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ESTIMATING ACCURACIES OF TIDAL DATUMS FROM SHORT TERM OBSERVATIONS

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Note: This report is the culmination of applied research in datum error estimation performed by former NOAA employee, A. Nicholas Bodnar in 1981. The methodology developed in this work for estimating errors has been operationally adopted to estimate individual tide station datum errors by NOAA/CO-OPS for several applications. It has been used in identifying gaps in the National Water Level Observation Network for estimating datum errors in the tidal models used in the NOAA VDatum tool and will be used to provide users information on datum uncertainty on the NOAA web site. We are publishing the final draft report in its original form provided by the author back in 1981.

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ESTIMATING ACCURACIES OF TIDAL DATUMS FROM SHORT TERM OBSERVATIONS

By
A. NICHOLAS BODNAR

BIOGRAPHICAL SKETCH

A. Nicholas Bodnar, Jr. is currently a commissioned officer in the National Oceanic and Atmospheric Administration (NOAA). Before joining NOAA he was a private engineer, contractor and surveyor. His 10 years with NOAA have been spent in geodesy, hydrography and oceanography. While working in oceanography LCDR Bodnar has held positions as Tidal Boundary Survey Coordinator, Principal Engineer for the Requirement Section and is presently Chief of the Tides and Water Levels Division of the National Ocean Survey. LCDR Bodnar is also a Profession Civil Engineer in California and Washington, and a member of the American Society of Civil Engineers and the American Congress on Surveying and Mapping.

ABSTRACT

This paper develops multiple curvilinear regression equations that estimate the accuracy of computed 19 year equivalent tidal datums at tide stations with one or more months of data. These regression equations are simple to use, quantitative, and consider individual station characteristics. The parameters affecting the accuracy of the computed tidal datums are discussed along with the relative accuracy of the standard method and the alternate method of simultaneous comparison.

BACKGROUND

Tidal datums are vertical datums derived from the rise and fall of the oceanic tide. Traditionally these datums were established as the reference surface for water depths on nautical charts and land elevations on maps. A relatively new use for tidal datums is the establishment of marine boundaries. The offshore oil and mineral industries have created the need for precisely defining the State-Federal boundary to determine governmental jurisdiction. The fisheries Conservation Management Act of 1976 extends the jurisdiction of the United States 200 nautical miles seaward creating a new international boundary. Finally, as society places increasing value on the coastal zone, wetlands in particular, Private-State marine boundaries are becoming even more critical.

These marine boundaries are defined by the intersection of a tidal datum with the land. In the case of offshore boundaries this intersection of water and land is the horizontal reference line from which the offshore boundaries are measured and is usually based on the mean lower low water line. The Private-State boundaries are usually defined directly by the mean high water line.

The accuracy of these horizontal marine boundaries is a function of the slope of the beach and the vertical error in determining the required tidal datum. Unfortunately, a small error in the vertical tidal datum results in a considerable error in the horizontal line on beaches with shallow slopes. For example, an error of 0.1 feet in the vertical datum results in a horizontal error of 10 feet on a beach with a one percent slope.

For technical and legal reasons, 19 years of tidal data are required for an accurate tidal datum at any given location. Technically, the forces affecting the tides are periodic. The longest period, considered for the computation of tidal datums, is the regression of the moons nodes which is 18.6 years. This period is rounded to 19 years to average the yearly weather cycle. Legally, the Supreme Court, in Borax Consolidated v. City of Los Angeles (296US1935) recognized these technical requirements when it ruled that "to ascertain the mean high tide line with requisite certainty in fixing the boundary of valuable tidelands …, an average of 18.6 years should be determined as near as possible." The Court went on to endorse the methods of tidal datum determination used by the National Ocean Survey.[1]

The National Ocean Survey (NOS) uses two methods of simultaneous comparison computations to estimate the 19-year tidal datums, "as near as possible" from shorter measurements. The "Standard Method" (sometimes called the range ratio method) assumes that: (1) The difference between the mean tide level over the period of observation and the actual 19-year mean tide level is the same at both the primary control and subordinate tide stations.[2] (2) The ratio of the observed ranges to the actual 19-year range is the same for both stations. Therefore, the mean high water (MHW) and mean low water (MLW) datums are computed by first determining the corrected mean tide level and then subtracting one-half the corrected mean range to get MLW. MHW is then determined by adding the corrected range to MLW.

The standard method is preferred by NOS. However, when the full range of tide can not be measure the "Alternate Method" (Sometimes called the height difference method) is used. This method computes each datum directly and only assumes that the difference between the desired datum over the period of observations and the actual 19 year value of that datum is the same at both control and subordinate stations (Marmer 1951). Of course, no simultaneous comparison method is perfect and the resulting computations have inaccuracies since the assumptions are not always valid.[3]

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[1] The National Ocean Survey (formerly the Coast and Geodetic Survey) is part of the National Oceanic and Atmospheric Administration (NOAA) which is in the U.S. Department of Commerce.
[2] A primary control station has at least 19 years of continuous observations. This data series is used to reduce a relatively short data series from subordinate tide stations.
[3] Appendix A list the equations used in the Simultaneous Comparison Computations.

PRESENT METHOD FOR ESTIMATING ACCURACY

Accuracy estimates for short term observations are presently based on an analysis by Swanson (1964). Swanson selected station pairs with 16 to 19 years of simultaneous data to determine the accuracy of the simultaneous method for computing 19-year means from a shorter series. In his analysis, one station was selected as a mock subordinate. Then 19-year equivalent datums were calculated using 1, 3, 6, and 12 month series of data. Since the true 19-year mean was known at the mock subordinate station, a set of residuals was generated by subtracting the value of the measured 19-year mean from each computed value. The mean and variance of each set of residuals were then computed for each datum for numerous stations pairing around the United States. The standard deviations for each station pair were pooled by region and have been the best estimate of accuracy for short term observations. The generalized one-sigma accuracy for tidal datums where determined from short series of tide record are shown in Table 1.

Table 1 Generalized Accuracy of Tidal Datums Based on One-Sigma (Swanson 1974:12)

Series Length (Months)	East Coast (ft.)	Gulf Coast (ft.)	West Coast (ft.)
1	0.13	0.18	0.13
3	0.10	0.15	0.11
6	0.07	0.12	0.08
12	0.05	0.09	0.06

However, as Swanson notes, “most secondary stations will be established no greater than half way between pairs used in the analysis. Thus the accuracies shown (above) can be thought of as a maximized mean accuracy for the tidal net.” (Swanson 1974:12)

Carrying this logic a step further, a minimum error would be expected when the control and subordinate stations were very close together. In fact, if the two stations were right next to each other, the error in predicting the 19-year equivalent mean values would only be measurement error since the assumptions used in the simultaneous method would be completely valid. Finally, it seems reasonable to assume that the error in computing tidal datums might increase proportionately with the difference in the tidal characteristics between the control and subordinate tide stations.

REGRESSION VARIABLES

Regression analysis was used to determine which independent variables might explain the variation in the standard deviations computed by Swanson (the dependent variables). The regression model is in the form:

$$Y = B_1X_1 + B_2X_2 + \ldots + B_iX_i + A$$

Where Y is the dependent variable; X_1, X_2 … X_i are the independent variables; B_1, B_2 … B_i are the slope coefficients for the respective independent variables, and A is a constant.

The independent variables (X_i) that proved to be highly significant are:

1. ADHWI – The absolute difference in high water intervals measured in hours. ADHWI is obtained by subtracting the high water interval (HWI) of the control station from the HWI of the subordinate tide station and using the absolute value. HWI is defined as the average interval for all phases of the moon between the moon's transit (upper or lower) over the local or Greenwich meridian and the following high water (Schureman 1975:9). ADHWI can be thought of as the average difference in time that the crest of the tidal waves passes the two tide stations. For example, if the Greenwich HWI for the control station is 6.21 hours and the Greenwich HWI for the subordinate station is estimated to be 7.5 hours then; ADHWI = |(7.5 – 6.21)| = 1.3 hours. Note that ADHWI is always positive. The HWI value for the control station will always be known and the HWI value for the subordinate station can be estimated to within ½ hour with a corresponding error in the prediction of the dependent variable of only 0.005 feet or less. This estimate of HWI can be obtained by interpolating HWI between historic tide stations or from cotidal charts. Once tidal data has been collected at the subordinate station the HWI can be computed to check the original estimate.

2. ADLWI – The absolute difference in low water intervals measures in hours. This is the low water equivalent to ADHWI. ADHWI and ADLWI are highly correlated and in most cases ADHWI can be used in the place of ADLWI.

