Dynamic Heights in the Great Lakes at Different Epochs (Abstract ID 120663)
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ABSTRACT

Vertical control in the Great Lakes region is currently defined by the International Great Lakes Datum of 1985 (IGLD 85) in the form of dynamic heights. Starting in 2025, dynamic heights will be defined through GNSS-derived geometric coordinates and a geopotential model. This paper explores the behavior of an existing geopotential model at different epochs when the Great Lakes were at significantly different (meter-level) geopotential surfaces. Water surfaces were examined in 2015 and 2010 at six sites on Lakes Superior and Lake Erie (three on each Lake). These sites have collocated a Continuously Operating Reference Station (CORS) and a Water Level Sensor (WLS). The offset between the antenna phase center for the CORS and the WLS datum are known at each site. The WLS then measures the distance from its datum to the Lake surface via an open well. Thus it is possible to determine the height above an ellipsoid datum at these sites as long as both the CORS and WLS are operational. The geometric coordinates are then used to estimate the geopotential value from the xGEOID16B model. This accomplished in two steps. To provide an improved reference model, EGM2008 was spectrally enhanced using observations from the GOCE satellite gravity mission and aerogravity from the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Project. This enhanced model, xGEOID16B_Ref, is still only a five arcminute resolution model (d/o 2160), but resolves dynamic heights at about 2 cm on Lake Superior for December 2015. The reference model was primarily developed to determine a one arcminute geoid height grid, xGEOID16B, available on the NGS website. This geoid height model was used to iteratively develop improved geopotential value for each of the site locations, which then improved comparisons to the cm-level. Comparisons were then made at the 2010 epoch for these same locations to determine if the performance of the geopotential model was consistent.

Introduction

This paper will discuss the determination of dynamic heights in the Great Lakes region using GNSS-derived ellipsoidal coordinates on CORS in conjunction with geophysical models. Such a model will likely replace the International Great Lakes Datum of 1985 (IGLD 85) in about 2025. The Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Project has been underway for the past eight years with the specific goal of providing the geopotential model that will serve as the basis for this. Experimental models are being developed that exclude (xGEOID16A) and include (xGEOID16B) the GRAV-D data.

This is necessary because IGLD 85 uses the same geopotential values as that of the North American Vertical Datum of 1988 (NAVD 88), which has demonstrated meter-level tilts when compared to GRACE-based EGM models at continental scales. Figure 1 highlights this and compares to Hydraulic Correctors (HC) developed primarily to ensure that the dynamic heights for IGLD 85 are level when comparing on the same Lake.

Available Data

Figure 2 shows the locations of WLS located in the Great Lakes. Three sites are circled in Lake Superior and three in Lake Erie. These sites contain a CORS antenna and receiver at the WLS site. Figure 3 shows a typical setup with CORS on a WLS station at Marquette. Figure 4 shows the relationship between the CORS, WLS sensor, and the Lake surface. An Electronic Tape Gauge (ETG) sited on a table (datum) in the WLS housing drops a plumb into a well connected to the Lake. When the plumb touches the surface, a circuit completes and the water surface is measured. Knowing the offset between the CORS ARP and ETG table, as well as the ETG table and the water surface, provides geometric coordinates for the water surface.

A mean value for the Summer months in 2015 was used. Figure 5 shows the monthly means in October for Buffalo (east end of Lake Erie) and Marblehead (west end of Lake Erie). Note the meter level changes in Lake level due to a Winter storm event. Hence monthly means can be skewed especially from October through December. Winter months are ice covered and problematic. So only data from June through September (Summer) were used (column G in Table 1). Ultimately, the ellipsoid heights of the water surface were derived (columns O1-O4 Table 1) for four different epochs: 2015, 2010, 2005, and 1997. The coordinates in Table 1 were used in Table 2 through 5 to develop dynamic heights.

