Water Level Datums, Datum Targets, References and Transformations (Defining the Horizontal from the Vertical)

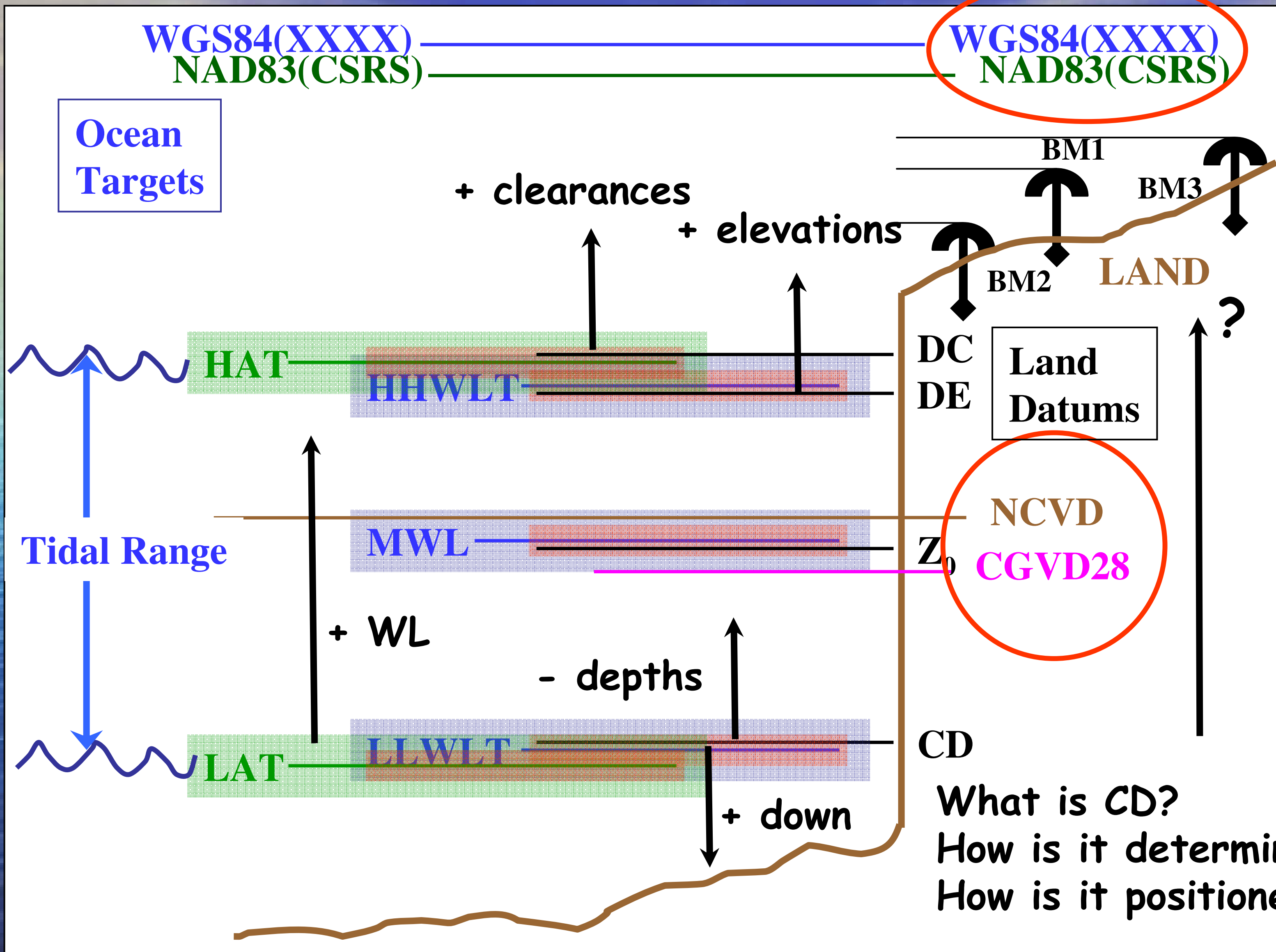
Phillip MacAulay
Canadian Hydrographic Service Atlantic

How can what we in the CHS have done, are doing, and plan to do with respect to our vertical datums and datum targets be used by the terrestrial survey world?

- What is this Chart Datum Based Coordinate System?
  - Water level variability – Tidal Theory
  - What are tides? how do they vary in space and time?
- What are Tidal Datums, Datum Targets and References, and how are they defined and used?
- Continuous Vertical Datum Surfaces (Gridded Transforms)
- The Canadian Continuous Vertical Datum Project: Evolving from discrete data (tide stations) to 2D Surfaces (Grids). Where are we in this process?

Hydrography is upside down and confused (We live in the World at World's End)

Pirates of the Caribbean



What is CD?
How is it determined?
How is it positioned?

What is CD (All Water Levels and Tides)
Gravitational Forcing of Tides
example: earth-sun system

Gravitational Force

$$F_G = \frac{GM_1 M_2}{R^2} \quad G = 6.673x10^{-11}\ m^3 kg^{-1} s^{-2}$$

$$F = Ma \quad a_g = \frac{GM_e}{r_e^2} = ? \quad M_e = 5.974x10^{24}\ kg$$

$$r_e = 6378.1\ km$$

But, gravitational force varies over earth's surface

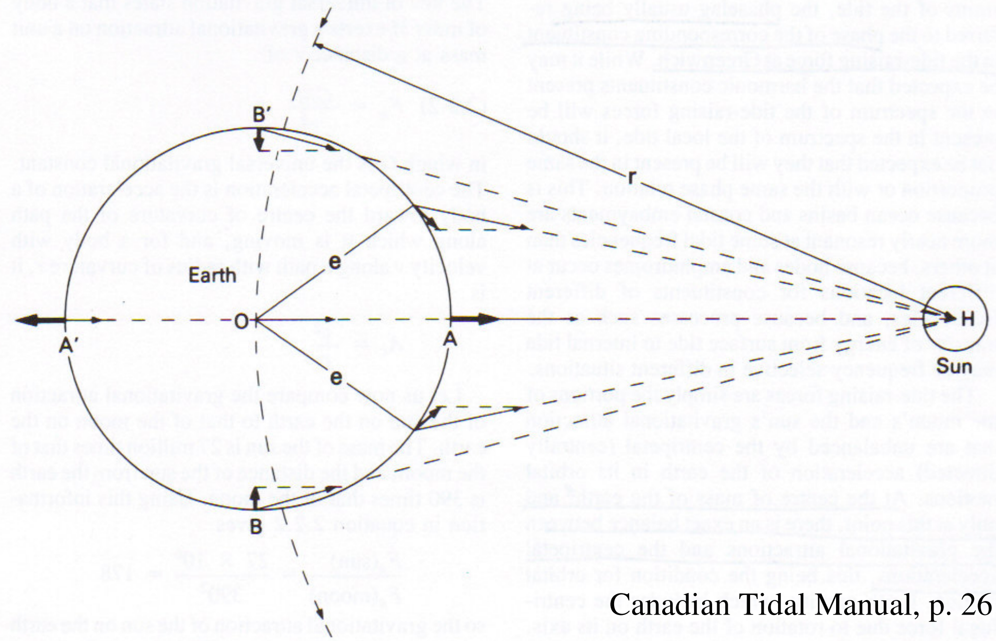
Example difference in force from A to A':
M_2 is unit mass: at *A*, R=(*r*-*e*); at *A'*, R= (*r*+*e*)

$$\Delta F_s(A) = \frac{GM_s}{(r-e)^2} - \frac{GM_s}{r^2} \approx \frac{GM_s e}{r^3}$$

$$\Delta F_s(A') \approx -\frac{GM_s e}{r^3}$$

Series Expansion

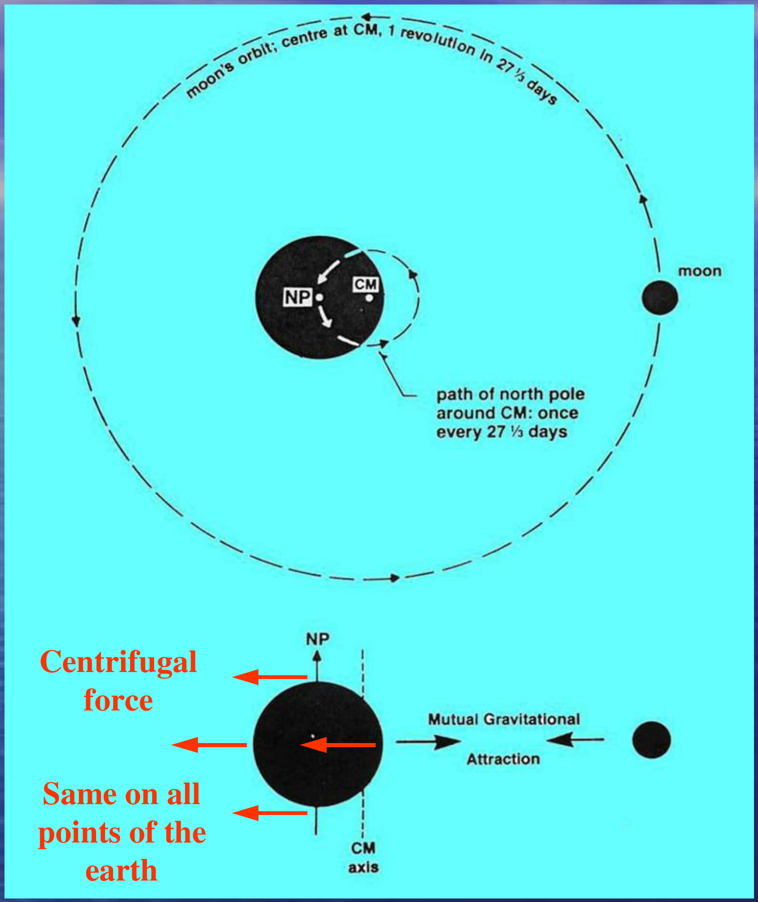
$$\frac{1}{(r-e)^2} = \frac{1}{r^2\left(1-\frac{e}{r}\right)^2} = \sum_{k=0}^{\infty} \frac{(2+k-1)!}{(k)!}\left(\frac{r}{e}\right)^k \approx \frac{1}{r^2}(1 + 2\frac{e}{r} + \Lambda)$$



Canadian Tidal Manual, p. 26

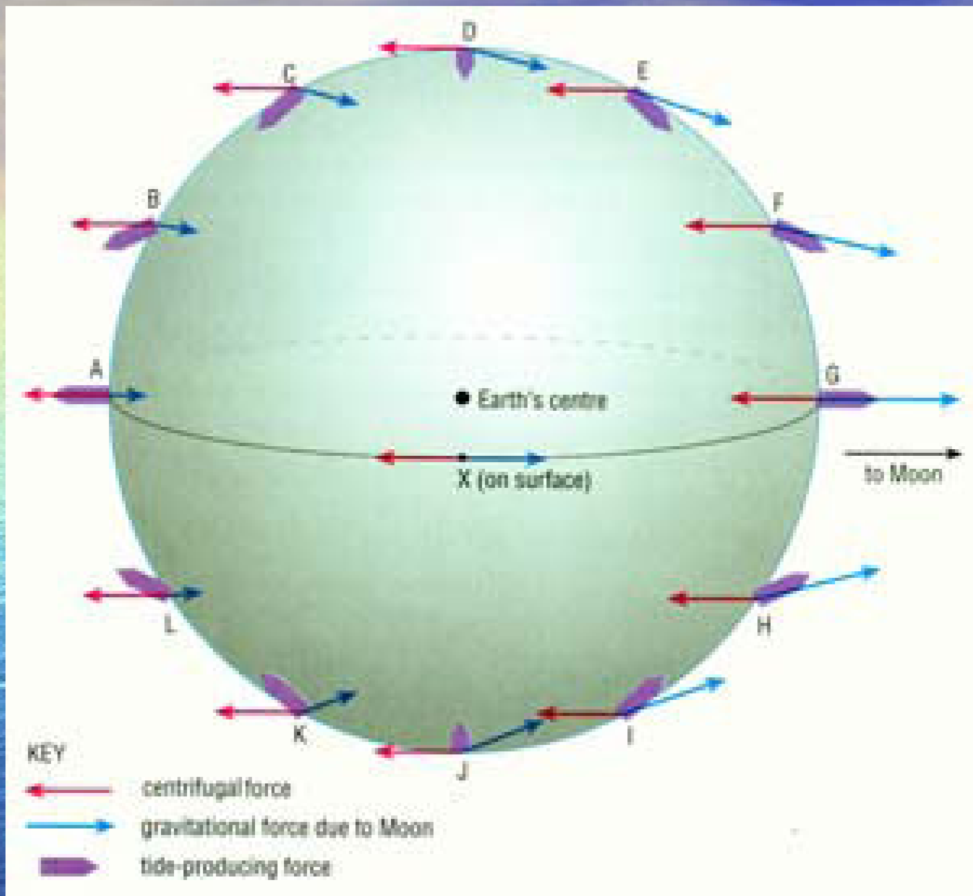
Reference for further reading:
Canadian Tidal Manual

Tidal forcing – Centrifugal force

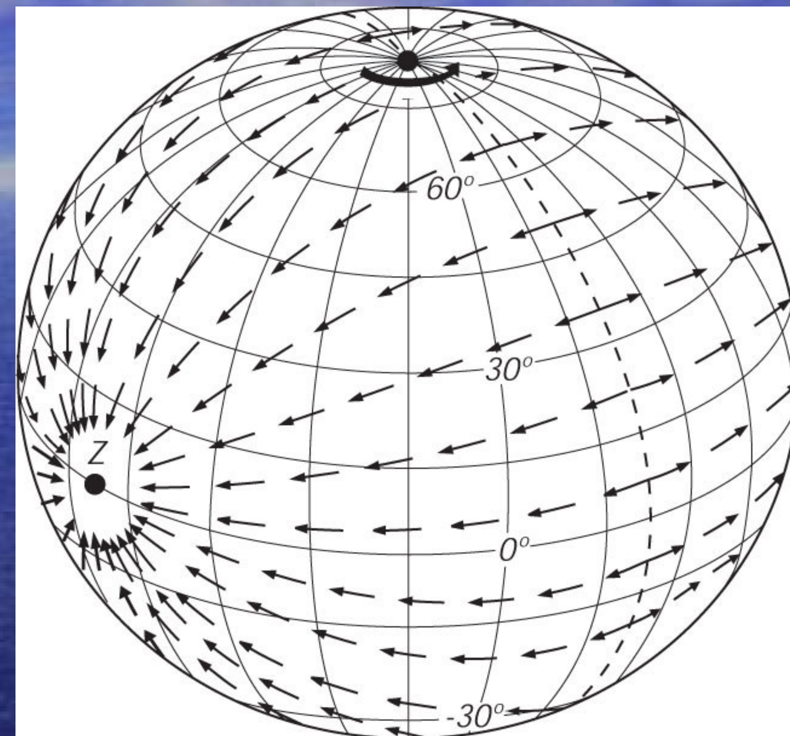


Basic tidal forcing arises from the difference between the gravitational attraction on the oceans by the moon and sun, and centrifugal forces on the oceans developed by the earth-moon, earth-sun orbital systems.

Net tidal forcing (earth-moon system)



Gravitational and centrifugal forces balanced at earth center, unbalanced elsewhere



Net effect, forced flow. Final result if water allowed to adjust until net forcing is finally balanced by building surface pressure gradient is an 'Equilibrium tide'.

The moon's Equilibrium Tide

The moon's equilibrium tide is the level that the water would final settle to or seek on a fully water covered earth (in the absence of all other influences on water levels) based purely on the earth-moon system's astronomical forcing on the water as it exists at any moment frozen in time. In other words, the static water level where pressure forces due to horizontal gradients in water levels exactly balance the tide's astronomical forcing. The total equilibrium tide is the water levels that would exist to force balance the sum of all astronomical forcing at any instance in time.

