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Monitoring the Coastal Environment; Part I: Waves and Currents

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ABSTRACT

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Measurement waves and currents in the high-energy, hazardous nearshore zone is one of the more challenging endeavors of coastal engineering and research. A measurement program must be thoroughly planned *before* any gauges are deployed to insure that useful data are collected: (1) Determine what data units and analyzed products are needed to answer the critical engineering or scientific questions at the site. (2) Determine how long the gauges must be at the site (*i.e.*, several years or just during the winter season?). (3) Consider placing gauges in locations that are compatible with previous measurement programs. (4) Evaluate environmental constraints such as ice or trawler activity. (5) Be sure that enough funding is allocated for the analysis of the data.

Two general types of wave gauges are commonly used: non-directional and directional. Despite the greater cost and complexity, the latter is preferred for most projects because of the need to evaluate wave refraction at the coast. Meticulous quality control is critical for all wave measurement programs!

Three general classes of current measuring technology are used in coastal projects: (1) Radar and Lagrangian methods (dye and drogues); (2) Point source (Eulerian) technology such as ducted impeller instruments; (3) Acoustic Doppler Current Profilers.

As gauges are improved, massive amounts of data are being collected at field projects. Clear, simple, and concise display of wave and current data are important aspects of the analysis procedure.

ADDITIONAL INDEX WORDS: *Current meters, coastal currents, sea state parameters, water levels, PUV wave gauge, seismic wave gauge, wave statistics.*

INTRODUCTION

This paper is the first in a series of four describing practical procedures for monitoring coastal processes and collecting geologic, sedimentary, hydrographic, and hydraulic data in the coastal zone. The companion papers in this series include:

- "Monitoring the Coastal Environment; Part II: Sediment Sampling and Geotechnical Methods"
- ". . .Part III: Geophysical and Research Methods"
- ". . .Part IV: Mapping, Shoreline Changes, and Bathymetric Analysis"

The procedures, hints, examples, and warnings contained in these papers are based on the authors' experiences at field projects throughout the United States and abroad while employed at the U.S. Army Corps of Engineers (USACE) Waterways Experiment Station and in private industry. Some of this material has been adapted from Corps of Engineers Engineer Manuals, in particular "Coastal Geology" (HEADQUARTERS, USACE, 1995).[1]

These papers cover a large amount of material and have ambitious goals. We recognize the danger of that they may appear to be a grab-bag of this and that and may contain too broad coverage. There is always the danger that practitioners in a particular field will consider the coverage of their specialty too trivial, while those uninterested in that topic will consider the coverage lengthy and boring. We have tried to bring together useful tables and definitions from diverse sources, and, where appropriate, have noted standard usage of terms. We trust that readers will be able to extract the material they need for their particular projects and refer to the reference lists for more detailed information, especially with regards to background mathematics and details on us-

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[1] U.S Army Corps of Engineers Engineer Manuals cover a broad range of engineering and technical topics. Single copies are available on written request from the USACE Publications Depot, 2803 52nd Avenue, Hyattsville, MD 20781-1102. Some manuals have been issued on CD-ROM and can be examined in libraries at Federal facilities.

age. Some of the citations are of a review nature and contain long bibliographies.

The intended audience of these papers is engineers, geologists, oceanographers, and managers who need to become more familiar with the many unique and challenging problems posed by the dynamic and intricate interplay of land, sea, and air that occurs at the coast. "Coastal zone" is loosely defined as the region between the edge of the continental shelf and the landward limit of storm wave activity. The definition is applicable to the edge of oceans, lakes, reservoirs and estuaries—effectively any shore that is influenced by waves. For those with extensive coastal practice, we hope that these papers will provide review material and suitable references to enable them to address more challenging projects. We welcome correspondence from readers.

As with any attempt to review complex subjects, omissions may be more significant to some readers than are the inclusions, and for this we apologize. Because of time and space limitations, we cannot explore all topics related to monitoring and measuring in the coastal zone. We acknowledge that biological sampling and the measurement of chemical properties are conspicuously lacking. We have not covered atmospheric measurements, despite the obvious importance of wind in the formation of surface gravity waves and the transport of sand on unvegetated barriers (see HSU (1988) for an introduction to coastal meteorology and BAGNOLD (1941) for a classic treatise on the formation of dunes). Finally, geotechnical aspects of coastal engineering, such as the choice and use of rock as a building material or calculation of underwater slope stability, are not covered here. ECKERT and CALLENDER (1987) summarize geotechnical engineering in the coastal zone. Use of rock in coastal and shoreline engineering is extensively covered in CONSTRUCTION INDUSTRY RESEARCH AND INFORMATION ASSOCIATION (1991) and HEADQUARTERS, USACE (1990).

WAVE MEASUREMENTS

Value of Wave Measurements

Sea surface water waves (sometimes called *gravity waves*) are the dominant force driving littoral processes on open coasts[2]. The following quotes from the *Shore Protection Manual* (U.S ARMY CORPS OF ENGINEERS, 1984)[3] underscore the significance of waves in the coastal zone:

> Waves are the major factor in determining the geometry and composition of beaches and significantly influence the planning and design of harbors, waterways, shore protection measures, coastal structures, and other coastal works. Surface waves generally derive their energy from the winds. A significant amount of this wave energy is finally dissipated in the nearshore region and on the beaches.
>
> Waves provide an important energy source for forming beaches; sorting bottom sediments on the shoreface; transporting bottom materials onshore, offshore, and alongshore; and for causing many of the forces to which coastal structures are subjected. An adequate understanding of the fundamental physical processes in surface wave generation and propagation must precede any attempt to understand complex water motion in the nearshore areas of large bodies of water. Consequently, an understanding of the mechanics of wave motion is essential in the planning and design of coastal works.

Energy in the nearshore zone occurs over a broad band of frequencies, of which gravity waves occupy the range from about 1 to 30 sec (Figure 1). Waves generated by local winds, known as seas, often have periods shorter than 5 or 6 sec, but can have periods greater than 10 sec in extreme cases. Waves that have traveled out of their generating area are known as *swell.* Swell waves are more regular and have longer period than locally-generated waves. Waves create currents, which move sediment both onshore and offshore as well as parallel to the coast by means of longshore currents.

Wave climate generally changes seasonally, thus resulting in regular adjustment of the beach profile. Along many coasts, the more severe wave climate of winter causes erosion of the shore. The eroded material is usually transported to the upper shoreface, where it forms submarine bars. Then, with the return of milder conditions in the summer months, the sand returns to the beach (BASCOM, 1964). In many other areas of the world, a seasonal pattern is less distinct, and beach erosion occurs during storms throughout the year, followed by mild weather periods of rebuilding.

Because of space limitations, a comprehensive discussion of waves is not possible in this paper. BASCOM'S (1964) *Waves and Beaches* is a readable and interesting general introduction to the subject of waves and coastal processes. Actual water-wave phenomena are complex and difficult to describe mathematically because of nonlinearities, three-dimensional characteristics, and random processes. As a result, much analysis work is based on the simplest theory, referred to as small-amplitude or linear wave theory (AIRY 1845). Concise overviews of water wave mechanics are presented in HEADQUARTERS, USACE (1992), KNAUSS (1978), and LEENKNECHT, SZUWALSKI, and SHERLOCK (1992); more detailed treatments are in KINSMAN (1965), HORIKAWA (1988), and LE MÉHAUTÉ (1976). Interpreting and applying wave and water level data are covered in HEADQUARTERS, USACE (1989).

Types of Wave Gauges

Wave gauges can be separated into two general groups: directional and non-directional. In general, directional gauges and gauge arrays are more expensive to build, deploy, and maintain than non-directional gauges. Nevertheless, for many applications, directional instruments are vital because the directional distribution of wave energy is an important parameter in many applications, such as sediment transport

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[2] Internal waves, also a form of gravity waves, can be found throughout a stratified fluid. Our knowledge of internal waves is fragmentary (Knauss, 1978), and we exclude further discussion in this paper.

[3] The U.S. Army Corps of Engineers' (1984) Shore Protection Manual can be purchased from the U.S. Government Printing Office. The SPM is scheduled to be replaced by an updated and greatly expanded Coastal Engineering Manual in 1999.

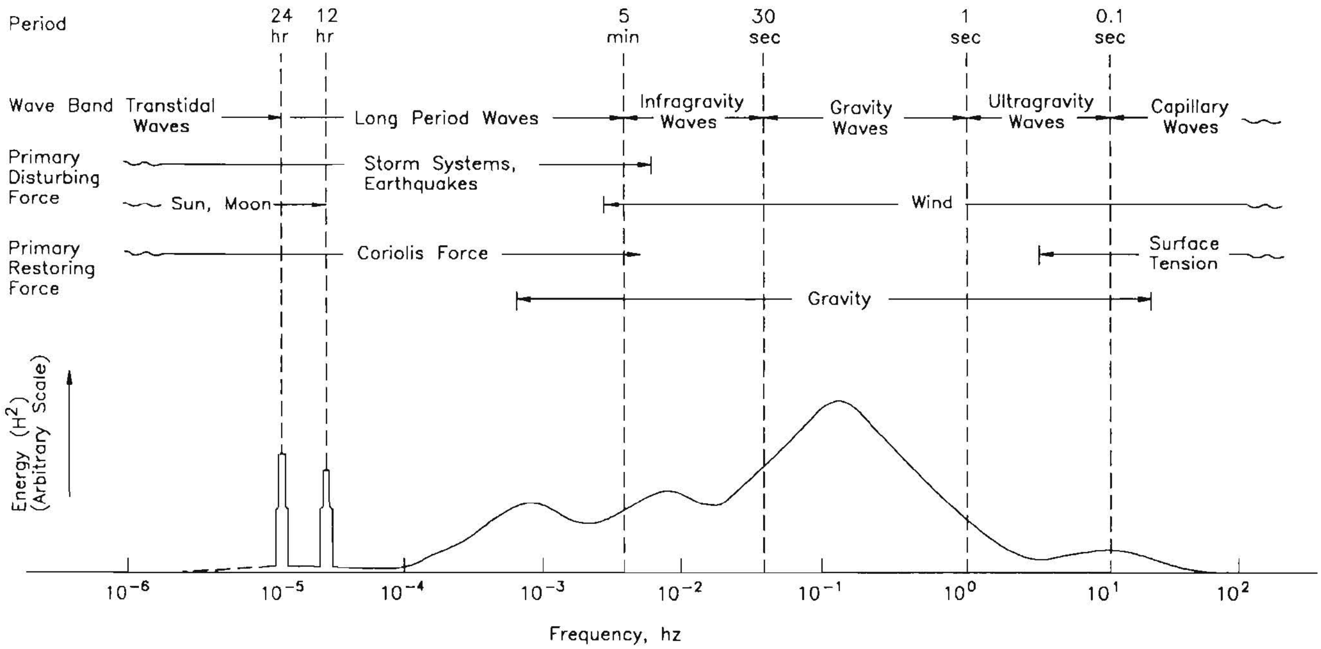

Figure 1. Distribution of ocean surface wave energy (after KINSMAN (1965)).

analysis and calculation of wave transformation. Wave gauges can be installed in buoys, placed directly on the sea or lake bottom, or mounted on existing structures, such as piers, jetties, or offshore platforms.

Of the non-directional wave gauges, buoy-mounted systems such as the Datawell Waverider are accurate and relatively easy to deploy and maintain. Data are usually transmitted by radio between the buoy and an onshore receiver and recorder. One major disadvantage of buoy gauges is that they are subject to being damaged if hit by ships. Bottom-mounted pressure gauges measure water level changes by sensing pressure variations with the passage of each wave. The gauges are either self-recording or are connected to onshore recording devices with cables. Bottom-mounted gauges must be maintained by divers unless the mount can be retrieved by hoisting from a work boat. Internal-recording gauges usually need more frequent maintenance because the data tapes must be changed or the internal memory down-loaded. Advantages and disadvantages of self-contained and cable-telemetered gauges are listed in Table 1. Structure-mounted wave gauges are the most economical and most accessible of the non-directional gauges, although their placement is confined to locations where structures exist and measurements may be distorted by the structure's effects on the waves. A major advantage is the recording devices and transmitters can be safely mounted above water level in a protected location.

Directional wave gauges are also mounted in buoys or on the seafloor (Figure 2). An array of non-directional gauges can be used for directional wave analyses when simultaneous measurements are recorded and the geometry and orientation of the array is precisely known. Directional buoy-type wave gauges are often designed to collect meteorological as well as oceanographic parameters.

A common type of self-contained, seafloor-deployed wave gauge is known as the pressure, u-velocity, v-velocity (puv). In these instruments, pressure is measured with a pressure transducer, while the directional components of the wave orbitals (u and v) are measured with an electromagnetic current meter (the black ball shown protruding above the mount in Figure 2). Current data can be extracted from the records, which is useful for many sediment transport studies. The dependability of puv gauges has improved greatly since the 1980's with the transition from tape-recording to solid-state data recording.

The Coastal Engineering Research Center has developed a directional wave gauge (DWG) that is used either independently or cable-telemetered to shore (HOWELL, 1992). The DWG has improved the reliability of wave measurements in shallow water at many projects compared to gauges used previously at these sites.

