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Rick Brennan
University of New Hampshire, Durham

Kurt Hess
NOAA

Lloyd C. Huff
University of New Hampshire, Durham

Steve Gill
NOAA

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LT Richard T. Brennan, NOAA, Joint Hydrographic Center
Dr. Kurt Hess, NOAA, Coast Survey Development Laboratory
Dr. Lloyd Huff, UNH, Center for Coastal and Ocean Mapping
Steve Gill, NOAA, Center for Operational Oceanographic Products and Services

ABSTRACT

Recent advances in processing multibeam sonar data brought about by the Combined Uncertainty and Bathymetric Estimator (CUBE) [1] have demonstrated the value of identifying and tracking survey uncertainties. Most of these uncertainties were outlined in Hare, Godin, and Mayer uncertainty model developed in 1995 [2]. That report identified the uncertainties in the various electronic systems used to acquire the bathymetric data. However, one of the largest contributors to the overall error budget in a near coastal hydrographic survey is that contributed by water level uncertainty.

As the ocean mapping industry pushes for ever finer spatial details in its data, the traditional method of discrete tide zoning [3] must be abandoned for a more robust method that can match the requirements of the data. The method currently under investigation by the National Oceanic and Atmospheric Administration is the Tidal Constituent And Residual Interpolation (TCARI) method [4]. TCARI has the ability to interpolate the water level at a vessel's position for any location and instance in time. It can also produce a gridded water level surface of the entire survey area.

While the potential of this method is encouraging, a rigorous investigation of the uncertainties associated with it has yet to be completed. This research seeks to close that gap by examining the uncertainties in this method, using both observed water level information from around the country as well as data acquired during the original 1995 NOS Kinematic GPS experiment in Galveston Bay, Texas [5].

INTRODUCTION

Water level corrections have always consumed the largest single portion of the error budget for a hydrographic survey. The traditional method for applying water level corrections to hydrographic survey data was accomplished using discrete tide zones. This method applied a constant phase and amplitude correction to the controlling water level gauge for a specific geographic polygon. The resultant water level departure from the Mean Lower Low Water (MLLW) datum was then applied to all soundings falling within this geographic polygon. In this way, an artificial "step" was introduced into the data at the boundary between two of these polygons.

A new method was introduced in 1995 called Tidal Constituent and Residual Interpolation (TCARI). TCARI has the ability to interpolate the amplitude and phase of numerous tidal harmonic constituents, the residual water level, and various datum for a given tide station to any point of interest within the survey area. These points could be along the track of a vessel or at predetermined grid nodes.

This method provides distinct advantages over discrete tide zoning. It can account for variations in the high water and low water intervals, changes in tide type (e.g., diurnal, semidiurnal, or mixed) between stations, it accommodates changes in space and time of non-tidal components, it produces no spatial discontinuities similar to those found at the boundaries between discrete tide zones, and it can be used to reference survey data to the GPS ellipsoid [4].

While TCARI was initially designed to apply tidal corrections to bathymetric data, it could also be used to apply real time water level corrections to an Electronic Navigational Chart (ENC). By using TCARI to provide water level topography and combining this with high resolution bathymetry, the possibility for creating a dynamic ENC, tailored to the particular draft and load conditions of a given vessel, is a much closer reality.

TERMINOLOGY

The following terms and their definitions will be used for consistency in this paper:

Tides - the alternating rise and fall in sea level with respect to the land, produced by the gravitational attraction of the moon and sun.

Water Levels - will refer to the total elevation of the water surface due to both the tide and any meteorological or hydrological conditions experienced within the region.

Residual - the difference between the water level and the tide.

Tidal Constituent - one particular component of the tide producing force (for example, the lunar semidiurnal constituent M2 or the solar semidiurnal constituent S2).

Harmonic Constants - the derived numerical values of the amplitude and phase of each of the tidal harmonic constituents.

Accepted Sets of Harmonic Constants - those amplitudes and phases produced by the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) and listed on their web-site for particular tide stations.

THEORY

Before TCARI may be implemented for use in either hydrographic surveying or real-time navigation, it is important to fully understand the uncertainties associated with it. There are four primary sources of error contribution within TCARI; the harmonic constants, the water level observations, the interpolation, and the datum.