Declination Effects:

Diurnal inequality

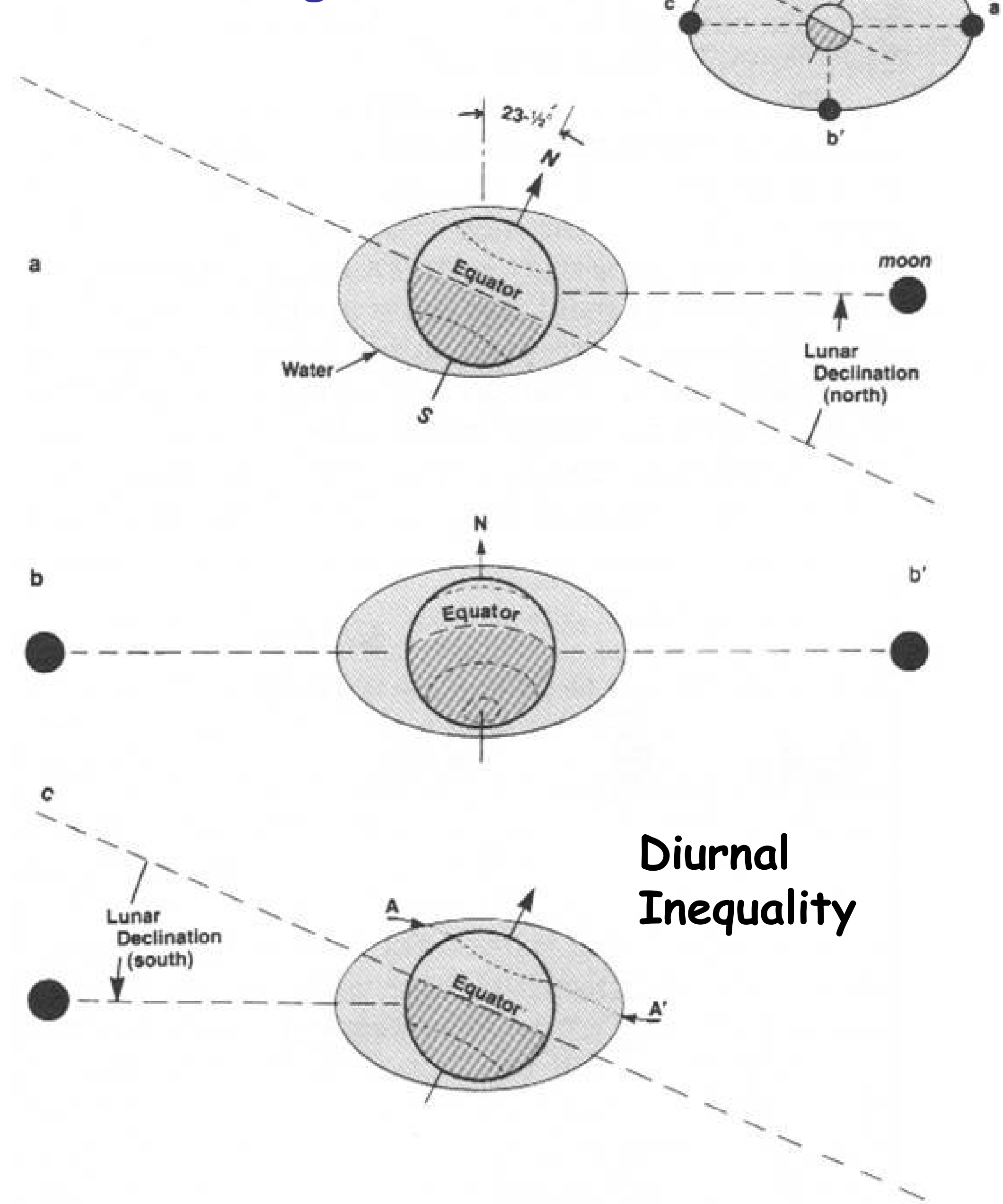
~12 and ~24 hour forcing

HHW – Higher High Water
LLW – Lower Low Water
LHW– Lower High Water
HLW – Higher Low Water

Period of lunar declination:

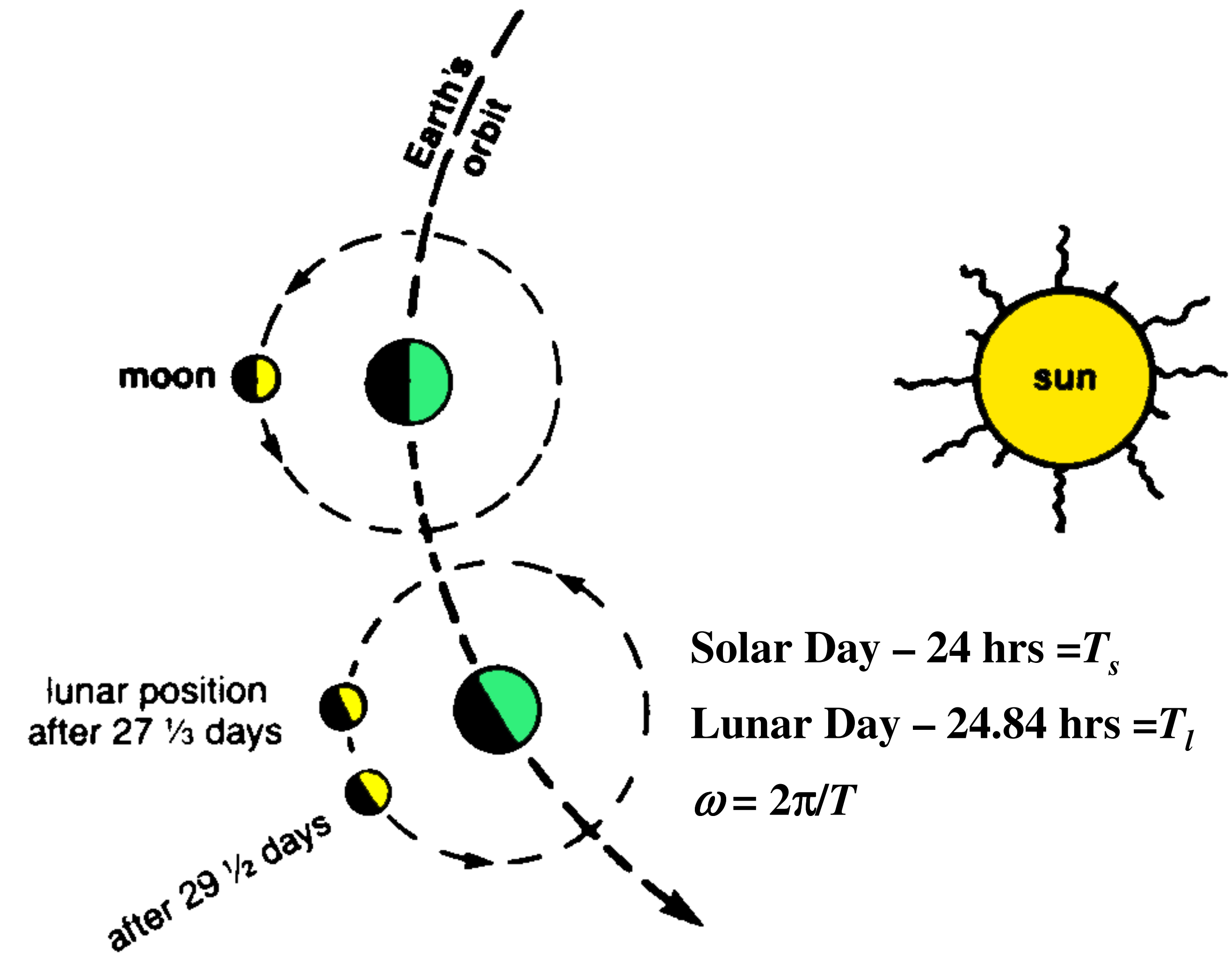
27.32 days

The Wrong Picture ?



Diurnal Inequality

Important forcing periods and frequencies: Lunar and Solar days (The ~ 12hr and ~24 hr components)



Solar Day – 24 hrs =T_s

Lunar Day – 24.84 hrs =T_l

$\omega = 2\pi/T$

Some Longer Forcing Timescales

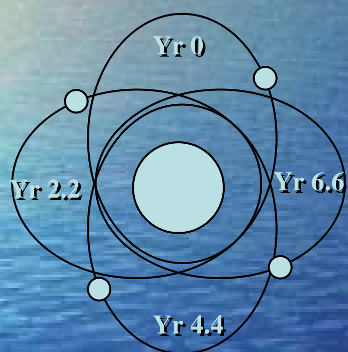
2) Moon's Elliptic Orbit Apogee and Perigee

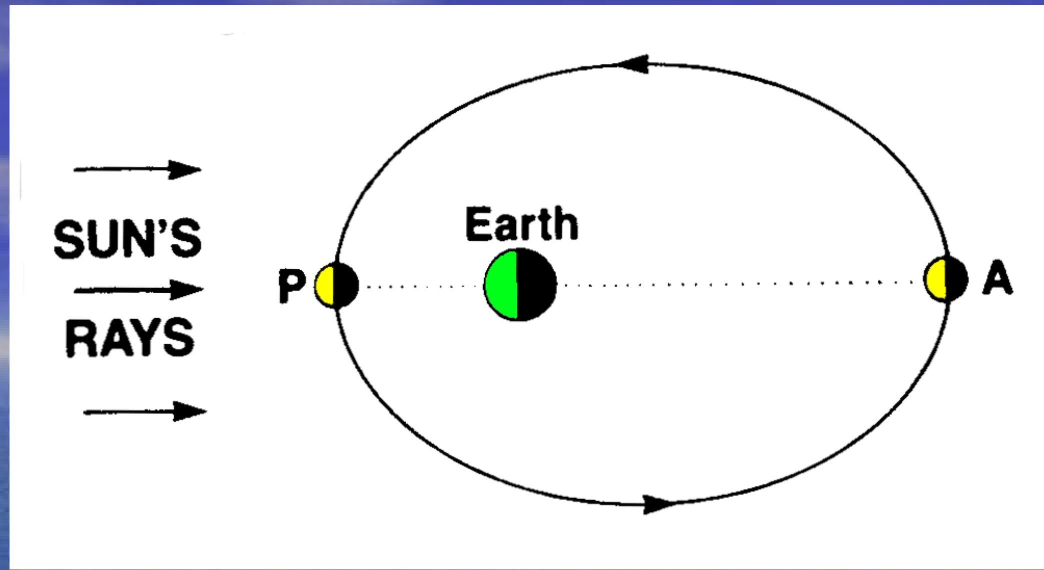
27.55 days,

Precession of moon's orbit

(caused by solar tidal forces)

8.847 years



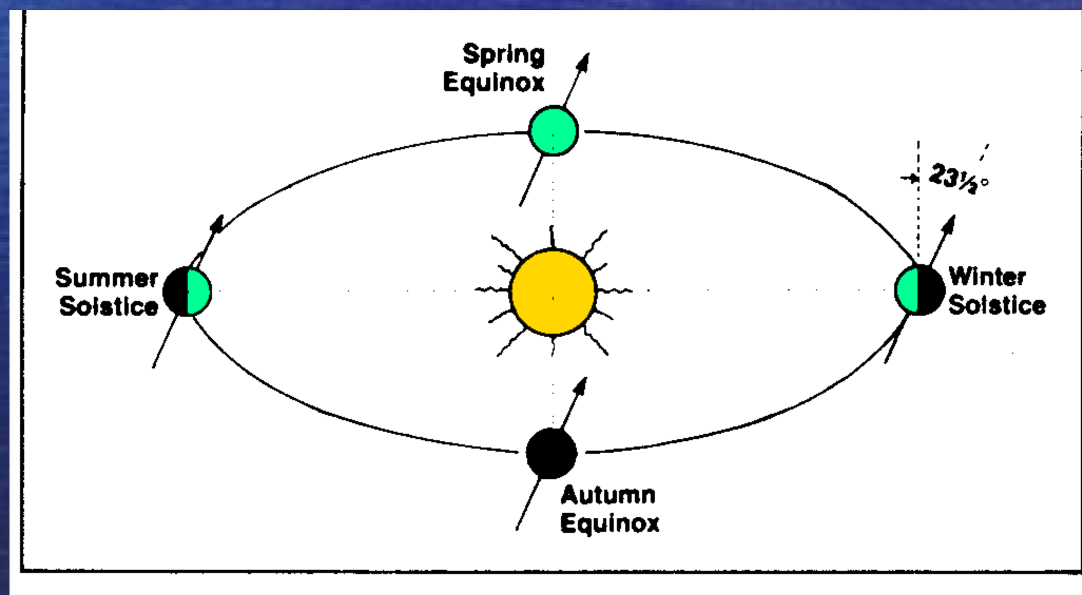


3) Earth's Elliptic Orbit Aphelion and Perihelion Solar Declination

365.24 days

Earth Orbital precession,

~26,000 years



Lunar nodal regression

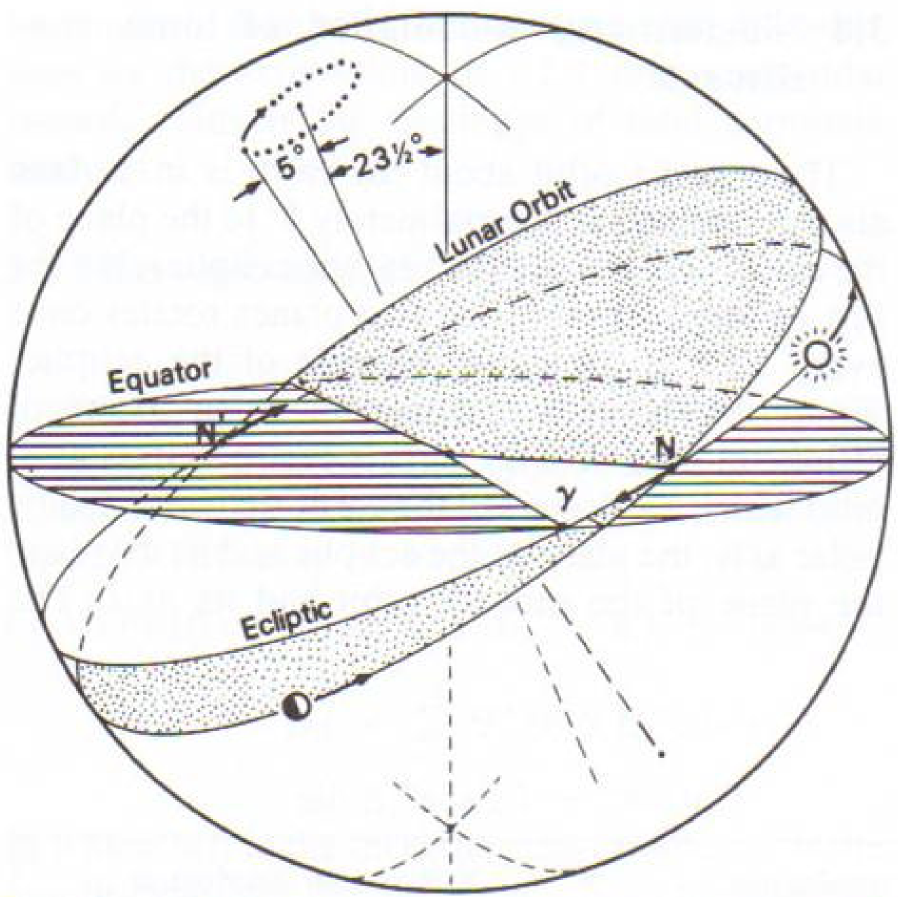


FIG. 24. Celestial sphere, showing equator, ecliptic, lunar orbit and regression of moon's ascending node, N.

Canadian Tidal Manual, p. 42

Over 18.6 year period, the moon's maximum declinations vary from 23.5+5 = +-28.5 degrees at most, to 23.5-5 = +-18.5 degrees at the least.
Results in modulations in the amplitude and phase of the lunar based tidal constituents.

18.6 yrs

Important periods/frequencies

Description	Frequency notation (1/period)	Period (mean solar units)
Sidereal day (one rotation wrt vernal equinox)	Ω	23.9344 hours
Mean solar day (one rotation wrt to the sun)	ω_S	24.0000 hours
Mean lunar **day** (one rotation wrt to the moon)	ω_L	24.8412 hours
Period of lunar declination (tropical **month**)	ω_1	27.3216 days
Period of solar declination (tropical **year**)	ω_2	365.2422 days
Period of lunar perigee	ω_3	8.847 years
Period of lunar node	ω_4	18.613 years
Period of perihelion	ω_5	20,940 years

<u>Note:</u> Long-period constituents do not change the range of the diurnal and semidiural tides but rather introduce long period fluctuations to the short-term mean water level. Long period modulation of the range of the tides is due to both constructive and destructive interference between the constituents, and slow modulations of the forces that generate them.

Major tidal constituents

Symbol	Period	Speed (°/hr)	Description	Derived from	Coeff. C
			Semidiurnal tides		
K_2^L	11.967 hours	30.0821373	declinational to M_2	$2\omega_L+2\omega_1$ $(=2\Omega)$	0.0768
K_2^S	11.967 hours	30.0821373	declinational to S_2	$2\omega_S+2\omega_2$ $(=2\Omega)$	0.0365
S_2	12.000 hours	30.0000000	principal solar	$2\omega_S$	0.4299
M_2	12.421 hours	28.9841042	principal lunar	$2\omega_L$	0.9081
N_2	12.658 hours	28.4397295	elliptical to M_2	$2\omega_L-(\omega_1-\omega_3)$	0.1739
L_2	12.192 hours	29.5284789	elliptical to M_2	$2\omega_L+(\omega_1-\omega_3)$	0.0257
			Diurnal tides		
K_1^L	23.934 hours	15.0410686	declinational to O_1	$(\omega_L-\omega_1)+2\omega_1$ $(=\Omega)$	0.3623
K_1^S	23.934 hours	15.0410686	declinational to P_1	$(\omega_S-\omega_2)+2\omega_2$ $(=\Omega)$	0.1682
P_1	24.066 hours	14.9589314	principal solar	$(\omega_S-\omega_2)$	0.1755
O_1	25.819 hours	13.9430356	principal lunar	$(\omega_L-\omega_1)$	0.3769
Q_1	26.868 hours	13.3986609	elliptical to O_1	$(\omega_L-\omega_1)-(\omega_1-\omega_3)$	0.0722
			Long-period tides		
Mf	13.661 days	1.0980331	declinational to M_o	$2\omega_1$	0.1564
Mm	27.555 days	0.5443747	elliptical to M_o	$(\omega_1-\omega_3)$	0.0825
Ssa	182.621 days	0.0821373	declinational to S_o	$2\omega_2$	0.0729

Table 2.2. Tidal constituents and their origin from astronomical frequencies. The "speed" is the angular speed, a classical form of frequency (see text). M_o and S_o represent constant lunar and solar forces. The coefficient C gives a global measure of each constituent's relative portion of the tide potential (reworked from Platzman, 1971).