Analysis

The xGEOID16B geoid height model was developed using the xGEOID16B_REF model. It is a one arcminute resolution model developed using R-C-R technique. It provides geoid heights only (column P) and can determine orthometric heights (Q). However, orthometric heights are not suited for use in determining water levels. Hence, dynamic heights were determined using geopotential values were derived from five arcminute EGM's. Models include: EGM2008 (R), EIGEN6c4 (S), xGEOID16A_REF (T), and xGEOID16B_REF (U). A W0 value of 62,636,856.00 m2/s2 was used, because that is the value adopted by the U.S. for the future vertical datum. Finally, the geoid height derived from the xGEOID16A_REF model was removed from the xGEOID16A value to determine the residual geoid signal for one to five arcminutes. Gravity values from xGEOID16A_REF were used to develop approximate residual geopotential numbers that were applied to develop more complete estimates of the dynamic height (V). This was then duplicated for xGEOID16B and xGEOID16B_REF in column W.

Next to each estimate of the dynamic height, a difference is developed between the maximum and minimum estimate of the dynamic heights for each of the two Lakes. Ideally, all values on the Lake surface would be nearly the same with some potential slope towards the ocean-side. As can be seen, the xGEOID16A and xGEOID16B do not always produce the best comparisons. For example, in 2015, xGEOID16B had a difference of 0.015 m, while the xGEOID16A_REF and EIGEN6c4 models had slightly lower comparisons (highlighted in red lettering). The xGEODI16B results was surpassed by one of the reference models in most cases but did have the lowest differences on a more consistent basis. Also, the addition of the airborne data had significant impact in that the xGEOID16B and xGEOID16B_REF models, surpassed the xGEOID16A and xGEOID16A_REF models. Including the airborne data improved the comparisons.

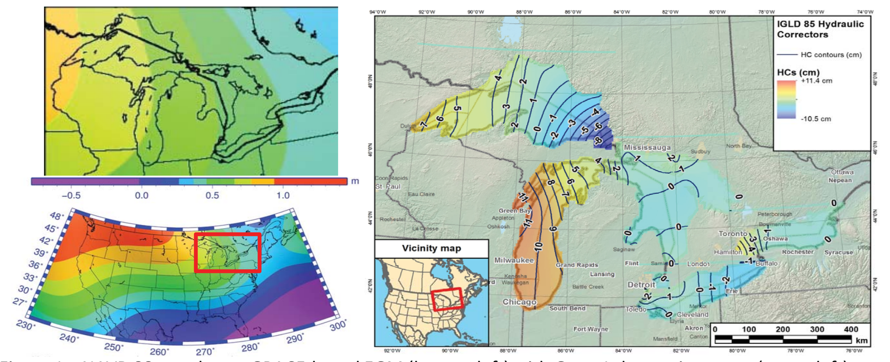

Figure 1. NAVD 88 trend w.r.t. GRACE-based EGM (bottom left) with Great Lakes region zoom (upper left) corresponds to hydraulic Correctors (HC) for each Lake. Relative trends conform to NAVD 88 trend surface.

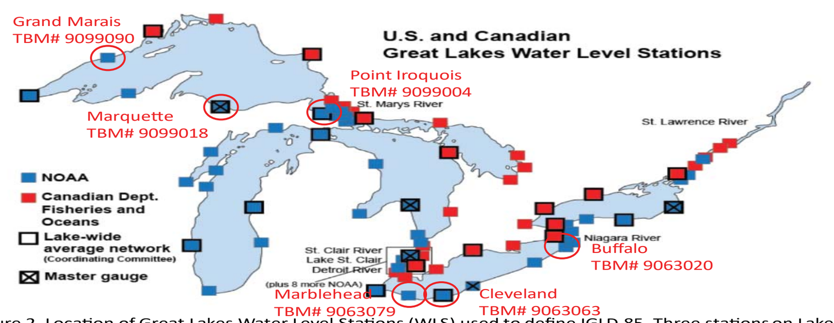

Figure 2. Location of Great Lakes Water Level Stations (WLS) used to define IGLD 85. Three stations on Lake Superior and three on Lake Erie (red circles) have collocated CORS and are examined in this paper.

Figure 3. WLS and collocated CORS i(MIMQ) n Marquette, Wisconsin. Distance was measured from CORS ARP to the Eletronic Tape Gauge (ETG) on the bench in the structure. Drops are made from the ETG table to a well freely connected to the water surface. When the sensor hits the water and completes an electric circuit, the distance is recorded. This provides a means to transfer the water level surface into geometric coordinates.