3. SRGDIST – The square root of the geodetic distance between the control and subordinate tide stations measured in nautical miles. It can be scaled off a nautical chart or computed by using the geographic coordinates of the two tide stations. The geodetic distance can be within 15% of the actual distance without degrading the results.

4. MNR- The mean range ratio is the absolute value of the difference in mean range of tide between the control and subordinate tide station divided by the mean range at the control station. For example, if the mean range of tide at the control station is 10.2 feet and the mean range at the subordinate station is estimated to be 12.1 feet then:

   $$MNR = |(12.1 - 10.2)| / 10.2 = 0.19$$

   Note that MNR is always positive. The mean range of the subordinate station can be estimated to within 20% of the true range without noticeably degrading the final results. Once tidal data has been collected at the subordinate station the estimate can be verified.

5. SRSMN – The square root of the sum of the mean ranges is computed by adding the mean ranges of the control and subordinate stations and then taking the square root of this sum. For example, if the mean range at the control station is 5.5 feet and the mean range of the subordinate station is estimated to be 6.0 feet then:

$$\text{SRSMN} = (5.5 + 6.0)^{1/2} = 3.4 \text{ feet}$$

   The mean range of the subordinate station can be estimated to within 50% of the true range without noticeably affecting the results.

6. ADMN – The absolute value of the difference in mean range of tide between the control and subordinate tide station measured in feet. It is significant only when using the Alternate Method of Simultaneous Comparison.

The dependent variables (Y) that were used in this investigation are the standard deviations (in feet) of the mean differences between computed and accepted values of MHW and MLW for station pairings along the east coast of the United States. These values were taken from Swanson's report (Swanson 1974: 22 - 28). A separate regression analysis was done for each table where Swanson used monthly mean values and running means of monthly values over 3, 6, and 12 months. The corresponding dependent variables (Y) are labeled S1M, S3M, S6M, and S12M respectively. When referring to these dependent variables in general, the symbol SiM is used.

DATA DEFICIENCIES AND REJECTIONS

The regression analysis is highly significant. However, validity of the results is also dependent on the validity of the data. The data used for the independent variables are reliable and accurate. Unfortunately, the data used for the dependent variable (SiM) have deficiencies in: (1) sample size, (2) interdependence of station pairs, and (3) representation of the population of interest.

1. Due to lack of control stations with sufficient simultaneous data, Swanson was only able to use 7 station pairs on the Gulf Coast, 11 stations pairs on the West Coast, and 30 station pairs on the East Coast.[4] The data from the West Coast and Gulf Coast were not used to develop the regression equations because of the small sample sizes and due to the fact that the distance between station pairs were so much greater than the population of interest. The average distance between station pairs on the West, Gulf, and East Coast are 166, 220, and 96 nautical miles respectively. Another reason for only using East Coast data is the fact that the tide along the entire East Coast is produced by the same Oceanic Oscillating System for the Semidaily Tide-Producing Forces. On the West coast, the relative sea level is changing at dramatically different rates between some station pairs, and on the Gulf Coast, the tide is mixed at some stations and diurnal at others. Therefore, the station pairs along the East Coast are more representative of typical control-

[4] Appendix B is a histogram for S1M and S12M (MHW).

subordinate station pairing that are relatively close together, generated by the same oceanic system, experience similar long term changes in sea level and are of the same type of tide. However, the results of this study can still be used for accuracy estimations on the West and Gulf coasts as will be shown later.

2. To test extreme conditions, Swanson used the same control station in more than one station pairing. For example, Baltimore, MD., the Battery, N.Y., and Mayport, Fla. are used four times each, and Washington D.C. is used three times. This raises questions about the interdependence and the randomness of the sample. To check the effect of using the same control station many times, an Oneway Analysis of Variance was used to test the hypothesis that the means of SiM for each group of stations having a common control station and all other station pairs on the East Coast are equal. This hypothesis was tested for MHW and MLW values separately. The hypothesis could not be rejected, even at the 0.8 level of significance, for MHW values.[5] However, the hypothesis was rejected at the 0.04 level of the significance for MLW values. A contrast t-test showed that this rejection was caused by the station Mayport, Fla. It is interesting to note that MHW values at Mayport are not noticeably affected by these problems in the low water datum.

   Although Swanson's analysis shows the computed MLW datum to be slightly less accurate than the MHW datums this difference is not statistically significant. Using a correlated t-test on the SiM values computed by the standard method the hypothesis that difference between the accuracy for MLW and MHW datums for each station pairing is zero could not be rejected at the 0.1 level of significance. This was true with or without the station pairs containing Mayport. This conclusion is verified by a nonparametric sing test. However, if the same correlated t-test is applied to the MLW and MHW datums computed by the alternate method the hypothesis is rejected at the 0.02 level of significance. When using the alternate method the computed MLW and MHW datums are completely independent of each other. In contrast, when using the standard method of simultaneous comparison the computed MLW and MHW datums are not completely independent.

   With the standard method both the corrected mean tide level and the range ratio are used to compute MLW and MHW, but they are dependent upon the observed MLW and MHW values. Fortunately, this interdependence is small. A positive error, for instance, in the corrected mean tide level is offset by a negative error in the range ratio calculation. The actual sign and magnitude depends on the ratio of the range of tide at the control station for the comparison period divided by the 19-year mean at the control station. For example, a measurement error that causes MLW to record 0.1 foot to low will only affect MHW by about 0.005 feet if the mean range of tide at the control station for the comparison period is 10% of the 19-year mean. If the mean range for the comparison period equals the 19-year mean, then the error in mean high water is zero.

[5] Appendix C summarizes the oneway analysis of variance results.

Separate regression equations were developed for MLW and MHW datums. The accuracy of these two datums is believed to be different because of the errors observed only in the low waters at Mayport. A twoway analysis of variance test, controlling for the covariates used in the regression equation, showed that the error in MLW at Mayport was 0.05 feet greater than would have been expected. Therefore, the four station pairs using Mayport were rejected for the MLW regression analysis. But all the data was used for the MHW analysis.

A second test for interdependence was to run the regression analysis without the other station pairs that might be interdependent. The results were basically the same, the small differences are assumed to be attributed to the smaller sample size. Therefore, with the exception of MLW values using Mayport, it is conclude that the interdependence of the dependent variables (SiM) is not great enough to significantly degrade the results of this analysis.

3. The final and most serious deficiency in the data is the representativeness of the sample to the population of interest. All of the station pairs used by Swanson were between control stations that are usually located far apart in harbors and adjacent to deep water channels. But most subordinates are relatively close to control stations and are located in shallow estuaries. However, at this time, the data from Swanson's report is the best data available.

The criteria used to select the recommended independent variables over other viable options are listed in order of importance.

1) The standard deviation of the dependent variable about the regression line ($S_{x.y}$).
2) The total percent of the variation explained by the regression equation (R^2).
3) The overall significance level of the regression equation.
4) The number and complexity of the variables.
5) The significance to enter a new variable.

STANDARD METHOD OF SIMULTANEOUS COMPARISION

The equations are in the form.

$$\underset{\text{(Ft.)}}{\text{S1M}} = 0.0112\ \underset{\text{(Hrs.)}}{\text{ADHWI}} + 0.0074\ \underset{(\text{N.M.}^{1/2})}{\text{SRGDIST}} + 0.017.$$

However, they are presented in Tables 2 and 3 in tabular form to facilitate the showing of the criteria parameters. Appendix D shows the Person coefficient of linear correlation (R) for all variables while Appendix E and F list all the data used to determine the regression coefficients.[6]

[6] The computations were done at the University of Washington Computer Center using the Statistical Package for the Social Sciences, version 7.0 dated June 27, 1977.

To demonstrate the value of these regression equations, let us look at examples using stations pairs from Swanson's report based on MHW monthly mean values. First, let us take the station pair Hampton Roads, Va. to Washington D.C., where the stations are far apart (120.1 n.m.).

S1M = 0.0112 ADHWI + 0.0074 SRGDIST + 0.017 (From Table 2)
= 0.0112 (12.05 Hrs.) + 0.0074 (120.1 N.M.$^{1/2}$) + 0.017 (From Appendix E)
S1M = 0.223 ft.

This is only 0.008 feet less than the 0.231 feet obtained from Swanson's report. But, the generalized accuracy statement is 0.13 feet or 0.131 feet in error. Obviously, the regression equation is much closer to the actual value in this case.