Tidal Analysis and Prediction, NOAA Special Publication NOS-OPS 3, p. 29,40

Water Level/Tidal Theory, What are Tides?

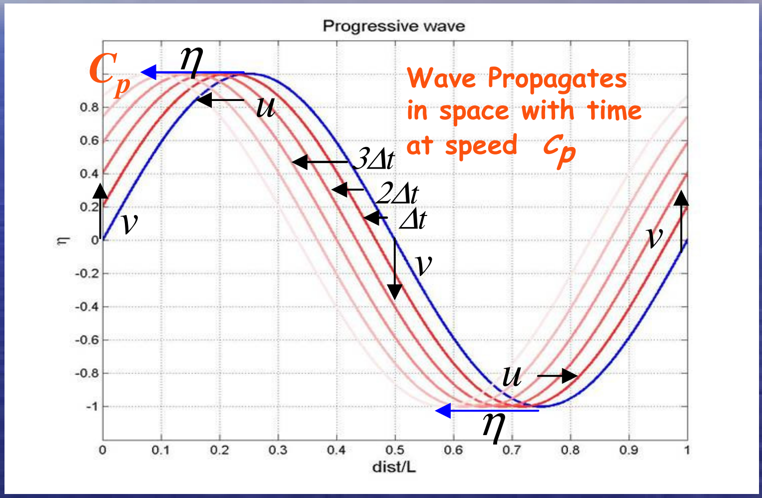
- Tides are forced *(Astronomic Forcing)* long period shallow water *(L>>D)* waves moving under the influence of the earth's rotation, i.e. the Coriolis force

- Progressive Wave

$$\eta = A\sin(kx - \omega t)$$
$$u = (gA/C_p)\sin(kx - \omega t)$$
$$\omega = 2\pi / T$$
$$k = 2\pi / L$$
$$C_p = \omega/\kappa = \sqrt{gD}$$

Constant, fn of water depth

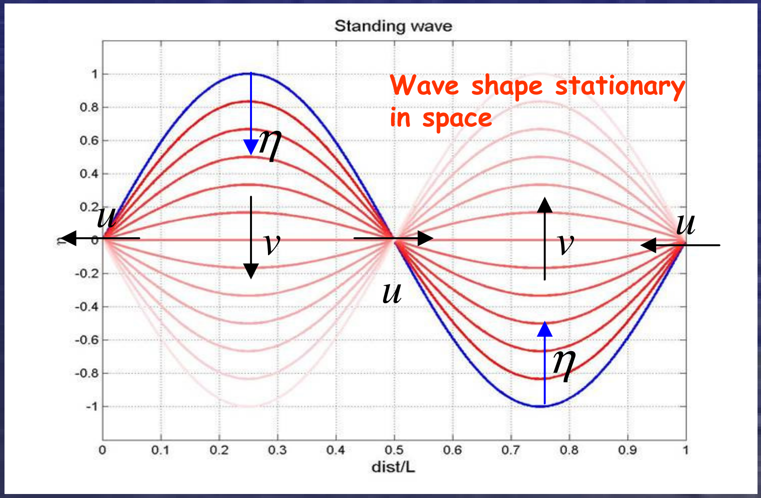
D – water depth
A – wave amplitude
L -- wave length (m)
T -- the wave period (s)
ω -- the frequency (rad/s)
k -- the wave number (rad/m)
C_p – phase speed (m/s) speed of crest



- Standing Wave

$$\eta = A/2\sin(kx - \omega t) + A/2\sin(kx + wt)$$

$$\eta = A\sin(kx)\cos(wt)$$
$$u = -(gAk/\omega)\cos kx \cos \omega t$$



- Tides are generally Standing waves, <u>but not always</u>

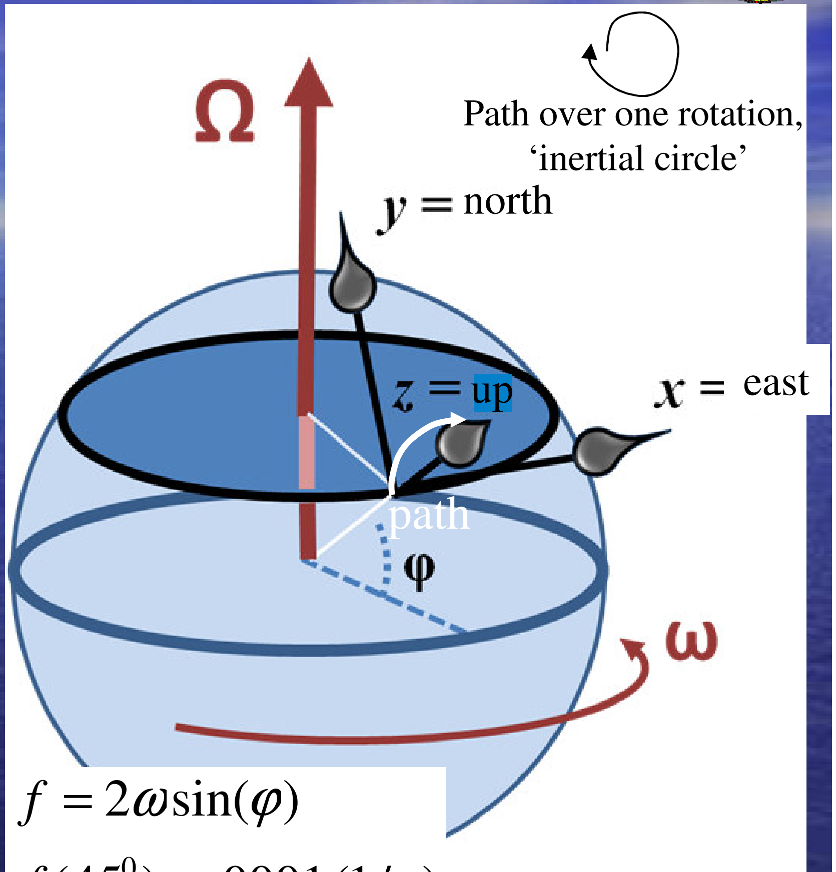
<u>Slinky Demonstration!</u>

Rotation: the Coriolis force

F=ma applies to inertial (non-accelerating) ref. frames. But, frames fixed to the earth are spinning with the earth and experience angular acceleration. To account for this, the equations in the rotating ref. frame incorporate a fictitious force, the coriolis force.

A simple visualization: In reality, objects obeying *F=ma* but moving along the earth's surface they appear to follow a slowly curving path relative to an observer fixed to the earth. This curvature is to the right in the northern hemisphere and to the left in the southern hemisphere. In the frame of reference of the observer this tendency to follow a curved path is accounted for by a fictitious acceleration or force proportional to the velocity (u,v) of the object (i.e. fv or -fu where f is the coriolis parameter and u is pos east, v positive north)

Northern hemesphere handwaving discussion:
Start fixed to the earth. Move North towards a region of reduced angular velocity (radius from the rotation axis is decreasing). Assuming angular velocity is conserved (no friction) you now have greater angular velocity than surroundings. It appears you have pick up eastward velocity. Inverse moving south. Moving east gives greater angular velocity than surroundings. One component makes you feel lighter. The other is towards the south. Inverse as you move west.



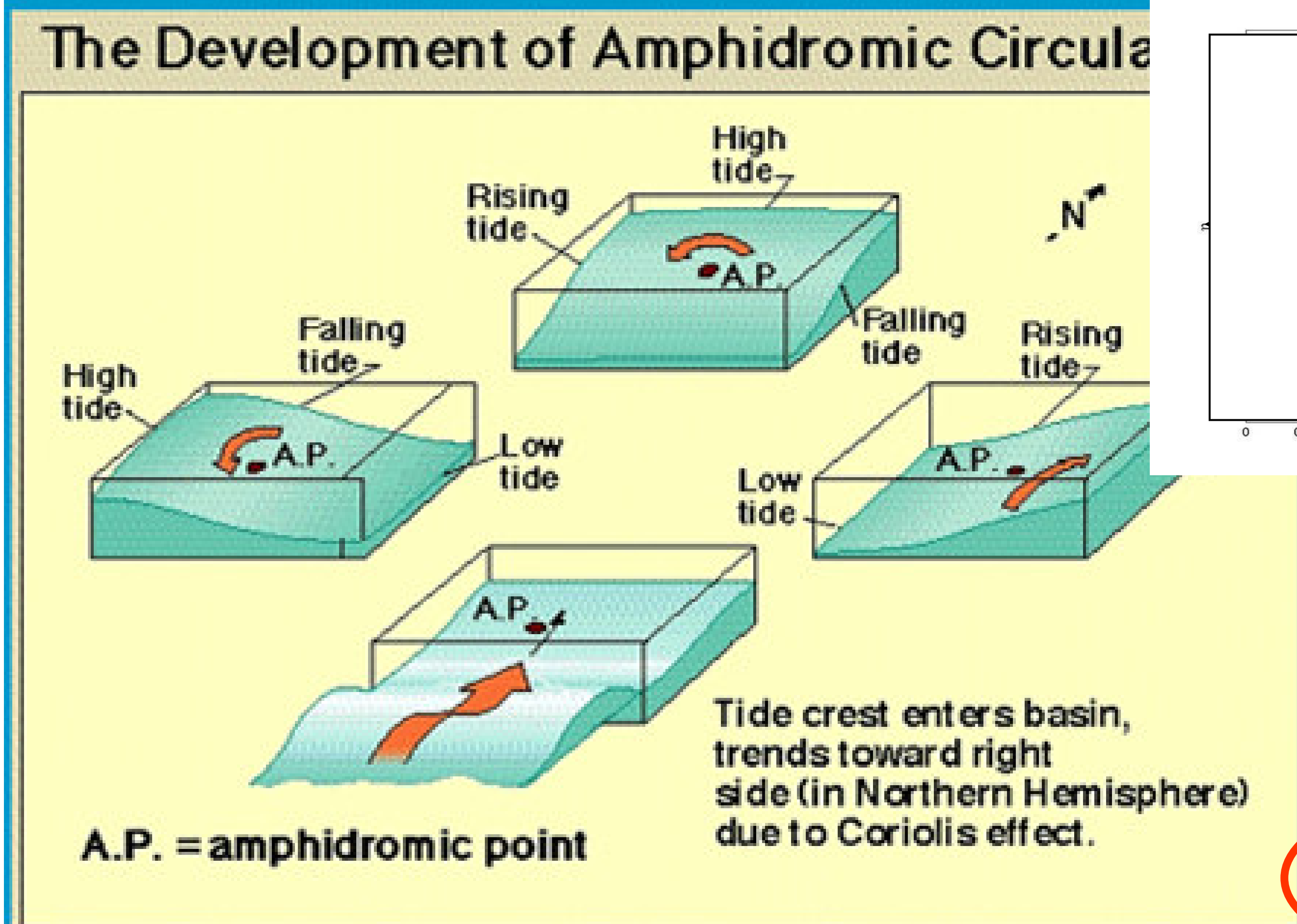
$$f = 2\omega \sin(\varphi)$$

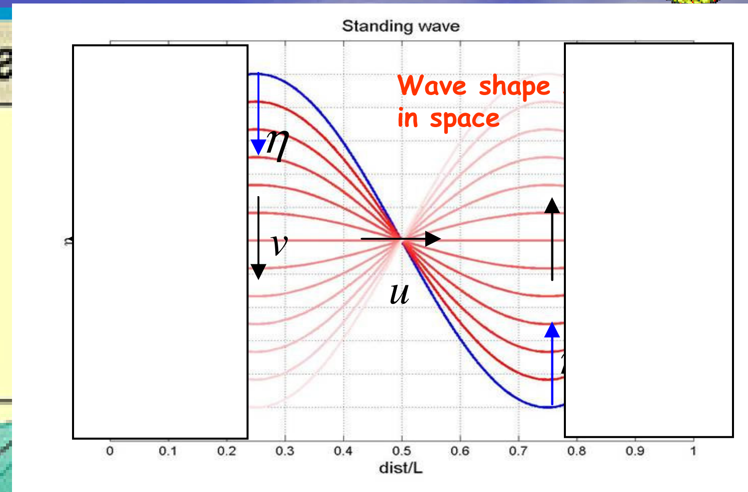
$$f(45^0) \sim .0001\,(1/s)$$

-- *f* is weak, it has no observable effect on what we see over short timescales or lenghscales. But, tides are long period and oceans permit large lengthscales, so f has time, and space to act.

The Coriolis effect on Tides, *Amphidromic Systems*

Bathtub wave





f – coriolis parameter
$10^{-4}(1/s)$

Timescale $1/f$

$\approx 2.8\,hrs$ @ 45^0

Lengthscale $C_p / f = \sqrt{gD} / f$

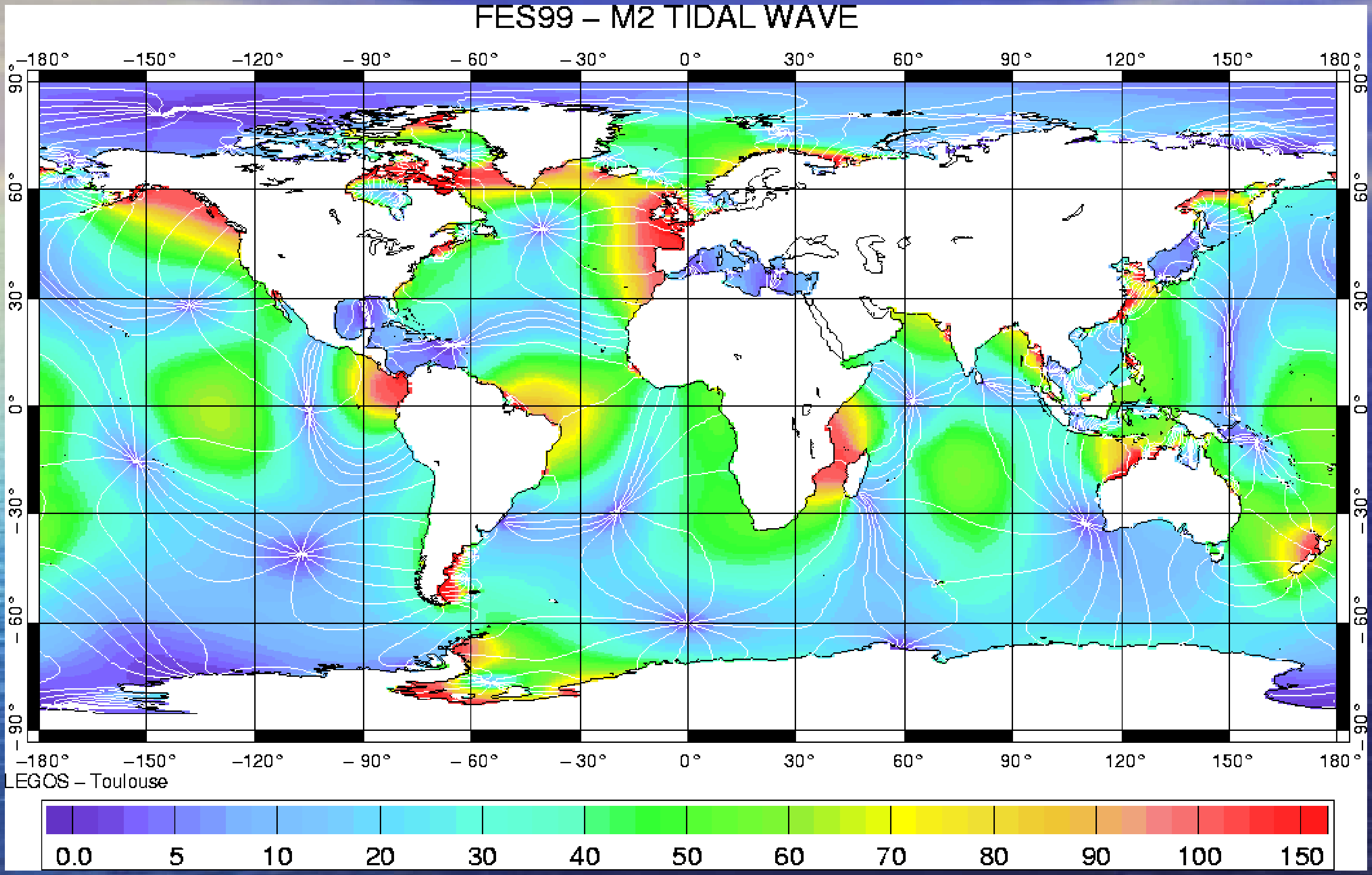
$\approx 1700\ km$ @ $D = 3.5\ km$

$\approx 140\ km$ @ $D = 20\ m$

In the northern hemisphere *f* acts to the right, thus wave height builds with the coast to the right. Tides are Kelvin waves, a wave that balances the coriolis force against a surface slope and pressure gradient built against a topographic boundary.