Each tidal constituent has two harmonic constants – its amplitude and its epoch (or phase). Each of these harmonic constants has an uncertainty associated with it. There are up to forty tidal constituents used to predict the tide at any given station. The harmonic constants for each of these constituents are particular to the geographic location of that particular station.

The next source of error in the TCARI method comes from the water level measurements themselves. The standard National Water Level Observation Network (NWLON) gauge measures water level acoustically using a self calibrating sensor which records 181 samples at one second intervals over a three minute period. These sampling intervals are centered every six minutes [6]. The mean and standard deviation of these measurements are then reported.

The third source of error is in the Laplace Equation interpolation. TCARI uses this method to create spatial weighting functions used in interpolating station values (harmonic constants for each of the tidal constituents, residuals, and various datum) across the survey region. This can be further broken down into the uncertainty in the algorithm itself and the modeling error.

The final source of error is in the determination of the datum. The datum is considered to be relatively static. While there is a time varying element associated with the tidal datum due to subsidence and climatological sea level rise, it is assumed to be constant for the relatively brief time period during which a hydrographic survey is conducted.

Of these four sources of error, the error in the observed water level measurements and the error in the datum are well characterized and understood. It is the uncertainties in the various harmonic constants and the interpolation of these and other station information using the Laplace Equation which are less well known. It is these latter two on which this research focuses.

DATA ANALYSIS

Tidal Constituents

To determine the uncertainty in the harmonic constants, the speed (angular frequency) from the Accepted Sets of Harmonic Constants provided by CO-OPS was used in a Discrete Fourier analysis to determine the associated amplitude and phase (epoch) of that particular tidal constituent. This calculation was repeated multiple times for periods of 30, 60, 90, and 365 days. The various computational periods were used to capture the varying wavelengths of the different harmonic constituents. For example, the M2 constituent has a period of 12.42 hours while the SSA has a period of 182.62 days. A Fourier analysis of less than 182.62 days would not be able to fully characterize the SSA constituent.

To provide sufficient statistical validity for the longer period harmonic constituents, five years of observed water levels, acquired at six minute intervals, were used for each station investigated. These calculations incremented through the five years of data in steps equal to half the computational period. Therefore if the Fourier analysis were being computed for a thirty day period with a sampling frequency of one measurement every six minutes starting at January first, the next iteration would start at January 15 and end thirty days later. This would yield 119 independent calculations of the amplitude and phase for each tidal constituent. This computation was then carried out for each of the tidal constituents defined for that station. With multiple independent calculations per constituent completed, the mean and standard deviation of these could then be easily computed. It should also be mentioned that the number of samples used in each constituent's Fourier analyses varied based on an even number of cycles per computational period. This method was chosen so an integer number of wavelengths per iteration could be used in the Fourier analysis.

To determine the combined standard deviation in the tide, which included the contributions from each of the constituents, a Monte Carlo Simulation was run using the computed mean and standard deviation values to compute the predicted tide and its error bounds. As shown in **Figure 1**, the blue line is the predicted tide, the green lines are the tide plus and minus the standard deviation, the dotted magenta line is the standard deviation, and the red line is