Placement of Wave Gauges

The siting of wave gauges along the coast depends on the goals of the monitoring project, funds and time available, environmental hazards, and availability of previously collected data. There are no firm guidelines for placing gauges at a site, and each project is unique. There are two approaches to wave gauging: one is to deploy instruments near a project site in order to measure the wave and sea conditions that directly affect a structure or must be accounted for in designing a project. The second approach is to deploy a gauge further out to sea to measure regional, incident waves. In the

Table 1. *Self-contained and cable-telemetry wave gauges; advantages and disadvantages.*

- I. Self-contained gauges
  - A. Advantages
    - 1. Deployment is often simple because compact instrument can be handled by a small dive team.
    - 2. Gauge can be easily attached to piles, structural members, or tripods.
    - 3. Field equipment can be carried by airplane to remote sites.
    - 4. Gauges will continue to function in severe storms as long as the mounts survive.
    - 5. Usually easy to obtain permits to deploy instruments (typically, notification to mariners must be posted).
  - B. Disadvantages
    - 1. Gauge must be periodically recovered to retrieve data or replace storage media.
    - 2. Data collection time is limited by the capacity of the internal memory or data tapes. Researcher must compromise between sampling density and length of time the gauge can be gathering data between scheduled maintenance visits.
    - 3. Battery capacity may be a limiting factor for long deployments.
    - 4. If bad weather forces delay of scheduled maintenance, gauge may reach the limit of its storage capacity. This will result in unsampled intervals.
    - 5. While under water, gauge's performance cannot be monitored. If it fails electronically or leaks, data are usually lost forever.
    - 6. Gauge may be struck by anchors or fishing vessels. The resulting damage or total loss may not be detected until the next maintenance visit.
    - 7. After especially severe storms (hurricanes), gauges may be difficult to find.
  - C. Notes
    - 1. Data compression techniques, onboard data processing, and advances in low-energy memory have dramatically increased the storage capacity of underwater instruments. Some can remain onsite as long as 12 months.
- II. Data transmission by cable.
  - A. Advantages
    - 1. Data can be continuously monitored. If a failure is detected (by human analysts or error-checking computer programs), a repair team can be sent to the site immediately.
    - 2. Because of the ability to monitor the gauge's performance, infrequent inspection visits may be adequate to maintain systems.
    - 3. Frequency and density of sampling are only limited by the storage capacity of the shore-based computers.
    - 4. Gauge can be reprogrammed in situ to change sampling program.
    - 5. Electrical energy is supplied from shore.
  - B. Disadvantages
    - 1. Permitting is difficult and often requires considerable effort.
    - 2. Lightning is a major cause of damage and loss of data.
    - 3. Cable to shore is vulnerable to damage from anchors or fishing vessels.
    - 4. Shore station may be damaged in severe storms, resulting in loss of valuable storm data.
    - 5. Shore station and data cable are vulnerable to vandalism.
    - 6. Backup power supply necessary in case of blackouts.
    - 7. Installation of cable can be difficult, especially in harbors and across rough surf zones.
    - 8. Installation often requires a major field effort, with vehicles on beach and one or two boats. Heavy cable must be carried to the site.
    - 9. Cable eventually deteriorates in the field and must be replaced.
    - 10. Cable may have to be removed after experiment has ended.
    - 11. Field costs are high because of the extensive permitting and site preparations.
  - C. Notes
    - 1. Some cable-based gauges have internal memory and batteries so that they can continue to collect data even if cable is severed.
    - 2. Ability to constantly monitor gauge's performance is a major advantage in conducting field experiments.

past, when wave gauges were exceedingly expensive, researchers often opted to collect regional data with a single instrument. Now, with lower costs for hardware and software, we recommend that several gauges be deployed near the coast flanking the project area. *A priori* knowledge of a site or practical considerations may dictate gauge placement. The user must usually compromise between collecting large amounts of data for a short, intensive experiment, and maintaining the gauges at sea for a longer period in order to try to observe seasonal changes. Table 2 summarizes some suggested practices based on budget and study goals. Suggestions on data sampling intervals are discussed later.

Seismic Wave Gauge

Wave estimates based on microseismic measurements are an alternative means to obtain wave data in high-energy environments. Microseisms are very small ground motions which can be detected by seismographs within a few kilometers of the coast. It is generally accepted that microseisms are caused by ocean waves and that the amplitudes and periods of the motions correspond to the regional wave climate. Comparisons of seismic wave gauges in Oregon with in situ gauges have been favorable (HOWELL and RHEE, 1990; THOMPSON, HOWELL, and SMITH, 1985). The seismic system has inherent limitations, but deficiencies in wave period estimates can probably be solved with more sophisticated processing. Use of seismometers as a substitute for wave gauges has not yet been proven, but the concept appears to be valid. Using seismographs for wave purposes will be a long-term commitment, requiring time to calibrate and compare the data. The advantage of a seismograph is that it can be placed on land in a protected building.

WAVE RECORDS

General Procedures

To an observer on the shore or on a boat, the sea surface usually appears as a chaotic jumble of waves of various heights and periods moving in many different directions. Wave gauges measure and record a signal indicative of the changing elevation of the water surface. Unfortunately, these data, when simply plotted against time, reflect the complexities of the sea's surface and provide little initial information about the characteristics of the individual waves which were present at the time the record was being made (Figure 3). Once the water elevation data are acquired, further processing is necessary in order to obtain wave statistics that can be used by coastal scientists or engineers to infer what wave forces have influenced their study area.

Wave data analysis typically consists of a series of steps:

- Data transfer from gauge to computer
- Conversion of data from voltage readings to engineering units
- Initial quality control inspection
- Spectral analysis
- Additional quality control (if necessary)
- Summary statistics in table and plot form
- Plots of individual wave bursts or special processing

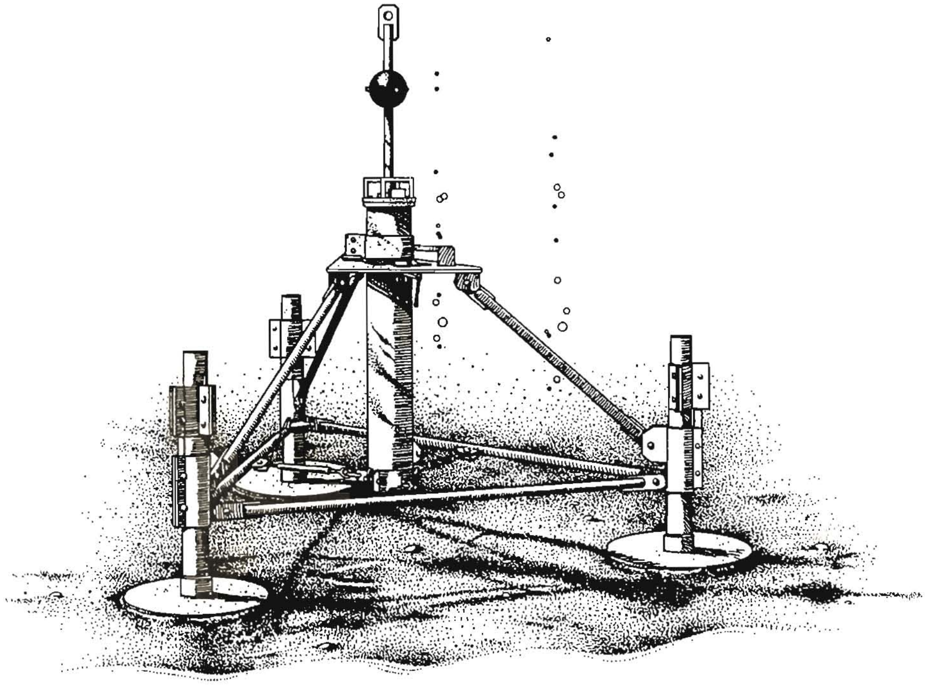

Figure 2. Bottom-mounted Sea Data® 635-12 *puv* directional wave gauge mounted in tripod using railroad wheels as corner weights.

It is beyond the scope of this paper to discuss details of the above procedures, and the reader is referred to BENDAT and PIERSOL (1986), EARLE and BISHOP (1984), EARLE, MCGEHEE, and TUBMAN (1995), HORIKAWA (1988), and WEAVER (1983) for additional references. This section will summarize some aspects of data collection, quality control, analysis, and terminology.

Data Collection Planning

A continuous time series of raw pressure values plotted with time along the x-axis is shown in Figure 3. Because it is impractical and too expensive to collect data continuously throughout the day, discrete time series or "bursts" are collected at predetermined intervals (often every 1, 2, 4, or 6 hr; Figure 3). Wave bursts typically consist of 1,024 or 2,048 consecutive pressure, u-velocity, and v-velocity[4] samples. At a sampling frequency of 1 Hz, these produce time series of 17.07 min and 34.13 min, respectively. Clearly, it would be desirable to acquire wave bursts frequently, but the sheer amount of data would soon overwhelm an analyst's ability to organize, interpret, and store the records. A researcher who plans a data acquisition program must balance the need to collect data frequently versus the need to maintain gauges in the field for an extended period. There is a temptation to assume that as long as the gauges are at sea, they should be programmed to collect absolutely as much data as possible. However, data management, analysis, and archiving can cost as much as the deployment and maintenance of the gauges. It is essential that these analysis costs be factored into the project budget. Typical sampling schemes used at Coastal Engineering Research Center (CERC) projects are listed in Table 3.

Quality Control of Wave Data

Absolutely critical to the validity of the overall results are the quality control procedures used to ensure that the raw data collected by the gauges are truly representative of wave climate at the site. Wave gauges are subject to mechanical and electrical failures. The pressure sensors may be plugged with sediment or may be covered with growth while underwater. Nevertheless, even while malfunctioning, gauges may continue to collect data which, on cursory examination, may appear to be reasonable. As an example, Figure 4 shows pressure records from two instruments mounted on the same tripod off the mouth of Mobile Bay, Alabama. The upper record in the figure is from a gauge with a plugged pressure orifice. The curve reflects the overall change in water level caused by the tide, but high frequency fluctuations caused by the passing of waves have been severely damped. The damping is more obvious when a single wave burst of 1,024 points is plotted (Figure 5). Without the record from the second gauge, would an analyst have been able to conclude that the first instrument was not performing properly? This type of determination can be especially problematic in a low-energy environment like the Gulf of Mexico, where calm weather can occur for long periods.

Another difficult condition to diagnose occurs when the

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[4] Orthogonal horizontal water velocity measurements.

Table 2. *Suggested wave gauge placement for coastal project monitoring.*

I. High-budget project (major harbor; highly populated area)
  A. Recommended placement:
    1. One (or more) wave gauge(s) close to shore near the most critical features being monitored (example, near an inlet). Although nearshore, gauges should be in intermediate or deep water based on expected most common wave period. Depth can be calculated from formulas in the *Shore Protection Manual* (U.S. ARMY CORPS OF ENGINEERS, 1984).
    2. In addition, one wave gauge in deep water if needed for establishing boundary conditions of models.
  B. Schedule:
    1. Minimum: 1 year. Monitor winter/summer wave patterns (critical for Indian Ocean projects).
    2. Optimum: 5 years or at least long enough to determine if there are noticeable changes in climatology over time. Try to include one El Niño season during coverage for North American projects.
  C. Notes:
    1. Concurrent physical or numerical modeling: Placement of a gauge may need to take into account modelers' requirements for input or model calibration.
    2. Preexisting wave data may indicate that gauges should be placed in particular locations. As an alternative, gauges may be placed in locations identical to the previous deployment in order to make the new data as compatible as possible with the older data. Long, continuous data sets are extremely valuable!
    3. Hazardous conditions: If there is a danger of gauges being damaged by anchors or fishing boats, the gauges must be protected, mounted on structures (if available), or deployed in a location which appears to be the least hazardous.

II. Medium-budget project
  A. Recommended placement:
    1. One wave gauge close to shore near project site.
    2. Obtain data from nearest National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) buoy for deepwater climatology.
  B. Schedule: minimum 1 year deployment; longer if possible
  C. Notes: same as IC above. Compatibility with existing data sets is very valuable.

III. Low budget, short-term project
  A. Recommended placement: gauge close to project site.
  B. Schedule: if 1-year deployment is not possible, try to monitor the season when the highest waves are expected (usually winter, although this may not be true in areas where ice pack occurs).
  C. Notes: same as IC above. It is critical to use any and all data from the vicinity, anything to provide additional information on the wave climatology of the region.

wave energy fluctuates rapidly. Some computerized analysis procedures contain user-specified thresholds to reject records that contain too many noise spikes. Occasionally, however, violent increases in energy do occur over a short time, and it is important that the analysis procedures do not reject these records without verification. As an example, one of two gauges in Long Beach harbor (the lower curve in Figure 6) may have malfunctioned and written noisy data on the tape. In reality, the gauge recorded unusual energy events within the harbor. Another example, from Burns Harbor, Indiana, is shown in Figure 7. When wave height was plotted against time, numerous spikes appeared. In this case, the rapid increase in energy was genuine, and the spikey appearance was caused by the plotting of many weeks of data on one plot. An examination of the individual pressure records (Figure 8) reveals how rapidly the energy increased in only a few hours (a characteristic of Great Lakes storms). This example demonstrates that the method of displaying wave statistics can have a major influence on the way the data are perceived by an analyst. Additional examples and quality control procedures for validating wave data are presented in EARLE, MCGEHEE, and TUBMAN (1995) and MORANG (1990).