Global M2 (12.42 hr) Amphidromic System

The ocean's response to forcing at M2 frequency

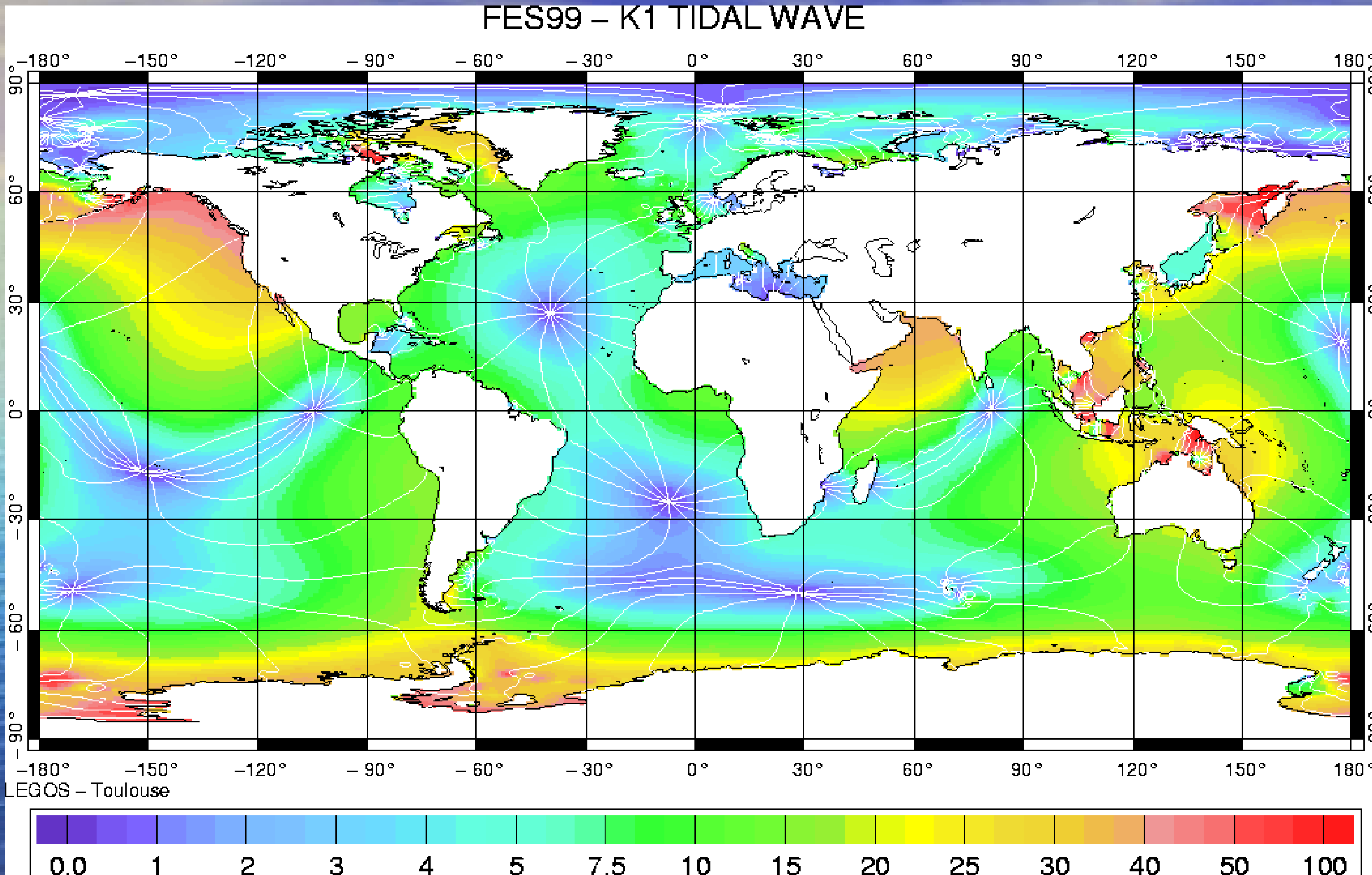


FES99 (FES2004) was produced by Legos and CLS Space Oceanography Division

Like the simple standing wave slinky example, global ocean responds with natural mode structure (determined by geometry and dynamics).

Global K1 (23.93 hr) Amphidromic System:

Link between frequency and wavelength through phase speed Cp



FES99 (FES2004) was produced by Legos and CLS Space Oceanography Division

Global M2 movie

Tides in essence are the linear spatial sum of the major tidal constituents

(Smaller, shallower basins, smaller scale systems)

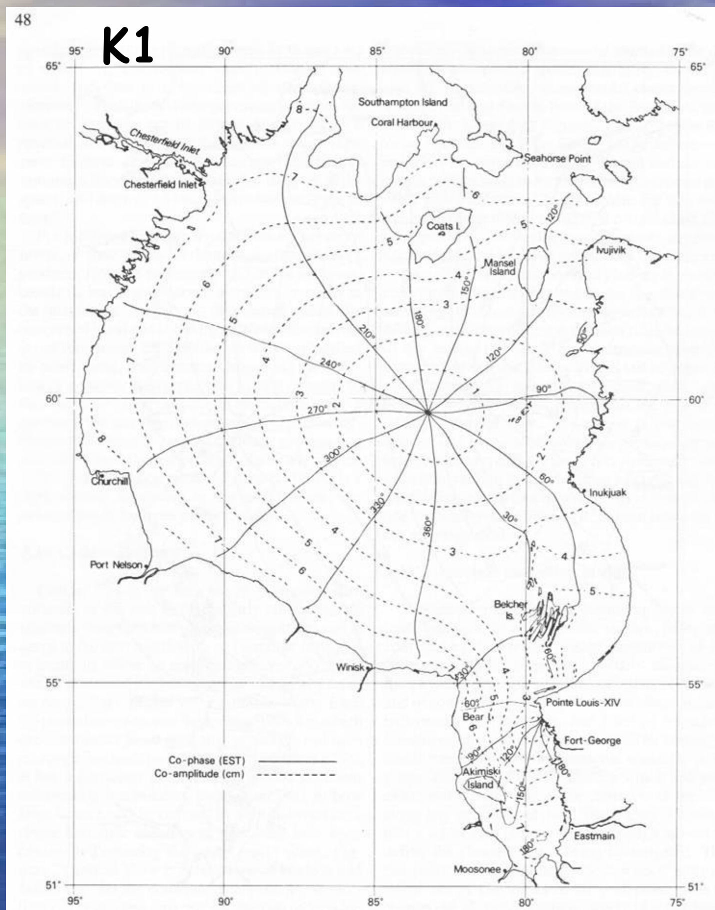


FIG. 28. Cotidal chart of K_1 constituent in Hudson and James Bays by numerical modelling. (from fig. 10 of Freeman and Murty, J. Fish. Res. Board Can. 33(10), 1976).

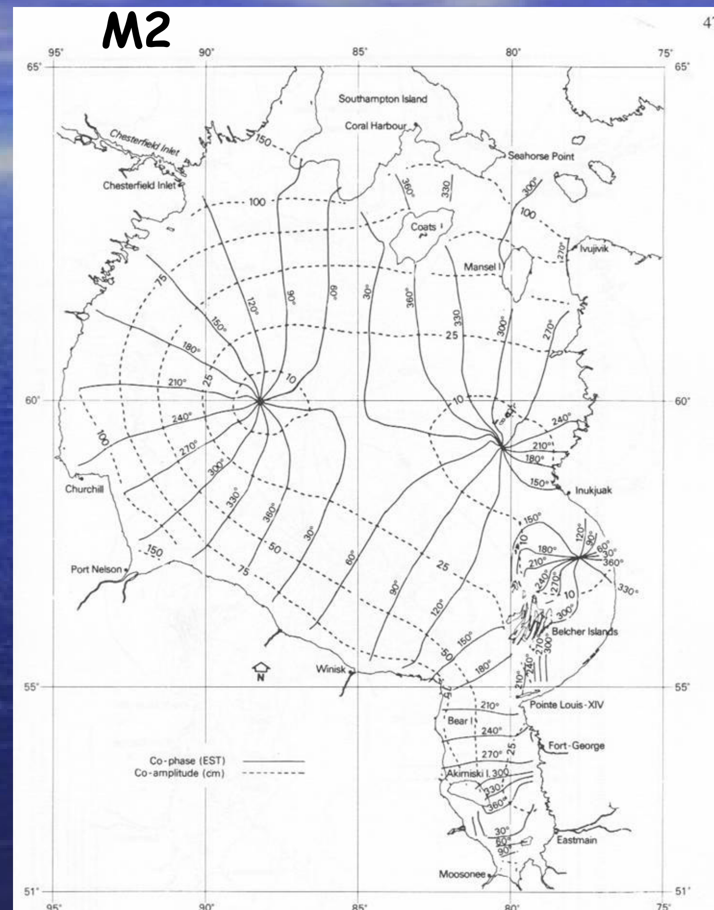
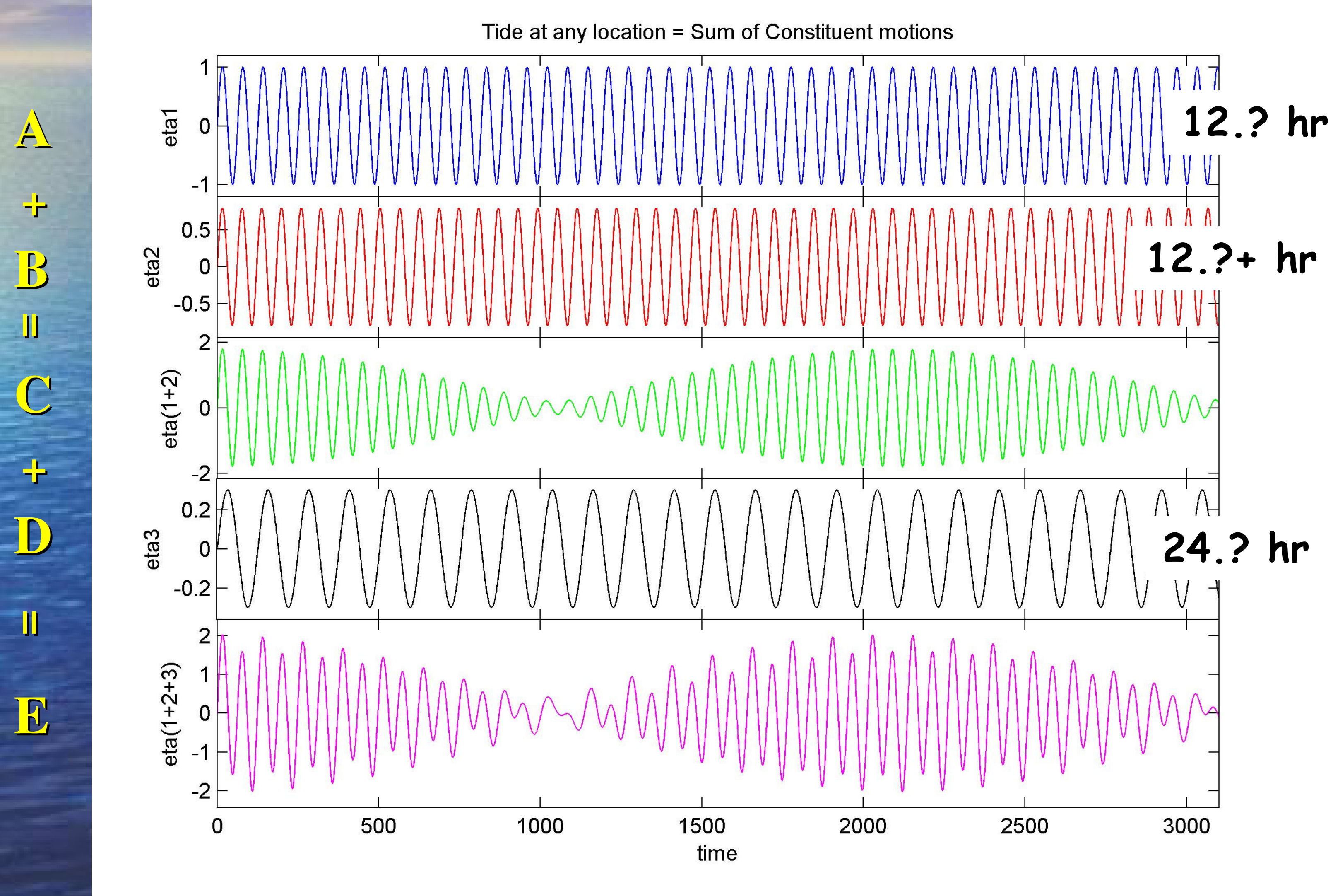


FIG. 27. Cotidal chart of M_2 constituent in Hudson and James Bays by numerical modelling. (from fig. 7 of Freeman and Murty, J. Fish. Res. Board Can. 33(10), 1976).

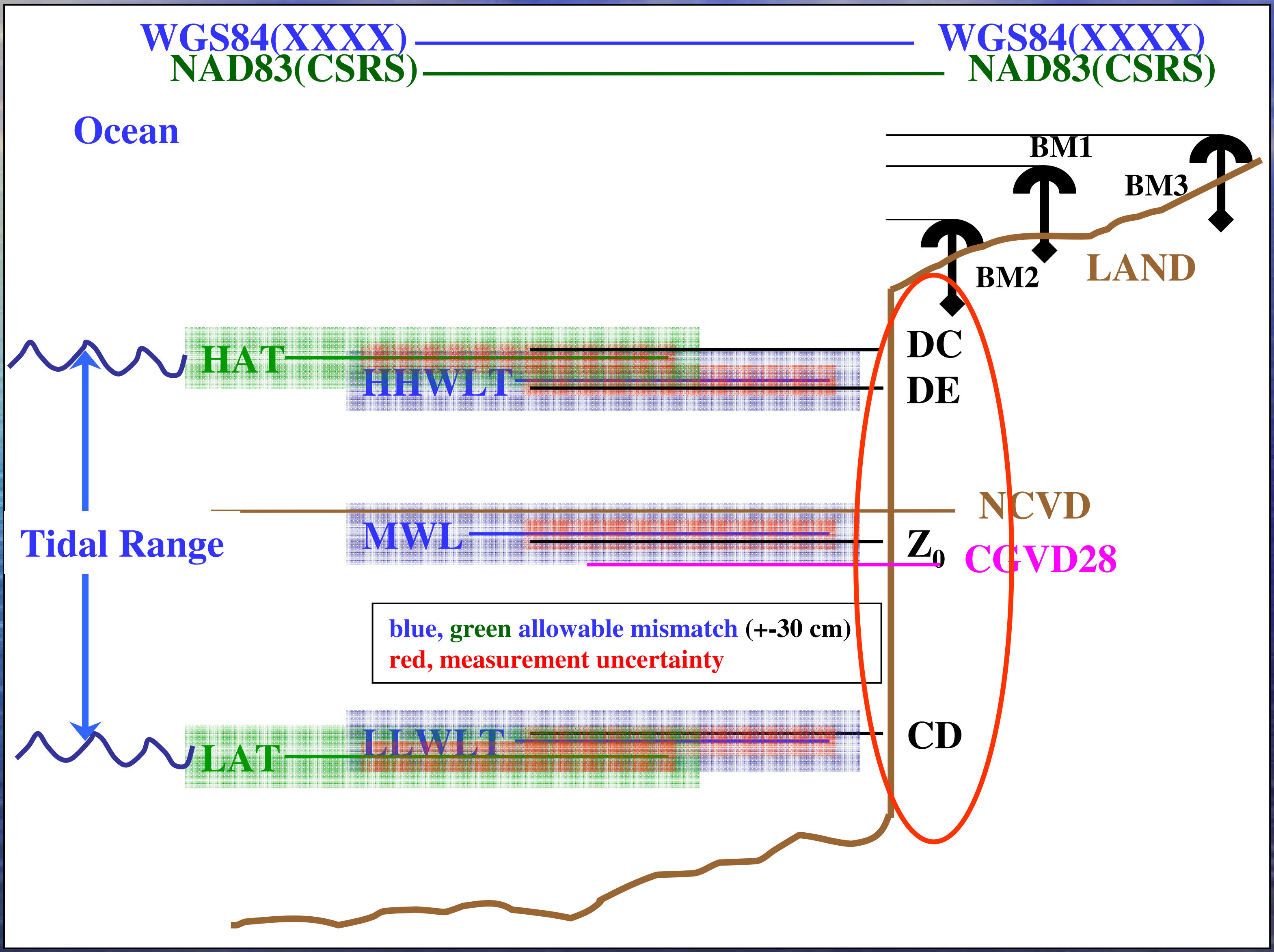
Canadian Tidal Manual, p. 47-48

Always keep in mind the 2D structure of the tidal constituents when thinking about our 1D experience of the tides at one place and time (tidal observations/data/predictions)

Tides at a Point (What we see)
Summing of constituents leads to complex behavior
(Assumption, constituents are linearly independent)



- What are Tidal Datums, Datum Targets and References, and how are they defined and used?



Definitions

- Vertical Hydrographic datums are the defined vertical references to which all hydrographic vertical measurements (bathymetric data) are ultimately reduced/referenced.
  - (The nails in the wall) Unfortunately these are not static and sometimes must be moved
- Vertical datum targets are agreed upon thresholds based on either observed or predicted water levels that define where we want the vertical datums to be.
  - We measure where these are (relative to something else). We only know them as realizations based on water level data sets.
- References and reference surfaces are established points, point networks, and modeled or mathematical surfaces to which one may define relative vertical position (by measurement).
  - You may only define where something is relative to something else.
- Vertical transformations are the vertical separations between: vertical references and reference surfaces, vertical datums, and vertical datum targets.
  - These allow us to determine where something is relative to other vertical references, i.e. to transform defined vertical location between vertical references.
    - Problem: References, datums and datum targets move, both together and relative to each other.