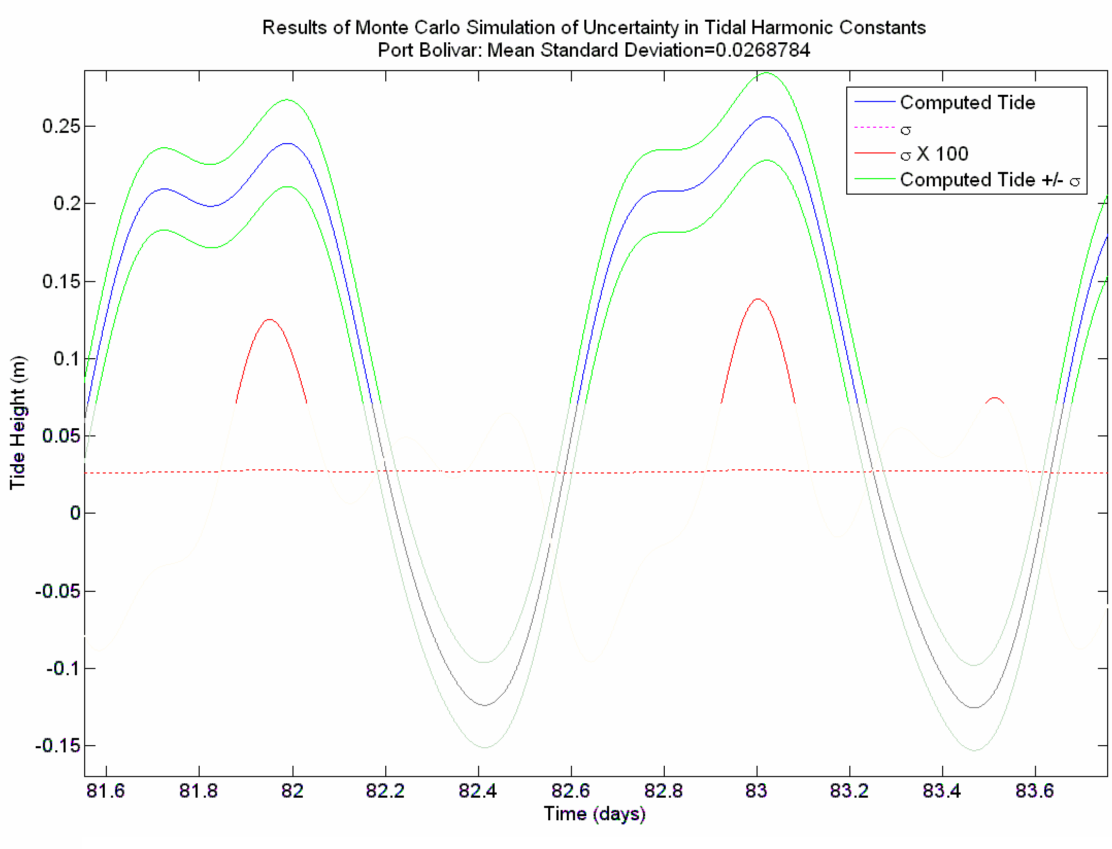


Figure 1: Results of Monte Carlo Simulation showing the combined uncertainties of all harmonic constituents at Port Bolivar, Texas. The combined standard deviation in the tide due to contributions of the harmonic constituents is 2.7 cm at this station.

the standard deviation multiplied by one hundred to illustrate how the amplitude of this value changes with time.

Laplace Equation Interpolation

While directly measuring the uncertainty in the interpolation is nearly impossible, this research has focused on determining its bounding limits by comparing TCARI water levels against actual observed water levels at eight stations around Galveston Bay, Texas (**Figure 2**). This was accomplished using an iterative process in which a single gauge was removed from the super set of eight gauges. TCARI was then used to interpolate the water level at the position of this removed gauge. The observed water levels and the TCARI interpolated water levels could then be compared. Specifically the RMS difference was computed between the two time series. This method was then repeated for all eight gauges in the project. The data for this portion of the study was mined from the NOS Kinematic GPS project conducted in Galveston Bay in 1995 [5].

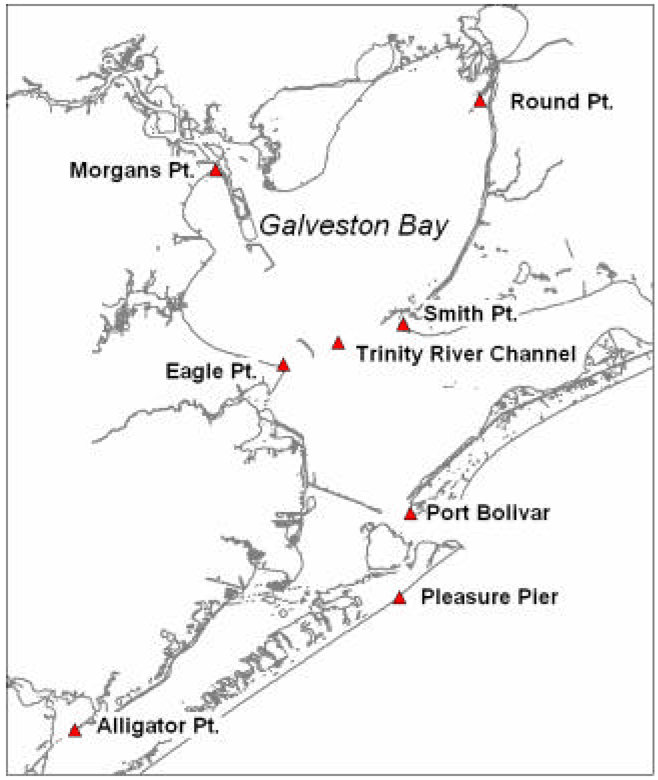


Figure 2: Water Level stations used in the interpolation uncertainty analysis.

