Web-based Tidal Toolbox Of Astronomic Tidal Data For The Atlantic Intracoastal Waterway, Esturaries Sic] And Continental Shelf Of The South Atlantic Bight

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WEB-BASED TIDAL TOOLBOX OF ASTRONOMIC TIDAL DATA FOR THE ATLANTIC INTRACOASTAL WATERWAY, ESTURARIES AND CONTINENTAL SHELF OF THE SOUTH ATLANTIC BIGHT

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering in the Department of Civil, Environmental, and Construction Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Spring Term
2011

Major Professor: Scott C. Hagen
ABSTRACT

A high-resolution astronomic tidal model has been developed that includes detailed inshore regions of the Atlantic Intracoastal Waterway and associated estuaries along the South Atlantic Bight. The unique nature of the model’s development ensures that the tidal hydrodynamic interaction between the shelf and estuaries is fully described. Harmonic analysis of the model output results in a database of tidal information that extends from a semi-circular arc (radius ~750 km) enclosing the South Atlantic Bight from the North Carolina coast to the Florida Keys, onto the continental shelf and into the full estuarine system.

The need for tidal boundary conditions (elevation and velocity) for driving inland waterway models has motivated the development of a software application to extract results from the tidal database which is the basis of this thesis. In this tidal toolbox, the astronomic tidal constituents can be resynthesized for any open water point in the domain over any interval of time in the past, present, or future. The application extracts model results interpolated to a user’s exact geographical points of interest, desired time interval, and tidal constituents. Comparison plots of the model results versus historical data are published on the website at 89 tidal gauging stations. All of the aforementioned features work within a zoom-able geospatial interface for enhanced user interaction.

In order to make tidal elevation and velocity data available, a web service serves the data to users over the internet. The tidal database of 497,847 nodes and 927,165 elements has been preprocessed and indexed to enable timely access from a typical modern web server. The
preprocessing and web services required are detailed in this thesis, as well as the reproducibility of the Tidal Toolbox for new domains.
ACKNOWLEDGMENTS

I would like to thank Dr. Scott C. Hagen for his tireless efforts in building up a premier and well-equipped lab (the CHAMPS Lab) at the University of Central Florida (UCF), and for sharing the facility and his expertise with me and his students. It has been a privilege to be a part of it. I also acknowledge Dr. Hagen for providing me with the opportunity to experience teaching the undergraduate hydrology course at UCF using highly developed course materials and lab procedures. I would also like to thank Dr. Peter Bacopoulos for his guidance and support throughout the last two years, and particularly for his efforts in reviewing and editing this thesis. It is all the more clear and complete due to his labors. I would like to thank Dr. Manoj Chopra and Dr. Dingbao Wang for serving on my thesis advisory committee. I also give thanks to Dana Smar for taking charge of teaching the hydrology labs when I moved into the instructor role, Derek Giardino for his assistance in getting me familiar with teaching the hydrology labs, and Matt Bilskie for setting up the FTP server used by the Tidal Toolbox and for his technical assistance in general. The CHAMPS Lab is more than the sum of its parts by virtue of the interaction and exchange of ideas between all its members, which during my time there included Steve Medeiros, Lillie Thomas, Hitoshi Tamura, and Amanda Tritinger. The department staff works hard in support of the lab. I would particularly like to thank Anne Marie Keyek, Margarida Trim, and Pauline Strauss for their support.
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LIST OF ACRONYMS/ABBREVIATIONS

API  Application Programmer Interface
ASCII  American Standard Code for Information Interchange
ASP  Active Server Pages
CO-OPS  Center for Operational Oceanographic Products and Services
CHAMPS  Coastal Hydroscience Analysis, Modeling & Predictive Simulations Laboratory
DNS  Domain Name System
HTML  Hypertext Markup Language
HTTP  Hypertext Transfer Protocol
IHO  International Hydrographic Organization
IIS  Internet Information Services
IOC  Intergovernmental Oceanographic Commission
MAC  Media Access Control
NAVD 88  North American Vertical Datum of 1988
NGS  National Geodetic Survey
NGWLMS  Next Generation Water Level Measurement System
NOAA  National Oceanic and Atmospheric Administration
NOS  National Ocean Service
PNG  Portable Network Graphics
SHTML  Server Side Include preprocessed HTML
SSI  Server Side Includes
UNESCO  United Nations Educational, Scientific, and Cultural Organization
CHAPTER ONE: INTRODUCTION

There are many websites on the internet that provide tide forecasting. Some of them are superb in both content and presentation. One factor that they all have in common, however, is that they use a history of observations at a point to forecast future conditions at the same point. This is optimal if the user of the information is satisfied with information at points, and there are tide gauges at the user’s points of interest. Modelers, on the other hand, are often more interested in tide signals along a boundary than at a point. Sometimes these boundaries of interest need to be located where there are no tide gauges or data buoys to report tide data.

Numerical modeling can fill this need for astronomic tide data where there are no gauges, and since only the astronomic tide is modeled, there is no need to separate out the astronomic portion of an observed signal from other periodic signals that may be present in an observed signal. On the other hand, modeling the astronomic tide from the deep ocean into the estuarine domain requires an extensive and highly-detailed mesh as well as computational resources that are not available to all modelers. The University of Central Florida CHAMPS Lab has the meshing expertise and computing resources, and has run a large model of the South Atlantic Bight, (P. Bacopoulos & S. C. Hagen, 2010) and would like to release those results to the modeling community. The results of that model run have been harmonically analyzed and reduced to the periodic components that can be used to recreate the astronomic tidal signal in other time intervals in the Sun-Moon-Earth astronomic cycle. Even in harmonically reduced form, however, the output files are still over 1.9 gigabytes in total file size.
Extracting what the user needs from the harmonically reduced form of the South Atlantic Bight model results, and resynthesizing the tidal signal for the user’s time and place, and communicating the results to the user, are the functions of the “Tidal Toolbox” described in this thesis.

The Astronomic Tide

The astronomic tide is that component of the ocean tide that can be explained by the gravitational attraction of heavenly bodies on the Earth's surface water. Other important contributors to tide, such as wind (i.e. storm tide), the morphology of the coastline and of the sea floor, fresh-water in-flows and thermal currents, can be viewed as being superimposed on the astronomic tide.

The Sun-Moon-Earth system accounts for practically all of the gravitational forces moving the tide, and are the only heavenly bodies included in most models. Additionally, nonlinearities within shallow water cause dispersion of the fundamental tide into higher frequencies, which also contribute to the overall tidal signal.
Measurement of Tides

Datums

To a first approximation the Earth is very nearly spherical, with a mean radius of 6371 kilometers. A second approximation considers the slight bulge at the equator due to the constant rotation of the Earth. The degree to which centrifugal acceleration counteracts Earth gravity is a function of latitude. This theoretical surface is referred to as the *ellipsoid*. The ellipsoid has a polar radius 21.3 km shorter than the equatorial radius. The equipotential surface of the ellipsoid fits the Earth much better than a sphere, but not perfectly. Satellite altimetry, in which the satellite position is known very accurately relative to the ellipsoid, has observed ocean surface elevations that vary 100m from the ellipsoid, even after the effects of wind, waves, and the tides are discounted. This *actual* average Earth surface elevation, determined by measurements, is called the *geoid*. (David T. Sandwell - Scripps Institution of Oceanography and Walter H. F. Smith - Geosciences Laboratory, NOAA, online article)


Observed tides are referenced to a local datum that NOAA refers to as the station datum. The zero of the station datum is usually chosen such that it is below the lowest tide observed. Once a station datum is chosen, the usual practice is to not change it. This means that a station datum
chosen long ago, before current practices were in effect, would be preserved rather than relocated. A geodetic datum is needed in order to compare the relative elevations of readings taken at different stations. The National Geodetic Survey (NGS) maintains the North American Vertical Datum of 1988 (NAVD 88) that is used by NOAA for this purpose.


See also (Gill & Schultz, 2000).

The largest tide range on Earth is observed at the Bay of Fundy, Canada where the tide range can reach 17 meters without unusual weather conditions. For comparison, the NOS tide gauge at Fort Pulaski, Georgia, which is located approximately in center of the coastline of the model domain presented, experiences a tide range of 2.29 meters.
Gauges

One of the most widely used sensors in the NOAA CO-OPS Next Generation Water Level Measurement System (NGWLMS) is the Aquatrak Air Acoustic sensor installed in a protective well. Its estimated accuracy is +/- 2 cm for a single measurement relative to datum. Averaging all measurements over a month the estimated accuracy is +/- 5 mm for the monthly mean. The resolution is 0.001 m. Measurements are transmitted every 6 minutes via GOES satellite or IP modem. Each measurement is computed from 181 one second samples centered on the tenth of the hour. A mean is computed over the 181 samples, a +/- 3 standard deviation outlier rejection test is applied; the mean is then recomputed without the outliers and reported along with the number of outliers. To summarize, a 3 minute water level average is transmitted every 6 minutes.


In order to gain an appreciation of how the Aquatrak Air Acoustic sensors are currently performing under actual field conditions, three stations were selected for analysis that are equipped with redundant Aquatrak Air Acoustic sensors for which raw data was available for both the primary and backup sensor, and analyzed 13 months of six-minute data for the variance between the two co-located identical gauges. Note that the data examined is the raw data that has not been through the NOAA verification process, which would have incorporated additional processing and engineering judgment to provide the verified version of the data. The raw data was used because the subject of interest here is the raw gauge performance, not the best estimate of the water level.
The following procedure was used for each of 3 stations:

1) Download 13 months of 6-minute data. (7/1/2009 to 7/31/2010)

2) Extract only records with 2 measures of the same water level at the same time.

3) Create a vector of (sensor 1 – sensor 2).

4) Take the standard deviation.

5) Discard as flyers records > 3 standard deviations out.

6) Take standard deviation again.

7) Construct a 95% confidence interval based on an assumption of Gaussian error.

8) Use bin sorting to test the assumption of Gaussian error.
Along the Florida coast Aquatrak Air Acoustic sensors are normally employed as primary sensors and bubbler type pressure sensors are employed as backup sensors, so it was necessary to select the 3 stations to analyze from the northwest region of the U.S. where both primary and backup sensors are Aquatrak Air Acoustic sensors. Figure 1 shows the northwest U.S. coastline, the blue markers indicate where clusters of NOS tide gauge stations are located. The three red circles on the coasts of Oregon, Washington, and the Gulf of Alaska indicate areas where the redundant Aquatrak Air Acoustic sensors selected for an analysis of raw sensor output variance are located. The first station selected for study was the Port Orford, Oregon station number 9431647. Figure 2 shows the location of the Port Orford, Oregon station, with an inset to magnify the bay like morphology of the coastline, which may help explain the numerical results. A MATLAB program was written to scan the data for anomalies like those depicted in Figure 3, so that obviously bad data could be discarded. The figure shows the primary water level sensor (red line) suddenly drops 3 m and remains flat for 6 hours, while the backup water level sensor (grey +) continues to track the predicted water level. Figure 4 shows the presence of a high frequency component on the tidal signal. The correlation of the two measurements is evidence that this high frequency component is really present, and the green (Observed - Predicted) plot suggests that it may even have periodic components, but it is still noise in the context of extracting harmonic constituents upon which to base a forecast of the astronomic tide. The second station selected for study was the Neah Bay, WA station number 9443090. The inset in Figure 5 shows that the gauge is located on the side of the Juan De Fuca Strait near the coast, and does not directly “face” the Pacific Ocean. Neah Bay had the smallest amount of raw data discarded, but as Figure 6 depicts, there was one instance where the primary water level sensor
output deviated significantly from the backup water level sensor output. Figure 7 shows five gaps in a two day record. The gaps were not included in the data analyzed, so they did not affect the numerical results of this experiment. The third station selected for study was the Anchorage, Alaska station number 9455920. The Figure 8 inset shows that the Anchorage station is much farther inland than Port Orford or Neah Bay, a factor which may have contributed to the much noisier data depicted in Figure 9 and the error in the (Observed – Predicted) signal at low tides. Figure 9 shows the much noisier data characteristic of the Anchorage, Alaska station.
Figure 1: Selected Redundant Aquatrak Air Acoustic Sensor Installations
Figure 2: Port Orford, Oregon Station 9431647
Figure 3: Example of Station 9431647 Data Discarded

Figure 4: Example of Less Accurate Station 9431647 Data Not Discarded
Figure 5: Neah Bay, Washington; Station Number 9443090
Figure 6: Example of Station 9443090 Data Discarded

Figure 7: Example of Gaps in Station 9443090 Data
Figure 8: Anchorage, Alaska Station Number 9455920
Figure 9: Noisy Station 9455920 Data Typical of 834 Points Discarded
The numerical results of the analysis of variance between two identical sensors co-located at each of three tide gauge locations in the northwestern U.S. coastline is summarized in Table 1.

