Error Analysis Procedures Used by the National Ocean Service to Compute Estimated Error Bounds for Tidal Datums in the Arctic Ocean

Michael MICHALSKI Lijuan HUANG, and Gerald HOVIS

Key Words: Tidal Datums, Tidal Characteristics, Alaska, Standard Deviation

SUMMARY

NOAA has established a National Water Level Observation Network (NWLON) along all U.S. coastlines. One purpose of the NWLON is to provide control for tidal datum determination at short-term tide stations installed for hydrographic and shoreline mapping surveys. There are significant gaps in NWLON coverage in Alaska. When short-term (1-12 months) water level stations are installed outside of an NWLON coverage area, a First Reduction (FRED) or arithmetic mean is used for datum determination instead of the preferred simultaneous comparison method using a nearby NWLON station to compute a 19-year equivalent National Tidal Datum Epoch (NTDE) datum. The datum error of a FRED is typically greater than the error computed by a simultaneous comparison procedure with an NWLON station. This report describes one method used by NOAA to establish error bounds on FRED tidal datums computed at short-term stations. The standard deviation of monthly Mean Tide level (MTL) at 29 operating and historical water level stations with varying time series lengths was used to infer FRED datum errors within the study region. The combined results show that FRED datum errors decrease from 0.12 m, 0.04 m, and 0.008m (one-sigma) for 1, 12, and 228 month time series respectively. Regional comparisons show only minor differences, supporting utilization of combined values as representing FRED datum errors for the entire study area. These results will help facilitate better estimates of total tide propagated error and required subordinate installation time series length in support of hydrographic and shoreline mapping surveys in Alaska.

1. INTRODUCTION

In 1983 the National Ocean Service (NOS) prepared a report detailing the methods and procedures used to establish error bounds on First Reduction (FRED) tidal datums computed by NOS for the Beaufort Sea and Arctic Ocean. A FRED is a method of determining water elevations, time intervals, and ranges from an arithmetic mean of observations without adjustment to a 19-year National Tidal Datum Epoch. This document expands upon the initial report by including more recent data, as well as, data from 23 additional water level stations that have operated in the region since the 1983 report (Stoney, et al, 1983). Seven of the additional stations are located within the Bering and the Beaufort Seas which provides long term data which were not available at the time of the initial report.

NOS standard procedures require the use of a 19-year NTDE to provide long term control for the computation of short term subordinate datums. Nineteen years is the time period necessary to incorporate all of the major astronomical (periodic) tide producing cycles (e.g. the 18.6 year nodal cycle (Parker 2007) and to average out the meteorological effects (non-periodic). The practice of NOS to review and/or update the National Tidal Datum Epoch approximately every 25 years assists in reducing problems related to long-term trends at most stations (CO-OPS, 2001). However, at some stations, datums must be updated periodically to account for relatively rapid long-term changes in the land-sea interface due to rapid vertical land motion. At these locations NOS standard procedure is to use a 5-year Modified Tidal Datum Epoch (MTDE) to account for rapid rates of sea level change.

All tidal datums are referenced to either a specific 19-year NTDE or 5-year MTDE. The present NTDE and MTDE are 1983-2001 and 2002-2006 (1997-2001 at Anchorage and Unalaska) respectively. When less than 19 years of data are available, NOS uses the procedure of comparison of simultaneous observations to adjust mean values of a short series of observations to equivalent 19-year mean values (CO-OPS, 2003). For the majority of the Alaskan coastline, this is not possible as no suitable long-term control station exists for the simultaneous comparison procedure. Areas without suitable control along the US coast were identified in the network gaps analysis for the National Water Level Observation Network, (Gill and Fisher, 2008). A FRED is used to calculate tidal datums for short-term stations where National Water Level Observation Network (NWLON) stations with the same tidal characteristics are not available. Because these time periods are typically much less than 19-years, the datum error at those stations is significantly greater than those with a full NTDE determination. Stations in the Arctic areas such as Port Moller, Nome, Red Dog Dock and Prudhoe Bay now have datums determined from several years of data but are still short of 19-years. Table 1 lists the stations used in this study, their sea level trend values (and time periods used), and the time period used in computation of their accepted tidal datums. Sea level trends listed as un-published were computed specifically for this paper. Published trends are from the CO-OPS Sea Level Online website: http://tidesandcurrents.noaa.gov/sltrends/index.shtml