Future work will include determining whether a spatial relationship exists between these gauges using the difference between the observed and TCARI interpolated water levels. It is speculated that by taking the cross correlation between each of these delta time series and comparing them against their inverse distances a spatial relationship may be identified.

Future work will also include investigating the spatial variability of the uncertainty by comparing the RTK GPS heights from a moving vessel with TCARI interpolated water levels. This is expected to describe how the uncertainty grows the further from a gauge the interpolation is made.

PRELIMINARY RESULTS

Although analysis is still underway, preliminary results indicate the harmonic constants contribute between 3 cm and 6 cm to the combined standard deviation in the tide computed using the Monte Carlo Simulation. These values are based on all constituents defined for the particular station under investigation. However, CO-OPS may eliminate certain constituents in their official computations if the amplitude values are less than 0.3 cm. Trials have been conducted where these constituents were similarly removed, and the

Monte Carlo simulation run again. As expected, the combined standard deviation was reduced, but only by an amount proportional to the magnitude of the amplitudes which were removed.

Areas like Galveston, Texas where responses to the astronomic driving forces contribute only about 40% to the total water level are known to have significant uncertainties in their harmonic constituents. In this study the variability in the combined standard deviation of the tide from one station in Galveston Bay to another was observed to vary by as much as 3 cm to 4 cm. However, the peak combined standard deviation of all the tidal harmonic constituents at each station varied by only 0.1 cm to 0.3 cm.

Preliminary results for the overall standard deviation in the TCARI interpolation at each of the eight gauge sites show a strong spatial correlation with the distance of the interpolation. The Trinity River Channel showed the best agreement with an RMS difference of 0.1 cm. The range to the nearest gauge at this location was approximately 6 km. The highest disagreement between observed and TCARI interpolated water levels was at Alligator Point with an RMS difference of 20.5 cm and a range to the nearest gauge of approximately 35 km (**Figure 3**).

For all stations within Galveston Bay proper, the RMS difference between their observed and TCARI interpolated water levels was less than or equal to 4.2 cm. Round Point and Port Bolivar had the highest RMS differences out of this subset of gauges. The performance is remarkable at Round Point and Alligator Point because they were positioned at remote locations with rather long expanses of shallow water leading to them. In particular, Alligator Point was in West Bay and subject to significantly different estuarine conditions. The performance was also remarkable at Port Bolivar because conditions there are more akin to open ocean conditions.

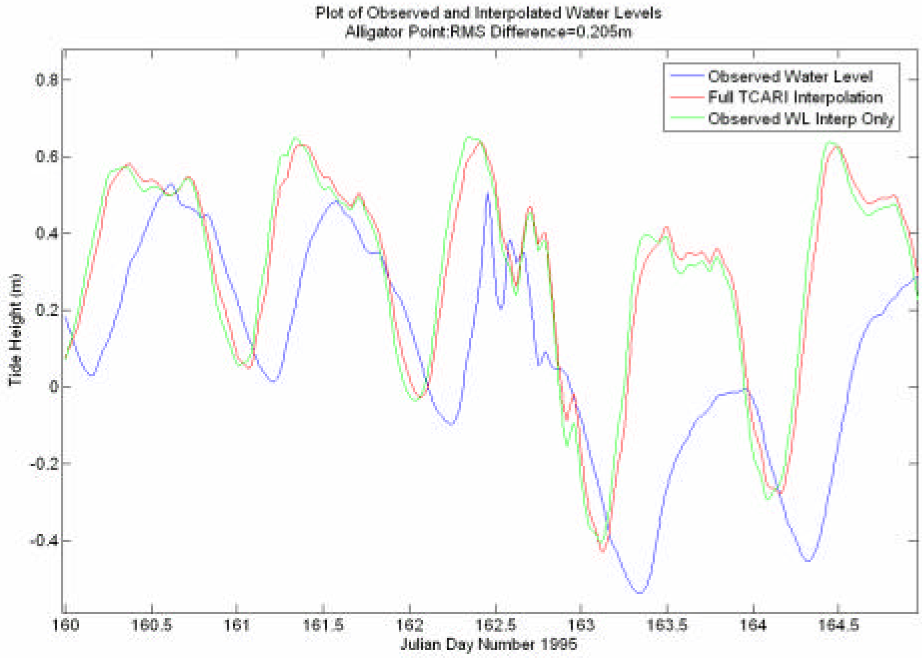
Observed Water Level Gauge	**RMS Difference Between Observed and TCARI interpolated water levels. (centimeters)**	**Total Standard Deviation in Tide (centimeters)**
Round Point (8770559)	4.2	n/a*
Morgans Point (8770613)	0.4	6.7
Smith Point (8770931)	0.7	n/a*
Eagle Point (8771013)	2.8	9.0
Trinity River Channel (8771021)	0.1	n/a*
Port Bolivar (8771328)	3.9	3.2
Pleasure Pier (8771510)	10.7	5.1
Alligator Point (8771801)	20.5	n/a*
*Note: Five years of observed water levels were not available to compute tidal constituent statistics for all stations in the Galveston Bay Kinematic GPS Project.		