Table 1: Summary of Analysis of 3 Stations with Redundant Aquatrak Air Acoustic Sensors

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Port, Orford # 9431647</th>
<th>Neah Bay # 9443090</th>
<th>Anchorage # 9455920</th>
</tr>
</thead>
<tbody>
<tr>
<td># Records Used</td>
<td>94,357</td>
<td>93,735</td>
<td>101134</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>37.4 mm</td>
<td>12.1 mm</td>
<td>104.5 mm</td>
</tr>
<tr>
<td># Records Discarded</td>
<td>17</td>
<td>72</td>
<td>834</td>
</tr>
<tr>
<td>Recomputed Std. Dev.</td>
<td>12.1 mm</td>
<td>6.29 mm</td>
<td>27.1 mm</td>
</tr>
<tr>
<td>Low Limit of 95% C.I.</td>
<td>-23.1 mm</td>
<td>-13.4 mm</td>
<td>-74.6 mm</td>
</tr>
<tr>
<td>High Limit of 95% C.I.</td>
<td>+24.3 mm</td>
<td>+11.3 mm</td>
<td>+31.6 mm</td>
</tr>
<tr>
<td>% &gt; 3 Std. Dev.</td>
<td>2.17%</td>
<td>1.56%</td>
<td>0.07%</td>
</tr>
<tr>
<td>Middle %</td>
<td>95.7%</td>
<td>94.8%</td>
<td>98.0%</td>
</tr>
<tr>
<td>% &lt; 3 Std. Dev.</td>
<td>2.15%</td>
<td>3.59%</td>
<td>1.23%</td>
</tr>
</tbody>
</table>

In the Port Orford, OR column, note that the +24.3 mm, -23.1 mm confidence interval agrees reasonably well with the +/- 20 mm estimated accuracy listed in the NOAA specification referenced above. The bin sorting test shows the assumption of Gaussian error is reasonably accurate.

In the Neah Bay, WA column, note that the +11.3 mm, -13.4 mm confidence interval is better than the +/- 20 mm estimated accuracy listed in the NOAA specification referenced above. The bin sorting test shows that the probability distribution of the error has some left skew indicating a small amount of systematic error.

So much of the Anchorage data had to be discarded due to the +/- 3 standard deviation test that an additional month of raw data, the month of August 2010, was added to preserve the statistical significance of the results. In the Anchorage, Alaska column, note that the +31.6 mm, -74.6 mm confidence interval is significantly worse than the +/- 20 mm estimated accuracy listed in the
NOAA specification referenced above. The bin sorting test shows that the probability distribution of the error is left skewed with almost no upper tail, hence the assumption of Gaussian distributed error is invalid. Most of the 834 data points that were discarded did not really look like flyers, but rather looked like noisy data, indicating that the +/- 3 standard deviation limit was actually too low for this station, and arbitrarily made the final confidence interval smaller than it should have been.
Introduction to Tidal Harmonic Analysis

Tidal analysis begins with observation then attempts to explain the observed record with known physical laws and principles. The process borrows much from the more general field of signal analysis, which holds that any continuous repeating waveform can be decomposed into a linear superposition of some number of sinusoidal waveforms of the proper frequency, amplitude and phase. For example, a square wave can be decomposed into a sinusoid of the same frequency, plus all of that fundamental frequency’s odd harmonics in the correct proportions. The sinusoidal “constituents” of a symmetrical square wave are a sinusoid of the same amplitude as the fundamental frequency, a sinusoid with $1/3^{\text{rd}}$ of the amplitude of the fundamental of the $3^{\text{rd}}$ harmonic of the fundamental frequency, $1/5^{\text{th}}$ of the $5^{\text{th}}$ harmonic, $1/7^{\text{th}}$ of the $7^{\text{th}}$ harmonic, and so on, to infinity, for a perfect square wave.
Figure 10 shows how the composite waveform made up of sinusoids approaches the shape of a square wave as more terms are included.

![Harmonic Synthesis of a Square Wave from Sine Waves](image)

Figure 10: Harmonic Synthesis of a Square Wave from Sine Waves

In general signal analysis, the first step is to identify the major sinusoidal constituent of the composite waveform. This can be done by performing a Fourier transform on the time domain signal to convert it to a series of spectral peaks in the frequency domain. Select the spectral peak of largest amplitude, subtract this sinusoid from the original time series waveform, then, repeat...
the process on the residual waveform until the remaining residual can be considered insignificant.

In tidal signal analysis the general method described above can be improved upon, and needs to be improved upon because of the presence of “noise” in the observed signal. Noise always includes the measurement error, but if the astronomic tide is the signal to be extracted, noise also includes setup due to prevailing winds, changes in water surface elevation due to barometric pressure variations in the atmosphere, and noise from a host of other sources. Random noise in the composite signal causes the spectral peaks in the frequency domain view to broaden and flatten, making it difficult to attribute major portions of the tidal signal to exact frequencies. Fortunately, observations by astronomers can provide much more precise values for the frequencies of the gravitational forces than could be obtained from a tide gauge. It is conventional to allocate observed tidal signal to these astronomic frequencies rather than attempt to extract the astronomic frequencies from the signal plus noise in the tide gauge record. The astronomic frequencies chosen as the basis of the tide signal that is to be extracted from a series of observations are called “constituents”.

The highest frequency constituent that can be extracted from an observation record is limited by the sampling interval. The sampling theorem requires at least two samples per cycle. The lowest frequency constituent that can be extracted from an observation record is limited by the record length. The record length must be at least as long as the period of the lowest frequency constituent to be extracted.
The ability to distinguish between two harmonic constituents that are closely spaced in frequency also places a lower bound on the length of the tide observation record required. The Rayleigh criterion states that the observation record must be at least long enough for the higher frequency of the constituents to be separated to pass through at least one complete cycle more than the lower frequency constituent. URL: http://www.hydro.gov.au/prodserv/tides/tidal-glossary.htm#r accessed 10/14/2010.

Each of the three aforementioned criteria is a theoretical limit that is sufficient only if the signal is noiseless. Additive noise in the observed signal always has the effect of requiring more samples to extract a constituent at the same level of confidence.
Tidal Constituents and Resynthesis

In tidal analysis, the harmonic frequencies extracted from an observed tidal signal are called constituents. The constituent frequencies are based on the frequency of the astronomic cycles whose gravitational effects influence the tides. In shallow water, nonlinearities arise that result in higher frequency signals that are accounted to multiples and combinations of the basic astronomic frequencies. These are referred to as “shallow water constituents”.

Table 2: Constituents Supported by the Tidal Toolbox

<table>
<thead>
<tr>
<th>Constituent Name</th>
<th>Period (mean solar day)</th>
<th>Speed (deg/hour)</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEADY</td>
<td>N/A</td>
<td>0.0000</td>
<td>Principal Water Level</td>
</tr>
<tr>
<td>MN</td>
<td>27.55</td>
<td>0.5444</td>
<td>Lunar monthly constituent</td>
</tr>
<tr>
<td>SM</td>
<td>14.77</td>
<td>1.0159</td>
<td>Lunisolar synodic fortnightly constituent</td>
</tr>
<tr>
<td>O1</td>
<td>1.076</td>
<td>13.9430</td>
<td>Lunar diurnal constituent</td>
</tr>
<tr>
<td>K1</td>
<td>0.997</td>
<td>15.0411</td>
<td>Lunar diurnal constituent</td>
</tr>
<tr>
<td>MNS2</td>
<td>0.547</td>
<td>27.4238</td>
<td>Arising from interaction between MN and S2</td>
</tr>
<tr>
<td>2MS2</td>
<td>0.536</td>
<td>27.9682</td>
<td>Variational constituent</td>
</tr>
<tr>
<td>N2</td>
<td>0.527</td>
<td>28.4397</td>
<td>Larger lunar elliptic semi-diurnal constituent</td>
</tr>
<tr>
<td>M2</td>
<td>0.518</td>
<td>28.9841</td>
<td>Principal lunar semi-diurnal constituent</td>
</tr>
<tr>
<td>2MN2</td>
<td>0.508</td>
<td>29.5285</td>
<td>Smaller lunar elliptic semi-diurnal constituent</td>
</tr>
<tr>
<td>S2</td>
<td>0.500</td>
<td>30.0000</td>
<td>Principal solar semi-diurnal constituent</td>
</tr>
<tr>
<td>2SM2</td>
<td>0.484</td>
<td>31.0159</td>
<td>Shallow-water semi-diurnal constituent</td>
</tr>
<tr>
<td>MN4</td>
<td>0.261</td>
<td>57.4238</td>
<td>Shallow-water quarter diurnal constituent</td>
</tr>
<tr>
<td>M4</td>
<td>0.259</td>
<td>58.9841</td>
<td>Shallow-water quarter diurnal constituent</td>
</tr>
<tr>
<td>MS4</td>
<td>0.254</td>
<td>58.9841</td>
<td>Shallow-water quarter diurnal constituent</td>
</tr>
<tr>
<td>2MN6</td>
<td>0.174</td>
<td>86.4079</td>
<td>Shallow-water twelfth diurnal constituent</td>
</tr>
<tr>
<td>M6</td>
<td>0.173</td>
<td>86.9523</td>
<td>Shallow-water overtides of principal lunar constituent</td>
</tr>
<tr>
<td>C</td>
<td>0.172</td>
<td>87.4238</td>
<td>Arising from interaction between M2, N2, and S2</td>
</tr>
<tr>
<td>M8</td>
<td>0.129</td>
<td>115.9364</td>
<td>Shallow-water eighth diurnal constituent</td>
</tr>
<tr>
<td>M10</td>
<td>0.104</td>
<td>144.9205</td>
<td>Shallow-water tenth diurnal constituent</td>
</tr>
<tr>
<td>P1</td>
<td>1.003</td>
<td>14.9589</td>
<td>Solar diurnal constituent</td>
</tr>
<tr>
<td>K2</td>
<td>0.499</td>
<td>30.0821</td>
<td>Lunisolar semi-diurnal constituent</td>
</tr>
<tr>
<td>Q1</td>
<td>1.120</td>
<td>13.3987</td>
<td>Larger lunar elliptic diurnal constituent</td>
</tr>
<tr>
<td>SA</td>
<td>365.25</td>
<td>0.0410678</td>
<td>Solar Annual constituent</td>
</tr>
<tr>
<td>SSA</td>
<td>182.625</td>
<td>0.0821355</td>
<td>Solar Semi-annual constituent</td>
</tr>
</tbody>
</table>
Once the magnitude and phase of the constituents of an observed tidal signal have been extracted (e.g. by a harmonic analysis), it is possible to resynthesize a forecast of the astronomic tide for another time interval. Since constituents by convention are only defined for periods of one year or less, the periodic influence of astronomic cycles having a period of greater than one year are accounted for by the application of “node factors and equilibrium arguments”. These will be explained in detail later.

**Shallow Water Equations Model**

The constituents presented by the Tidal Toolbox are extracted by harmonic analysis from the output of the South Atlantic Bight model. The numerical code used for tidal calculations is “ADvanced CIRCulation Model for Oceanic, Coastal and Estuarine Waters”, commonly called ADCIRC. (R. Luettich & J. Westerink, 2004) (R. Luettich & J. Westerink, 2000) The form of the model employed is the two-dimensional, depth-integrated version which is also parallelized to run on a computer cluster at the University of Central Florida. ADCIRC solves the Generalized Wave Continuity Equation (GWCE) using the finite element method in space, and the finite difference method in time.(Kolar, Wg Gray, & Jj Westerink, 1994) (Kolar, Jj Westerink, Me Cantekin, et al., 1994)
ADCIRC models the bottom stress term as a quadratic function of velocity and Manning’s $n$:

$$\frac{\tau_{u,v}}{\rho_0} = C_f \frac{\sqrt{U^2 + V^2}}{H} (U,V)$$  \hspace{1cm} (1)

where:

$$C_f = \frac{g}{H^{\frac{3}{2}}} n^2$$  \hspace{1cm} (2)

$\tau_{u,v}$ = bottom stress components in the longitudinal and latitudinal directions

$\rho_0$ = reference density of sea water

$U, V$ = depth-integrated velocity in the longitudinal and latitudinal directions

$H$ = total height of the water column

$C_f$ = dimensionless bottom friction coefficient

$g$ = acceleration due to gravity

$n$ = Manning’s roughness coefficient

Manning’s $n$ values were assigned based on NLCD 2001 landcover data as follows:

$n = 0.025$ for ‘open water’

$n = 0.050$ for ‘emergent herbaceous wetlands’

$n = 0.100$ for ‘woody wetlands’

These mid-range values were based on empirical data (Arcement & Schneider, 1989), and numerical experiments (Mattocks & Forbes, 2008).
The bathymetric data used to construct the model were obtained from the following sources: The St. John’s Water Management District, South Florida Water Management District, and U.S. Army Core of Engineers provided the data for the estuaries along the east coast of Florida. The Office of Coast Survey and National Geophysical Data Center provided the data for the estuaries of Georgia and the Carolinas. The National Geophysical Data Center’s Coastal Relief Model provided the bathymetric data for the continental shelf. The Western North Atlantic Tidal domain model (S. C. Hagen, Zundel, & Kojima, 2006) provided the bathymetric data for the deep ocean.

