NOAA Technical Report NOS CO-OPS 022

ASSESSMENT OF THE NATIONAL OCEAN SERVICE'S TIDAL CURRENT PROGRAM

Silver Spring, Maryland
April 1999

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE

National Ocean Service
Center for Operational Oceanographic Products and Services
Products and Services Division

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) collects and distributes observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and coastal current products required to support NOS' Strategic Plan mission requirements, and to assist in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), and a national network of Physical Oceanographic Real-Time Systems (PORTS) in major U.S. harbors. The Center: establishes standards for the collection and processing of water level and current data; collects and documents user requirements which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

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ACRONYMS AND ABBREVIATIONS

ADCP	acoustic Doppler current profiler
AK	Alaska
AL	Alabama
CA	California
CFR	Code of Federal Regulation
CO-OPS	Center for Operational Oceanographic Products and Services
C&GS	Coast and Geodetic Survey
D	diurnal tides
DOT	Department of Transportation
FL	Florida
GA	Georgia
HI	Hawaii
HR	House of Representatives
LA	Louisiana
MA	Massachusetts
MD	Maryland
ME	Maine
MEC	maximum ebb current
MFC	maximum flood current
MN	mostly nontidal tides
MMD	mixed mainly diurnal tides
MMS	mixed mainly semidiurnal tides
MS	Mississippi
MT	mostly tidal
NH	New Hampshire
NJ	New Jersey
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NWLON	National Water Level Observation Network
NY	New York
OR	Oregon
PORTS™	Physical Oceanographic Real-Time System (Trademark)
PSD	Products and Services Division
RI	Rhode Island
S	semidiurnal
TD	tidal dominated
TX	Texas
US	United States
USC	United States Code
$\mathbf{V_{NT}}$	nontidal variance
$\mathbf{V_{T}}$	total tidal variance
WA	Washington

EXECUTIVE SUMMARY

In an effort to provide quality data and information on a national level, the Center for Operational Oceanographic Products and Services is assessing the National Ocean Service's tidal current program. The intent of this document is to set guidelines for future current surveys in order to update the U.S. reference stations in the Tidal Current Tables and to identify areas where real-time monitoring of currents may be appropriate. The assessment of the Tidal Current Tables is based on a study of the 1) age, instrumentation, and duration of data coverage, 2) commercial importance of the region, and 3) tidal and nontidal dynamics of coastal areas. A method of using data from long term water level stations to characterize the importance of nontidal variance at tidal current reference stations is developed. Based on these results, recommendations are made for updating older reference stations and creating new reference stations. Potential locations for real-time current monitoring by Physical Oceanographic Real-Time Systems (PORTS^{TM}) are identified. In addition to real-time current data, PORTS^{TM} provides other critical navigational information such as water level, density, and meteorological data.

In view of the correlation between the factors of age, instrumentation, and length of observations, the Center for Operational Oceanographic Products and Services recommends updating thirteen of the existing tidal current reference stations where observations were collected with poles and floats before 1950, and updating twelve additional stations where data of short duration were collected between 1942 and 1985. Three existing reference stations have significant nontidal variability and are recommended for real-time monitoring of currents based on the economic importance of the ports they serve. Thirteen ports without tidal current reference stations, where vessel traffic and commerce exceed 10 million tons, are evaluated and recommended for a new tidal current reference station. The installation of a real-time current monitoring system is recommended at seven of these ports.

1. INTRODUCTION

The Center for Operational Oceanographic Products and Services (CO-OPS) provides the public with coastal oceanographic information necessary to support the National Oceanic and Atmospheric Administration's environmental assessment and prediction mission, in particular the strategic goal to promote safe navigation. The Center increases the efficiency of the maritime industry and the safe use of U.S. ports by providing tidal predictions, real-time water level and current observations, and forecasts. Operational water level and current information are important in assisting environmental preservation and restoration, and for monitoring, evaluating, and predicting hazardous spill response needs, effects of sea level rise in coastal regions, and risks associated with storm surges and tsunamis.

1.1 Tidal Current Predictions

Professional mariners and ship operators of all propelled vessels of 1600 gross tons or more are required by the Code of Federal Regulation (33 CFR Chapter I, 7/1/91 Edition, U.S. Coast Guard, DOT '164.01 and '164.33) to carry the current edition of the Tide Tables and the Tidal Current Tables published by the National Ocean Service (or its equivalent) when operating their vessel in navigable waters of the United States, except in the St. Lawrence Seaway. The Tables predict the daily magnitude and timing of high and low waters, maximum floods, maximum ebbs, and slacks for a limited number of representative stations known as reference stations. Predictions at these locations are the basis for predictions at thousands of subordinate stations through the use of scaling factors and time differences. These parameters are printed in the Tables and it is up to the user to apply them properly to daily predictions at the appropriate reference stations. It is clearly evident that all tidal predictions depend on the quality of the predictions at the reference stations.

1.2 NOS Responsibilities

The evolution of NOS began with The Organic Act of February 10, 1807 (2 Stat, 413), a Congressional Act which established the Survey of the Coast (later to be known as the Coast Survey, the Coast and Geodetic Survey, and finally, in 1970, the National Ocean Service). The study, collection, and dissemination of water level and current observations and predictions have remained a primary focus. The first Tide Tables were published in 1867, and by 1890 tidal current predictions were introduced for New York Harbor and vicinity. The two volumes of the Tidal Current Tables for the Atlantic Coast and the Pacific Coast of North America were first published separately from the Tide Tables in 1923.

NOS is statutorily authorized to collect, analyze, and disseminate data on tides and currents pursuant to the 33rd United States Code, Sections 883a - 883f established under the auspices of the Act of August 6, 1947 (61, Stat, 787). Specifically, 33 USC 883a authorizes NOS to conduct hydrographic surveys, water level and current observations, geomagnetic, seismological, gravity, and related geophysical measurements and investigations, and observations for the determination of latitude and longitude. In addition, 33 USC 883b authorizes NOS to analyze and predict tides and currents, and to process and publish data information, compilations, and reports. A bibliography of tidal current survey technical reports published since the establishment of NOAA in 1970 has been compiled in

Appendix A. These reports provide detailed information about the current survey data collected and the subsequent data analyses carried out.

The mission of NOS' recently-established Center for Operational Oceanographic Products and Services is to provide the national infrastructure, and the scientific and technical expertise to monitor, assess, and distribute tide, current, water level, and other coastal oceanographic products and services necessary to support NOAA's mission. An important aspect of this mission is promoting safe navigation and improving the efficiency of the maritime industry and the economic productivity of U.S. ports by providing real-time water level and current observations, predictions, forecasts, and other coastal oceanographic information.

The 105th U.S. Congress passed H.R. 3461 on March 12, 1998, approving a governing international fishery agreement between the United States and the Republic of Poland. This House of Representatives bill, which became Public Law 105-384 on November 18, 1998, authorizes appropriations for conducting tide and current measurements under the Act of 1947 for fiscal years 1999 through 2002. CO-OPS is authorized to implement and operate a national quality control system for real-time tide and current data, and to design and install real-time tide and current data measurement systems under section 303(b)(4).

In support of CO-OPS' mission, tidal current reference stations are being updated by the implementation of short term current surveys or the installation of Physical Oceanographic Real-Time Systems (PORTS™). PORTS™ is a decision support tool which improves the safety and efficiency of maritime commerce and coastal resource management through the integration of real-time environmental observations, forecasts, and other geospatial information. PORTS™ collects and disseminates observations and predictions of water levels, currents, temperature, salinity, and meteorological parameters (winds, atmospheric pressure, visibility, etc.) needed by the mariner to navigate safely. PORTS™ has been built upon CO-OPS' real-time water level measurement capabilities by adding incremental improvements to field systems, sensor capabilities, communications, information systems, and operational procedures to ensure that the full value of NOS' capabilities is realized by the marine transportation community and other users requiring operational oceanographic information [*NOS*,1998]. Although PORTS™ has been developed by NOS and a need for real-time current data may be identified in this document, the funding for installation and operation of a PORTS™ remains the responsibility of the local maritime community.

1.3 Objectives

In the past, NOS has relied upon input from local marine pilots associations, harbor officials, commercial shipping companies, and state and local marine managers to assist in selecting estuaries that require updated tidal current predictions or real-time current monitoring for increased navigational safety. This report is intended to provide a basis for evaluating these requests by identifying potential sites based on new current survey priorities that depend on shipping activity, economic value of cargo, and increasing vessel traffic and tonnage.

The objectives of this study are three-fold: 1) assess the quality of the reference station predictions in the NOS Tidal Current Tables, 2) prioritize the NOS tidal current reference stations based on economic and commercial importance of the ports they serve, and 3) characterize the tidal and nontidal dynamics of U.S. coastal areas. This evaluation will determine which tidal current reference stations should be updated, suggest locations for new tidal current reference stations, and indicate where real-time monitoring of currents would contribute to increased navigational safety. This document does not assess the accuracy of predictions at subordinate stations referenced to the tidal current reference stations. The assessment of the subordinate stations may be performed at a future time.

This report begins with a thorough review of the existing tidal current reference station information in Section 2. Shipping tonnage statistics for major U.S. coastal ports are associated with an appropriate tidal current reference station and are discussed in Section 3. Section 4 includes the harmonic analysis of long term water level stations in order to characterize the tidal and nontidal dynamics in the vicinity of tidal current reference stations. Recommendations for updating predictions at existing tidal current reference stations and creating new ones are presented in Section 5, along with a discussion of locations where nontidal dynamics are important and real-time current observations may be needed.

2. REVIEW OF TIDAL CURRENT REFERENCE STATIONS

The published NOS Tidal Current Tables are presented in the same format as the NOS Tide Tables. A limited number of stations known as reference stations have daily predicted times of floods, ebbs, and slacks and maximum current at floods and ebbs printed in a section known as "*Table 1*". The established tidal current constituents that are used to make these predictions should be based on the highest quality data available. Most tidal current predictions are based on data sets that would be considered inadequate for making tidal water level predictions. Historically, due to technological, logistical, and resource limitations, current measurements are of a shorter duration than water level measurements. The long term continuous operation of the National Water Level Observation Network (NWLON) stations, results in tidal water level constituents that are better resolved and more up to date than the tidal current constituents.

The tidal constituents are obtained by a process known as harmonic analysis. For short periods, a Fourier harmonic analysis is carried out [*Dennis and Long*, 1971]. Either a 15-day or a 29-day period of continuous data can be analyzed. The 15-day analysis results in 9 computed tidal current constituents and 15 constituents inferred from the computed constituents. The 29-day analysis results in 10 computed constituents and 14 inferred constituents. For longer sets of data, a least squares harmonic analysis is employed. A year of observations can be used to accurately resolve 32 of the 37 standard tidal constituents used by NOS for making predictions, although good results can often be obtained with only six months of data [*Zervas*, 1999]. With smaller data sets, either a least squares harmonic analysis for fewer constituents may be used or results from several 29-day Fourier harmonic analyses may be averaged together.

For a larger group of tidal current stations called subordinate stations, predicted floods, ebbs, and slacks are calculated by the user from the "*Table 1*" predictions with time differences and speed ratios. These constants are listed in a section of the Tidal Current Tables known as "*Table 2*". "*Table 2*" also indicates to which tidal current reference station to apply these constants. The constants are obtained by a nonharmonic analysis which compares a short period of data at the subordinate station with observations or predictions for the same period at the reference station. The amount of subordinate station data used is usually less than 15 days and in some cases as little as 1 day. Deciding which reference station to use for a subordinate station is a subjective decision usually based on proximity and similarity in the shapes of the tidal current curves.

Data from tidal current reference stations are the source for computing accepted values of harmonic and nonharmonic constants essential to daily tidal current predictions. Existing tidal current predictions are presently based on limited data sets from reference stations that date as early as 1901 (North Inian Pass). Reference station name, location, year the data were obtained, length of time series, type of instrument used, and number of secondary stations associated with each reference station are summarized in Appendix B. The data from these stations serve as the control for the reduction of short time series from subordinate current stations through comparison of simultaneous observations. Historically, reference stations require a minimum of 15 days of continuous velocity observations for harmonic analysis from which subordinate stations predictions can be computed with time differences and speed ratios. Longer time series improve predictions at reference stations by separating similar harmonic constituent frequencies.

A map showing existing tidal current reference stations in the United States illustrates the limitations of the predictions based on age and length of observations (Figure 1). The tidal current reference stations outside of the United States are not evaluated in this document.

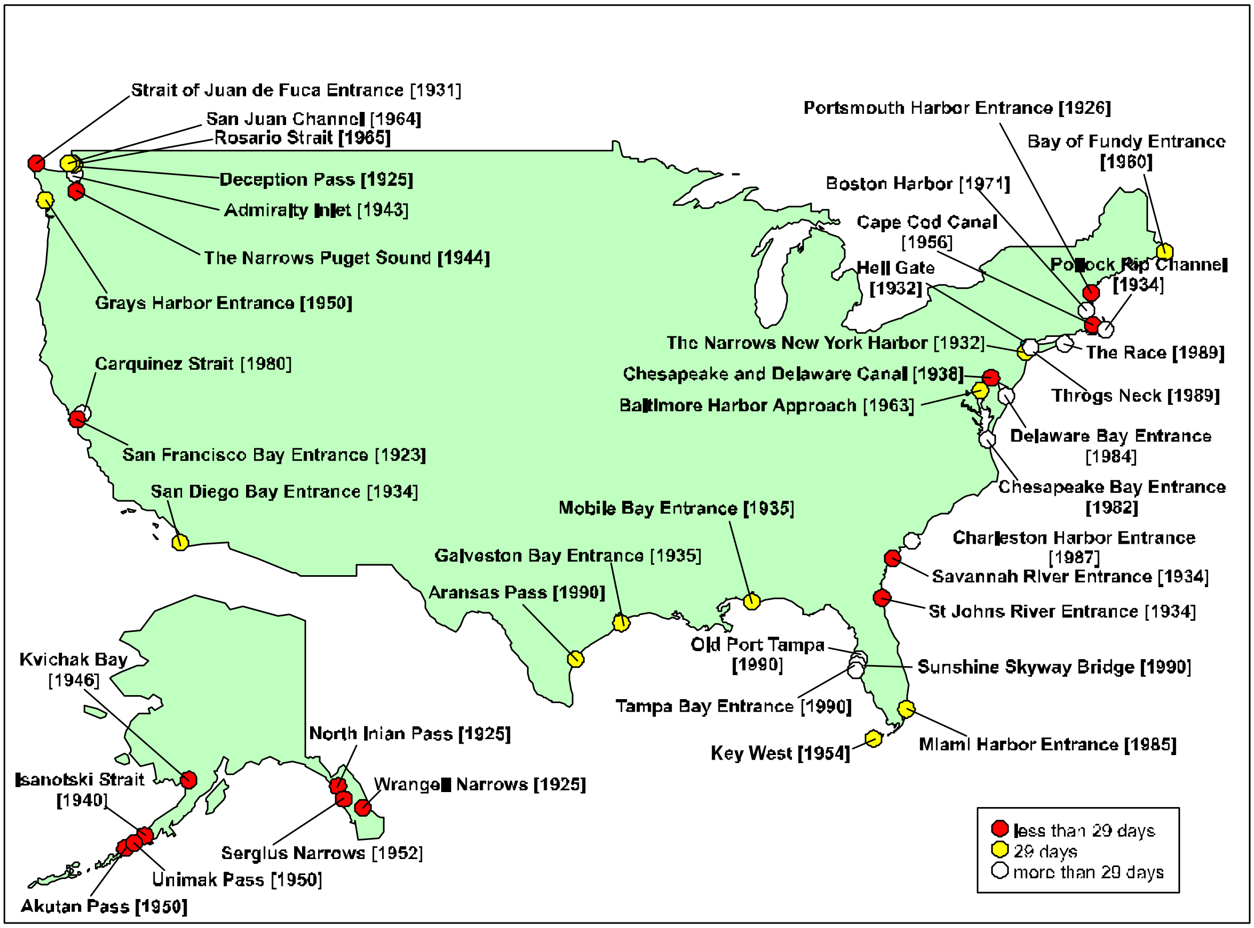

Figure 1. Tidal current reference stations of the United States categorized by duration of observations with the year of data acquisition in brackets.

2.1 Geographical Coverage

There are some noticeable geographical gaps between tidal current reference stations along the U.S. coastline. The most noticeable gaps along the Atlantic Coast are between Chesapeake Bay Entrance and Charleston Harbor Entrance and the Florida coast between St. Johns River Entrance and Miami Harbor Entrance. Geographical gaps along the Gulf Coast exist between Tampa Bay Entrance and Mobile Bay Entrance and from Mobile Bay Entrance to Galveston Bay Entrance. The most noticeable gaps along the Pacific Coast are between San Diego Bay Entrance and San Francisco Bay Entrance and between San Francisco Bay Entrance and Grays Harbor Entrance. There is a large geographical gap in tidal current reference stations along the southern coast of Alaska and Hawaii has no tidal current reference station.

For “*Table 2*" purposes, the subordinate station data collected in these gaps had to be associated with a distant reference station with similar tidal characteristics. The subordinate stations along the North Carolina coast are all referenced to Charleston Harbor Entrance. The east Florida coast (with the exception of St. Johns River) is referenced to Miami Harbor Entrance. Most of the Gulf coast of Florida (excluding Pensacola) is referenced to Tampa Bay Entrance. The Louisiana coast is divided between Mobile Bay Entrance and Galveston Bay Entrance.

All the subordinate stations along the California coast north of San Diego are referenced to San Francisco Bay Entrance. Many of the subordinate stations along the Oregon coastline are referenced to the reference station at Wrangell Narrows in Alaska, although the Columbia River stations are referenced to Grays Harbor Entrance. The subordinate stations along the southern coast of Alaska are referenced to the three reference stations in southeastern Alaska. The Hawaiian Islands have no regional tidal current reference station. All of the Hawaiian subordinate stations are referenced to San Diego Bay Entrance.

2.2 Characteristics of the Tidal Current Constituents

The tidal constituents for the 41 tidal current reference stations were developed at different times based on varying lengths of data collected with a variety of current-measuring instruments. These constituents are used to produce the daily predictions in the Tidal Current Tables every year. Table 1 is a list of properties for each of the tidal current reference stations which can be used to compare and contrast the predicted tidal currents.

The number of constituents used to make tidal current predictions varies between 8 for the Canadian station, Bay of Fundy Entrance, and 33 for Charleston Harbor Entrance. Predictions for the Bay of Fundy Entrance are provided by the Canadian Hydrographic Service and it is included in this study because 135 U.S. subordinate stations are referenced to it. If the Fourier harmonic analysis program, which requires 29 continuous days of data, was used to derive the tidal constituents, a maximum of 24 constituents could be obtained. (Ten constituents are calculated and 14 constituents are inferred.)

Smaller constituents were often zeroed out. For example, at a number of stations, calculated constituents less than 0.03 knots and inferred constituents less than 0.01 knots were deleted (Appendix B). When the least squares harmonic analysis program is applied to data sets longer than 29 days, more of the 37 standard tidal constituents used by NOS for tidal predictions can be obtained. The five long-term constituents (semimonthly, monthly, semiannual, and annual periods) are unreliable without multiple year data sets and are usually zeroed out for tidal current stations. These five constituents, while often important for tide predictions, are usually not significant for tidal current predictions.