Hydrographic vertical datums

- Chart Datum
  - Charted depths
  - Drying heights
  - Predicted WLs
- Datum for Elevations (tidal waters)
  - Island height
  - Tower height
- Datum for Clearances (tidal waters)
- Chart Datum (non-tidal waters)
  - Island height
  - Tower height
  - Clearances
- Sounding Datum

  The reference datum used when collecting bathymetric data, often (but not always) the same as chart datum.

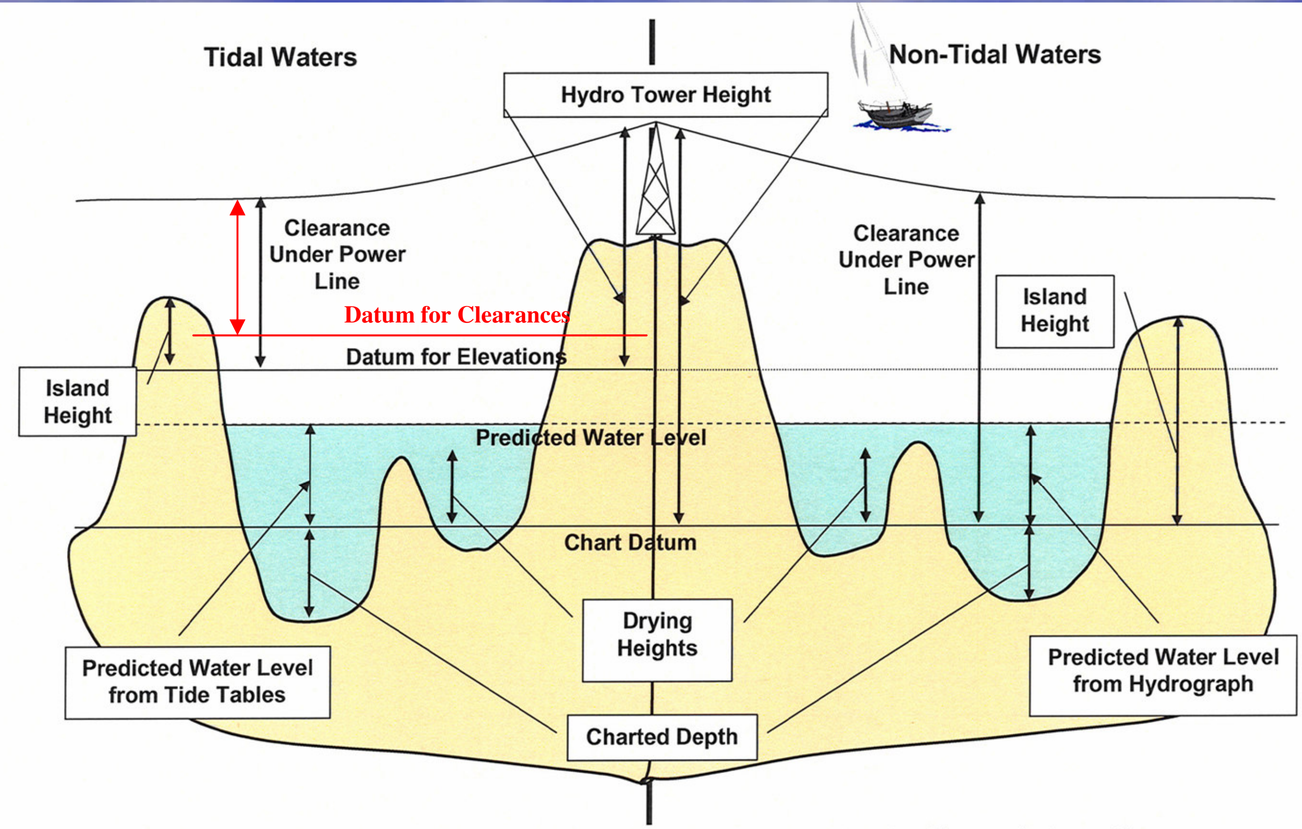


Fig. 1.7 Comparison of Vertical Datums for Tidal and Non-Tidal Waters. Note the difference between Clearances, Heights of Islands and Heights of objects like Transmission Towers in the two situations. The predicted depth of water is equal to the Charted Depth plus Predicted Depth. The Predicted Depth is obtained from the Tide Tables in Tidal Waters and from the Hydrograph in Non-Tidal Waters.

Vertical datums and their targets (Chart Datum)

- What is Chart Datum?
  - Low Water Datum (LWD)
  - 1926 IHO definition "*should be a plane so*
  - *low that the water level will but seldom fall below it.*"
- Chart Datum's Target (tidal waters)
  - Lowest Normal Tide (similar to IHO definition but has no specific measurable characteristic, specific definition left to the individual HO)
- Existing Canadian choice for definition of LNT (tidal waters)
  - Lower Low Water Large Tide (LLWLT).
    - The average of the lowest predicted water levels (predictions from tidal constituents determined by analysis of water level data) from each year over a 19 year nodal modulation cycle.
- New choice based on 1997 IHO recommendation for harmonization of member state low water datums
  - Lowest Astronomical Tide (LAT), the CHS is moving to LAT now.
    - The lowest predicted water level (predictions from tidal constituents determined from analysis of water level data) over a 19 year nodal modulation cycle.

Chart Datum (CD) Continued

- US choice for LNT target for Chart Datum (tidal waters)
  - Mean Lower Low Water (MLLW)
    - Average of all predicted lower low waters over a specified 19 year period. (Implication: both Chart Datum and its target change at the border between Canadian and US waters). US to LAT?
- Target for Chart Datum (non-tidal waters) example: Great Lakes
  - International Great Lakes Datum (IGLD). Original IGLD1955 from water level data (1941-1956). Present IGLD1985, data (1982-1988)
  - IGLD1955 zero target: MWL at Pointe-au-Pere, Que.
  - IGLD1985 zero target: MWL at Rimouski, Que.
  - Periodic Adjustment, ongoing crustal rebound

TABLE 7-1. Great Lakes Low Water Datums

Lake (1)	IGLD 55 (feet) (2)	IGLD 85 (feet) (3)
Superior	600.0	601.1
Michigan	576.8	577.5
Huron	576.8	577.5
St. Clair	571.7	572.3
Erie	568.6	569.2
Ontario	242.8	243.3

Hydrographic Surveying, American Society of Civil Engineers (1998) p. 109

Really a continuous datum

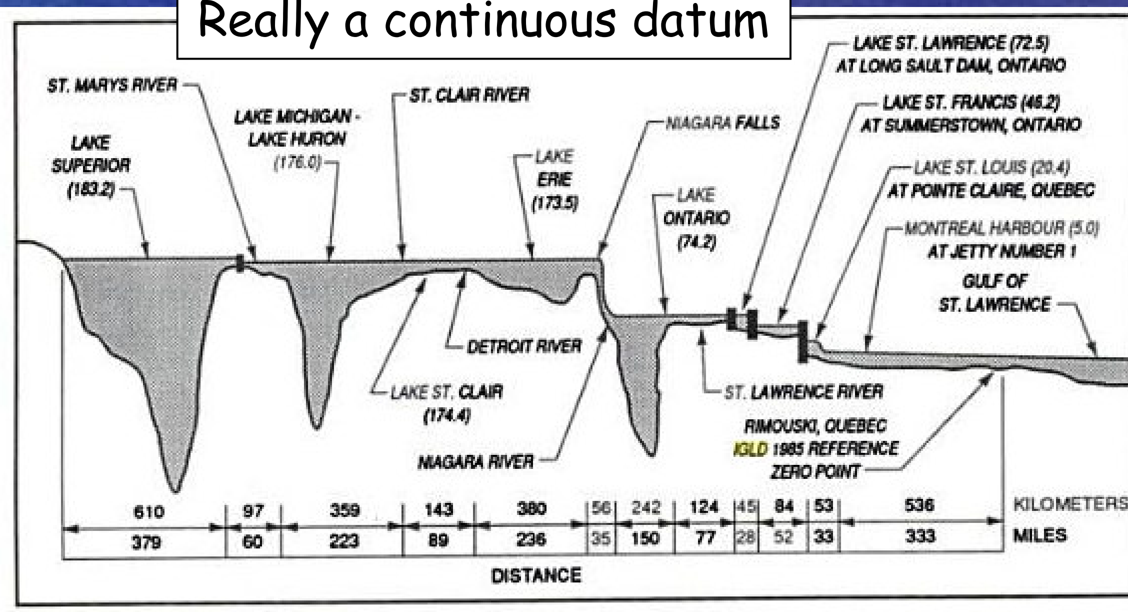


FIG. 7-13. IGLD 85 Hydraulic datum for the Great Lakes - St. Lawrence River system.

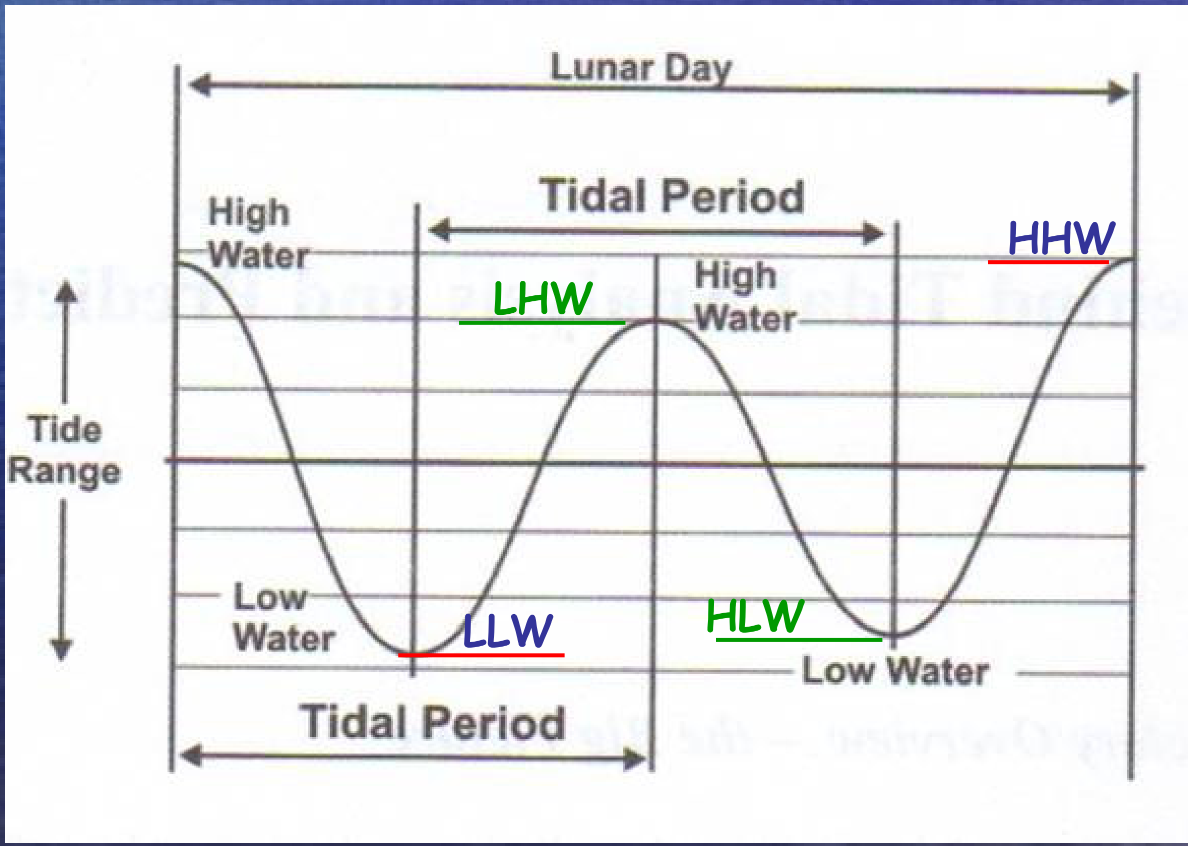
Hydrographic Surveying, American Society of Civil Engineers (1998) p. 108

Datum for Elevations (DE)

- What is the Datum for Elevations?
  - High Water Datum (HWD)
  - Similar to Chart Datum, it should be a plane so high that the water level will but seldom rise above it.
    - In practice this arguably defines the level of the shoreline, the division between bathymetry and elevation.
    - It should vary only gradually from area to area so as to avoid significant discontinuities. (Again not always possible to achieve)
- Datum for Elevation's Target (tidal waters)
  - Highest Normal Tide? Ordinary High Water?
- Existing Canadian choice (tidal waters)
  - Higher High Water Large Tide (HHWLT)
    - The average of the highest predicted water levels (predictions from tidal constituents determined by analysis of water level data) from each year over a 19 year nodal modulation cycle.
- Present US choice (tidal waters)
  - Mean Higher High Water (MHHW)
    - Average of all <u>observed</u> higher high waters over a specified 19 year period
- Existing Great Lakes Choice (non-tidal waters) IGLD1985

Other Targets? MHHW and MLLW

- Mean Higher High Water (MHHW): Average of all predicted higher high waters (HHW) over a specified 19 year period
- Mean Lower Low Water (MLLW): Average of all predicted lower low waters (LLW) over a specified 19 year period
- Higher High Water (HHW):
  The highest of the daily high waters
  - Due to diurnal inequality and combination of diurnal and semidiurnal forcing
- Lower Low Water (LLW):
  The lowest of the daily low waters
- Also:
  Lower High Water (LHW)
  Higher Low Water (HLW)



Datum for Clearances

- What is the Datum for Clearances?
  - High Water Datum (HWD)
  - Similar to Datum for Elevations, it should be a plane so high that the water level will but seldom rise above it (but perhaps even higher, since risk factors greater).
- Canada's Existing Datum for Clearances' target (tidal waters)
  - Higher High Water Large Tide (HHWLT)
    - Generally close to being the "high water mark" where debris accumulates on the shore annually
- Recent CHS recommendation based on IHO resolution for datum harmonization
  - Highest Astronomical Tide (HAT)
    - The highest predicted water level (predictions from tidal constituents determined from analysis of water level data) over a 19 year nodal modulation cycle.
- US Datum for Clearances target
  - Mean High Water (MHW)
    - The average of the observed high waters over the presently used US Nation tidal Datum Epoch (a 19 yr nodal modulation). Note: this is an observational value, not a derived one like HHWLT or LAT.

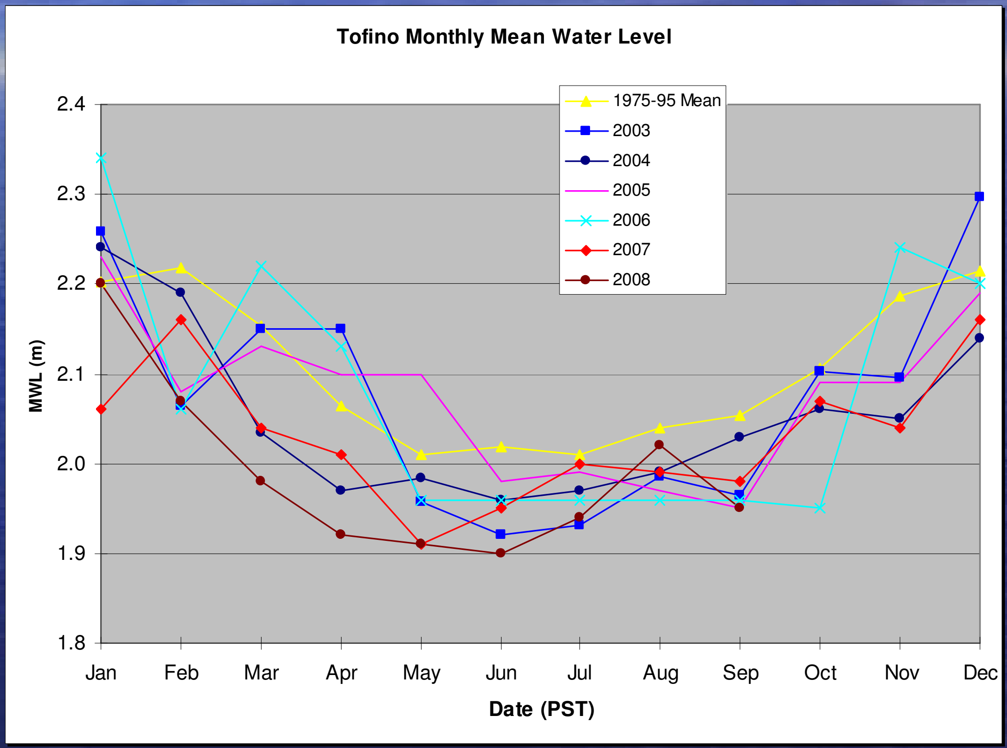
Mean Sea Level and Mean Water Level (Z_o)

Difficult to define without ambiguity.