The horizontal delineation between marshes, estuaries, and open water used to create the finite element mesh were based on NASA satellite surface imagery in GeoCover Landsat 7 mosaics (circa 2000) downloaded from URL: http://zulu.ssc.nasa.gov/mrsid/ accessed 6/15/2009.

LIDAR data collected in 2007 were available for the lower St. John’s River region of northeast Florida. Mean land elevations were calculated from this LIDAR data for marsh areas, and these land elevations were utilized in this region of the mesh. P. Sucsy (unpublished report 2009).
South Atlantic Bight Domain

The South Atlantic Bight encompasses the east coast of Florida, the coasts of Georgia, South Carolina, and North Carolina. The model mesh extends from the deep Atlantic Ocean at its west boundary, eastward across the continental shelf, into the Atlantic Intracoastal Waterway, and extends eastward into the estuaries and salt marshes. Please see Appendix One for figures.
CHAPTER TWO: LITERATURE REVIEW

Tide Theory

Tides have been a subject of study since ancient times. The interested reader is referred to (Ekman, 1993) for a concise but excellent compilation of the development of tidal theory. References below are included to aid in the development of the context in which the current high-resolution South Atlantic Bight model and the Tidal Toolbox that presents its results were developed.

The Equilibrium Theory of the Tides supposes that the Earth’s surface is completely covered by water, and that the water surface elevation at every point on the Earth has time to come to equilibrium with the astronomic tide-generating potential, that is, the resultant gravity vector of the Sun-Moon-Earth system. The water surface in this theory would form a prolate (egg-shaped) ellipsoid of revolution with the major axis directed toward the moon. The equilibrium theory is sufficient to produce a first approximation to the tidal elevation as it is distributed around the globe. The theory also explains the diurnal inequality of tides; that is, the daily difference between the lower high tide and the higher high tide, and the differences in elevation between spring and neap tides. (Darwin, 1898)

Doodson (Doodson, 1921) observed that "when all the Darwinian constituents are removed from the tidal height there is a residue composed of constituents that are not included in his schedules." He therefore undertook a more detailed development of the tide-generating potential
to include all terms that are greater than 0.00010 relative to the greatest. Doodson selected the following variables on which to base his calculations:

Table 3: Doodson Numbers

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>local mean lunar time reduced to angle</td>
</tr>
<tr>
<td>$s$</td>
<td>moon’s mean longitude</td>
</tr>
<tr>
<td>$h$</td>
<td>sun’s mean longitude</td>
</tr>
<tr>
<td>$p$</td>
<td>longitude of the moon’s perigee</td>
</tr>
<tr>
<td>$N'$</td>
<td>$-N$, where $N$ is the longitude of the moon’s ascending node</td>
</tr>
<tr>
<td>$p_1$</td>
<td>longitude of the sun’s perigee</td>
</tr>
</tbody>
</table>

These six numbers, later called Doodson numbers, define the gravity vector and hence the tide generating potential at any location on Earth, and at any time in an astronomic cycle of 21,000 years, the period of the precession of the longitude of the sun’s perigee. Doodson defined the term "constituent". He recommended that constituents should only include terms that can be distinguished in a 1-year record. Doodson proposed the independent variables $\tau$, $s$, and $h$ for determining constituents. He further proposed that the variables $p_1$ and $N'$ be handled using variable coefficients and phase corrections that are regarded as constants for short periods of time, to adjust for the location of the period of study in the 18.6 year cycle associated with the precession of the longitude of the moon’s ascending node. The precession of the longitude of the sun’s perigee, $p_1$, having a period of 21,000 years, is regarded as constant. Note that Doodson’s work preceded the advent of modern computers, so conventions to reduce hand calculation time were a practical necessity.

Paul Schureman, Senior Mathematician with the United States Coast and Geodetic Survey wrote a thorough development of the theory and practice of tidal analysis and prediction to document
practice at that agency. First published in 1924, the Manual of Harmonic Analysis and Prediction of Tides underwent revisions in 1940 and 1958. (Schureman, 1940) (Schureman, 1958) The interested reader is referred to this book, also known as Special Publication 98, for a thorough treatment of the subject, only selected details relevant to the current work are highlighted here. Whereas Doodson focused on astronomic geometry needed to explain the gravitational tide generating potential, Schureman developed Maclaurin series expansions that effectively translated the Doodson numbers (which captured Sun-Moon-Earth orientation) into angles and coefficients of circular functions that described the amplitude and phase of the tide – one constituent at a time. A summation of the major constituents produced the predicted tide elevation as a function of time and location. He expressed the tide elevation due to one constituent of the tide in equation (236) of his book as:

$$y_i = fH \cos(E - \kappa) = fH \cos(V + \mu - \kappa)$$  \hspace{1cm} (3)

It is convenient to consider the start of the tide cycle to occur at high water, so the cosine function is used, since $\cos(0) = 1$. $H$ then represents the peak value of the constituent measured relative to the mean value of the constituent. $f$ scales the value of $H$ according to the location of the year under study in the 18.6 year cycle of the moon’s ascending node. In Schureman’s tables, the values of $f$, called node factors were calculated at mid-year, and treated as constants for the year. $E$ is the angle which would produce the tide height of the constituent in the expression $y_i = fH \cos(E)$ if the tide were in equilibrium with the tide generating potential. $E$ is therefore known as the equilibrium argument. Real tides are always lagging the tide generating potential, the phase lag is represented by the Greek letter kappa $\kappa$. However, since the phase of the tide is measured relative to the previous high water and not relative to the tide generating potential, the
term used in the equation is $-\kappa$ which is defined as a revolution minus $\kappa$ or $(360^\circ - \kappa)$. Lastly, the equilibrium argument $E$ is considered to be comprised of two components, $V$ and $u$. $V$ is the equilibrium response of the tide at the positions on the Earth on the polar axis of the tide generating force, where the response is a maximum. $u$ is a factor that reduces the maximum response due to the location of the polar axis of $V$ being some angular distance away from the point of study over an arc on the surface of the Earth.

In shallow water, the attenuation of the bottom of the tidal wave due to bottom friction distorts the wave from the shape of a sinusoid in a manner that can be modeled with integer multiples of the basic constituent frequencies. Constituents of these frequencies are called overtones by analogy to overtones in a musical instrument. (Schureman, 1940, page 53, par. 139)

Friction attenuation contains a term that is proportional to the square of the velocity. In rivers there is a zero frequency velocity due to freshwater flow that augments or diminishes the velocity change due to the tidal cycle. The interaction of freshwater inflow with the tidal cycle in the presence of friction gives rise to compound harmonics such as $MS_0(S_2 - M_2 = MSf)$, $MN_0(M_2 - N_2 = Mm)$, $M_4(M_2 + M_2)$, and $MS_4(M_2 + S_2)$. (Godin, 1972). Note that one of the practical consequences of this non-linearity is that tidal constituents extracted from riverine gauge data during periods of normal flow are not useful for forecasting the timing or amplitude of peak influence of the tide on the stage of the river during periods of high flow. Numerical modeling can be used to address this problem by driving a river model with astronomic constituents from an ocean boundary in water that is deep enough to minimize the variation in
the constituents caused by variations in freshwater inflow. Additionally, since tide gauges are often located near the coastline in areas of rapidly changing bathymetry, interpolating between tide gauges may interpolate constituents that are only applicable in the immediate vicinity of each gauge, and not valid to interpolate spatially over the intervening bathymetry.

Dr. Peter Bacopoulos (P. Bacopoulos, 2009) demonstrated that it is necessary to include salt marshes and inland waterways in a finite-element model to continue to improve the accuracy of tide circulation modeling on the continental shelf. The current work seeks to provide tools to publish the results of that model to the user community.

**Tidal Harmonic Analysis**

Building upon the work of G. Godin, M. Foreman wrote a computer application in FORTRAN to extract harmonic constituents from hourly height data. Using the least squares optimization method for fitting, gaps in the tide data could be tolerated. The analysis is optimized for record lengths of approximately one year, as only the first three Doodson numbers are used in the optimization, and node factors are used to account for the rest. In general, the record length needs to satisfy the Rayleigh criterion to be of sufficient length to distinguish between constituents closely spaced in frequency, but Foreman’s code included provisions for inferring the amplitude and phase of satellite modulations – the smaller constituents spectrally close to a primary constituent- from a longer record, or a nearby station. The standard code supported the
extraction of 69 tidal constituents, with provisions for up to 77 additional shallow water constituents. (M. Foreman, 1977)

(M. Foreman, 1978) employs a similar harmonic analysis code to the analysis and prediction of currents.

R. Pawlowicz, et. al. expanded the audience of the Foreman FORTRAN code by porting it to MATLAB, a scientific programming language widely used by oceanographers with built in graphical capability to ease the visualization of output. This widely used program is called T-tide. The program calculates confidence intervals for the extracted constituents based on an assumption that the residual after fitting constituents is Gaussian. This assumption needs to be checked for each data set. In the tabular output format of the program, the confidence interval is expressed as a signal to noise ratio. Scanning the column for signal to noise ratios greater than one provides a quick assessment of which extracted constituents are likely to be useful. Like the Foreman code (M. Foreman, 1977), T-Tide is limited to extracting harmonic constituents from records of only about a year or less in length due to approximating node factors and equilibrium arguments. Source code is available at URL: http://www.eos.ubc.ca/~rich/ accessed 10/14/2010. (Pawlowicz, Beardsley, & Lentz, 2002)

The article (M. G. G. Foreman, Cherniawsky, & Ballantyne, 2009) introduces an improved version of the harmonic analysis functions of the FORTRAN code previously presented in (M. Foreman, 1978). The limitation of being able to use a record length of only one year or less of
tidal height data is removed by re-calculating the node factors and equilibrium arguments for each time step of the input record, rather than just once per record. The new code also supports arbitrary sampling in time, rather than just tolerating gaps in a record sampled at a regular sample rate. The cost of this versatility is that the user must now specify the constituents to fit manually, because the Rayleigh criterion and its variations are no longer valid for determining constituent selection. Being able to use longer records, and “embedding the nodal corrections into the least squares matrix and evaluating the astronomical argument exactly” means that an over-specified matrix is solved to fit the selected harmonic constituents. The result is better signal extraction from noise, i.e., the longer the record the more signal, but the noise is uncorrelated, therefore the ability to make use of tidal records longer than one year results in more accuracy in constituent extraction.

Tide Tables

The oldest surviving tide tables were recorded in 1056 AD in China for visitors wishing to observe the tidal bore in the Qiantang River. (Zuosheng, Emery, & X., 1989)

"The Admiralty Tide Tables were first published for the year 1833, and then contained the times of high water only for the four principal ports in the United Kingdom." (Warburg, 1919) Since that time, the Admiralty Tide Tables have been expanded into four volumes that contain the times and heights of high and low water for over 230 ports for which the U.K. provides the tide data, and 6000 ports for which the data is supplied by the respective governments in Ireland,
Europe, the Indian Ocean, South China Sea and Pacific Ocean for each day of the year. The document provides methods for adapting the tabulated data to routine and exceptional meteorological conditions. The coverage of the four volumes is delineated by the Figure 11. URL: http://www.ukho.gov.uk/ProductsandServices/PaperPublications/Pages/NauticalPubs.aspx accessed 9/26/2010.

Figure 11: Limits of Admiralty Tide Tables

The data is available in digital as well as printed format and is also distributed by the EASYTIDE web service described in the Tide Websites section of this document.