Table 1. Tidal Current Constituent Properties

Reference Station Name	Number of Subordinate Stations	Number of Constituents	MFC Speed (knots)	MEC Speed (knots)	Permanent Current (knots)	Tidal Ratio	Tidal Classification
Bay of Fundy Entrance (Canada)	135	8	2.3	2.4	-0.041	0.09	S
Portsmouth Harbor Entrance, NH	82	13	1.2	1.8	-0.300	0.11	S
Boston Harbor, MA	153	13	1.1	1.2	-0.280	0.15	S
Cape Cod Canal, MA	16	17	4.0	4.5	0.000	0.10	S
Pollock Rip Channel, MA	115	16	2.0	1.8	0.150	0.08	S
The Race, NY	155	22	2.7	3.0	-0.105	0.09	S
Throgs Neck, NY	16	21	1.0	0.6	0.035	0.04	S
Hell Gate, NY	33	20	3.4	4.6	-0.600	0.04	S
The Narrows, New York Harbor, NY	77	17	1.7	2.0	-0.200	0.14	S
Delaware Bay Entrance, DE	92	28	1.4	1.3	0.000	0.16	S
Chesapeake Bay Entrance, VA	247	32	0.8	1.2	-0.175	0.20	S
Baltimore Harbor Approach, MD	155	12	0.8	0.8	0.000	0.46	M M S
Chesapeake & Delaware Canal, MD	8	22	2.0	1.9	0.000	0.44	M M S
Charleston Harbor Entrance, SC	227	33	1.7	2.0	-0.217	0.11	S
Savannah River Entrance, GA	124	15	1.6	2.6	-0.450	0.10	S
St Johns River Entrance, FL	17	18	1.9	2.3	-0.350	0.17	S
Miami Harbor Entrance, FL	45	24	1.8	1.6	0.051	0.10	S
Key West, FL	18	16	1.0	1.7	-0.360	0.22	S
Tampa Bay Entrance, FL	54	29	1.3	1.3	0.037	0.80	M M S
Sunshine Skyway Bridge, FL	0	28	1.3	1.1	0.106	0.74	M M S
Old Tampa Bay Entrance, FL	16	29	1.0	0.9	-0.038	0.65	M M S

Reference Station Name	Number of Subordinate Stations	Number of Constituents	MFC Speed (knots)	MEC Speed (knots)	Permanent Current (knots)	Tidal Ratio	Tidal Classification
Mobile Bay Entrance, AL	14	15	1.4	1.5	0.000	18.6	D
Galveston Bay Entrance, TX	21	19	1.7	2.3	-0.250	1.76	M M D
Aransas Pass, TX	3	24	1.6	1.5	0.320	4.55	D
San Diego Bay Entrance, CA	27	16	1.2	1.5	-0.090	0.36	M M S
San Francisco Bay Entrance, CA	136	20	2.9	3.4	-0.200	0.38	M M S
Carquinez Strait, CA	57	29	2.1	2.2	-0.138	0.51	M M S
Grays Harbor Entrance, WA	44	20	1.9	2.8	-0.300	0.30	M M S
Strait of Juan de Fuca Entrance, WA	1	14	0.6	1.5	-0.500	0.53	M M S
Admiralty Inlet, WA	75	17	1.6	2.6	-0.500	0.53	M M S
The Narrows Puget Sound, WA	31	20	3.2	2.8	0.000	0.44	M M S
Deception Pass, WA	4	17	5.2	6.6	-0.650	0.29	M M S
Rosario Strait, WA	46	20	1.1	1.9	-0.400	0.70	M M S
San Juan Channel, WA	13	21	2.6	2.6	-0.050	0.50	M M S
Wrangell Narrows, AK	345	21	3.7	3.4	0.000	0.16	S
Sergius Narrows, AK	62	18	5.9	5.5	0.200	0.06	S
North Inian Pass, AK	28	21	2.9	5.1	-1.400	0.17	S
Isanotski Strait, AK	11	18	3.6	2.8	0.400	0.36	M M S
Unimak Pass, AK	35	20	3.4	3.0	0.500	0.72	M M S
Akutan Pass, AK	7	21	5.8	5.3	0.200	0.56	M M S
Kvichak Bay, AK	39	17	2.5	2.5	-0.300	0.29	M M S

S = Semidiurnal, M M S = Mixed Mainly Semidiurnal, M M D = Mixed Mainly Diurnal, D = Diurnal

The maximum flood currents (MFC) and maximum ebb currents (MEC), shown in Table 1, are the average of the greatest speeds during a flood or an ebb period. They provide an estimate of the strength of current at the reference stations which were usually chosen to be located where the strongest currents in a bay or estuary could be measured. The volume of water that must pass a given point in a bay or estuary is equal to the tidal prism above that location. The tidal prism is approximately the area of the bay multiplied by the mean tidal range of the bay. Tidal currents will be proportional to the tidal prism and inversely proportional to the cross sectional area through which the volume of water must pass. The strongest currents (> 5 knots) occur in narrow channels or channels through which large volumes of water must pass (Deception Pass, Sergius Narrows, and Akutan Pass). The weakest currents (< 1 knot) occur in wide or deep channels (Chesapeake Bay Entrance and Strait of Juan de Fuca Entrance) or at some distance from the ocean (Throgs Neck, Baltimore Harbor Approach, and Old Tampa Bay Entrance).

The permanent current in Table 1 is a unchanging current in the flood (positive) or ebb (negative) direction that is always assumed to be present when making tidal current predictions. It is obtained from the mean current measured during the deployment of the instrument. A permanent ebb current is commonly found in river estuaries. There are 24 reference stations which have permanent ebb currents, with the strongest at North Inian Pass (1.4 knots); all the other permanent ebb currents are less than 0.65 knots. Seven reference stations have zero for their permanent current. Ten reference stations have permanent flood currents. A permanent flood current is often driven by thermohaline circulation between fresh river water and salty ocean water. However, the strongest permanent flood current, at Unimak Pass (0.5 knots), is due to the exchange of water between the Pacific Ocean and the Bering Sea.

The accuracy of the permanent currents are dependent on the length of the data sets used to obtain them. A shorter deployment is less likely to give an accurate permanent current especially if there were anomalous river flow conditions at the time. Permanent currents can vary substantially with depth in the water column or with location in a channel. The presence of a strong permanent current affects the speeds of maximum flood and maximum ebb and the timing of the slacks. The reference stations where the permanent current is the greatest percentage of the average tidal current amplitude include the Strait of Juan de Fuca Entrance (48%) and North Inian Pass (35%). There were less than 3 days of current observations at these stations. All the other permanent currents are less than 27% of the average tidal current amplitude.

The tidal ratio as defined by Defant [1961] is a ratio of the amplitudes of the largest diurnal constituents ($K_1 + O_1$) to the largest semidiurnal constituents ($M_2 + S_2$), classifying tides as semidiurnal (< 0.25), mixed mainly semidiurnal (0.25 - 1.5), mixed mainly diurnal (1.5 - 3.0), or diurnal (> 3.0). A subordinate station should be associated with a reference station that has a similar tidal ratio. Table 1 identifies each of the reference station's tidal characteristics based on the tidal ratio. All of the east coast of the U.S. is semidiurnal with the exception of Baltimore Harbor Approach and Chesapeake & Delaware Canal, which are mixed mainly semidiurnal. In contrast, the Gulf of Mexico coast changes from semidiurnal to mixed mainly semidiurnal to diurnal to mixed mainly diurnal and back to diurnal, proceeding from Key West, FL to Aransas Pass, TX. All of the reference stations in California and Washington are mixed mainly semidiurnal. In Alaska, the southeastern stations are semidiurnal while the southwestern stations are mixed mainly semidiurnal.

2.3 Age of Data

Historical information for the 41 tidal current reference stations reveals the age of the observations used to derive the tidal constituents (Figure 1 and Appendix B). Tidal current predictions based on these observations are used to infer tidal currents at 2784 subordinate stations. Review of the NOAA tidal current reference station records shows that 20 of the 41 stations are based on data more than 50 years old, most of them derived from current pole or Zeskind float measurements (see section 2.4). The most recently acquired data were obtained by revisiting reference stations as requested by local pilots associations and harbor officials to update the tidal current predictions. Seven reference stations have been updated or added in the last 11 years with acoustic Doppler current profiler (ADCP) data. A complete summary of information for each tidal current reference station is presented in Appendix B.

The Atlantic Coast has 17 tidal current reference stations. The average age of the data is 38 years ranging from 1926 to 1989. There are 1697 (61% of the total) subordinate stations referenced to the Atlantic Coast reference stations. The most recently acquired data (1989) were used to update the Tidal Current Tables at Throgs Neck, and The Race, Long Island Sound. The reference station at Charleston Harbor Entrance was also recently updated with data collected in 1987 and 1988. (Since this assessment, NOS has updated Savannah River Entrance and St. Johns River Entrance with new tidal constituents.)

The Gulf Coast has 7 tidal current reference stations. The average age of the observations is 29 years ranging from 1935 to 1991. There are only 126 subordinate stations (4.5% of the total) referenced to the Gulf Coast reference stations. Predictions at four of the seven tidal current reference stations have been updated in the last eight years. The Galveston Bay Entrance predictions, which are based on data acquired in 1935, will be updated with PORTS^{TM} data, and should appear in the year 2000 Tidal Current Tables.

The Pacific Coast has 17 tidal current reference stations including 7 in Alaska. The average age of the observations is 55 years ranging from 1923 to 1980. There are 961 subordinate stations (34.5% of the total) referenced to the Pacific Coast reference stations. The most recent reference station is Carquinez Strait, first used in the 1989 Tidal Current Tables based on data from 1980. The most recent data used for an Alaskan reference station is six days of data from 1952 for Sergius Narrows. Although the reference station at San Francisco Bay Entrance is based on data from 1923 and 1930, the bay is monitored by PORTS^{TM} and real-time data are available. New San Francisco Bay Entrance predictions based on PORTS^{TM} data will appear in the Year 2000 Tidal Current Tables.

2.4 Instrumentation

There is a direct correlation between the age of the tidal current reference station and the type of instrument used to collect the observed data. Data collected from the early 1920s through much of the 1940s were of short duration using fixed-depth poles or Zeskind floats. Floats were used in narrow passages where the current was too swift to anchor a boat. Floats were either dropped from shore or upstream by boat and ranges were monitored by observers with stop watches [*C&GS*, 1950]. This type of measurement did not record direction and allowed for a wide margin of error.

The current pole and log line were the simplest form of apparatus used to measure observed surface current speed and direction. It consisted of a 15-foot pole weighted at the lower end to float upright with the top about a foot out of the water [*C&GS*, 1950]. The log line was attached to the pole and reeled out from a mounted stand. The line was graduated to reflect the velocity of the current in tenths of knots which was indicated by the amount of line carried out by the current pole in a specified interval of time. A full minute of recording current speed was measured using a stop watch noting the reference point (beginning mark on the log line). In strong currents, a 30-second run was used. The longest record of current pole observations was 748 days at Stonehorse Lightship in Pollock Rip Channel (August 6, 1934 through August 31, 1936). However, most current pole observations were for much shorter periods with only five reference stations having enough continuous data to allow a 29-day harmonic analysis.

Roberts Radio Current Meters were designed by Capt. Elliott Roberts of C&GS and used with success from the 1940s through the mid-1960s. The advantage of the Roberts Current Meter over the pole and log line was that it could be operated remotely from an anchored buoy and the length of data measurement was limited only by the life of the batteries. The buoy housed a radio transmitter, complete with batteries, electrically attached to the current meter and an above-water antenna. The current meter had a rotating impeller connected to a magnetic device that made and broke contact when actuated by the current. The devices were arranged so that when the instrument was heading south, both contacts occurred simultaneously. When the meter headed in any other direction, the time relation between the two sets of contacts changed with the meter heading. This time relation served as a measure of the direction of the current. The current speed was recorded as a number of seconds between contacts and transmitted by radio signals to a receiving station chronometer. The corresponding velocity was taken from a rating table prepared from the calibration of the meter [*C&GS, 1950*]. Instrument accuracy was plus or minus 0.1 knot for current speed and plus or minus 5 degrees for direction [*Long, 1978*].

Instrumentation used within the last 30 years have increasingly improved measurement accuracy. Current direction, speed, temperature, time, conductivity, and depth data were collected with the Grundy 9021G current meters between the mid-1970s and the mid-1980s. The nearly 5-foot long meter recorded data on an internal magnetic tape while attached to a taut line mooring secured at a specified depth from the surface. The Roberts-type rotor speed sensor was oriented into the current by a 20-inch long fin. The speed was measured by the number of rotations of the rotor averaged over a 10-minute sampling period. Current direction was measured instantaneously at the end of the rotor count by comparing direction with that of magnetic north from a gimbaled magnetic compass. A continuously running crystal oscillator ensured that the programming of sensors, sampling rate, and tape motor speed were consistent throughout the deployment [*Browne, 1983*]. The reported accuracy of the Grundy 9021G current meter was 2 cm/s [*Klavans*, 1986].

Current speed, direction, temperature, pressure, conductivity, and time data were collected during the 1970s and 1980s using the Aanderaa RCM4 current meters. The speed was calculated by averaging the number of rotations of the rotor over a 10-minute interval and direction recorded was an instantaneous value. The length of the current meter was nearly 4.5 feet in its entirety with a 3-foot long vane which oriented the meter to the prevailing current direction. As with the Grundy, data were internally recorded on magnetic tape. The Aanderaa RCM4 current meters had a theoretical accuracy of less than 1.5 cm/s.

The General Oceanics Niskin winged current meter (Model 6011 Mark II), which was deployed in Miami Harbor in 1985, used a tilt sensor (a force balance inclinometer) to measure the angle of tilt and three orthogonally mounted flux-gate sensors which acted as a solid state compass to measure direction. The angle of tilt varied with the speed of the current; the greater the current the greater the angle of tilt. The instrument was fitted with a winged stabilizer that oriented the instrument in the direction of current flow. The data and time stamp were recorded on a Philips type magnetic tape cassette. Speed could be determined directly from the angle of tilt. A calibration curve for each style of wing showed the relation between speed and tilt angle. The current direction was derived from readings of the three orthogonal sensors. Manufacturer-stated accuracy for instrument tilt was 0.5 degree, current direction sensors had a 2-degree accuracy, and current speed was plus or minus 1 cm/s at the 1-knot range [*General Oceanics*, 1984].

The most recent current meters in use by NOS are ADCPs which use acoustic rather than mechanical technology. Most of the water column can be profiled with an ADCP whether it is deployed on the bottom or towed from the surface. The data can be disseminated by radio transmitter in real time. The ADCP velocity data has a long term accuracy bias of 0.5 percent of the measured velocity, plus or minus 0.5 cm/s [*RD Instr*uments, 1992].

Eighteen (or 44%) of the 41 reference stations are based on current pole or Zeskind float data. A total of 1117 subordinate stations (40% of the total) are referenced to tidal current reference stations based on current pole or Zeskind float data. PORTS^{TM} current meters are in operation near two of those stations, Galveston Bay Entrance and San Francisco Bay Entrance. NOS plans to update their tidal constituents in the 2000 NOS Tidal Current Tables.

2.5 Duration of Measurement

The daily predictions published in the NOS Tidal Current Tables are based on current data which varies in length from 2 days (North Inian Pass and Strait of Juan de Fuca) to 748 days (Pollock Rip Channel). A tidal current reference station needs a minimum of 15 days of continuous velocity observations in order to compute tidal current constituents by harmonic analysis. Predictions based on longer data sets can resolve more constituents and provide a closer match to the observed astronomical tidal curves. The more recently acquired data are of longer duration due to advances in instrument technology.

As indicated in Appendix B, predictions at three reference stations have been inferred from water level data. These stations are San Francisco Bay Entrance (1923), Wrangell Narrows (1925), and North Inian Pass (1925). This was done for older stations where only limited current data were available but a tidal current reference station was needed. The constituents of a nearby water level station were adjusted in amplitude and phase to fit the limited current data available using a procedure known as harmonic comparison described in the Manual of Current Observations [*C&GS*, 1950]. A similar method was used to obtain constituents for the Strait of Juan de Fuca Entrance, by using constituents of another tidal current station (Admiralty Inlet) that were adjusted in amplitude and phase.

Six other tidal current reference stations are hydraulic current stations (Appendix B) which are located in channels with different tidal driving forces at both ends of the channel. The tides at both entrances may have different ranges and/or phases. The current in the channel is based on the difference in water levels between the entrances. A limited amount of current data collected in the channel was then used to adjust the tidal constituents obtained from the water level difference. The six hydraulic reference stations are Cape Cod Canal (1956), Chesapeake and Delaware Canal (1937-38), Hell Gate (1932), Deception Pass (1925), Sergius Narrows (1952), and Isanotski Strait (1940).

Of the tidal current reference stations, 15 (37%) are based on less than 29 days of data (Figure 1) including all 7 Alaskan reference stations. Eight tidal current reference station predictions are based on less than 15 days of data. Seven stations have predictions based on 15 days to 28 days of data. Of all U.S. subordinate stations, 942 (34%) are referenced to tidal current reference station predictions based on less than 29 days of current data.

Improvements in instrument technology have allowed NOS to obtain longer time series and to resolve more harmonic constituents. Twelve tidal current reference stations (29%) are based on data acquired within the last 30 years with an average of 227 days of Grundy 9021G, Aanderaa RCM4, or ADCP measurements (Figure 1). Data acquired within the last 10 years are based on an average of 211 days of ADCP data.

3. VESSEL TRAFFIC AND COMMERCIAL ACTIVITY

PORTS^{TM} is designed to provide real-time currents, water levels, salinity, temperatures, and wind conditions which are critical factors for the safe navigation of ships. At the same time, the real-time water level, salinity, and temperature information provided by PORTS^{TM} allows shipping companies to better plan the loading and lightering of vessels transiting the port. The oceanographic measurements collected by PORTS^{TM} are available to coastal managers to monitor salinity and temperature conditions in the estuary and in developing plans for hazardous materials spill response. Presently, PORTS^{TM} are located in San Francisco Bay, Tampa Bay, New York Harbor, Galveston Bay, and Chesapeake Bay.

Trends in vessel transit statistics show that U.S. commercial waterways are increasingly congested with larger deep-draft vessels. As shown in Figure 2, vessel draft has dramatically increased since the mid-nineteenth century. In conjunction with this trend, there is an increasing need for real-time water level and current data to maximize use of channel depths, to prevent costly delays in offloading cargo, and for hazardous spill response [*NOAA*, 1995].

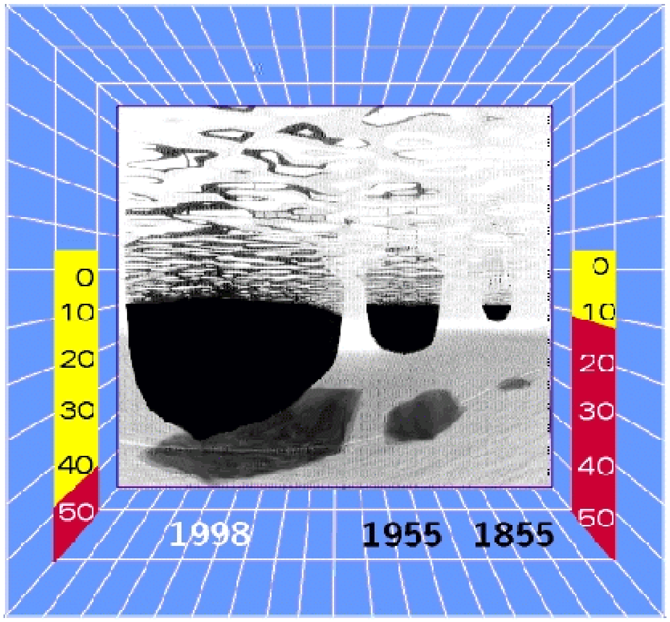

Figure 2. Changes in vessel draft [*NOAA*, 1999].

If predicted currents are inaccurate due to long term changes in channel bathymetry and repeated dredging activity, the incidence of hazardous spills may increase and impact more estuaries and sensitive environments. Spill response and cleanup can be hindered by inadequate current predictions.

Recent oil spills in Texas, Delaware, Alaska, and Rhode Island indicate that the safe transportation of crude oil is a national concern [*U.S. Coast Guard*, 1998]. Petroleum products and organic and inorganic chemicals transported as bulk cargo pose the greatest threat to the environment during a spill situation or vessel accident. Historical data suggests that an oil tanker spill can be 5 times larger than one from other vessel types [*U.S. Coast Guard*, 1998]. It is especially significant when these hazardous spills occur in high traffic areas such as Louisiana, Texas, and Alaska. Oil tanker transits in and out of the major Pacific coast ports in 1989, for example, represented about 18% of all deep-draft cargo-carrying vessels with drafts greater than 19 feet [*U.S. Coast Guard*, 1998]. The 1989 Waterborne Commerce data show that the percentage of oil tanker transits varied from 28% for San Francisco Bay, to less than 7% for the Columbia River.

The waterborne tonnage values presented in this report are based on the 1995 Waterborne Commerce statistics of the U.S. Corps of Engineers. *[U. S. Army Corps of Engineers*, 1997]. Appendix C presents the total tonnage (ranked from high to low) categorized as domestic, foreign, import and export tonnage at all the major U.S. coastal ports. Appendix D groups the total tonnage for coastal ports with the associated tidal current reference station (or stations) for each port. If a port does not contain a reference station, it is associated with the reference station for the subordinate stations in that port. Some of the tidal current reference stations have no total tonnage reported because they are not associated with a major coastal port, although substantial vessel traffic may pass nearby en route to a major port (e.g., Strait of Juan de Fuca Entrance). (Note that Chesapeake Bay Entrance does not include Baltimore tonnage and Admiralty Inlet does not include Tacoma tonnage.) The reference stations in the Aleutian Islands are not associated with a major port but are of significant economic importance due to the regional fishing industry.