Station ID	Station	Sea Level Trend (meters)	Time series of Datum
9450460	Ketchikan, Tongass Narrows	-0.19 +/-0.27mm/yr (1979-2006)	1983-2001
9451054	Port Alexander, Baranof Island	1.06 +/- 21.06 mm/yr (2007-2011)	09/01/2007-08/31/2008 & 06/01/2009-05/31/2011
9451600	Sitka, Baronof Island, Sitka Sound	-2.05 +/- 0.32 mm/yr (1924-2006)	1983-2001
9452210	Juneau, Gastineau Channel, Stephens Pass	-12.92 +/- 0.43 mm/yr (1936-2006)	2002-2006
9452400	Skagway, Taiya Inlet	-17.12 +/- 0.65 mm/yr (1924-2006)	2002-2006
9452634	Elfin Cove, Port Althorp	-20.36 +/- 12.65 mm/yr (2005-2011)	09/01/2005-08/31/20010
9453220	Yakutat, Yakutat Bay	-11.54 +/- 1.39 mm/yr(1940-2006)	2002-2006
9454050	Cordova, Orca Inlet, Prince William Sd	5.76 +/- 0.87 mm/yr (1964-2006)	1983-2001
9454240	Valdez, Prince William Sound	-2.52 +/- 1.36 mm/yr (1973-2006)	1983-2001
9455090	Seward, Resurrection Bay	-1.74 +/- 0.91 mm/yr(1964-2006)	1983-2001
9455500	Seldovia, Cook Inlet	-9.45 +/- 1.10 mm/yr(1964-2006)	2002-2006
9455760	Nikiski, Cook Inlet	-9.80 +/- 1.50 mm/yr(1973-2006)	1997-2008
9455920	Anchorage, Knik Arm, Cook Inlet	0.88 +/- 1.54 mm /yr(1972-2006)	1997-2001
9457283	Kodiak, St Pauls Harbor	-23.03 +/- 4.27 mm/yr (1966-1984)	10/01/1982-9/30/1984
9457292	Kodiak Island, Womens Bay	-10.42 +/- 1.33 mm/yr (1975-2006)	2002-2006
9457804	Alitak, Lazy Bay	7.59 +/- 19.33 mm/yr (2006-2011)	05/01/2007-04/30/2008 & 07/01/2009-06/30/2011
9459450	Sand Point, Popof Island	0.92 +/- 1.32 mm/yr (1972-2006)	1983-2001
9459881	King Cove, Deer Passage, Pacific Ocean	-0.51 +/- 15.67 mm/yr (2005-2011)	05/01/2006-04/30/2011
9461380	Adak Island, Sweeper Cove	-2.75 +/- 0.54 mm/yr (1957-2006)	1983-2001
9461710	Atka, Nazan Bay	7.25 +/- 29.71 mm/yr (2007-2011)	03/01/2008-02/28/2009
9462450	Nikolski	10.74 +/- 12.92 mm/yr (2006-2011)	12/01/2007-11/30/2009 & 09/01/2010-08/31/2011
9462620	Unalaska, Dutch Harbor	-5.72 +/- 0.67 mm/yr (1957-2006)	1997-2001
9463502	Port Moller, Bristol Bay	1.05 +/- 2.41 mm/yr (1984-2011)	07/01/07 - 06/30/10 & 09/01/10 - 08/31/11
9464212	Village Cove, St. Paul Island	4.72 +/- 12.18 mm/yr (2006-2011)	03/01/07 - 02/28/10 & 10/01/10- 09/30/11
9468756	Nome, Norton Sound	1.95 +/- 5.51 mm/yr (1992-2011)	08/01/97 - 07/31/04 & 01/01/06 - 12/31/06 & 09/01/08 - 08/31/10
9491094	Red Dog Dock	-4.79 +/- 11.01 mm/yr (2003-2011)	11/01/04 - 10/31/05 & 05/01/06 - 04/30/07 & 07/01/07 - 06/30/10
9491253	Kivalina	Time series not sufficient for Sea Level Trend calculation	10/01/85 - 09/30/86
9494935	Barrow Offshore	Time series not sufficient for Sea Level Trend calculation	09/01/08 - 08/31/09
9497645	Prudhoe Bay	2.13 +/- 2.39 mm/yr (1990-2011)	12/01/93 - 11/30/04 & 03/01/06 - 02/29/08 & 07/01/08 - 06/30/11

Table 1: Sea level trend values and datum computation time series for coastal Alaska stations.

Tidal heights are driven by astronomical forces and are modified by local hydrodynamics and meteorological forcing. Tides along Alaska's coastline are highly dynamic and transition between mixed semi-diurnal, mixed diurnal, and diurnal tides (see figure 1). The classification of tides is based on characteristic forms of a tide curve. The definition of different types of tides can be found at the NOAA tide and current glossary (http://www.tidesandcurrents.noaa.gov/publications/glossary2.pdf). In addition to the different types of tide, several amphidromic systems are present along the coastline of Alaska. Amphidromic systems have center points of zero tidal amplitude from which the range of tide or constituent of tide concentrically increases and about which the phases of the tide rotate (Parker, 2007). Topographic and bathymetric characteristics contribute to local hydrodynamic complexities as well. The varying types of tides and presence of amphidromic systems geospatially limit the extension of current NWLON coverage for primary datum control and use of subordinate stations for secondary datum control. The remote nature of the Alaskan coastline, the lack of infrastructure, and seasonal ice coverage cause logistical and operational difficulties in installing and maintaining water level gauges in the region which is another practical reason for lack of NWLON coverage.

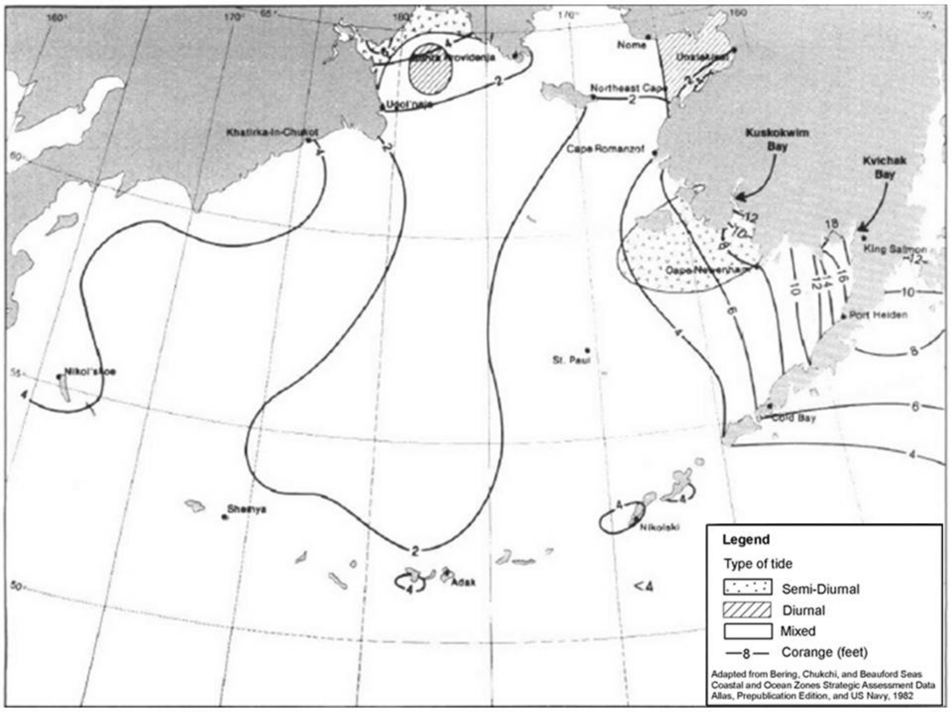

Figure 1: Types of tides along the Western Alaska Coastline (Brower et. al., 1988).

