

The AVHRR bands, being fairly broad, will probably provide only a general pigment indicator. Band 1 will have some sensitivity to dissolved pigments as well as to the various chlorophylls and other pigments. This broad response poses no problem for determining relative variations of pigments in a given scene, although it may, at times, obscure the interpretation. It may also preclude estimates of the actual quantity of pigments, thereby limiting comparisons between different scenes.

Figures 3 and 4 display an application of equation 5 using C_{ji} obtained from NOAA-7 and CZCS for the Chesapeake Bay on 14-15 April 1982. NOAA-6 data taken at 0830 EST on 14 April, showed the same results as NOAA-7. Recall that AVHRR band 2/band 4 indicate relative quantity of general pigments and CZCS band 5/band 4 indicate chlorophyll-a +phaeophytin. The concentrations were estimated using data collected by M. Tyler (Tyler and Stumf, 1987).

Both sensors show low concentrations at and above Annapolis, the region of the turbidity maximum. AVHRR shows moderate and low concentrations upstream of where the U.S. 301 highway bridge crosses the Potomac. CZCS does not give results in the upper Bay and the upper Potomac River because the high turbidity in those regions causes saturation of band 4. Both sensors indicate moderate concentrations in the lower Potomac and lower Chesapeake Bay. Very high concentrations, indicative of a bloom appear in Potomac River below highway U.S. 301. The bloom starts at the north shore on the upriver end and extends down river about 15 km to the south shore.

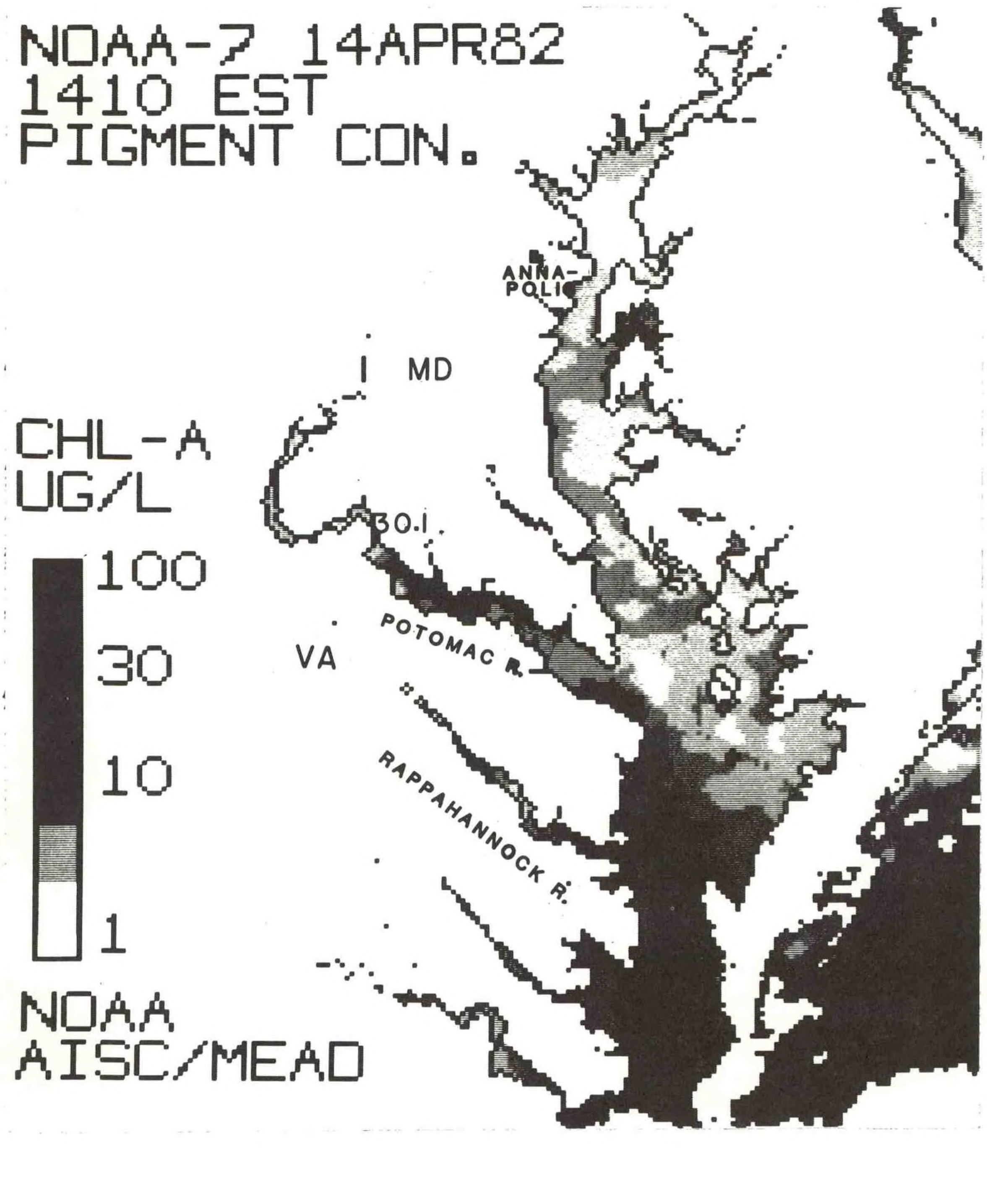

Figure 3: Relative pigment concentrations for Chesapeake Bay based on Cji from NOAA-7 AVHRR, 14 April 1982; note bloom in the Potomac River.

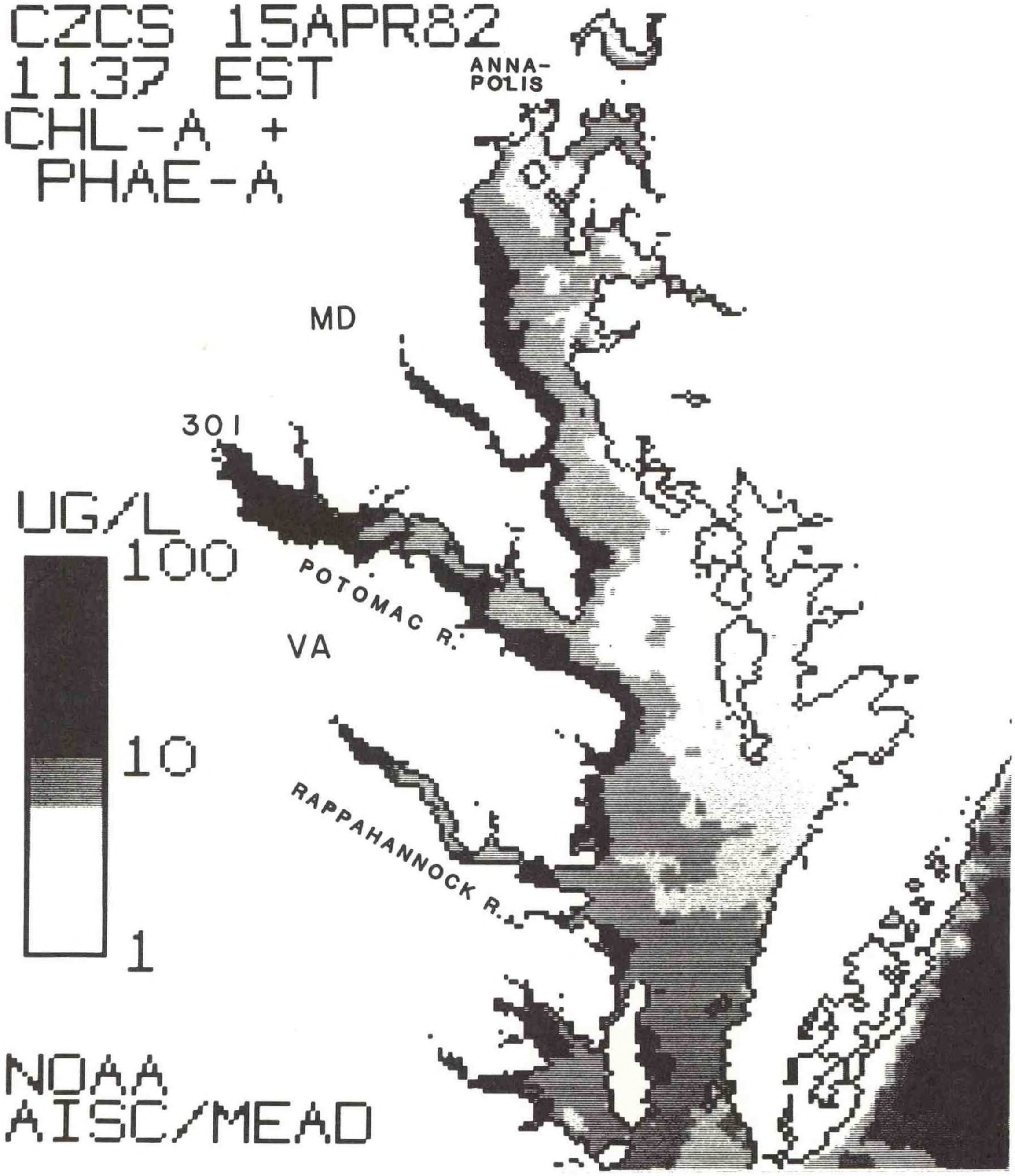

Figure 4: Relative concentration of chlorophyll and phaeophytin in Potomac River and Upper Chesapeake Bay based on Cji from CZCS, 15 April 1982.

One should note that the satellite data suggest a strong bloom in the Rappahannock River as well. The CZCS data suggest a gradient in chlorophyll across the Bay, with more chlorophyll on the western shore. This trend has been observed from ships so it may be real. However, band 4 sometimes shows some instability after the radiometer has been fully saturated, as would occur over land. If this instability led to an under estimate of the real radiance in the band, then it would produce the observed variation. Band 5 does vary across the Bay so the trend does not result from differences in radiometric resolution between the two bands.

LANDSAT data for Delaware Bay on 03 May 1982 shows the presence of a bloom in north-central Delaware Bay (Figure 6). In the analysis of this data, all three bands were used for better resolution.

Reflectance data can provide us with information on the movement and distribution of suspended sediments in estuaries. Figure 5 shows the western subestuaries of the Chesapeake Bay during the flood of November 1985. The flood crested in Washington (point A) at 1600 EST on November 7. Both images in the figure were corrected using equation 7 to allow direct comparison. Note the increase in turbid area in the upper Potomac River (between A and B) and in the lower Rappahannock (C) and the James River (D) (which is partially obscured by a cloud on November 7). This data set could later be calibrated to give sediment concentrations with the use of surface data in equation 6.

CONCLUSION

Satellites have the potential to estimate and map suspended sediment, to identify blooms and, in the case of the CZCS, even to estimate chlorophyll concentrations in estuaries. The technique of vector analysis has general applicability, being useful with LANDSAT MSS (Stumpf, 1984, 1985), AVHRR, and CZCS. The use of AVHRR is particularly worthwhile. The sensor collects thermal data that allows estimates of sea surface temperature to within 1^{o}C. AVHRR sensors will remain aloft for several more years, whereas the CZCS does not have a replacement. When two NOAA satellites are functioning, one can get day time coverage twice daily. Unfortunately the AVHRR, because of its poor spatial resolution will have limited application in monitoring small estuaries. Given the broad bands on the AVHRR and LANDSAT, neither can provide the precision of pigment data obtainable with the CZCS. Continued comparison of radiometrically-corrected AVHRR data with shipboard data may permit us to establish absolute relationships between C_{ji} and pigment presence and between reflectance and total seston. Thus, different images could be readily compared with AVHRR, as with CZCS, and major blooms could be detected as soon as they occur.

Figure 5: Reflectance in channel 1, NOAA-9 at 1340 EST, on 07-08 November 1985. Note change in turbidity in the Potomac River (A and B), Rappahannock (C) and James (D).

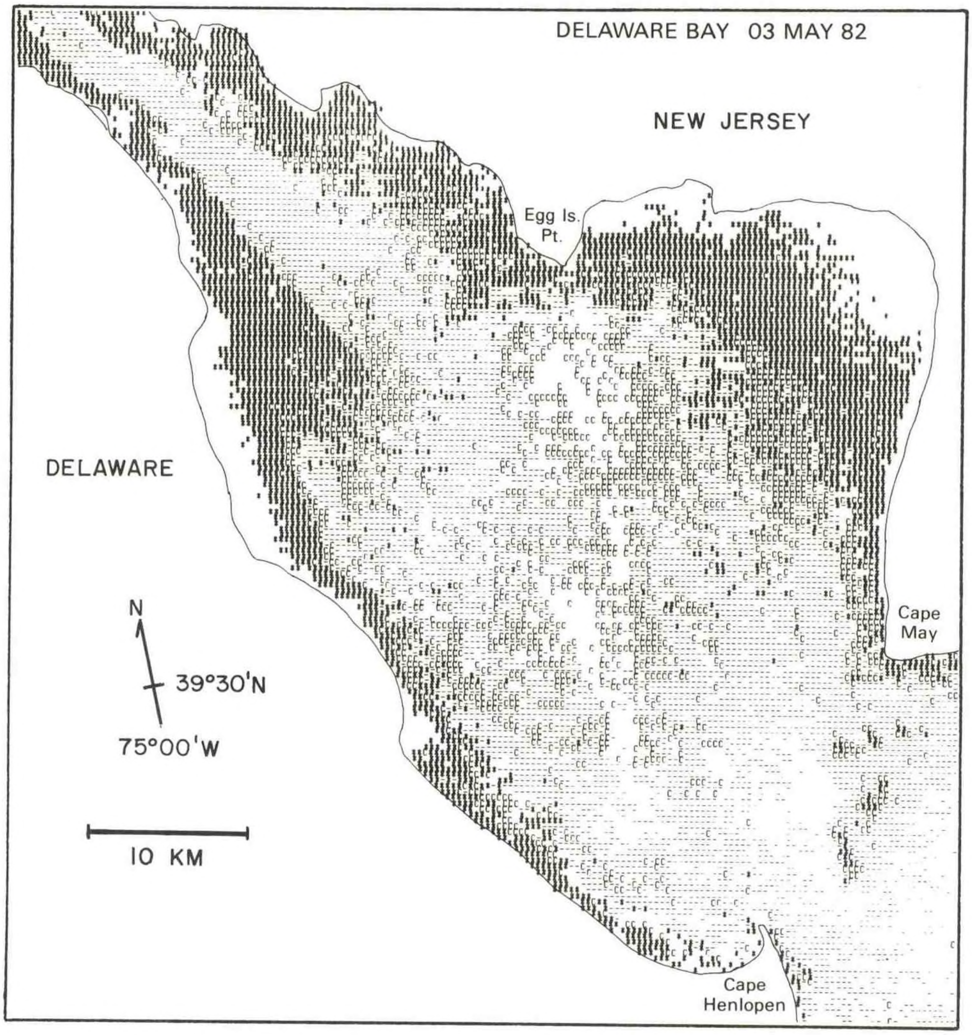

Figure 6: Major vectors in Delaware Bay, 03 May 82, using Landsat data. (from Stumpf, 1985) Clear areas are not classified. Concentrations as follow:

Vector symbol	***	ccc	---
np(ug/l)	25-50	25-35	10-30
nd(mg/l)	1-2mg	.5-1.5	.5-1.5

Table 1. Characteristics of Relevant AVHRR and CZCS bands

	AVHRR		CZCS	
resolution (nadir)	1.1km		.83km	
channel	1	2	4	5
bandwidth(nm)	580–680	720–1000	660–680	700–800
sensitivity mW/cm^2-sr-μm/count	.052	.034	.0107 (gain 0)	.093

	CZCS		
resolution (nadir)	.83km		
channel	1	2	3
bandwidth(nm)	433-453	510-530	540-560
sensitivity mW/cm^2-sr-μm/count	.044	.0031 (gain 0)	.024

	Landsat MSS			
resolution (nadir)	.08km			
band	4	5	6	7
bandwidth(nm)	500–600	600–700	700–800	800–1100
Sensitivity mW/cm^2-sr-μm/count	.17	.135	.10	.34

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REMOTE SENSING OF CURRENTS BY RADAR (CODAR)

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ABSTRACT

The application of land-based radars to estuarine remote sensing has considerable potential for providing information on the dynamics of the air-sea interface, including waves, currents, wind stress, and sea ice movements. These radar systems operate in the microwave and high frequency (HF) bands. The emphasis in this paper is on CODAR (Coastal Ocean Dynamics Applications Radar), which is a compact, HF radar system that has produced maps of surface currents over hundreds of square kilometers. We describe the components of CODAR, the principles of operation, and give examples of CODAR data products. A two-site CODAR deployment in Delaware Bay in the fall of 1984 provided three weeks of continuous surface current data. Resulting 1.5 hourly average maps, with 3 km resolution show spatial structure such as weak eddies, and areas of high current shear. The future of radar remote sensing in estuaries is bright. The resolution attainable with CODAR maps suggests application to large estuaries. By increasing resolution and by going to higher frequency, the benefits of radar remote sensing could be extended to rivers and small harbors.

THE ROLE OF LAND-BASED RADAR REMOTE SENSING SYSTEMS

1. INTRODUCTION

Land-based radar systems can provide nearly continous data, in all weather conditions, on ocean wave height and direction, current velocity, wind speed, ice drift, and drifting transponder location. In contrast, infra-red and microwave data from satellites and aircraft are usually available for only a few passes of the satellite or aircraft over the study area, e.g., LANDSAT, thus making quantitative description of a time-varying surface difficult or impossible. In this paper, we describe the main features of land-based radars, particularly high frequency (HF), or dekametric radars, and present examples of results from a recent deployment of an HF radar in Delaware Bay. A concluding section briefly reports on the operating principles and characteristics of land-based microwave radar systems.

High-frequency (HF), or dekametric radar, of wavelengths on the order of 10 m, and frequencies on the order of 25 MHz, are now being used to map surface currents at ranges of up to 70 km from shore stations. Perhaps the most well known and widely used HF radar is called CODAR (Coastal Ocean Dynamics Applications Radar), developed initially by D. Barrick and colleagues at NOAA's Wave Propagation Laboratory, and now marketed by CODAR Systems Inc. CODAR is an example of a ground wave radar, which operates on the principle of backscatter of the ground wave from ocean surface waves. Another type of HF radar, called sky-wave, relies on the refraction of electromagnetic waves by the ionosphere, and is capable of mapping currents at great distances from the radar.

2. WHAT IS CODAR?

CODAR is a tranportable remote-sensing HF radar that measures the dynamic properties of the ocean surface, i.e., surface wind waves, wind stress, surface currents, and movements of sea ice. It can track transponder drifters, for in situ measurement of currents, and thus contains a means of self-intercomparison. CODAR can operate from land stations, offshore platforms, and, in principle, from ships.

