Vertical Referencing of Ocean Mapping Data

Traditional water level reference and ellipsoid reference approaches will be compared and a detailed overview of the reduction process will be examined. Canadian vertical datums used in ocean mapping will be outlined. The process to establish an ellipsoid to chart datum offset surface will be developed using two approaches.

Dr. Ian Church

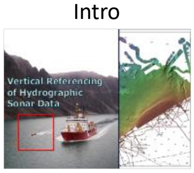
UNB EST. 1785 UNIVERSITY OF NEW BRUNSWICK | Engineering Fredericton

1

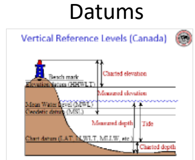
1

Overview

Intro

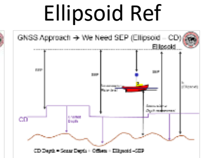


Datums

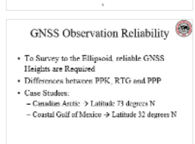


Traditional

Ellipsoid Ref



Implementation

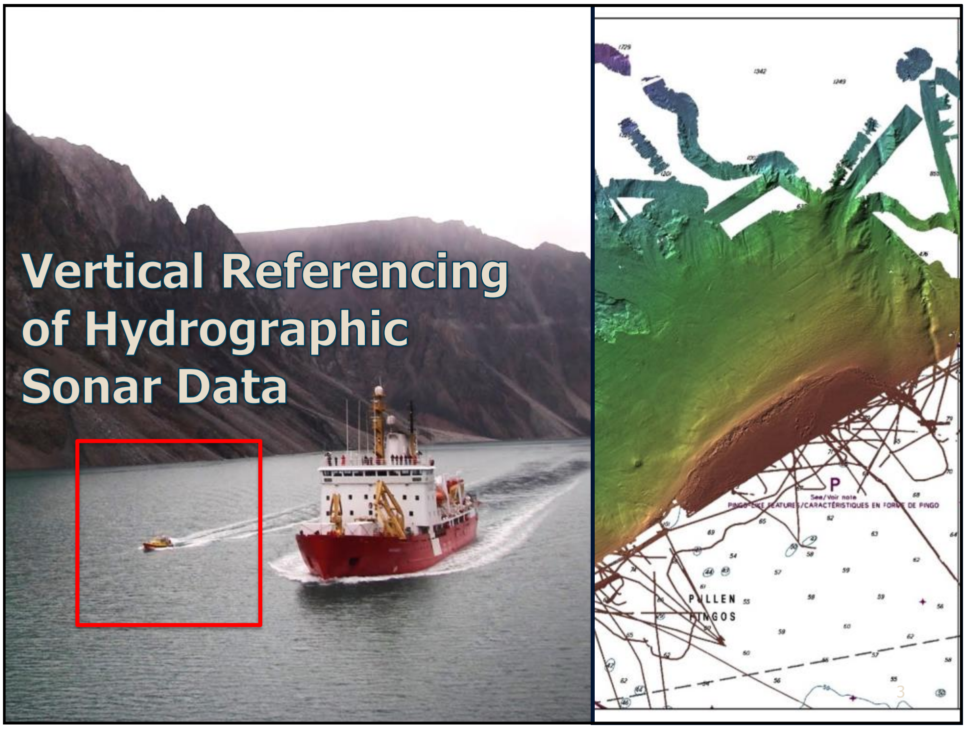


Reliability

Summary

2

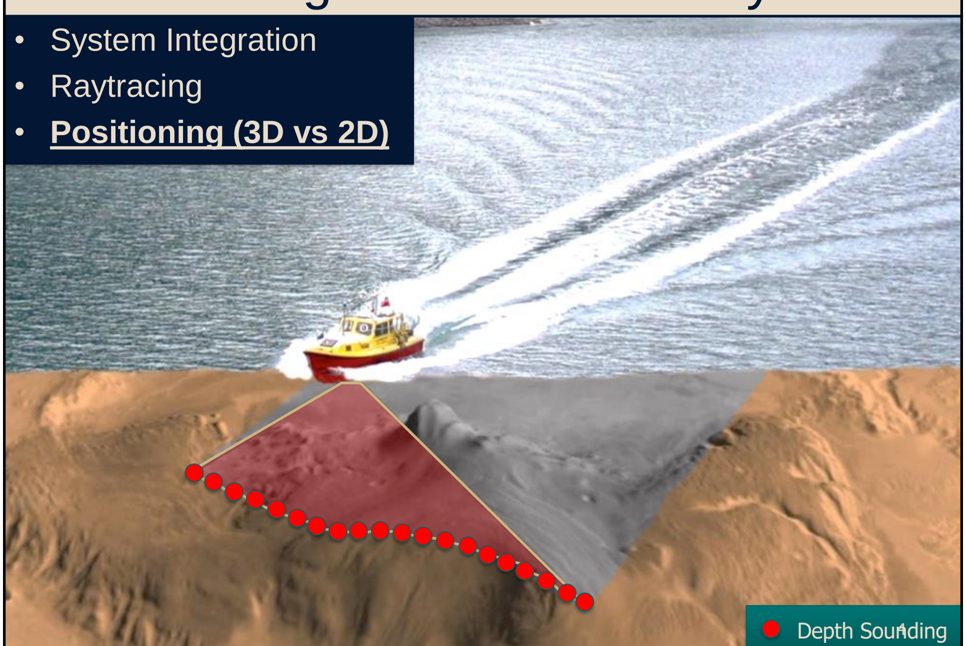
2



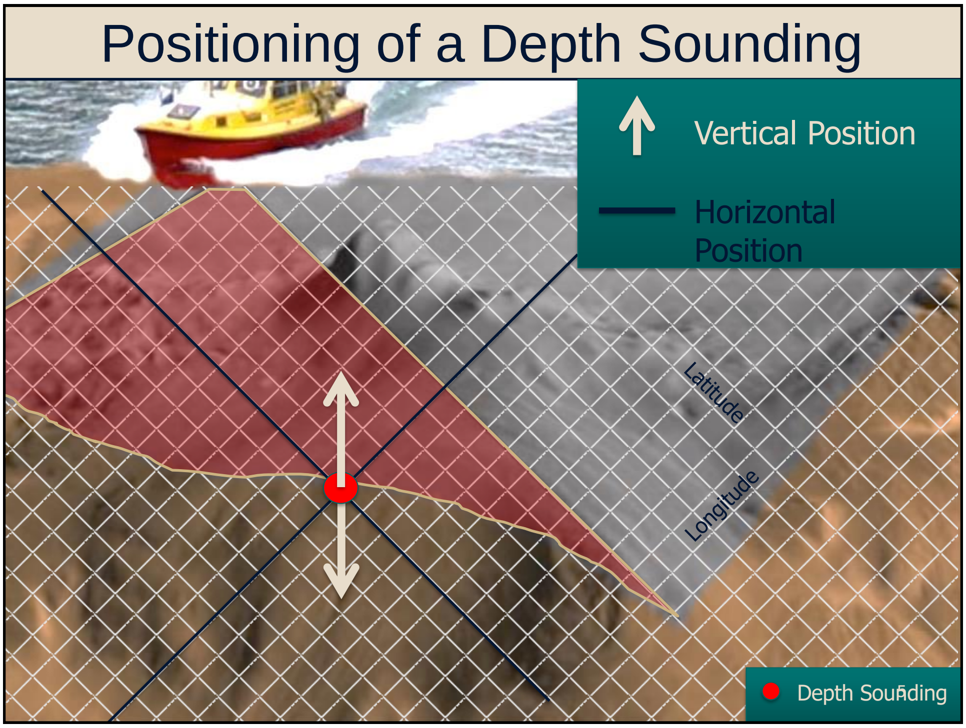
3

Processing Multibeam Survey Data

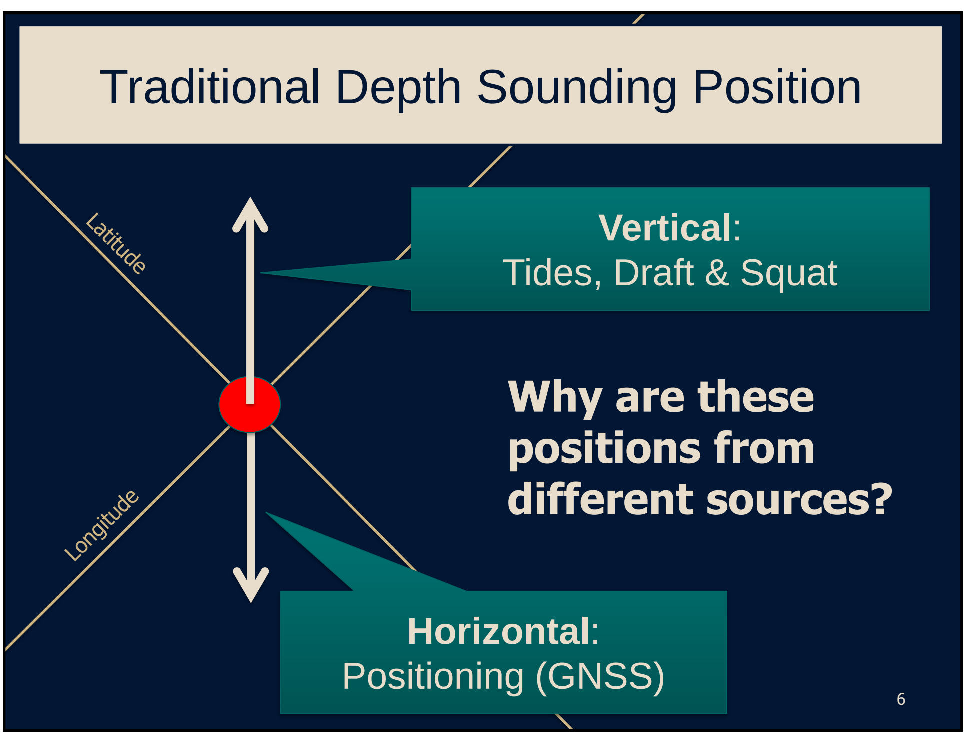
- System Integration
- Raytracing
- **Positioning (3D vs 2D)**



4

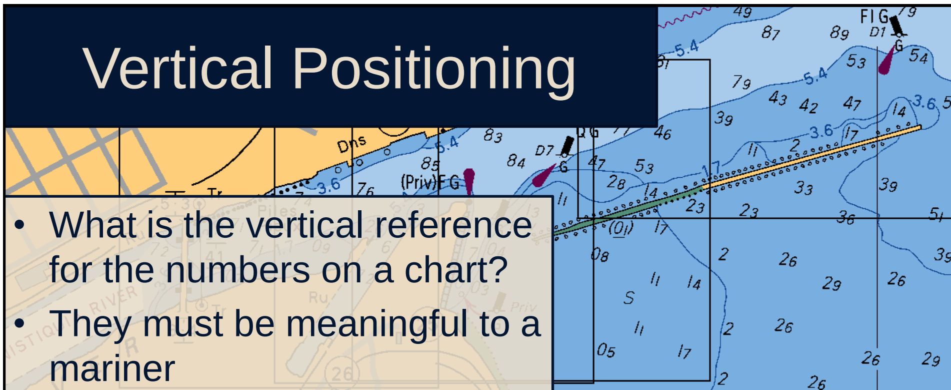

Positioning of a Depth Sounding
Vertical Position
Horizontal Position
Latitude
Longitude
Depth Sounding

5

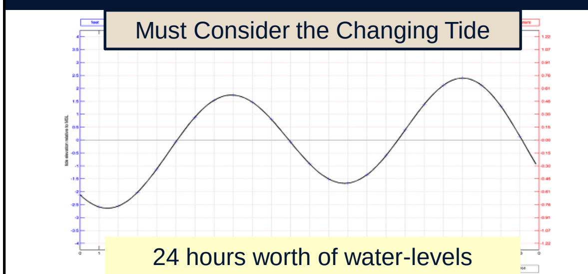

Traditional Depth Sounding Position
Vertical:
Tides, Draft & Squat
Why are these positions from different sources?
Horizontal:
Positioning (GNSS)
Latitude
Longitude
6

6

Vertical Positioning



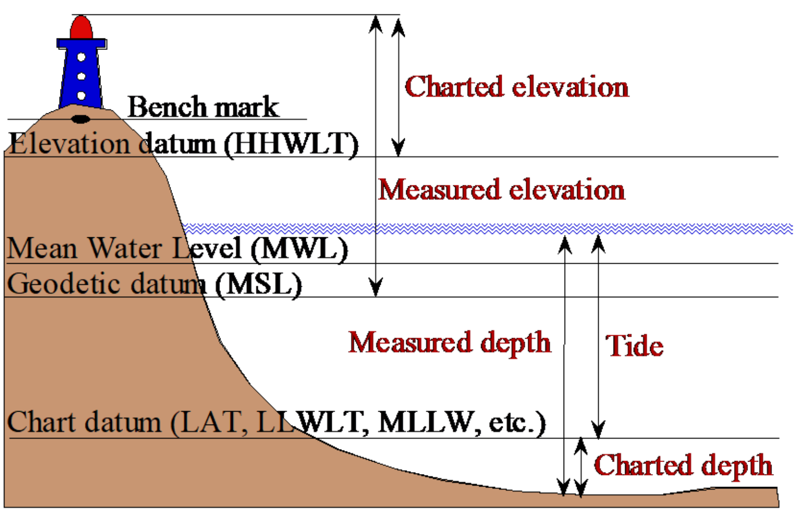
- What is the vertical reference for the numbers on a chart?
- They must be meaningful to a mariner



7

7

Vertical Reference Levels (Canada)



8

8

Canadian Tidal Datum Definitions:

•**MWL - mean water level** - average of all hourly water levels over the available period of record.

•**HHWLT - higher high water, large tide** - average of the highest high waters, one from each of 19 years of observations.