The U.S. Coast Survey was established by President Thomas Jefferson in 1807, and the first U.S. tide prediction tables were published in 1853. Publishing tide tables became the responsibility of NOAA when it was established in 1970 by President Richard Nixon. NOAA published hardcopy
tide tables through 1995, but beginning in 1996 the printing and distribution of hardcopy of the tide tables has been left to private publishers. Since then, the official NOAA tide tables have been distributed online. URL: http://tidesandcurrents.noaa.gov/tides10/ accessed 10/12/2010.

Sources of Error

The Van de Casteele Test consists of creating a scatter plot of the gauge under test measurement minus the reference gauge measurement plotted on the x-axis and the height reading of each gauge plotted on the y-axis. If the two gauges are in perfect agreement, the plot would be a vertical line. Usually there is a variation between the measurements that makes the graph appear as a vertical bar. Systematic differences between the two measurements may cause the plot to appear as a bar with a right or left slope, or as an ellipse. The plot doesn’t reveal the magnitude or the source of the error, only that a systematic error is present that merits investigation. (Miguez, Testut, & Wöppelmann, 2008)

Ray and Sanchez, (Ray & Sanchez, 1989) noted that the range of the loading tide in the open ocean can easily exceed 10cm, and estimated the error due to the radial deformation of the Earth in the open ocean to be about 0.5cm.

In the context of tide modeling, imperfect bathymetry data must be considered as a source of error. Bathymetric data sets for the open ocean combine bathymetry data gathered by ships at sea (accurate, but spatially sparse) with bathymetry estimates inferred from gravitational
measurements of orbiting satellites (more dense spatial coverage, but a less direct measurement). (Smith & Sandwell, 1994) explained that there exists a linear correlation between satellite gravity readings and features of the sea floor in the 15-160 km band. At shorter wavelengths the gravitational field is insensitive to seafloor topography; at longer wavelengths, the gravitational anomaly is diminished due to isostatic compensation, the thickening of the Earth’s crust under seamounts that pushes the denser mantle deeper. As to bathymetric accuracy, Smith & Sandwell state: "The prediction has a horizontal resolution limit of 5-10 km in position and is within 100 m of actual soundings at 50% of the grid points and within 240 m at 80% of these.” In other words, bathymetric readings inferred from gravity readings that could be calibrated to the soundings taken by vessel tracks not more than about 20 km apart were found to be accurate to +/-240 m at the 80% confidence level.

In the deep ocean, satellite altimetry measurements may provide a frame of reference for validating model results. Satellite altimetry measurements also have confidence intervals associated with them. The Ocean Surface Topography Mission (OSTM) Jason-2 Products Handbook reports the accuracy specification as "The sea-surface height shall be provided with a globally averaged RMS accuracy of 3.4 cm (1 sigma), or better, assuming 1 second averages." (Dumont et al., 2009)
Tide Programs

The FORTRAN program that NOAA uses to predict tides is available upon request and a nominal fee. Users are advised however that it is not “user friendly”. URL: http://www.co-ops.nos.noaa.gov/faq2.html#60. accessed 10/12/2010.

GeoMatix is a U.K. based consulting company that produces a commercial software package called GeoTide, marketed to the professional hydrographer. It is a set of Windows-based applications that run on a PC. Taking a tide gauge record as input, the Analysis program extracts harmonic constituents. The Predictor program resynthesizes selected constituents to produce tabular or graphical output, and even supports HTML output for posting to a website. Prism is a tide spectrum analyzer tool that assists the investigator in the search for the presence or absence of specific tidal harmonics. Frequencies can be manipulated individually, or grouped for analysis. The frequency grouping function is useful when the tidal record under consideration is too short to meet the Rayleigh criterion for distinguishing and assigning relative magnitudes to closely spaced constituents, but this information can be inferred from a longer record for a different time interval, or from another tide gauge nearby. Publisher is a program that formats the output of the Predictor program to produce tide tables and graphs for publishing. URL: http://www.geomatix.net/ accessed 9/26/2010.
XTide is a tide prediction program released into the public domain by David Flaterco. It takes as input harmonic constituents downloaded from NOS, and produces graphical and tabular output. The website even offers guidance on how to set up a tide web server. The software was originally written on a UNIX system, using X11 window management, in 1997. Since source code is available, it has been a contributor to many tide prediction websites on the internet. URL: http://www.flaterco.com/xtide/ accessed 9/26/2010.

Mr. Tides is a port of XTide to the Mac OS X operating system. URL:

JTides is a standalone program with nice graphics that has been ported to Windows, Linux, and Mac OS X. It uses the Java runtime environment for doing the numerical processing associated with tide forecasting, this makes JTides easy to port to any platform that supports the Java Runtime Environment. URL: http://www.arachnoid.com/JTides/index.html accessed 9/27/2010.

Tides ver. 2.32 is an astronomic tide predictor for Windows platforms up to XP. It contains a database of 800 ports. It appears to have been last updated in 2002. URL:
Observation

The NOAA Center for Operational Oceanographic Products and Services distributes both preliminary and verified data from NOS tide gauge stations in the United States of America. Predictions based on harmonic constituents at a gauge station are made up to 2 years in advance, for a period of a day, a week, or a month at a time. Predictions are based on a resynthesis of harmonic constituents derived from the history of observations at the gauge. Time series plots and a table of high and low tide times are provided. URL: [http://tidesandcurrents.noaa.gov/](http://tidesandcurrents.noaa.gov/) accessed 9/23/2010.


Admiralty Easy Tide is a tide prediction website that offers free 7 day tide predictions for ports in England based on a resynthesis of harmonic constituents derived from tide history in the port. For a fee, tide predictions can be obtained for any of 6000 ports worldwide, for 7 or 14 day durations, for up to 50 years into the future. Time series plots and a table of high and low tide times are provided. The URL is: http://easytide.ukho.gov.uk/EASYTIDE/EasyTide/index.aspx accessed 9/23/2010.

The WWW Tide and Current Predictor is a website by Dean Pentcheff of the University of South Carolina that uses the program XTide by David Flater to predict tides and currents at points coincident with NOS and other tide gauges. Maps are provided utilizing the Mapquest map server, tide resynthesis plots are done using GNUplot. The tabular output provides the time and elevation of high and low tides. URL: http://tbone.biol.sc.edu/tide/ accessed 9/23/2010.

The National Data Buoy Center monitors data from 1061 data buoys for meteorological data on a daily basis. Some data buoys are equipped with pressure sensors from which ocean depth can be inferred. The website offers a graphical display of buoy locations using Google Maps. Buoy data can be retrieved by clicking on a marker on the Google map. Other features include user downloadable KML files. The website assembles data files for download in text and FORTRAN code formats as well. URL: http://www.ndbc.noaa.gov/ accessed 9/23/2010.
Tidal Response of a Bay is a website by Robert Dalrymple that predicts a bay’s tide response based on the area of the bay, the dimensions of a channel leading to the bay, and the tidal range at the ocean side of the inlet. The calculation uses assumed friction and inlet and outlet losses, and a method by G. H. Keulegan. (Keulegan, 1967).


The Massachusetts Marine Trades Association operates a boating oriented website that distributes high/low tide height and time predictions for the ports of Massachusetts.


WWW.saltwatertides.com is an easy to use fishing oriented website that provides high/low tide times and heights for over 2500 locations. URL: http://www.saltwatertides.com/ accessed 9/26/2010.

ProTIDES is a nicely done website that uses Google Maps to allow the user to graphically select a tide gauge location for which to display a tide prediction. Tabular output is available with high/low tide times and heights, or output can in the form of a monthly map with a graph of tide elevation vs. time. The source of the constituent data is not stated. URL: http://www.protides.com/ accessed 10/14/2010.

Peter Brueggeman has compiled an extensive list of online tide websites.

It is noteworthy that all of the sources of tide predictions encountered in this review of internet resources are predicting tides at a point location, based on tide history at that point. The novelty of the data that is presented by the Tidal Toolbox is that prediction is available anywhere within a bounded region. The database required for making predictions over a region includes a set of harmonic constituents for each point in a mesh, not merely for each point where a tide gauge is located. For numerical comparison, the SOUTH ATLANTIC BIGHT mesh has over 497,000 nodes, whereas NOAA lists 7070 gauges and data buoys worldwide. URL: http://tidesandcurrents.noaa.gov/station_index.shtml?state=Complete+Index&id1=06&id2=1&id3=2&id4=7&id5=8&id6=9 accessed 10/14/2010. The techniques required for handling this much larger database are also explained in this thesis.
“It is not enough to develop state-of-the-art numerical prediction models for sea level and coastal currents. Forecasts from these models must be communicated in an efficient and appropriate manner to the user community.” (Blain, Preller, & Rivera, 2002) The “Tidal Toolbox” has been created for just this purpose: To communicate the results of a high-resolution model of the South Atlantic Bight, including estuaries and inland waterways, to the user community in an appropriate and efficient manner. This thesis also details the development of the Tidal Toolbox with respect to the reproducibility of the Tidal Toolbox given a different domain (and solution). Two aspects of what is appropriate concerning the development of any “tidal toolbox” are affordability, and training time. The Aquaveo Surface-water Modeling System is a very capable tool for model development and inspection, but it is costly for a user who simply wants to examine a model, and generally requires significant training time. (URL: http://www.aquaveo.com/sms accessed 11/15/2010). Similarly, ARC GIS is a fine tool for examining and processing geospatial data, but cost and training time can be obstacles. A web-based tool eliminates the need for specialized software to be purchased and installed on the user’s computer; it requires only a suitable web browser. The Tidal Toolbox is a web-based set of software tools that performs the function of extracting the desired constituents of a harmonic analysis of the model output of the CHAMPS Lab high resolution South Atlantic Bight mesh (P. Bacopoulos, 2009), interpolated to the user’s exact points of interest. There are additional capabilities of the Tidal Toolbox, each of which is detailed in the following sub-sections.
Capabilities

Visualization in Geospatial Context

The Google Maps map service provides the geospatial context for visualization within the Tidal Toolbox. Detailed in this section is how the Google Maps map service is utilized within the Tidal Toolbox for the purpose of visualizing the nodes and elements of the South Atlantic Bight mesh as well as the locations of tide gauge stations that fall within its boundary. The visualization offered by the Tidal Toolbox is meant to give the user the spatial environment in which to visualize the mesh boundary, select their points of interest, and view stations where model-data comparisons are available. Figure 12 shows a representation of the boundary of the South Atlantic Bight mesh as small yellow squares on a zoom-able Google Map. In this view, the satellite-roadmap hybrid view is selected; however, the user can select other display options, such as terrain, satellite-only, or roadmap-only. This zoom-level gives an overall view of the boundary of the entire South Atlantic Bight mesh. Figure 13 shows a close-up view of the southern portion of the South Atlantic Bight mesh boundary. Figure 14 shows a close-up view of the South Atlantic Bight mesh boundary in the local region of the Indian River lagoon. Figure 15 shows a close-up view of the South Atlantic Bight mesh boundary in the local region of Lake George (St. Johns River). Note how the boundary points identify Lake George and Little Lake George and the St. Johns River as being in the mesh, and Crescent Lake and Lake Disston as not being included in the mesh.
Figure 12: Zoom-able Boundary Representation of Entire South Atlantic Bight Mesh
Figure 13: A Zoom-in View of the Southern Portion of the South Atlantic Bight Mesh
Figure 14: A View of Boundary Points in the Local Region of the Indian River Lagoon
Figure 15: A View of Boundary Points in the Local Region of Lake George (St. Johns River)
Note that the details of the model-data comparisons are provided in a later section of this chapter (Validation). The visualization of the stations where model-data comparisons are available is discussed in this section on ‘Visualization in Geospatial Context.’ Figure 16 shows how the Historical / Model comparison page of the Tidal Toolbox uses red markers to identify the geographic location for each of the 89 tide gauge stations used for assessing the validity of the model results. Holding the mouse directly over the marker pops up a tooltip that identifies the station. Double-clicking the marker opens a new window that displays a tide elevation resynthesis of historical versus model constituents at that gauge station’s location. In addition to offering a visual indication of the amplitude and phase agreement between the historical and model resynthesis, the root-mean-square of the difference between model and historical resynthesis signals is provided as calculated over the 14 day interval (reported on the plot as a percentage value whereby the normalizing factor is the maximum tide range). All 89 comparison plots are in Appendix Two. Note that the Historical / Model comparison page is fully zoomable, as illustrated in Figure 17 when zoomed in on the St. Johns River.
Figure 16: Locations of Tide Gauge Stations Used for Historical / Model Comparison
Figure 17: Zoom-in of Tide Gauge Station Locations Along a Portion of the St. John's River
Computed Tide Elevation

For each point the modeler is interested in, several things need to happen. The element of the South Atlantic Bight mesh which contains the point needs to be identified. The constituents at the vertices of the element need to be interpolated (via a linear reciprocal distance weighting function) to the user’s point of interest. The node factors and equilibrium arguments of the point need to be calculated for the time interval of interest, and the selected constituents need to be resynthesized (see Eq. [3]) into a composite tidal elevation signal.