CONCLUSION

While this research is ongoing, the ultimate goal is to be able to compute a total propagated error for each water level correction applied to a hydrographic survey. As these errors are time dependant, it is reasonable to imagine that they may someday be computed as time series data. In the near term, it is more realistic to compute a generalized form based on recently acquired water level data.

The preliminary research in this study has demonstrated a straight forward method for measuring the uncertainty in the tidal harmonic constituents. The results of these computations indicate that the combined standard deviations for all harmonic constants yield a standard deviation in the tide of 3 cm to 6 cm. The total uncertainty in the TCARI interpolated water levels (which includes the uncertainty in the harmonic constants) was found to range between 0.1 cm and 20.5 cm.

A secondary benefit of this analysis will come in the form of greater understanding of the requirements for gauge placement in water level acquisition. The strong spatial correlation between observed and TCARI interpolated water levels indicates that work which is currently underway will be able to determine the rate of growth in the interpolation uncertainty with respect to range from a given water level station. This information will in turn be able to guide the survey planners in the location, density, and geometry needed to achieve the desired error budget for water levels.



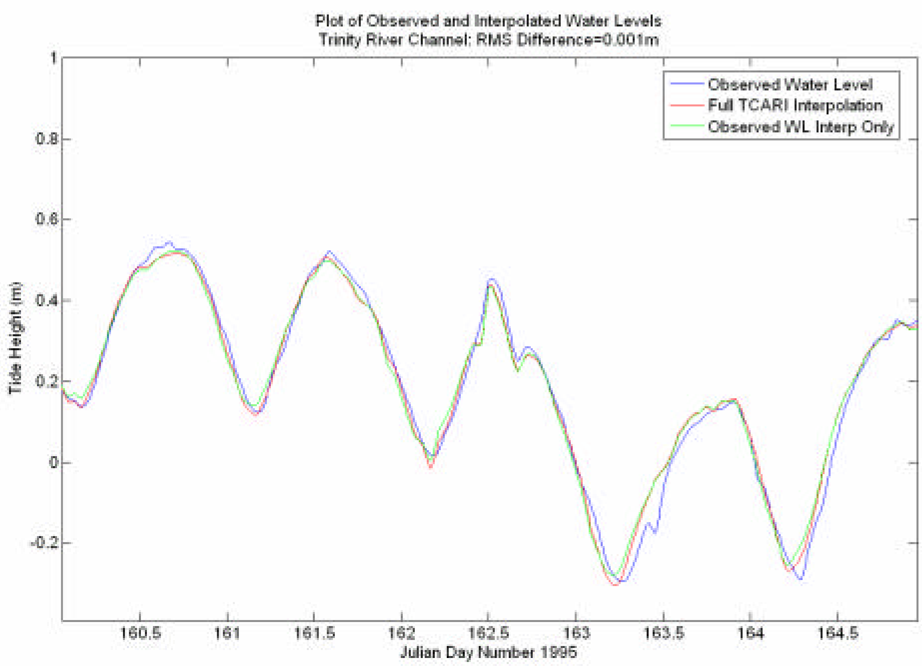


Figure 3: Plots of observed water levels and the corresponding interpolated water levels for Alligator Point (lowest agreement) and Trinity River Channel (highest agreement). Curves in red are TCARI interpolations using harmonic constants, and green are TCARI interpolations using only observed water levels.

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