CODAR has a range of up to 70 km, although 50 km would be more typical, especially in estuarine applications. CODAR measures the current in the upper one meter of the water column with a horizontal resolution of about 1.2 km. A typical grid size of a CODAR generated current map is 2 km by 2 km. The grid size is larger than the resolution to facilitate averaging to reduce the noise in the data. Two CODAR stations are, in general, required to measure surface currents. Each station acquires and processes its own radial map of surface currents. The two maps are then combined into a single map of current vectors over the chosen grid.

3. PRINCIPLES OF OPERATION

The principle of operation relies on Bragg scattering, by analogy with the diffraction of X-rays from the ordered rows of atoms in a crystal lattice. The radar filters, from the chaotic sea surface, those waves which are exactly half the radar wave length, which is 12 m, for CODAR. Since the waves are in motion, waves traveling toward or away from the radar antenna impart a Doppler shift to the signal. This Doppler shift is seen in the echo spectrum of the received backscattered signal as two sharp peaks, symmetrically located about the transmitted (carrier) frequency (Figure 1). The Doppler shift is directly proportional to the phase velocity of the scattering "Bragg waves" (as they are known in the trade), through the deep water gravity wave dispersion relation. Thus, the radar detects wave motions as a Doppler shift modulation about the transmitted frequency.

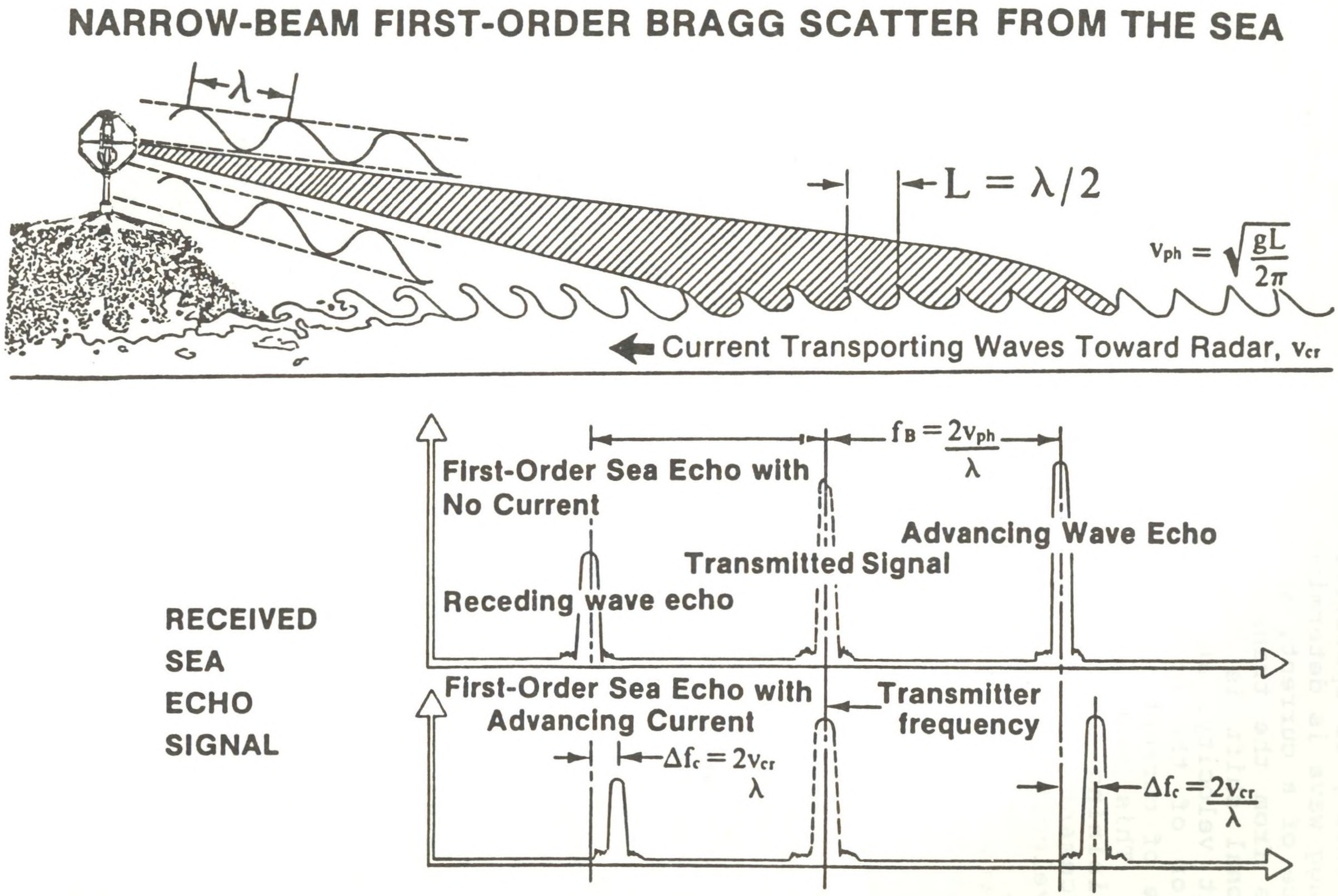


Figure 1. Bragg scatter causes two sharp peaks in the echo spectrum symmetrically placed about the carrier frequency. The location of the peaks in frequency is proportional to the phase velocity of the Bragg scattering wavetrains of 1/2 wavelength through the gravity wave dispersion relation. A surface current transporting the waves will produce small indentical shifts in the peaks which are proportional to the radial component of current.

In the absence of current, the location of the peaks or "side bands", is specified exactly, because the phase speed of the Bragg wave is determined by the dispersion relation. In the presence of a current, an additional Doppler shift occurs, which results from the transport of the waves by the current. This additional shift is proportional to U/λ, where U is the mean current velocity, and λ is the radar wavelength. Thus, the location of the Bragg peaks in the echo spectrum provides a measure of current velocity in the radial direction of the radar beam. This technique for measuring currents is analagous to determinining the speed of celestial bodies by means of the displacement of spectral lines from their known locations at rest velocity (the "red shift", for movements away from the earth). The variation of current with range from the radar site is obtained by measuring the travel time required by the radar pulse to and from a given sector of the sea surface. The length of the minimum size sector for CODAR is about 1.2 km, thus specifying the maxiumum resolution with the present hardware configuration.

The currents are mapped in direction, as well as range, by using a beam-forming antenna (Figure 2). The voltage outputs from the antenna, from the radar echoes are converted, by means of the equations of scattering theory (e.g., Barrick et al, 1984), into beam direction as a function of current velocity. An inversion of the equations provides the desired output, which is radial current velocity as a function of beam direction. Because a narrow beam HF antenna is usually very large, on the order of 100 m, considerable research was put into developing a compact antenna, which could be used, for example, on oil drilling platforms. The design of the antenna deployed by CODAR Systems Inc., in the recent Delaware Bay experiment, is shown in Figure 3. It stands 2 m high, and weighs less than 40 kg. The antenna consists of two loops and a monopole. Each loop radiates its power in a "figure 8" pattern. When the whole antenna is excited as a monopole, it radiates an omnidirectional pattern. By phasing and summing, a cardioid pattern is produced, which is electronically steered over the water surface.

The radial current vectors must then be used to produce a map of surface currents. This is done by using two geographically separated transceivers, and combining the two current vectors to form a total current vector, which can then be resolved into any desired components. When only one radar unit is available, either a simple model of the current, or the hydrodynamic equation of continuity can be applied to obtain current maps. Needless to say, the two site option provides the greatest accuracv.

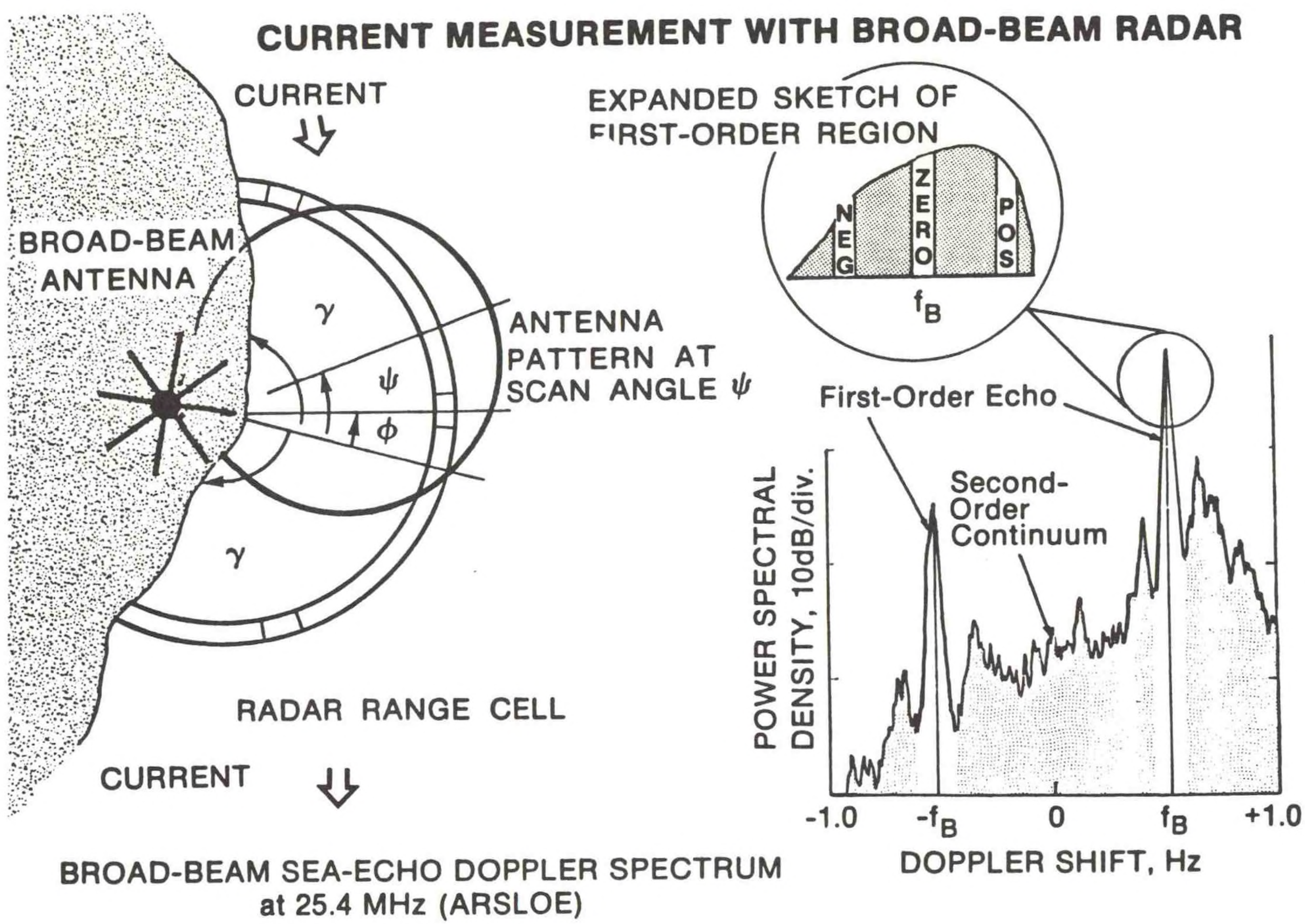
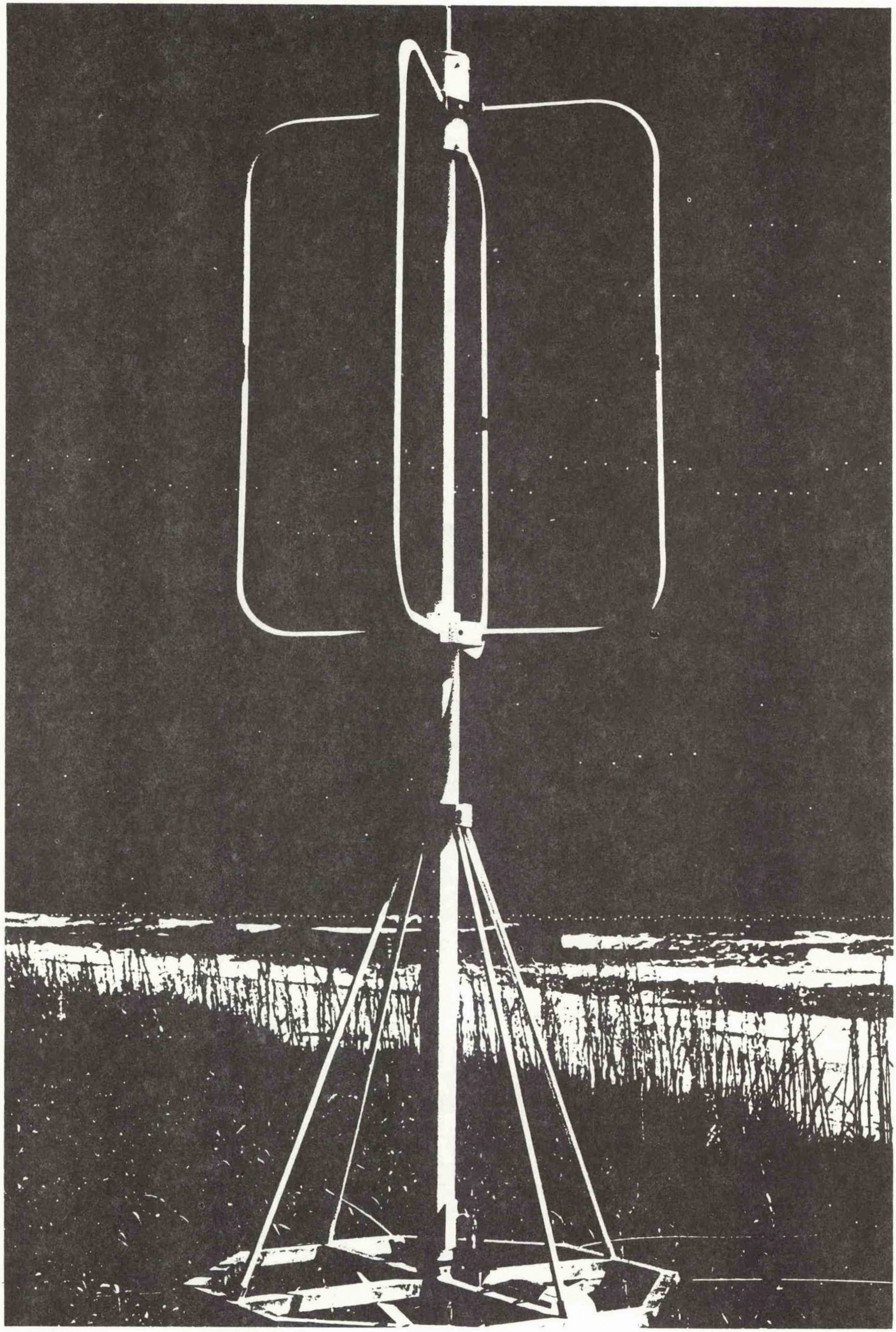


Figure 2. The CODAR antenna is compact and therefore radiates a broad beam. The spectral peaks of the returned radar signal are broadened, because of the wide range of radial velocity variations falling within the radar cell subtended by the radar beam. The beam is scanned in azimuth with the software by combining the signals from the three antenna elements in different proportions. The bearing from the CODAR to an area of the surface with a particular radial velocity is then computed using the antenna pattern, yielding a map of radial current velocities for each CODAR range cell.

Figure 3. The compact CODAR antenna, used in the Delaware Bay operation, showing three elements: two crossed loops and a monopole. Each loop transmits a "figure 8" pattern -- the monople an omnidirectional pattern. Proper phasing of the transmitted signal results in a cardioid pattern which can be steered electronically. The received voltage spectrum is estimated by means of a Fourier series expansion similar to the estimation of the surface wave spectrum for the "pitch-roll" buoy.



4. OCEANOGRAPHIC APPLICATIONS

The theory and experimental technique of the CODAR were developed in conjunction with a series of coastal applications which culminated in an experiment off Duck, North Carolina, the Atlantic Remote Sensing Experiment, where coastal currents were mapped under conditions of wind stress ranging from low to high (see references).

In the autumn of 1984, a dual-site CODAR field operation was conducted in lower Delaware Bay, in conjuction with the NOAA/NOS Delaware River and Bay survey. The CODAR deployment was jointly supported by NOAA and the U.S. Army Corps of Engineers' Coastal Research Center (CERC). NOAA and CERC hope to understand the factors that govern circulation in such complex, enclosed areas so that accurate models can be constructed to produce nowcasts and forecasts of the three-dimensional circulation.

CODAR provided maps of surface current at 1.5 hour intervals for a period of about 3 weeks, from mid-October through the first week in November, using two sites; a base site at Lewes, Delaware, and a remote site at Big Stone Beach, Delaware (Figure 4). In addition to CODAR, current meter moorings provided deeper currents at several locations. A remote acoustic Doppler system (RADS) on the bottom near Brandywine Shoals (see Appell, these proceedings), gave vertical profiles of the current to within 1 meter of the sea surface; meteorological data were acquired by anemometers mounted on a mast at Brandywine Shoals.

The basic CODAR data product is the current vector map of hour-and-half averages over a 2 km by 2 km grid, using all radial data within a 3 km radius of each grid point. An example of the current maps is given in Figure 5, which shows four successive maps for the period 16 October; 00:35 to 02:50 local time. The 3 km radius for each grid point is shown by the circle at the bottom of each figure. The current, predominantly semi-diurnal tidal, is seen to flow into the Bay, and then ebb during this measurement period. Grid points with no current vectors indicate insufficient signal-to-noise ratio to pass statistical tests for validity; hence these data were discarded. Figure 6 shows two current charts, the top one was made at 12:26 local time on the 15th of October, and the bottom one was made at 21:24 local time on the 24th of October, under similar wind conditions. Both maps, though made 9 days apart, are similar because they were made at about the same stage of the tide; that is, at high water, Lewes, Delaware. Note the weak gyre located at the mouth of the Bay. Barrick and Lipa (1986), have noted that these gyres are frequently seen in the CODAR data, and appear to propagate up the Bay at a phase velocity determined by the water depth.