3.1 Type of Tonnage

Cargo is classified as bulk (liquid and dry), container, general and breakbulk *[U. S. Army Corps of Engineers*, 1997]. Some examples of bulk cargo are petroleum products (crude petroleum, oil), coal, coke, iron, or steel scrap, and liquid bulk (organic and inorganic chemicals, vegetable oils, jet fuel). Container cargo may include agri-products, automobiles, and manufactured equipment and machinery. Examples of breakbulk cargo are steel, fruit, lumber, meat, motor vehicles, wood products, paper/pulp, and cocoa beans. General cargo could include anything not covered in the other categories and varies from port to port depending upon the type of traffic (domestic or foreign).

Domestic commerce is considered coastal when a vessel transits an ocean or the Gulf of Mexico (e.g. New Orleans to Baltimore, New York to Puerto Rico, San Francisco to Hawaii, Alaska to Hawaii). Domestic traffic is considered internal when vessel movements take place solely on inland waterways. An inland waterway (e.g. San Francisco Bay, Puget Sound, Delaware Bay and Chesapeake Bay) is one geographically located within the boundaries of the contiguous 48 states or within the boundaries of Alaska. The statistics presented in this section and in Appendices C and D do not include barge or tug tonnage through the intercoastal waterways nor do they include cruise liner traffic, military cargo moved in Department of Defense vessels, cargo carried on general ferries, or coal and petroleum products loaded from shore facilities directly into bunkers of vessels for fuel. The cargo does include fish landing data as internal and intraport domestic traffic. Intraport traffic is movement within a single port whether it has one or more arms or channels. It does not include car or general ferries. This report does not include discussion of the Great Lakes ports or the inland river ports on the Ohio or Mississippi rivers.

3.2 Total Tonnage

The total tonnage statistical data in Appendix C is presented in map form in Figure 3. There are three major ports where total 1995 tonnage exceeded 100 million tons. The Port of South Louisiana, LA had the greatest tonnage (204.5 million tons) followed by Houston, TX (135 million tons) and New York, NY (119 million tons). Of the twelve ports with total tonnage greater than 50 million tons, nine are on the Gulf of Mexico. The other three are New York, NY, Valdez, AK, and Long Beach, CA. The largest port in Alaska is Valdez (81 million tons) and the largest port in Hawaii is Honolulu (11.5 million tons).

The total tonnage grouped by tidal current reference station in Appendix D is displayed as a bar chart in Figure 4. This provides a measure of the relative importance of individual tidal current reference station predictions for U.S. commercial shipping. Two Gulf Coast reference stations alone (Mobile Bay Entrance and Galveston Bay Entrance) account for 46% of the total U.S. tonnage. The Gulf Coast tonnage (997 million tons) is 52.3% of the total. The two major Atlantic Coast reference stations are The Narrows (NY Harbor) and Delaware Bay Entrance. The Atlantic Coast tonnage (517 million tons) is 27.2% of the total. The major Pacific Coast reference station is San Francisco Bay Entrance. The Pacific Coast tonnage (390 million tons) accounts for 20.5% of the total.

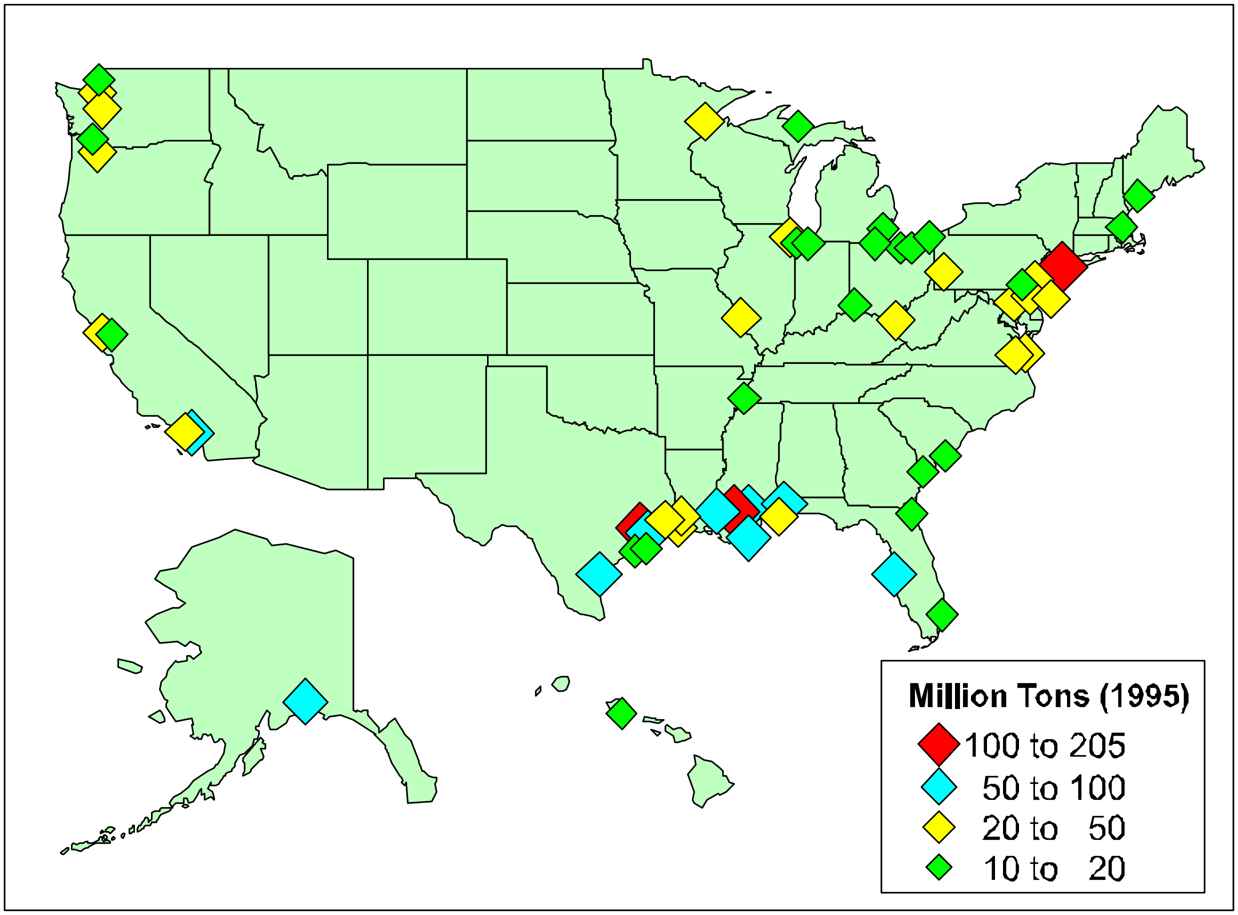

Figure 3. Total 1995 tonnage for major U.S. ports (with greater than 10 million tons of shipping) based on Waterborne Commerce of the United States statistics published by the Army Corps of Engineers.

The distribution of subordinate tidal current stations does not reflect the distribution of tonnage by coast. As stated in Section 2.3, 61% of the subordinate stations are on the Atlantic Coast, 34.5% are on the Pacific Coast, and only 4.5% are on the Gulf Coast. More current information for Gulf Coast locations may be needed to assist vessel operators with the safe transport of cargo.

Examination of the statistics in Appendix D shows that for some tidal current reference stations, the tonnage from a distant port is greater than the tonnage of the port in which the reference station is located. These reference stations and ports in parenthesis are: Portsmouth Harbor Entrance (Portland, ME), Miami Harbor Entrance (Port Everglades), Mobile Bay Entrance (the Mississippi River ports), San Diego Bay Entrance (Honolulu), San Francisco Bay Entrance (Long Beach and Los Angeles), Grays Harbor Entrance (the Columbia River ports), Wrangell Narrows (Nikishka, Coos Bay, and Anchorage), and Sergius Narrows (Valdez). Figure 5 shows U.S. coastal ports with more than 1 million tons of shipping which do not contain a tidal current reference station. Tidal Current Table predictions for these busy ports could be improved if they had a “*Table 1*" reference station instead of only “*Table 2*" subordinate stations.

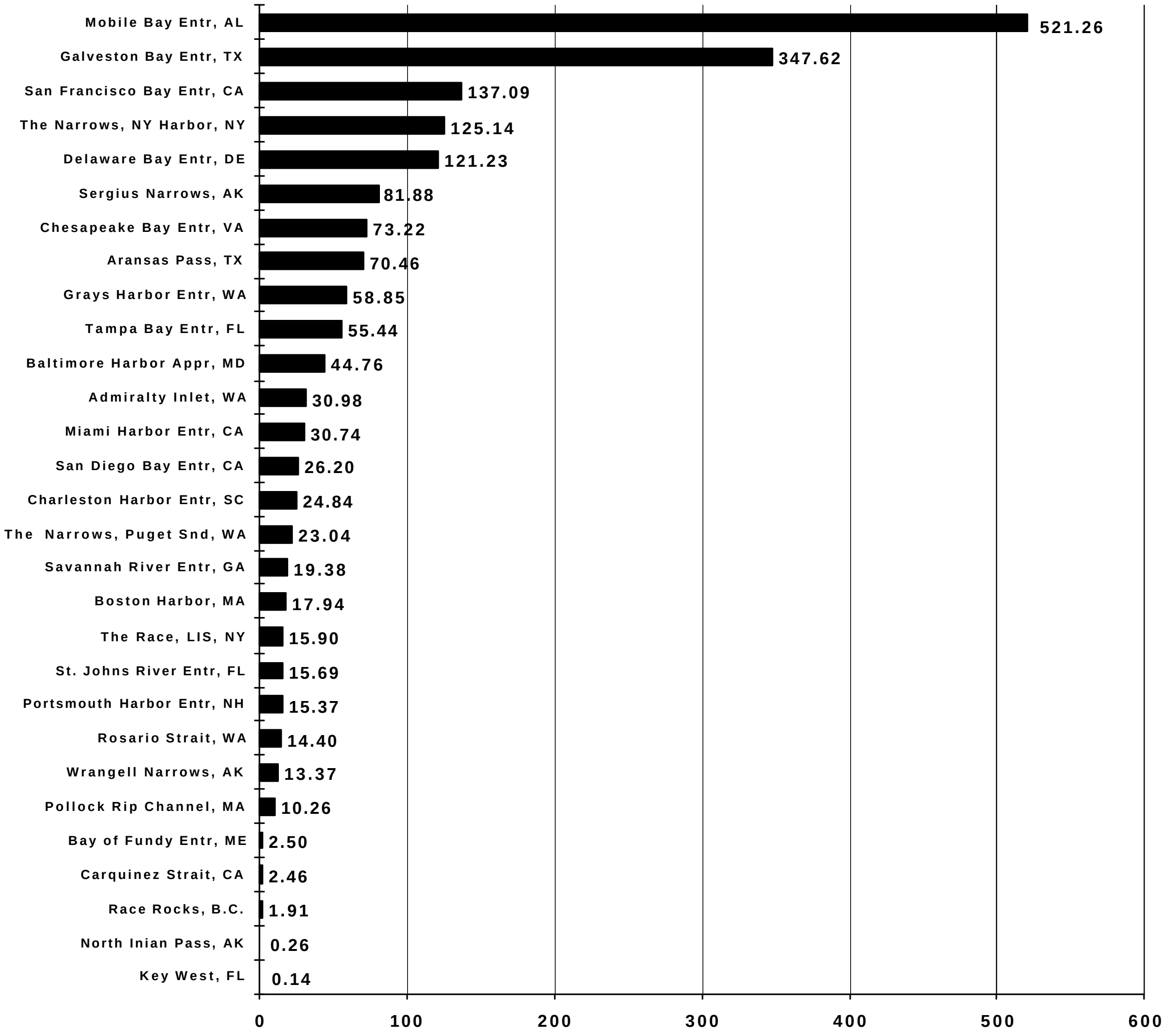

Figure 4. Total 1995 tonnage associated with tidal current reference stations.

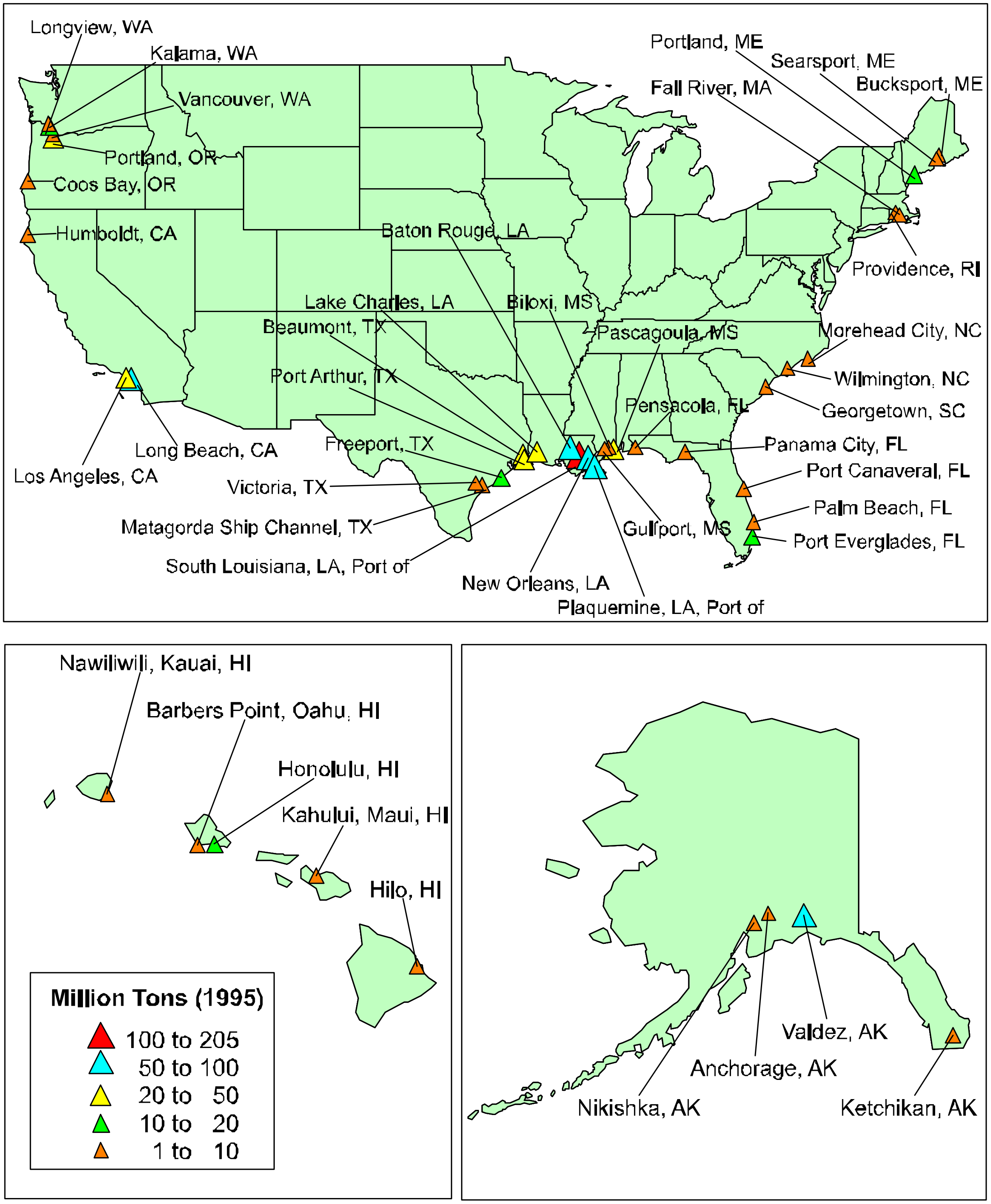

Figure 5. Total 1995 tonnage for U.S. ports without an existing tidal current reference station and greater than 1 million tons of shipping.

4. TIDAL AND NONTIDAL DYNAMICS

With the advent of ADCPs for measuring currents, there are new opportunities for improving navigational safety and aiding commercial shipping. The deployment of an ADCP enables the collection of more accurate data over longer periods of time in locations previously difficult to monitor such as busy shipping channels. The data collected can be used to calculate new, more accurate, tidal current constituents to update the Tidal Current Tables. With the development and deployment of real-time data delivery systems (PORTS^{TM}), an ADCP can continue to collect current data and distribute information operationally to users on demand.

Significant nontidal variability at a location important for safe navigation can justify real-time monitoring of currents to help identify dangerous situations. The decision whether to deploy an ADCP for a limited time to update tidal current predictions or to install an ADCP to measure currents in real time as part of a new PORTS^{TM} will depend in part on the relative importance of nontidal currents. Nontidal currents are seasonally-dependent with generally larger amplitudes in the winter due to storms. Therefore, a long current record from both summer and winter months is necessary to obtain a statistically accurate representation of the nontidal current variance. Long term time series from recent ADCP deployments provide a means of deriving the nontidal current variance at The Race, Throgs Neck, Bayonne Bridge, Charleston, Sunshine Skyway, Bolivar Roads, Golden Gate, and Benicia.

Nontidal and tidal variances resulting from least-squares harmonic analyses are used to characterize currents at several locations of navigational importance in Section 4.1 and 4.2. All tidal current reference stations are then associated with nearby National Water Level Observation Network (NWLON) stations in an effort to characterize tidal and nontidal current dynamics in each area (Section 4.3). The nontidal/tidal variance ratio plays a key role in classifying the NWLON stations in order to rank the relative importance of nontidal currents at the tidal current reference stations (Section 4.4).

4.1 Classification by Nontidal/Tidal Variance Ratio

A water level record measured at a single location can be a good representation of water levels for a large surrounding area, with a variable time lag as tidal and nontidal signals reach different locations. Unlike water level fluctuations, currents in bays and estuaries often vary by an order of magnitude at different locations and at different depths. Current records can show large variations in speed depending on the local bathymetry. Currents are generally slower near the sea floor due to bottom friction and, consequently, are also slower in shallower waters near shorelines. Currents are faster near the surface in deep water areas. Currents are also faster near the entrance to a bay or estuary where large volumes of water must be transported, compared with locations further from the ocean.

Owing to the spatial variability of current speeds, it is more useful to categorize currents by the nontidal to tidal variance ratio. The variances can be obtained in the course of performing a least squares harmonic analysis on a current time series. The least squares harmonic analysis program calculates the amplitudes and phases of the tidal constituents. The sum of all the resolvable tidal constituent variances is the total tidal variance, V_T. The remaining variance is the nontidal variance, V_{NT}. A water level or a current can be classified according to the ratio of the nontidal variance to the tidal variance, as proposed in Table 2.

Table 2. Classification of Water Levels and Currents

Tidally Dominated (T D)	$V_{NT}/V_T < 0.1$
Mostly Tidal (M T)	$0.1 < V_{NT}/V_T < 1.0$
Mostly Nontidal (M N)	$1.0 < V_{NT}/V_T < 10.0$
Nontidally Dominated (N D)	$10.0 < V_{NT}/V_T$

4.2 Classification of Currents

There are presently five PORTS^{TM} in operation in the United States. Four of them have ADCPs deployed to measure currents; San Francisco has five ADCPs, while New York/New Jersey, Houston/Galveston, and Tampa Bay each have two. Least squares harmonic analyses were performed on 6-minute real-time observations at the following five ADCP stations: Bayonne Bridge, Sunshine Skyway, Bolivar Roads, Golden Gate (outbound), and Benicia. Two of these stations were recently established as new reference stations in the Tidal Current Tables: Sunshine Skyway in 1994 and Bayonne Bridge in 1998. Although Bolivar Roads, Golden Gate, and Benicia were not exactly co-located with an existing tidal current reference station, they are in close proximity to the reference stations at Galveston Bay Entrance, San Francisco Bay Entrance, and Carquinez Strait, respectively, and are expected to have a similar tidal classification.

Least squares harmonic analyses were carried out for the five PORTS^{TM} stations. In addition, least squares harmonic analyses were performed on 10-minute ADCP data from The Race, Throgs Neck, and Charleston Harbor Entrance. All stations had at least half a year of data with data from both summer and winter months. All of the standard NOS tidal constituents were obtained except for the five long term constituents (Sa, Ssa, Mm, Mf, and Msf). The nontidal/tidal variance ratios (Table 3) ranged between 0.034 for Golden Gate and 0.224 for Bolivar Roads. Based on the classification proposed in Table 2, all the current stations are classified as tidally dominated except for Bolivar Roads which is classified as mostly tidal.