Table 2 Regression Equations and Parameters Standard Method of Simultaneous Comparison

Mean High Water

Independent Variables	B	STD Error of B	Sign to Enter	Sign. Overall	Sx.y (ft.)	R^2
S1M (Dependent Variable)						
ADHWI	0.0112	± 0.0014	< 0.0005			
SRGDIST	0.0074	± 0.0011	< 0.0005			
(Constant)	0.017	± 0.0110	0.135	< 0.0005	0.021	*0.79*
S3M (Dependent Variable)						
ADHWI	0.0085	± 0.0014	< 0.0005			
SRGDIST	0.0054	± 0.0011	< 0.0005			
(Constant)	0.018	± 0.0108	0.100	< 0.0005	0.021	*0.70*
S6M (Dependent Variable)						
ADHWI	0.0047	± 0.0012	0.001			
SRGDIST	0.0039	± 0.0009	0.000			
(Constant)	0.022	± 0.0091	0.023	< 0.0005	0.018	*0.54*
S12M (Dependent Variable)						
SRGDIST	0.0017	± 0.0007	0.019			
SRSMN	0.0068	± 0.0027	0.019			
(Constant)	*0.012*	*± 0.0099*	*0.238*	*0.004*	*0.015*	*0.28*

<= less than

Equation Form:

S1M = 0.0112 ADHWI + 0.0074 SRGDIST + 0.017
S3M = 0.0085 ADHWI + 0.0054 SRGDIST + 0.018
S6M = 0.0047 ADHWI + 0.0039 SRGDIST + 0.022
S12M = 0.0068 SRSMN + 0.0017 SRGDIST + 0.012

Table 3 Regression Equations and Parameters Standard Method of Simultaneous Comparison

Mean Low Water

Independent Variables	B	STD Error of B	Sign to Enter	Sign. Overall	Sx.y (ft.)	R^2
S1M (Dependent Variable)						
ADHWI	0.0068	± 0.0013	< 0.0005			
SRGDIST	0.0053	± 0.0014	0.001			
MNR	0.0302	± 0.0080	0.001			
(Constant)	0.029	± 0.0127	0.033	< 0.0005	0.019	*0.76*
S3M (Dependent Variable)						
ADHWI	0.0043	± 0.0011	0.001			
SRGDIST	0.0036	± 0.0013	0.010			
MNR	0.0255	± 0.0070	0.001			
(Constant)	0.029	± 0.0111	0.017	< 0.0005	0.017	*0.68*
S6M (Dependent Variable)						
ADHWI	0.0019	± 0.0010	0.084			
SRGDIST	0.0023	± 0.0011	0.062			
MNR	0.0207	± 0.0064	0.004			
(Constant)	0.030	± 0.0101	0.008	< 0.0005	0.015	*0.49*
S12M (Dependent Variable)						
MNR	0.0128	± 0.0057	0.034			
SRSMN	0.0045	± 0.0027	0.110			
(Constant)	*0.025*	*± 0.0088*	*0.010*	*0.038*	*0.014*	*0.18*

<= less than

Equation Form:

S1M = 0.0068 ADHWI + 0.0053 SRGDIST + 0.0302 MNR + 0.029
S3M = 0.0043 ADHWI + 0.0036 SRGDIST + 0.0255 MNR + 0.029
S6M = 0.0019 ADHWI + 0.0023 SRGDIST + 0.0207 MNR + 0.030
S12M = 0.0045 SRSMN + 0.0128 MNR + 0.025

Next let us look at the station pair Fernandina, Fla. to Mayport, Fla. where the stations are close to each other (16.6 n.m.)

$$
\begin{aligned}
S1M &= 0.0112\ ADHWI + 0.0074\ SRGDIST + 0.017 \\
&= 0.0112\ (40\ Hrs.) + 0.0074\ (16.6\ N.M.^{1/2}) + 0.017 \\
S1M &= 0.052\ ft.
\end{aligned}
$$

This is only 0.001 feet less than the 0.053 feet obtained from the Swanson analysis. But the generalized accuracy is still 0.13 feet or 0.08 feet in error. Again the regression equation is much closer to the correct value. Recall that Mayport had errors in the low water datums of about 0.05 feet greater than would have been computed by the regression equation.

Of course, not all station pairs will be as close to the actual value as shown in these examples. Table 4 compares the results of predicting S1M at MHW for all station pairs used in Swanson's report using the regression equations and the generalized accuracy statements. The standard deviation ($S_{x.y}$) of S1M about the regression line is 0.021 feet (from Table 2). A set of residuals was generated by subtracting the generalized accuracy (0.13 feet) from S1M determined by Swanson for each station pair. The standard deviation of these residuals is 0.047 feet. This is twice as large as the standard error about the regression line. The error in using the generalized accuracy would be even greater for typical subordinate stations that are closer together than the primary control stations used in Swanson's analysis.

At the 95% confidence level the actual value of the predicted S1M should be within ± 2 ($S_{x.y}$) or 2 (0.021) = $\pm$ 0.042 feet of the computed value. Finally, at the 99.7% confidence level the actual value should be within $\pm$ 3 ($S_{x.y}$) or 3 x (0.021) = $\pm$ 0.063 feet of the computed value.

TABLE 4 – COMPARISON OF REGRESSION EQUATION AND GENERALIZED ACCURACY STATEMENT

USING MONTHLY MEAN VALUES FOR MHW – EAST COAST

	CONTROL STATION	SUBORDINATE STATION	S1M(1) (Ft.°)	S1M(2) (Ft.r)	$S1M_o - S1M_r$ (Ft.)	$S1M_o$ – 0.13(3) (Ft.)
1.	Miami, FL	Mayport, FL	0.131	0.145	–0.014	+0.001
2.	Atlantic City, NJ	Sandy Hook, NJ	.131	.084	+ .047	+ .001
3.	Battery, NY	Atlantic City, NJ	.099	.096	+ .003	– .031
4.	Baltimore, MD	Solomons, MD	.085	.127	– .042	– .045
5.	Miami, FL	Key West, FL	.112	.121	– .009	– .018
6.	Baltimore, MD	Portsmouth, VA	.252	.218	+ .034	+ .122
7.	Baltimore, MD	Annapolis, MD	.050	.066	– .016	– .080
8.	Solomons, MD	Washington, D.C.	.102	.132	– .030	– .028
9.	Mayport, FL	Key West, FL	.182	.176	+ .006	+ .052
10.	Hampton Rds, VA	Solomons, MD	.156	.143	– .013	+ .026
11.	Battery, NY	Sandy Hook, NJ	.069	.052	+ .017	– .061
12.	Baltimore, MD	Washington, D. C.	.097	.071	+ .026	– .033
13.	Solomons, MD	Annapolis, MD	.056	.100	– .044	– .074
14.	Sandy Hook, NJ	Montauk, NY	.117	.104	+ .013	– .013
15.	Eastport, ME	Portsmouth, NH	.111	.128	– .017	– .019
16.	Battery, NY	New London, CT	.100	.103	– .003	– .030
17.	Charleston, SC	Fort Pulaski, GA	.090	.078	+ .021	– .040
18.	Charleston, kSC	Mayport, FL	.115	.118	– .003	– .015
19.	Woods Hole, MA	Montauk, NY	.079	.087	– .008	– .051
20.	Hampton Rds, VA	Washington, D.C.	.231	.223	+ .008	+ .101
21.	Fernandina, FL	Mayport, FL	.053	.052	+ .001	– .077
22.	Portland, ME	Eastport, ME	.116	.110	+ .006	– .014
23	Boston, MA	Portsmouth, NH	.064	.069	– .005	– .066
24.	New London, CT	Willets Point, NY	.140	.108	+ .032	+ .010
25.	New London, CT	Woods Hole, MA	.072	.092	– .020	– .058
26.	Hampton Rds, VA	Atlantic, NJ	.121	.134	– .013	– .009
27.	Portland, ME	Portsmouth, NJ	.079	.068	+ .011	– .051
28.	Boston, MA	Woods Hole, MA	.106	.105	+ .001	– .024
29.	Battery, NY	Willets Point, NY	.088	.082	+ .006	– .042
30.	Portland, ME	Boston, MA	.087	.088	– .001	– .043
Mean					.000	+ .020
Standard Deviation					.021	.047
Greatest Deviation					.047	.121

1. Observed value (Swanson 1974:22)
2. Predicted value: S1M = .0112 ADHWI + .0074 SRGDIST + .017 (See Appendix E for ADHW and SRGDIST values)