•**HHWMT - higher high water, mean tide** - average of all the higher high waters from 19 years of observations

•**LLWMT - lower low water, mean tide** - average of all the lower low waters from 19 years of observations

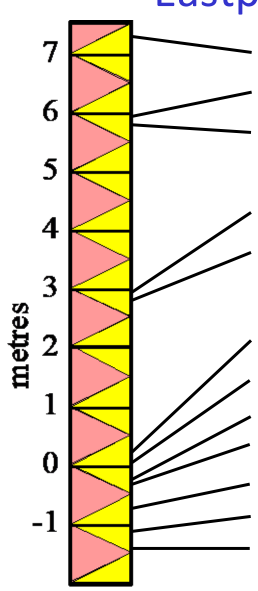
•**LLWLT - lower low water, large tide** - average of the lowest low waters, one from each of 19 years of observations.

Source : Canadian Tide Manual

9

9

Eastport Maine reference levels



- 7.35 Highest extreme
- 5.89 Mean Higher High Water
- 5.73 Mean High Water
- 2.93 Mean Water Level
- 2.83 National Geodetic Datum
- 0.13 Mean Low Water
- 0.00 Mean Lower Low Water
- -0.26 Low Water Equinoctial Springs
- -0.38 Indian Spring Low Water
- -0.74 Lower Low Water, Large Tides
- -1.07 Lowest Astronomical Tide
- -1.42 Lowest extreme

USA

Canada

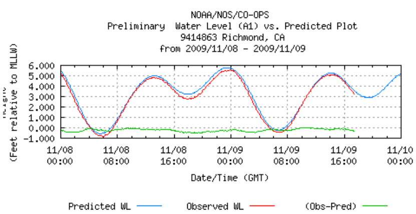
UK/IHO

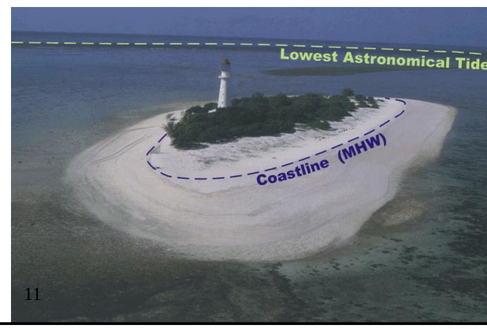
10

10

Lowest Astronomical Tide

- Lowest Astronomical Tide is the lowest level to which sea level can be <u>predicted</u> to fall under normal meteorological conditions.
- Determined by inspecting predicted sea levels over a number of years
  - Usually 18.6 Years $f(t) = A_0 + \sum_{i=1}^{m} f_i H_i \cos(\omega_i t + \varphi_i)$
- Unlike LLWLT, it is not an extreme level, therefore the water may fall below the LAT datum





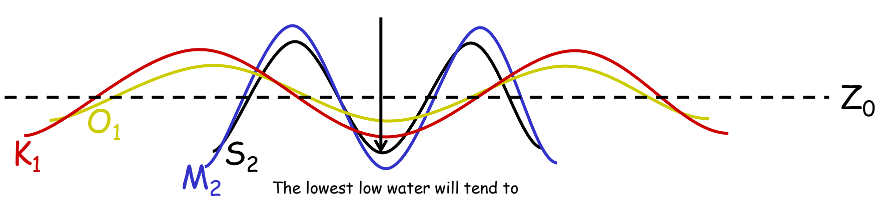
11

11

Indian Spring Low Water

A level suggested by Sir George Darwin for Indian Waters. It is found by obtaining the sum of the semi-ranges of the principal lunar and solar semi-diurnal tides, and of the lunar and luni-solar diurnal tides, subtracting it from Mean Sea Level. It is given by the formula:

$$ISLW = Z_O - (A_{M2} + A_{S2} + A_{K1} + A_{O1})$$

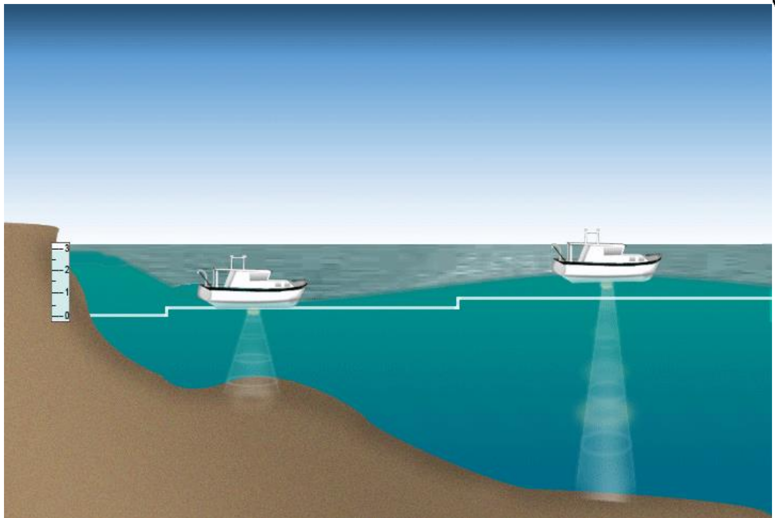


Admiralty Manual of Hydrographic Surveying, V. 2, Chpt. 2 Tides and Tidal Streams

12

12

Traditional Approach of Vertical Referencing



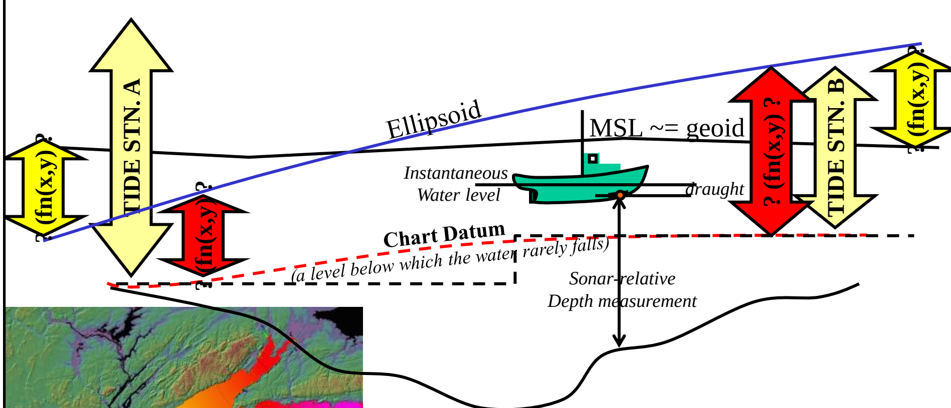
Animation courtesy of U.S. Naval Oceanographic Office

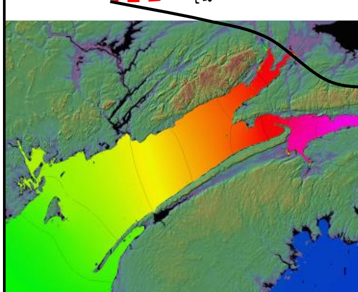
CD Depth = Sonar Depth + Draft (Static & Dynamic) +/- Heave - Tides

13

13

Variations in Reference Datums in X & Y



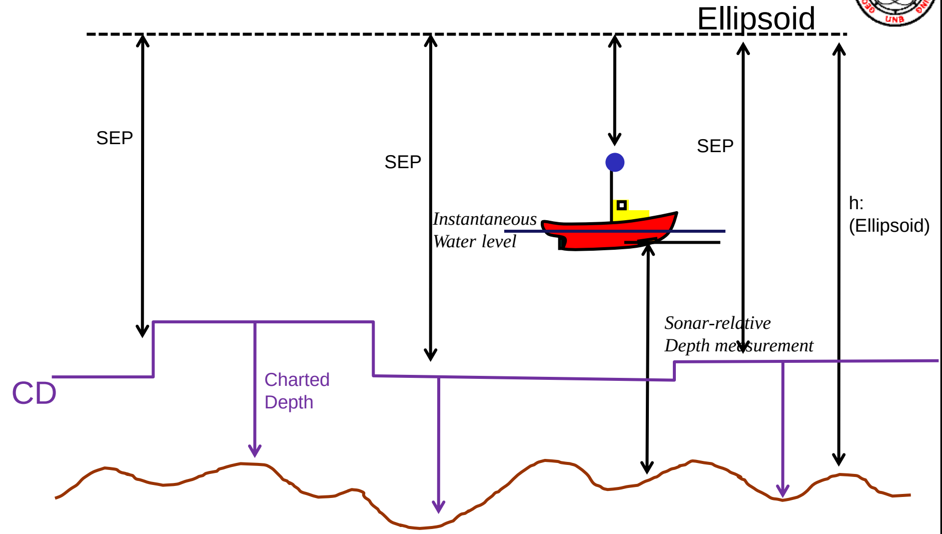


The problem with traditional vertical referencing

14

14

GNSS Approach → We Need SEP (Ellipsoid – CD)



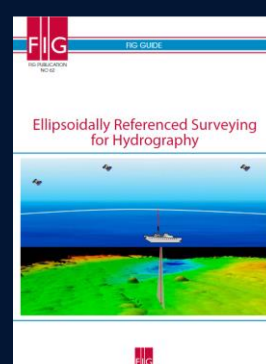
CD Depth = Sonar Depth + Offsets + Ellipsoid –SEP

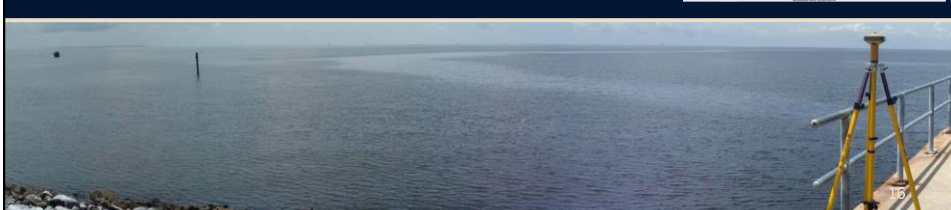
15

15

Ellipsoid Reference Survey (ERS)

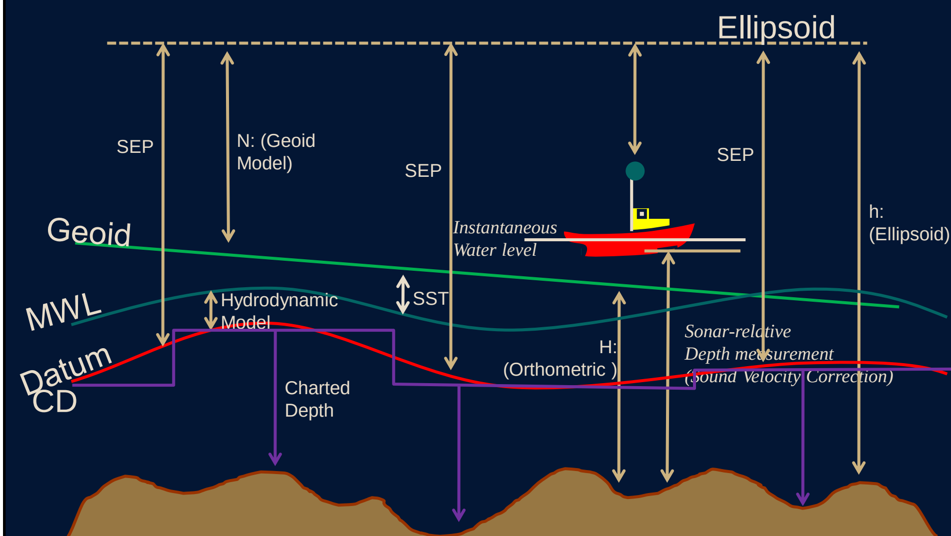
- Find a way to transform data from the **Ellipsoid to Chart Datum**
- FIG #62 (Mills & Dodd, 2014)
- Different methods available to obtain the separation





16

GPS Approach → We Need SEP (Ellipsoid – CD)



CD Depth = Sonar Depth + Offsets + Ellipsoid –SEP

SEP = N + SST + HModel

17

17

PPK / RTK GPS

- Differential Carrier Phase Positioning
  - Carrier Phase delay measured at Base and used to determine the phase delay at Rover
- Multiple Receivers (One at Known Location)
- Observing the Same Satellites at the Same Time
- Allows for very precise determination of the relative position of the base vs. rover
- RTK: **Real Time Kinematic**
  - Send RTCM corrections or measurements to Rover over Radio Link
- PPK: **Post Processed Kinematic**
  - Process Post Survey using Files from both Systems

$$\Phi = \rho + c\left(dt - dT\right) + \lambda N - d_{ion} + d_{trop} + \varepsilon_{\Phi}$$

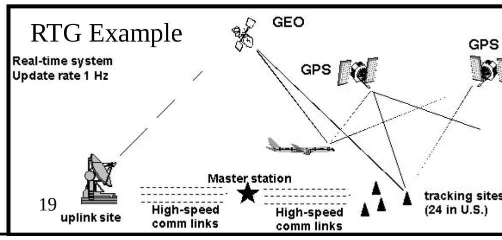
18

18

RTG / PPP GPS

- Only Need One Receiver: No Basestation
- **RTG**: Real-Time GYPSY
  - Sends the GPS Receiver Corrections in Real Time for Satellite Clock and Orbital Errors
  - Geosynchronous Satellites
    - Problems when working at high latitudes
  - 10 - 30 cm Accuracy
- **PPP**: Precise Point Positioning
  - Post Process using Measured Satellite Clock and Orbit Corrections
  - Rapid Orbits: Available in 17 hours after Collection
  - Final Orbits: Available in 12 days after Collection
  - Downside: Convergence Time
    - 30 minutes is normal

RTG Example



19

19

Heave Integration

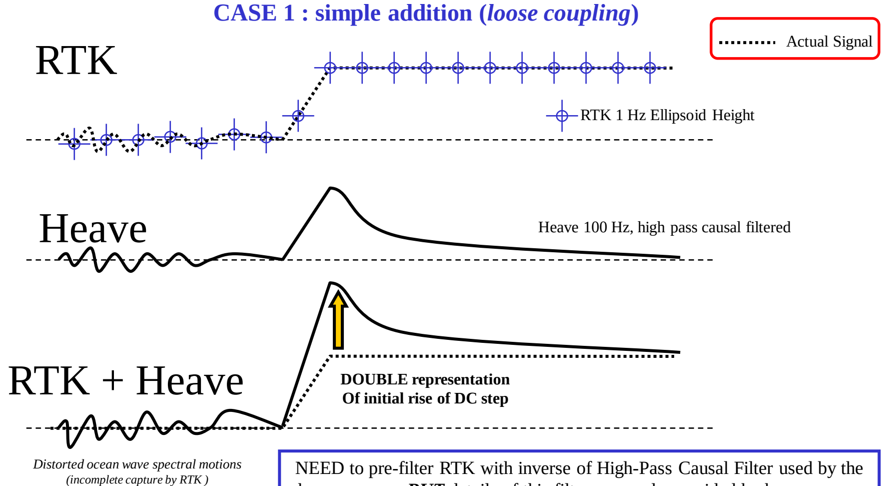
- Capture the High Frequency Vertical Motion
- Heave: Double Integration of Acceleration to get Vertical Motion
  - Gives you zero mean solution of vertical motions at 100Hz (High Frequency)
- Use the Heave with the GPS Data
  - High Frequency Heave and Low Frequency GPS Data Combined to give Vertically Referenced Solution
  - Heave accounts for all vertical motions under filter cut-off and RTK for motions over filter cut-off.
  - Combine the Solution

20

20

How do you integrate RTK and Heave?