In harbors without a PORTS^{TM}, the historical current data could be re-analyzed in the same manner, but in most cases the data are very old and far less than a year in length. Substantial changes have occurred to the bathymetry of the bays and estuaries since the measurements were made and nontidal variances obtained from the old current data are likely to be inadequate. Therefore, in order to make comparisons between tidal current stations, the tidal and nontidal variances at nearby water level stations will be examined.

Table 3. Nontidal/Tidal Classification of Current Stations

Station Name	Observed Variance $(m/s)^2$	Nontidal Variance $(m/s)^2$	Tidal Variance $(m/s)^2$	Nontidal/Tidal Variance Ratio	Classification Code	Days of Data
The Race, NY	0.345	0.015	0.330	0.045	T D	178.3
Throgs Neck, NY	0.075	0.004	0.071	0.056	T D	483.0
Bayonne Bridge, NY	0.388	0.019	0.369	0.051	T D	227.2
Charleston, SC	0.476	0.016	0.460	0.035	T D	315.1
Sunshine Skyway, FL	0.193	0.015	0.178	0.084	T D	305.8
Bolivar Roads, TX	0.266	0.060	0.217	0.224	M T	241.9
Golden Gate, CA	0.764	ERR	0.739	??	T D	248.3
Benicia, CA	0.376	0.013	0.369	0.036	T D	243.6

T D = Tidally Dominated, M T = Mostly Tidal, M N = Mostly Nontidal, N D = Nontidally Dominated

4.3 Tidal and Nontidal Variance at Water Level Stations

The NWLON operated by the National Ocean Service is composed of primary and secondary control water level stations along the coasts of the United States [*Hicks*, 1989]. This network provides the basic tidal datums for coastal and marine boundaries and the chart datum for NOS nautical charts. Observations at a secondary control or tertiary water level station are reduced to equivalent l9-year tidal datums through the comparison of simultaneous observations with a primary control water level station. Water level data in close proximity to tidal current reference stations will be used to examine the relative importance of nontidal dynamics near the reference stations listed in the published Tidal Current Tables.

Table 4 lists the NWLON station chosen for each tidal current reference station. In some cases, two tidal current reference stations are associated with the same NWLON station. St. Petersburg represents the tidal current reference stations at Old Port Tampa and Sunshine Skyway. Cherry Point represents the tidal current reference stations at Deception Pass and Rosario Strait. Sand Point represents the tidal current reference stations at Isanotski Strait and Kvichak Bay. Unalaska represents the tidal current reference stations at Unimak Pass and Akutan Pass.

An effort was made to chose a NWLON station as close as possible to the tidal current reference station, preferably in the same waterway, but this was not always possible especially in Alaska. Isanotski Strait, Kvichak Bay, North Inian Pass, Unimak Pass, and Wrangell Narrows are all more than a degree of longitude from their associated NWLON station, and the following analysis may be less applicable for the Alaskan stations than for the other stations.

There are 37 NWLON stations that were linked to tidal current reference stations. The NWLON data analyzed in this study were verified hourly observed water levels referenced to mean lower low water. For 30 of the stations, 366 days of observed 1996 data were analyzed. Three stations (Sandy Hook, Dauphin Island, and Cherry Point) were analyzed with 332, 362, and 358 days of 1996 data, respectively. Three other stations (Cape Cod Canal, Seavey Island, and Key West) were analyzed with 365 days of data from 1975, 1985, and 1995, respectively. Chesapeake City was analyzed with 319 days of data from 1982-1983, the most recent long term data set available.

Table 4 lists the variances of the long term water level stations linked to the published NOS tidal current reference stations. Figure 6 presents a plot of the tidal and nontidal variance, color coded by symbol for each coast. The range in tidal variance among the stations is more than two orders of magnitude whereas the range in nontidal variance is only one order of magnitude. It is apparent that the classification of the water level stations is more dependent on the level of tidal variance rather than the nontidal variance.

Two California stations, San Diego Bay Entrance and San Francisco Bay Entrance, have the lowest nontidal variances. Although nontidal variance appears to be roughly equivalent for all the other water level stations, they are due to different combinations of two driving forces at different locations. The first is the effect of winter storms over the continental shelf. The strength of this effect is strongest in the higher latitudes and weakest in the lower latitudes. It is especially weak in California where the continental shelf is narrow. The second effect is due to annual meteorological cycles in wind and ocean temperature. Routine water level predictions incorporate this effect in the tidal constituents, Sa and Ssa [*Hicks*, 1989]. The harmonic analyses performed on the water level data in this report did not include Sa and Ssa and as a result the annual cycle becomes a part of the nontidal variance. On the east coast, the annual cycle is very small for northern stations and gradually increases toward the south to a maximum in Florida. On the Pacific coast, the annual cycle is small in California, and is larger for the Pacific coast of Washington and for Alaska.

Table 4. Nontidal/Tidal Classification of NWLON Stations

NWLON Station	Associated Tidal Current Reference Station(s)	Total Variance m^2	Nontidal Variance m^2	Tidal Variance m^2	Variance Ratio	Classification Code
ATLANTIC COAST						
Eastport, ME	Bay of Fundy Entrance, CANADA	3.960	0.016	3.944	0.004	T D
Seavey Island, ME	Portsmouth Harbor Entrance, NH	0.788	0.014	0.774	0.019	T D
Boston, MA	Boston Harbor, MA	1.102	0.022	1.080	0.020	T D
Cape Cod Canal, MA	Cape Cod Canal, MA	0.908	0.017	0.891	0.019	T D
Nantucket, MA	Pollock Rip Channel, MA	0.133	0.019	0.114	0.166	M T
New London, CT	The Race, NY	0.104	0.024	0.080	0.295	M T
Willets Point, NY	Throgs Neck, NY	0.791	0.046	0.745	0.062	T D
The Battery, NY	Hell Gate, NY	0.294	0.034	0.260	0.130	M T
Sandy Hook, NJ	The Narrows, New York Harbor, NY	0.309	0.029	0.280	0.105	M T
Lewes, DE	Delaware Bay Entrance, DE	0.248	0.033	0.215	0.155	M T
Chesapeake City, MD	Chesapeake and Delaware Canal, MD	0.139	0.041	0.098	0.422	M T
Annapolis, MD	Baltimore Harbor Approach, MD	0.049	0.036	0.013	2.839	M N

NWLON Station	Associated Tidal Current Reference Station(s)	Total Variance m^2	Nontidal Variance m^2	Tidal Variance m^2	Variance Ratio	Classification Code
Chesapeake Bay Bridge Tunnel, VA	Chesapeake Bay Entrance, VA	0.113	0.028	0.085	0.325	M T
Charleston, SC	Charleston Harbor Entrance, SC	0.380	0.031	0.349	0.089	T D
Ft Pulaski, GA	Savannah River Entrance, GA	0.644	0.038	0.606	0.062	T D
Mayport, FL	St. Johns River Entrance, FL	0.274	0.029	0.245	0.119	M T
Virginia Key, FL	Miami Harbor Entrance, FL	0.060	0.011	0.049	0.224	M T
GULF COAST						
Key West, FL	Key West, FL	0.038	0.013	0.025	0.521	M T
St Petersburg, FL	Sunshine Skyway Bridge and Old Tampa Bay Entrance, FL	0.058	0.023	0.035	0.666	M T
Clearwater, FL	Tampa Bay Entrance, FL	0.077	0.022	0.055	0.401	M T
Dauphin Island, AL	Mobile Bay Entrance, AL	0.033	0.020	0.013	1.568	M N
Port Bolivar, TX	Galveston Bay Entrance, TX	0.044	0.027	0.017	1.588	M N
Corpus Christi, TX	Aransas Pass, TX	0.052	0.030	0.022	1.364	M N
PACIFIC COAST						
San Diego, CA	San Diego Bay Entrance, CA	0.270	0.005	0.265	0.018	T D
Golden Gate, CA	San Francisco Bay Entrance, CA	0.281	0.008	0.273	0.030	T D
Port Chicago, CA	Carquinez Strait, CA	0.225	0.015	0.210	0.072	T D
Toke Point, WA	Grays Harbor Entrance, WA	0.694	0.055	0.639	0.086	T D
Neah Bay, WA	Strait of Juan de Fuca Entrance, WA	0.546	0.034	0.512	0.066	T D
Port Townsend, WA	Admiralty Inlet, WA	0.627	0.023	0.604	0.037	T D
Seattle, WA	The Narrows, Puget Sound, WA	1.076	0.022	1.054	0.021	T D
Cherry Point, WA	Deception Pass and Rosario Strait, WA	0.694	0.019	0.675	0.029	T D
Friday Harbor, WA	San Juan Channel, WA	0.525	0.021	0.504	0.041	T D
Ketchikan, AK	Wrangell Narrows, AK	2.351	0.021	2.330	0.009	T D
Sitka, AK	Sergius Narrows, AK	0.898	0.022	0.876	0.025	T D
Juneau, AK	North Inian Pass, AK	2.622	0.022	2.600	0.009	T D
Sand Point, AK	Isanotski Strait and Kvichak Bay, AK	0.466	0.028	0.438	0.063	T D
Unalaska, AK	Unimak Pass and Akutan Pass, AK	0.133	0.019	0.114	0.165	M T

T D = Tidally Dominated, M T = Mostly Tidal, M N = Mostly Nontidal, N D = Nontidally Dominated

4.4 Classification of Water Level Stations

The next step in assessing the dynamics of the tidal current reference stations is to classify the appropriate NWLON stations. The tidal and nontidal variances are shown for each NWLON station in Table 4 and Figure 6. These values identify the NWLON stations as tidally dominated, mostly tidal, mostly nontidal, or nontidally dominated. The lines separating the categories in Figure 6 correspond to the classification presented in Table 2. The nontidal/tidal variance ratios are displayed as a bar chart in Figure 7.

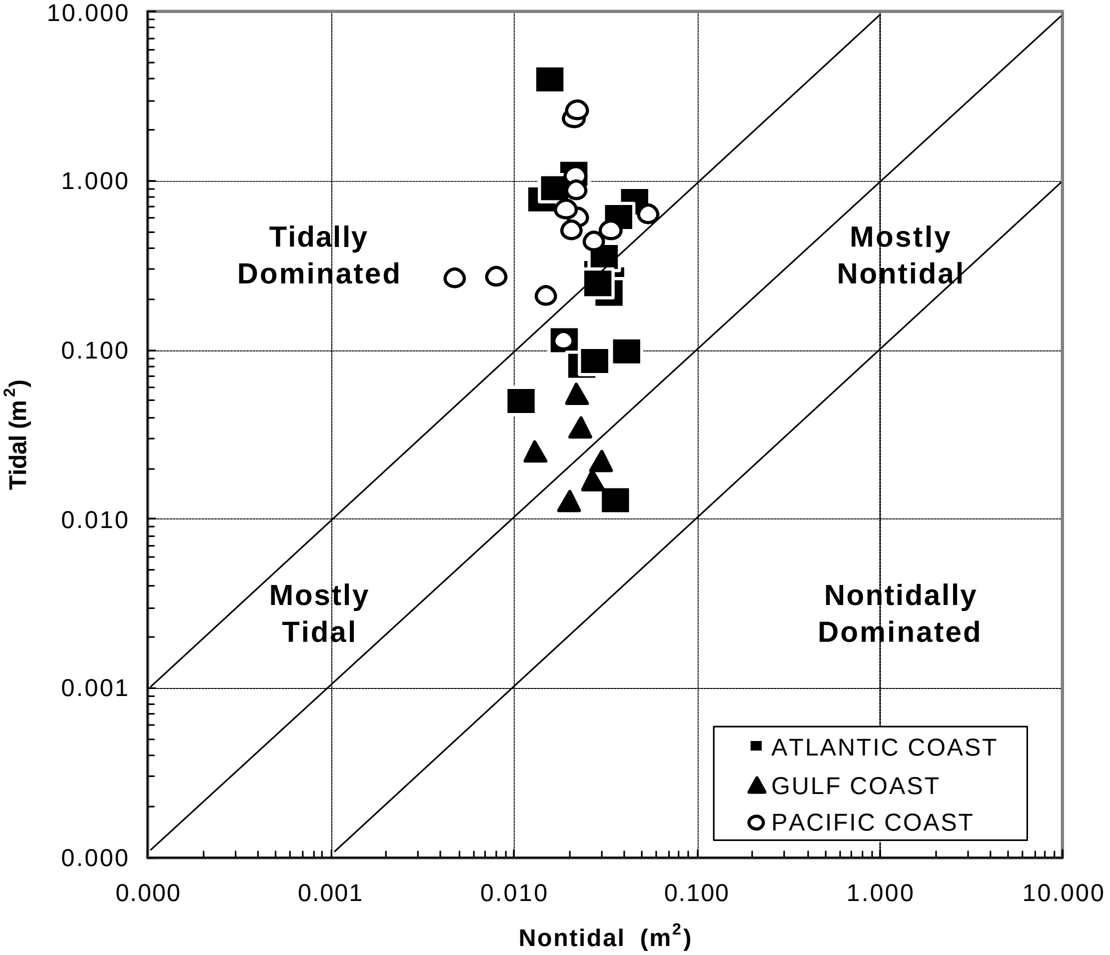

Figure 6. Tidal and nontidal variance at National Water Level Observation Network stations. The diagonal lines separating the categories correspond to the ratios presented in Table 2.

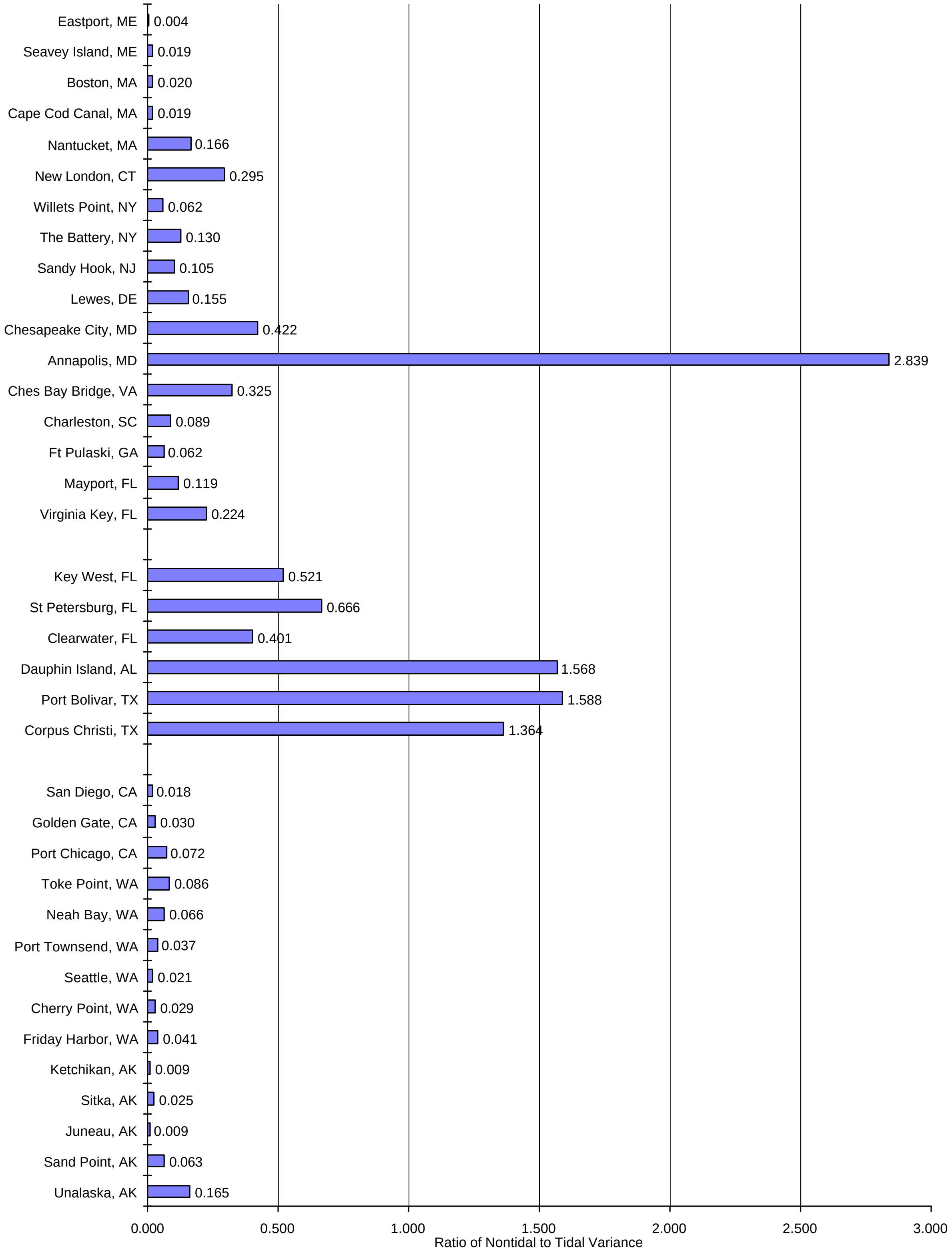

Figure 7. Nontidal/tidal variance ratio at NWLON stations.

The variance ratios of the Atlantic Coast NWLON stations range from 0.004 at Eastport to 2.839 at Annapolis. Based on Table 2, seven of the Atlantic Coast stations are classified as tidally dominated, nine Atlantic Coast stations are classified as mostly tidal, and Annapolis is classified as mostly nontidal. The variance ratios of the Gulf Coast NWLON stations range from 0.401 at Clearwater to 1.588 at Port Bolivar. The three Gulf Coast stations in Florida have variances that classify them as mostly tidal while the other Gulf Coast stations are classified as mostly nontidal. The variance ratios of the Pacific Coast NWLON stations range from 0.009 at Juneau and Ketchikan to 0.165 at Unalaska. All the Pacific Coast NWLON stations are tidally dominated with the exception of Unalaska in the Aleutian Islands, which is classified as mostly tidal.

Since the nontidal to tidal variance ratio of an NWLON station will be used to infer the classification of a nearby tidal current reference station, the variance ratios given in Table 3 for currents should be compared to the variance ratios of an appropriate NWLON station. It can be seen from Table 5, that the nontidal/tidal variance ratio is generally lower for current stations than for corresponding water level stations. This indicates that currents tend to be more tidal than nearby water levels. The current stations fall into a more tidal category than the associated water level station. Mostly tidal (M T) water level stations have tidally dominated (T D) currents in the vicinity. Mostly nontidal (M N) water level stations have mostly tidal currents (M T) in the vicinity. Of course, tidally dominated (T D) water levels are associated with tidally dominated (T D) currents.

Table 5. Comparison of Current and Water Level Classification

Current			Water Level		
Station	Variance Ratio	Classification Code	Station	Variance Ratio	Classification Code
Golden Gate, CA	0.034	T D	Golden Gate, CA	0.030	T D
Throgs Neck, NY	0.056	T D	Willets Point, NY	0.062	T D
Benicia, CA	0.036	T D	Port Chicago, CA	0.072	T D
Charleston, SC	0.035	T D	Charleston, SC	0.089	T D
Bayonne Bridge, NY	0.051	T D	The Battery, NY	0.130	M T
The Race, NY	0.045	T D	New London, CT	0.295	M T
Sunshine Skyway, FL	0.084	T D	St. Petersburg, FL	0.666	M T
Bolivar Roads, TX	0.224	M T	Port Bolivar, TX	1.588	M N

T D = Tidally Dominated, M T = Mostly Tidal, M N = Mostly Nontidal, N D = Nontidally Dominated

Although attempts were made, a reliable quantitative relationship between the nontidal/tidal variance ratio of water level and current stations could not be found. There were no significant correlations between nontidal water levels and currents when the variance ratios were low. There are significant correlations (up to 0.6) between nontidal water levels and currents when the variance ratios were higher (i.e., at Bolivar Roads, Sunshine Skyway, and Bayonne Bridge), but these correlations are dependent on varying amounts of smoothing applied to the nontidal water levels.

The clearest result of these comparisons is that a higher water level variance ratio corresponds to a higher current variance ratio and currents fall into a more tidal category than water levels in the same area. In the next section, it will be assumed that the classification of water level stations can be used as a guide in drawing up a priority list for the real-time monitoring of currents by a PORTS^{TM}.

