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Modeling tidal water levels for Canadian coastal and offshore waters: implications for coastal change and adaptation

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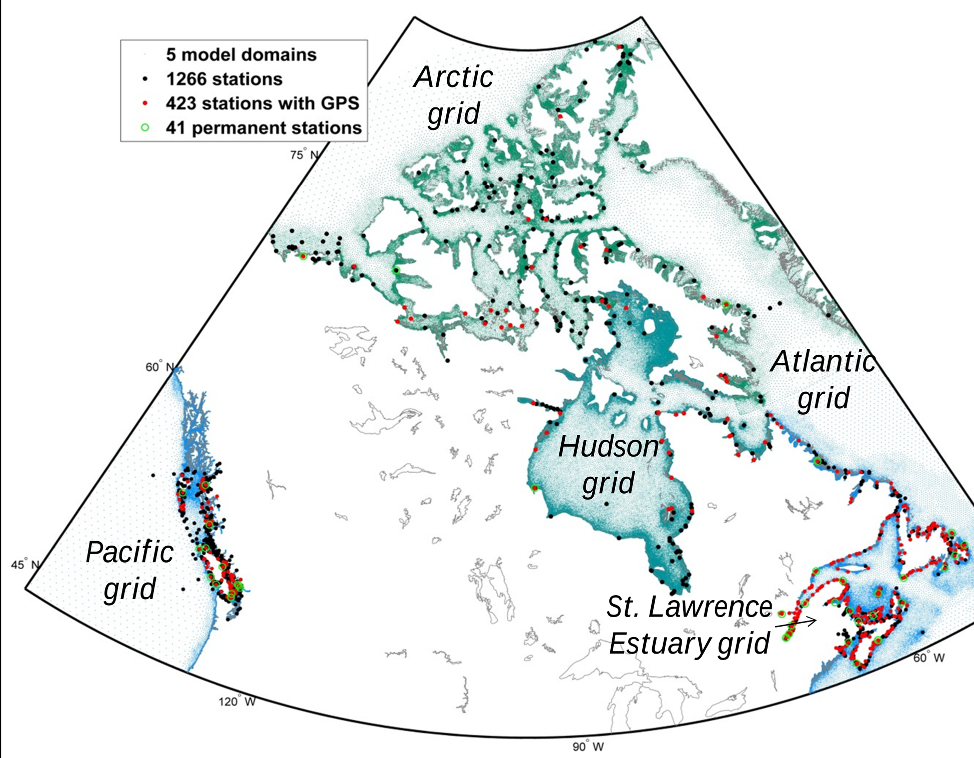
1. Introduction: Hydrographic Vertical Separation Surfaces (HyVSEPs)

The Canadian Hydrographic Service with support from the Canadian Geodetic Survey has created a set of surfaces which connect tidal levels and datums (high and low water levels, chart datum, etc.) to a national geodetic reference frame over all Canadian tidal waters[1,2,3]. HyVSEPs capture the spatial variability between stations and offshore by integrating ocean models, gauge data (water level analyses and/or GPS observations), sea level trends, satellite altimetry, and a geoid model.

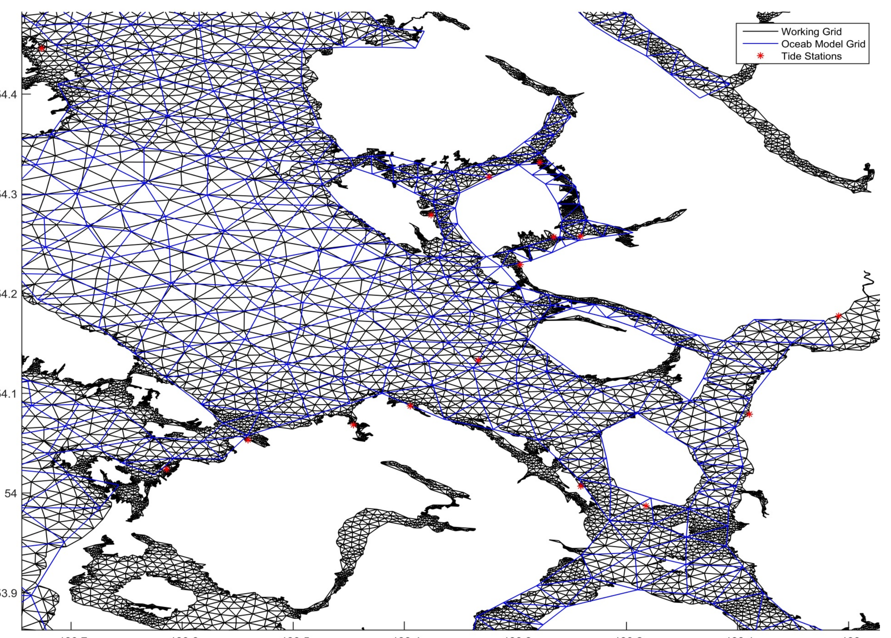
HyVSEPs will enable the use of GPS for hydrographers and navigators. It will also be useful for oceanographers, environmental and climate scientists, surveyors and engineers. It will allow the integration of hydrographic and terrestrial data through a common reference frame, provide a baseline for storm surge modeling and climate change adaptation, and aid with practical issues such as sovereignty and the definition of the coastline. High and low tide HyVSEPs will delineate flooding thresholds and inter-tidal ecosystem zones and boundaries.