3. Generalized accuracy fdrom Table 1.

TABLE 5 - COMPARISON OF REGRESSION EQUATION AND GENERALIZED ACCURACY STATEMENT

USING MONTHLY MEAN VALUES FOR MHW - WEST AND GULF COASTS

	CONTROL STATION	SUBORDINATE STATION		ADHWI (Hrs.)	GDIST (N.M.)	S1M(1) (Ft.)	S1M(2) (Ft.)	$S1M_O-S1M_T$ (Ft.)
WEST COAST								
1.	Los Angeles, CA	San Diego, CA	(3)	.08	81.7	.065	.085	- .020
2,	San Diego, CA	La Jolla, CA		.05	11.0	.068	.042	+ .026
3.	Los Angeles, CA	Santa Monica, CA		.02	20.6	.076	.051	+ .025
4.	San Francisco, CA	Alameda, CA		.56	8.2	.083	.044	+ .039
5.	San Francisco, CA	Los Angeles, CA		2.45	319.1	.151	.177	- .026
6.	Seattle, WA	Friday Harbor, WA	(5)	.01	62.7	.139	.076	+ .063
7.	Santa Monica, CA	La Jolla, CA		.15	92.5	.082	.090	- .008
8.	Los Angeles, CA	La Jolla, CA		.13	72.2	.088	.081	+ .007
9.	Crescent City, CA	San Francisco, CA	(4)	.19	249.1	.213	.136	(+ .077)
10.	Neah Bay, WA	Crescent City, CA		1.10	390.9	.234	.176	+ .058
GULF COAST								
1.	Cedar Key, FL	Key West, FL		3.79	281.8	0.244	0.184	+0.060
2.	Galveston, TX	Eugene Island, LA		1.13	178.5	.183	.129	+ .054
3.	Pensacola, FL	St. Petersburg, FL	(5) (6)	0.5	288.1	.143	.148	- .005
4.	St. Petersburg,FL	Cedar Key, FL		0.69	84.3	.141	.093	+ .048
5.	Pensacola, FL	Key West, FL	(5) (6)	3.5	453.0	.194	.214	- .020
6.	Port Isabel, TX	Galveston, TX	(5) (6)	1.0	233.9	.144	.141	+ .003
7.	Bayou Rigaud, LA	Galveston, TX	(5) (6)	5.0	252.8	.195	.191	+ .004

1. Observed Value (Swanson 1974:22)
2. Predicted value: S1M = .0112 ADHWI + .0074 SRGDIST + .017
3. The station pair Santa Monica to Alameda (pair No. 1) was not used because this data appears to be misprinted in NOS 64.
4. The relative change in sea level between Crescent City and San Francisco is unusually large. San Francisco is subsiding 2.0mm/yr while Crescent City is emerging 0.5mm/yr (Hicks:1973)
5. One of the stations has a mixed tide and the other has a diurnal tide for at least part of the month.
6. ADHWI was estimated from cotidal charts. (Harris:1904)

PREDICTING ACCURACIES FOR WEST AND GULF COAST STATIONS

When S1M is predicted for each of the 17 station pairs analyzed by Swanson on the West and Gulf coasts (See Table 4) only one station pair does not fall with ± 3 ($S_{x.y}$) (Crescent City, CA to San Francisco, CA). In this case the distance (250 n.m.) between station pairs is excessive. These equations, like all regression equations, are the most accurate at average parameter values and deteriorate as these values diverge from the mean values used to calculate the regression equation. Also, Crescent City and San Francisco experience drastically different meteorological conditions. Furthermore, relative sea level is rising at San Francisco but dropping at Crescent City. (Hicks 1973:10 - 11). Finally, there is a seiche at Crescent City that may affect the datum accuracy.

Only four station pairs do not fall within ±2 ($S_{x.y}$):

- Seattle, WA to Friday Harbor, WA
- Neah Bay, WA to Crescent City, CA
- Galveston, TX to Eugene Island, LA
- St. Petersburg, FL to Ceder Key, FL

In three of these cases the type of tide is different at the two tide stations for at least part of the month. In the one remaining case (Neah Bay to Crescent City) the distance (390 n.m.) is excessive and Crescent City may be adversely affected by the seiche.

The S12M (yearly means) for San Francisco to Crescent City and Neah Bay to Crescent City are much closer to their actual values than S1M. The difference between S12M and the observed value is only 0.007 feet with Neah Bay and 0.025 feet with San Francisco. Neah Bay is improved because the excessive effects o weather and distance have been averaged. The San Francisco pair is improved less than the Neah Bay pair because the effects of sea level change are not averaged with a year of data.

There is insufficient data to develop separate regression equations for the west and gulf coast. However, there is also insufficient information to reject the hypothesis that the east coast regression equations are also valid for west gulf coast stations. In fact, the limited data indicates that the regression equations are valid; especially when the weather changes between stations are modest, the sea level changes are approximately equal and the type of tide is the same at both stations.

ALTERNATE METHOD OF SIMULTANEOUS COMPARISON

When the full range of tide can not be measured at a subordinate station, the alternate method of simultaneous comparison is used for MHW determination. This method appears to be slightly more accurate than the standard method when the range of tide is about the same at both tide station. However, as the difference in the range of tide between the two stations increases, the accuracy of the alternate method deteriorates.

Table 6 shows the regression equations and parameters for the alternate method and Appendix G shows the regression data. ADMN is the absolute difference in mean range, measured in feet, between the control and subordinate tide station. If Table 6 is compared with Table 2, it will be seen that the slope coefficients (B) are slightly lower for ADHWI and SRGDIST. Therefore, when ADMN is zero S1M, S3M, and S6M will be slightly smaller using the alternate method. But, this difference is not statistically significant. However, the opposite affect of ADMN can be significant.

Table 6 Regression Equations and Parameters Alternate Method of Simultaneous Comparison

Mean High Water

Independent Variables	B	STD Error of B	Sign to Enter	Sign. Overall	Sx.y (ft.)	R^2
S1M (Dependent Variable)						
ADHWI	0.0108	± 0.0013	< 0.0005			
SRGDIST	0.0063	± 0.0010	< 0.0005			
ADMN	0.0020	± 0.0014	0.174			
(Constant)	0.019	± 0.0195	0.051	< 0.0005	0.019	*0.82*

<u>S3M (Dependent Variable)</u>						
ADHWI	0.0082	± 0.0013	0.0005			
SRGDIST	0.0046	± 0.0010	0.0005			
ADMN	0.0026	± 0.0014	0.084			
(Constant)	0.022	± 0.0096	0.034	< 0.0005	0.019	*0.71*
<u>S6M (Dependent Variable)</u>						
ADHWI	0.0044	± 0.0011	0.001			
SRGDIST	0.0031	± 0.0009	0.002			
ADMN	0.0026	± 0.0014	0.084			
(Constant)	0.024	± 0.0085	0.009	< 0.0005	0.017	*0.55*
<u>S12M (Dependent Variable)</u>						
SRGDIST	0.0017	± 0.0008	0.037			
SRSMN	0.0085	± 0.0035	0.023			
ADMN	0.0003	± 0.0014	0.856			
(Constant)	*0.006*	*± 0.0113*	*0.575*	*0.002*	*0.015*	*0.35*

< = less than

<u>Equation Form:</u>

S1M = 0.0108 ADHWI + 0.0069 SRGDIST + 0.0020 ADMN + 0.019
S3M = 0.0082 ADHWI + 0.0046 SRGDIST + 0.0026 ADMN + 0.022
S6M = 0.0044 ADHWI + 0.0031 SRGDIST + 0.0026 ADMN + 0.024
S12M = 0.0017 SRGDIST + 0.0085 SRSMN + 0.0003 ADMN + 0.006

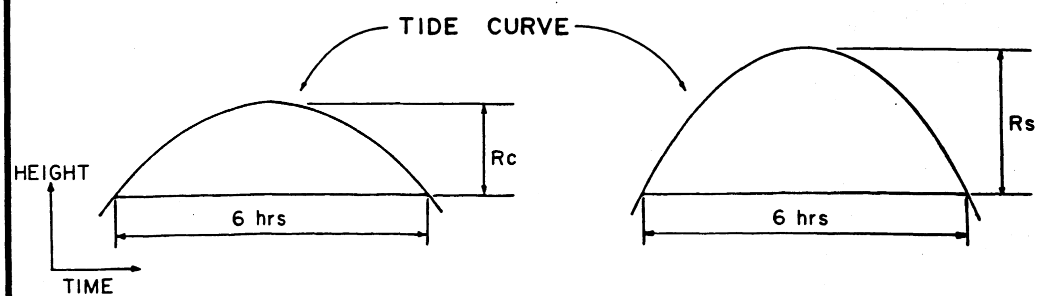
It is interesting to note that for yearly means (S12M) the independent variable ADMN is not significant. This implies that for the range of cases analyzed the difference in accuracy between the standard and alternate method is not significant for yearly means. The largest ADMN used to develop the regression was 10.4 feet.

To use these regression equations the mean range of tide at the subordinate station must be estimated since the full range is not measured. It should be estimated to within 2 feet. Fortunately, a method for approximating this mean range has been developed by Bernard Zetler (Zetler 1981). An arbitrary time scale between three and six hours is chosen for plotting the high water curve at both the subordinate and control station. Then the elevation on each plot is found where the tide is above this elevation for preferably six hours (See Figure 1.). The height from this elevation to high water is called Rc at the control station and Rs at the subordinate station. Then the mean range at the subordinate station is computed by:

MNs = Rs/Rc x MNc;

where MNc is the 19-year mean range at the control station.