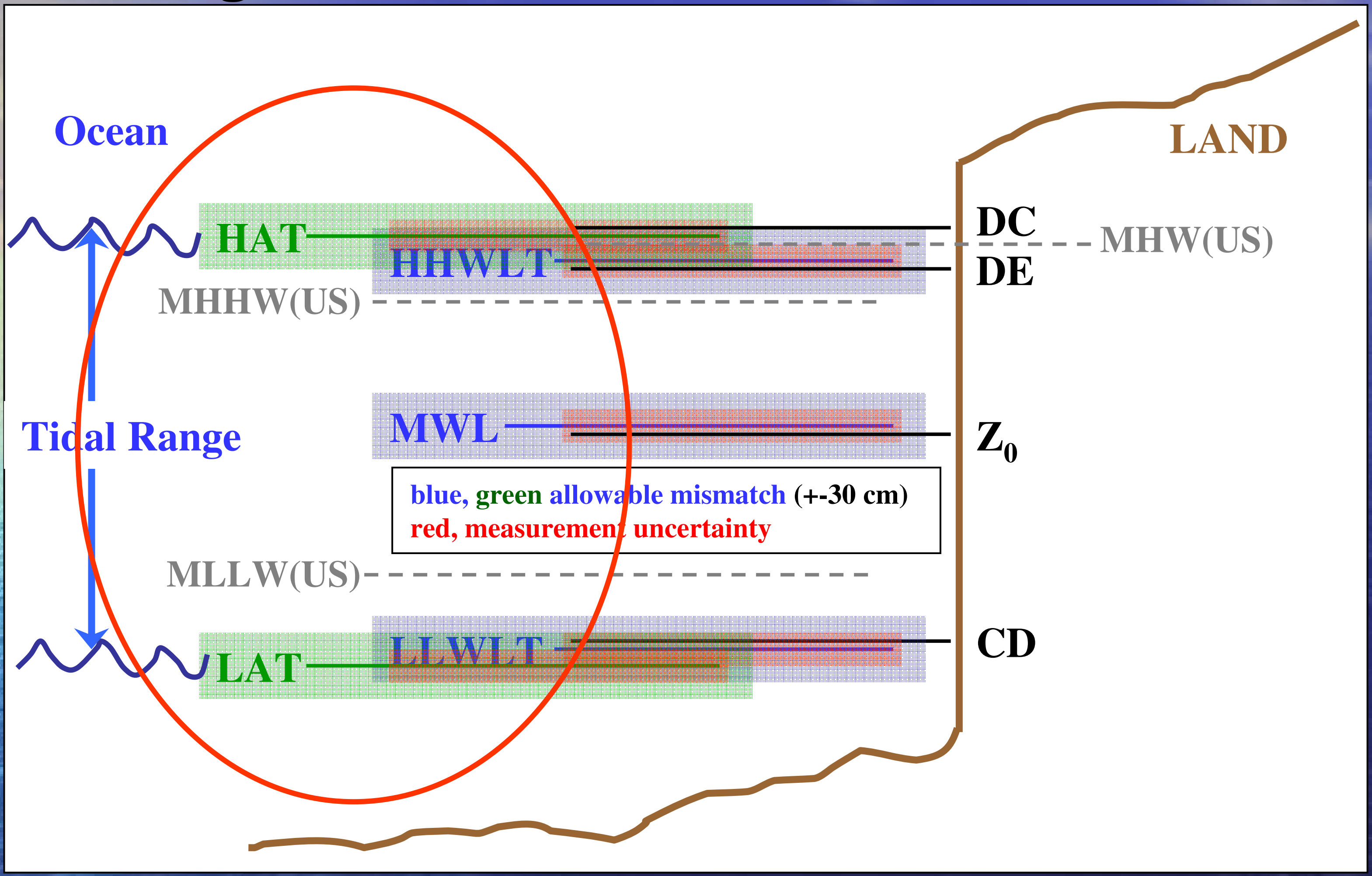
- Mean Sea Level (MSL) *{Not to be confused with Geodetic CGVD28}*
  - Mean Sea Level is the mean elevation of the sea surface over an entire sea, ocean, or the global ocean. Representative of a specific gravity potential.
- Mean Water Level (MWL)
  - The average observed water level at a specific point over a defined time period (i.e. the water level record length, monthly, yearly, 18.6 year nodal Epoch, …).
  - Different from MSL due to ocean surface slopes caused by local gravitational anomolies, prevailing wind patterns, ocean density variations, ocean currents through geostrophy and coriolis, … etc.
- Important hydrographic use of MWL.
  - Chart datum is rarely adjusted, usually only when absolutely necessary as adjustment necessitates alteration of all bathymetry referenced to it. However, MWL (the mean constituent Z_o) can be adjusted whenever new or better data or information becomes available. This adjustment is apparent in the waterlevels in the tide tables and effects the mariners calculated under-keel clearances.

MWL Cont. Implications of averaging period

- MWL for an area can change with time due to:
  - Sea level rise
  - crustal movement/rebound
  - Changes in meteorological and oceanographic conditions
  - better to think of MWL in terms of a range of averaging periods, i.e. monthly, annual nodal epoch
    - better enable you to see trends in water level variations



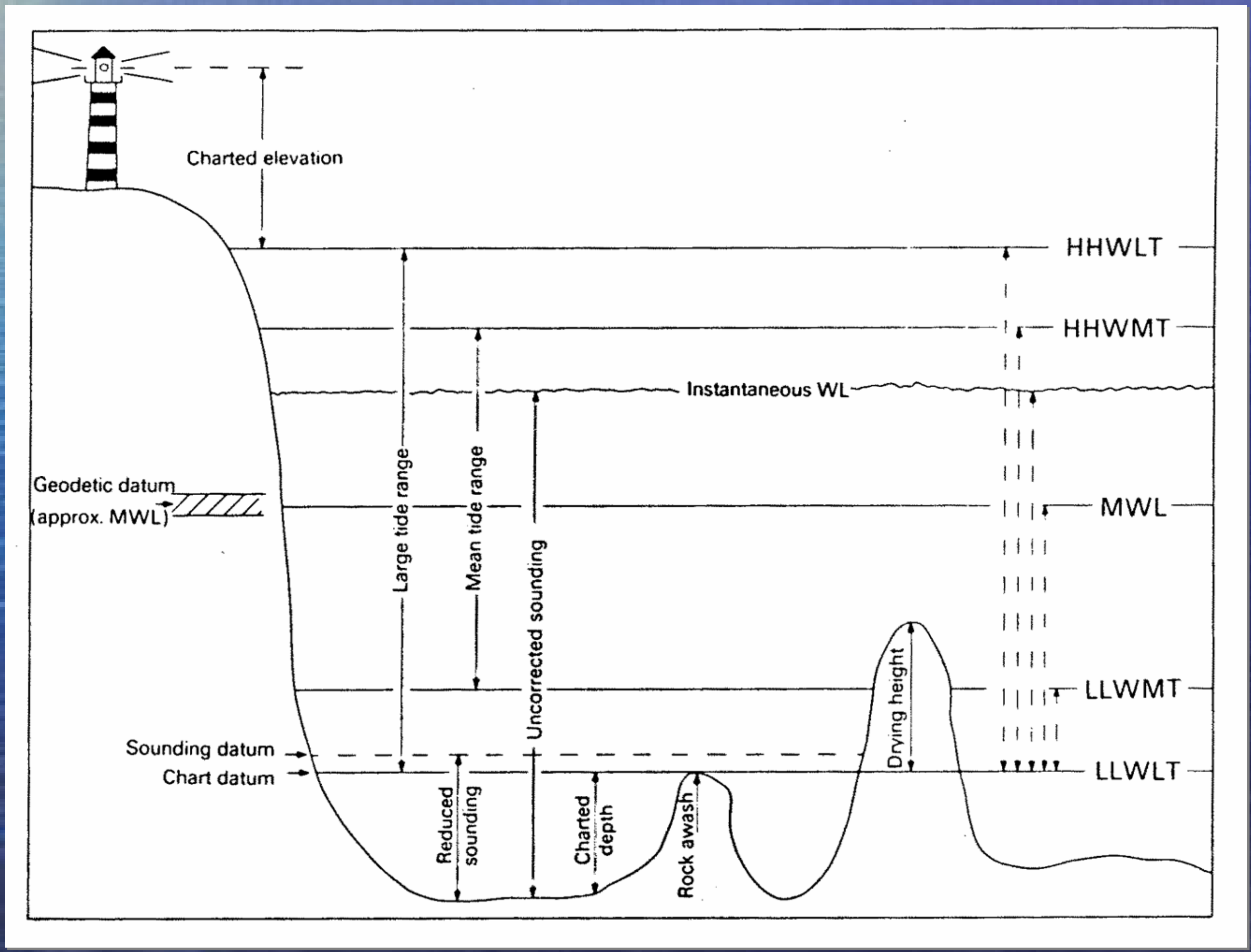
Targets (Based on WL measurements)



CHS Datum vs target standing orders: Datums should be with +- 30 cm of the present realization of their target values

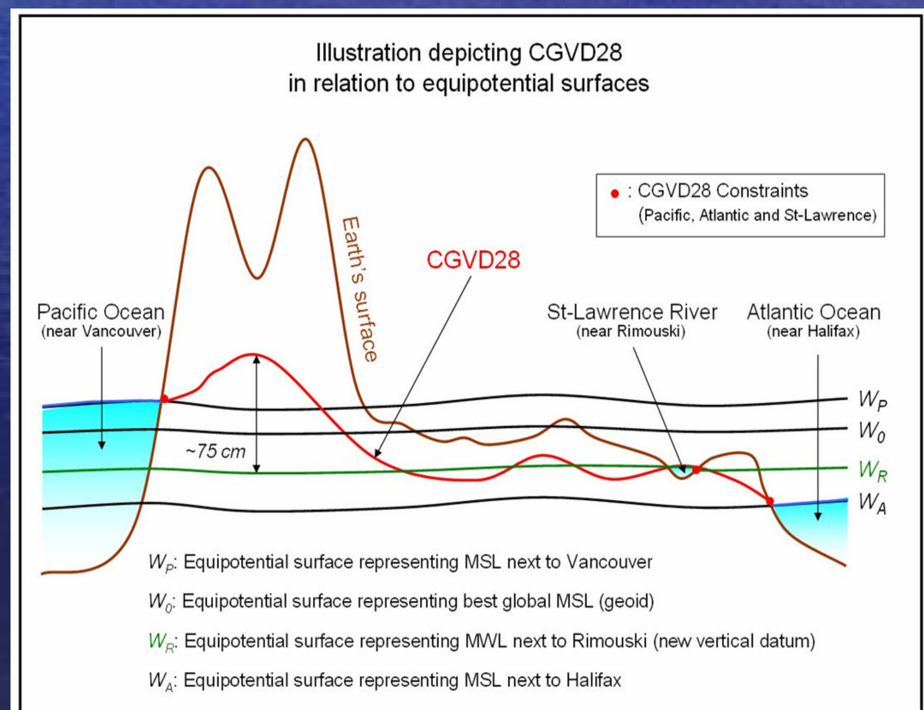
Targets - Datums
(the problem with the older perspective)

Note: Refering to datums by their target names can lead to confusion, we do not really know where the targets are (except by realization through analysis of water level data). We need to fix datums relative to references, targets can float.



Vertical References and Reference Surfaces

- Traditional Hydrographic Vertical Reference: Benchmarks
- Geodetic Datum – for Canada, Canadian Geodetic Vertical Datum 1928 (CGVD28): Network of Benchmarks
  - Established by the Geodetic Survey of Canada, Attempt to approximate a Geoid
  - Established by leveling, fixed by observed water levels at specific points, adjusted based on modeling
  - Only precisely defined with respect to Geodetic bench marks
  - Expensive, time intensive to maintain
  - In the absence of a Geodetic bench mark the MWL value provides a good approximation (usually within 0.1 to .2m) in all tidal waters provided:
    - The location is not a river
    - or a lagoon with restricted entrance.



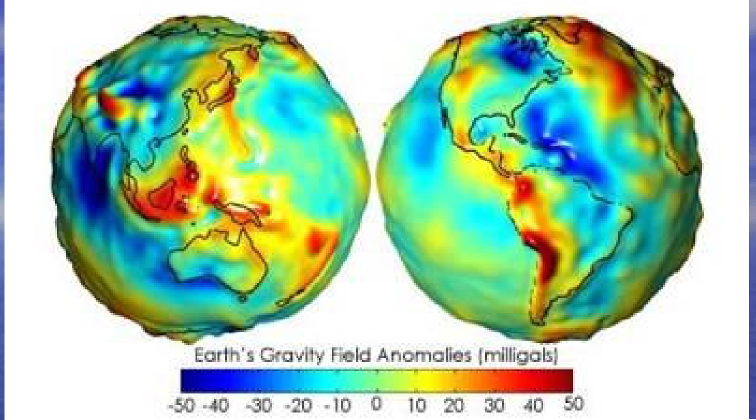
http://www.geod.nrcan.gc.ca/hm/ref_system_e.php

Note: Differences between spatial behavior of equipotential surfaces representative of geoid models and CGVD28

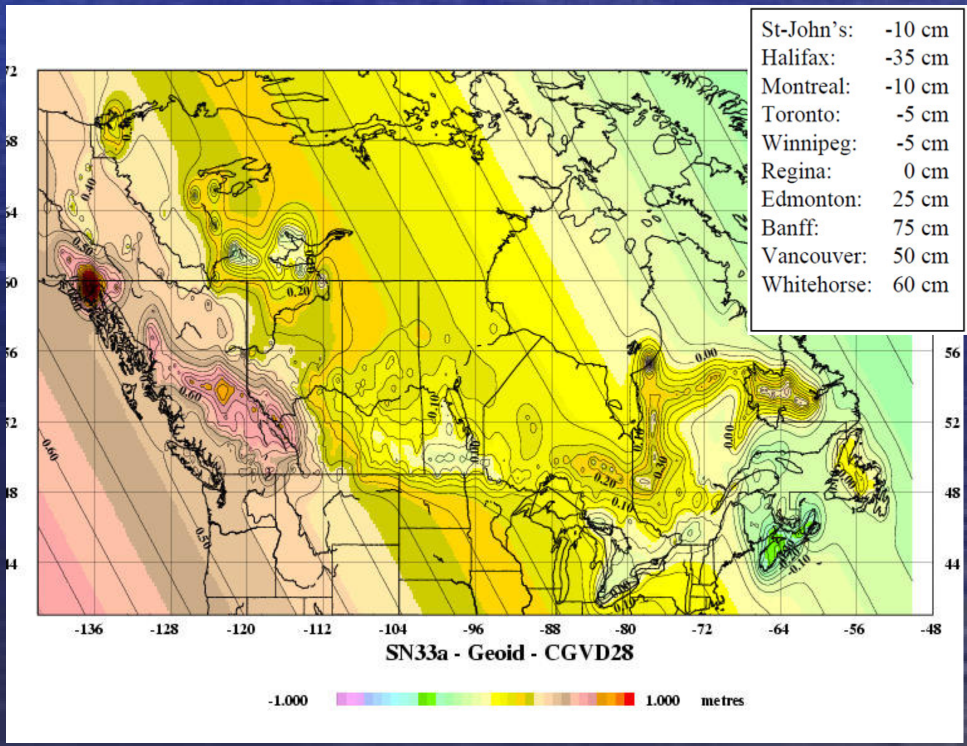
Vertical Reference Surfaces (Geoids)

- The global geoid is the modeled equipotential surface that best fits, in a least square sense, the global mean sea level.

- NRCan Height Reference System Modernization Program:
  - Establish new Canadian Vertical Reference
  - Gravity based datum based on geoid modeling, fixed to continent.
  - Since model based, once developed will provide for simple, accurate transformation between this new datum surface and 3D mathematical ellipsoids (i.e. WGS84, NAD83(CSRS)) and ITRFxx reference frames. Much better for use with GPS than CGVD28 because not dependent on location and quality of a degrading network of benchmarks.
  - For CHS, once established will permit easier recovery of hydrographic vertical control without maintaining benchmarks.
  - NVCD (New Vertical Canadian Datum)? (I made this up, no real name yet)



http://earthobservatory.nasa.gov/Features/GRACE/page3.php



Vertical Reference Surfaces (Ellipsoids)

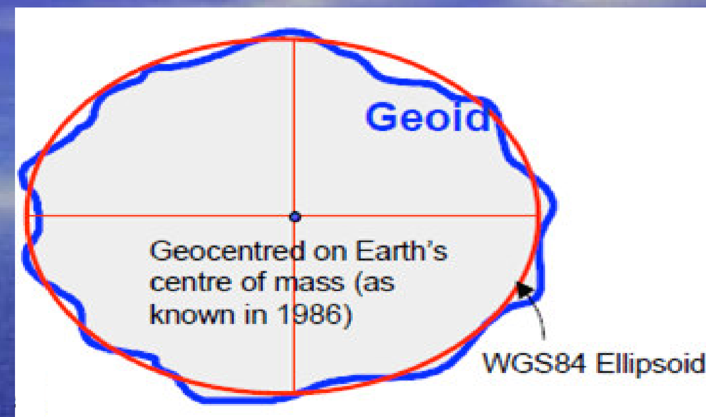
- Ellipsoids are mathematical oblate spheroids employing either six topocentric (for 2D horizontal datums) or geocentric (for 3D datums) parameters.