Computed Depth-Averaged Velocities

Depth-averaged velocity constituents are interpolated and computed in much the same manner as elevation constituents, except that the X and Y components are treated separately, i.e., a magnitude and phase is reported for each component. If resynthesis is enabled, a time series resynthesis will be performed for each POI’s X and Y components, and the results tabulated in a single text file with four columns for each POI (X magnitude, X phase, Y magnitude, Y phase).
Computed Residual Velocities

The products of a model run include a database of the residual velocities over a tidal cycle at each node in the mesh. For each in-bank user point of interest, the Tidal Toolbox accesses this database and interpolates the residual velocities from each vertex node of the enclosing triangular element to the exact user point of interest using a linear reciprocal distance weighting. The Tidal Toolbox reports this information to the user in the VelocityResiduals.txt output file.

Resynthesis of Selected Constituents

Resynthesis (see Eq. [3]) is enabled by default. If resynthesis is de-selected by un-checking the resynthesis check box, a resynthesis will not be performed and processing will finish more quickly.

In the shallow salt marsh areas, wetting and drying precludes any attempt at harmonic constituent extraction, and therefore prediction is offered only within bank (where the signal is always wetted).

Plots of Resynthesized Water Surface Elevation Constituents

Resynthesis plots are written to image files in the output folder, which allows the user to view them offline. These files are in Portable Network Graphics (PNG) format.
Tabular Output of Time-Series Resynthesis

For each in-bank user point of interest, enabling the resynthesis option causes a file to be written to the output folder that contains a tabular listing of water surface elevation versus time. Filenames take the form Point#Tide.txt, where # relates to the \(i^{th}\) user point of interest that is accepted for processing. The time column is reported in units of days. The water surface elevation column is reported in meters relative to NAVD88.
Use of the Tidal Toolbox

The following section details the general use of the Tidal Toolbox. Specific use of the Tidal Toolbox is at the user’s discretion.

Selection of User Points of Interest

Textual

The simplest way to specify points of interest is to type the geographic coordinates into the text box on the Tidal Toolbox Input Page. Enter the latitudinal and longitudinal coordinates (in decimal degrees separated by white space and terminated with a carriage return) for each point of interest. Note that values of west longitude are negative, which is consistent with ADCIRC (R. A. J. Luettich & J. J. Westerink, 2006). The text box supports the copying and pasting to and from the windows clipboard, e.g., as if the user was uploading their points of interest from a spreadsheet.

Graphical

The Graphical Input Page enables the visual selection of geographic coordinates by placing markers on a Google Map and then using the coordinates of those markers as the user’s points of interest.
Constituent Selection

Constituents are selected by placing a check mark in the check box next to the name of the constituent. By default, the 23 constituents employed by ADCIRC (cf. Luettich and Westerink [2006]) are preselected, and two are left unselected, the Solar Annual (SA) and Solar Semi-Annual (SSA) constituents. SA and SSA are placeholders in the database that are currently assigned a value of zero. Un-checking a constituent causes it’s magnitude to be forced to zero in the resynthesis.

Time Interval

The time interval in the Tidal Toolbox is specified in days. The minimum interval is one day. If resynthesis plots are to be used, a practical maximum is about 31 days; however, it is recognized that longer records may be desired by the user so as to acquire the numerical (tabular) data. Thus, there is no upper limit imposed on record length.

Time Step

The default time step for resynthesis of the selected constituents of the model output is 360 seconds (a standard time step; for example, NOS data are supplied at six-minute resolution). The user can change the time step by over writing the default in the time step field.
Initiation of Processing

When each of the Tidal Toolbox Input Page’s entries has been filled in, the job is submitted to the server for processing by pressing the “Submit” button located at the bottom of the page. To clear the page and start over the “Reset” button is pressed. After the submit button is pressed, processing a new page appears showing a text summary of the input parameters selected. This is the actual input file to the Tidal Toolbox back end processing that is performed on the server.

The input file is also echoed back to the user as one of the output files to provide a record of the parameters requested for processing. After about 20 seconds, the exact time is request dependent, a new folder appears on the CHAMPS lab FTP server with a current date and time stamp that contains the output files generated by the request. The processing performed on the server between submitting the job and the appearance of the output files is detailed in the Theory of Operation section under the heading “Tidal Toolbox Processing”.

Validation

During the coding phase of this effort, the implementation of the calculations of the node factors and equilibrium arguments were verified by regenerating the node factors and equilibrium arguments tables of (Schureman, 1958).

A validation of the South Atlantic Bight mesh is contained within the Tidal Toolbox. The validation is based on comparisons between resynthesized historical tidal constituents to model
tidal constituents. The historical tidal constituents are obtained directly from the reporting agencies: NOAA NOS, SJRWMD, and IHO. The model tidal constituents for the in-bank node that is nearest to the tide gauge were resynthesized and plotted against the historical resynthesis over an interval of 14 days. RMS error was calculated as percentages whereby the normalizing factor is the maximum tide range. The results of the comparisons at 89 stations are illustrated in the figures in Appendix Two.

**Tidal Toolbox Preprocessing for New Domains**

The Tidal Toolbox as presented in this thesis is demonstrated for a tidal application in the South Atlantic Bight. However, the Tidal Toolbox has been developed such that it can fit any model, i.e., geometry and dynamic/static solution over the geometry. To this end, the Tidal Toolbox is a general conceptualization more than it is a fixed device. This section details the preprocessing that would need to take place given a new triangular mesh and shallow water equations solution.

Most of the input data that drives this process is contained in three ADCIRC “fort.*” files. The ADCIRC fort.* files, (cf. (R. A. J. Luetich & J. J. Westerink, 2006) for a full listing) so named because they were originally output files from a computer application written in the FORTAN language, contain the mesh data and constituents data resulting from an ADCIRC simulation. The fort.14 file contains the node definitions and the element definitions that specify the mesh to the ADCIRC model. The fort.53 file contains the output water level elevation constituent frequencies, phases, and magnitudes for each node in the domain. The fort.54 file contains the
output water velocity constituent frequencies, phases, and magnitudes for each node in the
domain. The velocity residuals file contains a velocity vector for each node in the domain. Note
that velocity residuals are not calculated by ADCIRC, but are calculated from the fort.54 file as
generated from an ADCIRC simulation. See (Peter Bacopoulos & Scott. C. Hagen, 2009) for the
definition and an example calculation of velocity residuals.

The following general procedure applies to the preprocessing of each fort.* file:

1) Parse the text of the file.

2) Convert text strings that represent numbers to MATLAB data types.

3) Save the MATLAB data structure to a MATLAB format (.mat) file.

Table 4 documents each MATLAB program and the above preprocessing each performs on the
input files. The TTBcoordinates.mat output file is subject to considerable additional
preprocessing. It contains the binary form of the node list and element list. This information is
required to construct a set of sub-domain files containing spatially indexed element lists that are
short enough to be searched while the user is waiting on output. In the current implementation,
512 sub-domains are created from the South Atlantic Bight mesh (See Figure 18: A Visualization
of the Division of the Mesh Area into Sub-domains). The sub-domain data structures are also
processed into 512 javascript files that are included into 512 shtml files that display the
triangular mesh elements over a Google map. The sequence of this processing is documented in
Table 5. The process of boundary node extraction and processing proceeds as indicated in Table
6. SABboundary.xml is the file that is included into the web page SABborder.html at run time to
display the South Atlantic Bight boundary on a Google map.
The 89 Historical versus Model plots were produced with a series of scripts. The MATLAB function for plotting and saving plots without user interaction is the “publish” command. A script is prepared that generates the desired plot, and then it is invoked by supplying the script name to the publish command along with a data structure that defines the publishing options. The process is documented in Table 7.

Table 4: Preprocessing Programs

<table>
<thead>
<tr>
<th>Input File</th>
<th>Program</th>
<th>Output File</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fort.14</td>
<td>TTBcoor.m</td>
<td>TTBcoordinates.mat</td>
</tr>
<tr>
<td>Fort.53</td>
<td>Fort53_to_binary.m</td>
<td>Fort53.mat</td>
</tr>
<tr>
<td>Fort.54</td>
<td>VelocitiesFrequencyExtractor.m</td>
<td>Velocity_freq_rad_sec.mat</td>
</tr>
<tr>
<td>Fort.54</td>
<td>VelocityExtractor.m</td>
<td>Velocities.mat</td>
</tr>
<tr>
<td>Velocityresiduals.pts</td>
<td>Velocity.m</td>
<td>VelocityResiduals.mat</td>
</tr>
</tbody>
</table>
Figure 18: A Visualization of the Division of the Mesh Area into Sub-domains
Table 5: Preprocessing Programs 2

<table>
<thead>
<tr>
<th>Input File(s)</th>
<th>Program</th>
<th>Output File</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTBcoordinates.mat</td>
<td>MedianDivide.m</td>
<td>Divider.mat</td>
</tr>
<tr>
<td>Divider.mat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTBcoordinates.mat</td>
<td>ElementLookupFromNode-Number.m</td>
<td>E&lt;subdomain_number&gt;.mat</td>
</tr>
<tr>
<td>E&lt;subdomain_number&gt;.mat</td>
<td>SABjavascriptTriangles.m</td>
<td>E&lt;subdomain_number&gt;.js</td>
</tr>
<tr>
<td>E&lt;subdomain_number&gt;.js</td>
<td>SABpageGenerator.m</td>
<td>SAB_E&lt;subdomain_number&gt;.shtml</td>
</tr>
<tr>
<td>File_a.txt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>File_b.txt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>File_c.txt</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Preprocessing Programs 3

<table>
<thead>
<tr>
<th>Input File(s)</th>
<th>Program</th>
<th>Output File</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTBcoordinates.mat</td>
<td>BoundaryFinder.m</td>
<td>Boundaries.mat</td>
</tr>
<tr>
<td>Boundaries.mat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTBcoordinates.mat</td>
<td>BoundaryShrinker.m</td>
<td>Linked_boundaries.mat</td>
</tr>
<tr>
<td>Linked_boundaries.mat</td>
<td>BoundarySorter.m</td>
<td>Sorted_linked_boundaries.mat</td>
</tr>
<tr>
<td>Sorted_linked_boundaries.mat</td>
<td>BoundaryShrinker.m</td>
<td>Boundary_nodes.mat</td>
</tr>
<tr>
<td>Boundary_nodes.mat</td>
<td>BoundaryCodeGenerator.m</td>
<td>SABboundary.xml</td>
</tr>
</tbody>
</table>

Table 7: Preprocessing Programs 4

<table>
<thead>
<tr>
<th>Input File(s)</th>
<th>Program</th>
<th>Output File</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge locations</td>
<td>TTBbackend.m</td>
<td>ResyninData.mat</td>
</tr>
<tr>
<td>ResyninData.mat</td>
<td>ModelStationResynthesis.m</td>
<td>Station_model_resynthesis.mat</td>
</tr>
<tr>
<td>SAB_reference_constituents.mat</td>
<td>RefStationResynthesis.m</td>
<td>Station_historical_resynthesis.mat</td>
</tr>
<tr>
<td>Data.mat</td>
<td>RMSerror.m</td>
<td>Error_by_station.mat</td>
</tr>
<tr>
<td>Station_model_resynthesis.mat</td>
<td>SAB_Error_Plots.m</td>
<td>The actual plots</td>
</tr>
<tr>
<td>Station_historical_resynthesis.mat</td>
<td>PubScriptGenerator.m</td>
<td>SAB_Error_Graph&lt;#&gt;.png</td>
</tr>
<tr>
<td>Error_by_station.mat</td>
<td>HTMLgenerator.m</td>
<td>SAB_Graph&lt;#&gt;.html</td>
</tr>
</tbody>
</table>
The term resynthesis as it is used in this thesis refers to the linear summation of the harmonic constituents of a tide signal in time to produce a time series signal. The pseudo code example below illustrates the algorithm for the water surface elevation resynthesis. The variable “point” is an index into a data structure that corresponds to one of the user specified POIs. The percent “%” symbol represents the start of an explanatory comment.

```matlab
% A time vector in units of days
time_vector = time_seconds / 86400;

% For each time step on the x-axis...
for i = 1:length(time_seconds)
    % Find # of constituents
    [number_of_constituents] = length(NodeFactor);
    % For each constituent
    for j = 1: number_of_constituents
        % Look up the value for this constituent of this point for the current time in the tidal epoch, for each of the following quantities
        f = NodeFactor(j,point); % Node factor
        H = Amplitude(j,point); % Tidal amplitude from UCF model
        w = FrequencyRad(j,point); % Radian frequency of constituent
        Vou = EquilArgRad(j,point); % Vo + u equilibrium argument
        k = PhaseRad(j,point); % Epoch of constituent
        t = time_seconds(i); % Time in seconds
        temp = f * H * cos((w * t) + Vou - k); % Equation 3
        tidal_resynthesis_model(i,j) = temp;
    end % End of for each constituent loop.
    % Perform the summation over all the constituents for this time step.
    time_series_model(i,1,point) = time_vector(i);
    time_series_model(i,2,point) = sum(tidal_resynthesis_model(i,1:j)); % Sum
end % End of for each time step loop.
```
Suppose the user needs model results interpolated to 1000 points of interest from a mesh containing 1,000,000 elements. The first challenge is to determine which, if any, user points of interest (POIs) are in mesh elements. In order to test a particular point to see if it lies in a particular triangular element, the following method is used:

Map the nodes a, b, and c, of the triangle being tested to the quadrant I origin as:

Perform the same mapping on the POI, which after mapping is designated \((P_x, P_y)\).