Analysis Procedures and Terminology

Wave data analysis can be broadly subdivided into nondirectional and directional procedures. Although the latter are considerably more complex, the importance of delineating wave direction in coastal areas is usually great enough to justify the extra cost and complexity of trying to obtain directional wave spectra. The types of wave statistics needed vary depending on the application. For example, a geologist might want to know what the average wave period, height, and peak direction are along a stretch of the shoreline. This information could then be used to estimate wave refraction and longshore drift. An engineer who is building a structure along the shore would be interested in the height, period, and approach direction of storm waves. He would use these values to calculate stone size for his structure. Table 4 lists common statistical wave parameters.

Table 4 is intended to underscore that wave analysis is a complex procedure and should be undertaken by coastal researchers with knowledge of wave mechanics and oceanography. In addition, researchers are urged to be cautious of wave statistics from secondary sources and to be aware of how terms have been defined and statistics calculated. For example, "significant wave height" (H_s) is defined as the average height of the highest one-third of the waves in a record. How long should this record be? Are the waves measured in the time domain by counting the wave upcrossings or downcrossings? The two methods may not produce the same value of H_s. Might it not be better to estimate significant wave height by performing spectral analysis of a wave time series in the frequency domain and equating $H_s = H_{m0}$? This is the procedure commonly used now in experiments where large amounts of data are processed. The latter equivalency is usually considered valid in deep and intermediate water but may not be satisfactory in shallow water (HORIKAWA, 1988; THOMPSON and VINCENT, 1985).

Directional wave statistics are also subject to misinterpretations depending upon the computation method. At sea, very rarely do the waves come from only one direction. More typically, swell, generated by distant storms, may approach from one or more directions, while the local wind waves may have a totally different orientation. Researchers need to distinguish how the wave energy is distributed with respect to both direction and period (*i.e.*, the directional spectral density, $S(f,\Theta)$). The directional distribution of wave energy is often computed by a method developed by LONGUET-HIGGINS, CARTWRIGHT, and SMITH (1963) for use with floating buoys in deep water. Other distribution functions have been proposed and used by various researchers since the 1970's (HORIKAWA, 1988). Although the various methods do not produce the same directional wave statistics under some circumstances, it is not possible to state that one method is superior to another.

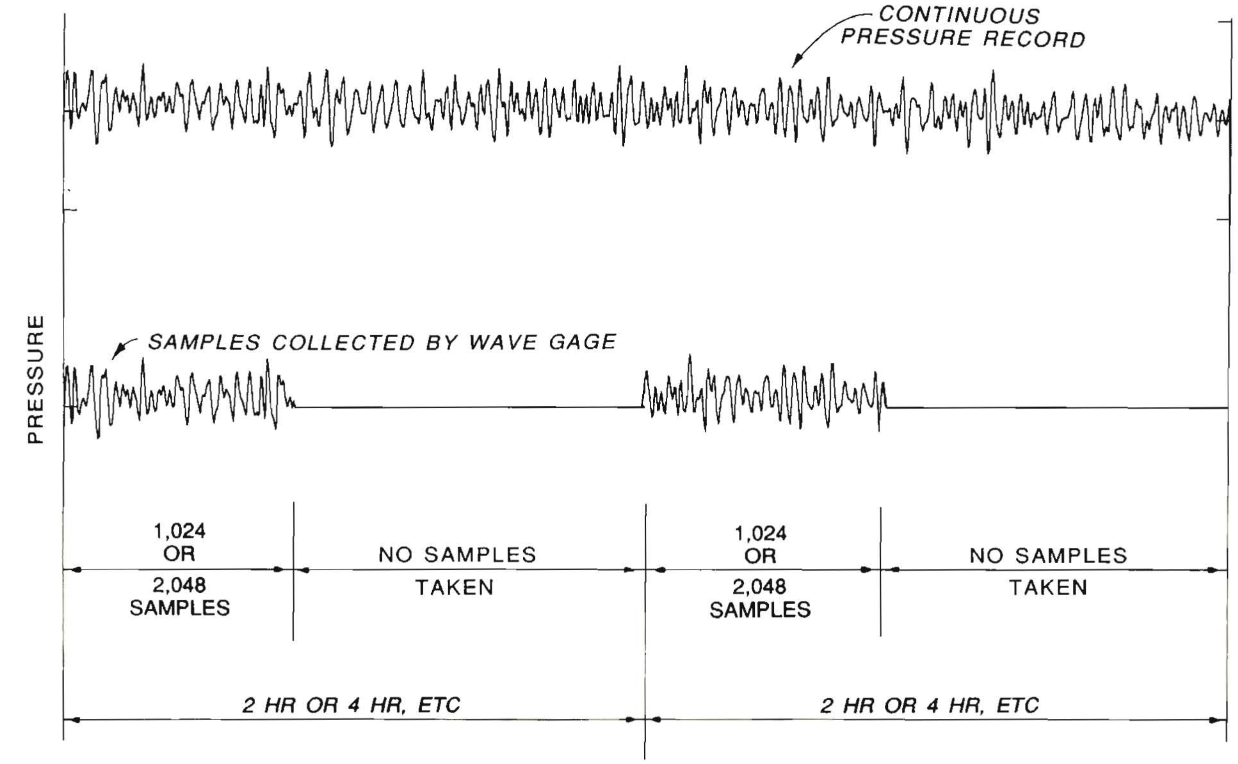


Figure 3. Example of continuous wave pressure record and wave burst sampling of pressure data.

The user of environmental data must be aware of the convention used to report directions. Table 5 lists the definitions used at CERC; other institutions may not conform to these standards.

Some oceanographic instruments are sold with software that performs semi-automatic processing of the data, often in the field on personal computers. In some instruments, the raw data are discarded and only the Fourier coefficients saved and recorded. The user of these instruments is urged to obtain as much information as possible on the mathematical algorithms used by the gauge's manufacturer. If these procedures are not the same as those used to analyze other data sets from the area, the summary statistics may not be directly comparable. Even more serious, this author (Morang) has encountered commercial processing software which was seriously flawed with respect to the calculation of directional spectra. In one field experiment in Lake Michigan, because the original raw data had not been archived in the gauge, the data could not be reprocessed or the errors corrected. As a result, the multi-month gauge deployment was rendered useless.

In summary, it is vital that the user of wave data be aware of how wave statistics have been calculated and thoroughly understand the limitations and strengths of the computational methods that were employed.

Table 3. *Wave data sampling intervals, typical CERC projects.*

Instrument	Location	Sample interval (hr)
Sea Data self-contained wave gauge	Ocean coastlines	4 or 6
Sea Data self-contained wave gauge	Great lakes	2 or 3
CERC Directional Wave Gauge	Ocean coastlines	1
NOAA wave and meteorology buoys	Oceans and lakes	1

Display of Wave Data and Statistics

In order to manage the tremendous amount of data that are typically acquired in a field experiment, perform quality control, and interpret the results, wave data should be analyzed as soon as possible. In addition, there is often an urgent need to examine the raw data to ascertain whether the gauges can be redeployed or must be repaired.

Figures 5 and 8 are examples of pressure plotted against time. The value of this form of display for quality control purposes has been demonstrated, but these plots are of limited value in revealing information about the overall nature of the wave climate in the study area.

To review the data from an extended deployment, summary statistics must be tabulated or plotted. Figure 9 is an example of tabulated directional wave data from a Florida project. These same data are graphically displayed in Figure 10. The upper plot shows H_{m0} wave height, the center peak period, and the lower peak direction. Although other statistics could have been plotted on the same page, there is a

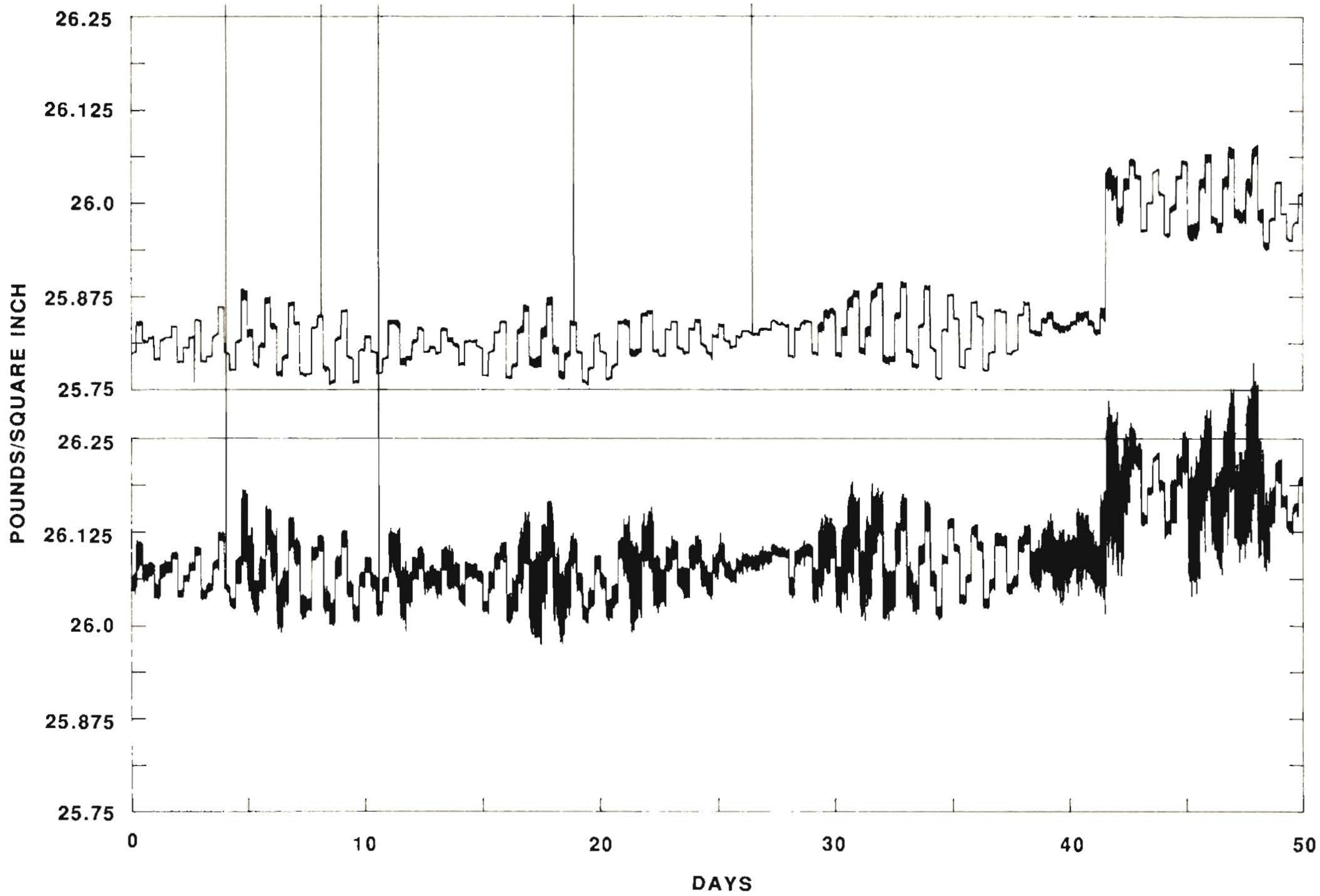


Figure 4. Pressure data collected by two gauges mounted on a tripod off Mobile Bay, Alabama. The upper record is from a gauge with a plugged pressure orifice. The abrupt increase in pressures near day 43 was caused when a fishing boat struck and overturned the tripod.

danger of making a display too confusing. The advantage of tables is that they provide exact numerical values for individual wave bursts. The disadvantage is that it is difficult to detect overall trends, especially if the records extend over many months. Because tables are voluminous and expensive to compose and print, they should probably not be used unless they are being bound in data reports. As with graphic displays of data, all captions, internal headings, and footnotes within a table should complement each other such that the content of the table is immediately apparent and the reader is not forced to guess at the meaning of obscure abbreviations or inarticulate labels (KENNEDY and KENNEDY, 1990). The efficient and meaningful display of graphic data is an art form, as discussed and illustrated in TUFTE'S (1983) excellent book, *The Visual Display of Quantitative Information.* As data collection and processing procedures improve, and as more and more data are acquired at field projects, it will be increasingly difficult to display the results in a useful and flexible format that does not overwhelm the end user but yet also does not oversimplify the situation.