  Examples of horizontal datums based on ellipsoids: NAD27, original NAD83

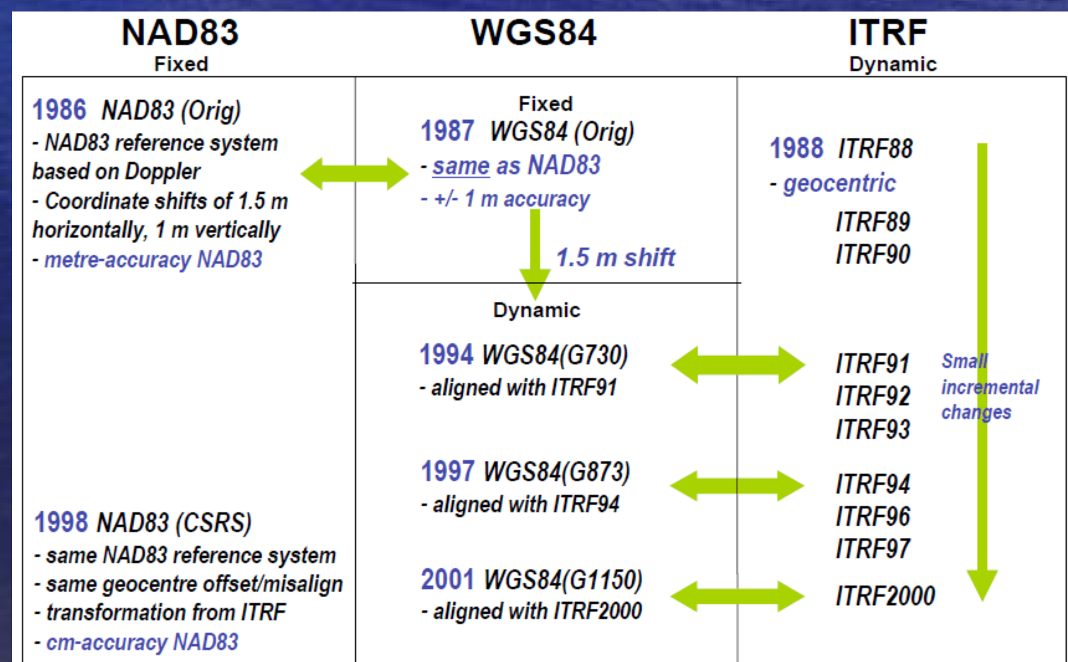
    NAD83 is really a geocentric fit ellipsoid, but locked to NA continent so is also used as a horizontal datum

  Examples of 3D or Vertical datums: Geocentric, best for satellites and GPS: WGS84, NAD83(1986), NAD83(CSRS), ITRFxxxx

    ITRF is cartesian (XYZ) system



http://www.naref.org/transf/nad83_hydroscan2006.pdf



Differences between WGS84 and NAD83(CSRS)

- NAD83 and WGS84 originally the same, but now difference between NAD83(CSRS) fixed to NA plate and WGS84 geocentric and updated to ITRF, two reasons: 1) refinement of WGS84 center to better coordinates from ITRF and 2) ongoing crustal motion.
- Intra-Plate relative motions.

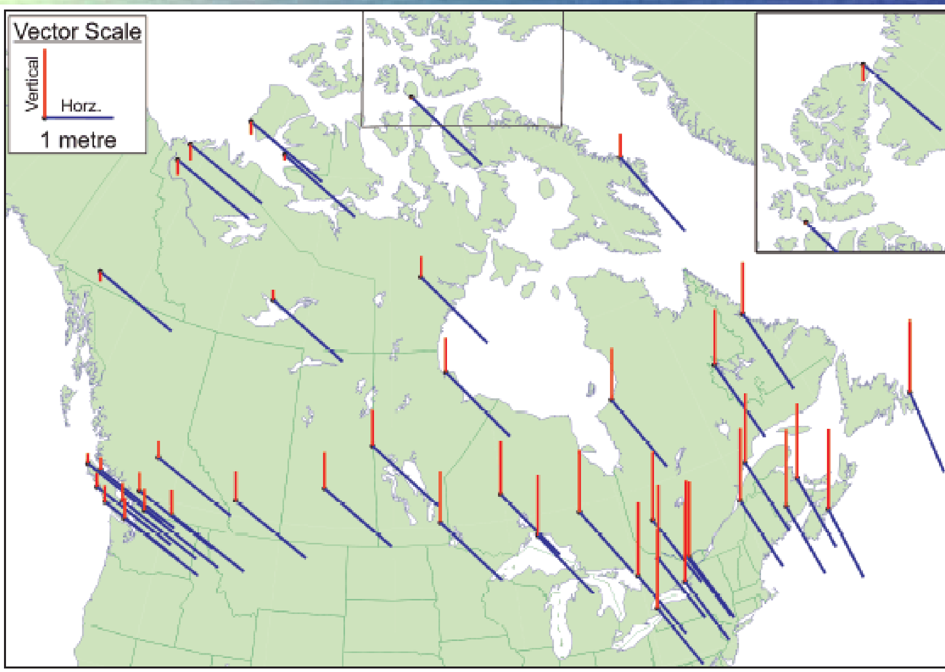


Figure 6: Horizontal (blue) and vertical (red) differences between NAD83(CSRS) and WGS84 in the sense NAD83(CSRS) minus WGS84.

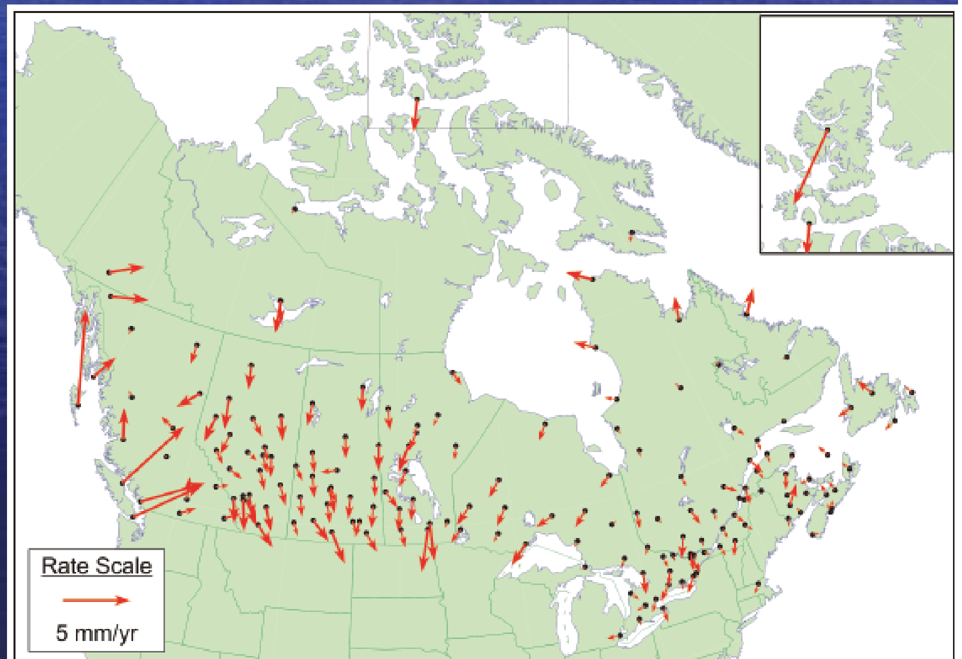
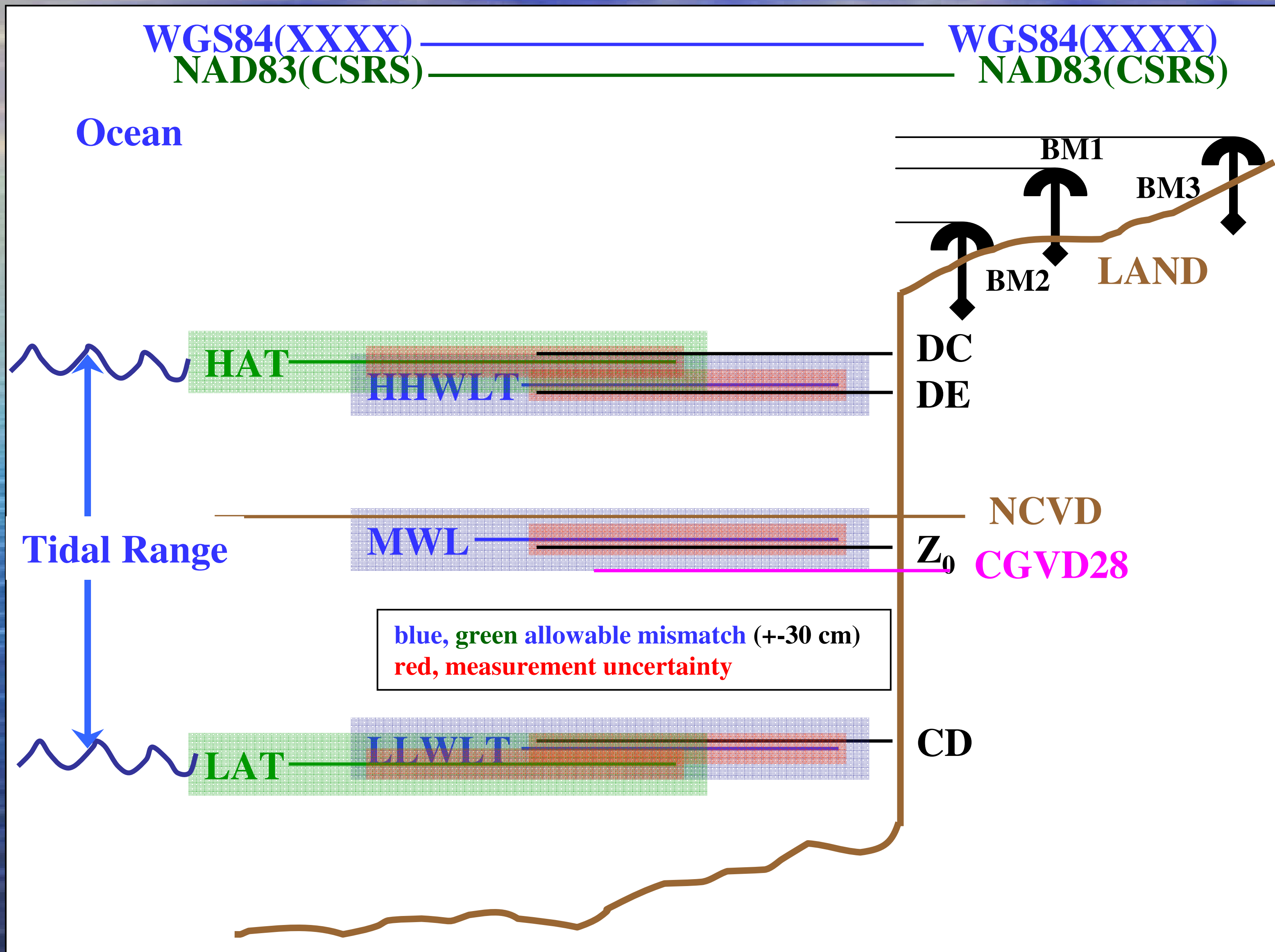


Figure 8: GPS horizontal velocities from repeated high accuracy GPS observations with respect to the SNARF 1.0 plate motion estimate for North America.

Craymer, M.R. The Evolution of NAD83 in Canada. Geomatica, Vol. 60, No. 2, pp. 151-164, 2006.

Datums - Targets - References

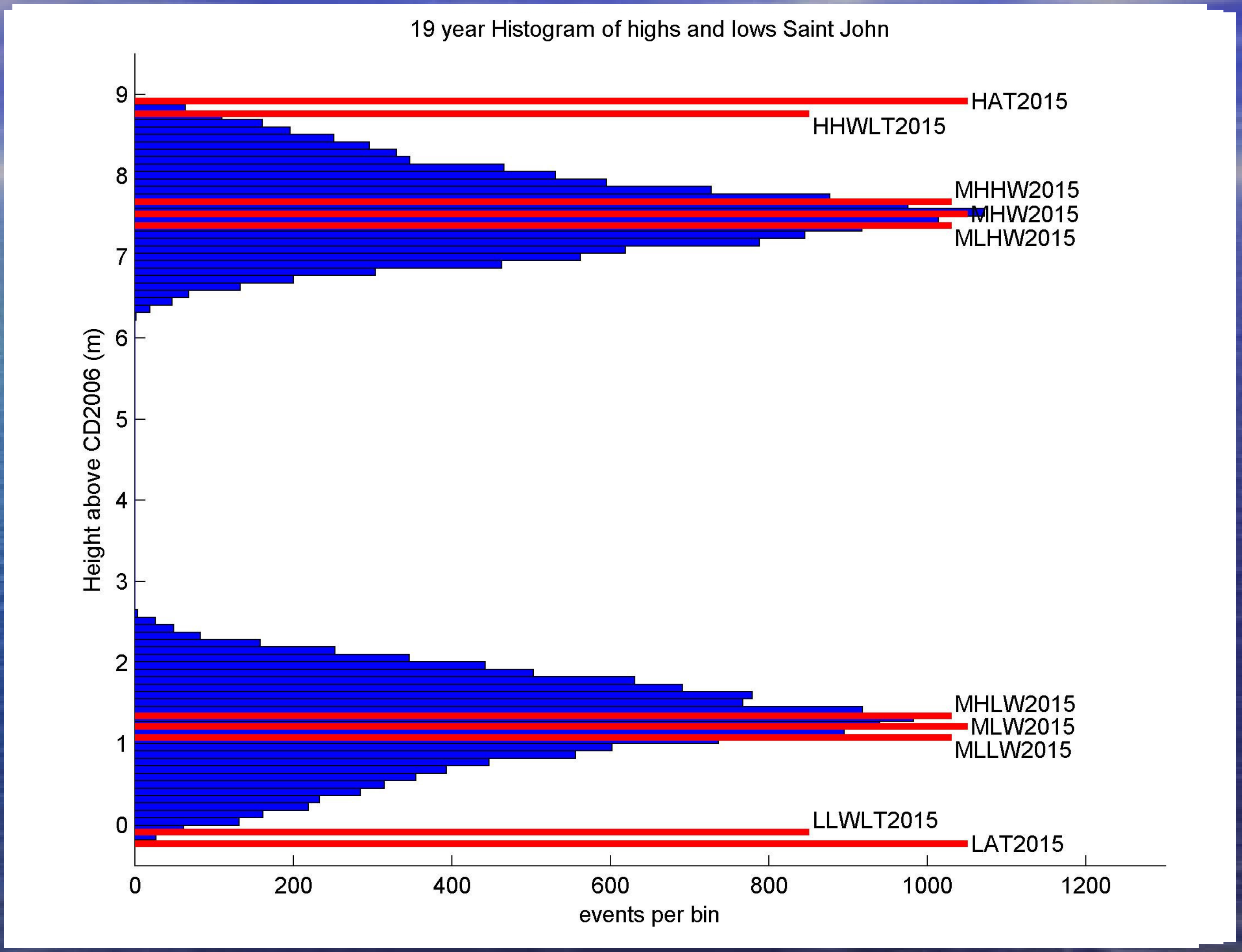
(Static 1D picture based on discrete point data)



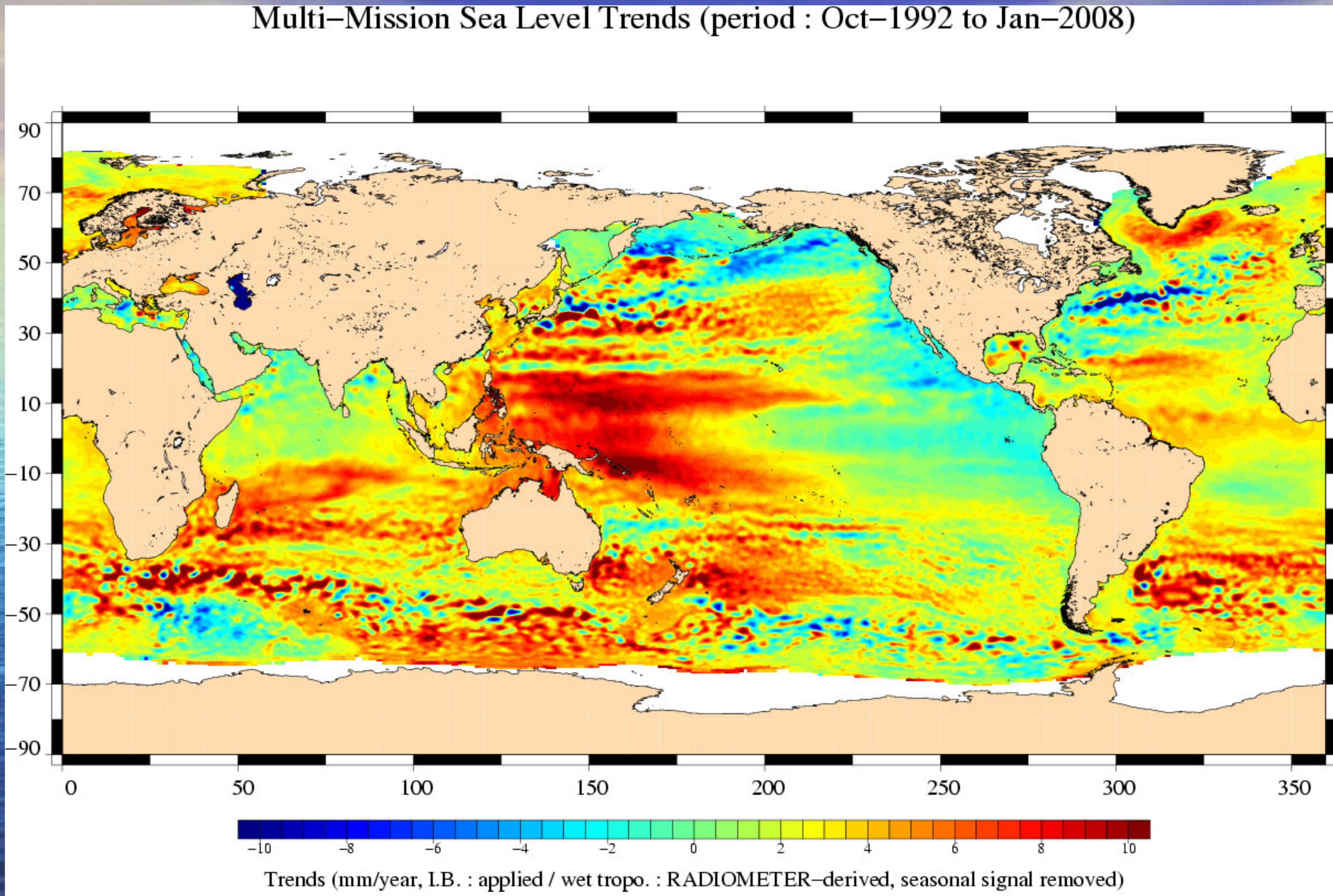
Calculation of Datum Targets

- Collect water level data
- Constituent analysis of data
- Predict highs and lows over 19 year tidal epoch (2007-2025)