If the mapped POI lies inside the triangle, \( (P_x, P_y) \) will satisfy the following tests:

\[
P_x \geq 0 \quad (4) \\
P_y \geq 0 \quad (5) \\
\sqrt{P_x^2 + P_y^2} \leq 1 \quad (6)
\]

Let us define obtaining the transformation matrix, and transforming the 4 points, and performing the 3 tests, as 1 unit of computational expense.

Let us consider an illustrative example of how dividing a large domain into sub-domains reduces the execution time requirements of determining if a POI is in the mesh, and if so, which mesh element contains it. Suppose that there are 1000 user specified POIs, and that the mesh contains
1,000,000 triangular elements. A list of 1,000,000 triangles much be searched for each of the 1000 points. If the point is actually in the mesh, and there is a uniform probability of finding it anywhere in the list of mesh elements, on average \( \frac{1}{2} \) of the 1,000,000 elements will have to be tested to find the match. An average of 500,000 units of computation expense would be expected for each of the 1000 points or 500,000,000 units of computational expense in total. If a point requested is not in the mesh, all 1,000,000 triangles in the mesh must be tested to confirm this, and the total computational expense will be greater. To summarize, this approach requires at least 500,000,000 units of computational expense.

Now let us consider a faster alternative. Instead of using one triangle list of 1,000,000 triangles, suppose the list is subdivided into 1,000 triangle lists of \( \sim 1100 \) triangles each (estimate 1100 because some triangles will straddle spatial boundaries and consequently appear in more than one list). Further suppose that an algorithm is available that enables us to select the correct list to search (one such algorithm is explained in the next section). Having identified the correct list to search, since the sub-domain list contains 1100 elements, on average, \( \sim 550 \) units of computational expense would be required per point. Multiplying 550 times 1000 points = 550,000 units of computational expense. This represents a 99.89% reduction in computation from the original 500,000,000 units of computational expense. The next section describes the algorithm used to choose the correct sub-domain list to search.
BSP Algorithm

A greater degree of uniformity in processing time can be achieved if the preprocessing of the list of mesh elements into a collection of sub-lists results in a collection of sub-lists of approximately equal length. Then any geographic coordinates that the user requests results in searching an element sub-list with a lower upper bound on the list length. An algorithm known as Binary Space Partitioning (BSP) was designed for just this purpose. The basic idea, as applied to the current problem is to bi-sect the mesh according to numbers of triangular elements. For example, if the mesh contains 800,000 elements, find the latitude that divides it into approximately 400,000 and 400,000. Then for each 400,000 element sub-mesh, find the longitude that divides it into approximately 200,000 and 200,000, and so on, until the list length is short enough that searching it adds little to the user’s wait time. In the South Atlantic Bight mesh this bisecting operation is performed 9 times resulting in 512 sub-domains of approximately 1810 elements each. To find the triangle that contains an arbitrary geographic point, the user’s POI is used to walk down a binary tree in which the branch points correspond to values of latitude and longitude that were found to be median points and used as dividing lines during the preprocessing. When the branch contains only one element list, that list contains the element that includes the user’s point of interest, if it is to be found in the mesh. As a practical matter of computational efficiency, it is much faster to view the domain as a cloud of points rather than a list of triangles during this step. BSP dividing lines are found by finding the median over the dimension being divided. For example, the median latitude over the domain divides the points almost equally by latitude, creating two sub-domains. The median longitude over each sub-domain divides the points almost equally by longitude. There are now four sub-domains created
Element Lookup from Points Algorithm

Having established that not a single point was lost in the creation of sub-domains, all of the elements associated with those points must be included in sub-domains of elements. This calls for a reverse lookup function where the element list is searched for all elements containing each point in the sub-domain as one of its vertices. Some elements will straddle sub-domain boundaries and will consequently be duplicated in more than one sub-domain, but this is not a problem because the BSP tree algorithm assures that only one sub-domain will be searched. Since a nodal point is usually a member of at least three elements, element numbers will be duplicated within a sub-domain, but this is also not a problem because the element list can easily be sorted and scrubbed of duplicates.

Algorithm to Find the Boundaries of a Triangular Mesh

Line segments that lay on the boundary of a triangular mesh have the distinguishing characteristic that they lay on the side of only one of the triangles of the mesh. In systems that define a triangular mesh by associating with each triangular element a triad of points, an algorithm is needed to redefine the triangular elements in terms of sides, rule out shared sides as boundary segments, and then the remaining unmatched sides are the boundaries of the mesh. Such an algorithm is described below:
1) Let a point identification number (a positive integer) be assigned to each tuple of scalars that makes up a "point".

2) Let a triangular element be defined by a triad of point index numbers.

3) Let an element identification number (a positive integer) be assigned to each triangular element.

4) In the case that points are defined in two dimensions, the processing proceeds as follows:

5) There is a list of triangles defined by vertex point ID numbers; example result:
   triangleID, point2, point1, point3

6) For each triangleID, sort the pointID numbers in ascending order; example result:
   triangleID, point1, point2, point3

7) Re-define each triangle in terms of sides. (substitute "pt" for "point"); example result:
   triangleID, (pt1, pt2), (pt1, pt3), (pt2, pt3)

8) Make a new list of sides associating parent triangleID with each side. Note: Each triangleID row becomes three rows. Example result:
   a.  (pt1, pt2), triangleID
   b.  (pt1, pt3), triangleID
   c.  (pt2, pt3), triangleID

9) Eliminate shared triangle sides by deleting rows in which both line segment end points match those in any other row. What remains are boundary line segments.

Step 9 can be accomplished as follows:
   a) Re-sort the list from step 8 by the leftmost pointID number. This will group sides with a shared point.
b) Within groups with matching left point number, sort by increasing right point number. This will place matching sides adjacent in the list. Delete matching sides (rows where both left and right pointID numbers match). What are left are only the rows that define sides that are members of only one triangle, i.e., the boundary line segments, and the triangleID they belong to.

Note that the input to this algorithm defines the finite element mesh elements in terms of node number indices; the geo-location of the node is not relevant to the algorithm. When using the ADCIRC model, this information is in the “fort.14” file. Note also that there is nothing about the basic algorithm that limits its use to two dimensions; it would work equally well if the elements were tetrahedral volume elements and shared sides were triangles. The extension to higher dimensions is algebraically straightforward.

This algorithm was coded and tested on the South Atlantic Bight mesh. Out of the original 927,165 elements comprised of 497,847 nodes, 69,326 nodes were found to be on the mesh boundary.
Figure 13 depicts the spatial distribution of the 69,326 boundary nodes as a visual verification that the algorithm works as intended. Of course, many of the nodes are going to be rendered to the same pixels at this image size.

Figure 20: Boundary Nodes of South Atlantic Bight Mesh
Mesh Display-related Challenges and Methods

Shown first in this section is a test of the feasibility of preprocessing stored images of the mesh in raster format to be stored on the server. Although it is shown to be not feasible, the calculation itself is instructive. Shown second, is a calculation performed to place an upper limit on the number of zoom levels a software tool (in this case, the Tidal Toolbox) needs to support in order to be able to display both the entire mesh domain in one window, as well as zoom-in to examine the smallest single triangular element in the mesh.

Mip-mapping is a technique for down-sampling a high resolution image by a fixed ratio, in order to achieve a stepped zoom-out effect on a display screen. Down-sampling the length dimension by a factor of two results in reducing the area of the down-sampled image by a factor of four. Recursively down-sampling each down-sampled image results in a theoretical storage requirement that is only 1/3 larger than the original image.

Server-Side Mesh Rendering to Raster Format

The following calculations were performed as part of an investigation into the feasibility of storing the mesh as a high resolution raster image then down-sampling to create overlays for each zoom level. The calculations were performed for the Western North Atlantic Tidal (WNAT) model domain, (S. C. Hagen, Zundel, & Kojima, 2006), but the principles apply equally well to the South Atlantic Bight model domain.
Suppose a 1024x768 pixel display area is to be filled with a 1 m equilateral triangle in any orientation, this would mean that a side would be a maximum of 768 pixels in length. The width represented by the screen at maximum zoom would be:

\[
\frac{1024}{768} \times 1m = 1.333m
\]  

(7)

The width of the WNAT model domain is about 4000 km.

\[
(4000\text{km})^2 = 16.00 \times 10^6 \text{km}^2 = 16.00 \times 10^{12} \text{m}^2
\]  

(8)

\[
16.00 \times 10^{12} \text{m}^2 \times \left(\frac{768 \text{pixelwidths}}{m}\right)^2 = 9.437 \times 10^{18} \text{pixels}
\]  

(9)

\[
9.437 \times 10^{18} \text{pixels} \times \frac{4\text{bytes}}{\text{pixel}} = 37.75 \times 10^{18} \text{bytes}
\]  

(10)

\[
\frac{37.75 \times 10^{18} \text{bytes}}{10^{12} \text{bytes/terabyte}} = 37.75 \times 10^6 \text{terabytes}
\]  

(11)

Rendering the entire WNAT model domain to a high resolution texture map for mip-mapping would require ~38 million terabytes for the base map and 1/3 of that for the lower resolution maps. This is clearly impractical. This is the disadvantage of raster graphics. On the other hand, the fort.* files that store the entire WNAT model domain unstructured finite element mesh (FEM) store it in a format that more closely resembles vector graphics, requiring ~1 gigabyte of storage for the entire mesh. One gigabyte is far too much data to serve for a browser page update, but it is not too much data to form the base map of a vector–graphics form of mip-map on the server.
Any geographic coordinate the user might specify is either in the mesh (including boundaries) or not. If it is in the mesh it can be associated with a single triangular element if it is inside a triangular element, or with as many elements as share a nodal point if it is a node point, or with two elements if it is on a side. Once a specified point is associated with a minimum number of elements, a bounding box with the same aspect ratio as the viewing area can be placed around the triangular elements. Once the physical coordinates of the viewing area have been determined, the next step is to associate with this viewing area a list of all the triangular elements that overlap it. The triangular elements that will be visible in the user’s viewing area can be rendered from their native geographic coordinate (vector) format to an image overly (raster) format on the servers GPU, and the image generated sent to the user as an overly for the map on the display. The physical area represented by this viewing area determines the maximum zoom-in that needs to be supported for that point. For example, in the deep ocean where an element may enclose many square kilometers, it is not necessary to be able to zoom down to resolve a 1 m triangle. An economy of processing could also be gained by not rendering triangles whose area would be less than a pixel area on the user’s display at the current zoom level. After eliminating the rendering of hundreds of thousands of triangles in this manner, the boundary information could be preserved by overlaying the boundary of the finite element mesh by the algorithm described above.
Zoom-level Requirements for Zooming a Large Mesh

Consider a computer monitor viewing window of 1024x768 pixels. Viewing the entire WNAT model domain width \((22^\circ 30' \text{ N} 98^\circ \text{ W} \text{ to } 22^\circ 30' \text{ N} 60^\circ \text{ W})\) is about 2491 miles. The narrowest possible line width that could be used to represent and element boundary is 1 pixel. The representation of the element boundary at this zoom level is \(\frac{2491 \text{ miles}}{1024 \text{ pixels}} = 2.43 \frac{\text{miles}}{\text{pixel}}\), this means a mesh line is nearly 2 \(\frac{1}{2}\) miles wide. At the other end of the spectrum, suppose it is desirable to permit triangular elements as small as 0.9m on a side. Zooming in to the make one of these small elements fill the monitor screen, and requiring a minimum length to width ratio of 20, so that the graphic is perceived as a line, means the width of the line on the monitor screen would be calculated as:

\[
\frac{0.9m}{20} \Rightarrow \frac{768 \text{ pixels}}{20}
\]

\[
45 \text{ mm} \Rightarrow 38 \text{ pixels}
\]

The width of the line is 38 pixels. The scale factor would then be calculated as:

\[
\frac{45 \text{ mm}}{38 \text{ pixels}} = 1.2 \frac{\text{mm}}{\text{pixel}}
\]

The scale factor would be \(1.2 \frac{\text{mm}}{\text{pixel}}\) for the maximum zoom-in case.