CASE 1 : simple addition (*loose coupling*)

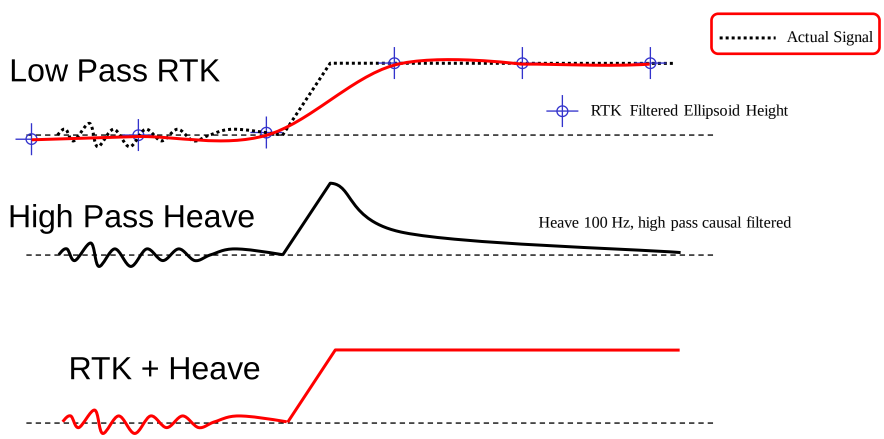


NEED to pre-filter RTK with inverse of High-Pass Causal Filter used by the heave sensor. ***BUT*** details of this filter are rarely provided by heave sensor suppliers *(and filter time constants are often changed dynamically)*

21

21

High Pass Filter the Heave and Low Pass Filter the RTK

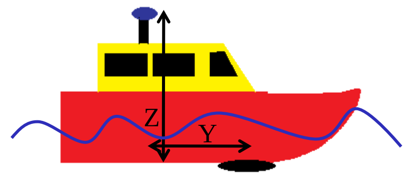


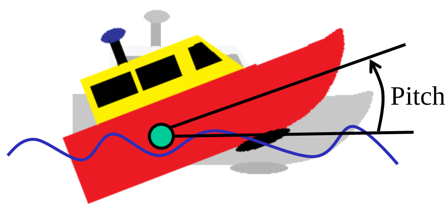
22

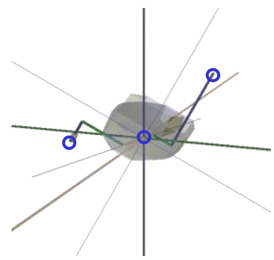
22

Lever Arms

- Need to Understand How Motion affects the Position of the Transducer Relative to the GPS Antenna or the Reference Point
- X, Y and Z offsets from the GPS Antenna to the Transducer
- Roll and Pitch



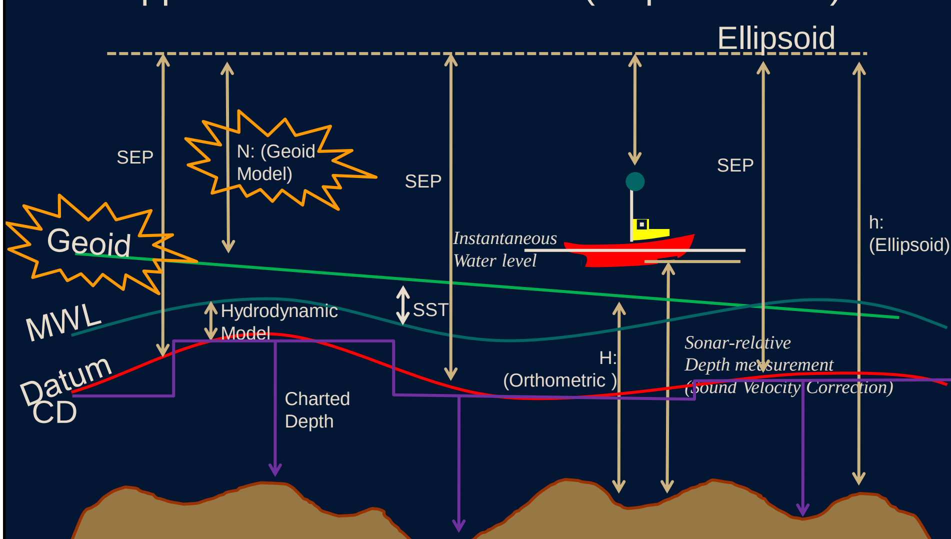




23

23

GPS Approach → We Need SEP (Ellipsoid – CD)

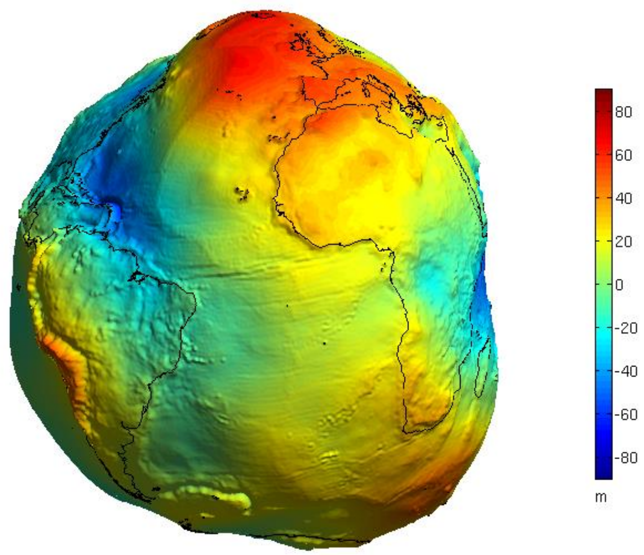


CD Depth = Sonar Depth + Offsets + Ellipsoid –SEP

SEP = N + SST + HModel

24

24



Geoid height (EGM2008, nmax=500)

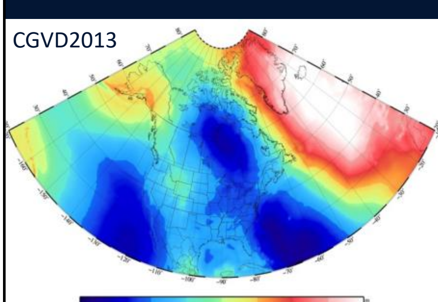
http://www.asu.cas.cz/~bezdek/vyzkum/rotating_3d_globe/rotating_3d_globe/manual.html

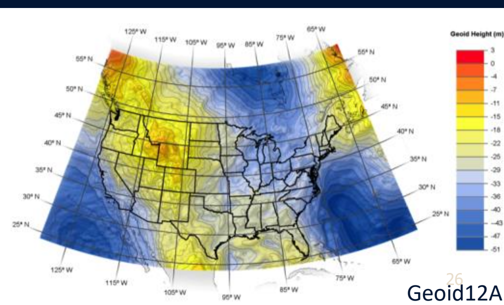
25

Geoid-Ellipsoid Separation Models

- *Canada:* CGVD2013 (CGG2013)
- *USA:* Geoid12A: NAD83 → NAVD88 (hybrid Geoid)
- *USA:* USGG2012: WGS84 → Geoid
- *International:* EGM08