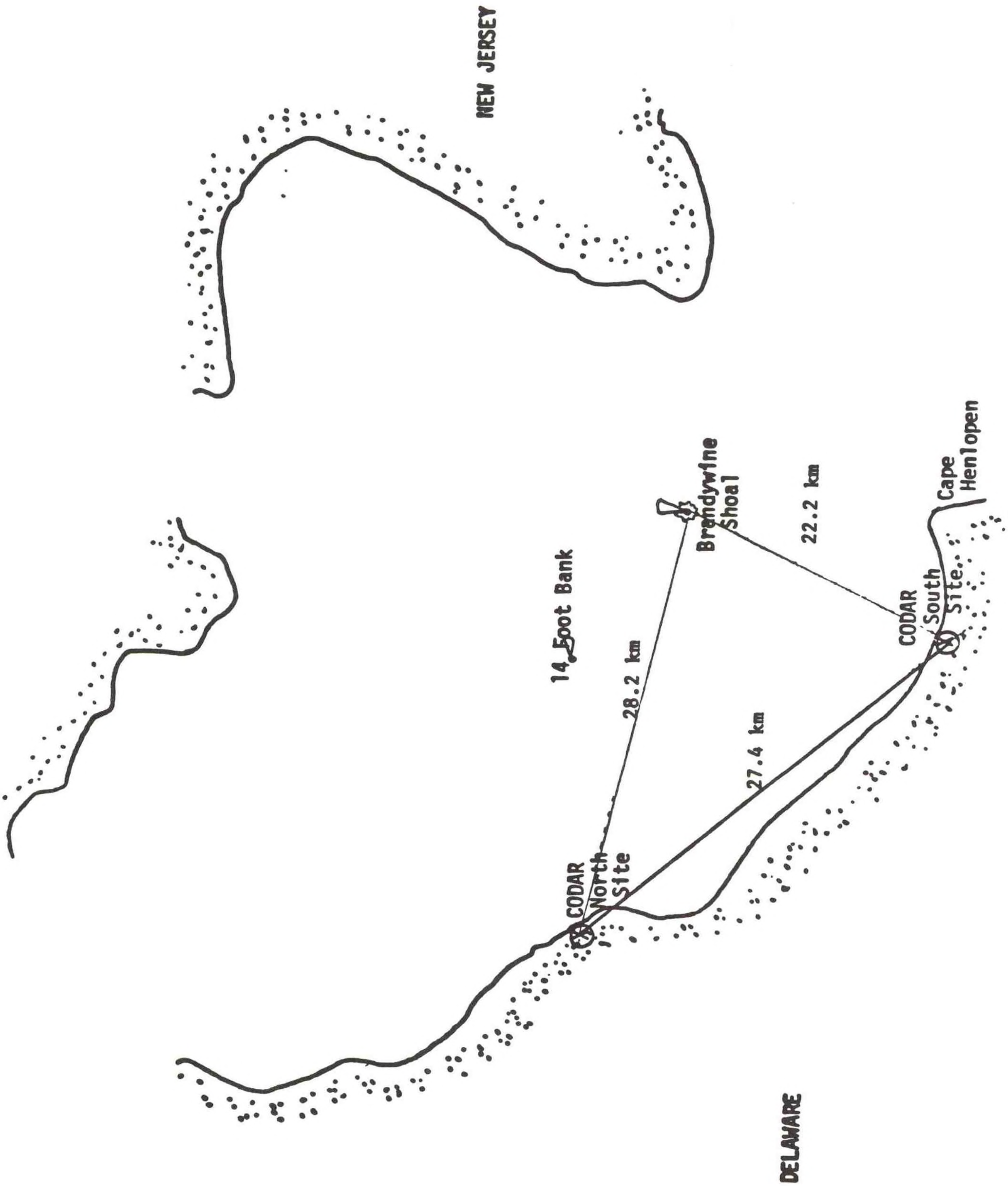


Figure 4. Location map and geometry of the CODAR deployment in Delaware Bay, Fall, 1984.

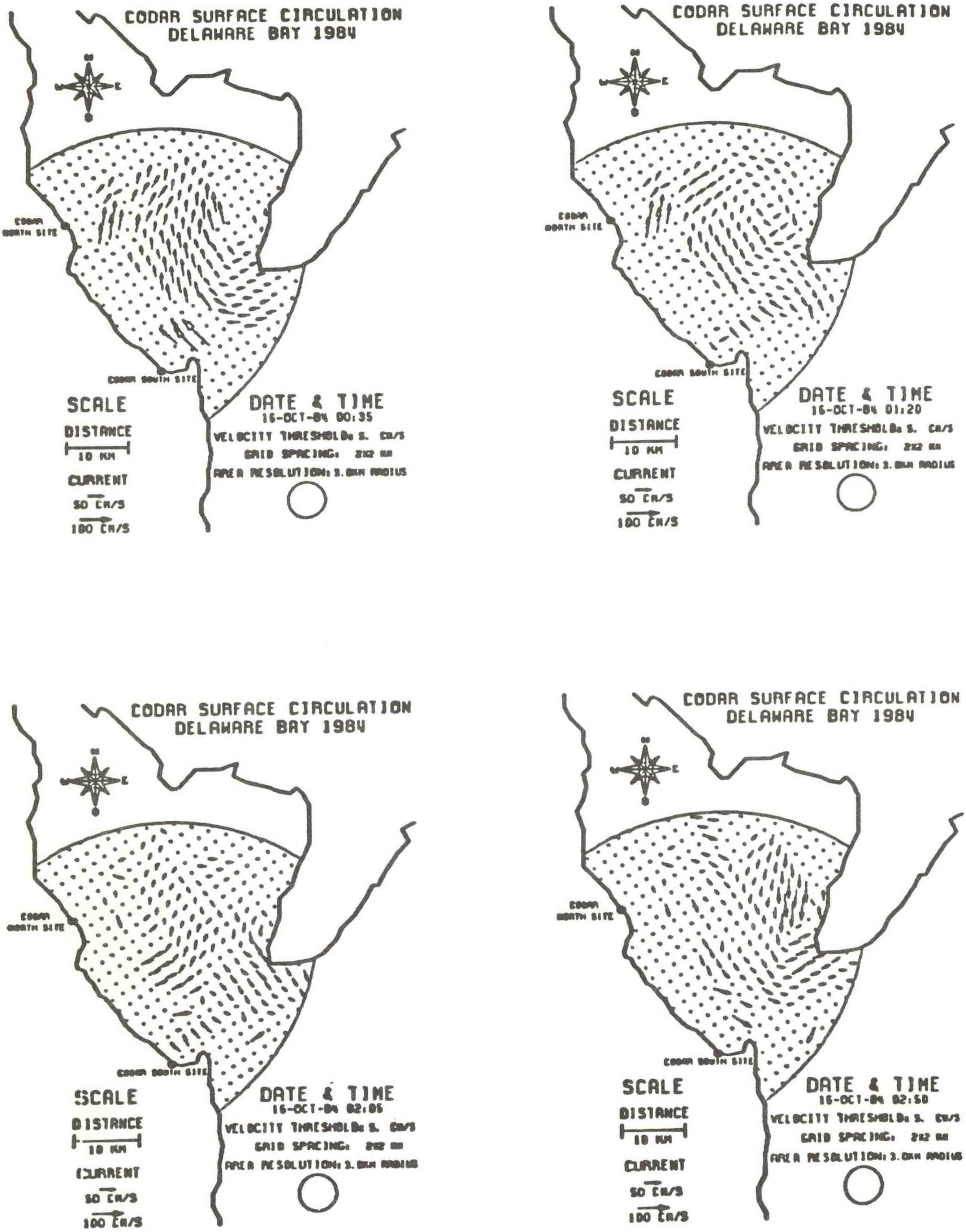
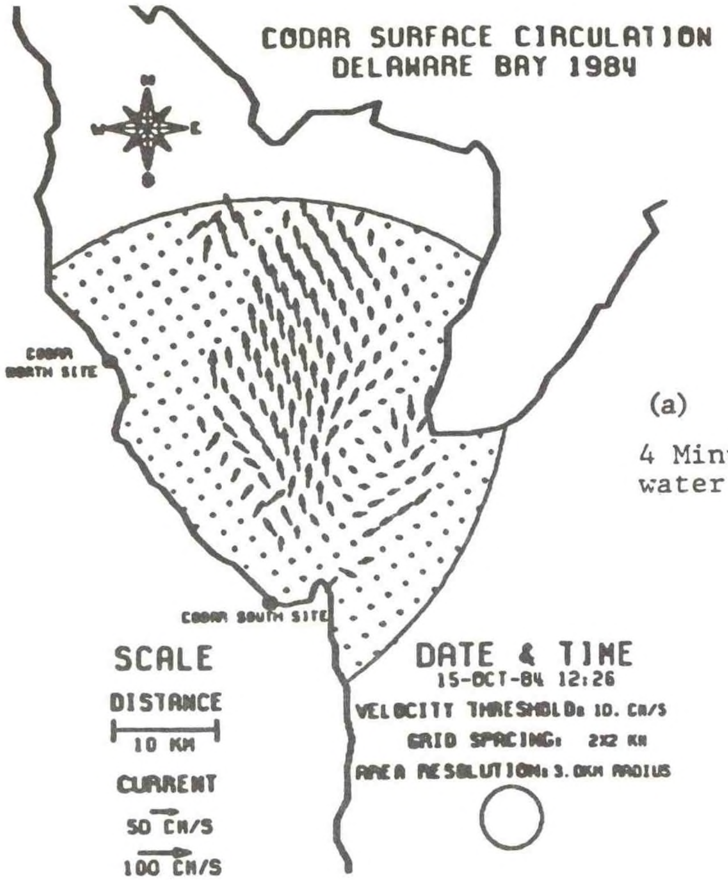
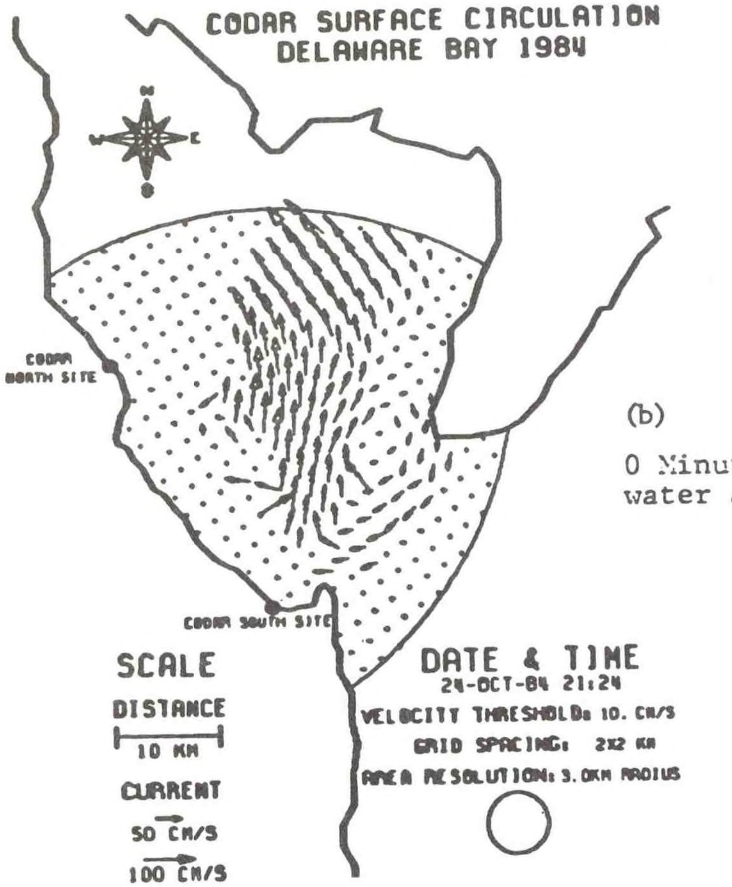


Figure 5. Four sequential CODAR current maps of Delaware Bay. The times given in the legend refer to the center of the 1.5 hour averaging interval.



(a)

4 Minutes before high water at Lewes, DE.



(b)

0 Minutes before high water at Lewes, DE.

Figure 6. CODAR maps for two different days, 9 days apart, at the same stage of the tide (high water at Lewes, Delaware).

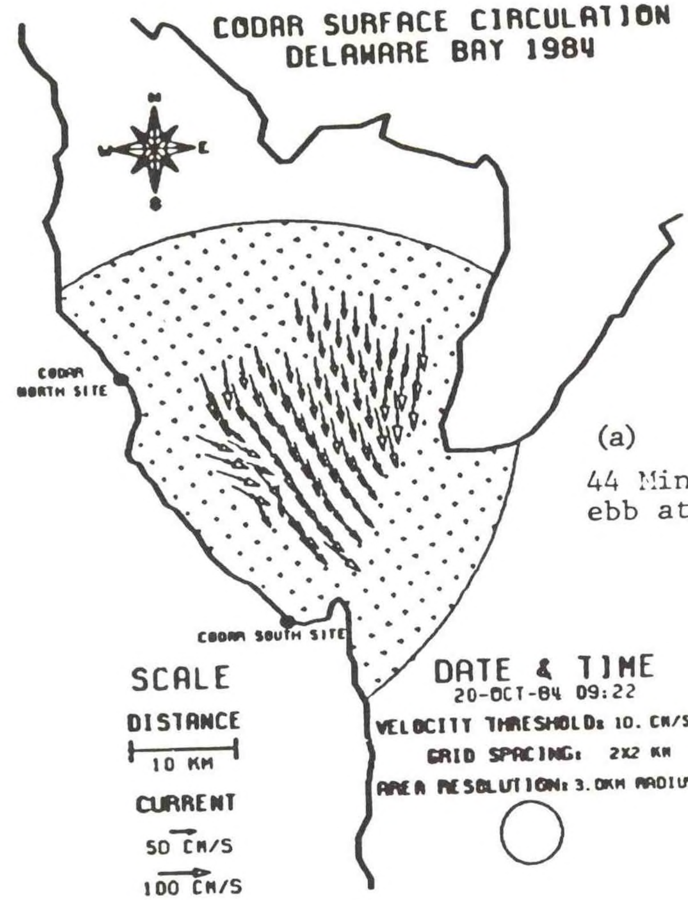
Figure 7 is another example of the repeatability of the ebb tide under similar weather conditions. The upper map was made 44 minutes before the maximum predicted ebb at Lewes, Delaware, whereas the lower map was made 19 minutes before the maximum ebb at Lewes. Once again, these flow patterns are similar. Note the flow parallel to the coast on the eastern side of the Bay, and the flow out from the western side of the Bay into the main channel. The current veers as it progresses from the center of the study areas down the mouth of the Bay.

In addition to the radar maps, CODAR Systems Inc. has provided NOAA with a computer program to extract time series of surface currents at given grid points. Missing data are interpolated by means of a least squares fit to a trigonometric series. A time series of CODAR-measured currents at the grid point nearest Brandywine Shoal has been compared to currents measured near the surface by RADS (Porter, Williams and Swassing, 1986).

During the radar mapping, CODAR Systems, Inc. deployed radar transponders on drogued floats. The CODAR interrogated the drifting transponders every 45 minutes for a 2-minute period to obtain drifter speed and direction. The purposes of these drifters were to provide in situ measurement of current, and to provide calibration signals to verify the CODAR antenna beam pattern. The drifters were based on a design by Russell Davis of the Scripps Institution of Oceanography (Davis, 1985), to follow the surface currents in the presence of wind and wave action, and also to be relatively inexpensive. Each drifter consists of a vertically floating PVC tube which contains ballast, a 12 volt battery, HF transponder, and whip antenna. Four drag-producing vanes extended radially outward from the center of the tube, with each vane buoyed up by a small float (Figure 8).

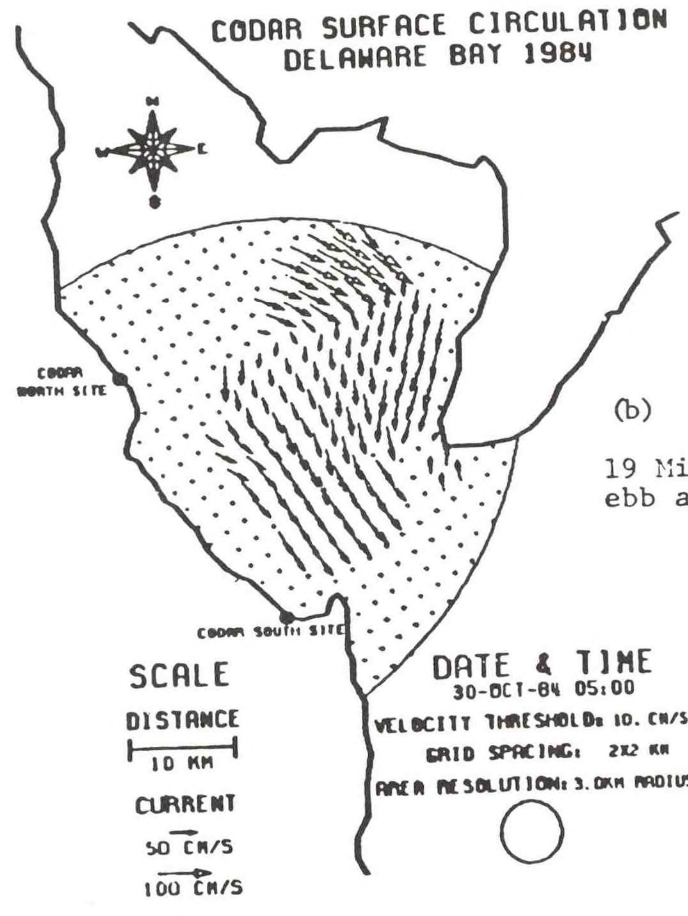
5. CODAR INTERCOMPARISON STUDY

For a 10 day period of the CODAR deployment, CODAR measurements were compared with the RADS and with a Vector Measuring Current Meter (VMCM) that was situated near the RADS site, at near Brandywine Shoals. The data from all measurement systems were rotated to a common coordinate system in which the "along-channel" direction of 340°T is the y axis. The "cross-channel" direction is 90° to the right, or 70°T, and is perpendicular to the general orientation of the bathymetric features. Time histories of cross-channel flow for the three instruments are shown in Figure 9, where bin 7 of the RADS, the bin closest to the surface which is fully submerged, was used. The agreement among instruments for this component is low. The RADS signal is small (about 5 cm/s peak), and where there is a signal, it appears to be 180° out of phase with both CODAR and the VMCM. THe CODAR data lags the VMCM data and has an amplitude about twice as great (20 cm/s versus 10 cm/s). Figure 10



(a)

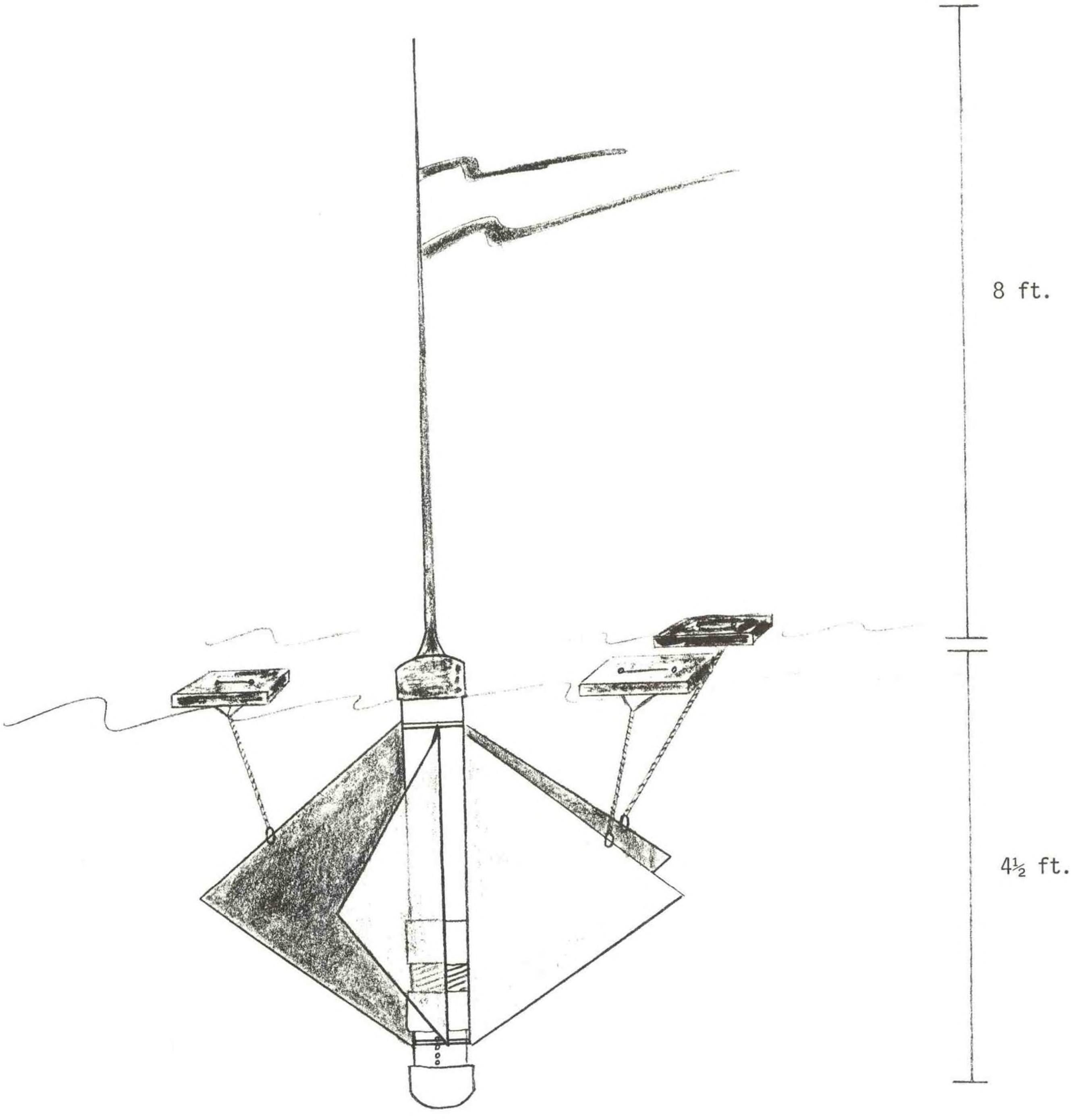
44 Minutes before maximum ebb at Lewes, DE.



