University of Victoria

Department of Physics & Astronomy

PROCESSING CRUSTAL MOTION

GPS DATA

By

Malcolm Newson

Geological Survey of Canada - Pacific Division

Sidney, B.C.

Acknowledgments:

I would like to acknowledge my supervisor Thomas James for the guidance and support he provided. I would also like to acknowledge and thank Joe Henton who works for the Canadian Geodetic Survey, Natural Resources Canada, and who provided advice and support for the primary software package SPARK that was used for processing GPS positions.

Table of contents:

List of Figures

Introduction:

Relative sea-level change along the coast is a combination of global sea-level change and the Earth's surface's vertical motion. The land can be rising or falling for reasons including glacial isostatic adjustment (GIA) and active tectonics, while the global sea-level changes due to thermal expansion of water with rising temperatures and meltwater from glaciers and polar ice caps shrinking. Models of the Earth have a solid lithosphere sitting on top of a fluid mantle, which is a system closely linked to Archimedes and his investigations into buoyancy. A solid body immersed in a fluid with a greater density will experience a vertical force proportional to the volume of fluid displaced. Because the fluid mantle has a very high viscosity, the time scale of changes in the lithosphere position in response to changing loads on the surface is thousands to millions of years. These load changes are often related to water weight and can vary with the season, either in the form of rainfall and water tables, or frozen water in the form of glaciers and snow. The ocean's height varies tidally due to the motion of the moon and the sun but is also influenced by the amount of water in the ocean on global and local scales and the temperature of the water.

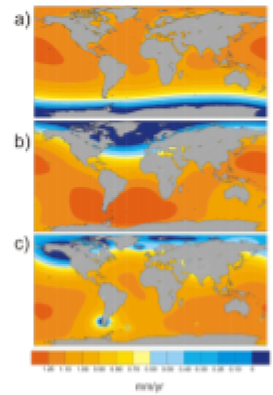

Figure 1: The amount of sea-level rise, in millimeters per year, for an assumed 1mm/yr contribution to global sea level rise from (a) Antarctica, (b) Greenland, and (c) mountains glacier and ice caps.

Consequences of sea level rise:

Relative sea-level change along our country’s coastlines significantly impacts infrastructure, coastal erosion, and water tables. Developing projections of relative sea-level change along Canada’s coasts provides information needed for policymakers to manage the effects of climate change. The projections require both vertical motion of the earth's surface and projections of global sea-level change.

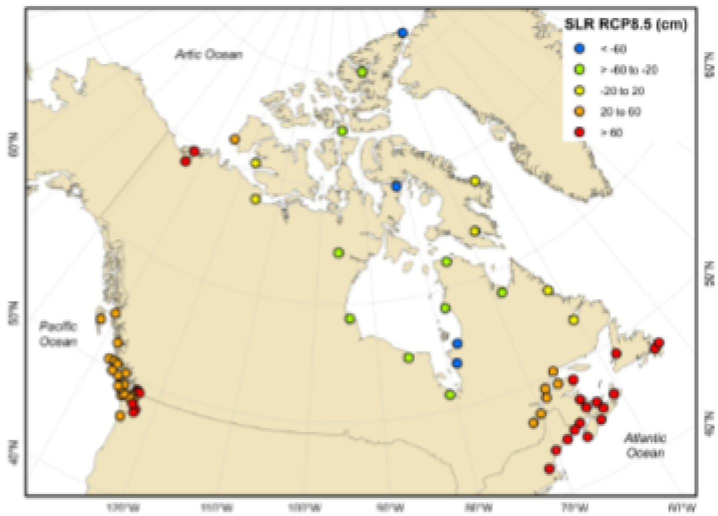

Figure 2: Projected median relative sea-level change by 2100, relative to 1986-2005, for RCP8.5.

Sea level rise can generate significant risk to infrastructure on the coastline, potentially increase coastal erosion and shoreline retreat, and affect groundwater through saline (ocean) water intrusion. Some of this can come directly from the higher sea level. However, another significant factor is the increased vulnerability of storm surge events affected by the changing water level over the nearshore sea bed. Storm surges can have drastic impacts on infrastructure and coastline erosion.

Glacial Isostatic Adjustment:

Canada was covered by an ice sheet between 3 and 5 km thick about 20 thousand years ago. This ice's weight caused the crust to deform and sink into the mantle, pushing mantle material downwards and outwards. The net effect was that the Earth's surface under the ice sheet sank, while the surface at the periphery of the ice sheet rose due to the interior flow of mantle material. After the ice-sheet retreated and

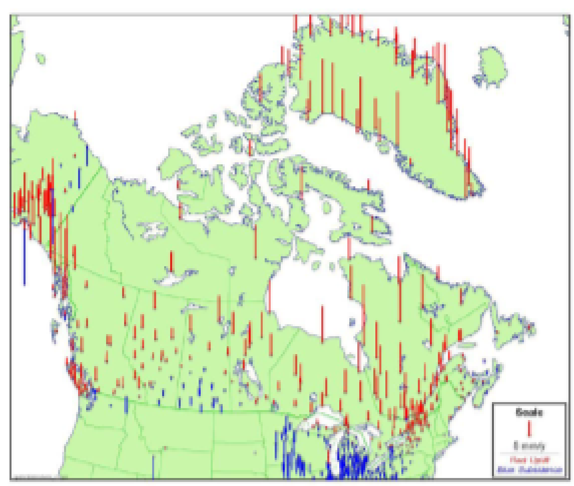

Figure 3: GPS-derived vertical crustal motion for Canada and Surrounding regions (Craymer et al., 2011)

shrank, the weight was removed, and the crust began to rebound in the process of Glacial isostatic adjustment (GIA).