WATER LEVEL MEASUREMENTS AND OBSERVATIONS

Types of Water Level Gauges

To collect continuous water level data for site-specific, modern process studies, tide gauges must be deployed near the project site. Three types of instruments are commonly used to measure water level:

Pressure Transducer Gauges

These instruments are usually mounted on the seafloor or attached to structures. They record hydrostatic pressure, which is converted to water level during data processing (similar to the wave gauge shown in Figure 2). A major advantage of these gauges is that they are underwater and somewhat inaccessible to vandals. In addition, ones like the Sea Data Temperature Depth Recorder are compact and easy to deploy.

Stilling-Well, Float Gauges

These instruments, in use throughout this century, consist of a float which is attached to a stylus assembly. A clockwork

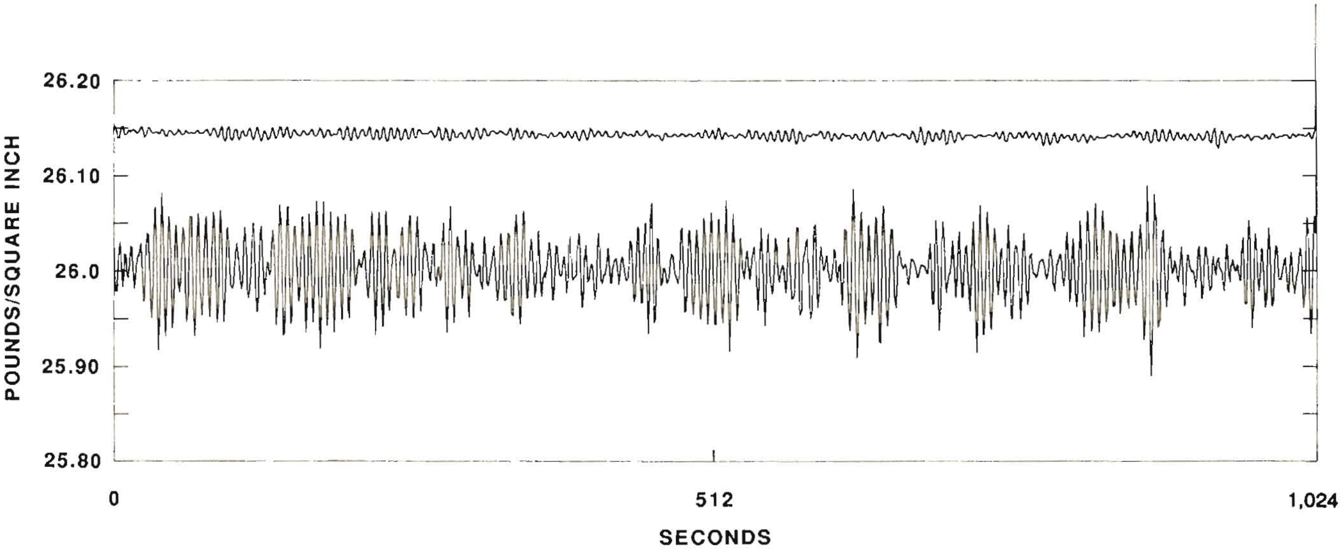


Figure 5. Example of a single wave burst of 1,024 pressure points from the same gauges which produced the records in Figure 4. The data from the plugged gauge (the upper curve) is not only reduced in amplitude but also shifted in phase. We are unaware of verifiable procedures that can correct the plugged data and recreate an approximation of the original record.

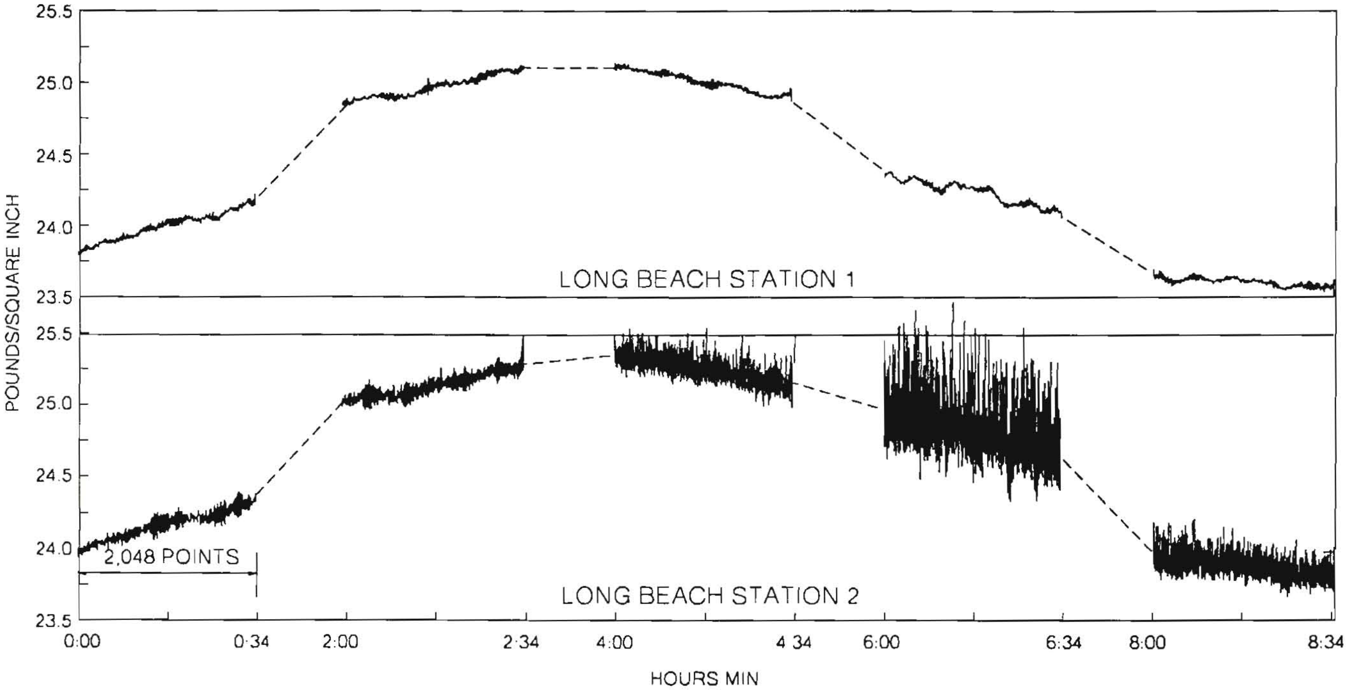


Figure 6. Comparison of wave gauge pressure measurements recorded at Long Beach Harbor, California, stations 1 and 2. Although the two stations were only a few hundred meters apart, unusual energy events were recorded at sta 2 which did not appear at sta 1. The abrupt shifts in the curve at each 2-hr interval represent changes in tide height. Each 2,048-point record is 34.13 min long and each new wave burst is recorded at a 2-hr interval.

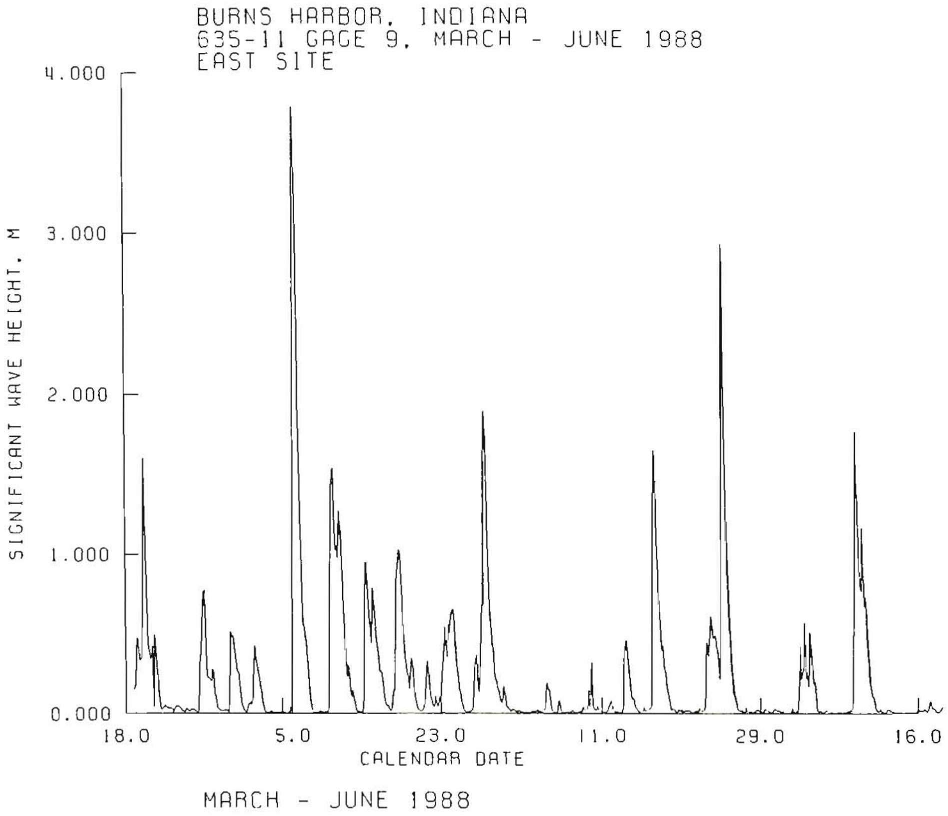


Figure 7 Summary wave statistics from Burns Harbor, Indiana. Spikey appearance is caused by plotting almost 3 months of data on one plot.

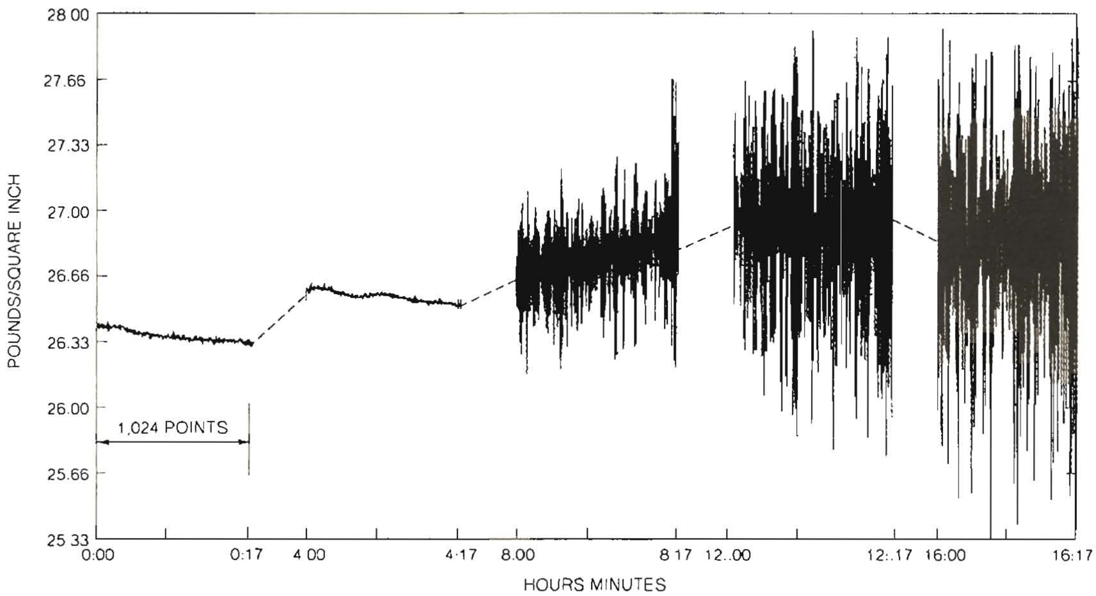


Figure 8. Pressure data from Burns Harbor, Indiana, April 6, 1988. This plot shows how dramatically the energy can increase in only a few hours. Each new wave burst begins at a 4-hr interval.

Table 4. *Sea state parameters.*

Symbol	Description	Units
	Basic Terms	
a	Amplitude	m
c	Phase velocity or celerity	m/sec
c_g	Group velocity	m/sec
f	Frequency	Hz
H	Wave height	m
L	Wave length measured in the direction of wave propagation	m
T	Wave period $1/f$	sec
Θ	Direction of wave propagation as used in directional spectra	deg
Δf	Basic frequency increment in discrete Fourier analysis	Hz
σ	Standard deviation	m
	General Parameters	
f_p	Spectral peak frequency $1/T_p$	Hz
H_s	Significant wave height defined as the highest one-third of the wave heights calculated as $H_{1/3}$; or estimated as H_{m0}	m
T_p	Spectral peak period $1/f_p$	sec
	Time Domain Analysis Functions	
$H_{1/3,d}$	Zero-downcrossing significant wave height. Average of the highest one-third zero-downcrossing wave heights	m
$H_{1/3,u}$	Zero-upcrossing significant wave height	m
	Frequency Domain Analysis Parameters	
H_{m0}	Estimate of significant wave height, $4\sqrt{m_0}$	m
m_n	nth moment of spectral density	m^2/sec^n
$S(f)$	Spectral density	m^2/Hz
	Directional Parameters and Functions	
$\vec{k}$	Wave vector	rad/m
$D(f,\Theta)$	Directional spreading function	deg
$S(f,\Theta)$	Directional spectral density	$(m^2/Hz)/deg$
α	Wave direction. This is the commonly used wave-direction parameter, representing the angle between true north and the direction from which the waves are coming. Clockwise is positive in this definition	deg
Θ	Direction of wave propagation describing the direction of $\vec{k}$. Counterclockwise is positive	deg
$\Theta_m(f)$	Mean wave direction as a function of frequency. The mean of all $\Theta_m(f)$ is known as the overall wave direction	deg

Condensed from IAHR Working Group on Wave Generation and Analysis (1989)

or electric motor advances chart paper past the stylus, producing a continuous water level record. The float is within a stilling well, which dampens waves and boat wakes. Many of these gauges also record their measurements on a punched paper tape. The main disadvantage of these gauges is that they must be protected from vandals. They are usually used in estuaries and inland waterways where piles or bridges are available for mounting the well and recording box. Figure 11 is an example of tide data from Choctawhatchee Bay, Florida, collected with stilling well and pressure instruments. Examples of instruments made by Fischer and Porter and Leupold & Stevens are described in the NOAA *Hydrographic Manual* (Umbach, 1976).