(b)

19 Minutes before maximum ebb at Lewes, DE.

Figure 7. CODAR maps for two different days, 10 days apart, roughly at the same stage of the tidal current (maximum ebb) at Lewes, Delaware.

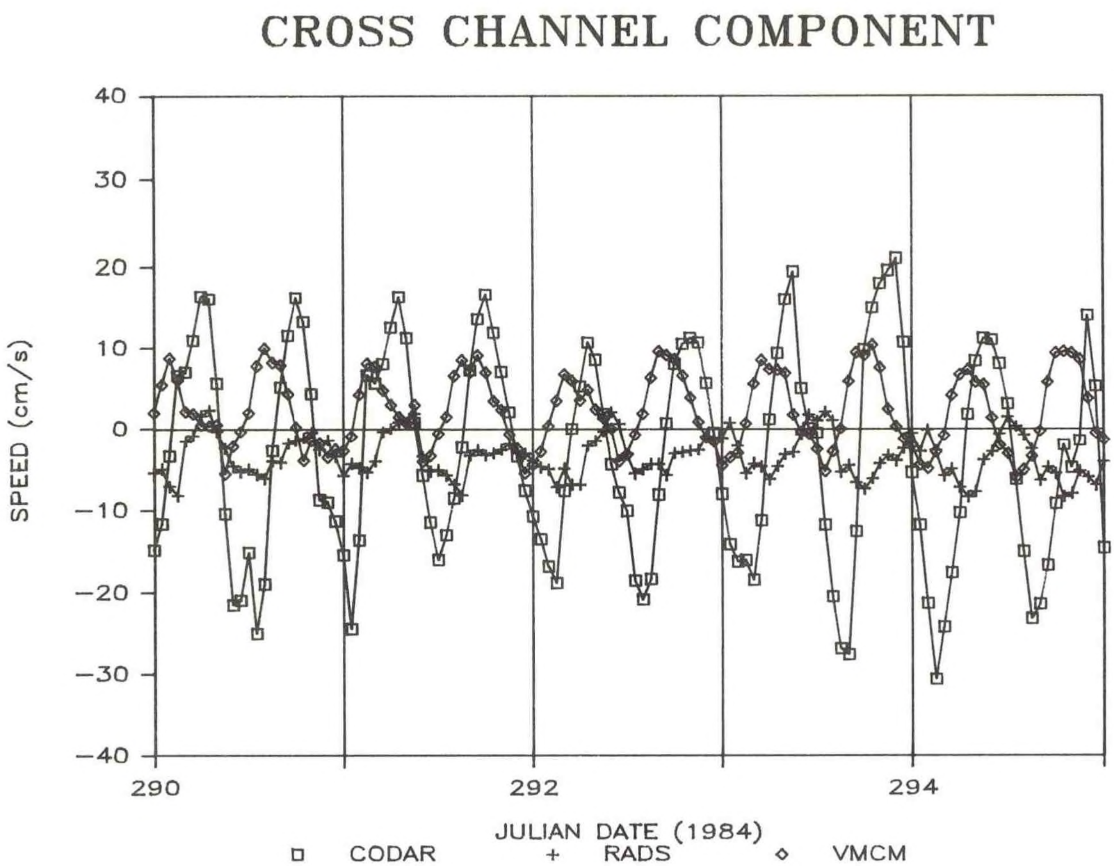


* Assembled drifter example. The drifter contains a 12 volt battery source, transponder hardware and antenna.

* The drifter is constructed from 4" PVC pipe, 1" PVC tubing, styrofoam, hose clamps, heavy plastic sheets, and rope.

* The ballast at bottom is filled with rocks.

Figure 8. Design of the drifting transponders deployed during the CODAR 1984 Delaware Bay deployment.



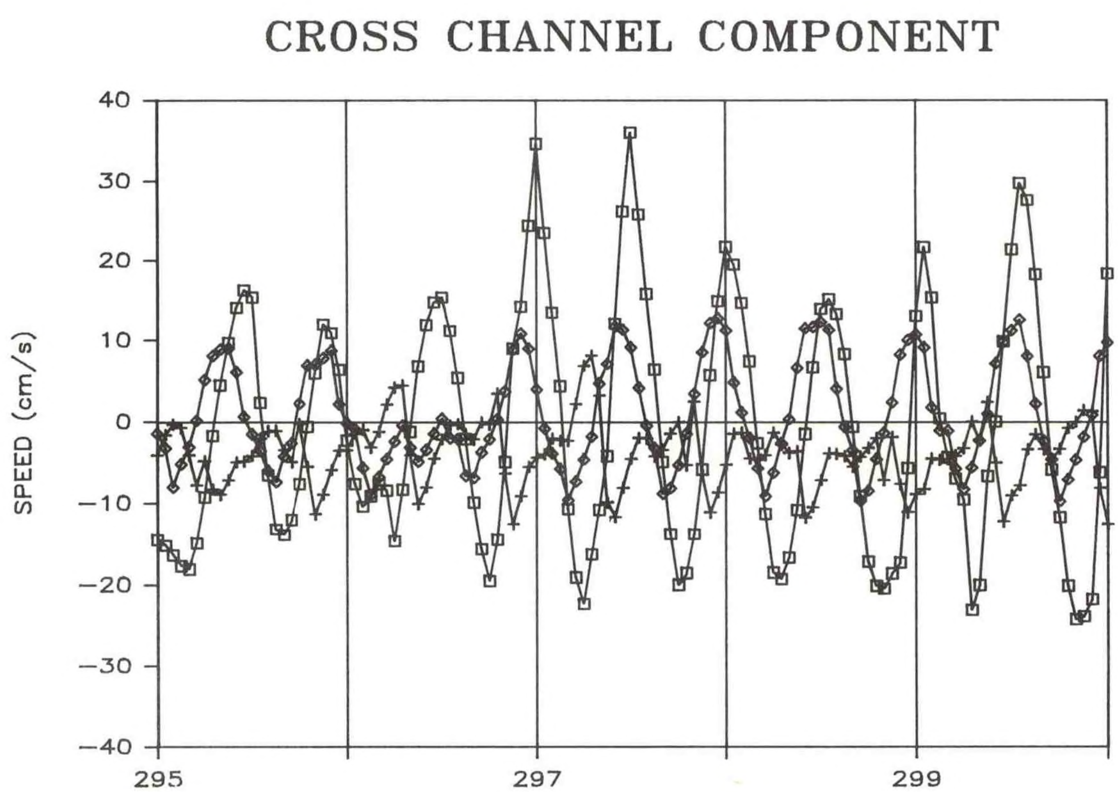
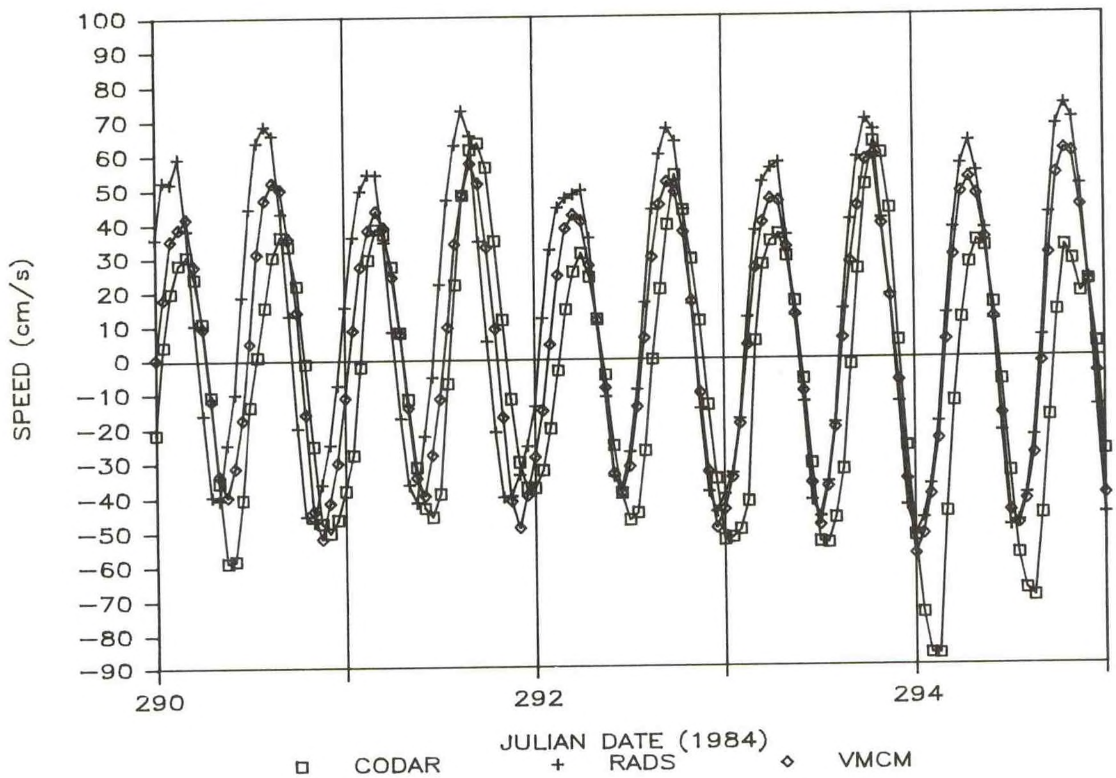


Figure 9. Time series of the cross-channel flow as measured by RADS, CODAR, and the VMCM.

ALONG CHANNEL COMPONENT



ALONG CHANNEL COMPONENT

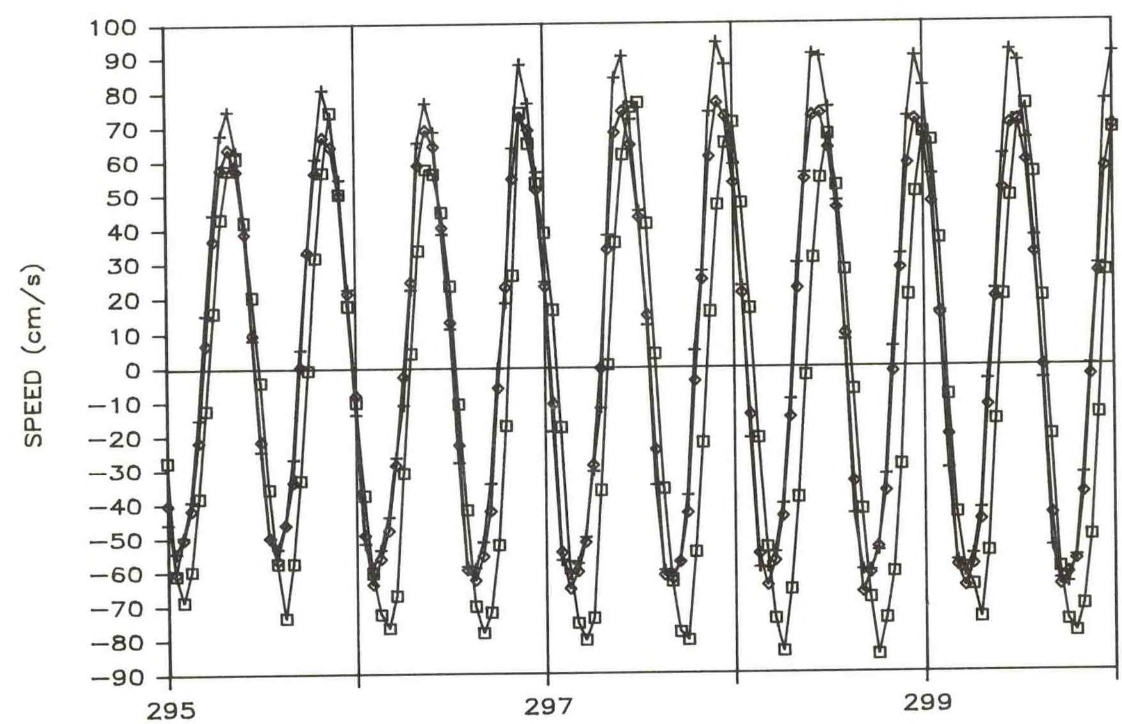


Figure 10. Time series of the along-channel flow as measured by the RADS, CODAR, and the VMCM.

shows the along-stream time series. The flood peaks measured by the CODAR and the VMCM are in agreement within 10 percent in amplitude, with the phase of the CODAR lagging. The RADS flood peaks are about 20 cm/s larger than the CODAR or the VMCM. The agreement in phase improves after Julian day 295. We believe that this improved agreement is due to the higher level of peak signal (almost twice as large as between days 290 - 295), which is the result of the spring tide, centered at Julian Day 298. Note also that in most cases, agreement is better on the ebb tide than on the flood tide. This may be the result of topographic modification of the flow fields.

We hypothesize that the differences seen in the measurements are the result of differences of the spatial and temporal averaging of the instruments (Porter, Williams and Swassing, 1986). We take special note that in the cross-channel direction, the bathymetric features associated with Brandywine Shoal result in a flow which is much smaller in scale than the effective CODAR resolution, whereas in the along-channel direction, the scale of flow is larger than the CODAR resolution. Furthermore, the CODAR is measuring average flow in the top 1 meter of the water column, whereas the RADS and the VMCM are measuring subsurface flow. Despite these difficulties of comparing a remote sensing system with <u>in situ</u> measurements, we are confidant that the CODAR is providing valid measurements of surface current, provided that the spatial scale of variability of the current is greater than the CODAR spatial averaging length, and that the temporal variations in the flow are not large on time scales shorter than the CODAR averaging period.

6. THE FUTURE OF RADAR SYSTEMS IN ESTUARINE REMOTE SENSING

The CODAR range and range cell size (1.2 km) are ideally suited to large estuaries such as Delaware Bay. The effective resolution of the CODAR maps in Delaware Bay was 3 km in space and 1.5 hours in time. The 3 km effective resolution could be increased to about 1.5 km, and the sampling interval reduced from 1.5 hours to 1.0 hours (D. Barrick, 1986, personal communication). However, a CODAR-type system could be operated, according to Barrick, with a shorter pulse length, and at higher frequency, in the VHF band, which could potentially improve resolution over present HF CODAR by a factor of three. As an alternative, one and two frequency microwave radars have been developed by the Naval Research Laboratory which could be used to measure currents at high spatial resolution -- on the order of a few meters (see references by Keller, Plant, and Schuler). A commercially produced 2-frequency current measuring radar system is available from MIROS, Norway, and is designed to operate from ships and drilling platforms (Gronlie and Brodtkorb, 1984).

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SATELLITE REMOTE SENSING OF SUBMERGED AQUATIC VEGETATION IN LOWER CHESAPEAKE BAY

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ABSTRACT

LANDSAT Multispectral Scanner (MSS) and Thematic Mapper (TM) imagery, obtained simultaneously over the Guinea Marsh area, Lower Chesapeake Bay, were analyzed and compared in the ability to detect submerged aquatic vegetation (SAV). An unsupervised clustering algorithm was applied to each image, where the input classification parameters were defined as functions of apparent sensor noise. Class confidence and accuracy were computed for all water areas by comparing the classified images, pixel-by-pixel, to rasterized SAV distributions derived from color aerial photography. To illustrate the effect of water depth upon classification error, areas of depth greater than 1.9 m (6 ft) were masked and class confidence and accuracy recalculated.

A single-scattering radiative transfer model is used to illustrate how percent canopy cover and water depth affect the volume reflectance from a water column containing SAV. For a submerged canopy that is morphologically and optically similar to _Zostera marina_ inhabiting Lower Chesapeake Bay, dense canopies may be isolated by masking optically deep water. For less dense canopies, the effect of increasing water depth is to increase the apparent percent crown cover, which may result in classification error.

INTRODUCTION

Submerged aquatic vegetation (SAV) is believed to play a major role in the ecosystem of coastal, estuarine, and inland waters. In Chesapeake Bay, species such as _Zostera marina_ (eel grass) provide food, shelter, and breeding areas for waterfowl, fish, shellfish, and many other forms of aquatic life. (Stevenson and Confer, 1978; Van Tine and Wetzel, 1983; Wetzel, 1983). Because of the enormous commercial value of these areas, there exists a need to periodically assess the distribution and abundance of submerged aquatic plant communities.