2. Data and Methods



Tidal HyVSPEPs cover all of the Canadian Coast and offshore waters in 5 large and highly detailed finite element grids (see figure). HyVSEPs are a sum of discrete layers, each of which fill a vertical portion of the separation between tidal levels and the GRS80 ellipsoid in the NAD83(CSRS) reference frame. Gauge data varies in quality, with stations operating between 3 weeks and 100+ years; we include as many as possible especially where shore observations are sparse. An ongoing campaign of GPS surveys at tide station benchmarks has been in operation since the early 1990's. Gauge and GPS data are brought to a common epoch with sea level and crustal motion adjustments.

Calculations are primarily done with a Laplacian Interpolator, in effect modeling spatial variations in tidal regime as a steady-state heat transfer problem. Thus it is important that our grid boundaries reproduce real coastlines with great detail, to keep tidally restricted areas numerically isolated. Because our calculations are simple, our grids can be much more detailed than the ocean model grids upon which they are based. The figure to the right shows a close up of the Pacific Grid around Prince Rupert.



3. Chart Datum

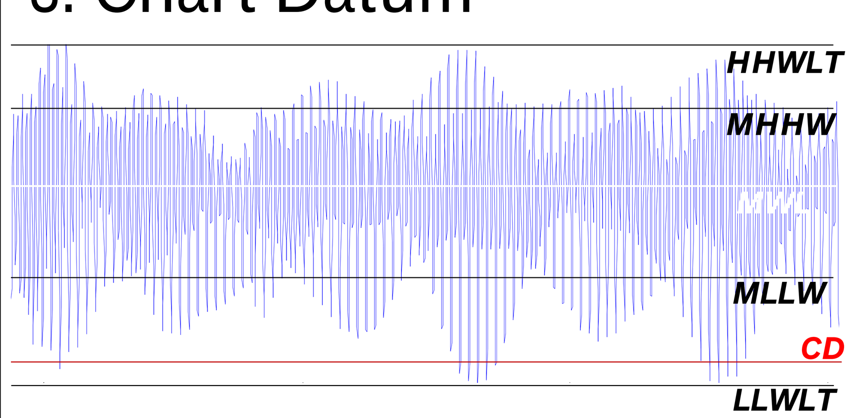
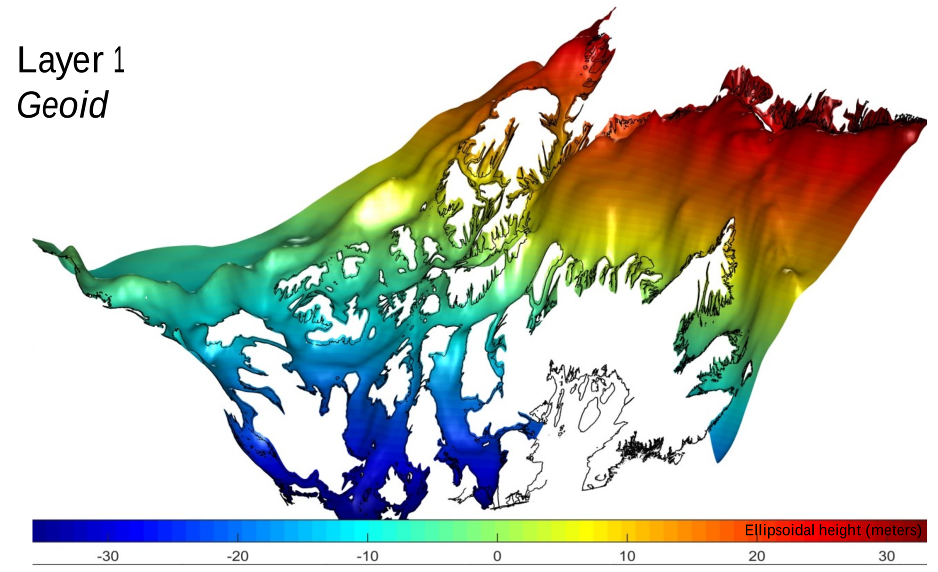
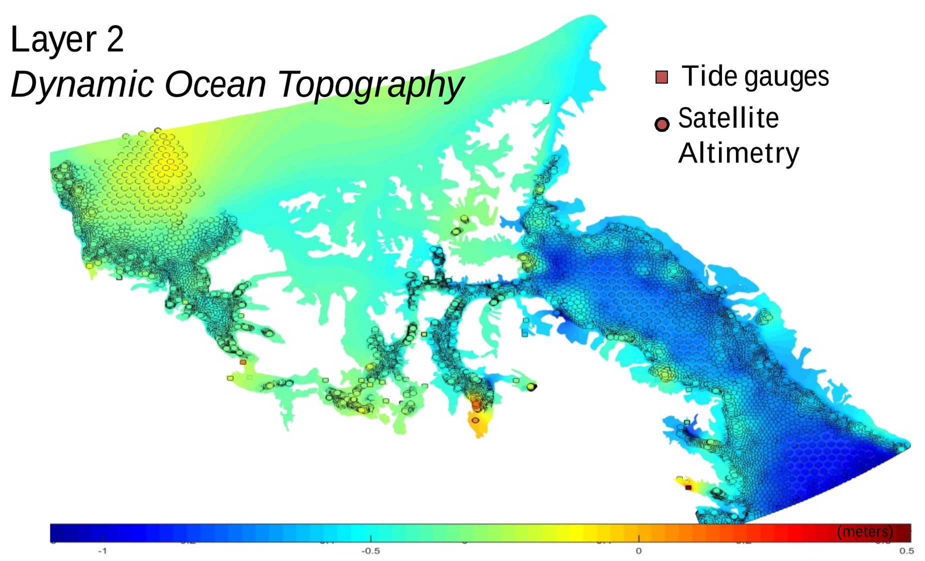


Chart Datum (CD) is the vertical datum for nautical charts. In Canada, CD targets Lower Low Water Large Tide (LLWLT), the lowest predicted tide in a 19-year astronomical cycle (see figure). It rarely coincides with LLWLT, however, especially where CD was set tens of years ago and where relative sea level rise is large. In this figure we show 4 tidal levels, but many more can be defined. We currently have HyVSEPs for CD, 6 high and low tidal levels, and Mean Water Level.