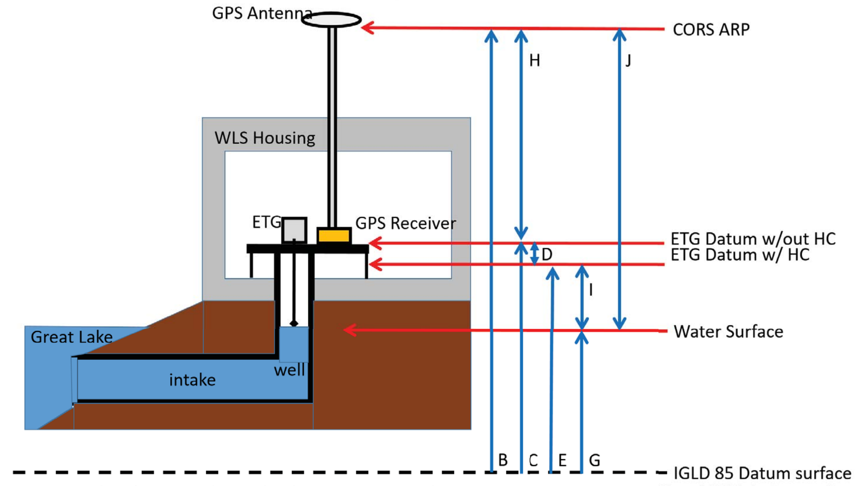

Figure 4. Graphic showing relationship between various datum points at sites with CORS and WLS. Letters refer to Table 1 columns. Note that ETG table doesn't move but that positions in HC & non-HC frames differ.

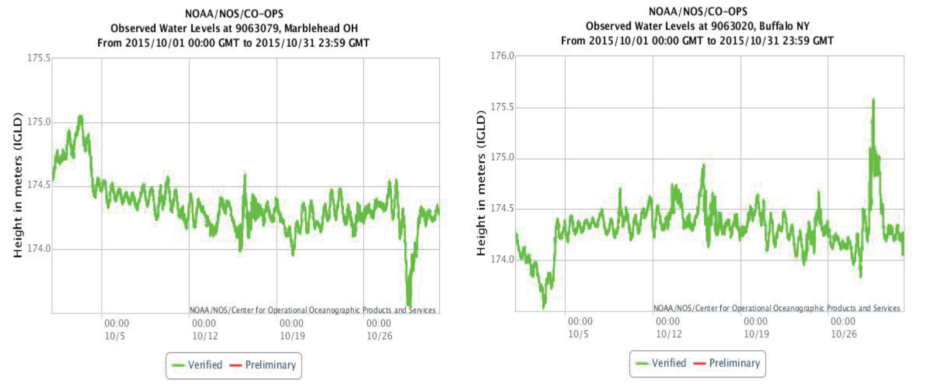

Figure 4. Observed water levels above IGLD 85 for the month of October 2015 at Marblehead (west end of Lake Erie) and Buffalo (east end of Lake Erie). Note inverse relationship of water levels. Storms blow strongly west to east starting in October and has significant (meter-level) effects on heights and monthly means.

Conclusion

Use of a geopotential model by itself is not yet sufficient to derive cm-level accurate dynamic heights. Incorporating shorter wavelength signal from a higher resolution geoid model holds some promise. This correlates with earlier analysis that showed a one arcminute model was necessary to keep omission errors at cm-level. Water topography issues must also be addressed. Significant wave action occurs on the Lakes. Meaning over the Summer months may not be sufficient to address the variability in water surface. Finally, only three sites are compared on each Lake. This is not sufficient for statistical analysis. While there are a few more CORS collocated with WLS stations, more sites will actually be gained from campaign GPS on WLS stations (i.e., all the sites given in Figure 2).

Table 1. Derived coordinates for six WLS staions with collocated CORS. Dynamic heights are given for (a) 2015, (b) 2010, (c) 2005 and (d) 1997.