Staff Gauges

Water levels are either recorded manually by an observer or calculated from electric resistance measurements. Resistance staff gauges require frequent maintenance because of corrosion and biological fouling. The manual ones are difficult to use at night and during storms, when it is hazardous for the observer to be at the site.

Typically, water level measurements recorded by gauges are related to an established datum, such as mean sea level or the National Geodetic Vertical Datum (NGVD). This requires that the gauge elevations be accurately measured using surveying methods. The maximum water level elevations during extreme events can also be determined by examining water marks on structures or other elevated features.

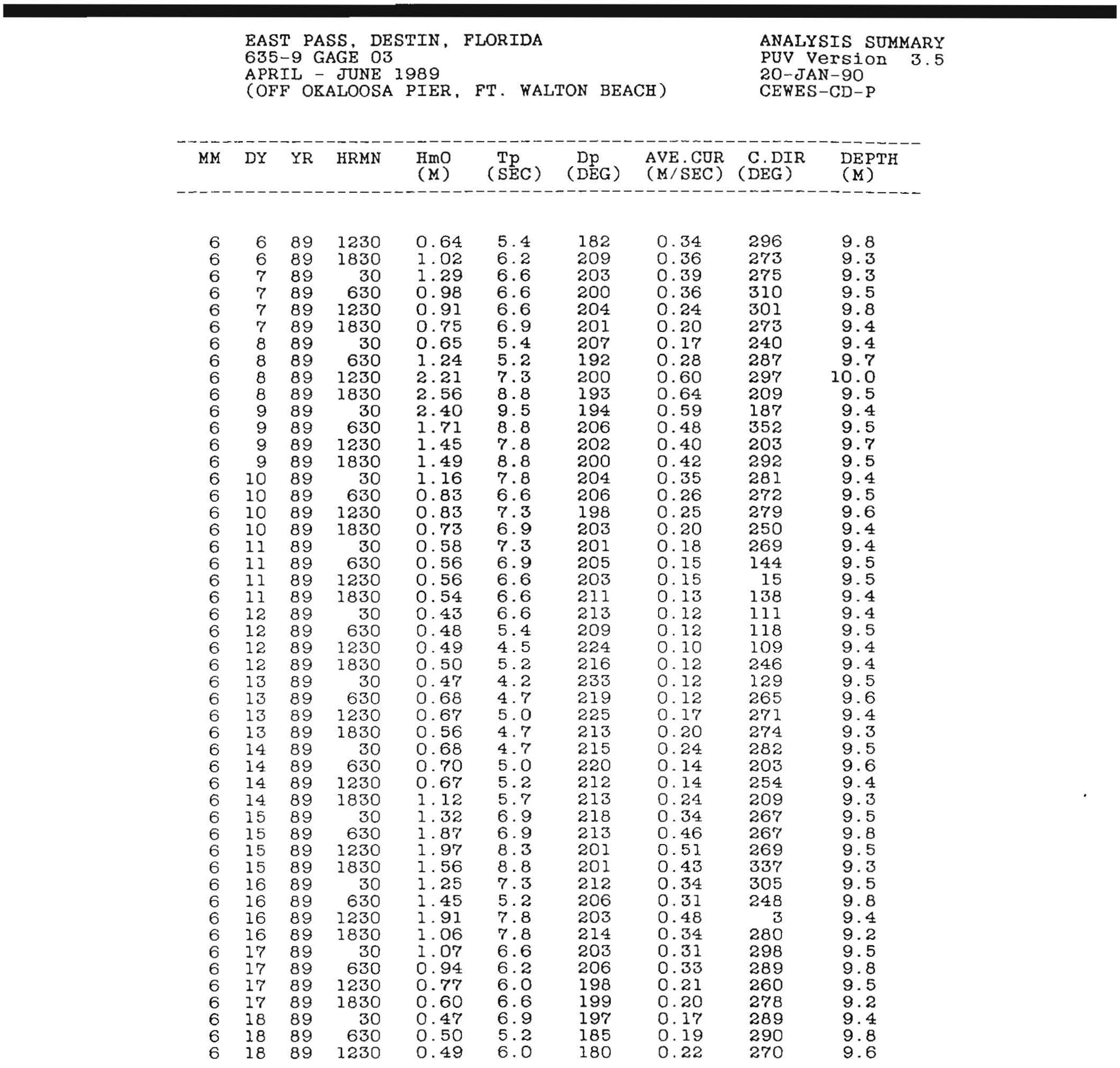
Water Level Records

Changes in water levels along coastlines have profound influence on the geology, the natural ecology, and human habitation in these regions. Predicting and understanding these changes can guide coastal planners in developing rational

Table 5. *Reporting conventions for directional environmental measurements.*

Type	Convention	Example[1]
Wind	FROM WHICH wind is blowing	North wind blows from 0 deg
Waves	FROM WHICH waves come	West waves come from 270 deg
Unidirectional currents	TO WHICH currents are flowing	East current flows to 90 deg

[1] These are compass directions (i.e, 0 deg. is at the top and angles are measured clockwise around the compass rose). Additional confusion is introduced when instruments read out in Cartesian coordinates (*i.e.*, 0 deg. is to the right and the angles increase anti-clockwise)



```
        EAST PASS, DESTIN, FLORIDA                          ANALYSIS SUMMARY
        635-9 GAGE 03                                       PUV Version  3.5
        APRIL - JUNE 1989                                   20-JAN-90
        (OFF OKALOOSA PIER, FT. WALTON BEACH)               CEWES-CD-P

 ---------------------------------------------------------------------------
  MM   DY   YR   HRMN    HmO     Tp      Dp     AVE.CUR   C.DIR    DEPTH
                         (M)    (SEC)   (DEG)   (M/SEC)   (DEG)     (M)
 ---------------------------------------------------------------------------

  6    6   89   1230    0.64    5.4     182     0.34     296       9.8
  6    6   89   1830    1.02    6.2     209     0.36     273       9.3
  6    7   89     30    1.29    6.6     203     0.39     275       9.3
  6    7   89    630    0.98    6.6     200     0.36     310       9.5
  6    7   89   1230    0.91    6.6     204     0.24     301       9.8
  6    7   89   1830    0.75    6.9     201     0.20     273       9.4
  6    8   89     30    0.65    5.4     207     0.17     240       9.4
  6    8   89    630    1.24    5.2     192     0.28     287       9.7
  6    8   89   1230    2.21    7.3     200     0.60     297      10.0
  6    8   89   1830    2.56    8.8     193     0.64     209       9.5
  6    9   89     30    2.40    9.5     194     0.59     187       9.4
  6    9   89    630    1.71    8.8     206     0.48     352       9.5
  6    9   89   1230    1.45    7.8     202     0.40     203       9.7
  6    9   89   1830    1.49    8.8     200     0.42     292       9.5
  6   10   89     30    1.16    7.8     204     0.35     281       9.4
  6   10   89    630    0.83    6.6     206     0.26     272       9.5
  6   10   89   1230    0.83    7.3     198     0.25     279       9.6
  6   10   89   1830    0.73    6.9     203     0.20     250       9.4
  6   11   89     30    0.58    7.3     201     0.18     269       9.4
  6   11   89    630    0.56    6.9     205     0.15     144       9.5
  6   11   89   1230    0.56    6.6     203     0.15      15       9.5
  6   11   89   1830    0.54    6.6     211     0.13     138       9.4
  6   12   89     30    0.43    6.6     213     0.12     111       9.4
  6   12   89    630    0.48    5.4     209     0.12     118       9.5
  6   12   89   1230    0.49    4.5     224     0.10     109       9.4
  6   12   89   1830    0.50    5.2     216     0.12     246       9.4
  6   13   89     30    0.47    4.2     233     0.12     129       9.5
  6   13   89    630    0.68    4.7     219     0.12     265       9.6
  6   13   89   1230    0.67    5.0     225     0.17     271       9.4
  6   13   89   1830    0.56    4.7     213     0.20     274       9.3
  6   14   89     30    0.68    4.7     215     0.24     282       9.5
  6   14   89    630    0.70    5.0     220     0.14     203       9.6
  6   14   89   1230    0.67    5.2     212     0.14     254       9.4
  6   14   89   1830    1.12    5.7     213     0.24     209       9.3
  6   15   89     30    1.32    6.9     218     0.34     267       9.5
  6   15   89    630    1.87    6.9     213     0.46     267       9.8
  6   15   89   1230    1.97    8.3     201     0.51     269       9.5
  6   15   89   1830    1.56    8.8     201     0.43     337       9.3
  6   16   89     30    1.25    7.3     212     0.34     305       9.5
  6   16   89    630    1.45    5.2     206     0.31     248       9.8
  6   16   89   1230    1.91    7.8     203     0.48       3       9.4
  6   16   89   1830    1.06    7.8     214     0.34     280       9.2
  6   17   89     30    1.07    6.6     203     0.31     298       9.5
  6   17   89    630    0.94    6.2     206     0.33     289       9.8
  6   17   89   1230    0.77    6.0     198     0.21     260       9.5
  6   17   89   1830    0.60    6.6     199     0.20     278       9.2
  6   18   89     30    0.47    6.9     197     0.17     289       9.4
  6   18   89    630    0.50    5.2     185     0.19     290       9.8
  6   18   89   1230    0.49    6.0     180     0.22     270       9.6
```

WORKING DRAFT

Figure 9. Example of tabular summary of wave data from offshore Fort Walton Beach, Florida.

plans for coastal development and in the design, construction, and operation of coastal structures and waterways.

Water level information over paleoenvironmental time scales has been investigated by researchers using stratigraphic coring, seismic techniques, and radiometric dating. Petroleum geologists have used seismic stratigraphy as a tool to reconstruct ancient sea levels (PAYTON, 1977; SHERIFF, 1980).

Tide gauge records may be analyzed for spatial interpolation and for assessing temporal variations such as surges, tides, seasonal changes, and long-term trends. Discrepancies between the predicted tide at one site and the actual tide measured only a short distance away may be considerable. A method for adjusting between predicted tides at a station and those at a nearby study area using only limited field mea-

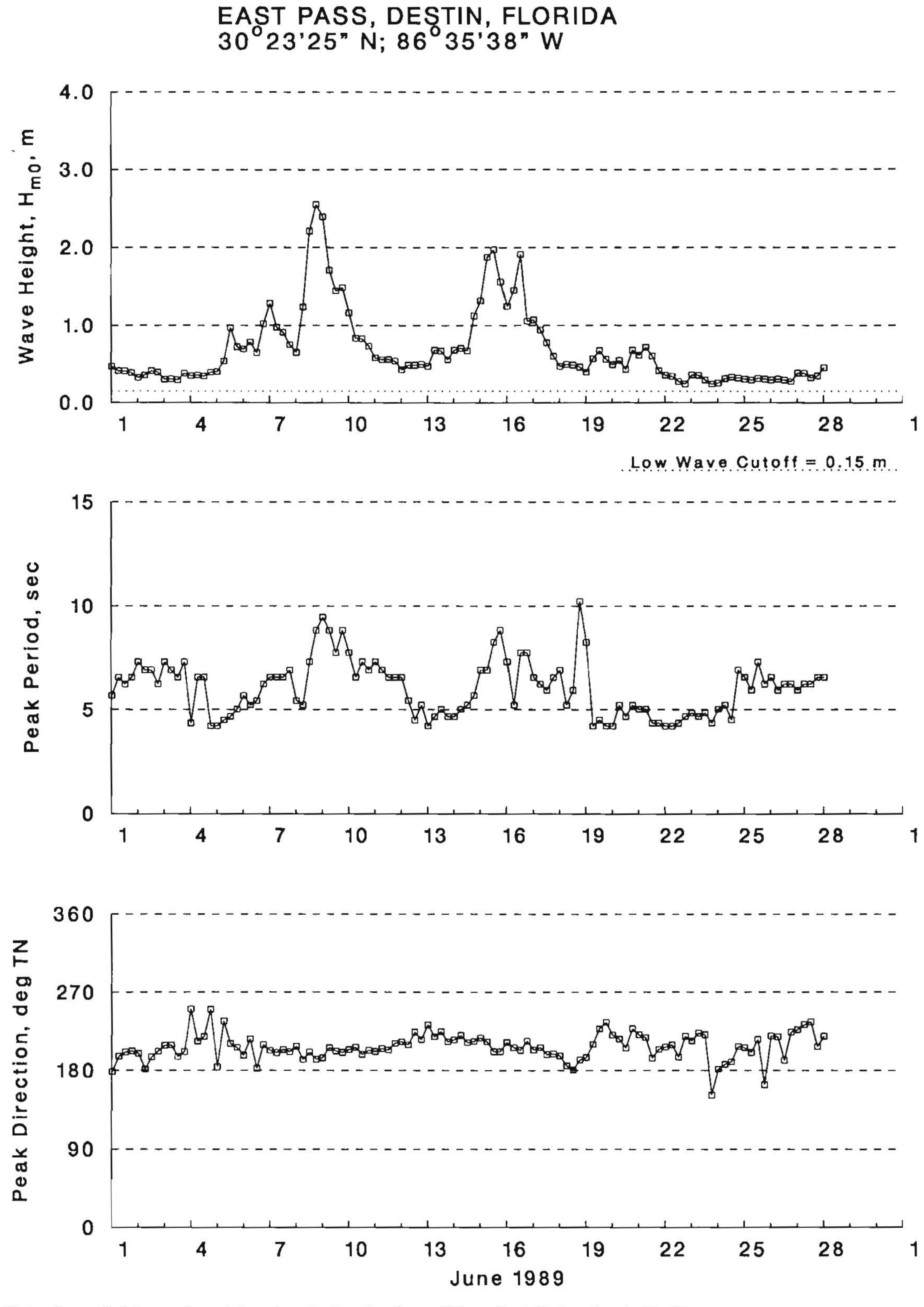


Figure 10. Plots of wave height, peak period, and peak direction from offshore Fort Walton Beach, Florida.