2. METHODOLOGY

The purpose of this analysis is to update the estimated uncertainties of computing First Reduction (FRED) tidal datums in Alaska. Data from 29 tide stations with long term records (greater than one year) were incorporated throughout Alaska (see table 1 and figure 2). For consistency, this analysis will retain the same procedure as the previous paper (Stoney, et al 1983) and will deal only with the observed variability of mean tide level (MTL). Mean high water (MHW) and mean low water (MLW) are symmetrical to this datum and the accuracy with which these datums can be determined depends on the accuracy with which MTL is determined.

The error model for MTL is: $\chi = \mu + E_s + E_t$

where χ is the computed first reduction MTL value,

μ is the true value of MTL (unknown),

E_s is the stochastic or random error in the first reduction value, caused by using less than 19 years of data in the datum computation, and

E_t is the deterministic error caused by the linear trend in the data.

The effect of the linear trend (E_t) on the overall error depends both on the absolute slope of the trend and the number of years between the center of the epoch chosen and the measurement time period. To a certain extent this error term is an artificial quantity since it depends on the relationship of the measurement time period to a 19-year time period chosen purely by convention. If the epoch happens to be centered exactly around the measurement time period, the error due to the linear trend would be zero regardless of the slope of the subordinate trend.

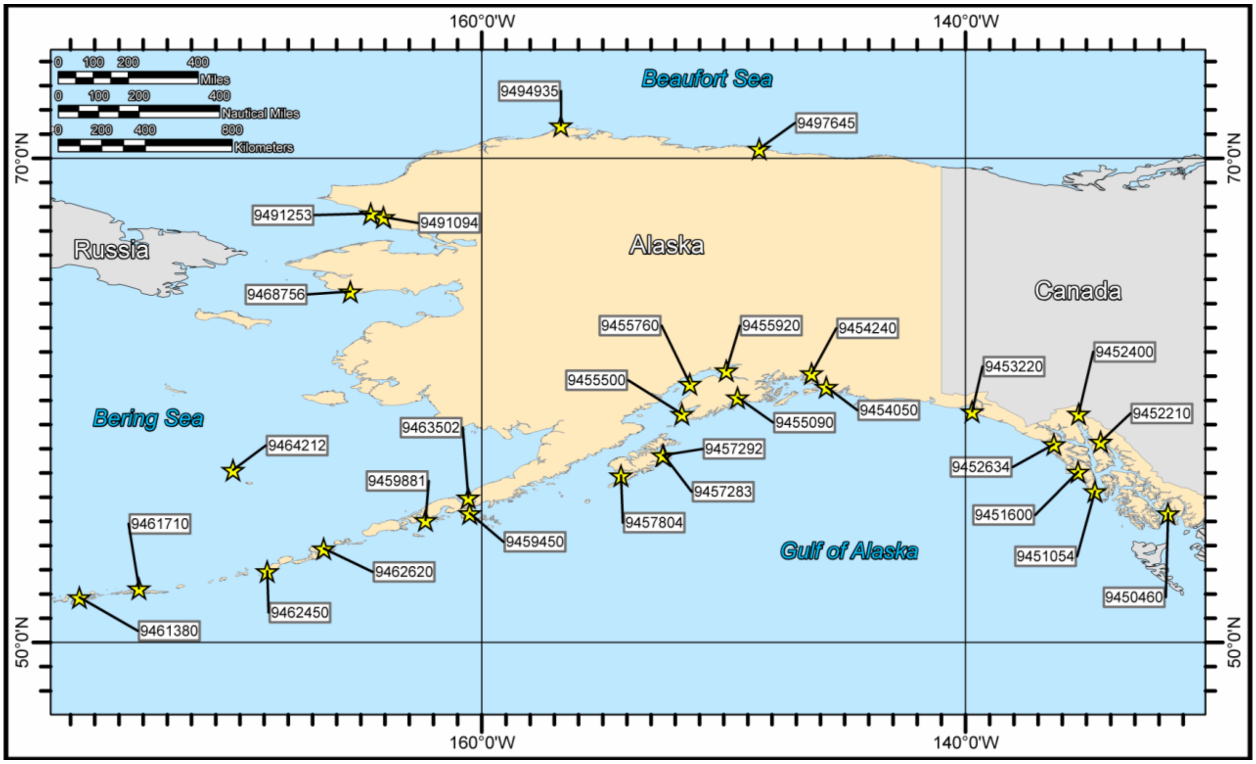

Figure 2: Gulf of Alaska and Bering Sea tide station used for analysis

Since most of the variability of a tidal series is comprised of both the variation due to long-term trends and annual variations caused by seasonal effects, it is necessary to remove the long-term trend from the data to isolate the annual variability. Removing the trend, by least-squares linear regression, from each series used provides a more consistent and compatible data set for analysis in determining error bounds. An extremely important point in this respect is there are limited numbers of long-term NOS tidal observations in the Beaufort and Bering Sea to determine the extent of long-term trends for the area. Where long series of observations are available in Alaska, the long-term sea level trends exhibit large geospatial variability, so it is not possible to make any assumptions about the trend in isolated areas (table 1). As an example, Sitka and Juneau are two relatively close tide stations in southeast Alaska which have very different long-term sea level trends. The long-term sea level trends values are presented in table 1 and figure 3.

To identify the long term sea level trends associated with the water level stations used in this analysis, data from the CO-OPS sea levels online website was used. CO-OPS published sea-level trends only for stations with record lengths greater than 30-years and sea level trends with less record lengths can have significant standard errors (Zervas, 2009). However, for purposes of this study, it was important to use a best estimate of the trends at each station in order to obtain the datum error estimates. Thus, a similar analysis was also independently done for those stations with shorter time periods that do not have published sea level trends. For the unpublished sea level trends, the annual MTL values were plotted for each station and a linear regression line was computed for each series. The slope of the MTL regression line approximates the long-term trend in MTL at each station. The MTL trends, along with their 95% Confidence Intervals for Alaska stations are plotted in figure 3. Note the stations with longer record lengths have relatively small confidence intervals.