Column	A	B	C	D	E	F	G1	G2	G3	G4	H	I	J	K	L	M	N	O1	O2	O3	O4
Station	Location	CORS ARP HT	ETG Table HT	Hydraulic Correctors (HC)	ETG (HC) Table HT	2015 mean WL HT	2015 Summer mean (HC) WL HT	2010 Summer mean (HC) WL HT	2005 Summer mean (HC) WL HT	1997 Summer mean (HC) WL HT	CORS ARP to ETG Table	ETG (HC) Table to Summer mean (HC) WL	CORS ARP to Summer mean WL	CORS Site ID	Latitude of CORS ARP	Longitude of CORS ARP	HAE of CORS ARP	2015 HAE of Summer mean WL	2010 HAE of Summer mean WL	2005 HAE of Summer mean WL	1997 HAE of Summer mean WL
Units		m	m	m	m	m	m	m	m	m	m	m	m		dec. deg. (N)	dec. Deg. (E)	m	m	m	m	m
Datum		IGLD85	IGLD85		IGLD85	IGLD85	IGLD85	IGLD85	IGLD85	IGLD85					IGS08	IGS08	IGS08	IGS08	IGS08	IGS08	IGS08
9063020	**Buffalo**	181.784	178.283	-0.026	178.309	174.306	**174.559**	**174.204**	**174.180**	**174.879**	3.501	3.747	7.248	BFNY	**42.8775570**	**281.1095550**	145.462	**138.214**	**137.859**	**137.835**	**138.534**
9063063	**Cleveland**	180.097	177.151	0.010	177.141	174.314	**174.599**	**174.195**	**174.188**	**174.880**	2.947	2.544	5.491	OHCD	**41.5407449**	**278.3648537**	144.582	**139.091**	**138.687**	**138.680**	**139.372**
9063079	**Marblehead**	179.493	177.187	-0.006	177.193	174.310	**174.606**	**174.190**	**174.192**	**174.882**	2.307	2.588	4.895	OHMH	**41.5436836**	**277.2685451**	142.866	**137.971**	**137.555**	**137.557**	**138.247**
9099004	**Pt. Iroquois**	188.880	186.091	-0.100	186.191	183.565	**183.660**	**183.182**	**183.376**	**183.669**	2.789	2.530	5.319	PTIR	**46.4845832**	**275.3691597**	151.362	**146.043**	**145.565**	**145.759**	**146.052**
9099018	**Marquette**	190.951	187.506	0.000	187.506	183.597	**183.694**	**183.201**	**183.397**	**183.683**	3.445	3.812	7.257	MIMQ	**46.5455481**	**272.6213039**	155.102	**147.845**	**147.352**	**147.548**	**147.834**
9099090	**Grand Marais**	189.158	186.239	0.046	186.193	183.592	**183.692**	**183.190**	**183.399**	**183.678**	2.918	2.500	5.418	GDMA	**47.7485523**	**269.6587485**	157.364	**151.946**	**151.444**	**151.653**	**151.932**

Table 2. Comparisons for 2015 water levels against various geoid model derived dynamic heights. Location information for the six sites in Table (1) for 2015 are given in this table. Columns A, G1, L, M, and O1 are repeated here. Columns Pa and Qa refers to geoid height information from xGEOID16A, while Qb refers to xGEOID16B. Columns R, S, T and U refer to dynamic heights derived from five arc-minute reference field models: EGM2008, EIGEN6c4, xGEOID16A_REF, and xGEOID16B_REF. Columns V and W refer to high resolution models xGEOID16A and xGEOI16B, respectively. The values then show dynamic heights for 2015 at three locations on Lake Erie and three on Lake Superior. 'Max - Min" describes the range in values. The expecatation is that all dunamic heights are nearly the same (0.00). Increased range of values means less certainty in result. Values in red refer to cases where the reference field values outperform the xGEOID16B high resolution value.