5. NEW CURRENT SURVEY PRIORITIES

The previous sections of this report have reviewed the reference stations where tidal current constituents may be inadequate due to age, instrumentation, or data length, evaluated the nations ports based on vessel traffic and shipping tonnage, and categorized the water levels and currents based on the nontidal/tidal variance ratio. Based on these results, recommendations for future current surveys are presented in this section.

A limited current meter deployment is required to update old tidal current constituents or collect data for establishing a new tidal current reference station. When the tidal constituents have been accurately resolved, tidal currents will be predictable until there are significant changes in channel bathymetry or harbor configuration. Short term current surveys are recommended for areas where reference station predictions are based on data more than 30 years old (Section 5.1). The waterborne commerce of the region defines the priority for updating existing reference stations.

The installation of a PORTS^{TM} to disseminate real-time current measurements is preferred for locations where nontidal signals comprise a significant part of the total current variance (Section 5.2). Major ports which do not presently contain a tidal current reference station are recommended for new tidal current predictions and are individually evaluated for real-time current monitoring by a new PORTS^{TM} (Section 5.3).

5.1 Recommendations for Updating Tidal Current Reference Stations

In Section 2, 41 tidal current reference stations for which daily predictions are published in the NOS Tidal Current Tables were evaluated on the basis of age, instrumentation, and the length of observations used to obtain the tidal constituents. There is a general correlation between these three factors, with older current data collected by current pole or float for periods shorter than 29 days and newer current data collected by ADCPs for periods longer than 29 days. Adequate tidal current constituents are obtained from a 29-day Fourier harmonic analysis. More accurate constituents are obtained with longer data sets. In view of the correlations between the three factors of age, instrumentation, and length of observations, recommendations for updating reference stations will be summarized for three groups of stations based on type of instrumentation.

The current pole or Zeskind float were used to collect data for 18 tidal current reference stations before 1946. As stated in Section 2.4, the longest current pole measurement was 2 years of observations from Stonehorse Lightship in Pollock Rip Channel. It is unlikely that this location needs to be revisited. It is recommended that all the 17 other pole or float stations be updated based on age, instrumentation, and length of data. These stations will be called Group 1.

Recently, NOS has obtained new current data for four of the stations in Group 1. Two current survey projects were completed in 1998 at Savannah River Entrance and St. Johns River Entrance and new tidal predictions for Savannah River Entrance appear in the 1999 NOS Tidal Current Tables. The St. Johns River Entrance reference station was updated in a January 1999 Notice to Mariners and will appear in the 2000 Tidal Current Tables along with seven new subordinate stations. A large set of PORTS^{TM} current data are available for locations near Galveston Bay Entrance and San Francisco

Bay Entrance and predictions based on new constituents are planned for the 2000 Tidal Current Tables.

It is recommended that new current data be obtained for the remaining 13 tidal current reference stations in Group 1. In order to prioritize the reference stations that need to be updated, the tonnage statistics discussed in Section 3 are used. The reference stations that need updating are ranked based on their associated tonnages as displayed in Figure 4. The ranking in Group 1 from most urgent to least urgent is as follows:

1. Mobile Bay Entrance, AL
2. The Narrows, New York Harbor, NY
3. San Diego Bay Entrance, CA
4. Portsmouth Harbor Entrance, NH
5. Wrangell Narrows, AK
6. North Inian Pass, AK
7. Hell Gate, NY
8. Chesapeake and Delaware Canal, MD
9. Strait of Juan de Fuca Entrance, WA
10. Deception Pass, WA
11. Isanotski Strait, AK
12. Unimak Pass, AK
13. Kvichak Bay, AK

A second group of stations are based on more recently acquired data obtained with better technology than the stations in Group 1. The Roberts Current Meter was used to collect data for 9 tidal current reference stations between 1942 and 1964. In 1965, a Geodyne current meter was used to collect 29 days of data at Rosario Strait. In addition, data were collected by the Canadian Hydrographic Service in 1960 for the Bay of Fundy Entrance with an unknown instrument. The station at Miami Harbor Entrance was updated in 1985 based on an analysis of 29 days of data using a Niskin winged current meter [General Oceanics, Inc., 1984]. These stations will be called Group 2. It is recommended that all 12 of these stations be updated based on age, instrumentation, and limited data sets. Based on the tonnage statistics in Figure 4, the ranking in Group 2 from most urgent to least urgent is as follows:

1. Sergius Narrows, AK
2. Grays Harbor Entrance, WA
3. Baltimore Harbor Approach, MD
4. Admiralty Inlet, WA
5. Miami Harbor Entrance, FL
6. The Narrows, Puget Sound, WA
7. Rosario Strait, WA
8. Bay of Fundy Entrance, ME
9. Key West, FL
10. Cape Cod Canal, MA
11. San Juan Channel, WA
12. Akutan Pass, AK

The remaining reference stations are placed in Group 3. Between 1971 and 1984, long term data sets were collected for updating 4 tidal current reference stations with the Aanderaa RCM4 or the Grundy 9021G current meters. Between 1987 and 1991, the ADCP was used to collect current data for updating 7 tidal current reference stations. Only the station at Aransas Pass was based on a short 29-day harmonic analysis. Since the data from all 11 of these reference stations are relatively recent, it is not recommended that new data be collected at this time.

5.2 Proposed Real-Time Current Monitoring at Existing Tidal Current Reference Stations

The nontidal/tidal variance ratios discussed in Section 4 can provide a method to evaluate a reference station for real-time current monitoring by a PORTS^{TM}, although other navigational safety requirements can be factored into the decision. For locations where a long term current time series is not available, a NWLON water level station in the vicinity was harmonically analyzed and its nontidal/tidal variance ratio was calculated. All the NWLON stations that were classified as mostly nontidal are considered to have a large enough nontidal/tidal variance ratio requiring continuous real-time monitoring of currents by a PORTS^{TM} (Table 4). These stations are in Chesapeake Bay or the Gulf of Mexico. One of these locations is already part of a PORTS^{TM} (Galveston Bay Entrance). The three other tidal current reference stations listed below are associated with significant vessel traffic and have strong enough nontidal variance to be candidates for a new PORTS^{TM}.

1. Mobile Bay Entrance, AL
2. Aransas Pass, TX
3. Baltimore Harbor Approach, MD

Another group of NWLON stations have nontidal/tidal variance ratios that are classified as mostly tidal (Table 4). The associated tidal current reference stations in the vicinity can be considered for real-time current monitoring by a PORTS^{TM}, but are not assigned as high a priority as the stations listed above. The stations at Sunshine Skyway and Old Port Tampa Entrance are already being monitored in real time as part of the Tampa PORTS^{TM}. The other tidal current reference stations that are associated with major ports (greater than 10 million tons) are ranked below according to the tonnage statistics shown in Figure 4:

1. The Narrows, New York Harbor, NY
2. Delaware Bay Entrance, DE
3. Chesapeake Bay Entrance, VA
4. Tampa Bay Entrance, FL
5. Miami Harbor Entrance, FL
6. The Race, NY
7. St. Johns River Entrance, FL

5.3 Recommendations for Adding New Tidal Current Reference Stations and Evaluation for Real-Time Current Monitoring by PORTS^{TM}

There are long stretches of the U.S. coastline without tidal current reference stations as discussed in Section 2.1. Over the years, major ports have developed in these geographical gaps. The subordinate stations in these ports are linked to a distant reference station. In some cases, discussed in Section 3.2, the tonnage at these subordinate station ports is greater than the tonnage of the port where the reference station is located. The major U.S. ports (greater than 1 million tons) without a tidal current reference station are shown in Figure 5. Consideration should be given to establishing new tidal current reference stations in some of these ports to assist mariners handling the increased vessel traffic at these locations.

Thirteen U.S. ports with more than 10 million tons of shipping are recommended for a new tidal current reference station and are evaluated for real-time current monitoring by a new PORTS^{TM}. The Tidal Current Tables were examined to determine how many subordinate stations are in these ports. The maximum flood and maximum ebb currents at these subordinate stations were examined to determine if strong currents exist in these ports (e.g., if both maximum flood and maximum ebb currents are greater than or equal to 1 knot). They are discussed in the following order based on tonnage, with the nearest NWLON station in parentheses:

1. Port of South Louisiana, Baton Rouge, New Orleans, Port of Plaquemine, LA (South Pass, LA)
2. Long Beach, Los Angeles, CA (Los Angeles, CA)
3. Valdez, AK (Valdez, AK)
4. Port Arthur, Beaumont, TX (Sabine Pass, North, TX)
5. Portland, OR / Kalama, Vancouver, Longview, WA (Astoria, OR)
6. Lake Charles, LA (Sabine Pass, North, TX)
7. Pascagoula, MS (Dauphin Island, AL)
8. Freeport, TX (Freeport, TX)
9. Port Everglades, FL (Virginia Key, FL)
10. Matagorda Ship Channel, Victoria, TX (Freeport, TX)
11. Honolulu, HI (Honolulu, HI)
12. Portland, ME (Portland, ME)
13. Providence, RI / Fall River, MA (Newport, RI)

Harmonic analysis and evaluation of a nearby NWLON station gives the expected tidal regime of the port with the results presented in Table 6. The tidal and nontidal variances are plotted in Figure 8, showing the classification of the stations according to the variance ratio. If water levels are classified as mostly nontidal, currents are likely to fall in the mostly tidal category and a PORTS^{TM} installation for monitoring currents is strongly recommended (indicated by an asterisk). The ports with mostly tidal NWLON stations (Port Everglades, Honolulu, and Providence/Fall River) can also be considered for current monitoring by PORTS^{TM} but are not assigned as high a priority. The ports with NWLON stations classified as tidally dominated are not recommended for current monitoring by PORTS^{TM}. (Although the NWLON station at Astoria, OR is classified as tidally dominated, the Columbia River is recommended for current monitoring for reasons discussed below.)

Table 6. Classification of NWLON Stations Associated with Major Ports without a Tidal Current Reference Station

Station Name	Observed Variance m^2	Nontidal Variance m^2	Tidal Variance m^2	Variance Ratio	Classification Code
South Pass, LA *	0.035	0.020	0.015	1.333	M N
Los Angeles, CA	0.246	0.004	0.242	0.017	T D
Valdez, AK	1.387	0.032	1.355	0.024	T D
Sabine Pass, North, TX *	0.057	0.039	0.018	2.167	M N
Astoria, OR *	0.653	0.047	0.606	0.078	T D
Dauphin Island, AL *	0.033	0.020	0.013	1.538	M N
Freeport, TX *	0.051	0.027	0.024	1.125	M N
Virginia Key, FL	0.060	0.011	0.049	0.224	M T
Honolulu, HI	0.035	0.004	0.031	0.129	M T
Portland, ME	1.100	0.018	1.082	0.017	T D
Newport, RI	0.177	0.021	0.156	0.135	M T

T D = Tidally Dominated, M T = Mostly Tidal, M N = Mostly Nontidal, N D = Nontidally Dominated

*Installation of a real-time current measuring system is recommended for ports near this NWLON station.

1. <u>Port of South Louisiana, Baton Rouge, New Orleans, Port of Plaquemine, LA</u> (Nearest NWLON station, South Pass, LA, is mostly nontidal) These four ports on the Mississippi River together account for 438 million tons of shipping which is 23% of the total U.S. tonnage. The vessels entering or leaving these ports pass through the mouth of the Mississippi. There are no subordinate current stations near the mouth of the Mississippi or on the river itself. There is only one subordinate current station at Seabrook Bridge in New Orleans which is on a waterway between the Mississippi and Lake Pontchartrain. This station has flood and ebb currents greater than 1 knot.

There is evidence that tidal currents may be important in some stretches of the Mississippi River itself. There are six subordinate water level stations at the mouth of the Mississippi which have tidal ranges from 0.9 to 1.4 feet. A subordinate water level station at Paris Road Bridge on a waterway in New Orleans has a tidal range of 1.1 feet. There is the following endnote about New Orleans in the Tide Tables:

> "At New Orleans the diurnal range of the tide during low river stages averages 0.8 foot. There is no periodic tide at high river stages."

Due to the importance of the Mississippi River to U.S. shipping and the complicated, frequently changing geography due to natural and man-made causes, it is recommended that a new tidal current reference station be established in the mouth of the Mississippi. Due to the important nontidal effects from the Gulf of Mexico and from the variability of river flow, installation of a PORTS^{TM} should be

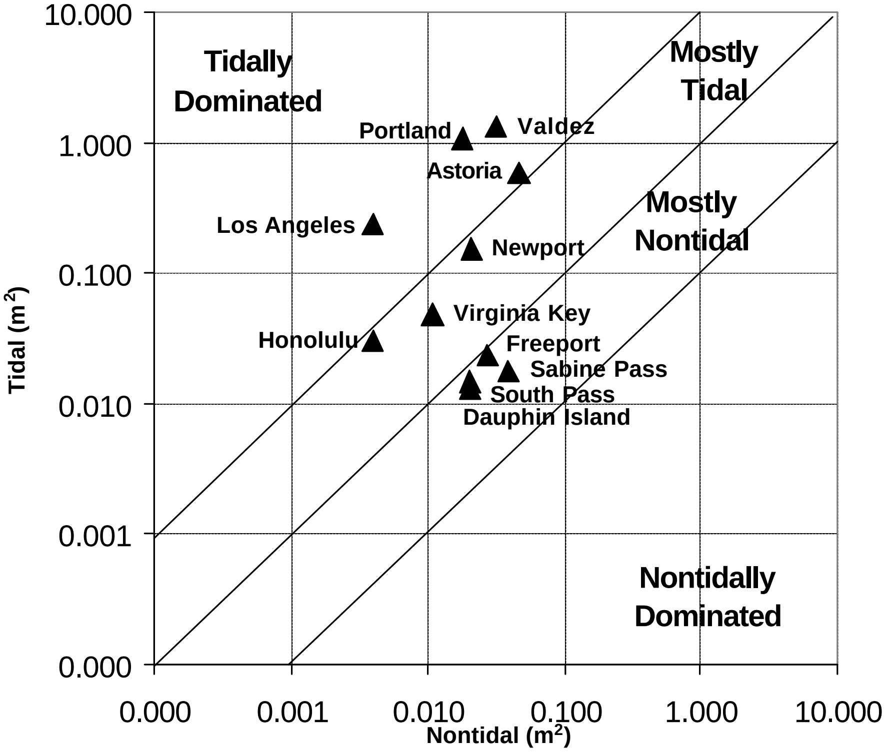

Figure 8. Tidal and nontidal variance at NWLON stations associated with major ports, without an existing tidal current reference station.

considered. There are likely to be challenges associated with working in such a waterway with a large volumetric flowrate and deposition of sediment not seen at previous PORTS^{TM} projects.

2. Long Beach, Los Angeles, CA (Nearest NWLON station, Los Angeles, CA, is tidally dominated) There is one subordinate station in this harbor with the following associated endnote:

> "In Los Angeles and Long Beach Harbors, the tidal current is weak. Currents can exceed 1 knot in the outer harbor at San Pedro, under strong wind conditions. Also, it is reported that three minute surge waves are responsible for major ship movements and damage."

It appears from the small enclosed area and geometry of these harbors that tidal currents are not important here. It should be investigated whether changes to the harbor since the endnote was written have increased tidal currents at any location. A PORTS^{TM} may be justified to monitor the three minute surge waves.

3. Valdez, AK (Nearest NWLON station, Valdez, AK, is tidally dominated) There are 43 subordinate stations in Prince William Sound and Orca Bay. Tidal currents are very weak with four rotary tidal current stations in the center of the bay. The only strong tidal currents are in narrow passages near the edges of the bay (Elrington Passage, Bainbridge Passage, and between Hinchinbrook and Hawkins Islands) which are far from the main shipping channels. The main entrance to Prince William Sound should be evaluated for locations with currents strong enough for a new tidal current reference station. Despite the significant tonnage for this port, it is not recommended for real-time current monitoring by a PORTS^{TM}.

4. Port Arthur, Beaumont, TX (Nearest NWLON station, Sabine Pass North, TX, is mostly nontidal) There are 4 subordinate stations in this waterway, with strong flood and ebb currents (greater than 1 knot) at Texas Point, Sabine, and Mesquite Point. This port is recommended for a tidal current reference station. Due to the importance of the nontidal signal in the Gulf of Mexico, real-time current monitoring by a PORTS^{TM} is recommended.

5. Portland, OR / Kalama, Vancouver, Longview, WA (Nearest NWLON station, Astoria, OR, is tidally dominated) There are 34 subordinate stations in the Columbia River. Both the tidal current and the river flow are large from the entrance up to the last subordinate current station at Kalama Upper Range. Both the flood and ebb currents are greater than 2 knots at the subordinate current stations near Sand Island Tower, Clatsop Spit, and Chinook Point. They are greater than 1 knot at a number of other locations. The tide is known to progress further upriver, with subordinate water level stations at Vancouver, WA with a diurnal range of 1.8 feet and into the Willamette River at Portland, OR with a diurnal range of 2.4 feet. The Tidal Current Table has the following endnote about the Columbia River:

> "The Columbia River bar can be very dangerous because of sudden and unpredictable current changes accompanied by breakers. It is reported that ebb currents on the north side of the bar attain speeds of 6 to 8 knots and that strong NW winds sometimes cause currents that set north in the area outside the jetties. In the entrance, the currents are variable and may reach a speed of over 5 knots on the ebb while the flood speed seldom exceeds 4

> knots. The tidal current in the river is always modified by the river discharge, sometimes to the extent that the flood current is indiscernible and the current ebbs continuously."

Due to the rapid currents and the volume of shipping, it is recommended that a new tidal current reference station be established in the Columbia River. Because of the importance of river flow variability, and repeated requests for information by mariners, a PORTS^{TM} installation is also recommended. As at the mouth of the Mississippi, there are significant challenges to establishing a PORTS^{TM} at the mouth of the Columbia River, but there are also strong tidal currents upriver where instruments could be located.

6. Lake Charles, LA (Nearest NWLON station, Sabine Pass North, TX, is mostly nontidal) There is one subordinate station in Calcasieu Pass which is the waterway leading to Lake Charles. Both flood and ebb currents are greater than 1 knot. This port is recommended for the establishment of a new tidal current reference station because of the ship tonnage, and for real-time current monitoring by a PORTS^{TM} because of the importance of nontidal effects from the Gulf of Mexico.

7. Pascagoula, MS (Nearest NWLON station, Dauphin Island, AL, is mostly nontidal) There is one subordinate station at the Pascagoula River highway bridge with both flood and ebb currents greater than 1 knot. Due to the ship tonnage and the nontidal effects of the Gulf of Mexico, this location is recommended for a new tidal current reference station and for real-time current monitoring by a PORTS^{TM}.

8. Freeport, TX (Nearest NWLON station, Freeport, TX is mostly nontidal) There are no subordinate stations and therefore no current predictions at this port. Due to the ship tonnage and the nontidal effects of the Gulf of Mexico, this location is recommended for a new tidal current reference station and for real-time current monitoring by a PORTS^{TM}.

9. Port Everglades, FL (Nearest NWLON station, Virginia Key, FL, is mostly tidal) There are six subordinate stations in this port. The stations at the entrance and at the 17th Street Bridge have flood and ebb currents greater than 1 knot. This port is recommended for the establishment of a new tidal current reference station.

10. Matagorda Ship Channel, Victoria, TX (Nearest NWLON station, Freeport, TX, is mostly nontidal) Together these two ports have more than 10 million tons of shipping. There is one subordinate station at Matagorda Channel (entrance jetty) which has flood and ebb speeds greater than 1 knot. Due to the ship tonnage and the nontidal effects of the Gulf of Mexico, this location is recommended for a new tidal current reference station and for real-time current monitoring by a PORTS^{TM}.

11. Honolulu, HI (Nearest NWLON station, Honolulu, HI, is mostly tidal) There are no subordinate current stations for the island of Oahu. The diurnal tide range at Honolulu is 2 feet. Based on the geometry of Pearl Harbor, tidal currents may be measurable at the entrance to Pearl Harbor. Although, the port of Honolulu is reached by dredged channels directly accessible from the ocean, the entrance to Pearl Harbor may be considered for the establishment of a new tidal current reference station for the state of Hawaii.

12. Portland, ME (Nearest NWLON station, Portland, ME, is tidally dominated) There are 11 subordinate stations for this port, with flood and ebb speeds greater than 1 knot at Portland Harbor Entrance. This port is recommended for the establishment of a new tidal current reference station but not for real-time current monitoring.