Historically, data concerning SAV distribution and abundance has been acquired through exhaustive field sampling programs, conducted from floating platforms. As is typical of such studies, permanent transects or stations are defined and the abundance and morphology of SAV is monitored through time (Stotts, 1960 and 1970). Today, with the exception of very small scale studies, such surveys have become prohibitively expensive.

More recently, color aerial photography has been shown to provide much useful information for mapping SAV (Benton and Newman, 1976; Austin and Adams, 1978; Orth et al., 1979; Macomber, 1981; Orth and Moore, 1981 and 1983). Orth and others were able to document changes in the distribution and abundance of SAV at six sites within Chesapeake Bay from aerial photography dating back to 1937. Orth was also able to map SAV distribution and percent crown cover within Lower Chesapeake Bay by manually interpreting color aerial photography collected in 1979, 1980, 1982, and 1984. For each of these years, SAV distribution was delineated on 1:24,000 USGS topographic quadrangles as several classifications of apparent crown cover.

Remote sensing data, generated by orbiting sensors, has shown promise in delineating SAV. Jensen et al. (1980) successfully used LANDSAT MSS imagery to map *Macrocystis pyrifera* (kelp) along the California coast. The degree to which these data may be used depends upon the configuration of the particular sensor -- i.e. the spatial and spectral resolution and the spectral location and radiometric sensitivity of the available bands. The spatial resolution of MSS data is approximately 80 meters. Although the LANDSAT MSS collects data in four bands, two visible bands and two near infrared bands, only band 1 (500-600 nm) and band 2 (600-700 nm) are useful for detecting submerged features because water is an efficient absorber of IR radiation and the radiometric sensitivities of bands 3 (700-800 nm) and 4 (800-1100 nm) are optimized for land features.

The two most recent LANDSAT satellites, LANDSAT 4 and 5, are equipped not only with a MSS, but a new series of scanner, the Thematic Mapper (TM). The spatial resolution of TM imagery is approximately 30 meters and 3 of the 7 bands are located in the visual portion of the spectrum -- band 1 (450-520 nm), band 2 (530-610 nm) and band 3 (620-690 nm). In addition, the radiometric sensitivity of the TM bands is roughly 50% greater than those of the spectrally similar MSS bands (Table 1). All of these attributes suggest that TM imagery may contain more submerged features information than MSS data. The purpose of this work is to compare MSS imagery to TM data in the ability to detect SAV within Lower Chesapeake Bay.

Table 1

Radiometric Sensitivity of Visible MSS (Alford and Imhoff, 1983) and TM (Irons, 1983) Bands

Band	Wavelength Region (nm)	--Calibration*-- Gain	Offset
MSS1	500-600	5.570	-1.114
MSS2	600-700	7.216	-2.886
TM1	450-520	15.944	2.423
TM2	530-610	8.199	2.329
TM3	620-690	10.814	1.265

* COUNT = (GAIN x L) + OFFSET
GAIN = COUNT/$mw\text{-}cm^{-2}\text{-}um^{-1}\text{-}str^{-1}$
L = $mw\text{-}cm^{-2}\text{-}um^{-1}\text{-}str^{-1}$

DESCRIPTION OF STUDY AREA

The area of interest is located in Lower Chesapeake Bay, at the mouth of the York River, along the southern shore of Mobjack Bay (Figure 1). The area encompasses 41.1 km^2, approximately 6.5 km^2 of which is inhabited by SAV. These bottom-adhering canopies are composed mostly of Zostera marina and Ruppia maritima and are typically situated in shallow water adjacent to the shoreline. During the summer, both of these species are abundant, with Ruppia dominating shallow areas to depths less than 0.5 m and Zostera dominating deeper areas to a depth of about 1.5 m. During the winter, the SAV distribution and abundance decreases as the Ruppia all but disappears and the Zostera dies back significantly.

The bottom substrate throughout the study area is composed of bright sand. From the air, the SAV canopies appear as dark patches upon an otherwise bright bottom.

The water clarity varies seasonally, with most clear conditions occurring in the winter months. During the summer, higher nutrient concentrations, warmer water, and increased surface light intensities often induce plankton blooms. The resulting turbidity may greatly reduce the ability of an observer or remote sensing device to detect SAV. Wetzel (1983) and Van Tine and Wetzel (1983) reported seasonal averages or irradiance attenuation measured at several sites in Lower Chesapeake Bay containing SAV. Their data indicate that during the winter, the mean attenuation depth, the depth at which the intensity has decreased to 1% of the surface intensity, for blue (410 nm), green (540 nm), and red (671 nm) light is respectively, 2.0 m, 5.7 m, and 3.2 m. During the summer, the mean attenuation depth decreases to about 0.8 m, 1.9 m, and 1.6 m for blue, green, and red light, respectively.

Guinea Marsh Study Area

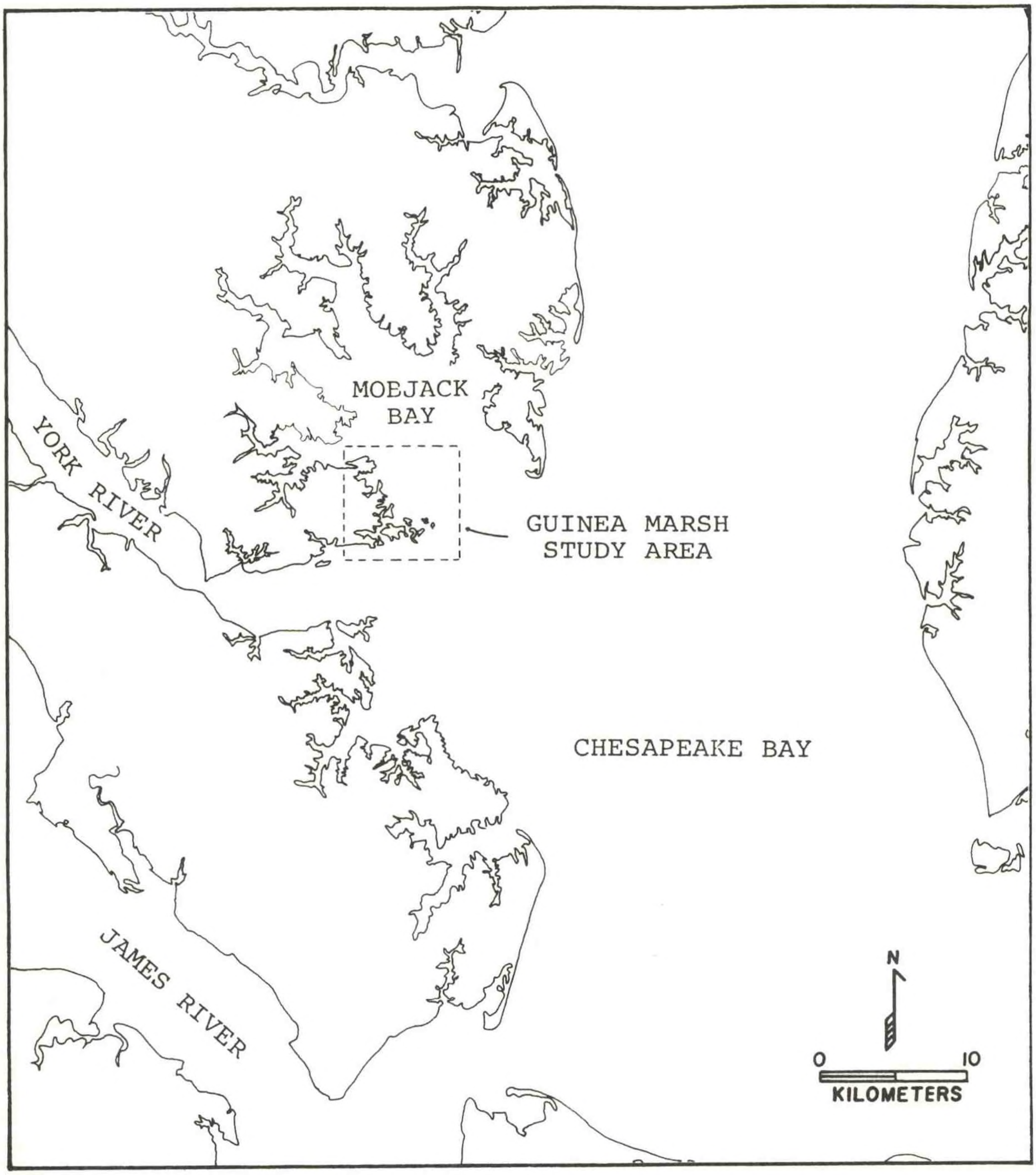

Figure 1: The study area is located at the confluence of the York River and the Chesapeake Bay, adjacent to the Guinea Marsh.

METHODOLOGY

LANDSAT MSS and TM imagery, generated simultaneously over the Guinea Marsh area, were classified using an unsupervised clustering algorithm. All data analysis was performed using an ERDAS/AT image analysis system. To provide a basis for comparing the MSS imagery to the TM imagery, the input parameters governing the operation of the clustering program were defined as functions of the system noise apparent within each image. The classified images were then compared, pixel-by-pixel, to rasterized SAV distributions delineated from color aerial photography. Class confidence and accuracy measures, which are defined in a later section, were computed for each clustered scene and used to compare the two image types.

LANDSAT Imagery

LANDSAT MSS and TM imagery of the Guinea Marsh area were generated simultaneously on 19 July 1984. At the time of the overpass, 1009 local time, the sky was cloud-free and reasonably clear of haze. The solar zenith angle was 32°. The tide at Guinea Marsh was flooding and low tide occurred at 0706 local time.

Prior to classification, each image, a standard product CCT-P, was geometrically registered to a 1:24,000 scale USGS topographic quadrangle of the Guinea Marsh area. The MSS data was resampled to form a 60-meter grid while the TM image was resampled to form a 28-meter grid. A nearest neighbor resampling scheme was used in order to preserve pixel spectra within each image.

SAV Ground Truth Maps

On 21 June 1984, 28 days prior to the LANDSAT overpass, the Virginia Institute of Marine Science conducted a survey of SAV distribution within Lower Chesapeake Bay (Orth et al., 1984). In this survey, color aerial photography was collected at a scale of 1:24,000. The camera used was a Fairchild CA-8 cartographic camera equipped with a 152 mm (6.5 in) focal length Bausch and Lomb Metrogon lens. The film used was Kodak 24 cm (9.5 in) square positive Aerochrome MS type 2448. The photography was classified into four categories of apparent SAV crown cover using visual interpretation techniques -- 0-10%, 10-40%, 40-70%, and 70-100%, hereafter referred to as SAV densities 1 through 4, respectively. The photographic SAV delineations were then transferred directly to 1:24,000 USGS topographic quadrangles by simply overlaying the classified transparencies. Orth et al (1984) presents these data as two quadrangles, Achilles (reference map 131) and New Point Comfort (reference map 132). A MSS ground truth map was created by digitizing the SAV quadrangles, using a CALCOMP 9100 digitizing table, and then rasterizing to form a 60-meter grid which was registered to the MSS image. To create the TM ground truth map, the SAV quadrangles were digitized and rasterized to form a 28-meter grid registered to the TM image. In both cases, the image to ground truth map registration was achieved using a nearest neighbor resampling scheme. To test the accuracy of the registration procedure, ground control points (prominent coastline features) were selected within each image-map pair. Care was taken to ensure that ground control points were selected from a variety of locations representing the entire study area. The mean registration error for each image was <1 pixel and in both cases 10 ground control points were used.

Landsat TM and MSS Image Clustering

The aim of the image classification was to isolate as many spectral signatures of water within an image as was possible within the limitations of system noise. For this reason, an unsupervised clustering algorithm was selected rather than a supervised technique because 1) it would have been difficult to isolate all spectrally unique signatures using a standard training site selection process and 2) using the unsupervised approach it was possible to define program controls that were consistent from one image type to the next.

The image classification algorithm, CLUSTER, was developed by ERDAS, Inc. and is based upon a program formulated by NASA/ Johnson Space Center as part of the ASTEP software package (ERDAS Image Processing and Geographic Information System User's Guide, 1983). CLUSTER is a two-pass unsupervised classifier designed to group pixels of a multi-band image into N number of spectral classes, where N is a function of the input parameters and the variance in spectral signature throughout the scene. In the first pass, the operator defines the maximum number of classes allowed (M), the maximum cluster radius (R), and the minimum distance between cluster centroids (D). Both R and D are expressions of spectral distance in Euclidean P-space, where P is the number of bands within the imagery. The program considers each pixel in a sequential manner, starting at the upper left corner of the scene and progressing line-by-line to the lower right corner. Class mean vectors, generated in the first pass, are used in the second pass, wherein a minimum distance classifier is applied to the entire image.

One disadvantage to using an unsupervised classifier, such as CLUSTER, is the relatively small amount of control that the operator has over the program. Because image classification is a function of the input parameters, the operator must have some prior knowledge of the scene variance in order to select reasonable values of R, D, and M. In this work, it is also necessary to standardize the selection of input values in order to provide a basis for comparison between the classified MSS and TM imagery.

As an image is constructed either the MSS or the TM scanner, system noise is introduced, primarily as a result of differences in detector degradation, voltage fluctuations, and round off error in the quantization process. The effect of this noise is to limit the ability of the sensor to detect more subtle variations in scene radiance than would normally be detected if the image were noise-free.

The maximum cluster radius and minimum distance between clusters were defined as functions of the apparent system noise;

$$R = V_s \qquad (1)$$

and

$$D = 2R, \qquad (2)$$

where V_s^2 is the total variance in count values as a result of system noise. The system noise variance may be estimated for each image band by calculating V^2, the observed variance in count values within a homogeneous region of the image. If the region is homogeneous and encompasses a large number of pixels, then V^2 will approximate V_s^2. Within the MSS and TM images, optically deep water appeared to be most homogeneous. Geographically similar deep water areas were selected within each image for the estimate of V_s^2. Within the MSS image the area comprised 20 pixels while 90 TM pixels were included. Using the V_s^2 estimates, R^s and D were computed for the MSS and TM images (Table 2).

Table 2.

Maximum Cluster Radius (R) and Minimum Distance Between Cluster Centroids (D) Used To Classify The MSS and TM Imagery (Values Expressed in Units of Digital Counts)

	MSS	TM
R	.580	.903
D	1.160	1.806

For each classification, M=50, the maximum number of classes that CLUSTER can create. However, classification error can occur when, during the execution of CLUSTER, the actual number of classes created equals the maximum number allowed, N=M. This will generally result in an overflow of classes because new clusters may not be created until two or more of the existing clusters are aggregated. Class overflow is most likely to occur when the selected values of R and D are small relative to the variation in count values throughout the scene. Within the MSS and TM scenes the majority of scene variation occurs within land areas. Therefore, prior to running the classifier, all land areas within both images were masked using an IR band -- MSS band 4 (800-1100 nm) and TM band 4 (770-900 nm). This forced the classifier to assign just 1 class to land and allow as many as 49 water classes to be created. The actual number of water classes created by CLUSTER within the MSS image was 45, while 41 were created within the TM image.

Calculation of Confidence And Accuracy

The classified MSS and TM images were compared pixel-by-pixel with the respective SAV ground truth maps of the Guinea Marsh area. For each class, measures of confidence (C) and accuracy (A) were computed in relation to each SAV crown cover category as

$$C = \frac{\#\ \text{Correctly Classified Pixels}}{\#\ \text{Class Pixels}} \times 100, \quad (3)$$

$$A = \frac{\#\ \text{Correctly Classified Pixels}}{\#\ \text{SAV Map Pixels}} \times 100. \quad (4)$$

where "#" reads "the number of". Within each MSS or TM class, a pixel is correctly classified if it maps to a specified class of SAV pixel within the respective ground truth image.

The confidence measure indicates how specific a particular class is to a given SAV density. It is the percentage of correctly classified pixels within an MSS or TM class generated by CLUSTER. For example, suppose that of the 49 water classes generated within the MSS imagery, C = 100 for class number 5 when compared to the SAV 4 category within the ground truth map. In this case, one can be quite sure (confident) that the spectral signature associated with MSS class number 5 is unique to at least a portion of SAV 4 vegetation. Clearly, ones willingness to associate pixels of a specific class to a particular SAV density decreases as C goes to 0.

The accuracy measure, on the other hand, gauges the percentage of ground truth pixels of a specified SAV density represented by a particular class or aggregate of classes within the classified imagery. It is possible, continuing with the above example, that although MSS class number 5 resulted in C = 100, it in fact represents only a small portion of the SAV 4 vegetation. Ideally, the classifier should construct aggregates of classes for each ground type where the C- and A-values approach 100.

Class confidence and accuracy were initially computed for each MSS and TM class in relation to each of the four SAV crown cover categories without regard to geographic location -- all water areas were considered. Classes were then aggregated to form four confidence groups, 0-25, 25-50, 50-75, and 75-100, and group accuracies were computed as the sum of the associated class accuracies.

Next, all water areas deeper than 1.9 m (the 6 ft depth contour) were masked within the MSS and TM classifications using NOAA chart 12238 (published in 1979) which had been rasterized and registered to each image in a manner identical to the SAV ground truth quadrangles. A 60-meter grid was used to construct the MSS depth mask and a 28-meter grid was used to construct the TM depth mask. The registration accuracy between the classified imagery and the rasterized depth chart was <1 pixel, using a nearest neighbor resampling scheme and the same ground control points as discussed earlier. Finally, class group accuracies were recomputed using the depth-masked classifications.

RESULTS

Classification accuracies computed for all water areas indicated no significant differences between MSS and TM imagery for detecting SAV in the Guinea Marsh area (Table 3). Both data types performed poorly in identifying SAV 1, 3, and 4 vegetation densities. In the latter case, classification accuracies appeared to be higher within the 50-75 and 75-100 C-intervals, but the differences were too small to be considered significant.

There appeared to be moderate success in detecting SAV 2 vegetation. At first glance, this was a somewhat surprising result. Since there existed such a large contrast between dense SAV covers and bare substrate, classification accuracies associated with high C-values (>50) were expected to increase steadily with respect to SAV crown cover. To further investigate this result, all pixels associated with classes for which C > 50% were overlaid with the digitized depth imagery. Virtually all of the pixels in both the MSS and TM classifications mapped with extremely shallow water. Evidently, this particular combination of SAV crown cover and depth to canopy results in a unique spectral signature within both the MSS and the TM imagery.

Table 3.

LANDSAT MSS and TM Classification
Accuracies For All Water Areas

SAV Class	Sensor	-------Group Confidence Interval------ 0<C<50	25<C<50	50<C<75	75<C<100
1	MSS	97.3	2.7	0.0	0.0
	TM	100.0	0.0	0.0	0.0
2	MSS	76.2	8.3	15.5	0.0
	TM	72.1	17.5	9.2	1.2
3	MSS	92.4	7.6	0.0	0.0
	TM	100.0	0.0	0.0	0.0
4	MSS	96.7	1.8	1.0	0.5
	TM	98.5	1.2	0.1	0.2

When all water areas of depth 1.9 m were eliminated from the classification analysis, mapping accuracies within the 50-75 and 75-100 C-intervals were found to increase significantly for SAV 4 (Table 4). Within the MSS classification, A increased from 0.5 to 13.7 within the 75-100 C-interval. Within the TM classification, a similar increase occurred -- A increased from 0.2 to 19.7.