FIGURE I. AMPLITUDE – RATIO METHOD



ACCURACY OF MEAN LOWER LOW WATER (MLLW), MEAN HIGHER HIGH WATER (MHHW), AND MEAN TIDE LEVEL (MTL)

Although insufficient data was available to test the accuracy of MLLW and MHHW datums, there is no reason to believe that they are not as accurate and MHW and MLW datums. Using the 11 west stations, where MLLW and MHHW were computed, the correlation (R) between MHW and MHHW is 0.998 and the correlation between MLW and MLLW is 0.996. Using a correlated t-test the hypothesis that the difference between the accuracy of the MHW and MHHW datums is zero can not be rejected at the 0.1 level of significance. The same conclusion is also valid for MLW and MLLW. Therefore, it is assumed that the accuracy of the MLLW and MHHW datums are the same as the MLW and MHW datums respectfully.

Separate regression equations were not developed for MTL. However, the correlation (R) between MHW and MTL is 0.919. Also, using a correlated t-test for all the station pairs in Swanson's report the hypothesis that the difference between the accuracy of MHW and MTL datums is zero can not be rejected at the 0.1 level of significance. Therefore, it is assumed that the accuracy of MTL datums is approximately the same as MHW datums.

ACCURACY USING SECONDARY CONTROL STATIONS

A common practice is to compute the 19-year equivalent tidal datums for a secondary control tide station (i.e., a tide station with 12 or more months of data) compared with a primary control. Then the tidal datums for nearby tertiary tide stations (i.e. a station with less than 12 months of data) are computed by comparing them with the secondary control station. If the simultaneous comparison between the primary and secondary is independent of the comparison between the secondary and tertiary then the accuracy of the tertiary tide station (SiM_t) would be:

$$SiM_t = \sqrt{SiM_{P\text{-}S}^2 + SiM_{S\text{-}T}^2}$$

Where $SiM_{P\text{-}S}$ and SiMS-T are the computed accuracies using the equations in table 2 and 3 for the secondary to primary pairing and the tertiary to secondary pairing respectfully. To demonstrate this technique assumes the following:

Station	HWI (Hrs.)	GDIST (n.m.)	MN (ft.)	Series
Primary	10.0		4.0	19 yr.
		50		
Secondary	8.0		3.0	12 mo.
		8		
Tertiary	8.1		3.0	1 mo.

Then:

$$\begin{aligned} S12M_{S\text{-}P} &= 0.0017\ SRGDIST + 0.0068\ SRSMN + 0.012 \\ &= 0.0017\ (50)^{1/2} + 0.0068\ (4.0 + 3.0)^{1/2} + 0.012 \\ &= 0.042 \text{ feet} \end{aligned}$$

$$\begin{aligned} S1M_{T\text{-}S} &= 0.0112\ ADHWI + 0.0074\ SRGDIST + 0.017 \\ &= 0.0112\ (8.1 - 8.0) + 0.0074\ (8)^{1/2} + 0.017 \\ &= 0.039 \text{ feet} \end{aligned}$$

$$\begin{aligned} S1M_t &= \sqrt{0.042^2 + 0.039^2} \\ &= 0.056\text{; say } 0.06 \text{ feet.} \end{aligned}$$

If the tertiary station was compared directly to the primary station the accuracy would be:

$$\begin{aligned} S1M &= 0.0112\ (1.9) + 0.0074\ (58)^{1/2} + 0.017 \\ &= 0.095 \text{ feet; say } 0.10 \text{ feet} \end{aligned}$$

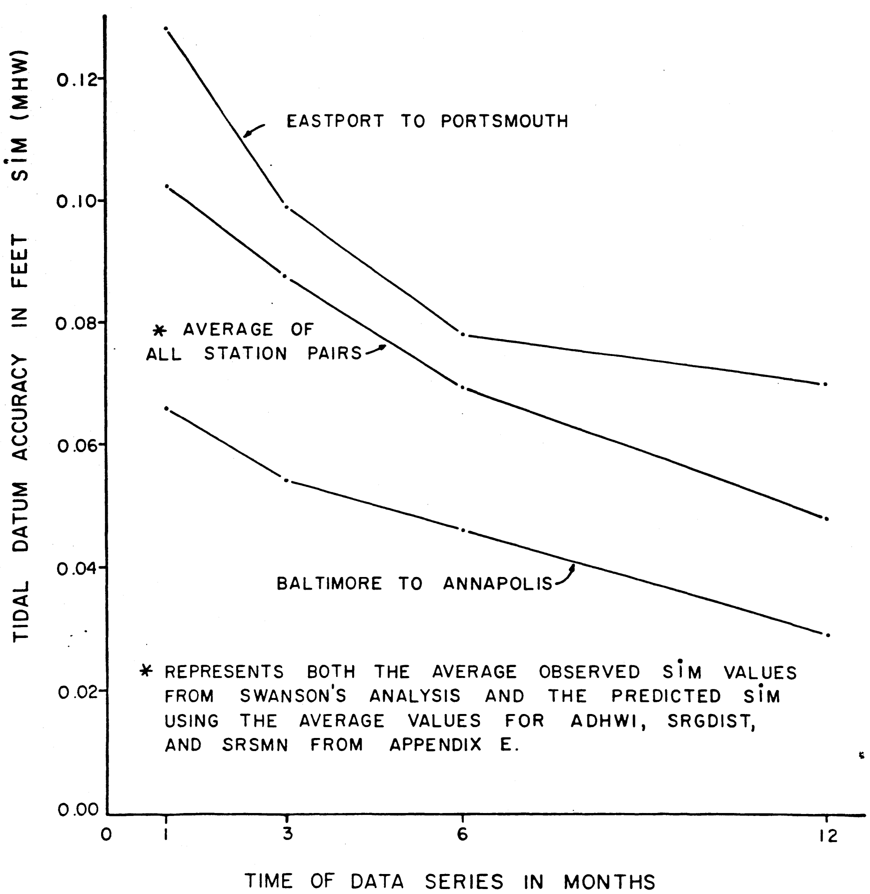
Note that the accuracy is improved 30%, in this case, by going through the secondary tide station.

INTERPOLATING AND EXTRAPOLATION OF THE DEPENDENT VARIABLE

Although the regression equations in table 2 and 3 are only for 1, 3, 6, and 12 months of data they can be used to estimate the accuracies of any other data series equal to or greater than one month. For periods less than one month an extrapolation could be dangerous since the astronomical cycles caused by the moons monthly orbit, declination, and interaction with the sun are not averaged as they are with the monthly data used in the regression analysis. These effects on the accuracy of a tidal series less than one month are not well documented.[7]

[7] Bernard Zetler discusses using short series of tidal data to compute tidal datums (Zetler 1981).

FIGURE 2 – COMPUTED TIDAL DATUM ACCURACY Vs. TIME IN MONTHS



For periods between one and 12 months the accuracy of tidal datums can be safely interpolated. Figure 2 shows a plot for the computed accuracy for 1, 3, 6, and 12 months at 2 diverse station pairs along with an average station pair. Note that the curves are smooth and can be conservatively approximated by straight line interpolation.

To compute the accuracy of a tidal datum based on 9 months of data, for example, first compute the accuracy for 6 and 12 months using the regression equations in table 2 or 3. Then use straight line interpolation to determine the 9 months value. In this case, the value would be half way between the 6 month and 12 month value.

An interpolation between one year of data and 19 years is risky; but, possible for practical purposes. At 19 years the theoretical error should be zero. Of course systematic measurement errors would still be present. But if the data is carefully collected these errors will be small. Also, Swanson (Swanson 1974:10) showed that the systematic error due to simultaneous comparisons is less than 0.005 feet in general over a 19 year period. Figure 3 shows a typical plot of accuracy versus the length of data series. Note that a smooth curve fit of the data points would produce a line that was below the straight lines shown. Therefore, accuracy statements based on the straight line interpolation should be conservative. The change in slope of the line after one year is reasonable. After one year of data all the major astronomical and meteorological cycles have been measured.

As an example, if S12M equals 0.06 feet then the accuracy for a 5 year data series (S60M) at the same subordinate station, compared with the same control station, would be:

$$\mathrm{S60M} = 0.06\,\frac{18\ \mathrm{yr.} - 5\ \mathrm{yr.}}{18\ \mathrm{yr.}} = 0.04\mathrm{feet}$$

These accuracy statements for data series greater than one year are the best estimate, however, they should not be considered as reliable as the $S_{x.y}$ values shown in tables 2 and 3.