13. Providence, RI / Fall River, MA (Nearest NWLON station, Newport, RI, is mostly tidal) Together these two ports have more than 10 million tons of shipping. There are 39 subordinate stations for Narragansett Bay. The stations at Tiverton, Bull Point, Mount Hope Bridge, Kickamuit River, Dutch Island, and India Point have flood and ebb speeds greater than 1 knot. It is recommended that a new tidal current reference station be established in Narragansett Bay.

If these new reference stations are added, the priority rankings for updating existing tidal current reference stations as discussed in Section 5.1 may change slightly. The only significant changes are the top two stations in Group 2. If a new tidal current reference station is created for Valdez, AK, the station at Sergius Narrows, AK loses priority. If a new tidal current reference stations is created for the Columbia River, the station at Grays Harbor Entrance loses priority.

6. CONCLUSIONS

In this report, a thorough review was conducted of the data which forms the basis for predictions at 41 NOS tidal current reference stations. The geographic distribution, number of subordinate stations, and characteristics of the tidal current constituents were described and compared. Almost half of the reference stations were based on data sets more than 50 years old. Most of these stations are based on data collected using current poles or floats. Over a third of the tidal current reference stations are based on less than 29 days of data, with tidal current constituents developed from various types of nonharmonic analysis. There is a clear correlation between age of data, type of instrument used, and duration of measurement.

Shipping tonnage statistics for leading U.S. coastal ports, as compiled by the U.S. Corps of Engineers, were examined as an indicator of the relative importance of the tidal current reference stations. Two Gulf Coast reference stations (Mobile Bay Entrance and Galveston Bay Entrance) were associated with tidal predictions for nearly half of the U.S. shipping tonnage. Despite the fact that over half of the U.S. shipping tonnage is associated with Gulf Coast ports, less than 5% of the subordinate tidal current stations are in the Gulf of Mexico. Six of the twelve ports with the greatest tonnages do not contain a tidal current reference station.

In order to determine the relative importance of nontidal currents at the tidal current reference stations, a method of classification was devised based on the nontidal to tidal variance ratio calculated from harmonic analysis results. Four categories were defined by the variance ratio: tidally dominated, mostly tidal, mostly nontidal, and nontidally dominated. The nontidal/tidal variance ratio was obtained for recent long term time series recorded at or near the location of eight reference stations. All of the stations were in the tidally dominated category, except for Bolivar Roads which was in the mostly tidal category. In order to infer the importance of nontidal currents at the other reference stations, the closest NWLON stations were chosen and the nontidal/tidal variance ratios were calculated. It was found that mostly nontidal water levels are associated with mostly tidal currents. Mostly tidal water levels are associated with tidally dominated currents.

Based on the findings summarized above, a number of recommendations concerning current survey priorities can be made. An update of the tidal current constituents is recommended for the reference stations that are based on older data of limited duration. A group of 13 reference stations are based on data collected before 1950 with current poles or floats. A second group of 12 reference stations are based on limited data sets collected by mechanical current meters between 1942 and 1985. Based on an analysis of nontidal/tidal variance ratios, four of the existing tidal current reference stations are most likely to have strong nontidal currents. Currents at one of them (Galveston Bay Entrance) are presently being monitored by a PORTS^{TM}. The three other locations (Mobile Bay Entrance, Aransas Pass, and Baltimore Harbor Approach) are associated with significant vessel traffic, and therefore are also recommended for real-time current monitoring.

A new tidal current reference station is recommended for 13 major ports (greater than 10 million tons) in order to provide improved tidal current predictions for these ports, which presently are represented by a limited number of subordinate stations. Six of these ports are expected to have significant nontidal currents, based on the nontidal/tidal variance ratio, and are recommended for real-time current monitoring. They are the mouth of the Mississippi River, Port Arthur/Beaumont, Lake Charles, Pascagoula, Freeport, and Matagorda Ship Channel/Victoria. The mouth of the Columbia River is also recommended for real-time current monitoring based on the expected importance of river flow variability.

ACKNOWLEDGMENTS

Stephen Gill provided guidance in using variance as a means of comparing NWLON stations to tidal current reference stations. Dale Deitemyer and Janet Culp of the Products and Services Division (PSD) provided assistance in acquiring data from long term water level control stations not readily available on the Internet.

Tom Kendrick, Richard Sillcox, and William Watson provided key information about the tidal current reference station cards, official form C&GS-444, and background information on the instruments used to obtain the current data. Information about the type of instrumentation and inferred values were obtained from documentation compiled by Tom Kendrick. Joseph Welch provided memoranda about the tidal current survey cards from former oceanographers in NOS. Darren Wright created the templates for the thematic maps with data provided by the authors.

Constructive comments and direction were provided by Kathryn Bosley and Stephen Gill. The draft technical report was reviewed by Kathryn Bosley, Stephen Gill, Tom Kendrick, and William Stoney. Brenda Via critiqued, edited, and finalized the figures and provided desktop publishing for this report.

REFERENCES

Browne, D. R. and Gary Dingle, 1983. New York Harbor Circulation Survey: 1980-81, *NOS Oceanographic Circulation Survey Report No. 5*.

C&GS, 1950. *Manual of Current Observations, Special Publication No 215*, Washington, DC, US Govt Printing Office.

Defant, A., 1961. *Physical Oceanography*, Vol. II Pergamon Press, New York, NY, 598 pp.

Dennis, R. E., and E. E. Long, 1971. A User's Guide to a Computer Program for Harmonic Analysis of Data at Tidal Frequencies, NOAA Technical Report NOS 41, Office of Oceanography and Marine Assessment, NOS, NOAA, Rockville, MD, 31 pp.

General Oceanics, Inc., 1984. *Technical Proposal and Response to Statement of Work, Circulation Survey, Port of Miami*, Volume II, 55 pp.

Hicks, Steacy D., 1989. *NOS Tide and Current Glossary*.

Klavans, Alan, Peter Stone, Gina Stoney, 1986. Delaware River and Bay Circulation Survey: 1984-1985, *NOS Oceanographic Survey Report No 9*.

Long, E.E., 1978. Tide and Tidal Current Observations from 1965 through 1967 in Long Island Sound, Block Island Sound and Tributaries, *NOS Oceanographic Circulatory Survey Report No. 1*.

NOAA, 1999. NOS, OPSD, National PORTS™ Program Plan.

NOAA, 1998. NOS, CO-OPS, Strategic Plan for the National Ocean Service Center for Operational Oceanographic Products and Services.

NOAA, 1995. NOAA Stratigic Plan: A Vision for 2005.

RD Instruments, 1992. Self-Contained Acoustic Doppler Current Profiler Technical Manual, Firmware Version 17.10.

U. S. Army Corps of Engineers, 1997. *Waterborne Commerce of the United States*, Navigational Data Center, Waterborne Commerce State Center.

U.S. Coast Guard, 1998. Evaluation of Oil Tanker Routing per Section 4111(b)(7) Oil Pollution Act of 1990. *Part 1: Pacific Coast, Part 2: Atlantic Coast*.

Zervas, C. E., 1999. Tidal Current Analysis Procedures and Associated Computer Programs, NOAA Technical Report NOS CO-OPS 021, Center for Operational Oceanographic Products and Services, NOS, NOAA, Silver Spring, MD, 101 pp.

APPENDIX A

List of NOS Tidal Current Survey Reports

Since the formation of NOAA in 1970, a number of in-house publications have been produced by NOS giving information about the data collected during circulation surveys and the resulting analysis of the data. These reports were written by the staff of the Coastal and Estuarine Oceanography Branch and its predecessors, the Estuarine and Ocean Physics Branch and the Circulatory Surveys Branch. The publications are a part of several numbered series.

The NOS Oceanographic Circulation Survey Report series were published in order to give detailed information about the data collected during a circulation survey. In general, data analysis results were not included in the Circulation Survey Reports.

#1. Tide and tidal current observations from 1965 through 1967 in Long Island Sound, Block Island Sound, and tributaries, Elmo E. Long, 1978.

#2. Tampa Bay circulatory survey, 1963, Demetrio A. Dinardi, 1978.

#3. Puget Sound approaches circulatory survey, Bruce B. Parker and James T. Bruce, 1980.

#4. Cook Inlet circulatory survey, 1973-1975, Richard C. Patchen, James T. Bruce, and Michael J. Connolly, 1981.

#5. New York Harbor circulation survey, 1980-81, David R. Browne and Gary Dingle, 1983.

#6. Southeast Atlantic coast estuaries: Sapelo Sound to St. Simons Sound, Georgia Circulation Survey, 1980, William A. Watson, 1990.

#7. San Francisco Bay area circulation survey : 1979-1980, Joseph M. Welch, Jeffrey W. Gartner, and Stephen K. Gill, 1985.

#8. Chesapeake Bay circulation survey, 1981-1983, David R. Browne and Carl W. Fisher, 1986.

#9. Delaware River and Bay circulation survey, 1984-1985, Alan S. Klavans, Peter J. Stone, and Gina A. Stoney, 1986.

#10. Long Island Sound Oceanography Project : 1988-1990, editor: Karen L. Earwaker, contributors: Gerald F. Appell et al., 1990.

#11. Tampa Bay Oceanography Project : 1990-1991, Fran Nowadly, contributors: Gerald Appell et al., 1992.

Data analysis results were published in a series of NOAA Technical Reports. The earlier ones were published in the series NOAA Technical Report NOS.

#69. Tidal hydrodynamics in the Strait of Juan de Fuca - Strait of Georgia, Bruce B. Parker, 1977.

#80. Circulation and hydrodynamics of the lower Cape Fear River, North Carolina, Joseph M. Welch and Bruce B. Parker, 1979.

#100. Tidal hydrodynamics and sediment transport in Beaufort Inlet, North Carolina, Alan S. Klavans, 1983.

They were followed by the series NOAA Technical Report NOS OMA,

#3. Tide and tidal currents in the Chesapeake Bay, David R. Browne and Carl W. Fisher, 1988.

and by the series NOAA Technical Report NOS OES.

#2. Tampa Bay Oceanography Project: physical oceanographic synthesis, editor: Chris E. Zervas, contributors: Kathryn T. Bosley et al., 1993.

#3. Long Island Sound Oceanography Project: summary report, Richard A. Schmaltz, Jr., 1994.

The results of data analysis for more limited projects (some known as miniprojects) were published as NOAA Technical Memorandums. The earlier publications were in the series NOAA Technical Memorandum NOS OMA.

#50. Tampa Bay current prediction quality assurance miniproject, Robert G. Williams, Thomas D. Bethem, and Henry R. Frey, 1989.

#53. Houston Ship Channel/Galveston Bay current prediction quality assurance miniproject, Robert G. Williams, Henry R. Frey, and Thomas D. Bethem, 1990.

#60. Corpus Christi Bay current prediction quality assurance miniproject, Robert G. Williams et al., 1991.

The following publications were in the series NOAA Technical Memorandum NOS OES.

#2. Quality assurance of Tampa Bay PORTS^{TM}: current measurementes at the Sunshine Skyway Bridge, C. Reid Nichols, Robert G. Williams, and Gerald F. Appell, 1992.

#3. San Francisco Bay current prediction quality assurance miniproject, Robert G. Williams, Wayne L. Wilmot, and Henry R. Frey, 1993.

#8. Special 1994 tidal current predictions for Aransas Pass, Corpus Christi, Texas, C. Reid Nichols, 1994.

#9. Tampa PORTS^{TM} voice data response system description and access statistics, May 1993 - May 1995, Thomas D. Bethem, 1995.

#10. National Ocean Service partnership: real-time environmental monitoring in upper San Francisco Bay: final report, Kurt W. Hess et al., 1996.

#14. Special 1995 tidal current predictions for Galveston Bay, Texas, Karen L. Earwaker, C. Reid Nichols, and William T. Ehret, 1995.

APPENDIX B

Tidal Current Reference Station Summary. Comments include information from Form C&GS-444, type of instrument, and number of secondary stations (based on the 1998 NOS Tidal Current Tables). National Water Level Observation Network Stations and long term control tide stations associated with the Tidal Current Reference Stations are listed in italics. Footnotes from Official Form 696 denoted by "<*x*>" are listed at the end of this table.

Station Name	Location		Year Data Obtained	Duration	Comments
	Latitude N	Longitude W			
Admiralty Inlet (off Bush Point), WA <5> *Port Townsend*	**48º01.8'** **48º06.9'**	**122º38.22'** **122º45'**	1908, 1942 & 1943	means of 29d(2), 32d, 26d & 36d	2 ebbs+flood=3 consecutive ebbs; short period comps inc 10%; M4, M6, M8 not used because of lg var in kappas from diff analyses. **Pole (1908) and Roberts CM (1942&1943),** **75 sub sta ref to Admiralty Inlet**
Akutan Pass, Aleutian Islands, AK *Unalaska*	**54º01'** **53º52.8'**	**166º03'** **166º32.3'**	1950	24 day series 7/31/50 - compared to tides; S2 kappas from 15-day HA	1 yr pred (1952) gives tropic ebb 8.0kts. T.M officially changed 10/30/83. Predicted speeds > or = 7.5 knots must be modified according to a scale on C&GS 444. Slack int & avg vel from 1952 pred; Fld & Ebb int & tropic vel from Form 180. Harmonic const from 24 day. **Roberts Current Meter at 15ft depth,** **7 sub sta ref to Akutan Pass**
Aransas Pass (btw jetties), TX *Corpus Christi*	**27º50.03'** **27º34.8'**	**97º02.65'** **97º13.0'**	1990	4/9-5/7	NOS Analysis for 15ft bel MLLW. **ADCP, 3 sub sta ref to Aransas Pass**
Baltimore Harbor Approach (off Sandy Point), MD *Annapolis*	**39º00.78'** **38º59'**	**76º22.10'** **76º28.8'**	1963	8/14 (29days)	C&GS 29d HA; short period components inc 7%; used anal values > or = 0.030; Used inferred values >or=0.010; published vel < 0.3 knot as "weak and variable". **Roberts Current Meter,** **155 sub sta ref to Baltimore Harbor Approach**
Bay of Fundy Entrance (Grand Manan Channel) *Eastport, ME*	**44º45.0'** **44º54.0'**	**66º56.0'** **66º59.0'**	1960	June -July, 1960 29d(2)	Data received from Canada; slack intervals obtained from 4 months reduction of 1964 Canadian predictions. Ratio = Spring vel/mean = 1.13 Time Meridian = 60º. **?instr, 135 sub sta ref to Bay of Fundy**

Station Name	Location		Year Data Obtained	Duration	Comments
	Latitude N	Longitude W			
Boston Harbor (off Deer Isl Light), MA (north component) *Boston*	**42º20.267'** **42º21.3'**	**70º57.317'** **71º03'**	1971	NOS lsqha 5/10-10/26	Supercedes rev cur pred beg w/1976 ACCT; rotary current; use both n&e component sheets for predictions. **Aanderaa RCM4, 153 sub sta ref to Boston Harbor**
Boston Harbor (off Deer Isl Light), MA (east component)	**42º20.267'**	**70º57.317'**	1971	lsqha 5/10-10/26	Rotary current; use both n&e component sheets for predictions
Cape Cod Canal (R.R.Bridge), MA *Cape Cod Canal, Buzzards Bay Entrance (1975)*	**41º44.5'** **41º44'**	**70º36.8'** **70º37'**	1956	15day cur & 29d (2) tide series	**Hydraulic cur sta**; two 29d tide obs (8/55) at @ end of canal land cut & 15 d cur (10/56); Col A includes time lag of 0.55hr & 15% inc in Col B; kappas derived from orig values of kappa primes from analysis. **Roberts Current Meter, 16 sub sta ref to Cape Cod Canal**
Carquinez Strait, w end bridge, CA *Port Chicago*	**38º03.68'** **38º03.4'**	**120º13.1'** **120º02.3'**	1980	4/3/80 -11/12/80 (224 days)	NOS 224d lsqha at 39ft bel MLLW; first used in 1989 PCCT; 2MN2 used in place of L2; **Aanderaa RCM4, 57 sub sta ref to Carquinez Strait**
Charleston Harbor Entr (off Fort Sumter), SC *Charleston*	**32º45.36'** **32º46.9'**	**79º52.22'** **79º55.5'**	1987-1988	5/26/87-7/28/88	NOS lsqha first used in 1997 ACCT; superceded 1962 C&GS 29dHA, **ADCP, 227 sub sta ref to Charleston Hbr**
Chesapeake Bay Entrance, VA *Chesapeake Bay Bridge Tunnel*	**36º58.78'** **36º58.1'**	**75º59.93'** **76º06.8'**	1982	330 days beginning 3/30/82	NOS analysis at 27 ft bel MLLW; 1st used in 1988 ACCT **Grundy current meter, 247 sub sta ref to Ches Bay Entr**
Chesapeake and Delaware Canal (Chesapeake City), MD *Chesapeake City (1972-1983)*	**39º32'** **39º32.023'**	**75º49'** **75º49.014'**	1938	5½ days obs at Ches City Bridge; June 7 - July 14, 1938	**Hydraulic cur sta**; Series by US Engineers; constant “C” factor = 1.85; Col A time lag correction = 0.86 hr; Orig form 444 gave values of kappa from which these kappas were computed; Constants rep diff in H_2O levels btw Cthouse Pt (369 days) & Reedy Pt (369 days), the fld or possitve flow taken as eastward. **Pole, 8 sub sta ref to Ches & DE Canal**

Station Name	Location		Year Data Obtained	Duration	Comments
	Latitude N	Longitude W			
Deception Pass (Narrows), WA <6>	**48°24'**	**122°38'**	1925	29 day series 9/9/25 - 10/9/25	**Hydraulic current sta**; M2 inc 5%, K1 adv 10°; constant "C" factor = 18.4, Col A time lag = 0.87 hr. Epochs modified by 180° so that east going stream may be considered as positive. Constants rep diff in elev btw Yokeko Pt. & Reservation Bay; the elev of YP above RB being taken as positive. **Zeskind float, 4 sub sta ref to Deception Pass**
Cherry Pt	**48°51.8'**	**122°44.9'**			
Delaware Bay Entrance, DE	**38°46.85'**	**75°02.58'**	1984	221 days; 4/25/84 -12/1/84	NOS analysis at 22ft bel MLLW; 1st used in 1987 ACCT **Grundy current meter,** **92 sub sta ref to DE Bay Entr**
Lewes	**38°46.9'**	**75°07.2'**			
Galveston Bay Entrance (between jetties), TX	**29°20.8'**	**94°42.3'**	1935	two 29day series beginning 4/5/35 & 4/10/35	Two 29-day series corrected by comparison w/Gal tides; short period comp inc by 5%; may be tabulated as 3 consecutive ebbs where spd <0.3kt is "weak & variable". **Pole, 21 sub sta ref to Galv Bay Entr**
Port Bolivar	**29°21.8'**	**94°46.7'**			
Grays Harbor Entrance, WA	**46°55.0'**	**124°07.5'**	1950	29 day (half hourly obs) beginning 3/25/50	Analysis of half hourly obs; short period comps inc by 1%. **Roberts current meter,** **44 sub sta ref to Grays Harbor**
Toke Point	**46°42.4'**	**123°57.9'**			
Hell Gate (off Mill Rock) East River, NY <1>	**40°46.7'**	**73°56.3'**	1932	35 days of time from stations 2,5,6 and 11 days of vel from station 6, which is in the center of the channel.	**Hydraulic cur sta**; Diff in elev btw Willets Pt and Gov Isl (GI above WP taken as positive); Constant "C" factor = 3.520, Col A includes time lag of 0.64 hr, Col D values for M4 and M6 are revised to agree w/mean from tidal and current constants from Station #6; **Pole, 33 sub sta ref to Hell Gate**
The Battery	**40°42'**	**74°00.9'**			
Isanotski Strait (False Pass Cannery), AK	**54°52'**	**163°24'**	1940 1925 (water levels)	6 days obs in May 1940	**Hydraulic current station**. Constants represent diff in ht of tide at King Cove & False Pass. Time zone officially changed from 165°W to 135°W on 10/30/83; New time reflected 1st in 1985 PCCT. Constant "C" factor = 6.0, Col A time lag = 1.1hr. Constants 1st used in 1973 PCCT. **Pole, 11 sub sta ref to Isanotski Strait**
Sand Point	**55°20.2'**	**160°30.1'**			

