Vertical Motion Observed by Satellite Altimetry and Tide Gauges

Chung-Yen Kuo[1], C.K. Shum[1], and A. Braun[2]

[1]Laboratory for Space Geodesy and Remote Sensing Research, Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, 2070 Neil Avenue, Columbus, Ohio 43210-1275, USA. Tel: 614-292-7118; Fax: 614-292 2957; Emails: kuo.70@osu.edu; ckshum@osu.edu.

[2]University of Calgary, Calgary, Canada.

ABSTRACT

In principle, the difference between the sea surface height changes measured by tide gauge and altimeter is the vertical motion at the tide gauge. Combining long-term tide gauge and decadal altimetry observations to infer vertical motion of the solid Earth has been proposed by prior studies. An attempt to use this technique resulted in vertical motion solutions with uncertainties >>2 mm/yr, rendering the technique not as viable. Here we describe a novel technique, which is an improved algorithm used by Kuo et al. [2004] which used long-term tide gauge records (>30 years) and decadal TOPEX altimeter and a stochastic network adjustment approach in the semi-enclosed Baltic Sea and in the Great Lakes to determine vertical motion at tide gauge sites at an accuracy <0.5 mm/yr. This extended algorithm could potentially apply to worldwide tide gauges for improved determination of vertical motions, which the primary purpose to improve sea level determination to also potentially include more sites which previously are not used because of unknown vertical motions, including tectonic activities.

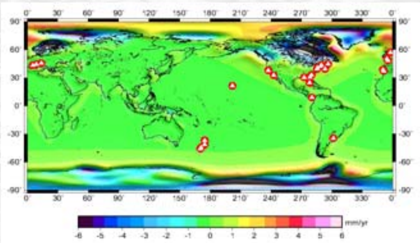
Objectives

This study explores the use of satellite altimetry (10 to 15 years data span) and tide gauge (decades to 100 years) data to "measure" crustal uplift component of the vertical motion in regions considered to be dominated by effect of Glacial isostatic adjustment (GIA) such as the Great Lakes and Scandinavia. Additionally, vertical motion in Alaska region caused by postseismic deformation is computed. Preliminary result of Vertical motion in Adriatic Sea is also presented.

GIA

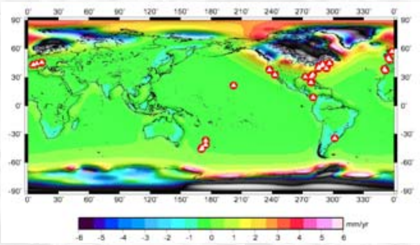
Glacial isostatic adjustment (GIA) of the solid Earth due to deglaciation since the last Ice Age is characterized primarily by its viscous rebound on the mantle as a result of relaxation of the shear stresses inside the Earth. In addition to models e.g., the ICE-4G (VM2) model [Peltier, 1998], the model from Wu et al. [2005], and the model based on BIFROST data (Milne et al. [2001]), GIA uplift has been recently measured using long-term GPS (e.g., the BIFROST project) [Milne et al., 2001].

ICE4G

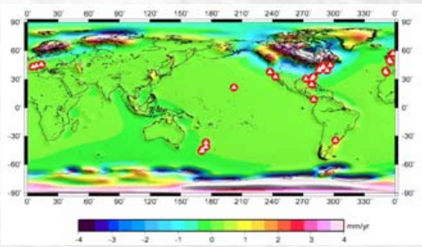


BIFROST model

withLT=120km, LMV=1×10[21] Pas, and UMV=3×10[21]Pas



Difference between ICE4G and BIFROST



Mean of the difference is 0.13±0.63 mm/yr

Method

The rate of vertical motion: $\dot{u}(\lambda,\varphi)=\dot{g}(\lambda,\varphi)-\dot{S}(\lambda,\varphi)$

$\dot{S}$ **is relative sea level change from tide gauges;** $\dot{g}$ **is the rate of absolute sea level change from altimetry.**

Relative vertical motion between two adjacent tide gauges:

$$r\dot{u}_{ij}=\dot{u}_i(\lambda_i,\varphi_i)-\dot{u}_j(\lambda_j,\varphi_j)$$
$$=\dot{g}_i(\lambda_i,\varphi_i)-\dot{S}_i(\lambda_i,\varphi_i)-\dot{g}_j(\lambda_j,\varphi_j)+\dot{S}_j(\lambda_j,\varphi_j)$$