Column	A	G1		L	M	O1	Pa	Qa		Pb	Qb		R		S		T		U		V		W	
Station	Location	Summer mean (HC) WL HT	Max – Min	Latitude of CORS ARP	Longitude of CORS ARP	HAE of Summer mean WL	Geoid Height	Ortho Height	Max – Min	Geoid Height	Ortho Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min
Units		m	m	dec. deg. (N)	dec. Deg. (E)	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m
Datum		IGLD85	<<	IGS08	IGS08	IGS08	xGEOID16A	xGEOID16A	<<	xGEOID16B	xGEOID16B	<<	EGM2008	<<	EIGEN6c4	<<	xGEOID16A_REF	<<	xGEOID16B_Ref	<<	xGEOID16A		xGEOID16B	
9063020	**Buffalo**	174.559		42.8775570	78.8904450	138.214	-35.843	174.057		-35.838	174.052		174.014		173.997		174.016		174.011		174.009		174.004	
9063063	**Cleveland**	174.599	0.048	41.5407449	81.6351463	139.091	-34.968	174.059	0.031	-34.996	174.087	0.036	174.023	0.021	174.011	**0.014**	174.011	**0.013**	174.033	0.022	173.991	**0.025**	174.019	**0.015**
9063079	**Marblehead**	174.606		41.5436836	82.7314549	137.971	-36.117	174.088		-36.117	174.088		174.002		174.005		174.024		174.026		174.016		174.016	
9099004	**Pt. Iroquois**	183.660		46.4845832	84.6308403	146.043	-36.949	182.992		-36.940	182.983		182.981		182.977		183.000		182.990		183.001		182.992	
9099018	**Marquette**	183.694	0.034	46.5455481	87.3786961	147.845	-35.136	182.981	0.061	-35.131	182.976	0.048	182.997	0.027	183.012	0.042	183.026	0.040	183.013	0.023	182.996	**0.025**	182.992	**0.012**
9099090	**Grand Marais**	183.692		47.7485523	90.3412515	151.946	-30.985	182.931		-30.989	182.935		182.970		182.970		182.986		182.995		182.976		182.980	

Table 3. Comparisons for 2010 water levels against various geoid model derived dynamic heights. Location information for the six sites in Table (1) for 2015 are given in this table. Columns A, G2, L, M, and O2 are repeated here. See Table 2 caption for further details.

Column	A	G2		L	M	O2	Pa	Qa		Pb	Qb		R		S		T		U		V		W	
Station	Location	Summer mean (HC) WL HT	Max – Min	Latitude of CORS ARP	Longitude of CORS ARP	HAE of Summer mean WL	Geoid Height	Ortho Height	Max – Min	Geoid Height	Ortho Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min
Units		m	m	dec. deg. (N)	dec. Deg. (E)	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m
Datum		IGLD85	<<	IGS08	IGS08	IGS08	xGEOID16A	xGEOID16A	<<	xGEOID16B	xGEOID16B	<<	EGM2008	<<	EIGEN6c4	<<	xGEOID16A_REF	<<	xGEOID16B_Ref	<<	xGEOID16A		xGEOID16B	
9063020	**Buffalo**	174.204		42.8775570	78.8904450	137.859	-35.843	173.702		-35.838	174.052		173.660		173.642		173.661		173.656		173.655		173.650	
9063063	**Cleveland**	174.195	0.048	41.5407449	81.6351463	138.687	-34.968	173.655	0.047	-34.996	174.087	0.036	173.619	0.073	173.607	0.052	173.607	0.054	173.629	**0.045**	173.588	**0.067**	173.616	**0.049**
9063079	**Marblehead**	174.190		41.5436836	82.7314549	137.555	-36.117	173.672		-36.117	174.088		173.587		173.590		173.609		173.611		173.601		173.601	
9099004	**Pt. Iroquois**	183.182		46.4845832	84.6308403	145.565	-36.949	182.514		-36.940	182.983		182.503		182.499		182.522		182.512		182.523		182.514	
9099018	**Marquette**	183.201	0.034	46.5455481	87.3786961	147.352	-35.136	182.488	0.085	-35.131	182.976	0.048	182.504	**0.036**	182.519	0.051	182.533	0.049	182.520	**0.027**	182.503	**0.049**	182.499	**0.036**
9099090	**Grand Marais**	183.190		47.7485523	90.3412515	151.444	-30.985	182.429		-30.989	182.935		182.468		182.468		182.484		182.493		182.474		182.478	

Table 4. Comparisons for 2005 water levels against various geoid model derived dynamic heights. Location information for the six sites in Table (1) for 2015 are given in this table. Columns A, G3, L, M, and O3 are repeated here. See Table 2 caption for further details.