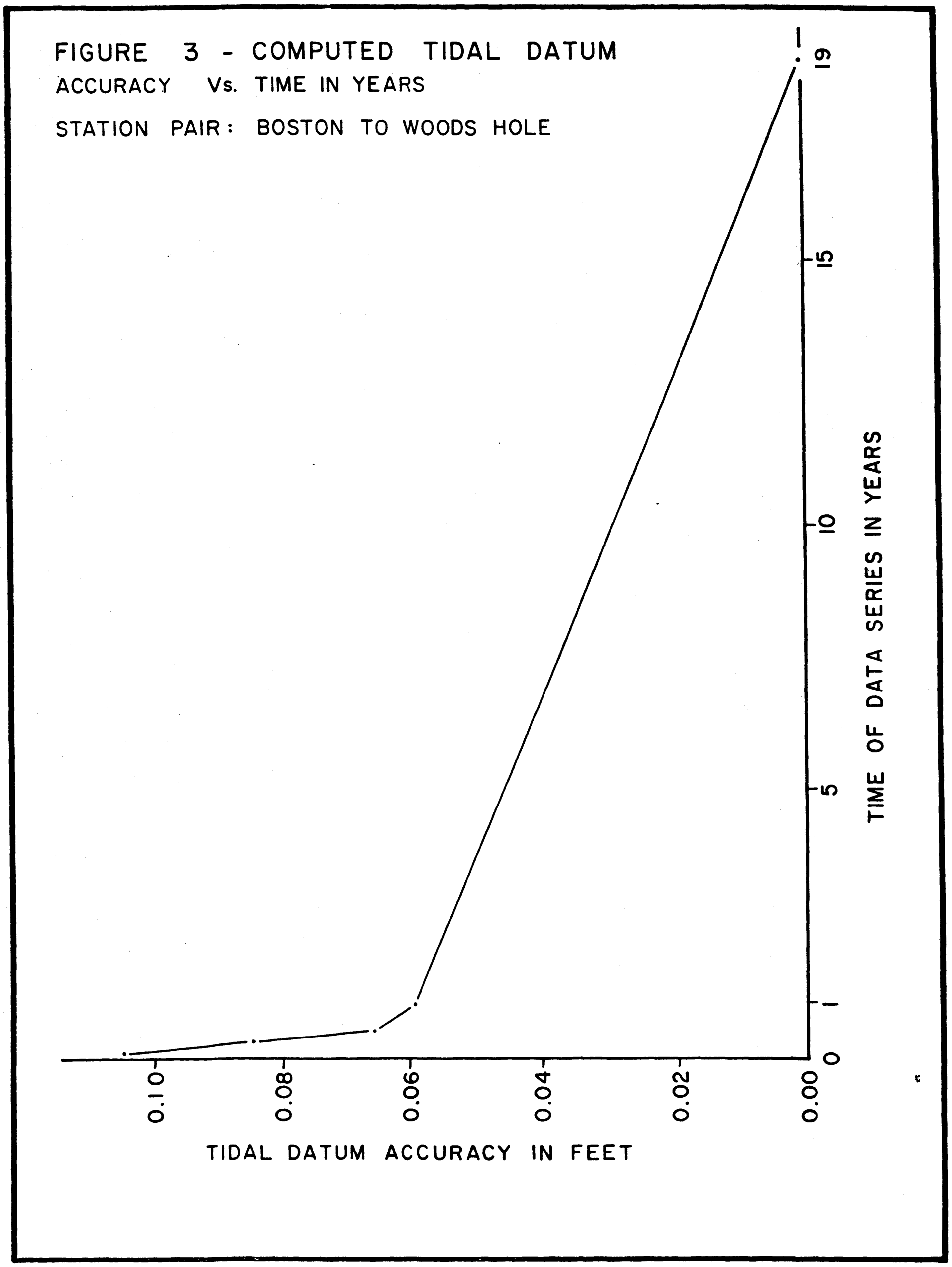


FIGURE 3 - COMPUTED TIDAL DATUM ACCURACY Vs. TIME IN YEARS

STATION PAIR: BOSTON TO WOODS HOLE

FINAL ACCURACY STATEMENT

The SiM values are standard deviations that have a standard deviation of $S_{x.y}$ about the regression line. Therefore, assuming that $S_{x.y}$ and SiM are independent, the final accuracy statement for a given station pair should be:

$$SiM_F = \sqrt{SiM^2 + S_{x.y}^2}$$

For example, if S1M = 0.080 for the MHW datum, then $S_{x.y}$ = 0.021 from Table 2 and:

$$SiM_F = \sqrt{0.080^2 + 0.021^2} = 0.083\,\text{feet}$$

Fortunately, this refinement is small compared to SiM and therefore can be ignored for practical purpose, except when the predicted error is smaller than 0.04 feet.

DISCUSSION OF INDEPENDENT VARIABLES

All regression equations are most accurate at the average values for the independent variables. Extrapolation beyond the range of independent variables can be risky. The average values for the independent variables are shown in Appendix E and F. The maximum values will rarely be exceeded; 11.2 hours for ADHWI, 350 n.m. for geodetic distance, and 18.2 feet for the mean range. The minimum values for ADHWI (0.01 hours) and mean range (0.9 feet) will rarely be encountered too. Unfortunately, the minimum geodetic distance analyzed was only 14.6 n.m. However, distances less than 14.6 n.m. are not a blind extrapolation since SiM for a geodetic distance of zero and ADHWI of zero is known to be zero plus the measurement error. This measurement error checks intuitively with the constants in the regression equations.

A comparison of Tables 2 and 3 also shows that the constant is generally larger for low water computations. This may be due to the fact that instrument errors involved in measuring the tide are more pronounced at low waters. For example, noise in the tide record is more likely at low water than at high water since as the tide rises, the stilling well becomes more effective at dampening the noise caused by waves.

The variation in the dependent variable (SiM) is caused by deficiencies in the assumptions of the Simultaneous Computation Method. These deficiencies are due to the fact that the tidal wave is continually being distorted in different ways by bottom friction, irregular basins, reflections, resonance, co-oscillation, weather and many other lesser factors. As the standing wave from the oceanic basins approaches the coastal waters it usually becomes a progressive wave. This progressive wave will travel at a velocity that is proportional to the square root of the depth of the water (Marmer 1926:79). Hence the shallower the water the longer it takes the tidal wave to progress inland through bays, rivers, and estuaries. Also, the longer the travel time of this wave the more it is going to be distorted by bottom friction and irregular basins. ADHWI is correlated to SiM since it is a direct measure of this travel time and therefore an indirect measure of the effects of bottom friction and irregular basins.

The second important variable used in the regression equations is SRGDIST. This measure of geodetic distance between stations is a surrogate for all geographic variables. Weather is probably the most significant factor. For example, a change in barometric pressure of one inch should be accompanied by a change in the level of the water of a little more than one foot (13 inches) since mercury is about 13 times heavier than water. The wind also has a great effect on the water level depending on the fetch, duration, and direction of the wind along with the depth of the water. The farther apart two stations are, the greater the likelihood that the weather will be different at each station.

Geodetic distance may also be an approximate measure of the distance traveled by the tidal wave and therefore a measure of its distortion. The water distance (i.e. the distance traveled by a boat) between the control station and the subordinate is just as significant as geodetic distance. Geodetic distance was selected for the regression equations because it is easier to obtain and is not subjective.

The last three independent variables used in the regression equations are SRSMN and MNR and ADMN. All of these measure the differences in the tidal wave between the control and subordinate stations directly. Examination of Table 2 and 3 shows that R2 decreases as the length of the data series increases. As more data is used in the simultaneous comparison computations the variations explained by ADWHI and SRGDIST become less as the variations they explain are averaged out. The smaller correlation between SRSMN and MNR with the dependent variable finally becomes more significant with 12 months of data (S12M).

A variable that could not be quantified is the quality of data collection at each station. I believe that a large part of the unexplained variation is due to poor data quality. If this is true it may be possible to improve accuracies substantially by improving the quality of data collection.

SUMMARY

When using these equations it should be remembered that the database used to develop the equations may not be totally representative of the population of all control-subordinate tide stations pairs. Although these regression equations are the best available estimate of the datum accuracy they may be unreliable in areas which have widely divergent characteristics. For example, stations in a river environment may be influenced by unusually large (or small) seasonally runoff. Also station pairs in which each station is influenced by different oceanic systems or different types of tide may not conform to the model. Finally, low water datums are more susceptible to measurement errors that can not be statistically quantified. These errors must be minimized through careful data collection.