Gauss-Markov (GM) model :

$$y=A\xi+e \quad with \quad e\sim(0,\sigma_0^2P^{-1}=\Sigma)$$

The solution of vertical motion:

$$\hat{\xi}=(A^TPA)^{-1}(A^TPy) \quad \hat{D}\{\hat{\xi}\}=\hat{\sigma}_0^2(A^TPA)^{-1}$$
$$with \quad \hat{\sigma}_0^2=(y^TPy-A^TPy\hat{\xi})/(n-m+l)$$

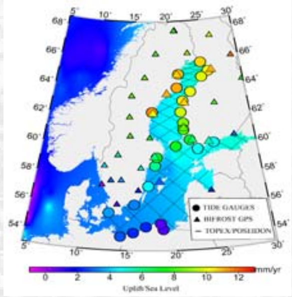
Conclusions

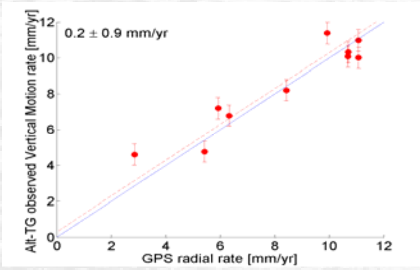
We used satellite altimetry and tide gauges to determine secular vertical (crustal uplift) motion in the Great Lakes region. Results indicate reasonable agreement with GIA models and Mainville and Craymer [2003] . Result in Baltic Sea agrees well with GPS solution. In addition, quadratic vertical motion due to postseismic deformation in Alaska region has been computed and analyzed.

In Baltic Sea

Tide gauge: Monthly tide gauge data from 25 Stations provided by PSMSL

Altimetry: TOPEX/POSEIDON Cycle 4-300 (1992~2001).

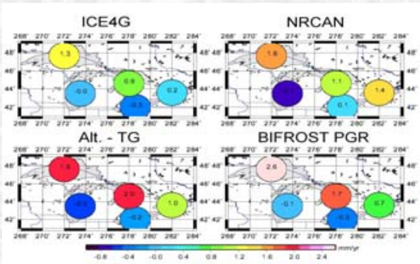




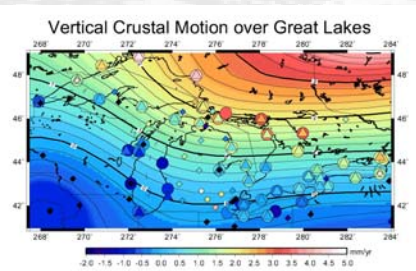
In Great Lakes

Water level gauge: Daily tide gauge data from 27 water level stations in USA from NOAA/CO-OPS and 23 Canadian stations from MEDS

Altimetry: TOPEX/POSEIDON Cycle 4-300 (1992~2001).



Estimates of absolute vertical motions averaged in each lake compared with ICE4G, BIFROST PGR, and water level gauge analysis [Mainville and Craymer, 2003].



Estimates of absolute or geocentric vertical motions (circles) at 50 water level gauge sites in the Great Lakes derived by combining TOPEX/POSEIDON decadal altimeter data and long-term water level gauge records. The background is ICE4G [Peltier, 2002]. The diamonds are GPS velocity [NGS solution, M. Cline and R. Snay, personal communications, 2004]. The triangles present the vertical motions from water level gauges analysis [Mainville and Craymer, 2003].

#	Observation/Model	Mean of difference (mm/yr)	STD. (mm/yr)
M1	BIFROST LT=120 UMV=1 LMV=10	1.4	1.2
M2*	BIFROST LT=120 UMV=1 LMV=10	1.3	1.0
M3	BIFROST LT=120 UMV=1 LMV=3	-0.1	0.9
M4*	BIFROST LT=120 UMV=1 LMV=3	0.1	0.8
M5	BIFROST LT=120 UMV=.5 LMV=3	-0.2	0.7
M6*	BIFROST LT=120 UMV=.5 LMV=3	0.0	0.6
M7	ICE4G LT=120 UMV=.5 LMV=3	0.1	0.9
M8*	ICE4G LT=120 UMV=.5 LMV=3	-0.1	0.9
M9	Wu at al. [2005]	1.8	1.0
M10*	Wu at al. [2005]	1.3	0.9
M11	ICE3G LT=120 UMV=1 LMV=2	-0.2	0.6
M12	Mainville and Craymer [2003] analysis	-0.1	0.5