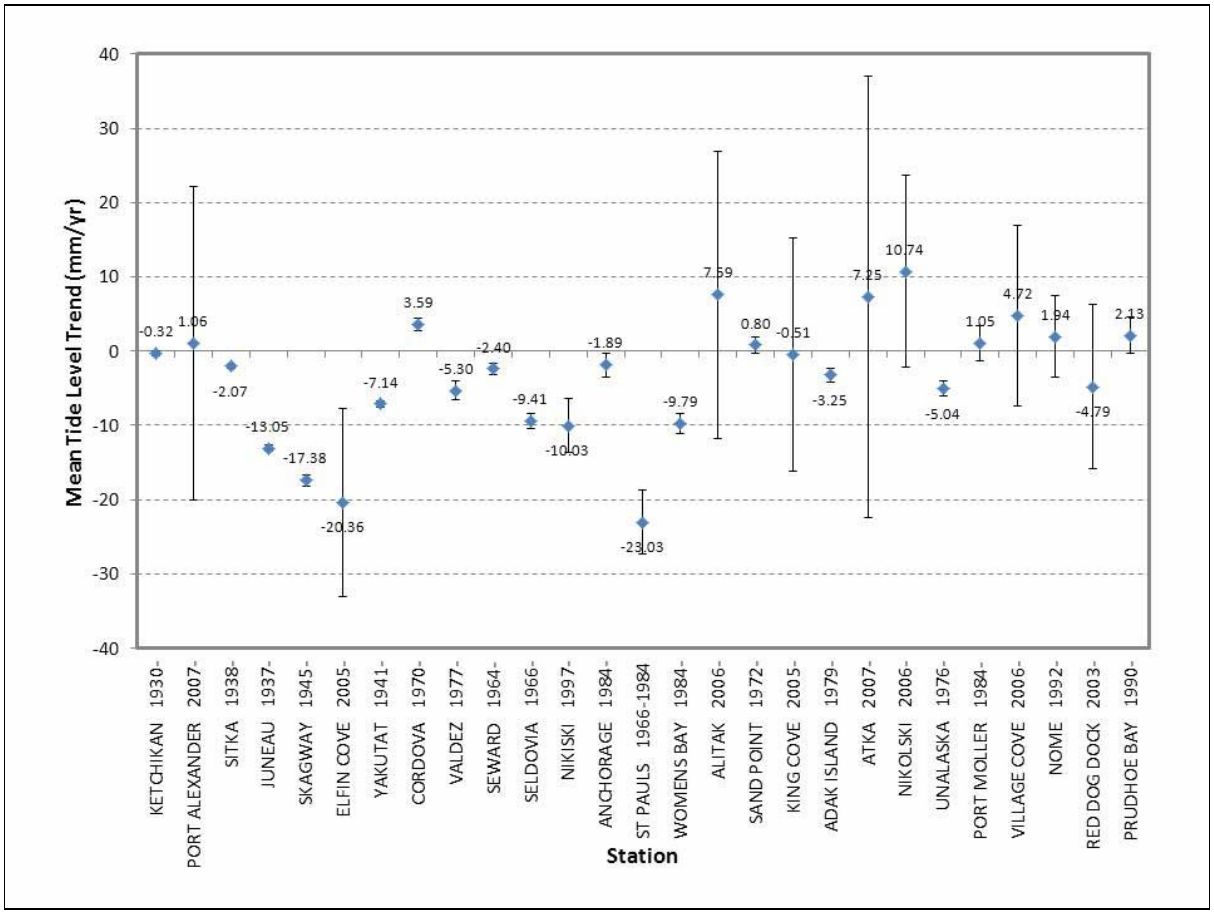

Figure 3: MTL trends and associated 95% Confidence Intervals along the Alaska coast

The remainder of this document will deal only with estimating the stochastic component of the error (E_S). The standard deviations computed with the detrended data series from existing long term Alaskan stations provide the best estimate for this error as only the stochastic component of the error is left. The stochastic error results from astronomic components not averaging out with less than 19 years of data, from meteorological effects, and from measurement variability. The stochastic error can only be measured at stations with a long continuous data series. For stations with tidal series less than 19 years, the stochastic error must be measured at the nearest stations with continuous long-term data series. These estimates can then be used to bound the first reduction datums.

The one standard deviation of MTL for 29 stations was estimated by the following procedures: First, the detrended monthly MTL values were binned into average time series of 1, 3, 6, 9….228 months. Second, the standard deviations were calculated for each of these bins (Equation 1). Third, the standard deviation of the individual bins, for all stations, were averaged to create a cumulative uncertainty value which represents the FRED datum computation error associated with each binned group (Equation 2). The stochastic error E_s for 1,3, 6…month FRED datum is approximated by averaging the standard deviation of each bin as calculated in Step 3.

The standard deviation (S_{ij}) for the MTL was computed for each station relative to the overall mean for series of varying lengths using the following equation:

$$s_{ij} = \left(\frac{\sum_{K=1}^{N_{ij}} \left(x_{ijk} - \overline{x}_i \right)^2}{N_{ij} - 1} \right)$$

Where i = station identification number (i = 1,2,3,4,5,6…),
j= length of running mean used (j = 1,3,6,9,12,24,36,48,60, 120, 180 and 228),
N_{ij} = number of j month running means for station i,
k = index number for running mean observations,
x_{ijk} = running mean observations with index k, and
$\overline{x}_i$= long-term mean for station i.

An average standard deviation (sj) for all 29 stations was then computed using the following relationship:

$$S_j = \frac{\sum_{i=1}^{29} \left(N_{ij} s_{ij} \right)}{\sum_{i=1}^{29} N_{ij}}$$

Where s_{ij} = standard deviation for running mean of length j for station i, and
N_{ij}=number of j month running means available for station i.