CGVD2013



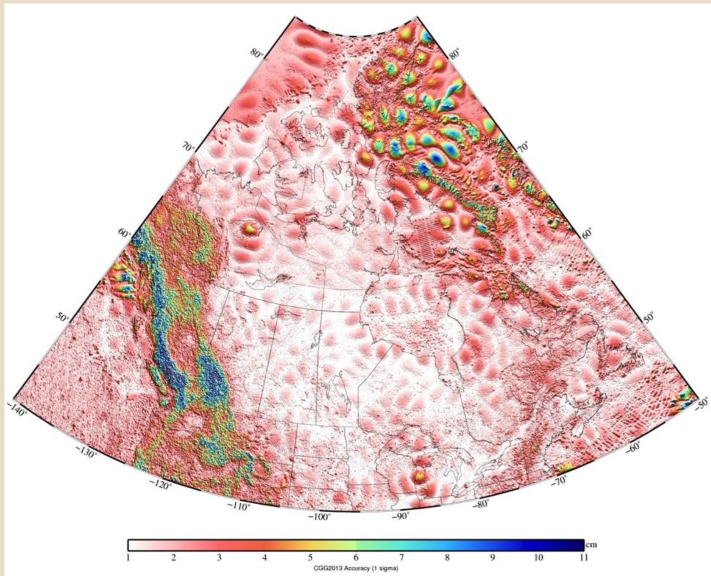


Geoid12A

26

Geoid Uncertainty

CGVD2013 Error Map

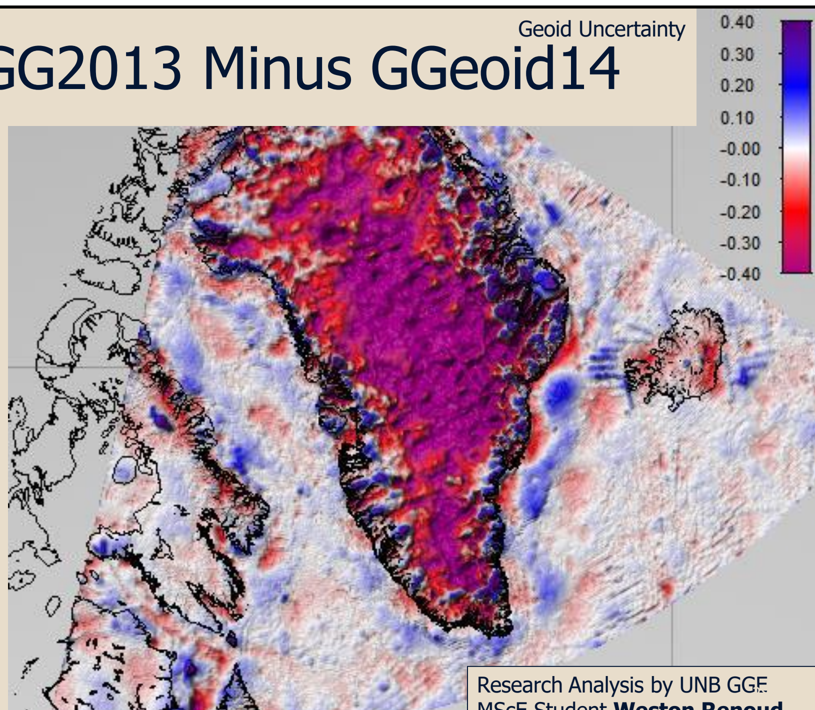


NRCAN, 2014

27

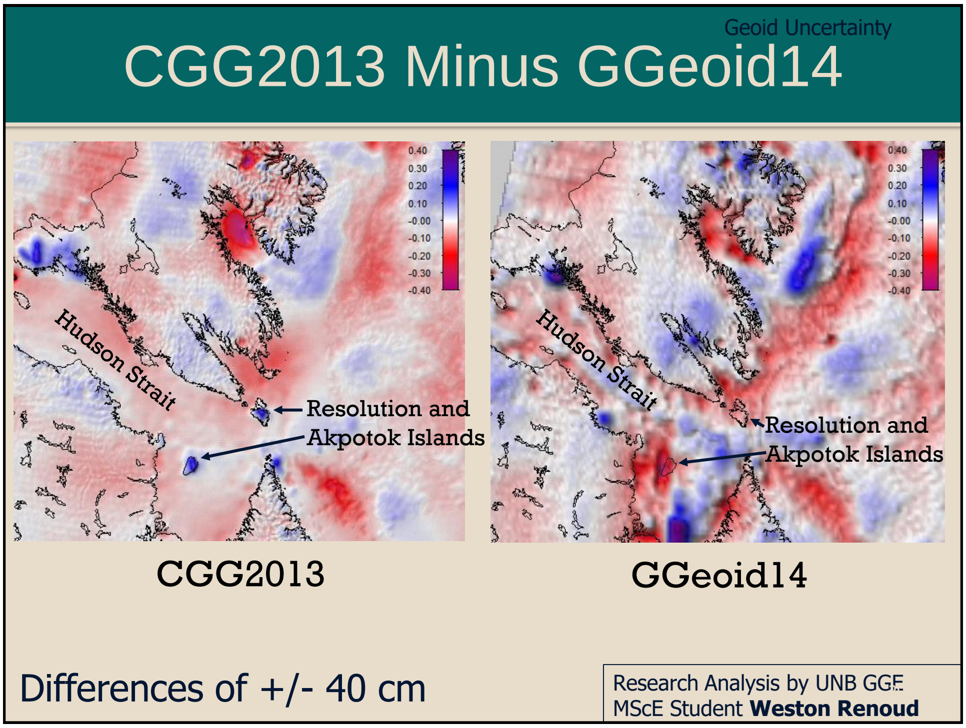
Geoid Uncertainty

CGG2013 Minus GGeoid14

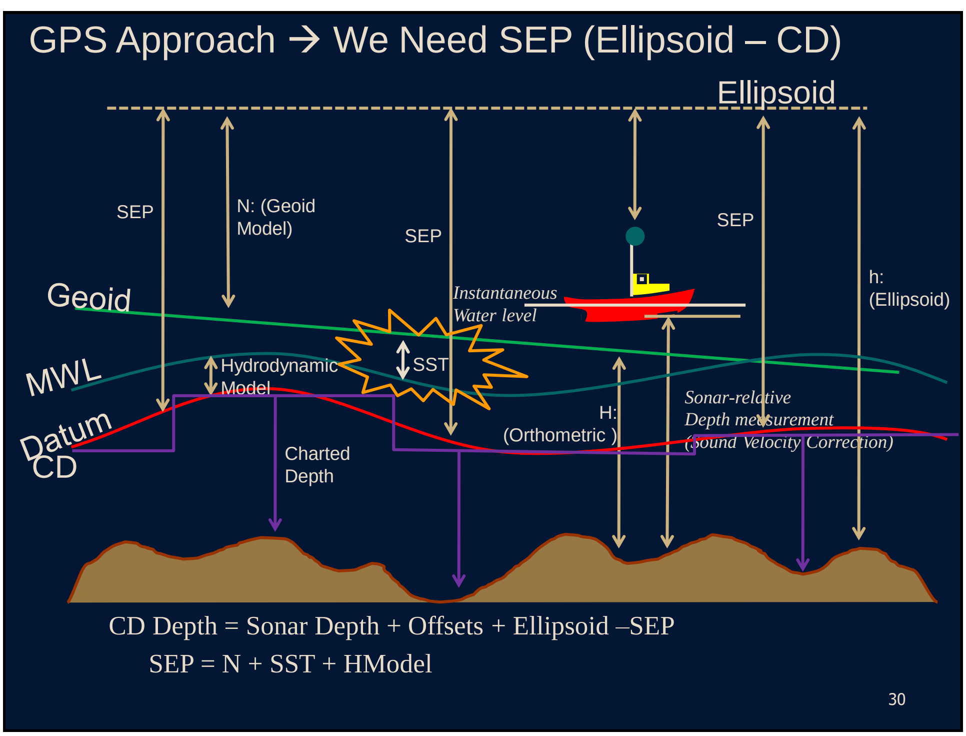


Research Analysis by UNB GGE
MScE Student **Weston Renoud**

28

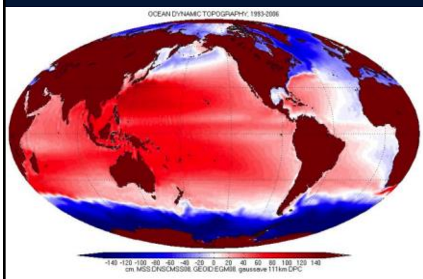

Geoid Uncertainty
CGG2013 Minus GGeoid14
Hudson Strait
Resolution and
Akpotok Islands
Hudson Strait
Resolution and
Akpotok Islands
CGG2013
GGeoid14
Differences of +/- 40 cm
Research Analysis by UNB GGE
MScE Student Weston Renoud

29


GPS Approach → We Need SEP (Ellipsoid – CD)
Ellipsoid
SEP
N: (Geoid Model)
SEP
SEP
h: (Ellipsoid)
Geoid
Instantaneous Water level
MWL
Hydrodynamic Model
SST
Datum CD
H: (Orthometric)
Sonar-relative Depth measurement (Sound Velocity Correction)
Charted Depth
CD Depth = Sonar Depth + Offsets + Ellipsoid –SEP
SEP = N + SST + HModel
30

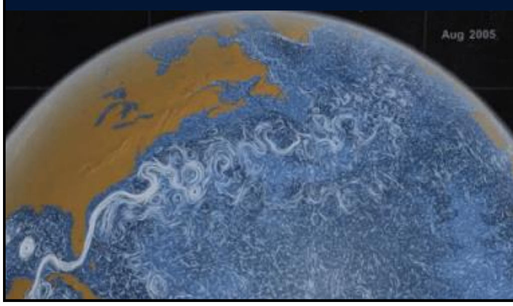
30

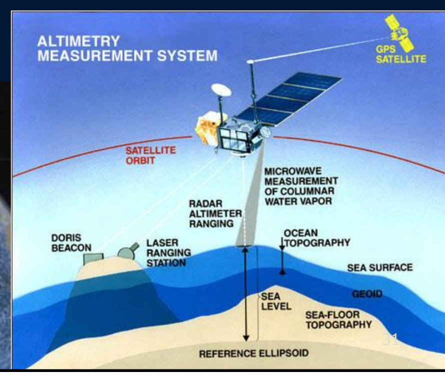
Dynamic Ocean Topography



DOT: Associated Epoch and a Reference Geoid

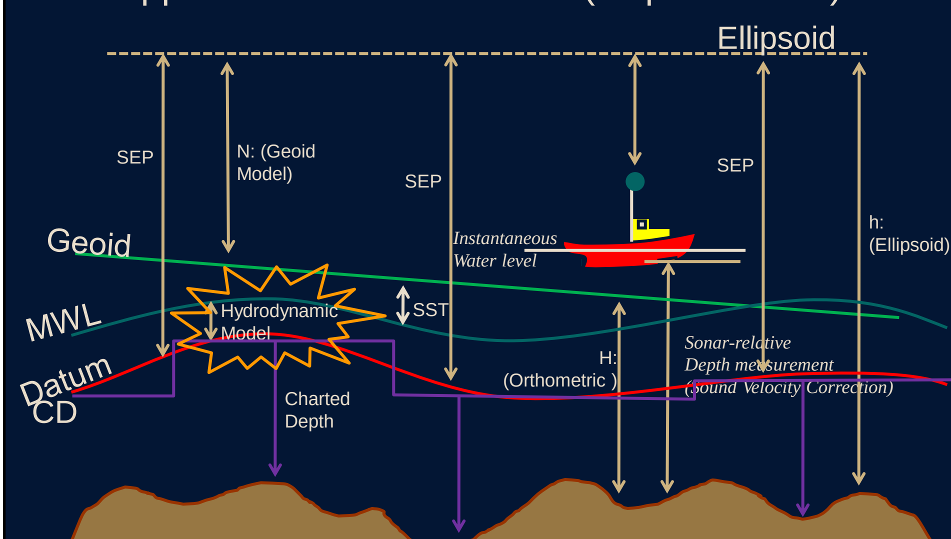
- Sea Surface Variations
  - Ocean Currents: 1 m
  - Waves
  - Sun Heating: 0.3 – 1 m
  - Storms, Pressure, Winds. etc





31

GPS Approach → We Need SEP (Ellipsoid – CD)



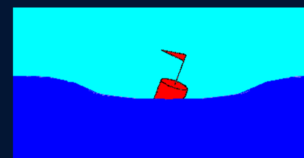
CD Depth = Sonar Depth + Offsets + Ellipsoid –SEP

SEP = N + SST + HModel

32

32

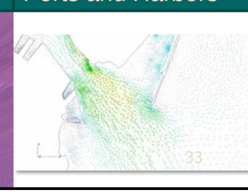
Hydrodynamic Model



Hydro → Water

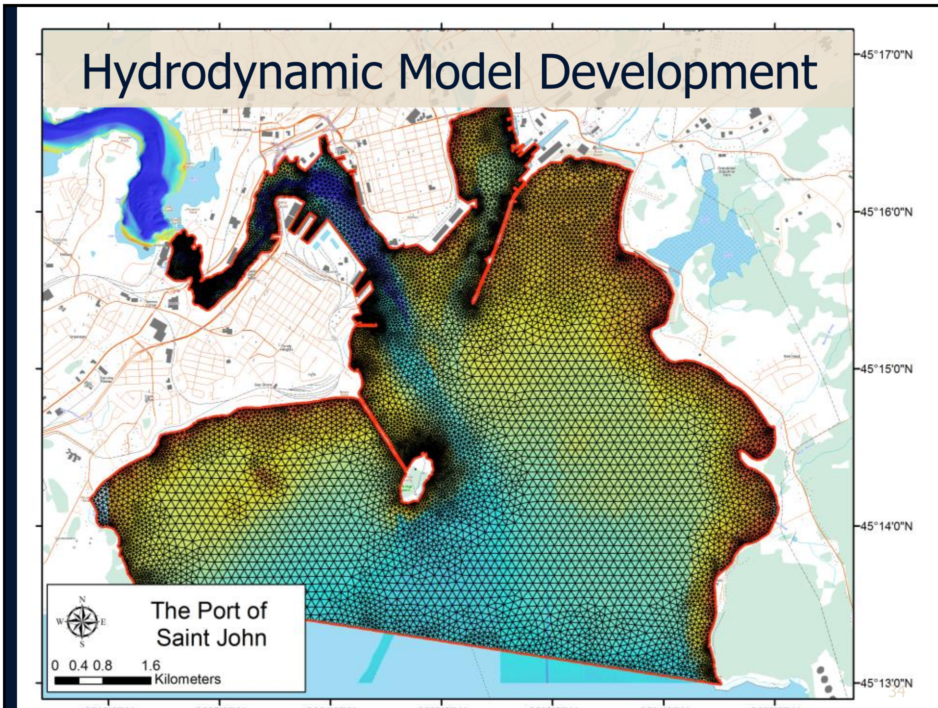
Dynamic → Motion

- A 3D computer model of water moving in an area
- Bounds + Water + External Forcing

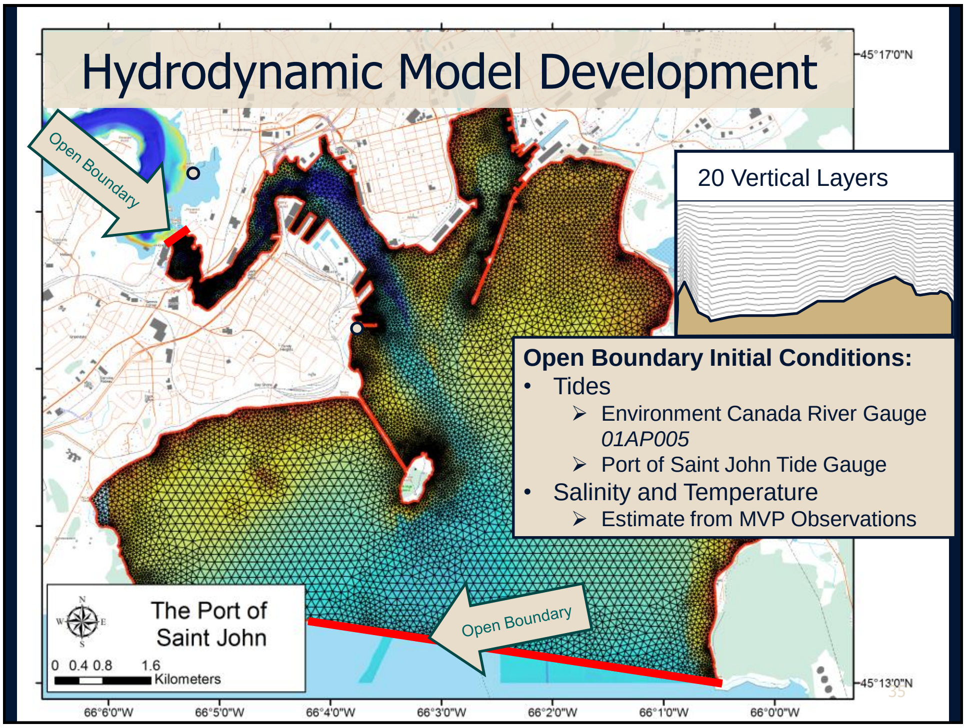
Tidal Power	Aquaculture	Sedimentation	Ports and Harbors
			

33

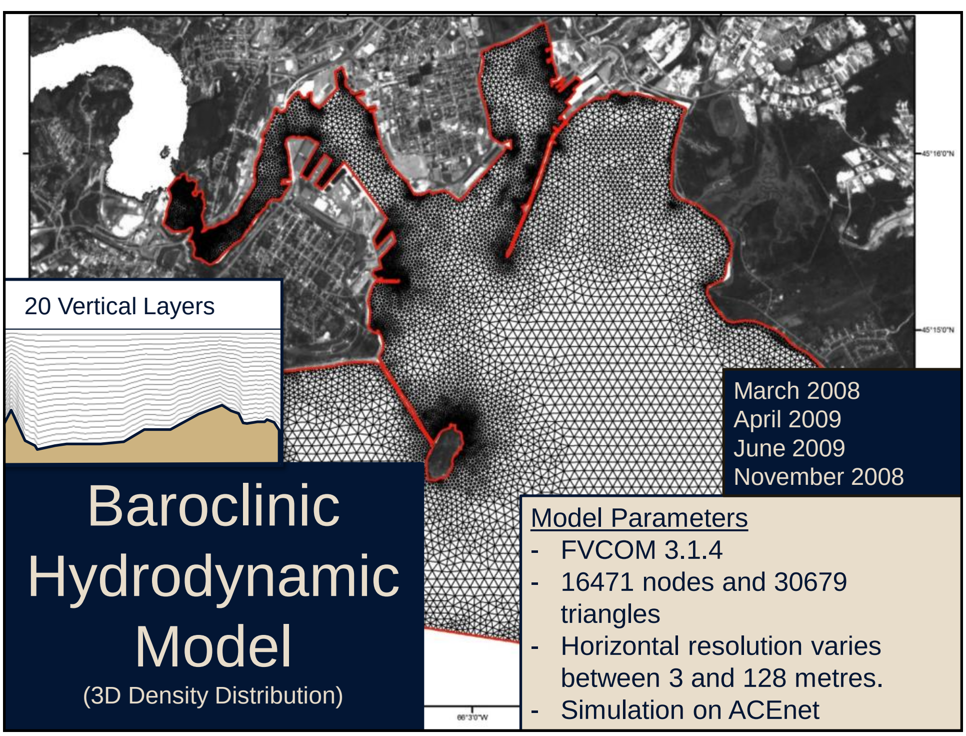
Hydrodynamic Model Development



34


Hydrodynamic Model Development
Open Boundary
20 Vertical Layers
Open Boundary Initial Conditions:
• Tides
➢ Environment Canada River Gauge *01AP005*
➢ Port of Saint John Tide Gauge
• Salinity and Temperature
➢ Estimate from MVP Observations
The Port of Saint John
0 0.4 0.8 1.6
Kilometers
Open Boundary
45°17'0"N
45°13'0"N
66°6'0"W
66°5'0"W
66°4'0"W
66°3'0"W
66°2'0"W
66°1'0"W
66°0'0"W