* : Crustal motion + geoid change

Method

Equations with time as a variable are to include quadratic vertical motion. The vertical motion:

$$u_{i,t}(\lambda_i,\varphi_i)=g_{i,t}(\lambda_i,\varphi_i)-S_{i,t}(\lambda_i,\varphi_i)=a_i+b_i(t-t_0)+c_i(t-t_0)^2$$

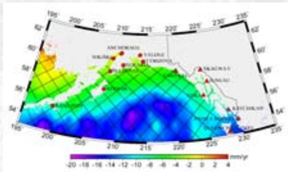
Relative vertical motion between two adjacent tide gauges:

$$ru_{ij,t}=-S_{i,t}(\lambda_i,\varphi_i)+S_{j,t}(\lambda_j,\varphi_j)=u_{i,t}-u_{j,t}=a_i+b_i(t-t_0)+c_i(t-t_0)^2$$
$$-a_j-b_j(t-t_0)-c_j(t-t_0)^2$$

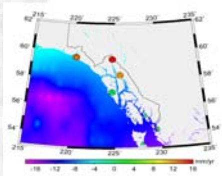
In Alaska

Tide gauge: Monthly tide gauge data from 15 Stations provided by PSMSL

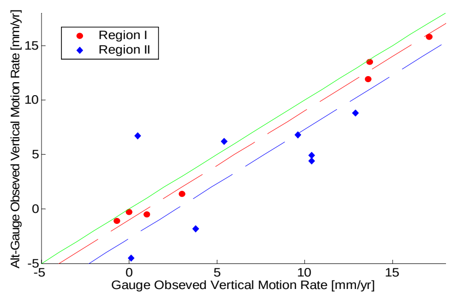
Altimetry: TOPEX/POSEIDON Cycle 4-360 (1992~2002).



All tide gauge stations are separated into two regions: Triangles (region I) and circles (region II).



Mean of difference is 0.65±0.85 mm/yr when comparing with GPS solution.



Mean of difference in region I is -1.0±0.7 mm/yr and in region II is -2.7±4.2 mm/yr (-4.8±1.2 mm/yr excluding stations NIKISKI and KODIAK) when comparing with solution from Larsen et al. [2003]

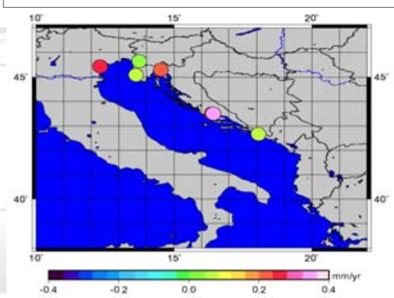
Tide gauge	Alt/TG (mm/yr) (parameters *a* and *b*)	GPS (mm/yr)	Larsen et al. [2003]
YAKUTAT	13.5 (8.6±1.2; 0.09±0.010)	13-14	13.7
SITKA	1.4	0 ~ -1	3.0
SKAGWAY	15.8	15 ~ 16	17.1
JUNEAU	11.9	11 ~ 12	13.6
KETCHIKAN	-0.3		0.0
PRINCE RUPERT	-1.1		-0.7
QUEEN CHARLOTTE CITY	-0.5		1.0
SAND POINT	-4.5		0.1
KODIAK	6.2 (7.7±1.7; -0.07±0.072)		5.4
ANCHORAGE	4.4 (-3.0±1.6; 0.35±0.060)		10.4
NIKISKI	6.7 (7.5±1.6; -0.04±0.081)		0.5
SELDOVIA	6.8		9.6
SEWARD	4.9 (-1.0±1.5; 0.28±0.041)		10.4
VALDEZ	8.8 (-1.2±1.5; 0.50±0.052)		12.9
CORDOVA	-1.8 (-7.5±1.5; 0.27±0.044)		3.8

Comparison of the absolute vertical motions derived from altimeter-tide gauges, GPS, and gauges [Larsen et al., 2003]. Uplift rates in year 2000. Parameters *a* and *b* are the coefficients of linear and quadratic terms respectively.

In Adriatic Sea

Tide gauge: Monthly tide gauge data from 7 Stations provided by PSMSL

Altimetry: TOPEX/POSEIDON Cycle 4-364.



Preliminary result of vertical motions are close to 0 mm/yr with formal errors at 0.7~0.8 mm/yr

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