3. RESULTS

Table 2 presents the individual, and combined averaged total MTL standard deviation values for varying lengths of time series for 29 water level stations in the coastal waters of Alaska. The individual results were combined to establish average error bounds that were more reliable and unbiased estimates of the expected error bounds for the FRED datum computations. Table 3 presents the final averaged standard deviation values for each of the specified time series as well as a region comparison. The data all show a decrease in standard deviations from 1 month to 228 month time series.

Station Name / Station ID	Months	1	3	6	9	12	24	36	48	60	120	180	228
Ketchikan, Tongass Narrows	N	968	950	934	922	910	866	840	816	792	672	552	456
9450460	DS	0.110	0.091	0.068	0.047	0.037	0.028	0.023	0.019	0.016	0.009	0.007	0.006
Port Alexander, Baranof Island	N	46	42	36	30	24							
9451054	DS	0.109	0.090	0.066	0.039	0.022							
Sitka, Baronof Island, Sitka Sound	N	875	872	867	862	858	834	810	786	757	637	517	421
9451600	DS	0.111	0.093	0.069	0.045	0.033	0.025	0.019	0.016	0.014	0.009	0.006	0.009
Juneau, Gastineau Channel, Stephens Pass	N	841	823	804	786	770	710	661	616	580	454	334	238
9452210	DS	0.103	0.082	0.063	0.048	0.040	0.030	0.026	0.022	0.020	0.015	0.012	0.009
Skagway, Taiya Inlet	N	688	671	648	627	606	522	441	376	318	125		
9452400	DS	0.112	0.088	0.066	0.049	0.041	0.030	0.023	0.016	0.012	0.007		
Elfin Cove, Port Althorp	N	73	71	68	65	62	50	38					
9452634	DS	0.110	0.090	0.066	0.041	0.027	0.016	0.010					
Yakutat, Yakutat Bay	N	822	815	806	797	788	752	716	680	644	496	376	280
9453220	DS	0.125	0.106	0.082	0.062	0.053	0.048	0.045	0.043	0.041	0.038	0.034	0.028
Cordova, Orca Inlet, Prince William Sd	N	501	499	496	493	490	478	466	454	442	382	322	274
9454050	DS	0.120	0.101	0.076	0.053	0.042	0.034	0.029	0.025	0.023	0.016	0.011	0.008
Valdez, Prince William Sound	N	417	415	412	409	406	394	382	370	358	298	238	190
9454240	DS	0.119	0.098	0.075	0.055	0.045	0.035	0.029	0.024	0.021	0.013	0.009	0.007
Seward, Resurrection Bay	N	538	527	517	511	505	481	457	433	409	289	228	180
9455090	DS	0.129	0.107	0.081	0.056	0.043	0.032	0.025	0.021	0.019	0.013	0.010	0.007
Seldovia, Cook Inlet	N	524	514	502	492	483	447	411	375	349	268	208	160
9455500	DS	0.127	0.105	0.080	0.057	0.045	0.032	0.025	0.021	0.017	0.010	0.005	0.002
Nikiski, Cook Inlet	N	177	175	172	169	166	154	142	130	118	58		
9455760	DS	0.113	0.093	0.069	0.046	0.032	0.019	0.016	0.014	0.011	0.003		
Anchorage, Knik Arm, Cook Inlet	N	330	325	319	315	312	300	288	276	264	204	144	96
9455920	DS	0.108	0.087	0.066	0.048	0.038	0.027	0.020	0.016	0.012	0.006	0.003	0.002
Kodiak, St Pauls Harbor	N	193	181	169	157	145	101	67	43	19			
9457283	DS	0.103	0.085	0.068	0.054	0.046	0.032	0.016	0.017	0.016			
Kodiak Island, Womens Bay	N	326	324	321	318	315	303	291	279	267	207	147	99
9457292	DS	0.093	0.075	0.057	0.041	0.033	0.023	0.018	0.015	0.012	0.007	0.005	0.002
Alitak, Lazy Bay	N	59	55	49	43	37	13						
9457804	DS	0.095	0.074	0.060	0.045	0.032	0.009						
Sand Point, Popof Island	N	459	453	444	438	432	408	384	360	343	283	223	175
9459450	DS	0.136	0.112	0.082	0.055	0.041	0.030	0.025	0.021	0.019	0.012	0.007	0.004
King Cove, Deer Passage, Pacific Ocean	N	73	71	68	65	62	50	38	26	14			
9459881	DS	0.125	0.098	0.073	0.049	0.035	0.020	0.012	0.006	0.002			
Adak Island, Sweeper Cove	N	388	381	373	367	361	339	327	315	303	243	183	135
9461380	DS	0.085	0.066	0.050	0.038	0.032	0.026	0.023	0.019	0.017	0.011	0.006	0.003
Atka, Nazan Bay	N	40	37	34	31	28	16	4					
9461710	DS	0.071	0.058	0.047	0.037	0.030	0.008	0.003					
Nikolski	N	46	40	31	25	19	4						
9462450	DS	0.079	0.052	0.040	0.026	0.019	0.003						
Unalaska, Dutch Harbor	N	393	372	354	342	330	306	282	258	234	154	94	46
9462620	DS	0.102	0.081	0.061	0.043	0.033	0.022	0.017	0.014	0.011	0.006	0.004	0.004
Port Moller, Bristol Bay	N	103	93	79	70	61	35	11					
9463502	DS	0.115	0.095	0.077	0.060	0.045	0.021	0.009					
Village Cove, St. Paul Island	N	56	50	44	38	32	18	6					
9464212	DS	0.076	0.055	0.040	0.028	0.022	0.010	0.003					
Nome, Norton Sound	N	178	163	145	130	115	76	59	47	35			
9468756	DS	0.163	0.116	0.081	0.066	0.056	0.040	0.027	0.022	0.016			
Red Dog Dock	N	84	76	67	58	49	29	17	5				
9491094	DS	0.175	0.125	0.079	0.042	0.019	0.008	0.007	0.002				
Kivalina	N	23	7	4	1								
9491253	DS	0.141	0.110	0.059	0.028								
Barrow Offshore	N	23	21	18	15	12							
9494935	DS	0.122	0.073	0.052	0.030	0.008							
Prudhoe Bay	N	237	221	202	187	172	136	109	90	78	18		
9497645	DS	0.129	0.100	0.068	0.045	0.034	0.026	0.021	0.018	0.014	0.005		
Ave. Std. for all stations	N	9481	9244	8983	8763	8550	7822	7247	6735	6324	4788	3566	2750
	DS	0.115	0.093	0.070	0.050	0.040	0.030	0.025	0.022	0.019	0.014	0.010	0.008