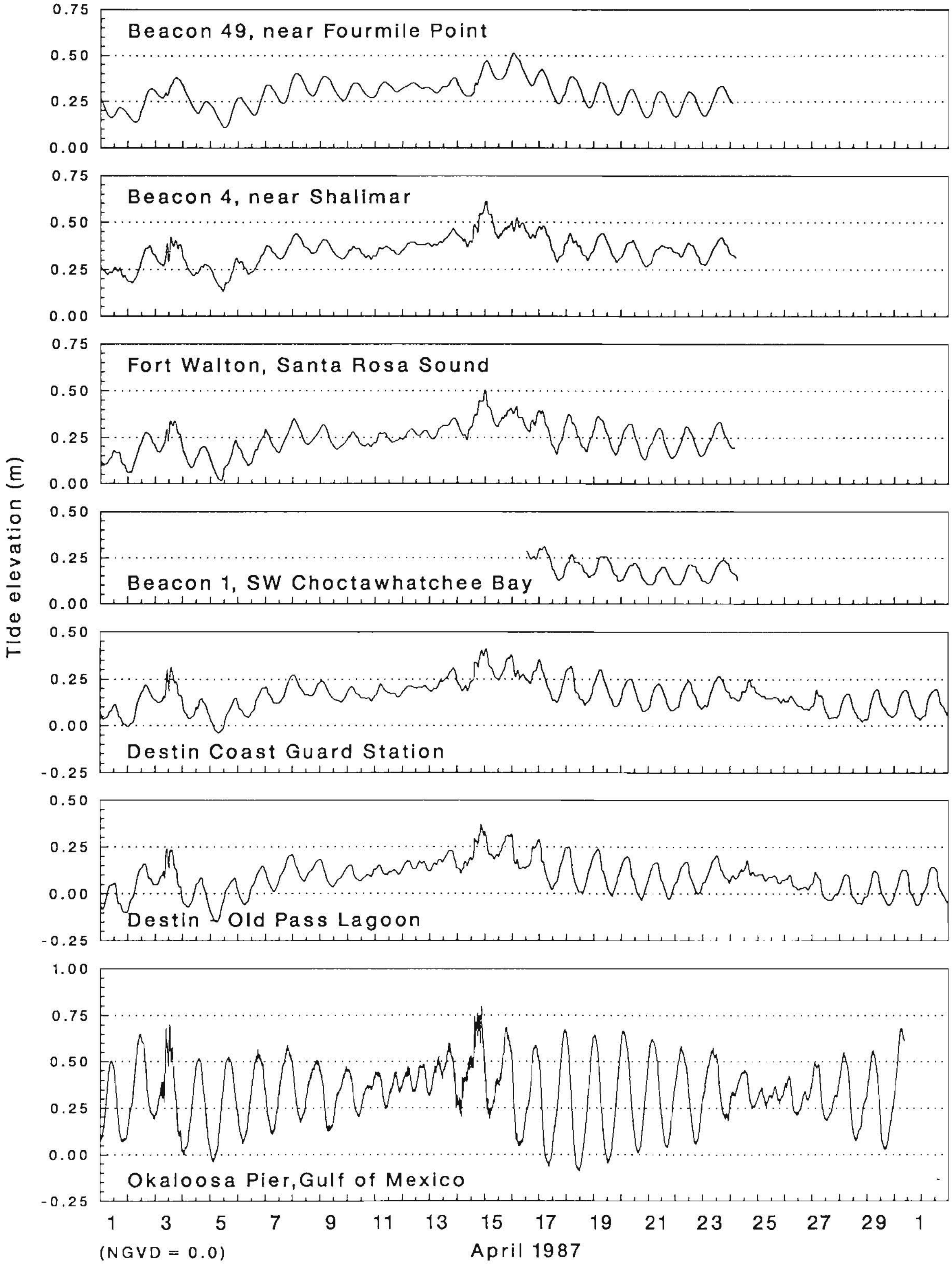


Figure 11. Tidal elevations from seven stations in Choctawhatchee Bay, Florida, and the Gulf of Mexico. The overall envelope of the seven curves is similar, but individual peaks are shifted in phase from station to station. Original tide records courtesy of U.S. Army Engineer District, Mobile.

surements is discussed by GLEN (1979). Other analysis methods are discussed in HEADQUARTERS, USACE (1989).

For engineering projects, assessments of short-term water level changes range from simple plotting of data to more sophisticated mathematical analyses. In some cases, some of the components that drive water level changes can be isolated. To assess longer (multi-year) trends, it is important to dampen or separate the effects of yearly variability so that the nature of the secular trends becomes more pronounced. Least-squares regression methods are typically inadequate because the secular trends often show pronounced nonlinearity (HICKS, 1972). It may also be important to examine long-term periodic effects in a long data record such as the 18.6-year nodal period, which WELLS and COLEMAN (1981) concluded was important for mudflat stabilization in Surinam.

HANDS (1976, 1979, 1980) used historic water levels to examine the changes in rates of shore retreat in Lake Michigan and to predict beach and nearshore profile adjustments to rising water levels. Additional research is being sponsored by the International Joint Commission to model how changing water levels affect erosion of various bluff stratigraphies and the nearshore profile.

CURRENT MEASUREMENTS AND OBSERVATIONS

General Techniques of Current Measurement

The observation of hydraulic phenomena can be accomplished by two general approaches. One of these, *Lagrangian*, follows the motion of an element of matter in its spatial and temporal evolution. The other, *Eulerian*, defines the motion of the water at a fixed point and determines its temporal evolution. Lagrangian current measuring devices are often used in sediment transport studies, in pollution monitoring, and for tracking ice drift. Eulerian, or fixed, current measurements are important for determining the variations in flow over time at a fixed location. Recently developed instruments combine aspects of both approaches.

Four general classes of current measuring technology are presently in use (APPELL and CURTIN, 1990):

- Radar and Lagrangian methods
- Spatially integrating methods
- Point source and related technology
- Acoustic Doppler Current Profilers and related technology

The large number of instruments and methods used to measure currents underscores that detection and analysis of fluid motion in the oceans is an exceedingly complex process. The difficulty arises from the large continuous scales of motion in the water. As stated by MCCULLOUGH (1980), "There is no single velocity in the water, but many, which are characterized by their temporal and spatial spectra. Implicit then in the concept of *a* fluid "velocity" is knowledge of the temporal and spatial averaging processes used in measuring it. Imprecise, or worse, inappropriate modes of averaging in time and/or space now represent the most prominent source of error in near-surface flow measurements." McCullough's comments were addressed to the measurement of currents in the ocean. In shallow water, particularly in the surf zone, additional difficulties are created by turbulence and air entrainment caused by breaking waves, by suspension of large concentrations of sediment, and by the physical violence of the environment. Trustworthy current measurement under these conditions becomes a daunting task.

Lagrangian

Dye, drogues, ship drift, bottles, temperature structures, oil slicks, radioactive materials, paper, wood chips, ice floes, trees, flora, and fauna have all been used to study the surface motion of the oceans (MCCULLOUGH, 1980). Some of these techniques, along with the use of mid-depth drogues and seabed drifters, have been widely used in coastal studies. A disadvantage of all drifters is that they are only quasi-Lagrangian sensors because, regardless of their design or mass, they cannot exactly follow the movement of the water (VACHON, 1980). Nevertheless, they are particularly effective at revealing surface flow patterns if they are photographed or video recorded on a time-lapse basis. Simple drifter experiments can also be helpful in developing a sampling strategy for more sophisticated subsequent field investigations. Floats, bottom drifters, drogues, and dye are used especially in the littoral zone where fixed current meters are adversely affected by turbulence. RESIO and HANDS (1994) analyzed the use of seabed drifters and commented on their value in conjunction with other instruments.

High frequency (HF) radar surface-current mapping systems have been tested since the 1970's. The advantage of using the radar is that these systems were able to accurately assess horizontal currents in a mean water depth of only 1 m (total layer thickness about 2 m). Hence, HF radar accurately senses horizontal currents in the uppermost layers of the oceans, where other instruments such as moored current meters and acoustic Doppler profilers become inoperable (BARRICK, LIPA, and LILLEBOE, 1990). Nevertheless, HF radar has had limited success in the oceanography community because of the difficulty in proving measurement accuracy and because of relatively high system costs (APPELL and CURTIN, 1990).

Spatially Integrating Methods

To date, experiments in spatially averaging velocity by observing induced electrical fields have been conducted by towing electrodes from ships or by sending voltages in abandoned underwater telephone cables. Some of these experiments have been for the purpose of measuring barotropic flow in the North Pacific (CHAVE, LUTHER, and FILLOUX, 1990; SPAIN, 1990—these two papers provide a substantial summary of the mathematics and methods). This author is unaware of whether these techniques have been tested in shallow water or in restricted waterways such as channels. At this time, therefore, spatially integrating methods appear to have no immediate application to coastal engineering studies.

Point Source (Eulerian) and Related Technology

In channels, bays, and offshore, direct measurements of the velocity and direction of current flow can be made by instruments deployed on the bottom or at various levels in the water column. Two general classes of current meters are available: mechanical (impeller-type) and electronic. Several types of electronic current meters are in common use, including electromagnetic, inclinometer, and acoustic travel-time (FREDETTE *et al.*, 1990; MCCULLOUGH, 1980; PINKEL, 1980).

Impeller current meters measure currents by means of a propeller device which is rotated by the current flow. They serve as approximate velocity component sensors because they are primarily sensitive to the flow component in a direction parallel to their axle. Various types of propeller design have been used to measure currents, but experience and theoretical studies have shown that the ducted propellers are more satisfactory in measuring upper ocean currents than rotor/vane meters (DAVIS and WELLER, 1980). One model, the Endeco 174, has been widely used by CERC for many years throughout the country. Impeller gauges are subject to snarling, biofouling, and bearing failures, but are more easily repaired in the field and are more easily calibrated than other types (FREDETTE *et al.*, 1990).

Electronic current meters have some great advantages: rapid response and self-contained design with no external moving parts. They can be used in real-time systems and can be used to measure at least two velocity components. The degree of experience of the persons working with the instruments probably has more influence on the quality of data acquired than does the type of meter used (FREDETTE *et al.*, 1990). The InterOcean Systems S4 electromagnetic meter has been successfully used by CERC at field experiments.

Acoustic Doppler Current Profilers

These profilers (known as ADCP's) operate on the principle of Doppler shift in the backscattered acoustic energy caused by moving particles suspended in the water. Assuming that the particles have the same velocity as the ambient water, the Doppler shift is proportional to the velocity components of the water within the path of the instrument's acoustic pulse (BOS, 1990). The backscattered acoustic signal is divided into parts corresponding to specific depth cells, often termed "bins." The bins can be various sizes, depending upon the depth of water in which the instrument has been deployed, the frequency of the signal pulse, the time that each bin is sampled, and the acceptable accuracy of the estimated current velocity. ADCP's have generated much excitement among scientists working in shallow water and in the deep ocean (a comprehensive bibliography is listed in GORDON *et al.* (1990)). A great advantage of using ADCP's in shallow water is that they provide profiles of the velocities in the entire water column, providing more comprehensive views of water motions than do strings of multiple point source meters. ADCP data are inherently noisy, and signal processing and averaging are critical to the successful performance of the gauges (TRUMP, 1990).