Table 4.

Landsat MSS and TM Classification
Accuracies For Water Areas Less
Than 1.9 m (6 ft Contour) Depth

SAV Class	Sensor	------Group Confidence Intervals----- 0<C<25	25<C<50	50<C<75	75<C<100
1	MSS	97.3	2.7	0.0	0.0
	TM	100.0	0.0	0.0	0.0
2	MSS	76.2	8.3	15.5	0.0
	TM	72.1	17.5	9.2	1.2
3	MSS	82.9	17.1	0.0	0.0
	TM	99.9	0.1	0.0	0.0
4	MSS	55.9	15.7	15.1	13.3
	TM	53.6	16.7	10.0	19.7

Accuracy associated with SAV 1, 2, and 3 remained unchanged from C > 50. This indicates that within both the MSS and TM imagery, SAV of dense crown cover is spectrally similar to optically deep water. As the SAV crown cover decreases, the increased reflectance from the substrate renders the canopy reflectance spectra dissimilar to the reflectance spectra of optically deep water and the classifier is unable to distinguish between the two. Also, by masking deep water areas, confusion between dense SAV and optically deep water is eliminated and classification accuracies associated with high confidence levels may be increased.

DISCUSSION

The volume reflectance from a submerged plant canopy may be divided into 3 components -- light which is reflected from the water column, light reflected from the plant material, and light which is reflected from the underlying substrate. For a dense canopy in shallow water, the vegetation component dominates the volume reflectance. As the canopy density decreases, the substrate component increases. As the canopy depth increases, the water signal increases to the point where it dominates within optically deep water. Within the Guinea Marsh area the situation is complicated by the fact that, within the MSS and TM bands, SAV reflectance is similar to optically deep water. In other words, increasing the depth of a sparse canopy or even bare substrate may have the same effect within the MSS and TM bands as increasing the SAV crown cover within shallow water.

The situation may be illustrated with a single-scattering volume reflectance model (Philpot, 1981) of the form

$$R = S\,[R_w(1 - e^{-Kd}) + (VR_v + (1-A)R_s)e^{-Kd}] \quad (5)$$

where R is the volume reflectance of a water column as measured immediately above the surface, S accounts for all air-water interface effects, R_w is the in-water volume reflectance of an optically deep water column, K is a single-scattering diffuse attenuation coefficient, d is water depth, R_v is the in-water volume reflectance of SAV, V is the percentage of substrate covered by SAV, and R_s is the substrate reflectance. Using equation (5), volume reflectance may be calculated for a variety of SAV densities, where canopy depth is varied from d=0 to some value representing an optically deep water column in this case 20 m (Figure 2). The values selected for these computations are

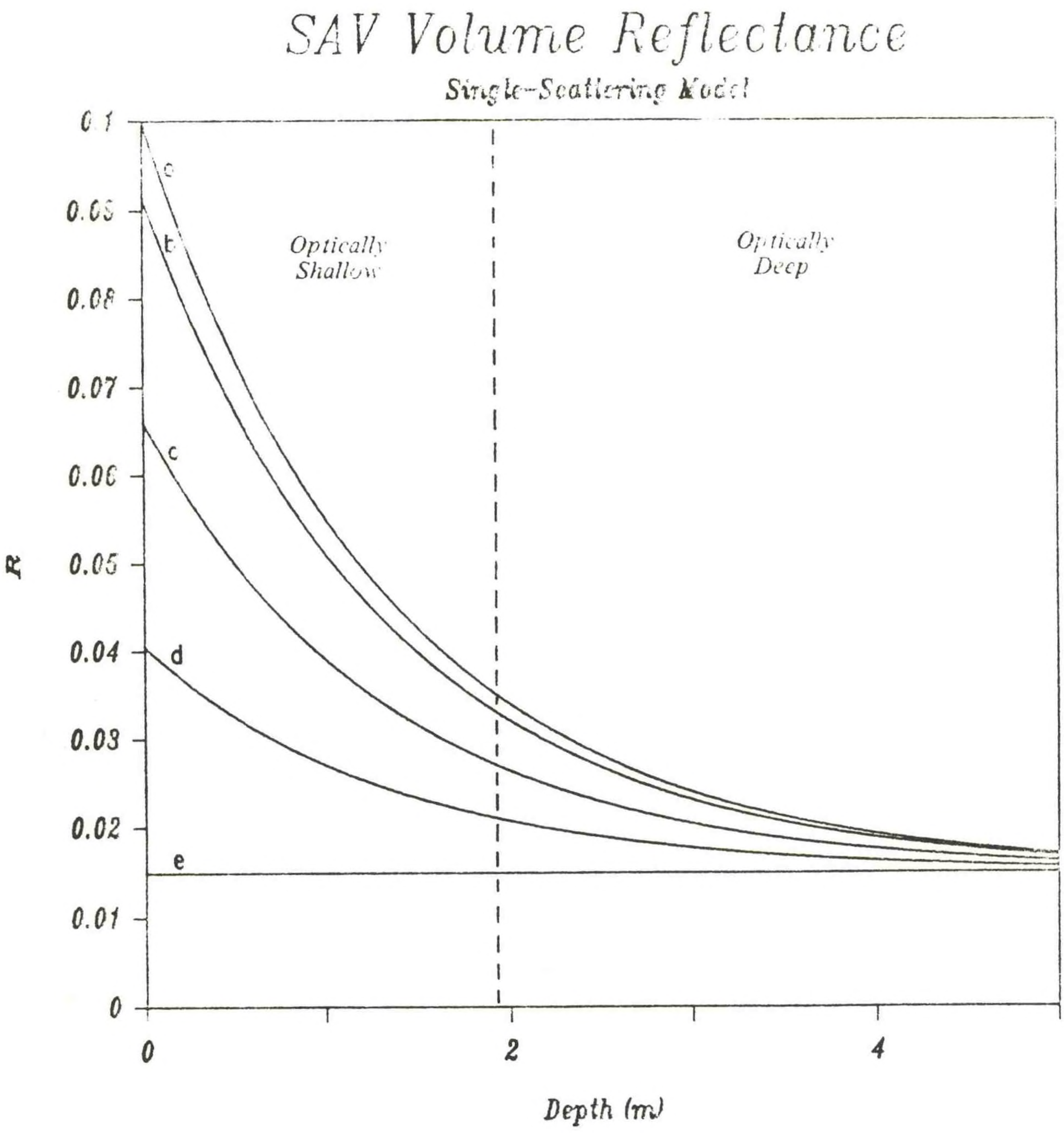

Figure 2: Volume reflectance of a water column containing SAV; a = bare substrate, b = 10% crown cover, c = 40% crown cover, d= 70% crown cover, and e = 100% crown cover. The vertical dashed line represents a depth of 6 ft., depths greater than which were masked within the classified MSS and TM imagery.

$$S = 1,$$
$$R_W = 0.03,$$
$$K = 0.75,$$
$$R_V = 0.03,$$
$$V = 0, .1, .4, .7, 1.0,$$
$$R_S = 0.2$$

This set of values is within the range of variability reported for the Guinea Marsh area (Wetzel, 1983; Van Tine and Wetzel, 1983; Ackleson, 1985) and is believed to be typical of Lower Chesapeake Bay where the substrate is composed of bright sand. To illustrate the difficulty in discriminating between dense SAV and optically deep water, R_V is set equal to R_W. The model results indicate that when the water depth is shallow the effect of canopy density upon volume reflectance is large. (This is based upon the assumption that the substrate reflectance is much different than the SAV reflectance.) As depth increases, the water column begins to dominate the volume reflectance until all curves converge to a single value representing optically deep water. It should also be noticed that because dense SAV canopies appear similar to optically deep water, the effect of water depth upon volume reflectance within these areas is small. The greater the difference between SAV-substrate reflectance and optically deep water, the greater the effect that depth will have upon volume reflectance.

The model also indicates that one way to increase mapping accuracies associated with high confidence is to include depth information within the classification routine. For the Guinea Marsh images, by masking all water areas greater than 1.9 m the possibility of confusing SAV with optically deep water is eliminated. Prior to masking deep water areas within the MSS and TM classifications, SAV 4 was mapped within the 50-100 C-interval with accuracies with A = 1.5 and 0.3, respectively. After masking accuracies increased to 28.4 and 29.7, respectively.

As SAV crown cover decreases, the probability of confusion with other canopy densities at different depths, including bare substrate, increases. Also, because the sandy substrate is much brighter than optically deep water, it is unlikely that the combination of sparse crown cover SAV and shallow water depth will be confused with optically deep water.

Finally, the model simulations indicate that classification accuracies should be expected to increase with the detail of depth information used within the classification routine. The fact that pixels classified with high confidence for SAV 2 correlate with bright areas within the unclassified imagery indicates that the classifier is not only identifying SAV of relatively low density, but that the vegetation is occupying a specific depth -- in this case, shallow water. This same result, however, would be difficult to achieve for all combinations of SAV density and canopy depth without depth information of significantly greater detail than was used here.

Using the MSS and TM classifications, confidence maps may be created for any of the four SAV categories by encoding pixels within each class according to the computed class confidence. Here, we present such maps for SAV 4 (Figures 3 and 4 representing MSS and TM classifications, respectively). Within each confidence map, two water classes are formed; pixels for which C > 50 and all others. A comparison of these maps indicates that both sensor systems perform similarly in terms of both the area and distribution of SAV detected. Within the MSS image, 98.97 hectares of SAV were classified with C > 50, while for the same confidence range within the TM image, 105.29 hectares of SAV were classified.

What is also interesting within the SAV 4 confidence maps is the similarity in the area and distribution of misclassified SAV pixels (pixels belonging to classes where C > 50 yet do not map to SAV 4). These occur in two specific geographic locations -- adjacent to the shoreline or in close proximity to the 1.9 m depth contour. Comparing the MSS and TM confidence maps with their ground truth map (Figure 5) shows that most of these misclassified pixels located adjacent to the shoreline map to other SAV types, particularly SAV 3 (Table 5). Within the TM classification, no misclassified SAV 4 pixels mapped to SAV 1 or SAV 2, while 3.76% mapped to SAV 3. A similar situation occurred within the MSS classification -- .86% mapped to SAV 1, no pixels mapped to SAV 2 and 3.54% mapped to SAV 3. Since the SAV survey represents spatially averaged crown cover density, it is possible that at least some of these "misclassified" pixels are actually small areas of dense SAV. Recall also that the photography used to create the ground truth images was obtained 28 days prior to the satellite overpass. Because the imagery was obtained during the height of the growing season, it is possible that areas of SAV 3 had increased in crown cover sufficiently to be characterized as SAV 4 in the 28 intervening days. The remaining misclassified pixels, those associated with the 1.9 m depth contour, are believed to represent areas of optically deep water that were not masked as such due to a combination of error associated with the digitization/rasterization/registration procedure applied to the NOAA chart and depth error within the NOAA chart.

MSS Confidence Map

70 - 100% SAV Crown Cover

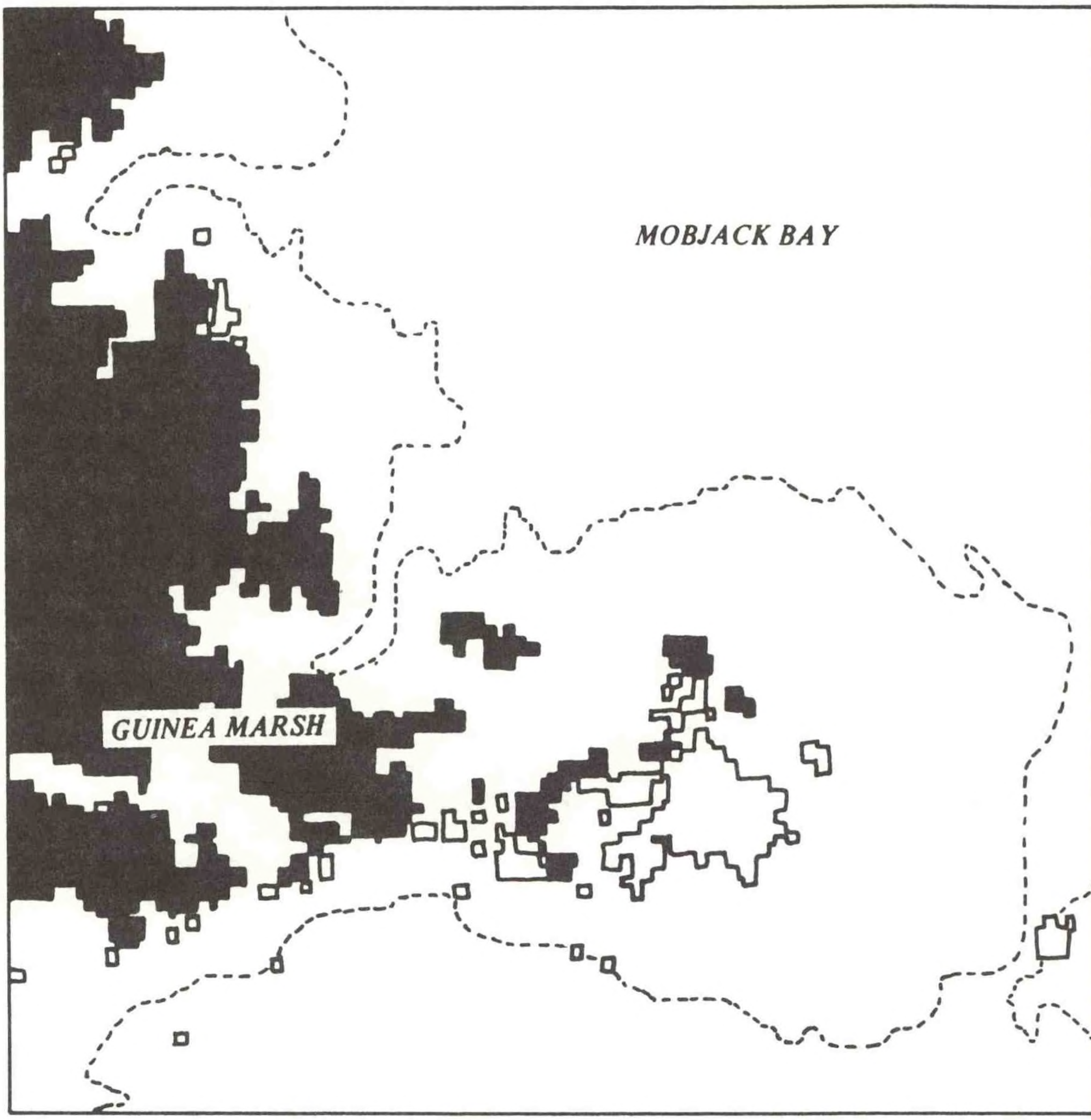

Figure 3: MSS confidence map of 70-100% crown cover SAV adjacent to the Guinea Marsh. Areas outlined with solid lines represent pixels classified with greater than 50% confidence, black areas indicate land, and the dashed line shows the 1.9m (6 ft.) depth contour.

TM Confidence Map

70 - 100% SAV Crown Cover

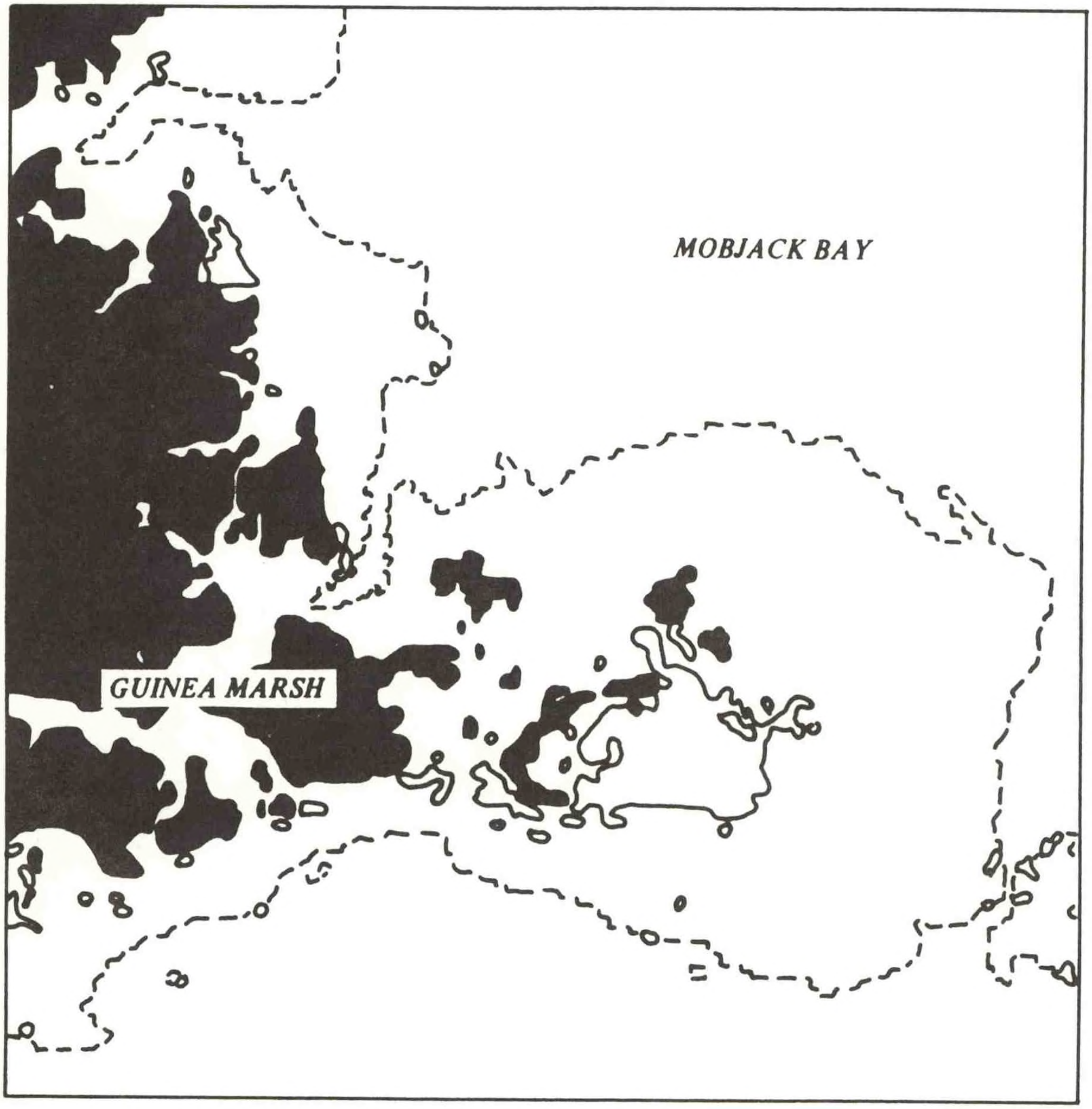

Figure 4: TM confidence map of 70-100% crown cover SAV adjacent to the Guinea Marsh. Areas outlined with solid lines represent pixels classified with greater than 50% confidence, black areas indicate land, and the dashed line marks the 1.9m (6 ft.) depth contour.