Table 2: The summary of results of computing the MTL standard deviation (s) for stations used for this analysis, [Detrended standard deviations (DS) are in meters, Sample size (N)].

Regions	Months	1	3	6	9	12	24	36	48	60	120	180	228
All Stations	N	9481	9244	8983	8763	8550	7822	7247	6735	6324	4788	3566	2750
	DS	0.115	0.093	0.070	0.050	0.040	0.030	0.025	0.022	0.019	0.014	0.010	0.008
South East Alaska	N	4313	4244	4163	4089	4018	3734	3506	3274	3091	2384	1779	1395
	DS	0.112	0.092	0.070	0.050	0.040	0.032	0.027	0.024	0.021	0.016	0.013	0.012
Gulf of Alaska	N	3597	3539	3469	3410	3353	3129	2926	2746	2583	1989	1510	1174
	DS	0.119	0.098	0.074	0.052	0.041	0.030	0.024	0.020	0.018	0.011	0.008	0.005
Aleutian Islands	N	923	880	836	803	770	683	619	573	537	397	277	181
	DS	0.091	0.071	0.054	0.039	0.032	0.024	0.020	0.017	0.014	0.009	0.005	0.003
Bering Strait to Beaufort Sea	N	545	488	436	391	348	241	185	142	113	18		
	DS	0.148	0.108	0.073	0.051	0.038	0.028	0.022	0.018	0.014	0.005		

Table 3: Regional distribution of FRED errors for coastal Alaska. [Detrended standard deviations (DS) are in meters, Sample size (N)].

A composite of the results of computing s_j for various lengths of series is presented in figure 4. This plot shows that s_j decreases with an increase in the length of series collected. In other words, there is an increase in the accuracy of the datum with an increase in length of series. Furthermore, it is important to note the slope of the curve between the 1-month and the 12-month series. The statistics indicate that with 1 month of data s is 0.115 meter (0.38 foot) and with 12 months of data it is 0.040 meter (0.14foot), which represents a significant improvement in accuracy (0.075 meter (0.25 foot)). After 12 months the slope is much more gradual. In fact, there is only 0.021 meter (0.07 foot) difference between the 12-month series and the 60-month series, indicating a smaller increase in accuracy for additional increments of data. The differences between 12-month series and the 228-month series showed an improvement in the vertical accuracy for MTL of (0.032 meter (0.11 foot)).

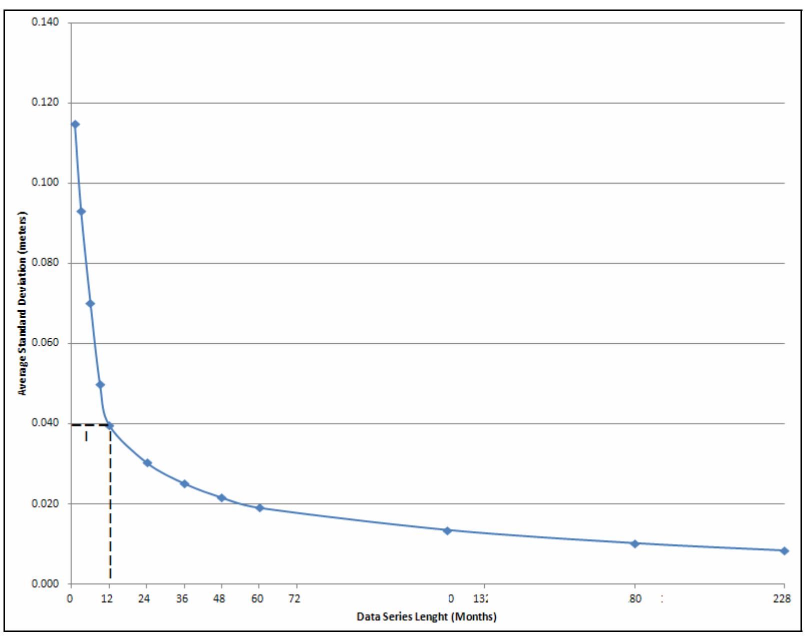

Figure 4: The average standard deviation (the error associated with FRED datum error) along the coast of Alaska.

4. DISCUSSION

The main purpose of this report was to update the analysis done by Stoney et. al. (1983) and to validate the error estimates for the computation of FRED datums. The current analysis expands on the work initially done by increasing the number of stations, sample size, and data series lengths, as well as including data in the Arctic regions of Alaska. Since the current analysis utilized a larger number of stations, including stations in the Beaufort Sea, it was deemed unnecessary to include data from Canadian water level stations as was done in the original publication.

Tide data collected in the coastal waters of Alaska were processed and analyzed using standard NOS techniques and procedures. The MTL monthly mean values were gathered for a series of 29 long term water level stations located throughout the Alaska coastal region. Error bounds for Alaska FRED tidal datums were derived from a statistical analysis of data from these 29 stations. Monthly MTL curves for these stations showed that each location exhibited some degree of a long-term trend. Therefore, the data were detrended using a least square linear regression fit to isolate the stochastic variations and to provide a more consistent and compatible data set for estimating the stochastic errors. Average standard deviations were computed for all stations and combined to establish average error bounds for varying lengths of series. This provides a reliable and unbiased estimate of the expected error bounds for the FRED datum computation.