Indirect Estimates of Currents

Indirect estimates of current speed and direction can be made from the orientation, size, and shape of bed forms, particularly in shallow water. Widespread use of side-scan sonar has made this type of research possible in bays, inlets, and offshore. Sedimentary structures on the seafloor are caused by the hydrodynamic drag of moving water acting on sediment particles. The form and shape of bottom structures reflect the effects and interaction among tidal currents, waves, riverine flow, and longshore currents. These complex interactions especially affect bedforms in tidal channels and other restricted waterways. Bedforms reflect flow velocity, but are generally independent of depth (CLIFTON and DINGLER, 1984; BOOTHROYD, 1985). Their shape varies in response to increasing flow strength (HAYES and KANA, 1976). Bedform orientation and associated slipfaces also provide clues to flow direction (MORANG and MCMASTER, 1980; WRIGHT, SONU, and KIELHORN, 1972).

CURRENT RECORDS

Types of Coastal Currents

Current data are often critical for evaluating longshore and cross-shore sediment transport and for evaluating hydraulic processes in inlets and other restricted waterways. Currents, which are generated by a variety of mechanisms, vary greatly spatially and temporally in both magnitude and direction. Four general classes of unidirectional flow affect coastal environments and produce geologic changes. These include:

- Nearshore wave-induced currents, including longshore and rip currents
- Flow in tidal channels and inlets, which typically changes direction diurnally or semi-diurnally, depending on the type of tide along the adjacent coast
- River discharge
- Oceanic currents, which flow along continental land masses

This section will briefly discuss the first two of these topics and present data examples. The third and fourth are beyond the scope of this paper, and the reader is referred to outside references for additional information.

Nearshore Wave-Induced Currents

In theory, one of the main purposes for measuring nearshore, wave-induced currents is to estimate longshore transport of sediments (KOMAR and INMAN, 1970; KOMAR, 1976). At the present level of technology and mathematical knowledge of the physics of sediment transport, the direct long-term measurement of longshore currents by gauges is impractical. Two main reasons account for this unfortunate situation. First, deployment, use, and maintenance of instruments in the nearshore and the surf zone are difficult and costly. Second, the mechanics of sediment transport are still little-understood, and no one mathematical procedure is yet accepted as the definitive method to calculate sediment transport, even when currents, grain size, topography, and other parameters are known (SEYMOUR, 1989). An additional consideration is how to monitor the variation of current flow across and along the surf zone. Because of the extreme difficulty of obtaining data from the surf zone, neither the cross-shore variations of currents nor the temporal changes in longshore currents are well known.

Longshore (or *littoral*) *drift* is defined as: "Material (such as shingle, gravel, sand, or shell fragments) that is moved along the shore by a littoral current" (BATES and JACKSON, 1984). Net longshore drift refers to the difference between the volume of material moving in one direction along the coast and that moving in the opposite direction (BASCOM, 1964). Along most coasts, longshore currents change directions throughout the year. In some areas, changes occur in cycles of a few days, while in others the cycles may be seasonal. Wind can be a particularly strong influence on longshore currents, and can even reverse the direction from what would be expected from wave influence alone. Therefore, one difficulty in determining *net* drift is defining a pertinent time frame. Net drift averaged over years or decades may conceal the fact that significant amounts of material may also flow in the opposite direction.

Because net longshore currents may vary greatly from year to year along a stretch of coastline, it would be desirable to deploy current meters at a site for several years in order to obtain the greatest amount of data possible. Unfortunately, the cost of a multi-year deployment can be prohibitive. Even a long deployment might not detect patterns that vary on decade-long scales, such as the climatic changes associated with El Niño. At a minimum, near-shore currents should be monitored at a field site for at least a year in order to assess the changes associated with the passing seasons. Coastal scientists must be aware of the limitations of field current data and recognize that long-term changes in circulation patterns may remain undetected despite the best field monitoring efforts.

Flow in Tidal Channels and Inlets

An inlet is "a small, narrow opening in a shoreline, through which water penetrates into the land" (BATES and JACKSON, 1984). Many coastal scientists use a broader definition and consider inlets to range in size from short, narrow breaches in barrier islands to wide entrances of major estuaries like Chesapeake Bay. Many geologic and engineering studies concern flow through tidal inlets in sand-dominated barriers, particularly when the inlets serve as navigation channels. Management and maintenance of navigation channels through inlets is a major expense for the Corps of Engineers throughout the United States.

Inlets exchange water between the sea and the bay during each tidal cycle. Therefore, currents in tidal inlets are typically unidirectional, changing direction diurnally or semidiurnally, depending upon the tides along the adjacent open coast. Flow through the inlets can be complicated by the hydrodynamics of the inland bay, especially if there are other openings to the sea.

Various numerical and conceptual models have been developed to describe flow through inlets and allow researchers to predict the effects of changing inlet dimensions, lengths, and orientations (AUBREY and WEISHAR, 1988; ESCOFFIER, 1977; SEELIG, HARRIS, and HERCHENRODER, 1977; U.S. ARMY CORPS OF ENGINEERS, 1984). Most models, however, benefit from or require calibration with physical measurements made within the inlet and nearby. The required field measurements are usually either tidal elevations from the open sea and within the adjacent bay or actual current velocities from within the inlet's throat.

Display of tidal elevation data is relatively straightforward, usually consisting of date or time along the x-axis and elevation on the y-axis. Examples of tidal elevations from a bay and an inlet in the Florida Panhandle are shown in Figure 11. Although the overall envelope of the curves is similar, each one is unique with respect to the heights of the peaks and the time lags. The curves could be superimposed to allow direct comparison, but, at least at this 1-month-long time scale, the result would be too complicated to be useful.

Display of current meter measurements is more difficult because of the large quantity of data usually collected. An added difficulty is posed by the changing currents within an inlet, which require a three-dimensional representation of the flow which varies with time. Current measurements from East Pass, Florida, collected during three field experiments in the mid-1980's are presented as examples. Currents were measured with manual Price type AA meters deployed from boats and with tethered Endeco 174 current meters. The manual measurements were made hourly for 24 hr to observe a complete tidal cycle. The measurements were made across the inlet at four stations, each one consisting of a near-surface, a mid-depth, and a near-bottom observation (Figure 12). Therefore, 12 direction and velocity data values were obtained at each hour (Figure 13). One way to graphically display these values is to plot the velocities on a plan view of the physical setting, as shown in Figure 12. This type of image clearly shows the directions and relative magnitudes of the currents. In this example, the data reveal that the currents flow in opposite directions in the opposite sides of the inlet. The disadvantage of the plan view is that it is an instantaneous snapshot of the currents, and the viewer cannot follow the changes in current directions and magnitudes over time unless the figure is redrawn for each time increment. Temporal changes of the currents can be shown on dual plots of magnitude and direction (Figure 14). Unfortunately, to avoid complexity, it is not reasonable to plot the data from all 12 measurement locations on a single page. Therefore, measurements from the same depth are plotted together, as in Figure 14, or all measurements from one site can be plotted together (top, middle, and bottom).

In summary, current data can be displayed in the form of instantaneous snapshots of the current vectors or as time series curves of individual stations. Many plots are usually needed to display the data collected from even short field projects. It may be advantageous to present these plots in a data appendix rather than within the text of a report.

Error Analysis of Current Data

Error analysis of current records can be broadly divided into two categories. The first concerns calibrations of the actual current sensing instruments. A user needs to know how closely the numbers reported by a particular instrument represent the water motions that it is purported to be measuring. This information is important for both evaluation of ex-

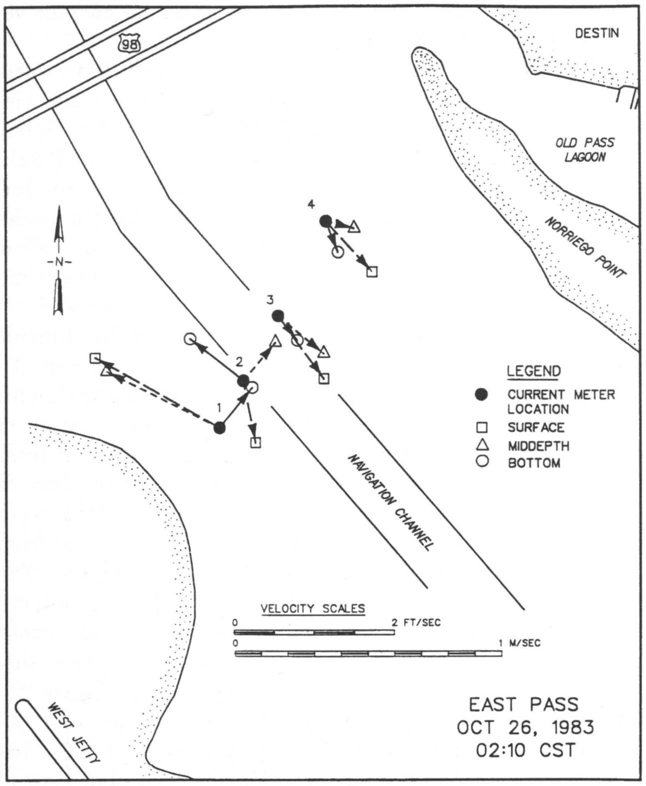


Figure 12. Current measurement stations in East Pass Inlet, Destin, Florida, during October, 1983. Measurements were made hourly from small boats. At 02:10 CST, currents were flowing to the northwest along the west side of the inlet and to the southeast along the center and east sides of the inlet. Station 2 was in the mixing zone.

isting data sets and for planning of new field experiments, where some instruments may be more suitable than others.

The second broad question pertains to whether the measurements which have been gathered adequately represent the flow field in the inlet or channel that is being examined. This second problem is exceedingly difficult to evaluate because it raises the fundamental questions of "How much data do I need?" and, "Can I afford to collect the data that will really answer my questions?" The user is typically tempted to respond that he wants just as much data as possible, but this may prove to be counterproductive. For example, if the currents in an inlet are being measured to determine variations in the tidal prism over time, will a dense grid of sampling stations in an inlet provide more useful data? Or might the excess data reveal unnecessary details about turbulence and mixing in the inlet? These are scientifically interesting questions, but may not be germane to the engineering problems that must be addressed. Although the dense grid pattern of data can be used to evaluate overall flow, the collection, analysis, and management of the excess data is costly and time-consuming. The money used on management of this data might be better spent extending a simpler sampling program for a longer period at the site. Unfortunately, there are no firm guidelines to planning current studies and placing instruments.

Analysis of error from various types of current sensors has been the subject of extensive study in the last 30 years. Numerous types of error can occur, both during field deployment of the instrument and during data processing. These can result from instrument calibration, clock time errors, and data recording and playback. In addition, the user is cautioned that each of the many types and brands of current meters is capable of recording accurately only a segment of the spectrum of water motions because of the influence of the mooring assembly, type of velocity sensor used, and recording scheme of the instrument (HALPERN, 1980). HALPERN's (1980) paper lists many references pertaining to the results of tests of moored current meters.

Manufacturers of current meters publish accuracy standards in their literature. These standards may be optimistic, especially under the adverse conditions encountered in many coastal settings. In addition, the type of mooring used for the instrument affects the quality of the measured data (HALPERN, 1978). For these reasons, the user of existing data is urged to obtain as much information as possible regarding the specifics of the deployment and the type of mooring in order to try to assess the accuracy of the results. Ultimately, successful use of current gauges is critically dependent upon the planning of the experiment and upon the care and skill of the technicians who maintain and deploy the instruments.