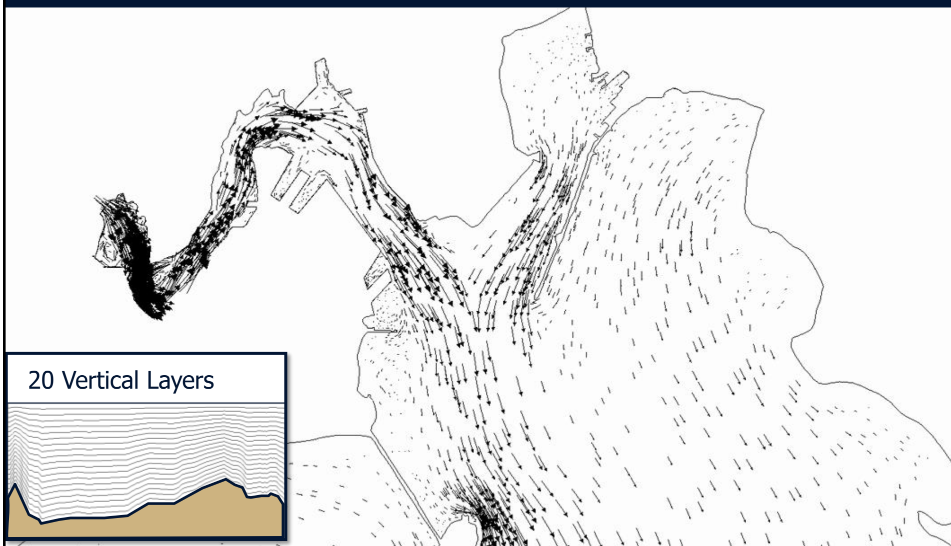
35


20 Vertical Layers
March 2008
April 2009
June 2009
November 2008
Baroclinic Hydrodynamic Model
(3D Density Distribution)
Model Parameters
- FVCOM 3.1.4
- 16471 nodes and 30679 triangles
- Horizontal resolution varies between 3 and 128 metres.
- Simulation on ACEnet

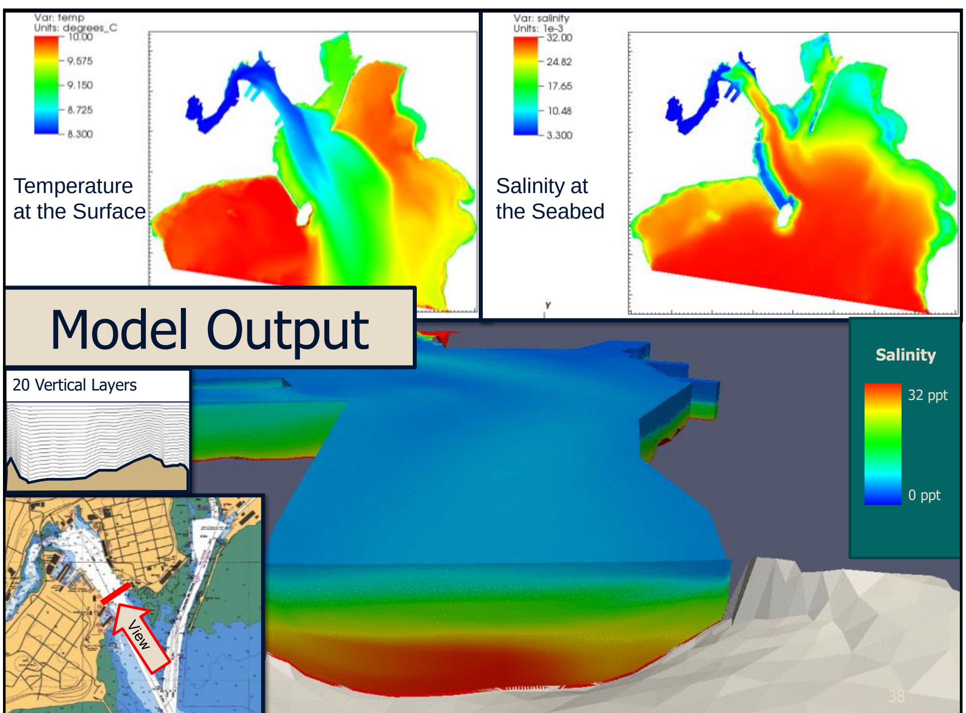
36

Model Output

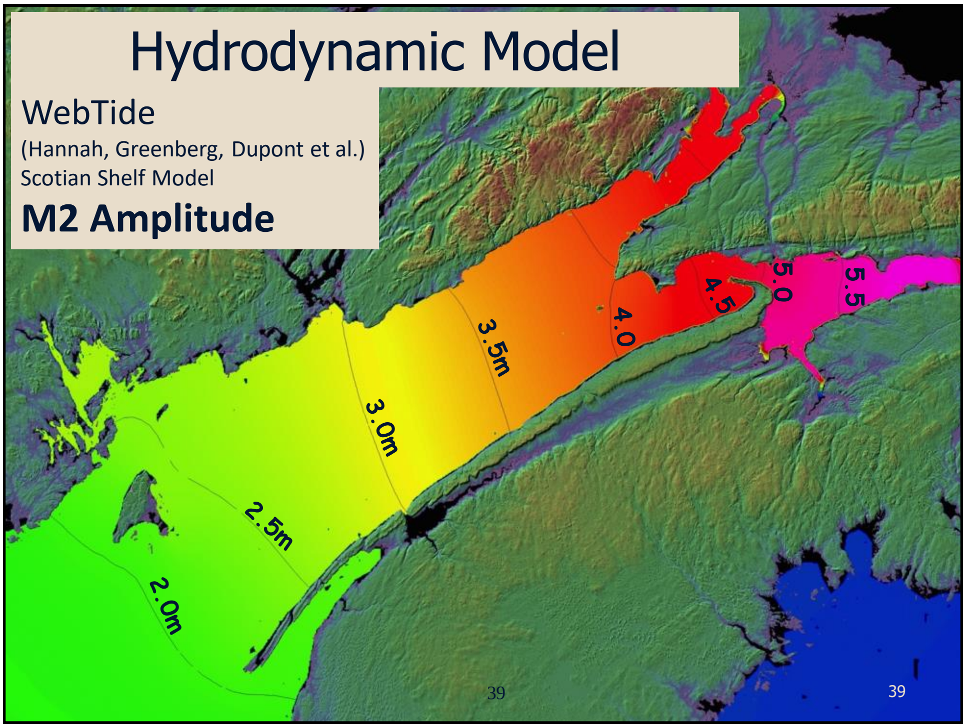
Surface Current Velocities



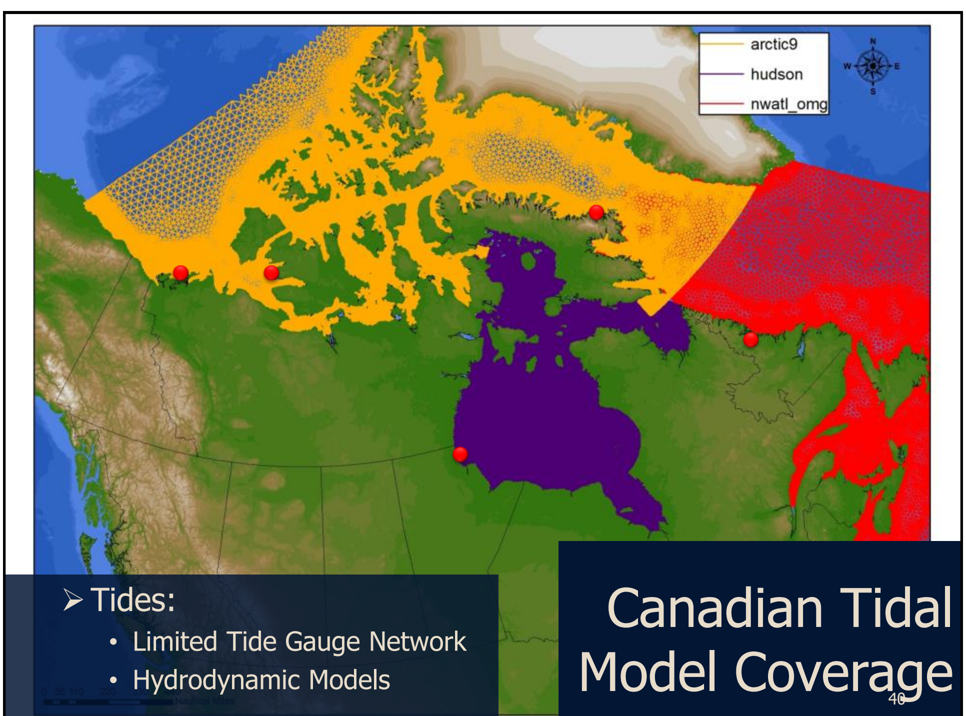
37



38

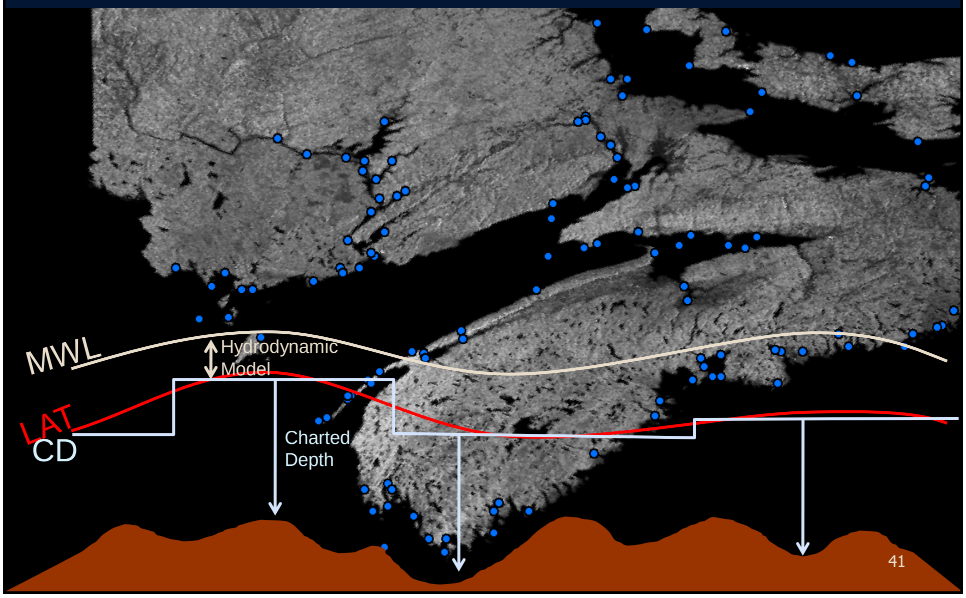

Hydrodynamic Model
WebTide
(Hannah, Greenberg, Dupont et al.)
Scotian Shelf Model
M2 Amplitude
2.0m
2.5m
3.0m
3.5m
4.0
4.5
5.0
5.5
39
39

39


arctic9
hudson
nwatl_omg
N
W
E
S
➢ Tides:
• Limited Tide Gauge Network
• Hydrodynamic Models
Canadian Tidal Model Coverage
40

40

Match the 2-Dimensionally Varying Chart Datum from Hydrodynamic Model to Established Chart Datum



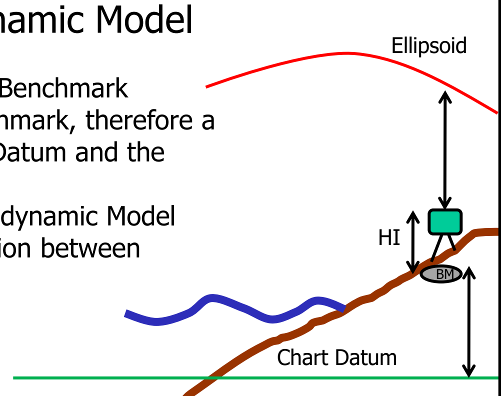
41

Now have Sufficient Information to Determine the Chart Datum Ellipsoid Separation

SEP = N + SST + Hydrodynamic Model

Simpler Solution… Determinee SEP without a Hydrodynamic Model

- Observe Ellipsoid Height at Tidal Benchmark
- Chart Datum Established at Benchmark, therefore a direct relationship between Chart Datum and the Ellipsoid
- **Advantage**: No need for a Hydrodynamic Model
- **Disadvantage**: Linear Interpolation between Benchmarks.