Station Name	Location		Year Data Obtained	Duration	Comments
	Latitude N	**Longitude W**			
Key West, FL *Key West*	**24°32.9'** **24°33.2'**	**81°49.0'** **81°48.5'**	1954	29 days of half hourly speeds beginning 1/22/54	C&GS analysis of half hrly obs. New obs in 1965 indicated a need to revise orig const. Dredging of channels caused a diff. Orig ampl were inc 26.6%. Times were adjusted to 0.2hr earlier via Col A. New perm current = -0.3kts. Constants 1st used in 1967 ACCT. **Roberts current meter, 18 sub sta ref to Key West**
Kvichak Bay (off Naknek River Entrance), AK *Sand Point*	**58°42.2'** **55°20.2'**	**157°15.0'** **160°30.1'**	1946	14 days beginning 9/16/46	Short period comps inc 12%. Time zone officially changed from 150° W to 135°W on 10/30/83. New time 1st reflected in 1985 PCCT. **Pole, 39 sub sta ref to Kvichak Bay**
Miami Harbor Entrance (Government Cut), FL *Virginia Key*	**25°45.9'** **25°43.9'**	**80°08.2'** **80°09.7'**	1985	29 days beginning 1/18/85	NOS analysis first used in 1987 ACCT **GONiskin winged CM (Model 6011 MK2), 45 sec sta ref to Miami Harbor Entrance**
Mobile Bay Entrance, AL *Dauphin Island*	**30°14'** **30°15'**	**88°02'** **88°04.5'**	1935	29 day beginning 5/24/35	29 day series in 1935 w/amplitudes inc 10% except M2 & S2 which are from 15 days in 1918 (weight 1) and 29 days in 1935 (weight 2). Inferred values > or = 0.01 except for M4 & M6, published speeds < 0.3 kts = "weak and variable" **Pole, 14 sub sta ref to Mobile Bay Entrance**
North Inian Pass, Cross Sound, AK *Juneau*	**58°17'** **58°17.9'**	**136°23'** **134°24.7'**	1925 1901 (104 days water levels)	2½ days	Harmonic tidal constants at Hoonak. Time zone changed from 120°W to 135°W on 10/30/83. New times reflected 1st in 1985 PCCT. Published spd < 0.3kts = "weak & variable"Tropic inequalities for flood & ebb as derived from pred for 1932 are flood=1.2 and ebb = 2.06. **Zeskind Float, 28 sub sta ref to North Inian Pass**
Old Port Tampa, Old Tampa Bay, FL *St Petersburg*	**27°51.9'** **27°46.012'**	**82°33.2'** **82°37.016'**	1990-91	6/25/90 - 9/11/91 (457 days)	NOS LSQHA, major axis only; minor axis insignificant. First used in 1994 ACCT. **ADCP, 16 sub sta ref to Old Tampa Bay**

Station Name	Location		Year Data Obtained	Duration	Comments
	Latitude N	Longitude W			
Pollock Rip (Butler Hole) **Channel**, MA <2> *Nantucket*	**41°32.8'** **41°17.2'**	**69°59.1'** **70°05.7'**	1934, 1935, 1936	748 days 8/6/34-8/31/36	Used analyzed values > or = 0.030 and inferred values > or= 0.010 from Narragansett Bay & Nantucket Sound, **Pole**, **115 sub sta ref to Pollack Rip**
Portsmouth Harbor Entrance, (off Wood Isl), NH <3> *Seavey Island, ME*	**43°04'** **43°04.9'**	**70°42'** **70°44.7'**	1926	15 days; **pole & Price** Current Meters from 1926; **Roberts** in 1953 wasn't used in tables	From HA of 3 short series of obs corrected by comparison w/constants from simultaneous tidal obs at Portland ME. Short period comp inc 20%. When times of max flood scan backwards, change them to make them progressive. **Pole & Price (1926)**; **Roberts (1953)**, **82 sub sta ref to Portsmouth**
Rosario Strait, WA *Cherry Point*	**48°27.53'** **48°51.8'**	**122°46.75'** **122°44.9'**	1965	29 days beginning 3/10/65	C&GS 29day HA first used in 1967 PCCT. Ampl inc 11%. **Geodyne current meter, 46 sub sta ref to Rosario Strait**
San Diego Bay Entrance (off Ballast Point), CA *San Diego*	**32°40.9'** **32°42.9'**	**117°13.8'** **117°10.4'**	1934	29 days beginning 8/24/34	Used analyzed $ 0.03kts and inferred $ 0.010kts. Mean of **Pole & meter, 27 sub sta ref to San Diego Bay Entr (20 in CA&7 in HI)**
San Francisco Bay Entrance (Golden Gate), CA <7> *Golden Gate*	**37°48.63'** **37°48.4'**	**122°30.13'** **122°27.9'**	1923 & 1930 (3 days)	7 days beginning 10/19/23	These constants are inferred from an analysis of hourly speeds for 7 days compared w/ a simultaneous tidal analysis at Presidio and best determined values for Presidio. M2, M4, M6 obtained by combining orig constants from above method w/ constants from an analysis of diff btw predicted & obs speeds for the same series. Empirical corrections for K1, O1, and P1 obtained through comparison w/obs **Pole; 136 sub sta ref to SF Bay Entr**
San Juan Channel (south entrance), WA *Friday Harbor*	**48°28'** **48°32.7'**	**122°57'** **123°00.7'**	1964	29 days beginning 5/21/64	C&GS analysis where short period components are increased 6% and published speeds < 0.3kts are "weak and variable". **Roberts Current Meter, 13 sub sta ref to San Juan Channel**

Station Name	Location		Year Data Obtained	Duration	Comments
	Latitude N	Longitude W			
Savannah River Entrance (between jetties), GA *Ft Pulaski*	**32º02.2'** **32º02'**	**80º51.5'** **80º54.1'**	1934	two 15-day series beginning 5/1/34	Means of two 15-day series of hourly speeds beginning 5/1/34 corrected by comparison w/Tybee Light, GA tides. Correction of 0.15 hr to speeds of each component to make predicted times later. **Pole, 124 sub sta ref to Savannah River Entr**
Sergius Narrows, Peril Strait, AK *Sitka*	**57º24.4'** **57º03.1'**	**135º37.6'** **135º20.5'**	1952	6 days beginning 5/25/52	**Hydraulic cur sta**. Kappa prime is mean of values derived from 6 days of obs analysis & derived from tidal constants from Sitka and Sergius Narrows. Time zone officially changed from 120ºW to 135ºW on 10/30/83. New TM 1st appear in 1985 PCCT. “C” factor = 5.0. (Oldest sec sta 1895). **Roberts Current Meter, 62 sub sta ref to Sergius Narrows**
St. Johns River Entrance, FL *Mayport*	**30º24.0'** **30º23.6'**	**81º23.0'** **81º25.9'**	1934	means of two 15-day series beginning 1/4/34	Corrected by comparison w/Mayport tides. Series are half hourly where M2, M4, & M6 were inc 3%. **Pole, 17 sub sta ref to St Johns River Entrance**
Strait of Juan de Fuca Entrance, WA <8> *Neah Bay*	**48º27'** **48º22.1'**	**124º35'** **124º37'**	1931 (2 days obs direction)	7/23/31 - 7/25/31 (2 days) & 1 mo pred (1945) at Admiralty Inlet	Inferred from Admiralty Inlet such that constants in Col B = ½ those at Admiralty Inlet and kappa prime values = 30 min earlier. Short period components inc 10% Pub speeds may be tabulated as 3 consecutive ebbs +/or “weak and variable”. **Pole, 1 sub sta to Strait of Juan de Fuca**
Sunshine Skyway Bridge, Tampa Bay, FL *St Petersburg*	**27º37.2'** **27º46.012'**	**82º39.3'** **82º37.016'**	1990 - 1991	292 days; 8/22/90 - 6/10/91	NOS LSQHA at 15 ft below MLLW first used in 1994 ACCT. Minor axis insignificant. **ADCP, no subordinate stations**
Tampa Bay Entrance (Egmont Channel), FL *Clearwater*	**27º36.3'** **27º58.6'**	**82º45.6'** **82º49.9'**	1990 - 1991	401 days; 8/20/90 - 9/25/91	NOS LSQHA at 15 ft below MLLW 1st used in 1994 ACCT. Minor axis insig. **ADCP, 54 sub sta ref to Egmont**

Station Name	Location		Year Data Obtained	Duration	Comments
	Latitude N	Longitude W			
The Narrows (north end), **Puget Sound**, WA *Seattle*	**47°18'** **47°36.2'**	**122°33'** **122°20.2'**	1944	28 day series beginning 1/19/44	Based on 28-day series at station 26 & compared w/tides at Seattle. Short period comp inc 5%. Values for N2 spec determined from 2 short series. Pred are for midstream. W side currents flood most of the time; east side ebbs most of the time. **Roberts Current Meter, 31 sub sta ref to The Narrows Puget Snd**
The Narrows, New York Harbor, NY <4> *Sandy Hook, NJ*	**40°36.6'** **40°28.0'**	**74°02.8'** **74°00.6'**	1932	29 days; 8/18/32 - 9/16/32	C&GS analysis of US Engineers' obs. Short period components inc 9%. **Pole, 77 sub sta ref to The Narrows New York Harbor**
The Race, Long Island Sound, NY *New London, CT*	**41°14.0'** **41°21.3'**	**72°03.6'** **72°05.2'**	1989	72 days (1/1/89 - 3/13/89)	NOS average of 2 29-day HA's at 38 ft below MLLW. First used in 1994 ACCT. Minor axis negligible. **ADCP (89); 155 sub sta ref to The Race**
Throgs Neck, Long Island Sound, NY *Willets Point*	**40°48.6'** **40°48'**	**73°47.1'** **73°47'**	1989	483 days; 3/30/88 - 10/3/89	NOS average of 16 29-day HA's at 15 ft below MLLW. First used in 1994 ACCT. Minor axis negligible **ADCP (89), 16 sub sta ref to Throgs Neck**
Unimak Pass (off Scotch Cap), Aleutian Islands, AK *Unalaska*	**54°21.9'** **53°52.8'**	**164°48'** **166°32.3'**	1938 and 1950	11 ¼ days (1938) and 33 broken days (1950)	Combination of constants from 3 series of **pole obs** in 6/38 & 7/38 of 4 ¼, 4 & 3 days w/33 days of broken series w/meter beg 6/14/50. Short period components inc 3%. Station exhibits a min flood (0kt). Time zone officially changed from 165° to 135°W on 10/30/83. New times reflected 1st in 1985 PCCT. **Pole, 35 sub sta ref to Unimak Pass**
Wrangell Narrows (off Petersburg), AK *Ketchikan*	**56°49'** **55°20'**	**132°58'** **131°37.5'**	1925	16 days in Aug	Derived from tidal constants for Petersburg, AK. Corrected by using channel dir & inc speeds by10%(25). Short period comps inc 6%. Time zone officially changed from 120° to 135°W on 10/30/83; new TM appeared in 1985 PCCT **Zeskind Float, 345 sub sta ref to Wrangell Narrows**

Footnotes:

<1> Hell Gate (off Mill Rock) East River, NY: Observations by US Engineers 1932. Greenwich interval times are from mean of results from stations 2, 5, & 6 totaling about 35 days. Velocities are from Station 6 (11 days) which is in the center of the channel. Predictions are made w/harmonic constants derived from tidal constants at Willets Pt. (2 yrs, 1891&1894) and Governors Island (3 yrs., 1876-1878), the constants giving the diff in elev of tide at WP and GI. Predictions for 1934 obtained from revised constants using lag of 0.64 hr, ebb set of 0.6kt, M4 kappa prime = 106.6, M6 kappa prime = 111.0. Using these constants, predictions for May 1932 are: Gr SBF=9:03, Gr MFC=11:59 3.26kt, Gr SBE=2:33, Gr MEC =5:35 4.53kts. Spring vel = 3.8kts (flood) and 5.0kts (ebb) where Spring (Sg) vel = avg vel * sqrt (1.2) where 1.2 = Sg/Mean at The Battery and Willets Point.

<2> Pollock Rip Channel (Butler Hole) MA: One year of observations at Stonehorse Lightship (9/1/34 - 8/31/35) w/15 ft pole. Two years “plus” (748 days) 8/6/34 - 8/31/36 w/15 ft pole. First used as reference station in 1937. Sg vel = Av vel * [(M2 + S2)÷M2] where [(M2 + S2)÷M2] = 1.15. From predictions for Jan 1937: Greenwich Intervals and corrected velocities are: SBF 7:55, MFC 11:17, MFC vel 1.92 (kt), SBE 1:59, MEC 4:48, MEC vel 1.69 (kt). Notified by Englebrecht that Lightship was removed. Form 696 has (Butler Hole, MA). Flood differences = 6 hr 32 min; Ebb differences = 5 hr 53 min. Velocities at strength MFC = 2.0 kts, MEC = 1.8 kts; Spring tide MFC = 2.3 kts and MEC = 2.1 kts.

<3> Portsmouth Harbor Entrance (off Wood Island) NH: Data from pole and meter (9ft and 22ft) copied from “Standard Station Summary” sheet. Radio current meter at Sta 7 9/16/53 - 10/1/53 at 15 ft depth may have questionable directions, particularly flood. Channel is almost N-S (dated 4/26/55) and directions for MFC = 40^{o} and MEC = 170^{o}. Maximum obs vel = 2.2kts, 142^{o} (1953). Data first used in 1934. Remarks: flood diff = 5hr 47min and [(M2 + S2)÷M2] where [(M2 + S2)÷M2] = 1.16. Average flood vel = 1.2kts, ebb = 1.8kts; mean spring tide = 1.7kts.

<4> The Narrows, New York Harbor, NY: 28 days of data (8/18/32 - 9/16/32) collected by US Engineers - Sta 1 (meter at 16.8 ft) Directions are from 11 days in 1922 at Sta 9. Amplitudes are multiplied by 1.09 to make predictions agree with observations. This station was first used as a reference station beginning with 1976 Current Tables. It is predicted with north and east components as a rotary current. Average flood vel = 1.7 knots, ebb = 2.0 knots, mean spring tide = 2.2 knots.

<5> Admiralty Inlet, WA: Mean of the results from following series: 26 days 1908 (Derickson), 32 days 1942 (EB Roberts), 26 days 1943 (Sta 14) (EB Roberts) and 36 days 1943 (Sta 1) using EB Roberts. Using constants from obs in those 4 years give predictions for 1946 as FL vel 1.6 knots and EB vel 2.6 knots. Remarks: Total current vel from Form 180 - Constants used for predictions. Predictions for years 1945 and 1946 give total current flood 2.6 knots and total current ebb 3.2 knots. Mean GI (from 4 years): SBF=8.06hr, MFC=10.32hr, SBE=0.29hr, MEC=4.11hr. There are 26 secondary stations referenced to Admiralty Inlet. Most surveyed in 1946 and 1965 with Roberts Current Meters.

<6> Deception Pass, WA: Based on float (Zeskind) observations from 9/9/25 - 10/9/25. Slacks (9/9/25 - 10/9/25) and strengths (9/13 - 9/17/25). Slacks averaged 3 min later than the full time series so strengths were decreased by 3 min to obtain the GI: SBF=5hr20min, MFC=8hr16min, SBE=11hr14min, MEC=1hr31min. Avg flood vel 5.2 & ebb 6.6 knots.

<7> San Francisco Bay Entrance (Golden Gate): Weighted mean of 7 days, Oct 19-26, 1923 (Shoppe Sta No 10 - Weight 2). Pole only. Weight 1 = 3 days May 1-2, 27-29, 1930 by US Eng Sec. R, Sta 3 at 10 foot depth. Velocities are from Shoppe’s observations. Tropic velocities are from 1 year predictions in 1935. 22 Secondary stations are referenced to San Francisco Bay Entrance. In 1990 ref sta changed from Alcatraz to SFB Entr.

<8> Strait of Juan de Fuca: One month prediction (July 1945) using new Admiralty Inlet constants; less 30 min and amplitudes times 0.5. Directions are from 2 days observations by K.T. Adams, July 22-25, 1931, Station #1. Observations five flood velocity 0.5 knots, ebb velocity 1.4 knots.

APPENDIX C

Leading U. S. Ports Ranked by Total 1995 Tonnage

PORT_NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
South Louisiana, LA, Port of	204,482,591	106972579	97510012	28867399	68642613
Houston, TX	135,231,322	63694434	71536888	42859905	28676983
New York, NY and NJ	119,341,574	71281214	48060360	38728644	9331716
Baton Rouge, LA	83,612,788	45384087	38228701	26564120	11664581
Valdez, AK	80,955,084	80881706	73378	0	73378
New Orleans, LA	76,984,036	37962557	39021479	18770926	20250553
Plaquemine, LA, Port of	72,897,301	48466434	24430867	7854328	16576539
Corpus Christi, TX	70,456,033	25885340	44570693	38624945	5945748
Long Beach, CA	53,227,490	19738999	33488491	15994553	17493938
Tampa, FL	51,911,335	31812115	20099220	6069656	14029564
Mobile, AL	50,972,223	25083220	25889003	11711441	14177562
Texas City, TX	50,402,938	19213208	31189730	29980279	1209451
Port Arthur, TX	49,799,977	6763743	43036234	36864423	6171811
Pittsburgh, PA	48,849,508	48849508	0	0	0
Norfolk Harbor, VA	47,658,182	10283351	37374831	5543382	31831449
Lake Charles, LA	46,569,641	19740706	26828935	21615421	5213514
Los Angeles, CA	46,478,586	19063467	27415119	13550393	13864726
Duluth-Superior, MN and WI	45,049,184	34932890	10116294	1425472	8690822
Baltimore, MD	44,695,812	13098369	31597443	14359323	17238120
Philadelphia, PA	40,634,284	12763551	27870733	27151633	719100
Portland, OR	31,255,509	13616851	17638658	2714802	14923856
Marcus Hook, PA	30,818,134	14549103	16269031	16222985	46046
St. Louis, MO and IL	30,137,632	30137632	0	0	0
Huntington, WV	28,265,731	28265731	0	0	0
Pascagoula, MS	26,926,582	9481727	17444855	14735302	2709553
Seattle, WA	26,179,838	6041194	20138644	7567122	12571522
Chicago, IL	25,329,030	22082501	3246529	2206262	1040267
Paulsboro, NJ	24,780,664	11645610	13135054	12984722	150332
Newport News, VA	23,365,005	5170196	18194809	1794695	16400114
Beaumont, TX	20,937,132	14922961	6014171	4026335	1987836
Tacoma, WA	20,878,751	7026469	13852282	4009359	9842923
Richmond, CA	20,839,258	15034485	5804773	3649403	2155370
Freeport, TX	19,661,621	5475882	14185739	12271130	1914609
Detroit, MI	18,660,925	15002672	3658253	3051172	607081
Port Everglades, FL	18,367,389	10238202	8129187	6254011	1875176
Savannah, GA	17,379,724	3566640	13813084	6437974	7375110
Boston, MA	16,744,386	9637706	7106680	6363958	742722
Memphis, TN	15,944,945	15944945	0	0	0
Indiana Harbor, IN	15,700,153	15019457	680696	640254	40442

PORT_NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
Jacksonville, FL	15,692,999	8740054	6952945	5062499	1890446
San Juan, PR	15,477,965	10900245	4577720	3775480	802240
Cleveland, OH	15,393,496	12323290	3070206	2655471	414735
Lorain, OH	14,964,284	14839878	124406	124406	0
Toledo, OH	14,074,499	7240352	6834147	1376781	5457366
Oakland, CA	13,224,118	2523900	10700218	4330630	6369588
Anacortes, WA	13,109,828	11120181	1989647	538040	1451607
Cincinnati, OH	13,068,362	13068362	0	0	0
New Castle, DE	12,455,809	4874803	7581006	7540893	40113
Honolulu, HI	11,545,102	9374582	2170520	1923739	246781
Portland, ME	11,456,007	2015780	9440227	9295191	145036
Kalama, WA	11,346,546	660579	10685967	15754	10670213
Charleston, SC	11,171,597	3818269	7353328	3326472	4026856
Galveston, TX	10,465,119	3815125	6649994	1986010	4663984
Burns Waterway Harbor, IN	10,275,176	7603119	2672057	2206600	465457
Presque Isle, MI	10,099,422	8307672	1791750	30173	1761577
Ashtabula, OH	10,010,229	6172507	3837722	1074963	2762759
Gary, IN	9,978,301	9626559	351742	181175	170567
Taconite, MN	9,247,361	9247361	0	0	0
Matagorda Ship Channel, TX	9,237,437	2689155	6548282	5771996	776286
Louisville, KY	8,999,282	8999282	0	0	0
New Haven, CT	8,812,648	6402487	2410161	2218489	191672
Escanaba, MI	8,479,428	8479428	0	0	0
Stoneport, MI	8,467,755	7413215	1054540	33215	1021325
Calcite, MI	8,380,892	6520896	1859996	0	1859996
Two Harbors, MN	8,265,384	8265384	0	0	0
Barbers Point, Oahu, HI	8,232,732	3507894	4724838	3974002	750836
Mount Vernon, IN	8,225,907	8225907	0	0	0
Wilmington, NC	7,860,740	3969329	3891411	2717451	1173960
Vancouver, WA	7,534,764	2173470	5361294	893875	4467419
Providence, RI	6,932,109	4821471	2110638	1613395	497243
Miami, FL	6,578,860	1235938	5342922	2483652	2859270
Longview, WA	6,166,724	1172181	4994543	674806	4319737
Camden-Gloucester, NJ	5,919,077	2747343	3171734	2457449	714285
Albany, NY	5,802,920	4348716	1454204	870288	583916
Conneaut, OH	5,611,533	2986146	2625387	29123	2596264
Vicksburg, MS	5,127,950	5127950	0	0	0
Port Inland, MI	5,050,272	4630101	420171	31144	389027
St. Clair, MI	5,028,413	5026826	1587	1587	0
St. Paul, MN	4,769,608	4769608	0	0	0
Nikishka, AK	4,699,710	3376826	1322884	3	1322881
Victoria, TX	4,624,192	4624192	0	0	0
Morehead City, NC	4,577,242	1815307	2761935	732469	2029466