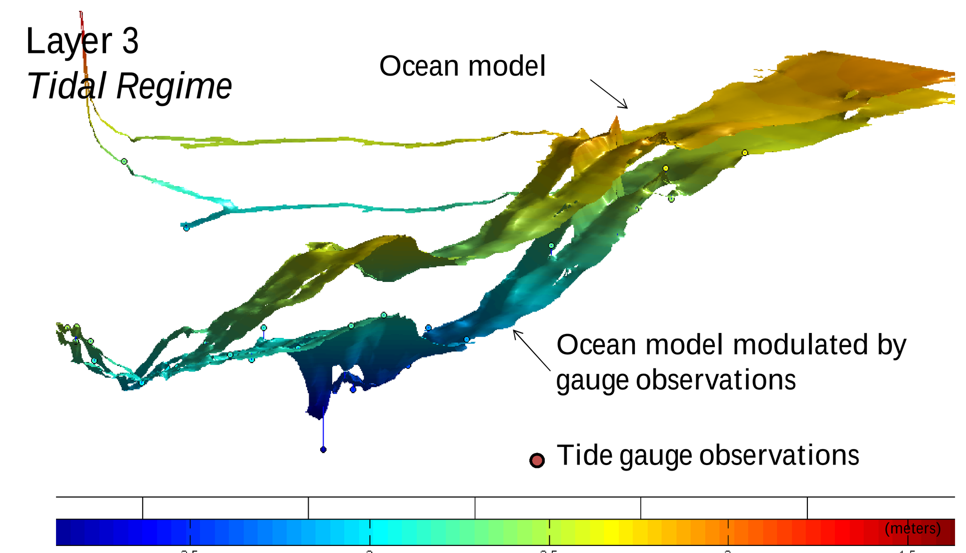
4. Modeling tidal water levels



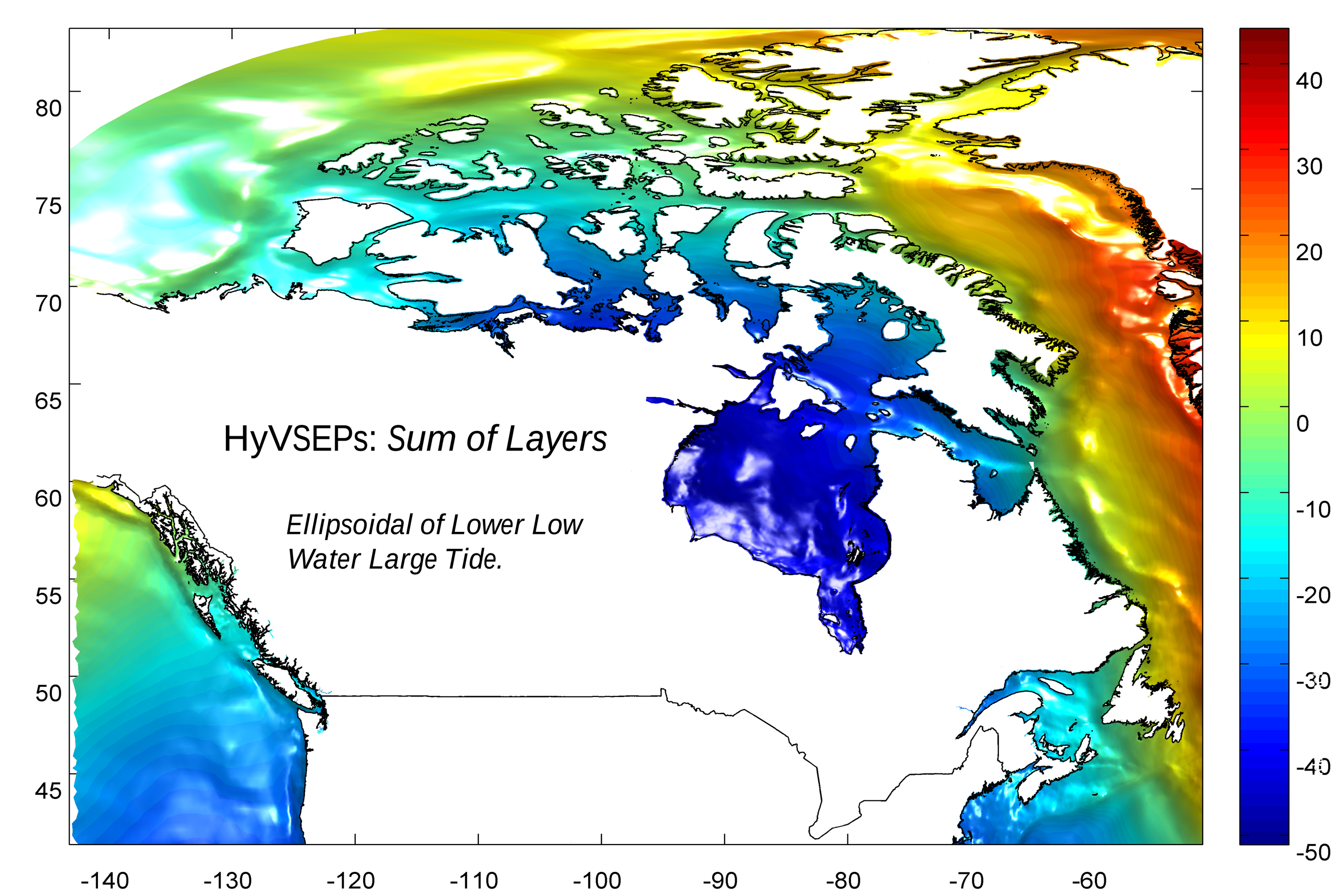
Layer 1: *The Geoid (Arctic grid).* The foundation of HyVSEPs is a geoid model, a gravitational equipotential (or 'level') surface which best represents Mean Sea Level (MSL); it maps where water would rest if it were all of the same density. We use the Canadian Gravimetric Geoid model of 2013, which integrates data from terrestrial gravity measurements (land, ship and airborne observations) as well as from the dedicated satellite gravity missions GRACE and GOCE. CGG2013 provides HyVSEPs with their link to the ellipsoid, and their spatial variability is to first order the result of geoid undulations.