The data were divided into regional areas (South East Alaska, Gulf of Alaska, Aleutian Islands and the Bering Strait to Beaufort Sea) along the Alaskan coastline to look for regional bias. Figure 5 shows a 6 cm regional difference of the 1 month standard deviation down to a 1 cm regional difference for 120 months. Tides in the Bering Strait, Chuckchi Sea to Beaufort Sea are characterized by relatively shallow water, low tidal ranges (< 0.3 m (1ft)) and significant meteorological influence. These meteorological influences have a larger impact on the variability of the short period FRED datum computation (1 and 3 month), but are increasingly muted out by the averaging of data over the longer time periods. Starting at the 6 month time period, the Bering and Beaufort Sea errors converge with South East and Gulf of Alaska. The Aleutian Islands on the other hand have a relatively larger tidal range (~ 1 m (3.3ft)) and are of a tidally dominated regime and are generally isolated islands surrounded by relatively deep water. The smaller standard deviations may be the result of the absence of significant random meteorological effects on water levels. Similarly, the smaller values and trends of the FRED datum errors in Southeast Alaska and Gulf of Alaska probably is a result of the comparable tidal characteristics (very large tidal ranges) between the two regions. Given the minimal differences between regions, it is reasonable to use the sum total average for all stations to provide a representative FRED datum computation error for the entire region.

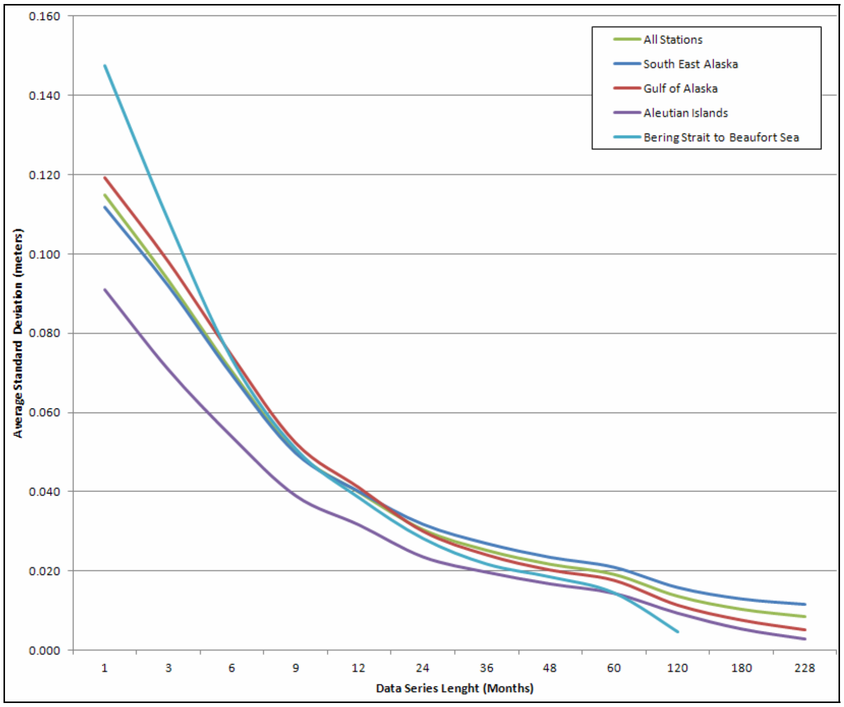

Figure 5: Regional distribution of FRED errors for coastal Alaska.

A comparison of the averaged error for the FRED datum between the present study and the earlier analyses (Stoney et al, 1983) shows a variation of 0.7cm to 1.1cm. The current results have a slightly higher error over all. Table 4 shows the results of these comparisons and a graphical representation can be viewed in figure 6. There are multiple factors that may impact the results. First, the current data series includes a significantly larger number of stations and covers a broader area of Alaska having different tidal dynamics than those presented in the original publication notably in the area of the Bering Strait to Beaufort Sea areas. Secondly, many of the stations have significant uncertainty in their estimated sea level trends which may in turn add uncertainty to the detrended data series. For instance, Sitka has a long-record with a sea level trend (-2.05 mm/yr) determined with low standard error, shows no evidence of acceleration or deceleration over time and the data series show no obvious discontinuities. Thus the comparison of the earlier and updated results for Sitka show very good agreement (Table 5.)

	Current Analysis	Origional Paper	
Months	**DS**	**DS**	**differences**
1	0.115	0.104	0.011
3	0.093	0.085	0.008
6	0.070	0.060	0.010
9	0.050	0.041	0.009
12	0.040	0.031	0.009
24	0.030	0.023	0.007
36	0.025	0.018	0.007
48	0.022	0.014	0.008
60	0.019	0.011	0.008
120	0.014		
180	0.010		
228	0.008		

Table 4: Comparison of the sum total FRED error values between the current analysis and original paper (values are in meters)

	Current Analysis	Origional Paper	
Months	DS	DS	differences
1	0.111	0.110	0.001
3	0.093	0.091	0.001
6	0.069	0.067	0.001
9	0.045	0.043	0.002
12	0.033	0.030	0.003
24	0.025	0.024	0.000
36	0.019	0.018	0.001
48	0.016	0.015	0.001
60	0.014	0.012	0.001
120	0.009		
180	0.006		
228	0.009		

Table 5: Comparison of the FRED error values for Sitka 9451600 station between the current analysis and original paper (values are in meters)