PORT_NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
Everett, WA	4,440,858	3017536	1423322	384659	1038663
Silver Bay, MN	4,348,458	4348458	0	0	0
Wilmington, DE	4,272,719	782514	3490205	3051774	438431
Portsmouth, NH	3,913,882	813055	3100827	2770435	330392
Marine City, MI	3,850,333	3850333	0	0	0
Nashville, TN	3,748,978	3748978	0	0	0
Coos Bay, OR	3,628,036	151748	3476288	52140	3424148
Sandusky, OH	3,536,000	888431	2647569	3500	2644069
Marblehead, OH	3,517,954	2990864	527090	4	527086
Bridgeport, CT	3,447,062	3001601	445461	433546	11915
Fall River, MA	3,279,988	2542609	737379	720330	17049
Milwaukee, WI	3,262,288	1632597	1629691	868474	761217
Port Dolomite, MI	3,261,858	2975002	286856	13635	273221
Anchorage, AK	3,221,587	2269546	952041	251338	700703
Palm Beach, FL	2,972,159	2154336	817823	315169	502654
Fairport Harbor, OH	2,941,343	2376289	565054	47576	517478
Panama City, FL	2,890,579	2395807	494772	68266	426506
Port Canaveral, FL	2,816,904	1218140	1598764	1245094	353670
Alpena, MI	2,766,717	2604507	162210	31833	130377
Guntersville, AL	2,754,096	2754096	0	0	0
Brownsville, TX	2,656,193	1043221	1612972	497062	1115910
Kahului, Maui, HI	2,586,230	2510919	75311	74941	370
Chattanooga, TN	2,525,377	2525377	0	0	0
Kansas City, MO	2,371,609	2371609	0	0	0
Olympia, WA	2,165,575	1998723	166852	4858	161994
Green Bay, WI	2,122,138	1899193	222945	190486	32459
Gulfport, MS	2,023,084	86089	1936995	1231432	705563
Port Jefferson, NY	2,018,078	1855389	162689	162689	0
Brunswick, GA	2,002,489	232582	1769907	996787	773120
Helena, AR	1,964,582	1964582	0	0	0
Monroe, MI	1,919,912	1867024	52888	6578	46310
Port Angeles, WA	1,910,512	1010344	900168	305137	595031
Greenville, MS	1,873,694	1873694	0	0	0
Buffalo, NY	1,872,534	1324335	548199	487459	60740
Muskegon, MI	1,824,617	1648715	175902	175902	0
Ketchikan, AK	1,821,127	1473285	347842	108889	238953
Biloxi, MS	1,739,456	1739456	0	0	0
Pensacola, FL	1,622,528	1143417	479111	123584	355527
Drummond Island, MI	1,606,078	1402869	203209	0	203209
Charlevoix, MI	1,584,187	1521893	62294	0	62294
Grays Harbor, WA	1,565,708	101185	1464523	130	1464393
Tulsa, Port of Catoosa, OK	1,473,584	1473584	0	0	0
Buffington, IN	1,447,039	1416589	30450	0	30450

PORT_NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
Chester, PA	1,388,968	271641	1117327	885718	231609
Hilo, HI	1,354,365	1303890	50475	49986	489
San Diego, CA	1,351,482	616598	734884	258589	476295
San Francisco, CA	1,330,066	517591	812475	324458	488017
Stockton, CA	1,320,462	129887	1190575	724516	466059
Minneapolis, MN	1,299,922	1299922	0	0	0
Bellingham, WA	1,291,373	530812	760561	400547	360014
Searsport, ME	1,262,712	417246	845466	808638	36828
Bucksport, ME	1,237,542	379639	857903	856294	1609
Georgetown, SC	1,233,580	69198	1164382	1072812	91570
Humboldt, CA	1,220,383	599221	621162	59016	562146
Salem, MA	1,197,416	395561	801855	801732	123
Ludington, MI	1,149,952	1107581	42371	8311	34060
Sacramento, CA	1,137,456	199390	938066	58379	879687
Richmond, VA	1,135,106	581063	554043	300572	253471
Ponce, PR	1,134,115	231	1133884	959193	174691
Nawiliwili, Kauai, HI	1,129,612	1113657	15955	15955	0
Erie, PA	1,056,727	936901	119826	108534	11292
Stamford, CT	994,083	994083	0	0	0
Astoria, OR	985,471	160976	824495	101747	722748
Trenton, NJ	963,860	963860	0	0	0
Grand Haven, MI	961,189	769042	192147	68016	124131
Hopewell, VA	934,835	634493	300342	9891	290451
Seward, AK	927,669	28210	899459	4975	894484
Marquette, MI	835,761	835761	0	0	0
Redwood City, CA	753,912	383784	370128	217211	152917
Orange, TX	692,720	619158	73562	0	73562
Charlotte, FL	637,175	637175	0	0	0
New London, CT	623,313	571372	51941	51941	0
Port Huron, MI	487,905	361332	126573	110171	16402
Oswego, NY	435,065	25623	409442	409433	9
Manistee, MI	431,966	426402	5564	5564	0
Dunkirk, NY	373,946	373946	0	0	0
Port Townsend, WA	362,406	339272	23134	7061	16073
Lake Providence, LA	314,957	314957	0	0	0
Christiansted, St Croix, VI	286,710	144250	142460	79825	62635
Skagway, AK	264,519	24113	240406	93182	147224
Traverse City, MI	226,187	226187	0	0	0
Rochester, NY	169,563	0	169563	155879	13684
Key West, FL	140,676	140344	332	24	308
Cape Charles, VA	126,195	126195	0	0	0
Ashland, WI	100,051	100051	0	0	0
Harbor Beach, MI	87,642	87642	0	0	0

PORT_NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
Sturgeon Bay, WI	71,250	71250	0	0	0
Alexandria, VA	62,137	0	62137	62023	114
Newport, RI	47,629	0	47629	47629	0
Ventura, CA	22,082	22082	0	0	0
Mackinac, MI	10,944	10944	0	0	0
Monterey Harbor, CA	9,330	9330	0	0	0
Cambridge, MD	5,081	5081	0	0	0
Morro Bay, CA	3,083	3083	0	0	0
Santa Monica, CA	193	193	0	0	0
Sackets Harbor, NY	12	12	0	0	0

APPENDIX D

1995 U.S. Port Tonnage Grouped by Tidal Current Reference Station

STATION NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
Bay of Fundy Entrance, ME	**2,500,254**	**796,885**	**1,703,369**	**1,664,932**	**38,437**
Searsport, ME	1,262,712	417,246	845,466	808,638	36,828
Bucksport, ME	1,237,542	379,639	857,903	856,294	1,609
Portsmouth Harbor Entr., NH	**15,369,889**	**2,828,835**	**12,541,054**	**12,065,626**	**475,428**
Portsmouth, NH	3,913,882	813,055	3,100,827	2,770,435	330,392
Portland, ME	11,456,007	2,015,780	9,440,227	9,295,191	145,036
Boston Harbor, MA	**17,941,802**	**10,033,267**	**7,908,535**	**7,165,690**	**742,845**
Boston, MA	16,744,386	9,637,706	7,106,680	6,363,958	742,722
Salem, MA	1,197,416	395,561	801,855	801,732	123
Cape Cod Canal, MA	**0**				
Pollock Rip Channel, MA	**10,259,726**	**7,364,080**	**2,895,646**	**2,381,354**	**514,292**
Newport, RI	47,629	0	47,629	47,629	0
Fall River, MA	3,279,988	2,542,609	737,379	720,330	17,049
Providence, RI	6,932,109	4,821,471	2,110,638	1,613,395	497,243
The Race, NY	**15,895,184**	**12,824,932**	**3,070,252**	**2,866,665**	**203,587**
Port Jefferson, NY	2,018,078	1,855,389	162,689	162,689	0
Stamford, CT	994,083	994,083	0	0	0
Bridgeport, CT	3,447,062	3,001,601	445,461	433,546	11,915
New Haven, CT	8,812,648	6,402,487	2,410,161	2,218,489	191,672
New London, CT	623,313	571,372	51,941	51,941	0
The Narrows, N.Y. Harbor, Hell Gate and Throgs Neck, NY	**125,144,494**	**75,629,930**	**49,514,564**	**39,598,932**	**9,915,632**
New York, NY and NJ	119,341,574	71,281,214	48,060,360	38,728,644	9,331,716
Albany, NY	5,802,920	4,348,716	1,454,204	870,288	583,916
Delaware Bay Entrance, DE	**121,233,515**	**48,598,425**	**72,635,090**	**70,295,174**	**2,339,916**
New Castle, DE	12,455,809	4,874,803	7,581,006	7,540,893	40,113
Wilmington, DE	4,272,719	782,514	3,490,205	3,051,774	438,431
Marcus Hook, PA	30,818,134	14,549,103	16,269,031	16,222,985	46,046
Paulsboro, NJ	24,780,664	11,645,610	13,135,054	12,984,722	150,332
Chester, PA	1,388,968	271,641	1,117,327	885,718	231,609
Philadelphia, PA	40,634,284	12,763,551	27,870,733	27,151,633	719,100

STATION NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
Camden-Gloucester, NJ	5,919,077	2,747,343	3,171,734	2,457,449	714,285
Trenton, NJ	963,860	963,860	0	0	0
Chesapeake & Delaware Canal,MD	**0**				
Baltimore Harbor Approach, MD	**44,763,030**	**13,103,450**	**31,659,580**	**14,421,346**	**17,238,234**
Cambridge, MD	5,081	5,081	0	0	0
Alexandria, VA	62,137	0	62,137	62,023	114
Baltimore, MD	44,695,812	13,098,369	31,597,443	14,359,323	17,238,120
Chesapeake Bay Entrance, VA	**73,219,323**	**16,795,298**	**56,424,025**	**7,648,540**	**48,775,485**
Norfolk Harbor, VA	47,658,182	10,283,351	37,374,831	5,543,382	31,831,449
Newport News, VA	23,365,005	5,170,196	18,194,809	1,794,695	16,400,114
Cape Charles, VA	126,195	126,195	0	0	0
Hopewell, VA	934,835	634,493	300,342	9,891	290,451
Richmond, VA	1,135,106	581,063	554,043	300,572	253,471
Charleston Harbor Entr., SC	**24,843,159**	**9,672,103**	**15,171,056**	**7,849,204**	**7,321,852**
Charleston, SC	11,171,597	3,818,269	7,353,328	3,326,472	4,026,856
Georgetown, SC	1,233,580	69,198	1,164,382	1,072,812	91,570
Wilmington, NC	7,860,740	3,969,329	3,891,411	2,717,451	1,173,960
Morehead City, NC	4,577,242	1,815,307	2,761,935	732,469	2,029,466
Savannah River Entrance, GA	**19,382,213**	**3,799,222**	**15,582,991**	**7,434,761**	**8,148,230**
Brunswick, GA	2,002,489	232,582	1,769,907	996,787	773,120
Savannah, GA	17,379,724	3,566,640	13,813,084	6,437,974	7,375,110
St. Johns River Entrance, FL	**15,692,999**	**8,740,054**	**6,952,945**	**5,062,499**	**1,890,446**
Jacksonville, FL	15,692,999	8,740,054	6,952,945	5,062,499	1,890,446
Miami Harbor, FL	**30,735,312**	**14,846,616**	**15,888,696**	**10,297,926**	**5,590,770**
Miami, FL	6,578,860	1,235,938	5,342,922	2,483,652	2,859,270
Port Everglades, FL	18,367,389	10,238,202	8,129,187	6,254,011	1,875,176
Palm Beach, FL	2,972,159	2,154,336	817,823	315,169	502,654
Port Canaveral, FL	2,816,904	1,218,140	1,598,764	1,245,094	353,670
Key West, FL	**140,676**	**140,344**	**332**	**24**	**308**
Key West, FL	140,676	140,344	332	24	308

STATION NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
Tampa Bay Entrance, Sunshine Skyway, and Old Port Tampa, FL	**55,439,089**	**34,845,097**	**20,593,992**	**6,137,922**	**14,456,070**
Charlotte, FL	637,175	637,175	0	0	0
Tampa, FL	51,911,335	31,812,115	20,099,220	6,069,656	14,029,564
Panama City, FL	2,890,579	2,395,807	494,772	68,266	426,506
Mobile Bay Entrance, AL	**521,260,589**	**276,319,566**	**244,941,023**	**109,858,532**	**135,082,491**
South Louisiana, LA, Port of	204,482,591	106,972,579	97,510,012	28,867,399	68,642,613
Baton Rouge, LA	83,612,788	45,384,087	38,228,701	26,564,120	11,664,581
New Orleans, LA	76,984,036	37,962,557	39,021,479	18,770,926	20,250,553
Plaquemine, LA, Port of	72,897,301	48,466,434	24,430,867	7,854,328	16,576,539
Mobile, AL	50,972,223	25,083,220	25,889,003	11,711,441	14,177,562
Pascagoula, MS	26,926,582	9,481,727	17,444,855	14,735,302	2,709,553
Gulfport, MS	2,023,084	86,089	1,936,995	1,231,432	705,563
Biloxi, MS	1,739,456	1,739,456	0	0	0
Pensacola, FL	1,622,528	1,143,417	479,111	123,584	355,527
Galveston Bay Entrance, TX	**347,622,099**	**141,558,564**	**206,063,535**	**155,375,499**	**50,688,036**
Matagorda Ship Channel, TX	9,237,437	2,689,155	6,548,282	5,771,996	776,286
Victoria, TX	4,624,192	4,624,192	0	0	0
Freeport, TX	19,661,621	5,475,882	14,185,739	12,271,130	1,914,609
Galveston, TX	10,465,119	3,815,125	6,649,994	1,986,010	4,663,984
Texas City, TX	50,402,938	19,213,208	31,189,730	29,980,279	1,209,451
Houston, TX	135,231,322	63,694,434	71,536,888	42,859,905	28,676,983
Port Arthur, TX	49,799,977	6,763,743	43,036,234	36,864,423	6,171,811
Beaumont, TX	20,937,132	14,922,961	6,014,171	4,026,335	1,987,836
Orange, TX	692,720	619,158	73,562	0	73,562
Lake Charles, LA	46,569,641	19,740,706	26,828,935	21,615,421	5,213,514
Aransas Pass, TX	**70,456,033**	**25,885,340**	**44,570,693**	**38,624,945**	**5,945,748**
Corpus Christi, TX	70,456,033	25,885,340	44,570,693	38,624,945	5,945,748
San Diego Bay Entrance, CA	**26,199,523**	**1,842,754**	**7,771,983**	**6,297,212**	**1,474,771**
San Diego, CA	1,351,482	616,598	734,884	258,589	476,295
Nawiliwili, Kauai, HI	1,129,612	1,113,657	15,955	15,955	0
Barbers Point, Oahu, HI	8,232,732	3,507,894	4,724,838	3,974,002	750,836
Honolulu, HI	11,545,102	9,374,582	2,170,520	1,923,739	246,781
Kahului, Maui, HI	2,586,230	2,510,919	75,311	74,941	370
Hilo, HI	1,354,365	1,303,890	50,475	49,986	489

STATION NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
San Francisco Bay Entr., CA	**137,086,419**	**57,874,053**	**79,212,366**	**38,125,664**	**41,086,702**
Long Beach, CA	53,227,490	19,738,999	33,488,491	15,994,553	17,493,938
Los Angeles, CA	46,478,586	19,063,467	27,415,119	13,550,393	13,864,726
Santa Monica, CA	193	193	0	0	0
Morro Bay, CA	3,083	3,083	0	0	0
Monterey Harbor, CA	9,330	9,330	0	0	0
Redwood City, CA	753,912	383,784	370,128	217,211	152,917
San Francisco, CA	1,330,066	517,591	812,475	324,458	488,017
Oakland, CA	13,224,118	2,523,900	10,700,218	4,330,630	6,369,588
Richmond, CA	20,839,258	15,034,485	5,804,773	3,649,403	2,155,370
Humboldt, CA	1,220,383	599,221	621,162	59,016	562,146
Carquinez Strait, CA	**2,457,918**	**329,277**	**2,128,641**	**782,895**	**1,345,746**
Stockton, CA	1,320,462	129,887	1,190,575	724,516	466,059
Sacramento, CA	1,137,456	199,390	938,066	58,379	879,687
Grays Harbor Entrance, WA	**58,854,722**	**17,885,242**	**40,969,480**	**4,401,114**	**36,568,366**
Kalama, WA	11,346,546	660,579	10,685,967	15,754	10,670,213
Longview, WA	6,166,724	1,172,181	4,994,543	674,806	4,319,737
Astoria, OR	985,471	160,976	824,495	101,747	722,748
Grays Harbor, WA	1,565,708	101,185	1,464,523	130	1,464,393
Vancouver, WA	7,534,764	2,173,470	5,361,294	893,875	4,467,419
Portland, OR	31,255,509	13,616,851	17,638,658	2,714,802	14,923,856
Strait of Juan de Fuca Entr., WA	**0**				
Admiralty Inlet, WA	**30,983,102**	**9,398,002**	**21,585,100**	**7,958,842**	**13,626,258**
Seattle, WA	26,179,838	6,041,194	20,138,644	7,567,122	12,571,522
Everett, WA	4,440,858	3,017,536	1,423,322	384,659	1,038,663
Port Townsend, WA	362,406	339,272	23,134	7,061	16,073
The Narrows, Puget Sound, WA	**23,044,326**	**9,025,192**	**14,019,134**	**4,014,217**	**10,004,917**
Olympia, WA	2,165,575	1,998,723	166,852	4,858	161,994
Tacoma, WA	20,878,751	7,026,469	13,852,282	4,009,359	9,842,923
Deception Pass, WA	**0**				
Rosario Strait, WA	**14,401,201**	**11,650,993**	**2,750,208**	**938,587**	**1,811,621**
Anacortes, WA	13,109,828	11,120,181	1,989,647	538,040	1,451,607

STATION NAME	TOTAL	DOMESTIC	FOREIGN	IMPORTS	EXPORTS
Bellingham, WA	1,291,373	530,812	760,561	400,547	360,014
San Juan Channel, WA	**0**				
Wrangell Narrows, AK	**13,370,460**	**7,271,405**	**6,099,055**	**412,370**	**5,686,685**
Coos Bay, OR	3,628,036	151,748	3,476,288	52,140	3,424,148
Ketchikan, AK	1,821,127	1,473,285	347,842	108,889	238,953
Nikishka, AK	4,699,710	3,376,826	1,322,884	3	1,322,881
Anchorage, AK	3,221,587	2,269,546	952,041	251,338	700,703
Sergius Narrows, AK	**81,882,753**	**80,909,916**	**972,837**	**4,975**	**967,862**
Seward, AK	927,669	28,210	899,459	4,975	894,484
Valdez, AK	80,955,084	80,881,706	73,378	0	73,378
North Inian Pass, AK	**264,519**	**24,113**	**240,406**	**93,182**	**147,224**
Skagway, AK	264,519	24,113	240,406	93,182	147,224
Isanotski Strait, AK	**0**				
Unimak Pass, AK	**0**				
Akutan Pass, AK	**0**				
Kvichak Bay, AK	**0**				

NOTE: No port is associated with the Tidal Current Reference Station when total tonnage is zero.