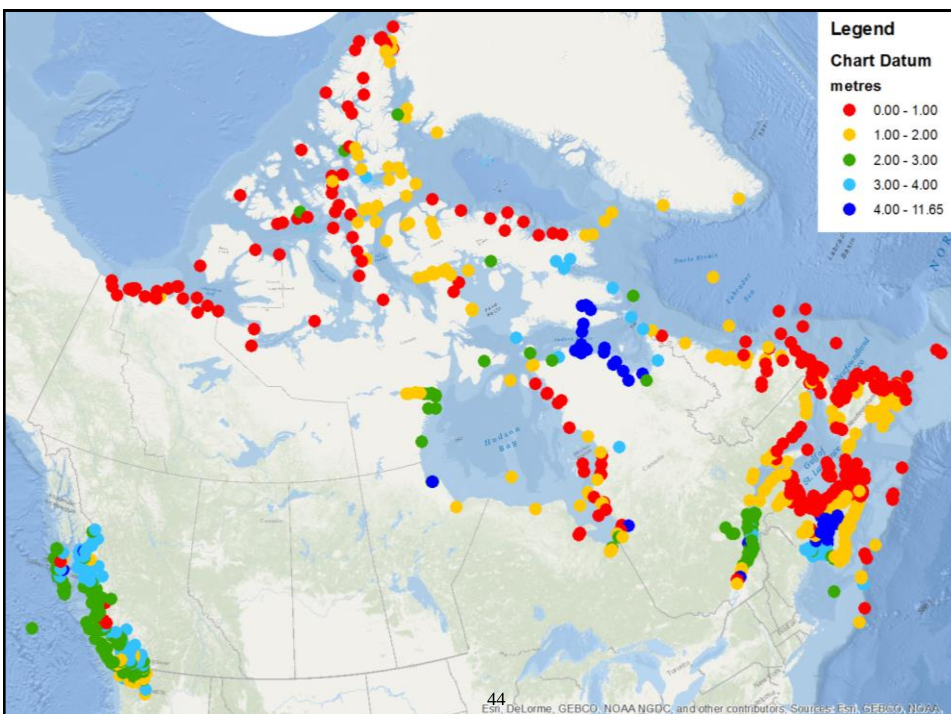
42

42

Implementation Challenge for Canada

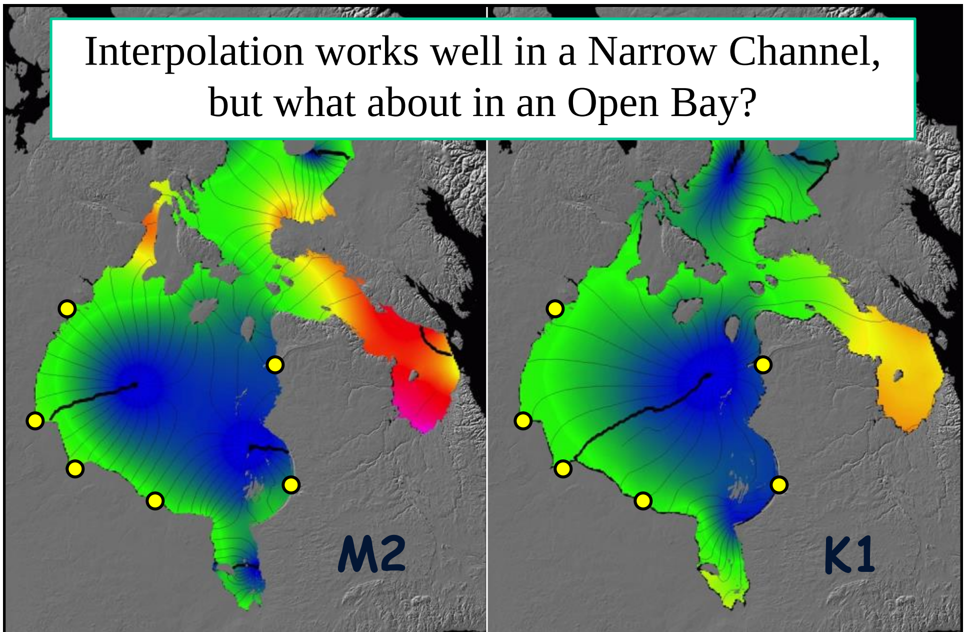
- Canada has a special challenge
  - We need to have agreement across the country - long coastline, lots of water and limited resources
  - Few tide gauges and lots of open water
    - Makes interpolation of CD between gauges impossible.

43



44

Interpolation works well in a Narrow Channel, but what about in an Open Bay?



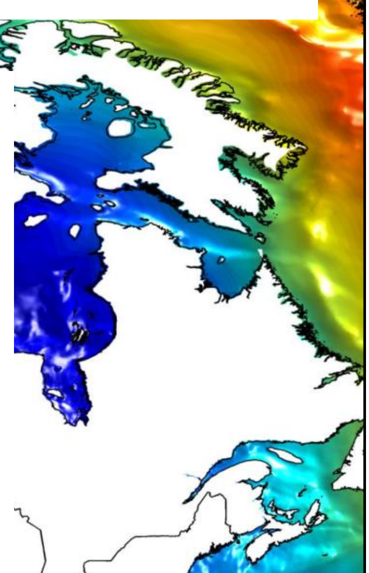
Hudson Bay M2 and K1 Amphidromes (Co-Tidal Charts) 2005 Version (WebTide)

45

45

Hydrographic Vertical Separation Surfaces (HyVSEPs)

- Translation from “Terrestrial” Vertical Datum (compatible with GNSS, ie. CGVD2013) down to Chart Datum
- Continuously Varying Chart Datum for Canada
- Combines tide gauge, satellite altimetry and GNSS data with a geoid model and dynamic ocean model solutions



46

46

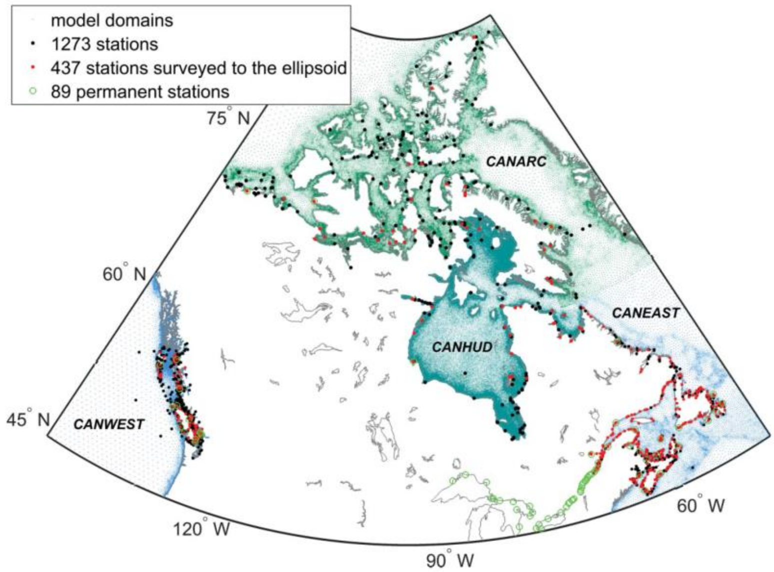


Figure 1. Tide stations and the four working grid domains, each portrayed in a separate color.

47

47

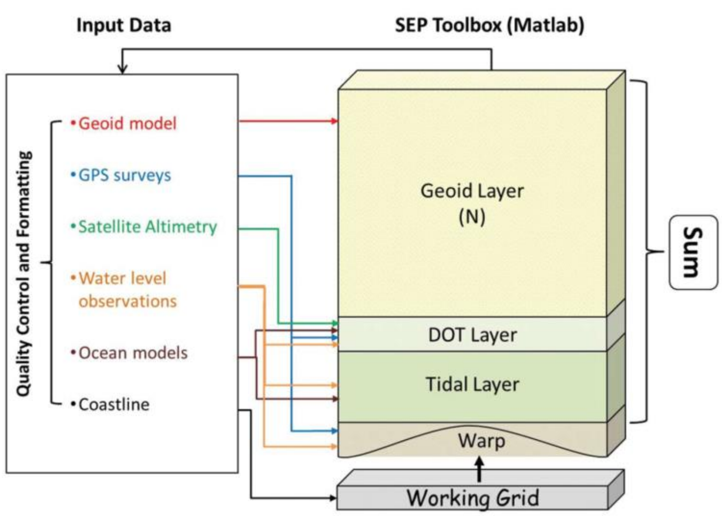


Figure 2. Flowchart of the CVDCW modeling process illustrating how input data is used in each HyVSEP layer. The feedback arrow connecting "SEP Toolbox (Matlab)" and "Input Data" highlights the interactive and iterative nature of HyVSEP model development and data validation and acquisition. This stack of layers is analogous to figures commonly drawn to describe the relationship between vertical datums (e.g., Robin et al. 2012).

48

48

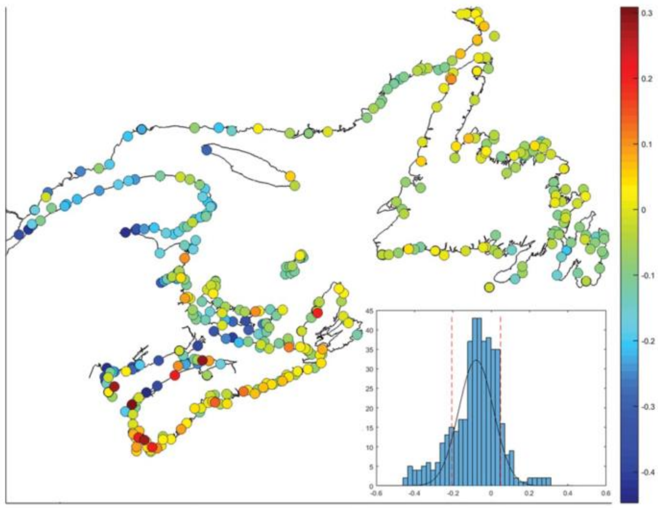


Figure 4. Difference between tide station and ocean model estimates of sep^{MSS}_{LLWLT} for the Gulf of St. Lawrence region, plotted in 2D and as a histogram (inset). The 2D plot shows where the model has underestimated the tide range on the west side of the Gulf, and overestimated it on the south shore of Nova Scotia. It also highlights inconsistencies between stations stemming from variable station data quality. Inconsistencies appear greater in areas where tide range is large (e.g., the Bay of Fundy); this effect disappears when using a ratio (Figure 5; Section 5.2).

49

49

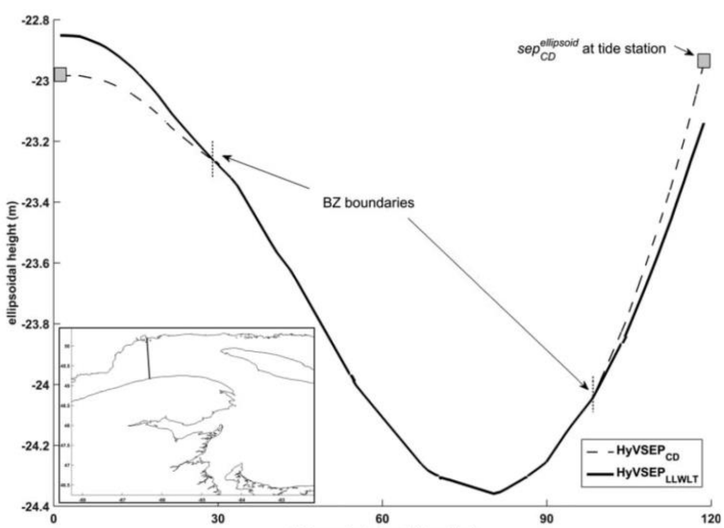
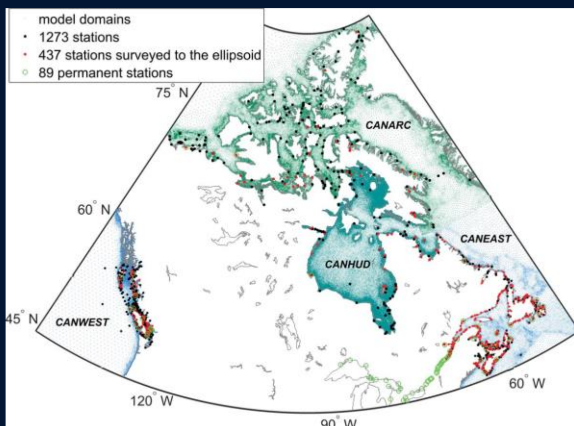


Figure 9. A north-south section of $HyVSEP_{LLWLT}$ and $HyVSEP_{CD}$ across the St. Lawrence Estuary (inset). $HyVSEP_{CD}$ is a warped version of $HyVSEP_{LLWLT}$ which honors the current definition of CD at tide stations and merges back to $HyVSEP_{LLWLT}$ at the seaward boundary of the BZ.