In the maximum zoom-out case:

\[
2.43 \frac{\text{miles}}{\text{pixel}} \times 5280 \frac{\text{ft}}{\text{mile}} \times 12 \frac{\text{in}}{\text{ft}} \times 2.54 \frac{\text{mm}}{\text{in}} = 3.911 \times 10^6 \frac{\text{mm}}{\text{pixel}}
\]

The scale factor would be \(3.911 \times 10^6 \frac{\text{mm}}{\text{pixel}}\) for the maximum zoom-out case.
The ratio of the linear distance covered per pixel between the maximum zoom-out case and the maximum zoom-in case is then:

\[
\frac{3.911 \times 10^6 \text{ mm/pixel}}{1.2 \text{ mm/pixel}} = 3.259 \times 10^6
\]

Since the maps server, Google maps, zooms by powers of 2, and noting that:

\[
2^{22} = 4.196 \times 10^6 > 3.259 \times 10^6
\]

22 zoom levels would accommodate the WNAT model domain. Since the South Atlantic Bight mesh is spatially smaller and the smallest element size larger, 22 zoom levels would be more than adequate for it also. The maximum number of zoom levels currently supported by Google maps is 23. In most areas on land images are available for not more than 19 zoom levels. In view of the foregoing, 23 zoom levels will be considered an upper limit for sizing code and data structures in the Tidal Toolbox.
Computing Environment

This section details the software tools and technologies utilized in the development and deployment of the Tidal Toolbox.

HTML

ASCII is the standard computer code for representing alphabetic characters and numerals in computer files and communications links (between a computer and a printer for example). A plain ASCII text file contains no typesetting information (such as font types, sizes, bolding and underlining, etc.) An ASCII text file can be printed and read from paper in the same manner that it can be read from a computer screen. This type of reading is referred to as linear, or "novel style". A hypertext document is designed to be read using a computer application program called a hypertext reader. A hypertext document contains highlighted clickable embedded links that can be used to jump to another part of the document or even to a different document. Hence, the document can be read in a non-linear fashion, sometimes hypertext readers are referred to as non-linear text readers. Hypertext has the advantage of making it practical to navigate efficiently in an extremely large document. When the world wide web was in its infancy, hypertext became the vehicle for allowing a client (internet user) to access a vast amount of information on internet servers, and minimizing the communications bandwidth required to give the client instant access to anything on the server as if it was a hypertext document residing on the client computer. This type of web server supported the hypertext transfer protocol (URL prefix http://) and the data sent to the client, hypertext markup language (file suffix .html). HTML became the first
language of the internet, and it is still all that is required for publishing good-looking documents that don't change. HTML is good for publishing help files, user manuals, history books, technical specifications, any document with static content. The user interaction in an HTML document is limited to the user selecting links in the document to change the part of the document (or the document itself) that is being displayed in the browser, but the document itself doesn't change. HTML was originally intended to be a language for capturing content, and it was up to the browser to determine the appearance of the content. Style markers crept in with the introduction of HTML 3.2, and were continued with HTML 4, but mixing style with content made HTML programming more difficult than it needed to be. Cascading Style Sheets (CSS) technology was invented to enable the segregation of style into separate files from content information. Draft proposed HTML 5 enforces the segregation of style and content, as well as defining new data input field features that formerly required additional coding. HTML 5 is chosen for the implementation of the input page form of the Tidal Toolbox. As of the time of this writing, it is expected that HTML 5 will become a formally accepted standard by the end of 2011. In the interim, the browser known as Opera is taking the lead in implementing HTML 5 features and is the recommended browser for use with the Tidal Toolbox. URL:
http://www.w3schools.com/html5/default.asp accessed 9/23/2010. See also URL:
One way for the document to display dynamic content is for the user request for a web page to initiate processing on the server that produces HTML as output to be sent to the user. One technology used for this purpose in the Tidal Toolbox website is Active Server Pages. Active Server Pages, usually abbreviated ASP, is a web-scripting interface by Microsoft. ASP uses Visual Basic Script (VBS) as the scripting language. Each time a web page with an “.asp” suffix is requested by the client, the server submits the .asp file to the ASP processor on the server for processing. The HTML output of this processing is what is sent to the client who made the request. In the Tidal Toolbox website, ASP files are used to launch requests to Google Maps for map downloads, the placement of markers, the geo-coding of marker locations, the compilation of user points of interest into lists, and the output of the lists and other user selected options to a text file. The appearance of that text file in a special directory that is consistently monitored for the appearance of new files is the mechanism that triggers the execution of the mathematical processing. The mathematical processing that must be done on the server to extract model data for the user is done in MATLAB. After MATLAB produces a set of output files and copies them to a share folder, an ASP script creates a directory listing of the folder and presents the directory to the user with links to the output files.
SHTML

If a large number of users are likely to request the same dynamic content in a web page, it is more efficient to produce the dynamic HTML once, save it on the server side, and then include it in the page served at the time of the request. Since HTML does not support include files, SHTML was developed as an extension of HTML that supports Server Side Includes (SSI). The “.shtml” suffix indicates to the server that tags indicating include files should be replaced by the content of the include files before the HTML is served to the user. Even if the inserted data does not change often, SHTML may still optimize code size when many web pages are identical except for a small amount of includable data. The NOAA Tides and Currents website employs SHTML in the station information page to modify a base web page design with the information particular to the station requested. URL:


DNS

The Domain Name System (DNS) translates human-friendly computer hostnames into the numeric internet protocol (IP) addresses required to connect to a website over the internet. Commercial websites frequently purchase static IP addresses to make it easy for a customer who has once visited their site to find it again. Residential customers of internet service providers (ISPs) normally are assigned a dynamic IP address from a bank of IP addresses assigned to the ISP. A dynamic IP address is assigned to the customer’s router upon connection for the duration
of a “lease” time specified in the connection metadata that is typically 24 hours. In order for a returning user to find the website again after the IP address has changed, the name of the website must be resolved to the current IP address by a dynamic DNS name host that keeps track of the IP address currently assigned to that website. The Tidal Toolbox utilizes DynDns.com for that function. The mechanism of keeping the DNS name host up to date works as follows: Each time the ISP assigns a new IP address to the router, the router sends a message to the name host telling it the new IP address to associate with its name.

To access the Tidal Toolbox website the user enters http://sealevel1.dyndns.org into the URL field of a browser, and the web page appears. Several steps occur in between. The domain name dyndns.org goes to a name server that looks up the IP address of Dynamic Network Services, Inc. associated with the domain name dyndns.org. The name sealevel1 is mapped to the dynamic IP address currently associated with router the Tidal Toolbox website server is connected to. The router is set up to forward incoming requests on port 80, (the port used for http sites) to the local IP address that the router itself assigned to the Tidal Toolbox website server. When the request reaches the server, if a specific web page is not addressed, the server serves the website's default web page, traditionally called index.html, which in this case is the Tidal Toolbox's home page. Upon release, the domain name will be http://www.tidaltoolbox.com.

Router Setup and Configuration

A global internet protocol (IP) address is assigned by an internet service provider (ISP) to a customer. A global IP address needs to be unique over the entire worldwide web. In a typical
residential setup with one cable modem, one router and a few computers, a packet sent to a customer's global IP address gets as far as the router, then; it is up to the router to decide which computer to forward it to. When a computer is turned on behind the router, the router assigns it a local IP address, starting from some preconfigured base address, and then assigns successive local IP addresses sequentially according to the order that the computers were turned on. A local IP address needs to be unique on the local network, but since it is not visible to the WWW, it does not have to be unique globally. In order to operate a server behind a router, the router needs to be configured to forward incoming requests to the local IP address of the server. In order for the web server to receive the packets, the local IP address assigned to the website on the server side, must match the local IP address to which the router is configured to forward incoming requests.

This can be a problem if a computer or router reset results in a local IP address mismatch between the address that the router is configured to forward incoming requests to, and the address dynamically assigned to the computer after a reset. Commercial routers have a feature to allow "static" assignment of local IP addresses, i.e., it assigns the same local IP address to the same computer after a reset, based on the MAC address computer’s Ethernet interface.

XP Pro and IIS

XP Pro is the popular 32-bit Microsoft operating system used for the development and initial hosting of the Tidal Toolbox. Internet Information Services (IIS) is a component of XP Pro that enables a PC to be set up as a web server. A typical default installation of XP Pro does not
include IIS, but IIS can be installed as an add-on from the original XP Pro installation disk. IIS permits a PC to host only one website at a time, and the user must choose either HTTP or FTP as the protocol to support. For this reason, the Tidal Toolbox employs two computers, one to host the HTTP site that collects the parameters of the request from the user; and another to host the FTP site to which a set of output files are posted.

Google Maps

Google Maps Version 3 API is the software interface used to access the web service upon which the graphical input capabilities of the Tidal Toolbox are based. There are other similar web services available, including: Yahoo! Maps, MapQuest, Microsoft Virtual Earth, and ArcWeb Service, to name a few. The API’s of each of these map services is based on the JavaScript programming language. Google Maps took an early technological lead when free map servers became available on the web in 2005. Today the technology does not differ as much between services, but the Google Maps Version 3 API is well supported by online tutorials and documentation, so it was selected for this project. A free map service does not offer the extensive capabilities of a GIS server, it does not provide the containment relationship between a submitted point and 927,000 polygons. However, by preprocessing the mesh data into sub-domains, and making containment calculations on the Tidal Toolbox server, it is possible to develop this GIS-like containment relationship function. (Chow, 2008) The model output data, having been pre-processed into sub-domains, provides the additional GIS database element required to serve tide elevations, velocities, and residual velocities to the user.
MATLAB version 2010a was used to pre-process the model files containing the mesh definition, the tidal elevation constituents, the tidal velocity constituents, and the velocity residuals for fast service on a web server. It was also used to programmatically generate the vast majority of the code that makes up the Tidal Toolbox website. Most of the code is JavaScript embedded in the headers of HTML files that provide mesh definition information to the user.
Tidal Toolbox Processing

The following discussion details the processing that takes place between the time the user presses the "Submit" key to initiate processing, and the time the output files appear in a new folder on an FTP server.

Pressing the "Submit" key tells the browser to gather up all the data in the Tidal Toolbox input page that is designated as "form" data in the index.html page and send it in a message to the Tidal Toolbox server. The form data specifies what processing is to be performed on the data by including a filename in the message, in this case, process.asp. Process.asp parses the message it has received from the client and creates from it a text file called TTBweb.txt. TTBweb.txt is written to a shared file to pass the information between IIS, which is in effect a user account under the XP Pro operating system, and the user account that is going to be used to invoke the Tidal Toolbox "backend" processing under MATLAB. The folder to which TTBweb.txt is written is called C:\Documents and Settings\All Users\Documents\TTBuploads.

The user account being used for backend processing has previously had MATLAB loaded and is running a MATLAB script called Launcher.m in an infinite loop. Every second, Launcher.m checks the folder C:\Documents and Settings\All Users\Documents\TTBuploads for the existence of a file named TTBweb.txt. If TTBweb.txt is present, Launcher.m copies TTBweb.txt to the user accounts document space, renames the local file to the name TTB.txt, and deletes the
TTBweb.txt file in the shared folder so it will not be processed more than once. Once the TTB.txt file is present in the local directory, Launcher.m calls the "main" program in the Tidal Toolbox, TTBbackend.m.