SAV Ground Truth Map

1984 VIMS SAV Survey

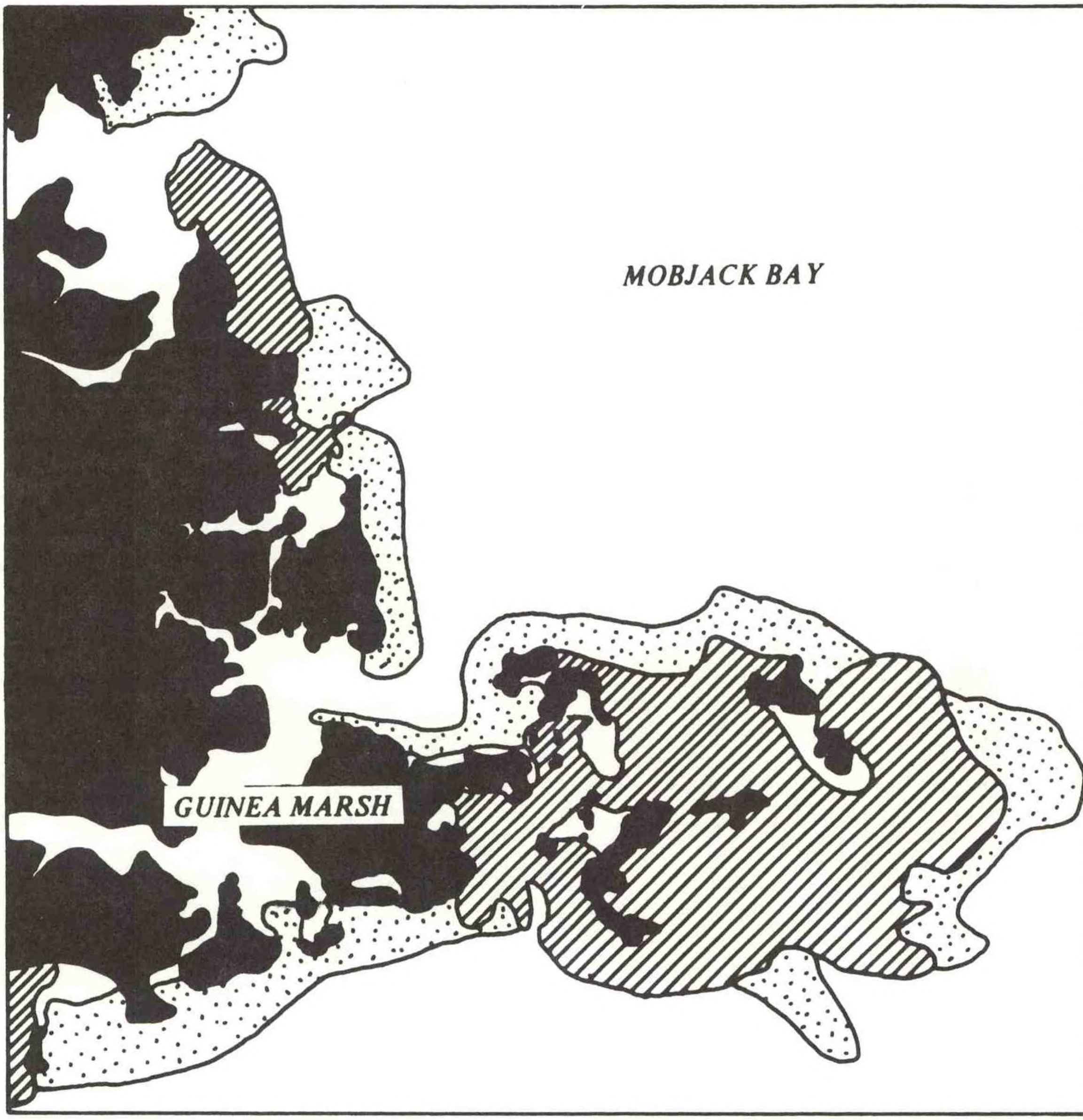

Figure 5: VIMS 1984 SAV survey of the Guinea Marsh area. Hatched areas indicate 70-100% crown cover SAV, dotted areas show SAV of less than 70% crown cover, and black areas are land.

Table 5.

SAV4 Percent Misclassification for all Classes Having C-Values Greater then 50 (Depth-Masked Classifications)

	SAV 1	SAV 2	SAV 3
MSS	.86	0	3.54
TM	0	0	3.76

CONCLUSIONS

LANDSAT MSS and TM imagery are similarly effective in detecting SAV within the Guinea Marsh area of Lower Chesapeake Bay. Increased radiometric sensitivity, greater spectral and spatial resolution, and the addition of a third visible band does not afford TM imagery a significant advantage over MSS data. However, the reader is cautioned about extending this conclusion to all possible SAV habitats. In cases where the SAV occupies a substrate having a spectral reflectance more closely resembling the submerged canopies, when the SAV forms smaller canopies, or when the volume reflectance characteristics of the water are much different than the submerged vegetation, the TM bands may offer an improvement over those of the MSS.

For both data types, classification accuracies associated with high confidence levels may be increased by merging depth information with the classified image. Within the Guinea Marsh area, classification confidence for SAV 4 was increased significantly by masking water areas of 1.9 m and greater. This conclusion is supported with a model simulation of volume reflectance from a water column containing SAV, where the optical characteristics of the water and SAV are similar to those found within the Lower Chesapeake Bay. In addition, the modeling results indicate that when the volume reflectance of SAV is similar to the volume reflectance of optically deep water, classification confidence for all SAV crown covers may be increased by increasing the detail of the bathymetric information.

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REMOTE SENSING APPLIED TO THE BENTHIC ENVIRONMENT

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ABSTRACT

A wide range of remote sensing techniques are available for obtaining information about surficial seafloor structures and processes. These include overflight imaging, subsea acoustic imaging, and subsea optical imaging. Overflight imaging, because of rapid attenuation of electromagnetic radiation in water, is limited to shallow, clear water areas. Nevertheless, aircraft and satellite imaging, using different spectral bands, may be used to relate sea surface temperature and chlorophyll concentrations to benthic secondary productivity and organic sedimentation.

At present, all deeper water applications require deployment of either acoustical or optical sensors from surface vessels. Subsea acoustics may involve single beam sonar units operating in the KHz or MHz range. These provide high resolution information about very small areas of the bottom. Multiple narrow beam or sidescan sonar can provide rapid coverage of large areas of the seafloor yielding panoramic views of surficial seafloor structures.

Subsea optical techniques employ either still or video cameras mounted on towed systems, in situ instrumented tripod or quadrapod systems, or Remotely Operated Vehicles (ROV) submersibles. All of these systems require relatively clear water conditions for obtaining high quality images. The sediment-profile camera or optical corer is the only optical system not adversely affected by turbidity. This system is routinely used to image the upper 20 cm of the sediment column to a resolution of about 60 micrometers.

The most successful application of the above techniques has been realized when both far-field and near-field imaging techniques have been combined. For example, deployment of sidescan sonar and high altitude still cameras, and a ROV for close-up inspection or sidescan and sediment-profile imaging.

INTRODUCTION

The term remote sensing is usually associated with overflight imaging using either conventional aircraft or satellites. Passive imaging systems, using the visible and infrared range of the electromagnetic field, are limited in use to relatively shallow water because of the adsorption and scattering properties of water. Attenuation may also be enhanced by suspended solids which are usually high in concentration in coastal waters. For this reason, overflight, approaches may have only limited application for clear-water shoal areas. Acquisition of information about the seafloor below the critical penetration depth (Figure 1) requires deployment of "remote sensing" instruments from vessels. I have therefore broadened the definition of remote sensing to include ship-deployed unmanned instruments that allow efficient collection of data by either acoustical or optical methods. I have focused this summary on imaging techniques which allow mapping of biological, geological, and geochemical properties of the seafloor with a high degree of resolution. Subbottom acoustic profiling is not covered in this review. It should be clear that all of the systems described in this paper require precision navigation so that the obtained records can be located accurately in x-y space. For towed systems, depth control between the bottom and the fish is also important.

OVERFLIGHT IMAGING

For purposes of benthic mapping, overflight imaging systems are currently limited to near shore environments where the water is relatively free of dense plankton and suspended sediment. If these conditions are met, overflight imaging using the visible or infrared spectrum can prove very efficient in delimiting the locations of shoals, channels, reefs, and dense stands of subtidal attached vegetation (SAV). This is accomplished by relating water depth to bottom reflectance (albido). Reflectance patterns are measured digitally with 256 grey scale resolution (Figure 1). In ideal cases, the grey-scale values are tied to contemporaneous ground-control so that actual depth values can be accurately correlated with grey-scale values. In practice, ground-control often does not exist and therefore imaged gradients in grey-scale values (the depth dependent component) is, at best, a relative measure of depth. Also, the precision of this technique suffers from the changing relationship between grey-scale values and water depth because of the hourly, daily, and seasonal changes in incident light intensity, incident light angle, adsorption and reflectance properties of the water column and benthic structures. Therefore, time-series overflight maps may be difficult to intercompare quantitatively. Nevertheless, this type of qualitative information may be sufficient for many mapping tasks. The application of overflight information for measuring SAV is discussed in detail by Ackleson (this volume) and so I will not duplicate his description here.

The application of satellite imaging to biological oceanography has largely been limited to the indirect measurement of sea surface temperature or chlorophyll. However, in the coastal

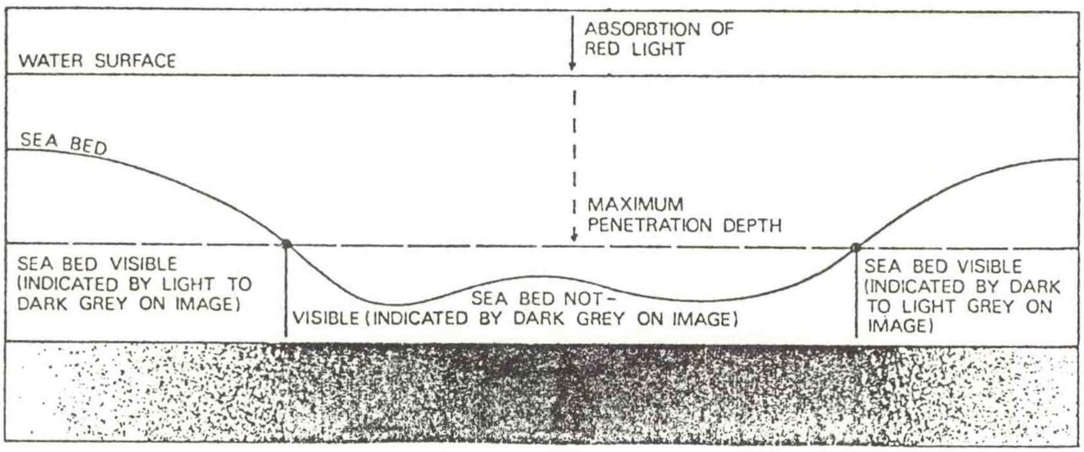

Figure 1. Depth of penetration of light into water and reflectance of incident light from bottom structures as measured by grey scale. From Bullard (1983)

zone, thermal imagery may be used to relate the distribution of invertebrate benthos to mesoscale oceanographic processes. Such an application has been made by Larsen (1985) in order to help explain three sharply demarcated benthic faunal facies recognized along a 300 km stretch of coastline in the Gulf of Maine. Three laterally contiguous benthic zones were observed to correspond closely to two thermally distinct unstratified water masses (Fundy and Jeffries Bank fronts) and a third area of stratified warm water. This synoptic zoogeographic approach lends itself particularly well to benthic investigations associated with upwelling or perideltaic nutrient fronts. Thermal imagery should be one of the basic data sets for any regional study of secondary benthic productivity or zoogeographical mapping.

SUBSEA ACOUSTICS

Downward-looking narrow beam sonar acoustic records from normal incident narrow beamwidth (6 degrees) instruments have long been used to deduce seafloor properties such as descriminating between "soft" and "hard" bottom types and "smooth" from "rough" topography. The resolution of these systems is set by the ratio of the scale of the mean surface roughness elements to the incident sound wavelength. By appropriate return signal processing, such data may be able to be correlated quantitatively with particle or bed roughness scales (Pace, 1978; Williams 1978). However, for large-scale mapping, the narrow beam width of conventional downward-looking sonar has obvious drawbacks unless coupled with larger coverage sonar. One such approach is the SWATH survey system which employs 21 acoustic beams, each 5 degrees wide, for a total swath coverage of 105 degrees. This 36 kHz system is designed to be used in depths up to 600 meters (Perry, 1982).

Narrow beam high frequency ultrasonic sonar, operating in the MHz range, has been used to study sediment resuspension, sediment transport, and suspensates (Flammer, 1962; Proni et al., 1976; Orr and Hess, 1978; Proni, et al. 1980; and Orr and Grant, 1982). Ultrasonic imaging, pioneered in the medical diagonostic field, appears to have promise for remote acoustic imaging of sedimentary fabrics and biological structures in the upper few centimeters of the seafloor (Orr and Rhoads, 1982). This technique deserves further work, especially in light of increased sophistication in signal processing of ultrasound records.

Because of the small areal coverage of orthogonal acoustic sounding, sidescan sonar was developed in the early 1960s to allow "panoramic" coverage of larger areas of the seafloor. Long range sidescan (i.e. >20 km) has subsequently appeared in two forms; one of these is the multibeam swath sounding technique (SEABEAM) which has a combined multibeam swath of 30 degrees from the vertical. This gives a continuous strip view of the seafloor which is roughly equal to the water depth and has a resolution of better than 10 meters (Laughton, 1981). The second approach involved the development of GLORIA (Geological Long Range Inclined Asdic), Mk I and Mk II (Sommers, et al. 1978). With the most recent scaled down version (Mk II), the operating frequency is in the range of 6.2-6.8 kHz with a 100 Hz pulse sweep frequency. Acoustic imaging may be done at three scales: 7, 15, and 30 km. Both the SEABEAM and GLORIA units may be operated at normal vessel speeds so that several hundred square kilometers can be covered each hour. The GLORIA mk II system is presently being used to efficiently map the U.S. continental shelf which lies within the newly established Exclusive Economic Zone (EEZ). These acoustic maps are useful for relating surficial structure and sedimentary facies to subsurface structure and gravity maps. Benthic processes may also be deduced from imaged structures such as slope slump scars and large-scale bedforms (Laughton, 1981). In one case, GLORIA was used to identify and follow the movement of a 5 km long herring shoal (Rusby, et al., 1973).

For shallow-water work, the much smaller and more manageable side-looking 30 to 750 kHz sonar units can be operated from small boats in lakes, rivers, and estuaries (Borot, 1982). Most of these units operate with a frequency of 100 to 200 kHz and are capable of imaging objects about 1 meter in size. Therefore this type of acoustic reconnaissance mapping is best applied to imaging local patches of hard or soft bottom,intermediate to large scale bed forms, disposal mounds, geological outcrops, surficial tectonic structures, bioherms, reefs, and deep vegetation (Menzie and Mariani, 1981). Such acoustic "facies" maps have proven useful in producing relatively cheap reconnaissance maps which help in efficiently locating ground control benthic sampling stations for biological, geological, or geochemical studies. The combination of sidescan and optical coring techniques can provide a wealth of remotely acquired data (see optical coring section).

Sidescan acoustic records obtained in this way have the potential for classifying bottom sediments from relative signal level variations (Pace 1982). As indicated earlier, long-range sidescan is presently being used by the USGS to map surficial geological structures within the EEZ. Short-range sidescan is routinely used to map structures associated with disposal sites in the New England Region (e.g. Lockwood and Gruntal, 1982).

SUBSEA CAMERA SYSTEMS

An excellent historical review of the use of deep-sea photography to acquire information about the seafloor is given in Hersey (1967). A recent book edited by Smith (1984) provides descriptions of systems which are state-of-the-art. These fall into three main operational categories: towed systems, in situ operations, and submersible photography. The most famous towed systems are the U.S. Navy's LIBEC (light behind the camera) system which pioneered the photographic mapping of the Mid-Atlantic ridge. This was followed by another unmanned towed system called ANGUS (Acoustically Navigated Geological Undersea Surveyor) which has been used to map the mid-Atlantic ridge and rift valley, and was instrumental in the discovery of the eastern Pacific hydrothermal vents. The ANGUS photographic system is often used together with a multi-narrow-beam sonar and a manned submersible (Ballard, 1984). Because these towed systems "fly" several meters off the seafloor, they are restricted to waters which have low concentrations of suspended solids. These are exclusively deep-sea systems. The development of deep-water towed systems continues to evolve. The most recent configuration has been developed at the Woods Hole Oceanographic Deep Submergence Laboratory. The towed search unit, called ARGO, consists of an acoustic system, low light level video cameras, and still cameras. When fully developed, the system will also carry a ROV called JASON for close inspection of objects of interest. ANGUS and JASON JR. (a prototype ROV) were successfully deployed at the TITANIC site this past year. Other types of towed camera systems are mounted on sleds or skis. Such systems are towed along the bottom and a continuous photographic or video record of the transect is obtained (Smith, 1984). Again, the success of this technique depends on relatively clear bottom water in order to obtain high quality images.

In situ operations involve instrumental tripod or quadrapod rigs which are deployed on the seafloor typically for several days to weeks. Downward-looking time-lapse camera(s) are mounted on the rigs as well as other sensors such as transmissometers, current meters, water samplers, and salinity-temperature probes. They may be programmed to sample at various frequencies depending on the phenomenona of interest. Such systems are excellent for obtaining a great deal of information about biological and physical processes active within the benthic boundary layer (Butman, et al, 1979; Caccione and Drake, 1979; Sternberg and Creager, 1965; Bohlen 1982; Wimbush and Mayer, 1984). Photographic success is again affected by near-bottom suspended load. However, these systems have the potential to be programmed to take photographs only when ambient turbidity (measured with transmissometers) is below a critical threshold value. To my knowledge, this option has not yet been engineered into existing systems.

Unmanned ROV submersibles may also provide important documentation about benthic habitats. The use of such vehicles has been largely limited to investigations of drilling platforms, submerged cables, and other structures or wrecks of historic interest. The application of ROVs to investigation of benthic processes appears to be in the near future because two workshops were held in October 1986 to explore the potential of this technology. One of these was held at MIT (Undersea Teleoperators and Intelligent Autonomous Vehicles) and the other at the University of Rhode Island (The Marine Research Community and Low-Cost ROVs and submersibles--Needs and Prospects).