50

50

Continuous Vertical Datum Uncertainty



Accuracy estimates:

CANEAST	7.5cm
CANWEST	6.9cm
CANNORTH	6.6cm
CANHUD	17.7cm

Tide stations and the four working grid domains, each portrayed in a separate colour, duplicated from Robin et al (2016)

51

51

Vdatum

- Software developed by NOAA
- Transforms points from one horizontal and vertical datum to another
- Uses Hydrodynamic models to determine the tidal datums
- "VDatum is designed to vertically transform geospatial data among a variety of tidal, orthometric and ellipsoidal vertical datums - allowing users to convert their data from different horizontal/vertical references into a common system and enabling the fusion of diverse geospatial data in desired reference levels." http://vdatum.noaa.gov/

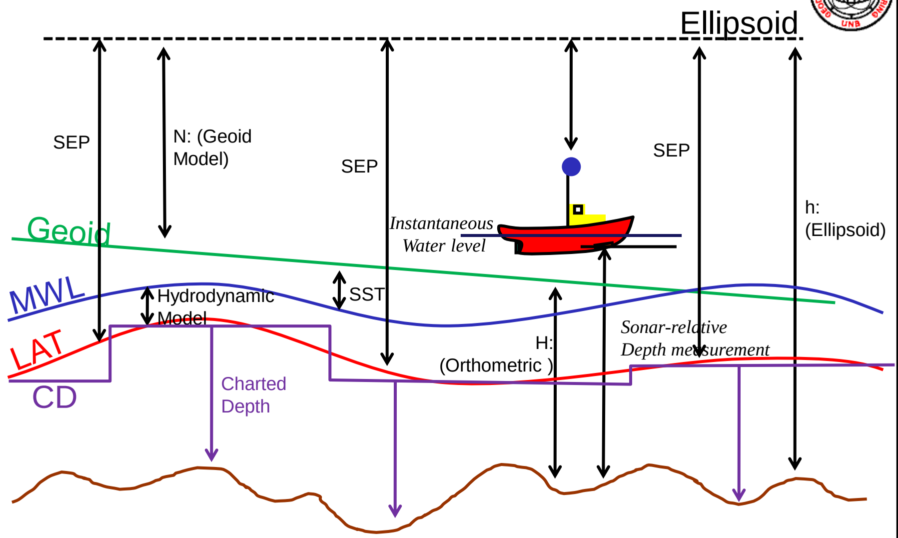
- **Converts the following:**
- **Horizontal datums**: from NAD 27 or NAD 83(1986) to NAD 83(HARN). NAD83(HARN) is currently considered as being equivalent to NAD 83(NSRS2007/CORS96), WGS 84 or ITRF
- **Vertical datums**: among three vertical groups: tidal datums, orthometric datums and ellipsoidal datums (i.e. three-dimension or 3-D datums), in which:
  - Transforms among ellipsoidal and orthometric datums are available throughout the United States;
  - The HTDP v2.9 is partially utilized to support conversions among ellipsoidal datums;
  - Current GEOID models such as GEOID 99, GEOID 03, GEOID 06 and GEOID 09 are used to support direct conversions between the NAD 83 ellipsoidal datum and the NAVD 88 orthometric datum;
  - The VERTCON model is employed to support conversions between the NGVD 29 datum and the NAVD 88 datum;
  - The IGLD 85 model is employed to support conversions between IGLD 85 datum and the NAVD 88 datum;
  - Tidal datums are available in 27 areas.
- **Input elevation data** in geographic (Latitude, Longitude) and UTM coordinates.

http://vdatum.noaa.gov/

52

52

GPS Approach → We Need SEP (Ellipsoid – CD)



CD Depth = Sonar Depth + Offsets + Ellipsoid –SEP

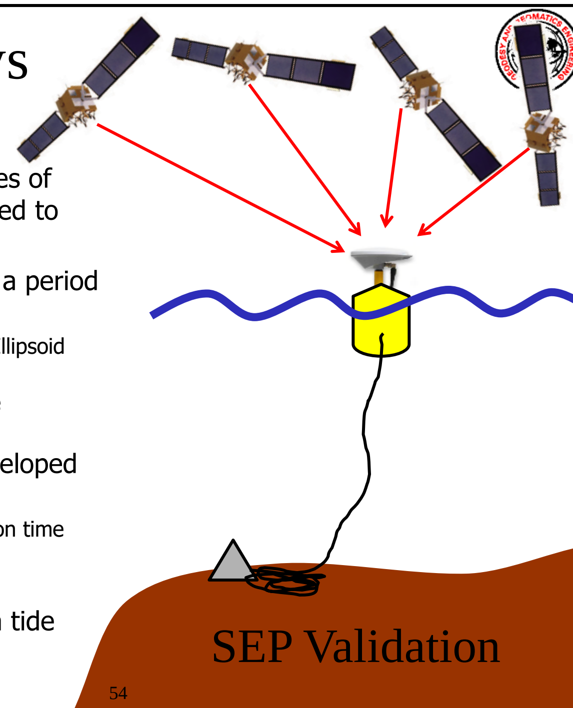
SEP = N + SST + HModel

53

53

GNSS Buoys

- Provides a vertical time series of water level heights referenced to the Ellipsoid
- Can determine a MWL after a period of time
  - Can be compared to Geoid – Ellipsoid Separation
  - Difference is likely Sea Surface Topography
- A vertical datum can be developed based on the observations
  - Quality of Datum will depend on time series length
  - Can use datum transfer
- Provides the same data as a tide gauge (offshore), only it is referenced to the Ellipsoid



54

54

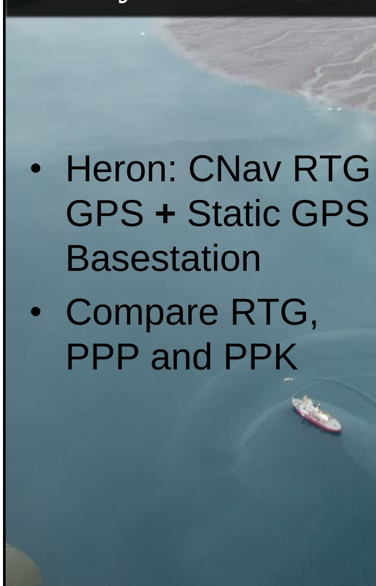
GNSS Observation Reliability

- To Survey to the Ellipsoid, reliable GNSS Heights are Required
- Differences between PPK, RTG and PPP
- Case Studies:
  - Canadian Arctic → Latitude 73 degrees N
  - Coastal Gulf of Mexico → Latitude 32 degrees N

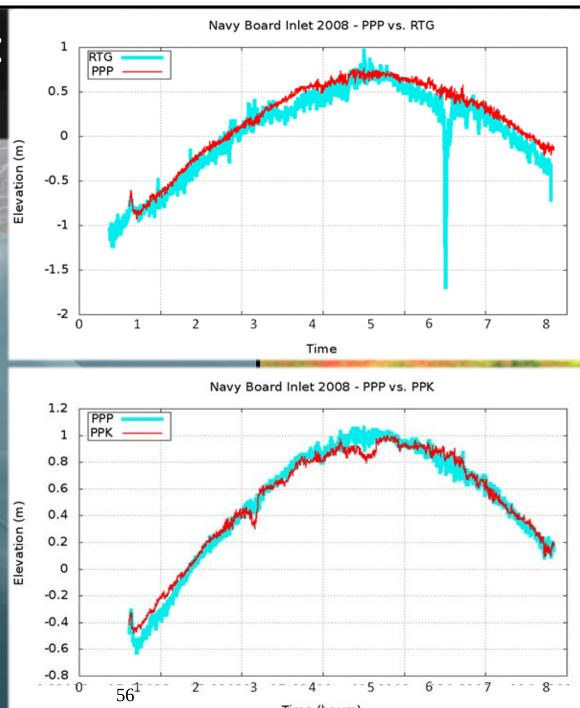
55

55

Canadian Arctic:
Navy Board Inlet

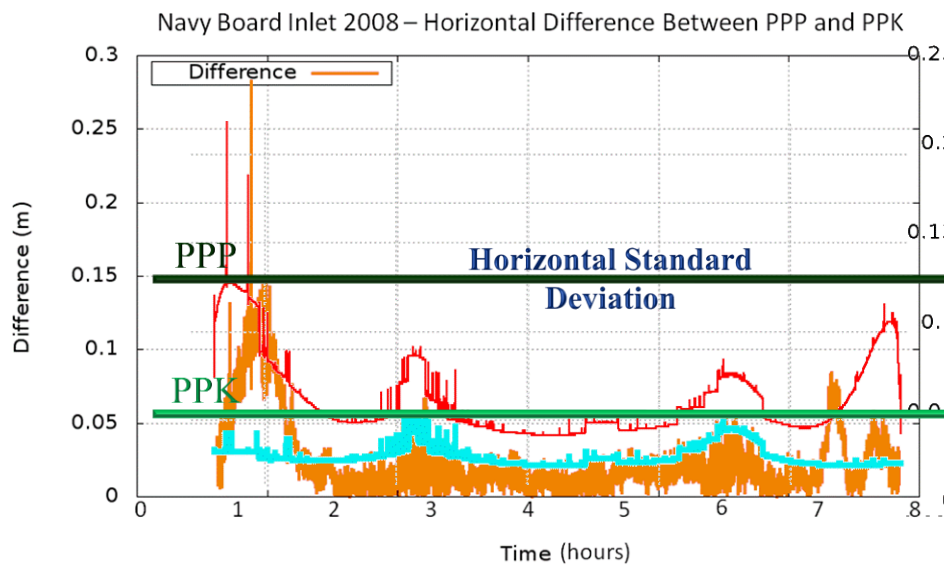


- Heron: CNav RTG GPS + Static GPS Basestation
- Compare RTG, PPP and PPK



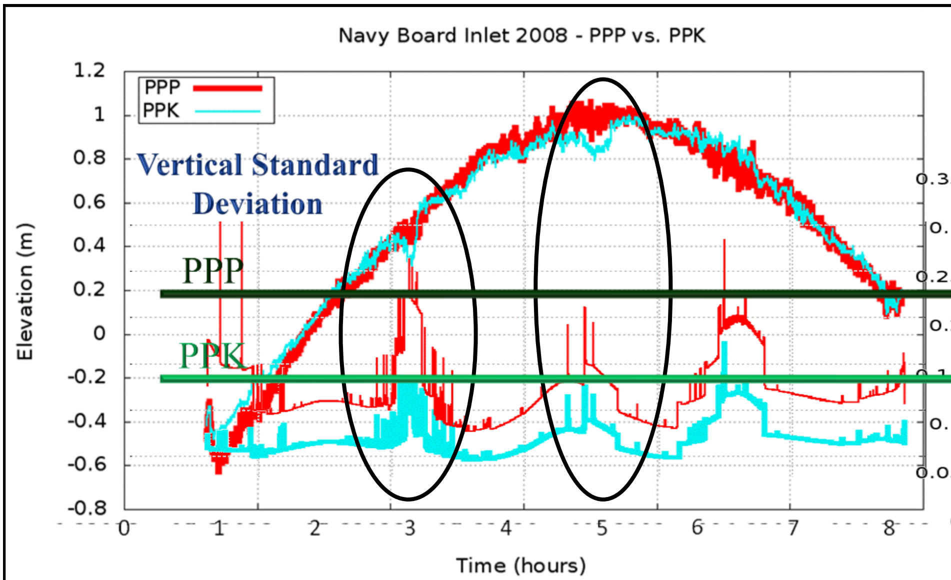
56

56



Navy Board Inlet
PPP vs. PPK Horizontal Difference

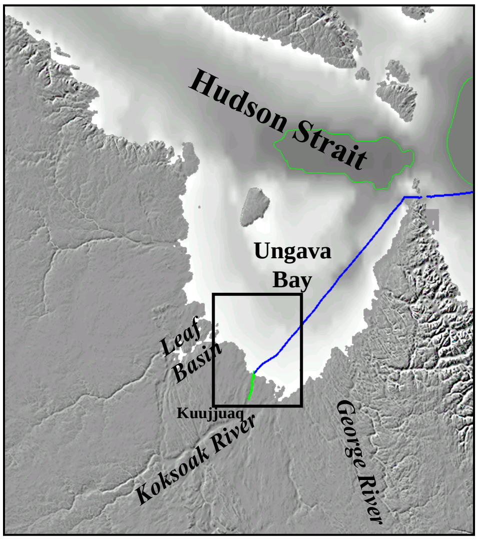
57

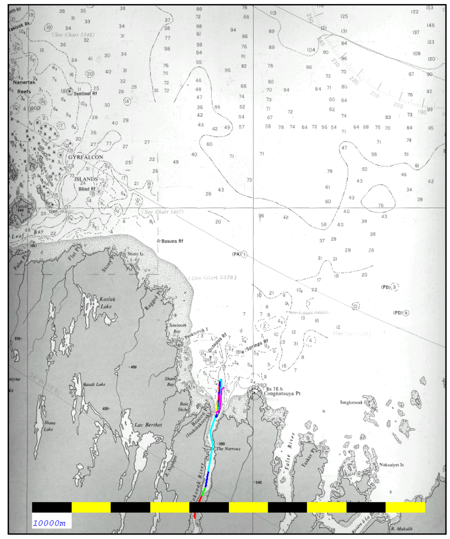


NAVY BOARD INLET PPP VS. PPK

58

Vertical Datum Issues, Hydrography in Ungava Bay

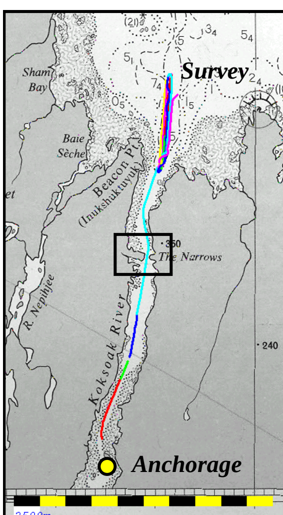


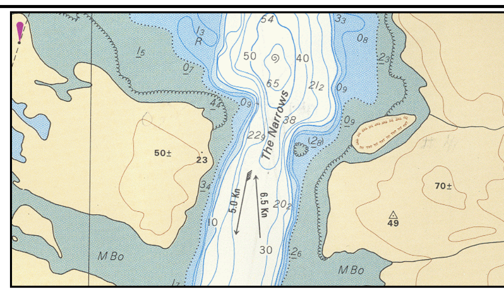


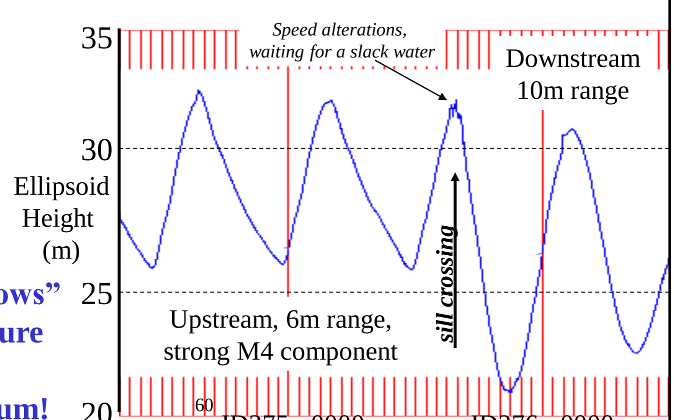
CCGS Amundsen EM300 survey
Approaches to Koksoak River (10m+ tides)

Extract of CHS Chart 5300
Hudson Strait, Ungava Bay
1:500,000, depths in fathoms

59





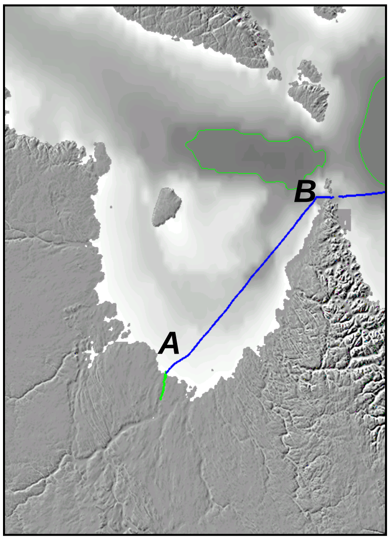


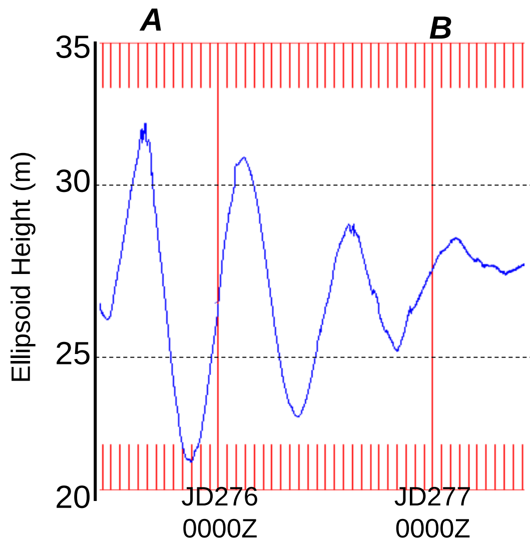
Effect of the "Narrows" on the tidal signature

Shift in Chart Datum!