The regression equations in Table 2 and 3 are at least twice as accurate as the present generalized method of predicting the standard deviation (or accuracy) of Simultaneous Comparison Method computations for 19-year equivalent tidal datums form short series of tidal data. These regression equations have the additional benefit of accounting for the fact that most subordinate stations are much closer together than those control station pairs used to develop the present generalized accuracy statements.

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Appendix A

Simultaneous Comparison Computational Methods

Notation:

MTL - The 19 year accepted value of mean tide level
MHW - The 19 year accepted value of mean high level
MLW - The 19 year accepted value of mean low water
MR - The 19 year accepted value of mean range
TL - Observed monthly mean tide level
HW - Observer monthly mean high water
LW - Observer monthly mean low water
R - Observed monthly mean range
s - Subscript used to indicate subordinate station
c - Subscript used to indicate control station
C - Observed values corrected to estimate the 19 year accepted values

Equations:

<u>Standard Method</u>

CTLs = (TLs - TLc) + MTLc
CRs = (Rs/Rc) MRc
CLWs = CTLs - (½) CRs
CHWs = CLWs + CRs

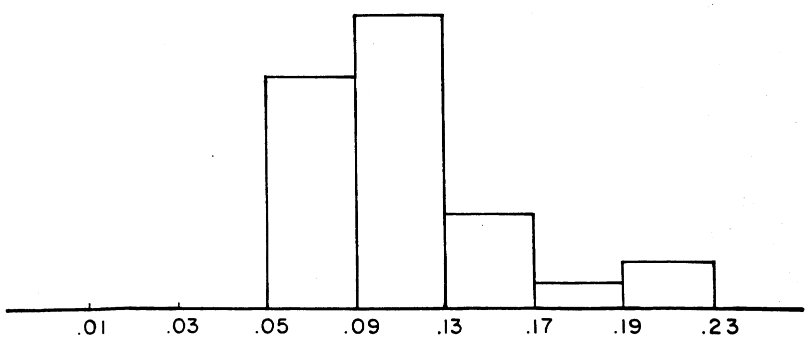
Mixed tide computations required correction to the diurnal inequalities that are not shown here.

<u>Alternate Method</u>

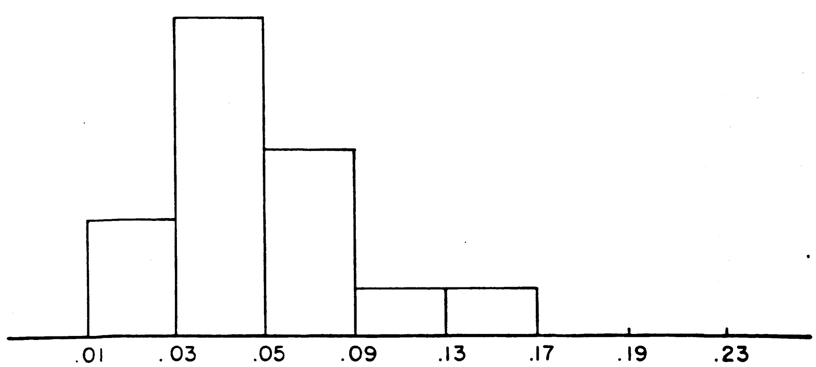
CTL = TLs -TLc + MTLc
CLW = (LWs - LWc) + MLWc
CHW = (MWs - HWc) + MHWc

APPENDIX B – HISTOGRAM – SIM and SI2M

SIM (MHW)



SI2M (MHW)



Appendix C

Analysis of Variance - Interdependence of Station Pairs

(SIM_{mlw} - SIM_{mhw}) by Station Pairs Containing a Common Station

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Between Groups	4	0.015	0.004	6.04	0.002
Within Groups	25	.015	.001		
Total	29	.030			

Group	Count	Mean	Standard Deviation	Standard Error
1. Mayport	4	0.063	.022	.011
2. Wash., D.C.	3	- .004	.011	.006
3. Battery	4	- .004	.010	.005
4. Baltimore	4	.008	.044	.022
5. All Other Sta. Pairs	15	- .003	.023	.006
Total	30	.012		

Appendix C

(Continued)

Analysis of Variance

SIM by Station Pairs Containing a Common Station

Mean Low Water Data (Standard Method)

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	4	0.025	0.006	3.01	0.037
Within Groups	25	.052	.002		
Total	29	.077			

Group	Count	Mean	Standard Deviation	Standard Error
1. Mayport	4	.183	.075	.038
2. Wash., D.C.	3	.090	.030	.018
3. Battery	4	.085	.009	.005
4. Baltimore	4	.129	.071	.036
5. All Other Sta. pairs	15	.110	.035	.009
Total	30	.117		

Appendix C

(Continued)

Analysis of Variance

SIM by Station Pairs Containing a Common Station

Mean High Water Datum (Standard Method)

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Between Groups	4	0.004	0.001	0.368	0.829
Within Groups	25	.060	.002		
Total	29	.064			

Group	Count	Mean	Standard Deviation	Standard Error
1. Mayport	4	.120	.053	.027
2. Wash.,D.C.	3	.094	.020	.011
3. Battery	4	.089	.014	.007
4. Baltimore	4	.121	.090	.045
5. All Other Stat. Pairs	15	.113	.043	.011
Total	30	.110		

Appendix D

Correlation (R) Matrix

	ADHWI	ADLWI	SRGDIST	SRSMN	MNR
<u>MHW</u>					
SIM	0.7	0.7	0.6	-0.1	0.4
S3M	.7	.6	.6	- .0	.4
S6M	.5	.5	.6	.1	.3
612M	-.2	-.2	.4	.4	.1
<u>MLW</u>					
SIM	.7	.7	.5	-.1	.6
S3M	.5	.6	.5	-.0	.5
S6M	.4	.5	.4	.1	.6
S12M	-.1	-.1	.2	.3	.4
ADHWI	1.0				
ADLWI	1.0	1.0			
SRGDIST	.0	.0	1.0		
SRSMN	-.4	-.5	.1	1.0	
MNR	.3	.3	-.2	-.1	1.0

Values of 0.5 and larger are significant at the 0.01 level.

Values of 0.3 and larger are significant at the 0.05 level.

Appendix E - Regression Analysis Data-Mean High Water Datums
Standard Method of Simultaneous Comparison

STATION PAIRS		DEPENDENT VARIABLES[1]				INDEPENDENT VARIABLES[2]	
CONTROL STATIONS	SUBORDINATE STATION	S1M (ft)	S3M (ft)	S6M (ft)	S12M (ft)	CDIST (N.M.)	ADHWI (Hrs)
1. Miami, Fl	Mayport, Fl	0.131	0.086	0.068	0.054	285.2	0.31
2. Atlantic City, NJ	Sandy Hook, NJ	.131	.117	.106	.101	69.4	.49
3. Battery, NY	Atlantic City, NJ	.099	.075	.060	.049	82.0	1.09
4. Baltimore, Md	Solomons, Md	.085	.062	.045	.027	57.2	4.86
5. Miami, Fl	Key West, Fl	.112	.079	.053	.032	116.7	2.13
6. Baltimore, Md	Portsmouth, Va	.252	.200	.138	.049	147.4	9.90
7. Baltimore, Md	Annapolis, Md	.050	.038	.028	.017	17.6	1.59
8. Solomons, Md	Washington, D.C.	.102	.070	.052	.037	42.9	5.94
9. Mayport, Fl	Key West, Fl	.182	.136	.103	.070	350.0	1.82
10. Hamptom Rd, VA	Solomons, Md	.156	.125	.086	.030	82.3	5.25
11. Battery, NY	Sandy Hook, NJ	.069	.062	.058	.057	14.6	.60
12. Baltimore, MD	Washington, D.C.	.097	.066	.049	.033	31.4	1.08
13. Solomons, Md	Annapolis, Md	.056	.041	.032	.025	40.0	3.27
14. Sandy Hook, NJ	Montauk, NY	.117	.097	.074	.047	99.4	1.22
15. Eastport, Me	Portsmouth, NH	.111	.092	.081	.068	196.2	.67
16. Battery, NY	New London, Ct	.100	.080	.059	.034	99.0	1.10
17. Charleston, SC	Pulaski, Ga	.090	.071	.058	.046	66.8	.05
18. Charleston, SC	Mayport, Fl	.115	.096	.074	.051	162.5	.60
19. Woods Hole, Ma	Montauk, NY	.079	.062	.054	.048	65.0	.90
20. Hampton Rd, Va	Washington, DC	.231	.181	.125	.042	120.1	11.19
21. Fernandian, Fl	Mayport, Fl	.053	.044	.036	.031	16.8	.40
22. Portland, Me	Eastport, Me	.116	.095	.080	.061	159.2	.28
23. Boston, Ma	Portsmouth, NH	.064	.049	.038	.024	45.7	.19
24. New London, Ct	Willets Pt., NY	.140	.120	.095	.064	83.8	2.11
25. New London, Ct	Woods Hole, Ma	.072	.059	.049	.042	64.8	1.38
26. Hampton Rd., Va	Atlantic City, NJ	.121	.089	.074	.061	170.4	1.86
27. Portland, Me	Portsmouth, NH	.079	.068	.059	.049	40.8	.39
28. Boston, Ma	Woods Hole, Ma	.106	.093	.073	.047	52.6	3.10
29. Battery, Ma	Willets Pt., NY	.088	.069	.061	.056	15.2	3.21
30. Portland, Me	Boston, Ma	.087	.073	.064	.059	85.7	.20
Mean (N=30)		.110	.086	.068	.047	96.0	2.22
Minimum		.050	.038	.028	.017	14.6	0.05
Maximum		.252	.200	.138	.101	350.0	11.19