Archimedes principle encourages a system of a solid body floating on top of fluid to sink until it has displaced an equal mass of liquid so that the buoyant force imposed by the liquid equals the force of gravity on the solid body. This can be visualized by different dimension wooden blocks floating on water. If the blocks are uniform density, then the larger ones will extend further from the mean water level in both vertical directions. This interaction depends on the densities of the fluid and the solid body, and it is crucial to consider the situation of a nonuniform solid body. When the crust is in isostatic equilibrium, the concept of isostasy is used to explain how different topographic heights can exist on Earth's surface. If the whole Earth's lithosphere was in isostatic equilibrium and uniform density, then the whole surface would be everywhere perpendicular to the gravity vector. However, the whole surface is not in isostatic equilibrium because of the very long time scales of isostatic adjustment, which is a consequence of the fluid mantle's high viscosity. The lithosphere is also nonuniform, the density of the material varies significantly between rock types and geological features. There are three models to explain how different topographic heights can exist.

1. The Airy-Heiskanen model - where different topographical heights are accommodated by changes in the crustal thickness and the crust has constant density.
2. The Pratt-Hayford model - where changes in crustal density accommodate different topographical heights.
3. The Vening Meinesz model is where the lithosphere acts as an elastic plate that distributes local topographical loads over a broad region by bending.

Vertical Motion Data Processing:

Measurements of vertical crustal motion are obtained using high precision Global Positioning System (GPS) stations set on bedrock around the country. GPS operates by receiving signals from a constellation of GPS satellites and triangulating its position relative to the satellites, comparing the time between when the satellites transmit a signal and when it arrives at the GPS device. Various corrections need to be applied to the raw data to obtain mm accuracy. Because the satellites move at high speeds around the earth, general relativity predicts a drift in their clocks relative to the stationary earth clocks. The orbits of the satellites also decay, and so corrections to their orbits must be considered. There is an ocean loading correction because the regular tidal cycle on earth will periodically load the crust with weight, causing it to rise slightly twice per day.

These are taken into account to produce a measurement once a day of a three-dimensional position for each station using a software package called SPARK. The measurements are repeated daily, for many years, to construct a time series of positions. Steps can occur in this time series during station maintenance or antenna replacements and the physical motion of the bedrock due to earthquakes. There are also small signals induced by seasonal changes in water loading. Several corrections are applied to calculate the vertical velocity, a least-squares regression fits a linear trend, annual and semiannual sinusoids, and offsets generated by antenna upgrades and real displacements caused by earthquakes. A second method for determining linear trends was developed by Geoffrey Blewitt et al at the University of Nevada as a robust trend estimator for GPS stations that can handle steps, seasonal variation, and skewness that is termed Median Interannual Difference Adjustment for Skewness (MIDAS). It calculates linear trends from pairs of points separated by integer years, creates a scatter plot of these velocities, discards outliers created by step discontinuities, and then averages the remaining linear-motion estimates.

Table 1

	Linear Reg. (mm/yr)	Midas (mm/yr) (no steps)	Midas (mm/yr) (steps)	Differnce (nosteps)	Differnce (steps)
ALBH	0.58	-1.00	0.40	1.58	0.18
ALRT	5.99	6.50	5.90	-0.51	0.09
ATRI	3.21	2.80	3.10	0.41	0.11
BAKE	11.33	13.50	12.80	-2.17	-1.47
BCDI	2.61	2.60	2.60	0.01	0.01
BCSS	0.08	0.00	0.20	0.08	-0.12
BDCK	-1.82	-1.78	-1.78	-0.04	-0.04
BLYN	-0.96	-2.40	-0.52	1.44	-0.44
CHUR	11.59	11.50	12.00	0.09	-0.41
ELIZ	1.35	1.50	1.00	-0.15	0.35
EUR2	7.94	9.43	8.30	-1.49	-0.36
HOLB	2.95	1.80	2.80	1.15	0.15
INVK	-0.48	-1.20	-0.50	0.72	0.02
LPOC	2.68	2.50	2.50	0.18	0.18
NAIN	4.49	4.80	4.29	-0.31	0.20
NEAH	1.65	3.30	2.50	-1.65	-0.85
P415	0.13	-0.05	-0.05	0.18	0.18
QIKI	3.69	4.30	3.50	-0.61	0.19
SEPT	4.56	4.60	4.60	-0.04	-0.04
STJO	-0.13	-0.50	-0.50	0.37	0.37
TSKT	-1.19	-1.19	-1.19	0.00	0.00

MIDAS was investigated as a possible alternative to the standard linear regression method described above. Using MIDAS, uplift rates were calculated for several sites with and without a step file provided that identified steps. Table 1 shows the calculated velocities and the difference from the linear regression method. The motivation to replace the linear regression method was to remove the manual step identification that was required. The difference between the linear regression method and MIDAS without steps ranges up to 2 cm/yr. Providing steps to MIDAS did decrease the difference, but with measurements on the order of 10 mm/year or less a difference of 1-2 mm/year is unacceptable and so MIDAS was deemed an inappropriate replacement.

References:

- Lemmen, D.S., Warren F.J., James T.S. and Mercer Clarke, C.S.L editors (2016): Canada’s Marine Coasts in a Changing Climate; Government of Canada, Ottawa, ON, 274p.
- Blewitt, G., C. Kreemer, W. C. Hammond, and J. Gazeaux (2016), MIDAS robust trend estimator for accurate GPS station velocities without step detection, J. Geophys. Res. Solid Earth, 121, 2054–2068, doi:10.1002/2015JB012552.