Layer 2: *Dynamic Ocean Topography (DOT) (Arctic grid).* Observed MWL does not fall on an equipotential surface due to variations in density, currents, and other factors. The difference between CGG2013 and MWL is DOT, which can be observed or modeled. Our DOT layer includes a model DOT from a hydrodynamic ocean model, which we modulate using observations from tide gauges and satellite altimetry. We use Satellite Altimetry more than 14 km away from the shore, and remove the variance between tide stations by smoothing. Thus the DOT layer covers all grid nodes, and fits observations where they are available. Adding the DOT layer to the geoid layer gives us a Mean Sea Surface (MSS), the ellipsoidal height of observed MWL.

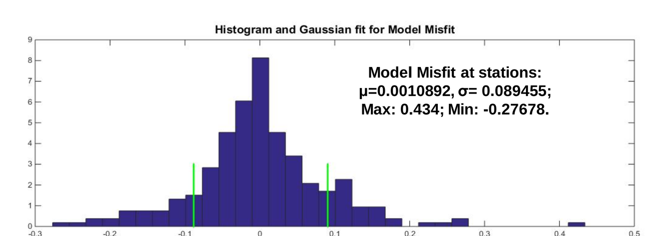


Layer 3: *Tidal Regime (St. Lawrence Estuary Grid).* The third layer joins MSS to the target water level, LLWLT in the case presented here. The amplitude of MSS to LLWLT (see figure) is approximately half the tidal range. Since gauges capture tidal regime only at isolated and unevenly distributed coastal points, we rely on hydrodynamic ocean models to inform this layer between stations and offshore. Ocean models are not optimized for predicting tidal extremes, as seen in the figure, so we modify them using trends in tide station observations. This procedure exploits the connectivity of the highly detailed grid, in effect modeling changes in tidal regime with much greater detail than hydrodynamic models can achieve.