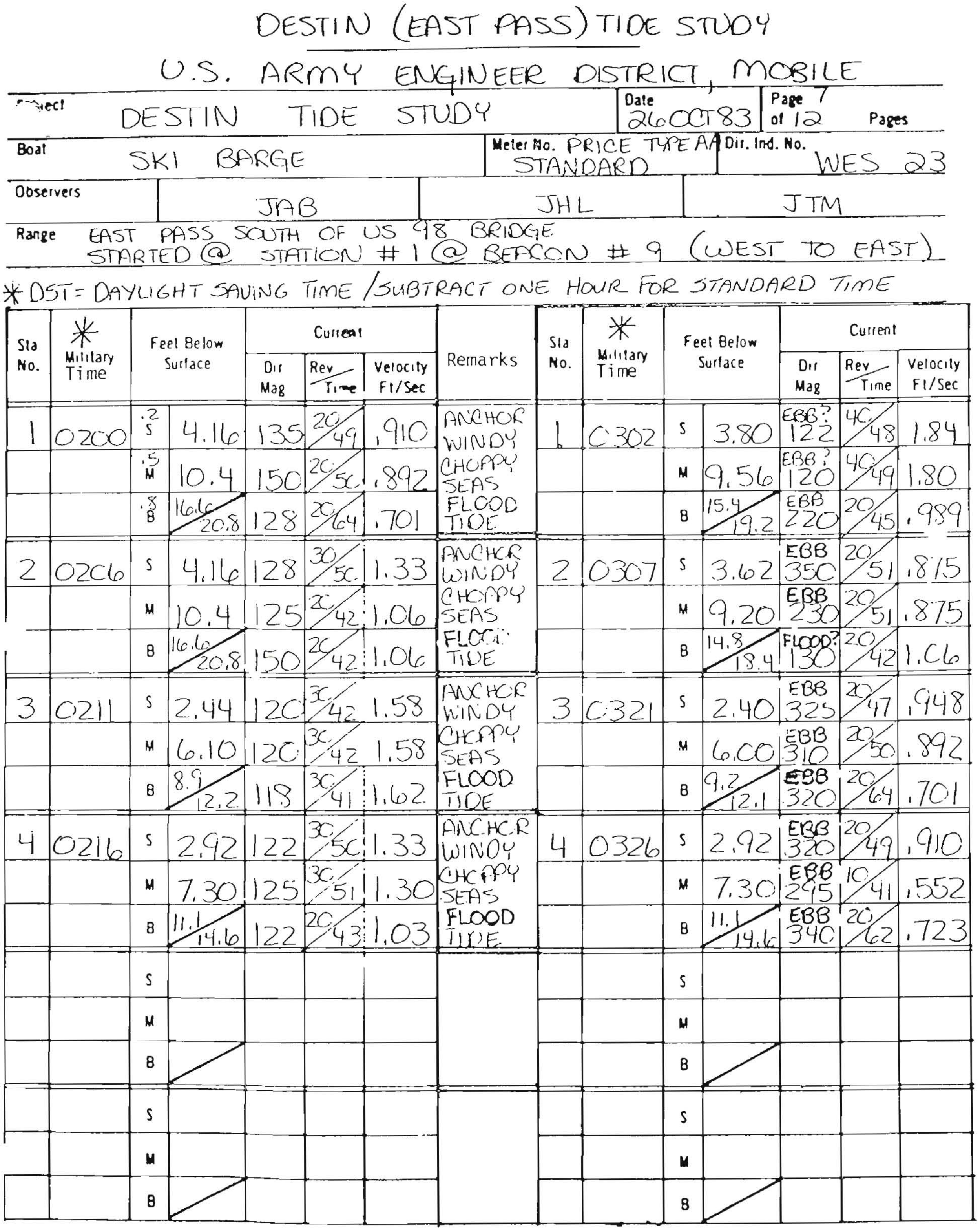
River Discharge

River outflow has a major effect on some coastlines, particularly where massive deltas have formed (*e.g.,* Mississippi River) (WRIGHT, 1985). Even if a study area is not located on a delta, coastal researchers must be aware of the potential impact of rivers on coastal processes, especially if the study region is affected by freshwater runoff at certain seasons or if longshore currents carry river-derived sediment along the shore.

River discharge data are available for many coastal rivers. A cursory examination of the annual hydrograph will reveal the seasonal extremes. Because of the episodic nature of coastal flooding, annual discharge figures may be misleading. A useful parameter to estimate river influence on the coast is the hydrographic ratio (H_R), which compares tidal prism volume with fluvial discharge volume (PETERSON *et al.,* 1984).

Ocean Currents

Major oceanic currents intrude onto some continental shelves with enough bottom velocity to transport sandy sediments. The currents operate most effectively on the outer shelf, where they may transport significant volumes of fine-grained sediments but presumably contribute little if any new sediment (BOGGS, 1987). Along most coastlines, ocean currents have little direct effect on shoreline sedimentation or erosion. Even off southeast Florida, where the continental shelf is narrow, the western edge of the Gulf Stream flows at least 1/2 km offshore. However, in some locations where currents approach the coastal zone, sediment discharged from



DESTIN (EAST PASS) TIDE STUDY

U.S. ARMY ENGINEER DISTRICT, MOBILE

Project DESTIN TIDE STUDY		Date 26OCT83	Page 7 of 12 Pages
Boat SKI BARGE	Meter No. PRICE TYPE AA STANDARD	Dir. Ind. No. WES 23	
Observers	JAB	JHL	JTM

Range EAST PASS SOUTH OF US 98 BRIDGE STARTED @ STATION #1 @ BEACON #9 (WEST TO EAST)

*DST = DAYLIGHT SAVING TIME / SUBTRACT ONE HOUR FOR STANDARD TIME

Sta No.	* Military Time	Feet Below Surface		Current			Remarks	Sta No.	* Military Time	Feet Below Surface		Current		
				Dir Mag	Rev / Time	Velocity Ft/Sec						Dir Mag	Rev / Time	Velocity Ft/Sec
1	0200	.2 S	4.16	135	20/49	.910	ANCHOR WINDY CHOPPY SEAS FLOOD TIDE	1	0302	S	3.80	EBB? 122	40/48	1.84
		.5 M	10.4	150	20/50	.892				M	9.56	EBB? 120	40/49	1.80
		.8 B	16.6 / 20.8	128	20/64	.701				B	15.4 / 19.2	EBB 220	20/45	.989
2	0206	S	4.16	128	30/50	1.33	ANCHOR WINDY CHOPPY SEAS FLOOD TIDE	2	0307	S	3.62	EBB 350	20/51	.815
		M	10.4	125	20/42	1.06				M	9.20	EBB 230	20/51	.875
		B	16.6 / 20.8	150	20/42	1.06				B	14.8 / 18.4	FLOOD? 130	20/42	1.06
3	0211	S	2.44	120	30/42	1.58	ANCHOR WINDY CHOPPY SEAS FLOOD TIDE	3	0321	S	2.40	EBB 325	20/47	.948
		M	6.10	120	30/42	1.58				M	6.00	EBB 310	20/50	.892
		B	8.9 / 12.2	118	30/41	1.62				B	9.2 / 12.1	EBB 320	20/64	.701
4	0216	S	2.92	122	30/50	1.33	ANCHOR WINDY CHOPPY SEAS FLOOD TIDE	4	0326	S	2.92	EBB 320	20/49	.910
		M	7.30	125	30/51	1.30				M	7.30	EBB 295	10/41	.552
		B	11.1 / 14.6	122	20/43	1.03				B	11.1 / 14.6	EBB 340	20/62	.723
		S								S				
		M								M				
		B								B				
		S								S				
		M								M				
		B								B				

Figure 13. Example of handwritten field notes listing times and data values of East Pass current measurements. The data are efficiently presented but difficult to visualize.

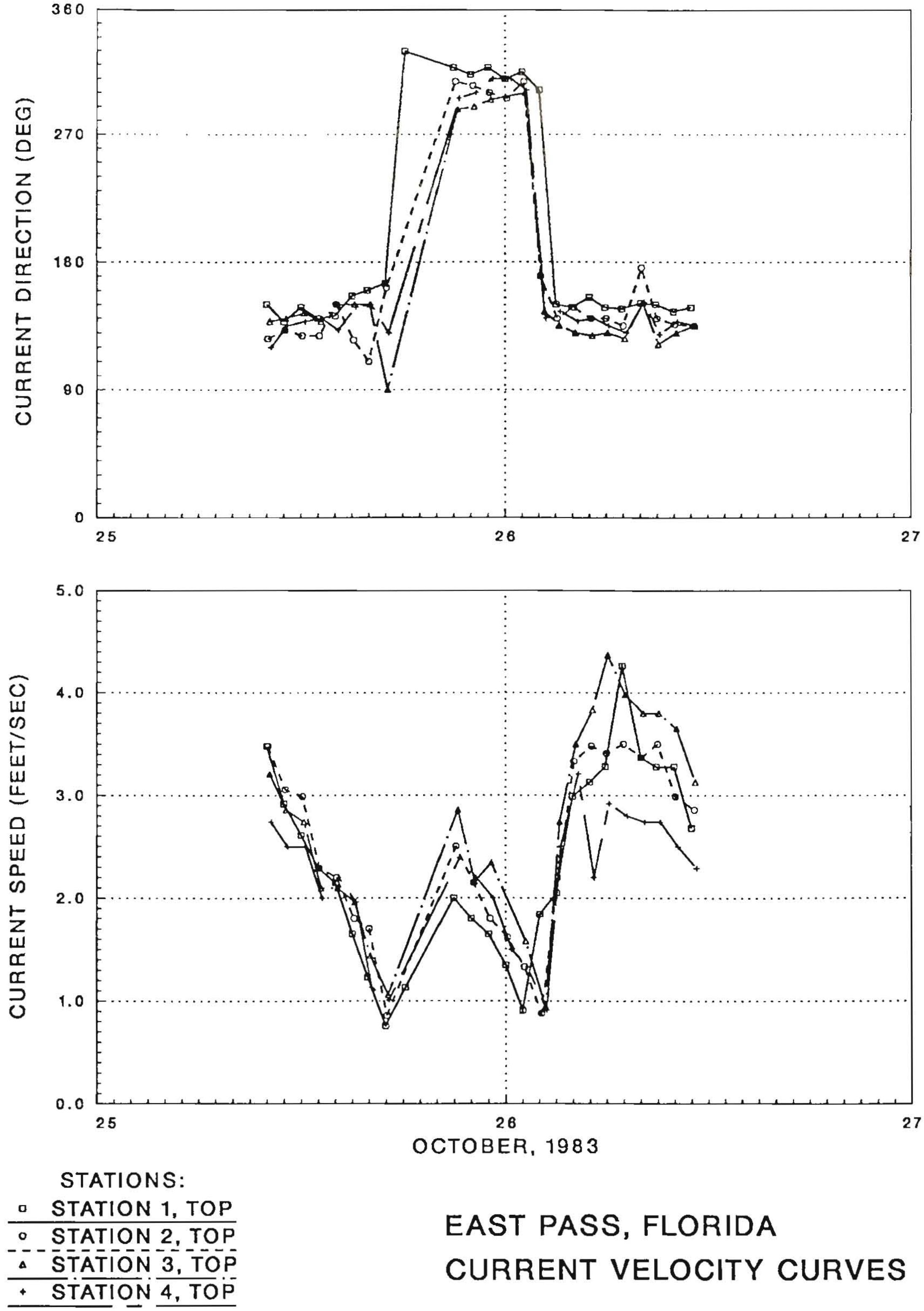


Figure 14. Time series plots of East Pass current speed (bottom) and direction (top).

rivers is transported and dispersed along the adjacent coastline. This process may arrest the seaward progradation of the delta front, while causing extensive accumulations of riverine-derived clastics downdrift of the river mouth (WRIGHT, 1985).

In shallow carbonate environments, reefs thrive where currents supply clean, fresh ocean water. Reefs stabilize the bottom, provide habitat for marine life, produce carbonate sediment, and sometimes protect the adjoining shore from direct wave attack (*i.e.*, the Great Barrier reef of Australia). In the United States, live reefs are found in the Gulf of Mexico off Texas and west Florida and in the Atlantic off Florida. Coral atoll islands are found throughout the south Pacific. For geologic or engineering studies in these environments, there may be occasional need to monitor currents. Procedures of deep-water current measurement are presented in APPELL and CURTIN (1990) and MCCULLOUGH (1980).

In summary, the effect of tide or wave-induced currents is likely to be much more important to most coastal processes than ocean currents. Measurement of ocean currents may occasionally be necessary for geologic studies in deltaic or carbonate environments.

SUMMARY

The measurement of waves and currents in the high-energy, hazardous nearshore zone is one of the more challenging endeavors of coastal engineering. A measurement program must be thoroughly planned *before* any gauges are deployed to insure that useful data are collected. We suggest the following steps be followed as part of the planning process:

(1) Determine what data are needed to answer the critical engineering or scientific questions. This is especially true of wave measurements: what units are to be reported? How are the statistics to be computed? How thoroughly must the flow be evaluated in an inlet?

(2) Determine how long the measurements must be collected. For example, to determine seasonal changes in wave climate, wave gauges are needed for several years, whereas to determine the tidal prism flowing through an inlet, several discrete 24-hour experiments might be adequate.

(3) Is there any pre-existing wave or current data from the study area? Possibly the new experiment's instruments should be placed in the same locations to make the new and old data as compatible as possible. Is the old raw data available so that it can be reprocessed?—(usually it is lost).

(4) Are there environmental factors that might impose constraints on the measurement program? For example, if ice is likely, surface buoys can be damaged. During the ice season, bottom gauges probably cannot be serviced. Bottom-mounted wave or current meters are highly vulnerable to fishing trawlers. Current measurements are difficult to collect in busy navigation channels.

(5) How critical are the measurements? Many oceanographic instruments are notoriously unreliable (even when they are not damaged by external hazards like fishing boats), and a researcher may want to deploy two gauges at each mount to increase the likelihood of retrieving data at critical times such as during storms.

(6) How much funding is available? This may require that the previously determined parameters be adjusted or the sponsor diplomatically approached for more money.

Wave gauges and current meters are constantly being improved, and since the late 1980's there have been dramatic improvements in data-storage capacity and energy management. Solid-state data recording has greatly improved reliability compared to cassette tape recording. Some wave gauges can be deployed for over twelve months. Acoustic Doppler current profilers can now record current flow throughout the water column in bins as small as a few decimeters, an accomplishment that was impossible in the days of moored inducted current meters. Researchers are urged to review the pertinent literature and take advantage of these new instruments whenever possible (with the caveat that they remain skeptical of wonder instruments until their use is proven and scientific validity verified).

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