All of the above optical systems are adversely affected by suspended solids or colloids which backscatter light. For this reason they are most successful when used in clear water environments such as the deep-sea or when deployed on stable sand or rock bottoms. The muddy bottoms of estuaries present a major problem for conventional bottom photography. Only one optical imaging system is unaffected by ambient turbidity -- the sediment-profile camera or optical corer. This camera system was designed to cut a vertical profile of the bottom and to photograph the upper 15 to 20 cm of the sediment column, including the sediment-water interface and overlying water and associated biology, (Rhoads and Germano, 1982). The reason that ambient turbidity does not affect image quality is that the camera and strobe "look" through a pressure compensated prism filled with either filtered or spring water. This system has an optical resolution of ca. 60 micrometers and the resulting images are processed by computer aided image analysis. Data on small-scale boundary roughness, major modal grain-size, depth of methane gas bubbles, depth of the apparent redox potential discontinuity (RPD), biological mixing depth, and other biological parameters are routinely mapped with this system. The optical corer may be used together with a sidescan sonar survey. The sidescan survey is run first to provide quick coverage of the area of interest. The resulting acoustic map is divided into acoustic "subfacies". The sediment-profile camera is then deployed at specific sites of interest to acquire the higher resolution data (Menzie, et al 1982). Figure 2A shows a sidescan record where several parallel linear elevations were observed with sidescan sonar. The question is asked are these active bedforms? Figure 2B is a cross-sectional sediment profile image of one of these linear features. This optical image shows them to consist of very fine sand mixed with mud, they appear to be symmetrical in cross-section, and they are covered with small tube-dwelling polychaetes. This information suggests that the structures, when imaged, were physically stable and not active.

CONCLUSIONS

Many remote sensing techniques exist for efficiently obtaining information about seafloor structures and processes. No single technique appears to be ideal for this purpose. The most successful applications use a combination of far-field imaging followed by near-field (higher resolution) imaging. Such examples are the combined used of ANGUS/JASON JR. for deep

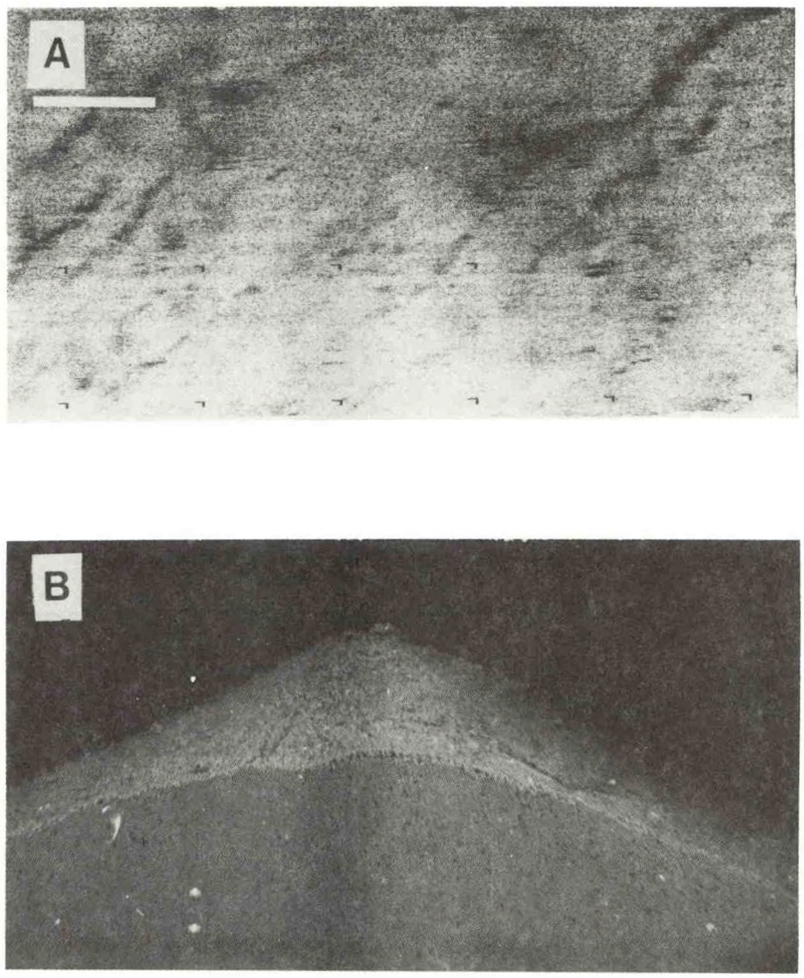

Figure 2. Example of combining far-field (sidescan sonar) and near-field (sediment profile optical imaging) remote techniques to obtain detailed information about benthic structures. A.) Sidescan record of a set of subparallel ridges on the seafloor. Bar scale equals 25 meters. B.) Sediment-profile image taken with a optical corer showing that the ridges are symmetrical in cross-section, consist of a major grain-size mode of 62 micrometers to 250 micrometers. The surface is covered with small tube-dwelling polychaetes indicating that the structures, when imaged, were physically stable. Width of profile image equals 7.5 cm. From Rhoads and Germano (1982).

water work or sidescan/sediment profile imaging in shallow water. These technologies are developing rapidly. Ground-truth sampling, using conventional samplers such as grabs or box cores, results in labor intensive and costly analysis. For this reason, it is important that such remote sensing techniques be used to their fullest to make such sampling efficient.

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REMOTE ACOUSTIC DOPPLER SENSING

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ABSTRACT

Remote Acoustic Doppler Sensing (RADS) is a generic term applied to sensors that use backscattered acoustic signals to infer oceanic processes. The Doppler shift of the backscattered acoustic signal is a result of the scatterers traveling at a velocity relative to the transmitter. The National Oceanic and Atmospheric Administration (NOAA) has explored this technology for the measurement of estuarine currents. This paper provides a discussion of the operating principle of RADS, NOAA's experience with RADS, and recommendations for consideration.

INTRODUCTION

The term "remote sensing" implies the ability to detect automatically from a large distance; it also implies that the detection process (in this case a measurement) will not create a disturbance or bias in the parameter measured. The "Doppler effect" states a change in frequency will occur from a given source of either light or sound when the receiver is in motion with respect to the source and that the frequency increases or decreases according to the speed at which the relative distance is increasing or decreasing. The Doppler principle has been exploited over the years in a variety of sensing systems using radar, sound, and laser technology for the detection of the speed of a variety of objects. Remote Acoustic Doppler Sensing (RADS) uses narrow beam high frequency acoustic pulses transmitted through water in which the particles (scatterers) entrained in the water column reflect part of the acoustic energy and shifts the frequency proportionately to the scatterers velocity with respect to the transmitter. This technique allows remote profiling of water velocity over distances approaching 500 meters depending on the particular system configuration and environment.

There are a variety of Doppler system configurations that have or are being developed to measure various oceanographic parameters. Commercial systems presently available have the capability of obtaining vertical profiles of horizontal currents with 1 meter depth resolution and acceptable data quality over 6 minute averaging intervals.

PRINCIPLE OF OPERATION

Commercial RADS technology uses an acoustic transducer which transmits sound pulses at a frequency typically in the range of from 75 KHz to 1.2 MHz depending on range and resolution requirements. The pulse of sound energy is a narrow beam of approximately 3 degrees which is partially scattered off acoustic targets in the water column as it propagates and some of its energy returns back toward the transducer. The transducer receives the returned energy which is then processed over discrete time periods (bins) which correspond to the returns from scanned, selected ranges from the transducer. The frequency of the returns from each bin are added randomly and the first moment of the spectrum is computed and assumed to be the Doppler-shifted frequency resulting from the scatterers moving along the beam axis. This frequency, which is the peak of the Doppler spectrum, represents an amplitude-weighted average velocity of the scatterers. Successive pulses are transmitted at a rate such that the scatterers have changed their relative position from the last pulse and are incoherent. This provides measurements which are statistically independent so that a number of pulses can be averaged to improve the statistical confidence of the velocity estimate.

The major assumption is that the scatterers are coupled with the water and their velocity is accurately represented by the first moment of the spectra. A second consideration is that the velocity estimate is made from a volume of scatterers that increases with range; the acoustic beam spreads at a ratio of range to beam width of approximately 100 to 5. At a range of 10 meters from the transducer and a bin width that allows 1 meter range resolution, the volume is 0.5 cubic meters or a cyclinder of 1 meter length and 0.5 meter in diameter; at 20 meters from the transducer the volume has doubled to 1 cubic meter. The maximum range of the system is dependent on the attenuation of the acoustic signals which is related to the frequency used, the amount of scatterers in the water column and the ability of the processing electronics to interpret a useful signal above the ambient noise level.

In order to obtain a measure of the horizontal component of current velocity it requires the arrangement of multiple beams to yield a resultant vector. A Janus configuration is used in which four beams are mutually orthogonal and at an angle to each other; typical beam angles from the source are from 15 to 30 degrees. Each beam yields a radial measure of velocity and opposing beam velocities are combined to determine the horizontal velocity component. Simple trigonometry resolves the vectors into either north and east components or speed and direction, as with conventional systems. An important consideration is that the Janus configuration results in a spreading in the measurement volume with range; in a 30 degree system the volume spreads at 1.15 times the range. As an example, at 10 meters from the transducer the beam spread or measurement volume is 11.5 meters. This requires spatial homogeneity of the current over these distances to assure accurate interpretation of the current velocity field.

The system internally controls and processes the signals and the resultant data stream provides the horizontal velocity magnitude for each beam/bin combination plus a series of diagnostic data including a measure of the backscattered signal strength over some pre-selected averaging interval. In a typical system, the user can optimize system operation in software by such means as adjustment of transmit and receive pulse length. The transmit frequency of the transducer should be selected based on the range and vertical resolution required; the lower the frequency the greater the range and coarser the range resolution.

MANUFACTURERS

There are two major manufacturers of RADS systems for current measurement applications in the United States. AMETEK Straza Division was the first manufacturer to develop systems as an offshoot of their shipboard Doppler speed logs. The first applications were applied to ships in an effort to measure currents while underway from research vessels. RD Instruments began to develop self contained RADS systems for use in bottom mounted applications and later developed their own shipboard systems. At the present time there are numerous RADS models available for various applications. There are several foreign manufacturers, the best known being Thompson CSF, a French firm that developed some of the first RADS systems. In addition, many academic institutions and government agencies are experimenting with the technology using different processing techniques, transducers, and beam configurations.

FIELD EXPERIENCE

NOAA has been involved with RADS technology for over a decade. In the past few years, several commercial systems have been evaluated and used by NOAA program activities. The first two systems were acquired from AMETEK, one a shipboard 115 KHz unit and the other a 300 KHz system that was reconfigured by NOAA engineers to operate from a bottom mounted platform and provided data to Rockville, Maryland, in real time. Tests of the shipboard system were encouraging and several comparisons were made to current measurements made with more conventional systems (Mero, Appell & Porter, 1983). The comparisons provided sufficient confidence in the RADS ability to measure currents that the NOAA research laboratories are now using the system routinely. Several other shipboard systems are now being used within the NOAA research fleet.

Shipboard systems are less useful in estuaries, where tidal and other time-varying currents require a long time series of data at a given location; also, the draft of the vessel limits the useful profiling range with hull mounted transducers. In shallow water estuaries NOAA has been using fixed location, bottom mounted RADS systems. The 300 KHz system was tested in the Chesapeake Bay in August of 1982 in preparation for a long term deployment of the system at Ambrose Light Tower at the entrance to New York harbor. These tests in the Bay were conducted over a 3-day time period and provided comparison with conventional current meters as well as measurements of the biological and physical properties of the water column. The flow field was dominated by tidal currents of approximately 40 cm/s magnitude. From this experiment it was concluded that 30 minute averages of the RADS data had a 95 percent confidence of better than 12.5 cm/s and 3 day average data had a 95 percent confidence of better than 2.5 cm/s (Mero, Appell & Porter, 1983).

The AMETEK system was deployed at Ambrose Light in August of 1983 where it provided real time current profiles for a period of 3 months. During that time a sea truth experiment was conducted from October 19 through November 8, 1983, with conventional current meters at various locations on several subsurface moorings. Tidal currents of from 10 to 15 cm/s amplitude were found to dominate the current field. The RADS and the intercomparison instruments reproduced the basic features of the mean and low-frequency flow field to within about 1.5 cm/s; mean direction differences were typically 5 to 10 degrees. All of the instruments produced comparable measurements of the tidal constituents to within 1 cm/s. The six minute averages from RADS contained a relatively high "noise" level of about 4.6 cm/s root mean square (RMS) compared with 2.3 cm/s on the other current meters in the same frequency band (Magnell, 1984).

The AMETEK RADS systems was redeployed in the Government Cut shipping channel in the entrance to the Port of Miami in December of 1984, and continued to operate at this location until mid 1986. In January 1985, intercomparison measurements were made for a period of 4 days with an RD Instruments 1.2 MHz RADS system, a VMCM current meter, and surface drifters. These tests were aimed at obtaining performance characteristics in the near surface bins. Tidal currents were predominant with amplitudes of up to 140 cm/s. Comparisons with the drifters and the RD RADS indicated six minute averages of RADS current magnitudes were 15 to 20 cm/s lower than the drifters; the AMETEK was 25 to 30 cm/s lower. At the mid-depth level, comparison to the VMCM indicated the RD was on average 2.5 cm/s lower than the VMCM and the AMETEK was 11 cm/s lower. These tests pointed out the hazards of intercomparisons in which the flow regimes within the intercomparison site are non-homogeneous and provide misleading results; it was concluded that this was the cause of wide discrepancies. The AMETEK system required the use of a side lobe deflector to obtain measurements in the near surface bins; this apparatus is described in Appell, et al, (1985). The deflector prevents acoustic beam side lobe energy from scattering off the surface and returning to the receiver which is then averaged with the current signal as a zero Doppler shift. The RD acoustic beam side lobe energy is sufficiently reduced from the main beam as to not effect the near surface measurement.

An RD Instruments 1.2 MHz system was deployed in Delaware Bay in August of 1984 and remained until the spring of 1986. In October of 1985 an extensive intercomparison experiment was conducted to define the performance characteristics of the RD system in comparison to the conventional methods. Intercomparison instruments consisted of two NBIS Smart Acoustic Current Meters (SACM), two EG&G Sea Link Vector Measuring Current Meters (VMCM), one Marsh-McBirney Model 585 electromagnetic current meters, three Grundy currents meters, and three Anaderaa current meters. Data was collected over a three week period and intercomparisons conducted at three depth levels; data were averaged to a common 15 minute time base. The 95% confidence limits on the RD system 15-minute averages when compared to the other systems was approximately 8 cm/s; this is generally comparable to the other vector averaging instruments. Systematic, tide-synchronized direction offsets on the RD system of 10 degrees clockwise on the ebb phase were noted. In comparison at tidal frequencies, the M2 tidal constituent of the RD and VMCM's agreed within 3 cm/s.

DISCUSSION

The field experiences with RADS systems have been very encouraging with a great deal of information being extracted from several field intercomparisons. These intercomparisons have been restricted to the particular environmental conditions of the test site and levels where other instruments were placed; the representativeness of the performance characteristics of RADS under all conditions can only be interpolated with caution. Most of the field intercomparison data has been acquired in the mid-depth ranges and the performance figures referenced in the previous section reflect that unless otherwise stated.

The system used in the aforementioned estuarine applications were or are all operated in a bottom mounted upward looking configuration in a real time mode. In Miami, the system is hard wired to a shore station via a 300 meter electrical cable and provides real time displays of past, present, and predicted currents with various optional formats. Remote station software is also available that allows the system to be interrogated via a dial-up phone line and similar data display obtained. In Delaware, the underwater RD RADS is hard wired to Brandywine Shoal Light Station and data is transmitted via ultra high frequency (UHF) radio to a shore station in Lewes, Delaware. A dedicated phone line provides real time data to NOAA personnel in Rockville, Maryland.

RADS units can be deployed in various system design configurations depending on the requirements for measurements and data. The RD systems can be used in a self-contained mode recording data internally on magnetic tape as was the case in the Miami intercomparison. NOAA is considering a system configuration that allows the RADS unit to be hard wired to a surface buoy that retransmits data to a shore station. This would allow the RADS to be located in the center of a shipping channel and the buoy located out of the channel; this would provide portability to the system and collection of real time data.

There are many benefits of RADS systems over conventional technology. Remote profiles of currents can be obtained over ranges approaching 500 meters without disturbing the water column or having to deploy moorings. The cost benefit of obtaining this high density of measurements compared to the deployment of multiple numbers of current meters on a mooring is substantial. The systems have also proved to be reliable over periods of one year of continuous unattended operation in a shallow water estuary, being immune to fouling and flotsam contamination.

There are also drawbacks to RADS technology. They have a high initial sensor procurement cost of $55K to $60K and the entire system, if operating in real time can be over $100K. They present unique considerations in system design, and deployment and retrieval operations requiring that the beam orientation remain stable with time. They also present a data quality problem in that it is impractical to calibrate them in a tow basin or flume and compare to a standard as with conventional technology. The beam spreading presents a diverging volumetric measurement as opposed to a point source when using a standard Eularian current meter. The physics of the scattering process itself and the relationship of the scatterers velocity and mean stream velocity are not well understood.

RECOMMENDATIONS

The evaluations that have been performed to date indicate that the RADS technology has application in the measurement of estuarine currents. Although the technology may yet be in its infancy, it has been shown that these systems can now be applied to measurement programs. However, the application of RADS technology into measurement programs requires an extra degree of caution to verify the quality of measurements. In particular, the near surface bins are questionable as to what they are measuring and the degree of contamination by the acoustic beam side lobes (Appell, et al 1985). The spatial homogeneity of the environment is critical in view of the beam separation, which in estuaries becomes important when considering the time and space scales of turbulence.

Continued RADS system development, test, and evaluation should be encouraged to obtain the maximum benefits and understanding of the measurement process. In particular, the near surface bins offer the opportunity to make current measurements directly to the surface and it is strongly recommended that research into the near surface measurement continue. Backscattered signal intensity offers information on the environment that has not been fully explored and requires further investigation. It is recommended that information on RADS be shared within the community to avoid duplication of expensive tests and collection of erroneous data. One method of information exchange is through Omnet, Inc., which has an acoustic Doppler mail box on its telemail service for exchange of information. The Current Measurement Technology Committee of the Oceanic Engineering Society of IEEE sponsors conferences on RADS technology and provides information in the society newsletter.

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APPENDIX A

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Panel on Remote Sensing of Water Column Properties

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D. Parsons
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R. Stumpf
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Panel on Physical Processes and Estuarine Dynamics

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Panel on Remote Sensing of the Benthic Environment

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APPENDIX B

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