Column	A	G3		L	M	O3	Pa	Qa		Pb	Qb		R		S		T		U		V		W	
Station	Location	Summer mean (HC) WL HT	Max – Min	Latitude of CORS ARP	Longitude of CORS ARP	HAE of Summer mean WL	Geoid Height	Ortho Height	Max – Min	Geoid Height	Ortho Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min
Units		m	m	dec. deg. (N)	dec. Deg. (E)	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m
Datum		IGLD85	<<	IGS08	IGS08	IGS08	xGEOID16A	xGEOID16A	<<	xGEOID16B	xGEOID16B	<<	EGM2008	<<	EIGEN6c4	<<	xGEOID16A_REF	<<	xGEOID16B_Ref	<<	xGEOID16A		xGEOID16B	
9063020	**Buffalo**	174.180		42.8775570	78.8904450	137.835	-35.843	173.678		-35.838	174.052		173.636		173.618		173.637		173.632		173.631		173.626	
9063063	**Cleveland**	174.188	0.048	41.5407449	81.6351463	138.680	-34.968	173.648	0.030	-34.996	174.087	0.036	173.612	0.047	173.600	0.026	173.600	0.037	173.622	**0.019**	173.581	**0.050**	173.609	**0.023**
9063079	**Marblehead**	174.192		41.5436836	82.7314549	137.557	-36.117	173.674		-36.117	174.088		173.589		173.592		173.611		173.613		173.603		173.603	
9099004	**Pt. Iroquois**	183.376		46.4845832	84.6308403	145.759	-36.949	182.708		-36.940	182.983		182.697		182.693		182.716		182.706		182.717		182.708	
9099018	**Marquette**	183.397	0.034	46.5455481	87.3786961	147.548	-35.136	182.684	0.070	-35.131	182.976	0.048	182.700	0.023	182.715	0.038	182.729	0.036	182.716	**0.014**	182.699	**0.034**	182.695	**0.021**
9099090	**Grand Marais**	183.399		47.7485523	90.3412515	151.653	-30.985	182.638		-30.989	182.935		182.677		182.677		182.693		182.702		182.683		182.687	

Table 5. Comparisons for 1997 water levels against various geoid model derived dynamic heights. Location information for the six sites in Table (1) for 2015 are given in this table. Columns A, G4, L, M, and O4 are repeated here. See Table 2 caption for further details.

Column	A	G4		L	M	O4	Pa	Qa		Pb	Qb		R		S		T		U		V		W	
Station	Location	Summer mean (HC) WL HT	Max – Min	Latitude of CORS ARP	Longitude of CORS ARP	HAE of Summer mean WL	Geoid Height	Ortho Height	Max – Min	Geoid Height	Ortho Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min	Dynamic Height	Max – Min
Units		m	m	dec. deg. (N)	dec. Deg. (E)	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m	m
Datum		IGLD85	<<	IGS08	IGS08	IGS08	xGEOID16A	xGEOID16A	<<	xGEOID16B	xGEOID16B	<<	EGM2008	<<	EIGEN6c4	<<	xGEOID16A_REF	<<	xGEOID16B_Ref	<<	xGEOID16A		xGEOID16B	
9063020	**Buffalo**	174.879		42.8775570	78.8904450	138.534	-35.843	174.377		-35.838	174.052		174.334		174.317		174.336		174.331		174.329		174.324	
9063063	**Cleveland**	174.880	0.048	41.5407449	81.6351463	139.372	-34.968	174.340	0.037	-34.996	174.087	0.036	174.304	0.056	174.292	0.036	174.292	0.044	174.313	**0.029**	174.272	**0.057**	174.300	**0.032**
9063079	**Marblehead**	174.882		41.5436836	82.7314549	138.247	-36.117	174.364		-36.117	174.088		174.278		174.281		174.300		174.302		174.292		174.292	
9099004	**Pt. Iroquois**	183.669		46.4845832	84.6308403	146.052	-36.949	183.001		-36.940	182.983		182.990		182.986		183.009		182.999		183.010		183.001	
9099018	**Marquette**	183.683	0.034	46.5455481	87.3786961	147.834	-35.136	182.970	0.084	-35.131	182.976	0.048	182.986	**0.034**	183.001	0.045	183.015	0.043	183.002	**0.021**	182.985	**0.048**	182.981	**0.035**
9099090	**Grand Marais**	183.678		47.7485523	90.3412515	151.932	-30.985	182.917		-30.989	182.935		182.956		182.956		182.972		182.981		182.962		182.966	