60

Observing the decay in tidal range across Ungava Bay





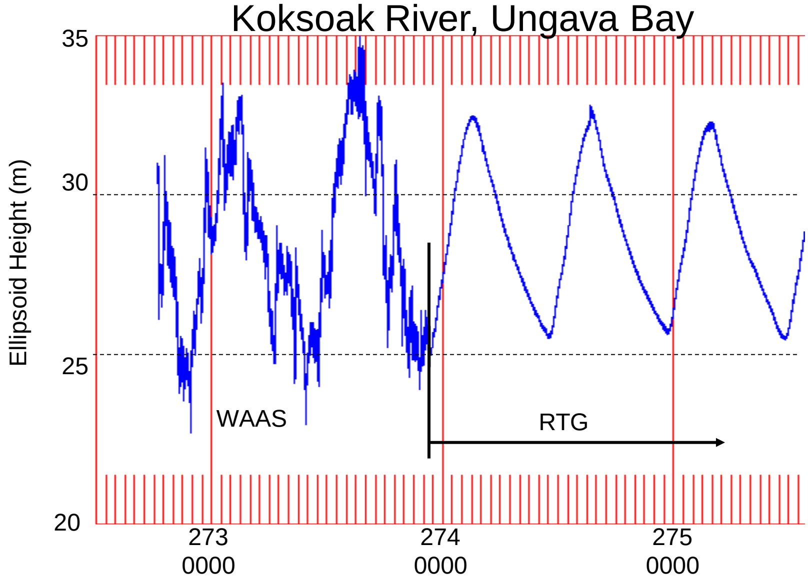
61

From John Hughes Clarke

61

Antenna Solutions – at anchor

Koksoak River, Ungava Bay



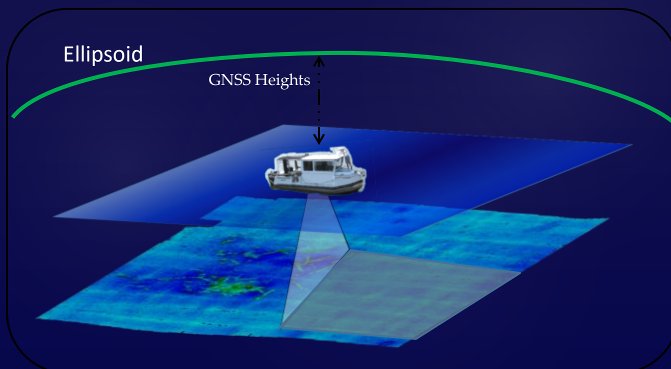
62

From John Hughes Clarke

62

Comparison of Horizontal and Vertical Resolvable Resolution between Repetitive Multibeam Ellipsoid Referenced Surveys using Different GNSS Methods

Christopher R. McHugh, Ian Church, Min Sung Kim, David Maggio



THE UNIVERSITY OF SOUTHERN MISSISSIPPI
COLLEGE OF SCIENCE AND TECHNOLOGY

UNB EST. 1785 UNIVERSITY OF NEW BRUNSWICK | Engineering Fredericton

63

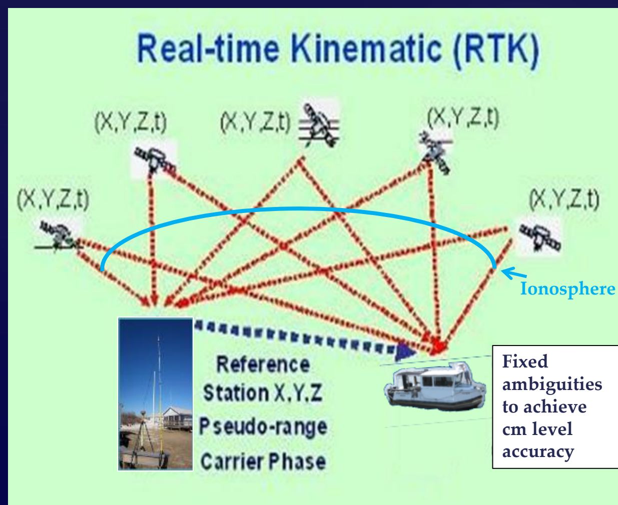
- Ellipsoid referenced surveying is quickly becoming the standard in hydrographic surveying.
- This places heavy dependence on GNSS techniques to consistently provide accurate positioning in the horizontal and vertical with low uncertainty.
- Hydrographers need to know: which GNSS technique yields the best solution? Does that method work in all conditions?

Survey Area. Site 1 average depth 7 meters. Site 2 average depth 5 meters.

RTK base station on Ship Island.

64

- RTK uses a stationary base station to help resolve ambiguities.
- The base station transmits phase and range corrections to the rover for use in real time or post processing (Post Processed Kinematic (PPK)).

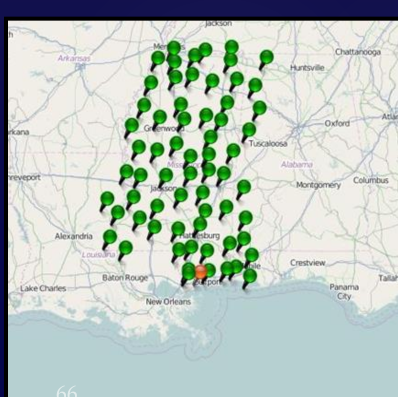


65

http://www.sage.unsw.edu.au/currentstudents/ug/projects/JacksonB/Bradley%20Jackson%20Thesis%20Page_files/image1597.jpg

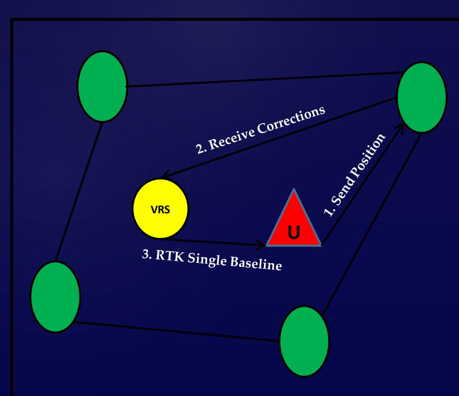
65

- The development of Real Time Kinematic Networks (RTN) allow for a triangulated Virtual Reference Station (VRS) to be established anywhere in the survey area
- Eliminating the need for a physical base station set up over a benchmark.



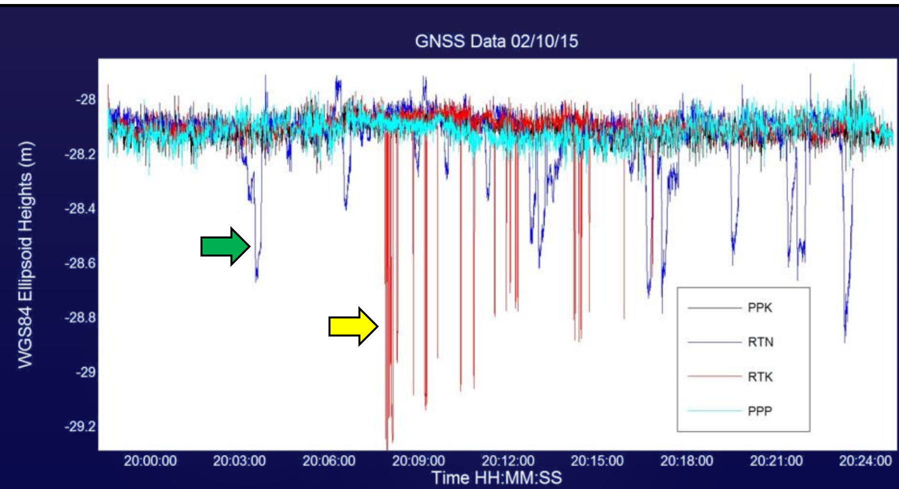
66

GCGC RTN network in MS operated by USM.



Basic concept of a VRS.

66



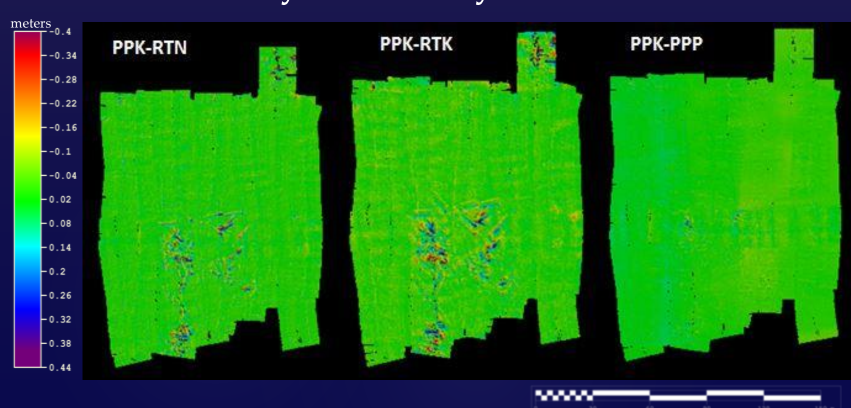
RTN lapses believed to be from cell signal degradation and VRS geometry.

RTK lapses from changes in satellite geometry and length of baseline.

67

67

Two Surveys – Same Day – PPK Reference



- Large position uncertainties do not propagate enough to significantly affect bathymetric measurements for the February 10th (DOP's < 2.1).
- Each survey on February 10th meets IHO Special Order requirements.
- Differences between surfaces are only seen over target areas.

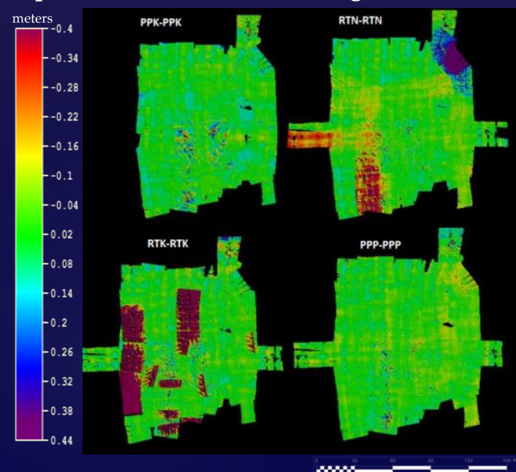
68

68

Two Surveys – Two Weeks Apart – Same GNSS Processing Method

Difference of 01/27 -02/10	PPK vs PPK	RTN vs RTN	RTK vs RTK	PPP vs PPP
Average Difference	0.046 m	0.010 m	-0.199 m	0.016 m
2 x Sigma (95% CI)	0.126 m	0.274 m	1.268 m	0.118 m
RMS	0.078 m	0.138 m	0.665 m	0.061 m

Statistics from difference surfaces of GNSS data between 01/27 and 02/10. Real time methods have large uncertainty.



- To demonstrate survey repeatability, base surfaces for each Kinematic method were differenced between two survey days (01/27/15 and 02/10/15).
- RTN and RTK positions have large uncertainties (mainly on the 01/27/15; DOP's>4.0) causing large differences between the two survey days.
- Neither of these methods meet IHO Special Order requirements for 95% of soundings in the survey area.

69

69

- The hydrographic community has unique challenges for vertical referencing vs. land surveying
- Ellipsoid Referenced Surveys (ERS) are possible for all Canadian Waters
- The CVD solution must be continually refined and improved as better Geoid Approximations, DOT estimates and Tidal Estimates become available
- There needs to be additional validations throughout the CVD domain to verify stated uncertainties and to confirm that vertical accuracy requirements are being met

Overview

70

70

GPS Tides - In Summary

- A method that decouples the vertical from any assumptions about:
  - tidal phases or amplitudes or
  - draft and squat.

- Many hydrographic organizations are moving towards this method, but there are still a number of hurdles
  – LLWLT datum is difficult to determine from Tidal Models – Requires move to LAT
  – Requires confident ellipsoid to geoid and geoid to chart datum **separation models**
  – Hydrodynamic Tidal Models can have problems if model does not represent reality
  – GNSS often plagued by **reliability issues**.

- PPK or PPP potentially meet accuracy needs and continues to improve

- Ellipsoid to Chart Datum offset can be a **Surface** or a **Single Value**
  – Requirements depend on the survey area

UNB EST. 1785 UNIVERSITY OF NEW BRUNSWICK | Engineering Fredericton

71

71