The processing sequence described above meets several system level requirements simultaneously. The first concerns security, servers purposely do not allow clients to initiate processing of their own executable code on the server. The system is set up such that all processing on the server is initiated by the server, or the user account in which MATLAB is executed. The internet client supplies a request in a structured format, but cannot get additional control over the server. Secondly, clearing the TTBweb.txt file from the shared folder after it has been copied readies the system to queue another processing request from the network. Calling the TTBbackend.m script from within Launcher.m suspends the Launcher thread from initiating another TTBbackend.m processing job until the previous one is complete. Thirdly, passing the input file through the shared folder prevents the operating system from stopping the processing due to file access violations. Initiating MATLAB first avoids the several seconds of delay it would take MATLAB to load and run its startup scripts, and assures that no other application running on the server will be able to allocate memory that the server needs to be ready to service a request.

TTBbackend processing begins by clearing the data workspace and reloading the large binary format files containing the model domain and model output information. As the TTB.txt file is parsed, the user input data, which is in ascii format, is converted to MATLAB binary formats.
Since the geographic coordinates list can be of variable length, the occurrence of keywords in the input file controls the interpretation of the lines to follow, until the next keyword changes the interpretation.

Once all of the model data and user input data is in memory in binary format, each geographic point of interest in the input list is checked to determine if it is in the mesh and whether or not it is in-bank. FindEnclosingElement.m performs this function. A user output file called PointInformation.txt is generated during this process to report these findings to the user. For each in-bank POI, the nodal model output data is interpolated to the users exact POI, Vector3PointAvg.m is the function that performs this operation. Linear reciprocal distance weighting is the default. Similar processes are executed to produce three user output files, ElevationConstituents.txt, VelocityConstituents.txt, and VelocityResiduals.txt. Velocity residuals processing is finished at this time, but binary forms of the elevation constituents and velocity constituents are retained in memory for resynthesis.

Node factors and equilibrium arguments are calculated for the start date of the time interval to be used in the resynthesis. NodeFac.m is the name of the function that performs this calculation for each constituent frequency. The output of this calculation is written to a file called NodeFacSorted.mat, which is then read in by TTBbackend.m and utilized to resynthesize a time series of water surface elevation at each user point of interest (POI), and depth averaged velocity at each POI. The VelocityResynthesis.txt output file contains a single time column for all POIs, and two columns corresponding to X and Y components of velocity for each POI. The time
series resynthesis of elevation constituents for each point is saved to a separate text file having a name of the form Point<#>Tide.txt where <#> is the index of the accepted POI.

The MATLAB publish command is used to invoke the PlotGraph.m script to produce a resynthesis plot in ".png" (Portable Network Graphics) format for each point for which a tabular time series output file was created.

At this stage all of the output files have been created. A connection is opened to an FTP site and a new folder is created named with a date and time stamp. All of the files in the local user output subdirectory are uploaded to this newly created subdirectory, and then deleted from the local subdirectory so that old files not overwritten will not be copied again to another FTP output folder.

The connection to the FTP server is then closed, and the Tidal Toolbox processing is finished. Program control returns to Launcher.m which resumes checking the TTBuploads shared folder for the appearance of a new text file called TTBweb.txt to signal a new processing request.
CHAPTER FOUR: CONCLUSIONS AND FUTURE WORK

The Tidal Toolbox presented herein disseminates harmonic constituents as extracted from a large-scale, high-resolution tidal model of the South Atlantic Bight. The web-based approach offers wide accessibility to the large-scale, high-resolution model data without the user requiring any costly specialized software (e.g., ArcGIS or SMS). Only a web browser and internet access are required. A valuable feature of the Tidal Toolbox is that it permits web access to complex data through user interaction in a geospatial environment.

Visualization in geospatial context is implemented within the Tidal Toolbox for the purpose of giving the user a geospatial environment in which to visualize the mesh boundary, select their points of interest, and view stations where model-data comparisons are available. The utility of the Tidal Toolbox is based on the delivery of resynthesized water surface elevations and depth-integrated velocities as well as velocity residuals. The model-data comparisons contained within the Tidal Toolbox are provided both qualitatively (by plot) and quantitatively (by RMS error) which allows the user to make their own assessment of the results being obtained.

The Tidal Toolbox as presented in this thesis is demonstrated for a tidal application in the South Atlantic Bight. However, viewed more generally, the data input to the Tidal Toolbox could be any triangular element mesh model that spans a geospatial domain, and any model output that associates static or dynamic values with the nodes of that mesh. The list of harmonic constituents utilized could be expanded, changed or contracted. Mesh preprocessing programs are provided to prepare new model meshes for constituent extraction and resynthesis, and publishing the results
over the internet. To this extent, the Tidal Toolbox really is a “toolbox” of software programs to facilitate tidal modeling, and is not limited to the first model it is being utilized to publish. There is strong value to the modeling community to have such a resource as the Tidal Toolbox available. Potential applications include: validation of an in-progress model, visualization of a model under construction overlaid on aerial photography, an aid to expediting the selection of the model constituents required to be supported for a given level of accuracy, and of course the current application, dissemination of model data, to name a few.

Future work dealing with the Tidal Toolbox can continue to enhance the basic features it provides. The visualization function can be enhanced by providing a top-level view of the entire mesh that is zoomable to the element level without consciously having to change pages. The function of visually selecting points of interest can be enhanced by displaying the mesh in the same view. As new tide gauge stations become available to provide historical tidal constituents, the model-data comparisons used within the Tidal Toolbox can be updated to include the newly reporting stations. Lastly, as new geometries and solutions become available, they can be implemented within the Tidal Toolbox.
APPENDIX A: HIGH RESOLUTION HYDRODYNAMIC MODEL FOR THE SOUTH ATLANTIC BIGHT, INCLUDING FLORIDA’S EAST COAST AND THE ATLANTIC INTRACOASTAL WATERWAY
High-Resolution Hydrodynamic Model for the South Atlantic Bight, Including Florida’s East Coast and the Atlantic Intracoastal Waterway

The hydrodynamic model for the South Atlantic Bight describes Florida’s east coast and the Atlantic Intracoastal Waterway with resolution on the order of tens of meters.

Landcover data (circa 2003) were used to delineate channel and wetland boundaries and to assign bottom roughness in the model (a base value for open water and two higher values for wetlands).

Figure 21: High Resolution Hydrodynamic Model for the South Atlantic Bight, Including Florida’s East Coast and the Atlantic Intracoastal Waterway
APPENDIX B: HISTORICAL VERSUS MODEL RESULTS PLOTS IN THE SOUTH ATLANTIC BIGHT
Figure 22: WWTD, Mayport Naval Station, FL; NOS 8720211
Figure 23: Bar Pilots Dock, FL; NOS 8720218
Figure 24: Dame Point, FL; NOS 8720219

RMS Error 4.482 % of Peak to Peak Signal
Figure 25: Mayport, FL; NOS
Figure 26: Main Street Bridge, FL; NOS 8720226
Figure 27: Longbranch, FL; NOS 8720242
Figure 28: I-295 Bridge, West End, FL; NOS 8720357
Figure 29: Red Bay Point, FL; NOS 8720503
Figure 30: Racy Point, FL; NOS 8720625
Figure 31: Buffalo Bluff, FL; NOS 8720767
Figure 32: Palatka, FL; NOS 8720774
Figure 33: Welaka, FL; NOS 8720832
Figure 34: St. Mary’s River, Cut 2, FL; SJRWMD
Figure 35: Little Talbot Island, FL; NOS 8720194
Figure 36: Clapboard Creek, FL; NOS 8720198
Figure 37: Blount Island Bridge, FL; NOS 8720203
Figure 38: St. John's River, WWTP, FL; SJRWMD 8720221
Figure 39: Navy Degaussing, FL; SJRWMD
Figure 40: Jacksonville, Navy Fuel Depot, FL; NOS 8720215
Figure 41: Moncrief Creek Entrance, FL; NOS 8720217
Figure 42: Fulton, St. John's River, FL; NOS 8720221
Figure 43: Phoenix Park, FL; NOS 8720225
Figure 44: USACE Dredge Depot, FL; SJRWMD

USACE Dredge Depot, FL; SJRWMD

Deviation from NAVD 88 (m)

Days into Resynthesis

RMS Error 5.96 % of Peak to Peak Signal
Figure 45: Jacksonville, Acosta Bridge, FL; NOS 8720268
Figure 46: Little Pottsburg Creek, FL; NOS 8720274
Figure 47: Jacksonville Pier, FL; SJRWMD
Figure 48: Ortega River Entrance, FL; NOS 8720296
Figure 49: Piney Point, St. Johns River, FL; NOS 8720333
Figure 50: Orange Park, St. John's River, FL; NOS 8720374
Figure 51: Doctor's Lake, Peoria Point, FL; NOS 8720406
Figure 52: Julington Creek, FL; NOS 8720409
Figure 53: Green Cove Springs, St. John's River, FL; NOS 8720496
Figure 54: East Tocoi, St. John's River, FL; NOS 8720596
Figure 55: Palmetto Bluff, St. John's River, FL; NOS 8720653
Figure 56: Pablo Creek Entrance, FL; NOS 8720232
Figure 57: Palm Valley, FL; SJRWMD
Figure 58: Tolomata River, AIW, FL; SJRWMD
Figure 59: Vilano Bridge, FL; SJRWMD
Figure 60: St. Augustine, FL; NOS 8720576
Figure 61: CR312 Bridge, St. Augustine, FL; SJRWMD
Figure 62: St. Augustine Beach, Atlantic Ocean, FL; NOS 8720587
Figure 63: Anastasia Island, FL; NOS 8720623
Figure 64: Crescent Beach, FL; SJRWMD
Figure 65: Fort Matanzas, FL; NOS 8720686
Figure 66: Matanzas Inlet, FL; SJRWMD
Figure 67: Matanzas River Headwaters, FL; NOS 8720729
Figure 68: Daytona Beach, Atlantic Ocean, FL; NOS
Figure 69: Port Orange, FL; SJRWMD
Figure 70: Daytona Beach Shores, FL; NOS 8721120
Figure 71: Halifax River, Ponce Inlet, FL; NOS 8721138
Figure 72: Ponce de Leon Inlet (South), FL; SJRWMD
Figure 73: Edgewater (FDEP 2005), FL; SJRWMD
Figure 74: Oak Hill (FDEP 2005), FL; SJRWMD
Figure 75: Cocoa Beach, Atlantic Ocean, FL; SJRWMD
Figure 76: Sebastian Inlet, FL; SJRWMD
Figure 77: Sebastian River, Roseland, FL; SJRWMD
Figure 78: Vero Bridge, FL; SJRWMD
Figure 79: Fort Pierce Causeway, FL; SJRWMD
Figure 80: Fort Pierce Inlet, FL; SJRWMD
Figure 81: Fort Pierce, FL; SJRWMD
Figure 82: Ankona, Indian River Lagoon, FL; SJRWMD
Figure 83: Jensen Beach, FL; SJRWMD
Figure 84: South Point, St. Lucie Inlet, FL; SJRWMD
Figure 85: Coast Guard Dock, FL; SJRWMD
Figure 86: Pompano Drive, FL; SJRWMD
Figure 87: Boy Scout Dock, FL; SFWMD
Figure 88: Kitching Creek, FL; SFWMD
Figure 89: River Mile 9.1, FL; SFWMD
Figure 90: Wrightsville Beach, NC; NOS 8658163
Figure 91: South Port, NC; IHO 428
Figure 92: Sunset Beach Pier, Atlantic Ocean, NC; NOS 8659897
Figure 93: Springmaid Pier, Atlantic Ocean, SC; NOS 8661070
Figure 94: Charleston, Cooper River Entrance, SC; NOS 8665530
Figure 95: Hunting Island Pier, Fripps Inlet, SC; NOS 8668498
Figure 96: Fort Pulaski, Savannah River, GA; NOS 8670870
Figure 97: St. Simons Lighthouse, St. Simons Island, GA; NOS 8677344
Figure 98: Trident Pier, Port Canaveral, FL; NOS 8721604
Figure 99: Canaveral Harbor Entrance, FL; NOS 8721608
Figure 100: Lake Worth Pier, Atlantic Ocean, FL; NOS 8722670
Figure 101: Haulover Pier, North Miami Beach, FL; NOW 8723080
Figure 102: Miami Beach, City Pier, FL; NOS 8723170
Figure 103: Miami Beach, Government Cut, FL; NOS 8723178
Figure 104: Virginia Key, Biscayne Bay, FL; NOS 8723214
Figure 105: Settlement Point, Grand Bahamas, Bahamas; NOS 9710441
Figure 106: Nassau, Bahamas; IHO 315
Figure 107: Atlantic Ocean; IHO 422
Figure 108: Atlantic Ocean; IHO 41
Figure 109: Atlantic Ocean; IHO 360
Figure 110: Atlantic Ocean; IHO 355
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