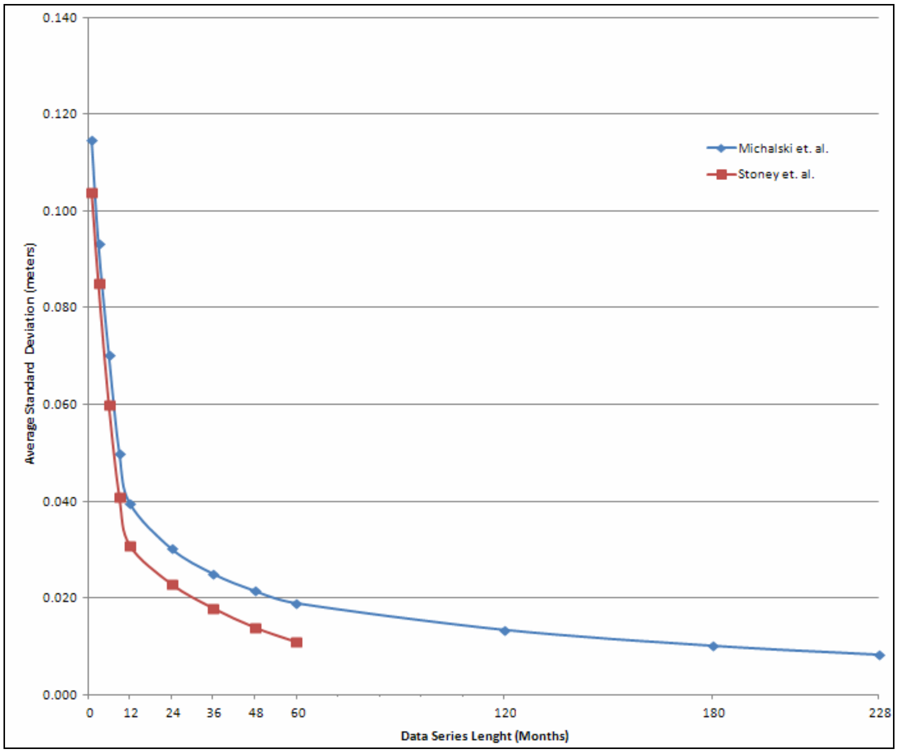

Figure 6: Comparison of current analysis and original paper error estimates

Table 2 also shows two stations that appear to be outliers relative to the other stations because they have significantly larger standard deviations. Water levels at Nome (9468756) are affected routinely by coastal storms with extreme events often masking the tidal signal during ice-free months, Yakutat (9453220) may have non-linear rates of vertical land motion. Thus, there are multiple factors that may attribute to the anomalies. It is possible that the rate of terrestrial movement due to isostatic rebound has changed during the observed data series. This would affect the relative trend of MTL data and cause an increased standard deviation in the data. Though this study detrended the data, it did not eliminate the non-linear trends in terrestrial movement. Tectonic shifts from seismic activity have been known to severely change the rates and directions (up or down) of crustal movement. Since Alaska is a tectonically active area, there have been multiple tectonic events that have occurred during the time period of data used in this analysis. Some of the water level stations have shorter time periods than necessary to compute accurate sea level trend. These stations may have data observations during a short term regional oceanographic anomaly (storm surge, small scale eddy, local current, etc) lasting a few weeks or months, which affected a significant portion of the time series. More analysis is necessary to determine the cause of these stations to appear to be outliers.

5. SUMMARY

There are large coastal areas in Alaska and other parts of the US coastline where sufficient NWLON datum computation control does not exist as defined by Gill and Fisher (2008). For these areas, it is still necessary to compute the tidal datum using a FRED analysis technique. The use of a FRED datum computation method causes there to be a higher datum error than the surrounding area where there is sufficient NWLON coverage for datum control. This is an important factor that needs to be considered when using the tidal datums for various applications. Users need to be aware of the errors in the vertical accuracy for the tidal datum they are using and ensure the errors do not exceed their allowance for the total error. The northern extent of Alaska is an example of an area with extensive NWLON gaps and its unique environment (remote location, lack of infrastructure, seasonal ice coverage, shallow bathymetric slope, etc.) limits the ability to install a long term water level gauge. The seasonal ice coverage results in a 3-4 month window allowing for short-term station installation. Current technology and lack of infrastructure do not facilitate the installation of standard long term NWLON water level stations within the Arctic. For the time being, until technology improves and infrastructure is established, the method for installing a long term water level station in these regions is limited to offshore bottom mounted pressure system as utilized in Barrow, Alaska (Sprenke et. al. 2011). However, this style of installation is expensive and requires special procedures to be able to verify stability and accuracy of the sensor.

This analysis estimates the standard deviations for short term FRED tidal datum computations in Alaska (see figure 4 and table 3). These standard deviations can be used to infer the vertical accuracies of FRED tidal datums. The average standard deviation for all stations used in this analysis suggests that the vertical error of a one month FRED datum and a 19 year FRED datum are 0.115 m (0.38ft) and 0.008 m (0.03ft) respectively. This results in an improvement of 0.107 m (0.35ft) between the short term and long term time periods. From figure 4 the slope of the line shows that the greatest reduction in error occurs between 1-12 months. After that time period the slope of the line decreases. Until sufficient NWLON coverage is available in western and northern Alaska, the vertical error associated with the FRED tidal datums will remain one of main errors of tide reductions. This analysis presents a mechanism for determining the vertical errors associated with FRED datum computations for varying time series.

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BIOGRAPHICAL NOTES

Michael Michalski is the Datums team lead for the Center for Operational Oceanographic Products and Services, Oceanographic Division.

Lijuan Huang works with the Hydrographic Planning team for the Center for Operational Oceanographic Products and Services, Oceanographic Division.

Jerry Hovis is the Chief, Products and Services Branch of the Center for Operational Oceanographic Products and Services, Oceanographic Division.

CONTACTS

Michael Michalski (Michael.Michalski@noaa.gov)
Lijuan Huang (Lijuan.Huang@noaa.gov)
Gerald Hovis (Gerald.Hovis@noaa.gov)

Products and Services Branch
Oceanographic Division
Center for Operational Oceanographic Products and Services
National Ocean Service
NOAA
1305 East-West Highway, Silver Spring, MD 20910-3218
USA
1-301-713-2890
1-301-713-4437
www.tidesandcurrents.noaa.gov