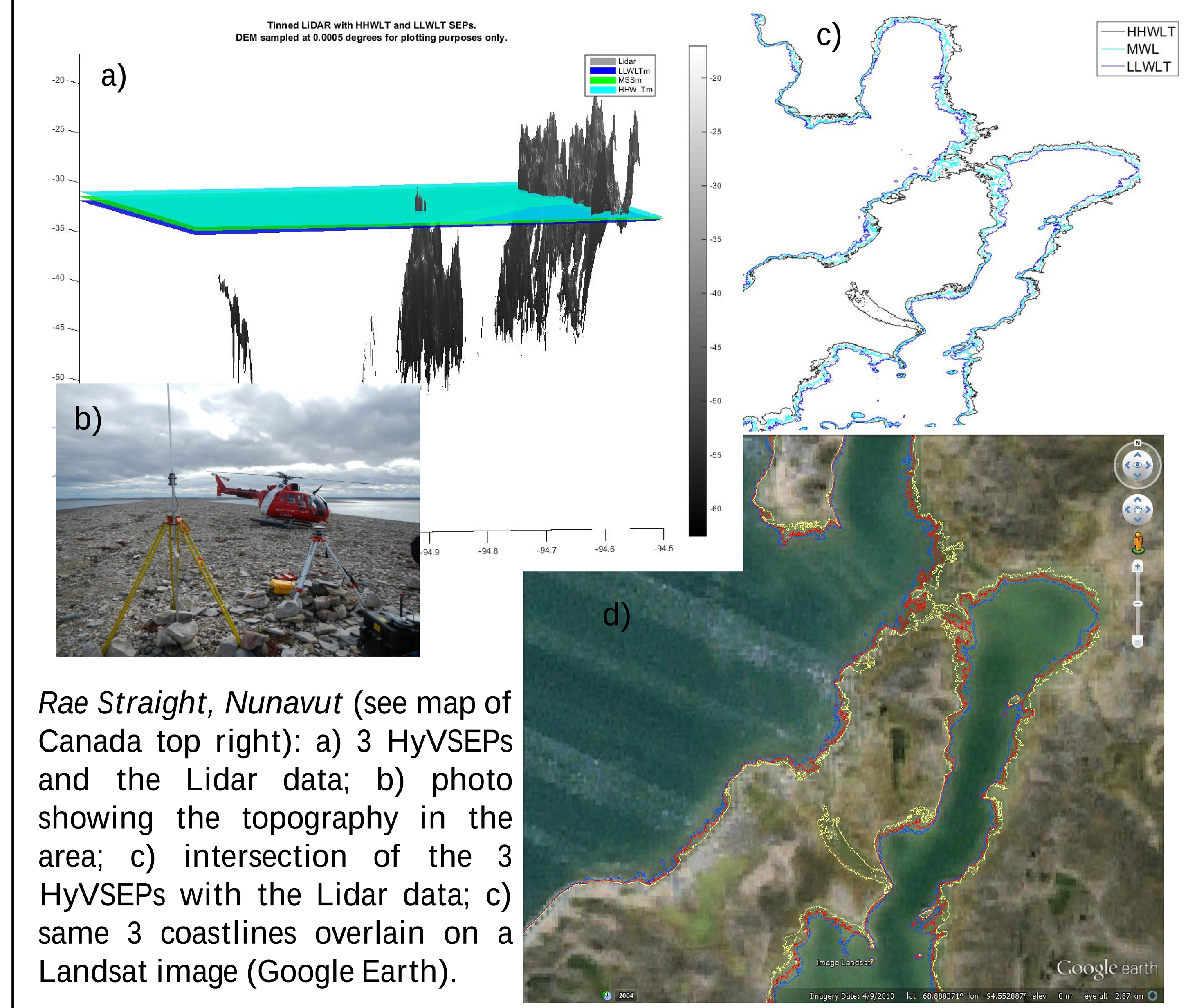
The final product is a sum of the layers, connecting the GRS80 ellipsoid to a target tidal level (LLWLT shown in this figure). Because CD targets but rarely reaches LLWLT, $HyVSEP_{CD}$ includes a final Layer 4 (not shown) which is used to 'warp' $HyVSEP_{CD}$ so that it honours currently adopted CD close to shore and in the vicinity of tide stations.

A histogram of the misfit between $HyVSEP_{LLWLT}$ the ellipsoidal height of LLWLT at tide stations is shown below for the Atlantic region.



5. Coastlines 4 Canada

HyVSPEPs intersected with coastal DEMs can be used to define a suite of shorelines representing high, low and mean tide coastlines. We have tested the intersection process using data from airborne bathymetric Lidar surveys, which is the most accurate and detailed coastal DEM we have at this time (see Figures). Since Canada contains 25% of the world's coastline, and much of it is remote and uninhabited, we will only be able to do this on a small portion of the coast. However, HyVSEPs also link bathymetry (typically referenced to CD) and topography through a common reference frame. Thus, it will be possible to create digital elevation models of coastal areas including the intertidal zone.



Rae Straight, Nunavut (see map of Canada top right): a) 3 HyVSEPs and the Lidar data; b) photo showing the topography in the area; c) intersection of the 3 HyVSEPs with the Lidar data; c) same 3 coastlines overlain on a Landsat image (Google Earth).

6. Conclusions

HyVSEPs are a new 3D paradigm in vertical referencing for the CHS. $HyVSEP_{CD}$ will permit the use of GNSS technologies in data collection and reduction, will improve the quality of bathymetric data on nautical charts, and will help connect bathymetry with topography. While other hydrographic organizations have created similar products[4,5], our methods are unique in order to accommodate the size and complexity of the Canadian coast. HyVSEPs themselves will improve over the next few years as new data is collected and methods are further developed.

HyVSEPs will also be used as a tool to address climate change impacts and adaptation in coastal regions,, in particular the HyVSEP-based coastlines delineating high and low waters.

7. References

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Canadian Hydrographic Service/Canadian Geodetic Survey