1. MHW Standard Deviations (Swanson 1974:22)
2. See Appendix F for mean range values.

Appendix F - Regression Analysis Data-Mean Low Water Datums
Standard Method of Simultaneous Comparison

Station Pairs	Dependent Variables[1]				Independent Variables[2]		
	S1M (ft)	S3M (ft)	S6M (ft)	S12M (ft)	ADLWI (hrs)	Mean Range (ft) Control	Subordinate
1. Miami, Fl - Mayport, Fl	(.197)	(.142)	(.101)	(.063)	(.19)	(2.5)	(4.5)
2. Atlantic City, NJ - Sandy Hook, NJ	.112	.098	.088	.081	.58	4.1	4.6
3. Battery, NY - Atlantic City, NJ	.091	.067	.049	.027	1.18	4.5	4.1
4. Baltimore, Md - Solomons, Md	.091	.069	.048	.020	4.99	1.1	1.2
5. Miami, Fl - Key West, Fl	.120	.087	.063	.044	1.56	2.5	1.3
6. Baltimore, Md - Portsmouth, Va	.210	.158	.111	.050	10.07	1.1	2.8
7. Baltimore, Md - Annapolis, Md	.051	.039	.031	.025	1.79	1.1	0.9
8. Solomons, Md - Wash, D.C.	.154	.119	.094	.065	6.72	1.2	2.9
9. Mayport, Fl - Key West, Fl	(.273)	(.207)	(.153)	(.104)	(1.37)	(4.5)	(1.3)
10. Hampton Rd, Va - Solomons, Md	.129	.096	.066	.028	5.33	2.5	1.2
11. Battery, NY - Sandy Hook, NJ	.079	.073	.069	.068	.60	4.5	4.6
12. Baltimore, Md - Wash, D.C.	.162	.131	.104	.068	1.73	1.1	2.9
13. Solomons, Md - Annapolis, Md	.063	.050	.039	.028	3.20	1.2	0.9
14. Sandy Hook, NJ - Montauk, NY	.100	.075	.053	.036	1.40	4.6	2.1
15. Eastport, Me - Portsmouth, NH	.124	.102	.084	.059	.26	18.2	7.8
16. Battery, NY - New London, Ct	.095	.072	.054	.035	1.21	1.2	2.6
17. Charleston, SC - Ft. Pulaski, Ga	.112	.084	.063	.040	.24	5.2	6.9
18. Charleston, SC - Mayport, Fl	(.172)	(.140)	(.101)	(.059)	(.47)	(5.2)	(4.5)
19. Woods Hole, Ma - Montauk, NY	.073	.061	.054	.047	.25	1.8	2.1
20. Hampton Rd., Va - Wash., D.C.	.190	.136	.092	.037	12.05	2.5	2.9
21. Fernandian, Fl - Mayport, Fl	(.090)	(.079)	(.069)	(.058)	(.19)	(6.0)	(4.5)
22. Portland, Me - Eastport, Me	.125	.104	.087	.067	.01	9.0	18.2
23. Boston, Ma - Portsmouth, NH	.066	.049	.040	.029	.03	9.5	7.8
24. New London, Ct - Willets Pt., NY	.113	.087	.068	.051	2.21	2.6	7.1
25. New London, Ct - Woods Hole, Ma	.062	.049	.041	.035	.66	2.6	1.8
26. Hampton Rd., Va - Atlantic City, NJ	.128	.092	.072	.054	1.87	2.5	4.1
27. Portland, Me - Portsmouth, NH	.069	.057	.050	.045	.27	9.0	7.8
28. Boston, Ma - Woods Hole, Ma	.099	.083	.063	.035	2.10	9.5	1.8
29. Battery, NY - Willets Pt., NY	.076	.057	.044	.033	3.42	4.5	7.1
30. Portland, Me - Boston, Ma	.077	.060	.049	.041	.24	9.0	9.5
Mean (N = 26)	.107	.082	.065	.044	2.46	4.5	4.4
Minimum	.051	.039	.031	.020	.03	1.1	0.9
Maximum	.210	.158	.111	.081	12.05	18.2	18.2

1. MLW Standard Deviations (Swanson 1974:22)
2. See Appendix E for geodetic distances

Appendix G - Regression Analysis Data - Mean High Water Datums
Alternate Method of Simultaneous Comparison

STATION PAIRS		DEPENDENT VARIABLES[1]				INDEPENDENT VARIABLES[2]	
CONTROL STATIONS	SUBORDINATE STATION	S1M (ft)	S3M (ft)	S6M (ft)	S12M (ft)	GDIST (N.M.)	ADHWI (Hrs)
1. Miami, Fl	Mayport, Fl	0.132	0.086	0.066	0.049	285.2	0.31
2. Atlantic City, NJ	Sandy Hook, NJ	.130	.115	.106	.098	63.4	.49
3. Battery, NY	Atlantic City, NJ	.090	.075	.059	.048	82.0	1.09
4. Baltimore, Md	Solomons, Md	.090	.065	.046	.027	57.2	4.86
5. Miami, Fl	Key West, Fl	.114	.080	.052	.032	116.7	2.13
6. Baltimore, Md	Portsmouth, Va	.230	.179	.124	.052	147.4	9.90
7. Baltimore, Md	Annapolis, Md	.052	.041	.024	.017	17.6	1.59
8. Solomons, Md	Washington, D.C.	.119	.087	.064	.037	42.9	5.94
9. Mayport, Fl	Key West, Fl	.177	.129	.096	.066	350.0	1.82
10. Hamptom Rd, VA	Solomons, Md	.155	.120	.083	.033	82.3	5.25
11. Battery, NY	Sandy Hook, NJ	.069	.063	.060	.057	14.6	.60
12. Baltimore, MD	Washington, D.C.	.093	.065	.050	.037	31.4	1.08
13. Solomons, Md	Annapolis, Md	.062	.044	.036	.029	40.0	3.27
14. Sandy Hook, NJ	Montauk, NY	.120	.098	.072	.039	99.4	1.22
15. Eastport, Me	Portsmouth, NH	.120	.097	.083	.068	196.2	.67
16. Battery, NY	New London, Ct	.108	.088	.066	.036	99.0	1.10
17. Charleston, SC	Pulaski, Ga	.091	.074	.061	.048	66.8	.05
18. Charleston, SC	Mayport, Fl	.118	.099	.076	.051	162.5	.60
19. Woods Hole, Ma	Montauk, NY	.077	.062	.054	.047	65.0	.90
20. Hampton Rd, Va	Washington, DC	.230	.181	.124	.038	120.1	11.19
21. Fernandian, Fl	Mayport, Fl	.059	.050	.043	.036	16.8	.40
22. Portland, Me	Eastport, Me	.136	.116	.103	.089	159.2	.28
23. Boston, Ma	Portsmouth, NH	.065	.052	.040	.029	45.7	.19
24. New London, Ct	Willets Pt., NY	.119	.098	.072	.032	83.8	2.11
25. New London, Ct	Woods Hole, Ma	.067	.052	.042	.035	64.8	1.38
26. Hampton Rd., Va	Atlantic City, NJ	.121	.092	.077	.064	170.4	1.86
27. Portland, Me	Portsmouth, NH	.077	.066	.055	.046	40.8	.39
28. Boston, Ma	Woods Hole, Ma	.134	.117	.093	.063	52.6	3.10
29. Battery, Ma	Willets Pt., NY	.072	.054	.044	.038	15.2	3.21
30. Portland, Me	Boston, Ma	.089	.074	.067	.060	85.7	.20
Mean (N=30)		.111	.087	.068	.047	96.0	2.22
Minimum		.052	.041	.024	.017	14.6	0.05
Maximum		.230	.181	.124	.098	350.0	11.19

1. MHW Standard Deviations (Swanson 1974:22)
2. See Appendix F for mean range values.