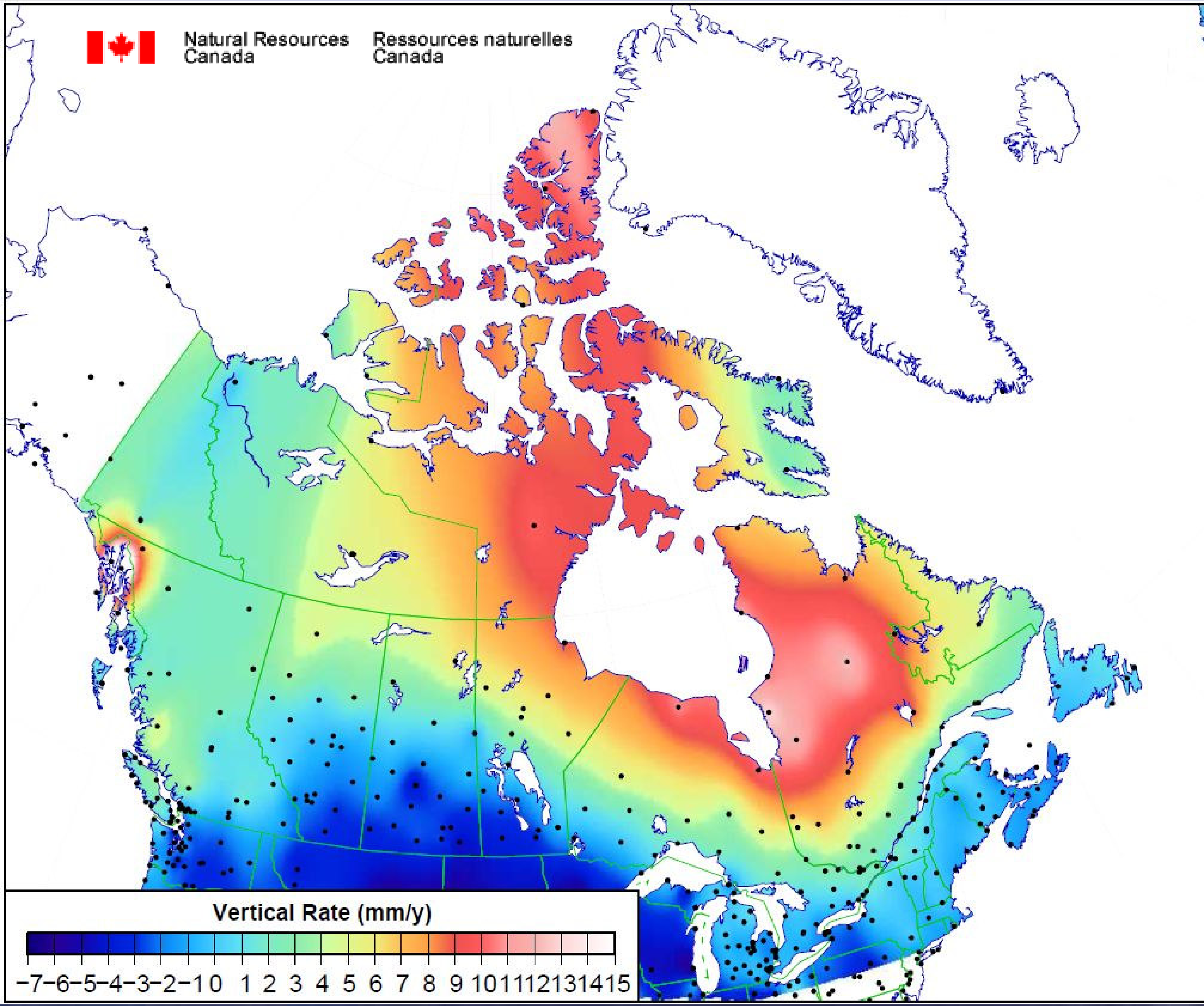
  2015 central year
- Calculate statistics
- Account for relative sea level rise (land subsidence and sea level rise) from time CD2006 established up to 2015



Global trends sea level rise

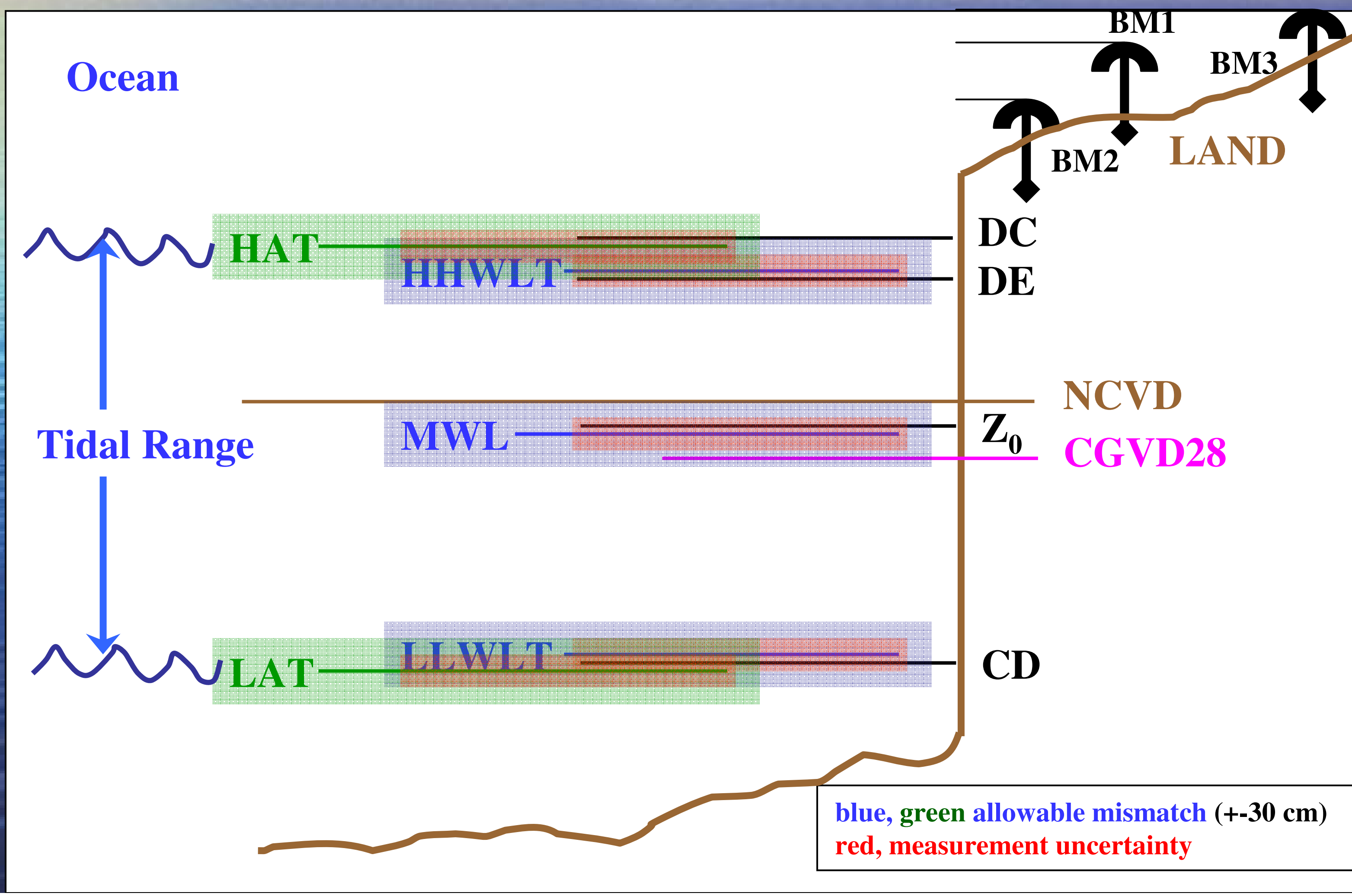


Land Subsidence Rates



Datum Adjustments

- **Relative sea level rise (sea level rise + land subsidence):** Need to move Datums up
- **Migration to new target (LAT):** If present datum complies with allowable mismatch, do nothing and claim LAT compliant



Reasons for Datum Adjustments

- Relative sea level rise (sea level rise + land subsidence)
- Changes in tidal behavior (increasing or decreasing tidal range)
  - Bay of Fundy Power Projects,
  - Man made restrictions or dredging
  - Changing tidal amplification from resonance (possible in bay of Fundy)
- Improved water level data
- Improper Datum placement (Blunder)
- Change in Datum Targets
  - IHO recommendation for harmonization of low water datum Migration from LLWLT to LAT
  - Change from HHWLT to HAT for Datum for Clearances

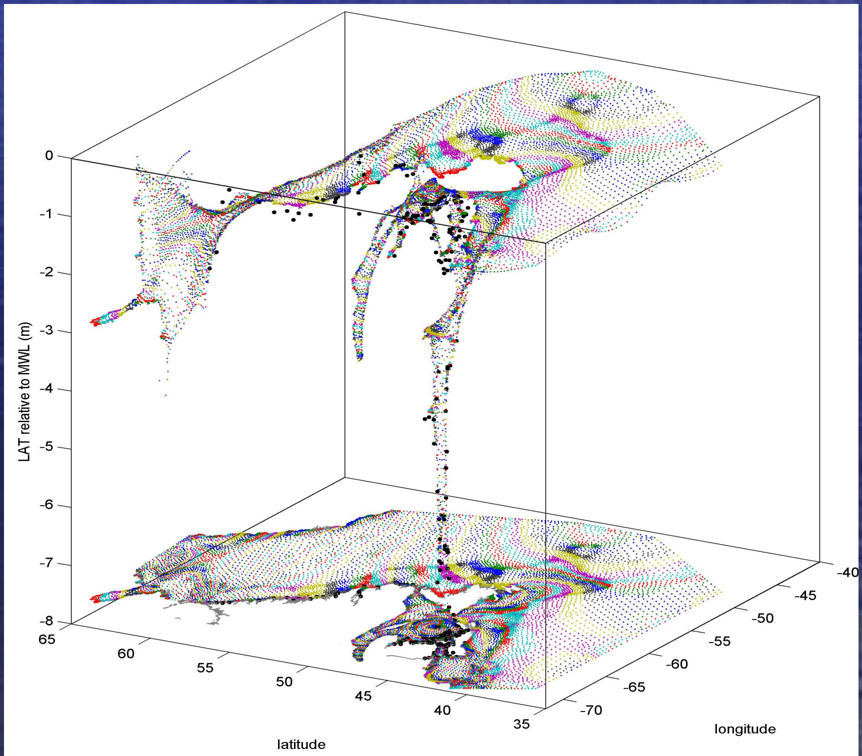
Datum Adjustments Cont.

- Presently done on a station by station basis driven by Chart recompilation. We often live with our datum non-conformities until Chart update. May not be advisable with increasing relative sea level rise rates.
- Need to track where our Datums are <u>and were</u> so we can easily and consistently make the proper adjustments to the associated bathymetric, elevation and clearance data.
- Epoch Based Datum and Target naming convention
  - CDxxxx, MWLxxxx, DExxxx, DCxxxx (Grandfather all existing to 2006, CD2006), LATxxxx, HATxxxx ….
- Datum transform convention
  - Example: CD2007_CD2015 (from_to + up)
    - Good for bathymetry, bathymetry adjustment is simply
      Existing value + transform
    - Opposite for clearances and elevations
      Existing value - transform

Moving to the Future

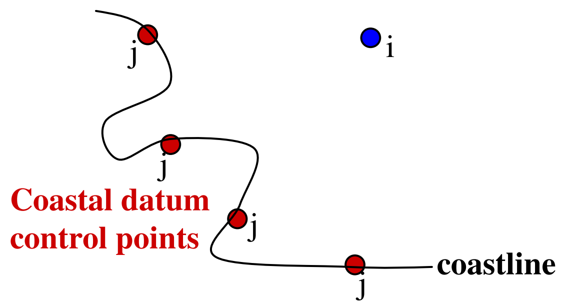
- Problem: We really only know (have measured) our datums, targets and transforms at discrete points, the tide stations. What about in between?
- Partial solutions have been used: tidal zoning, zoned Cotidal models, interpolation techniques …
- But, for OTF methods using GPS for both horizontal and vertical control (GPSTides) what we really need are!

Continuous datums, targets, transforms and reference systems



Already on the road (An interim example)

Distance weighted datum transform MWL_CD used with Webtide (anywhere waterlevel predictions wrt MWL)

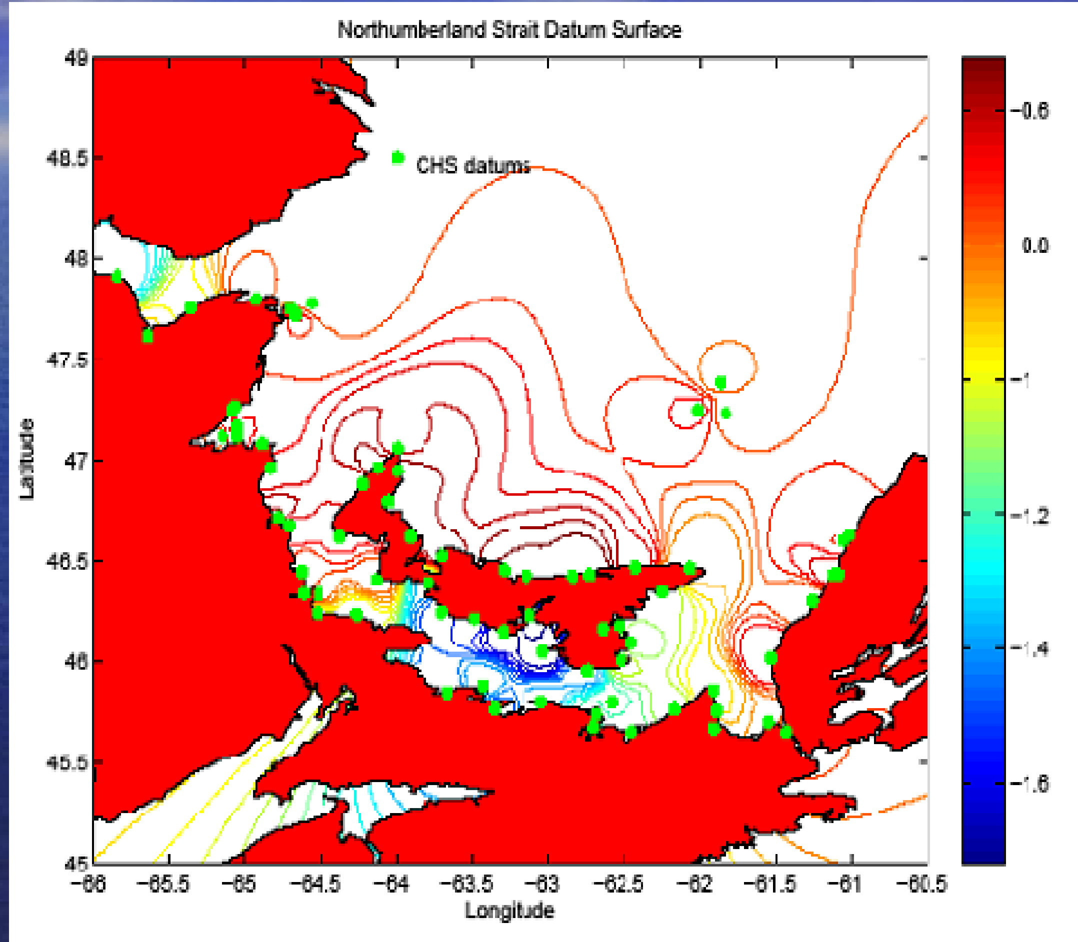


$$T_i = \sum t_j w_j, \quad \sum w_j = 1$$

$$w_j = \frac{(far - dist_j)^p}{\sum_j (far - dist_j)^p}$$

t_j = transform at tidal datum j
w_j = weighting function

Exponent p determines local flatness and width of transition zone



Used in:

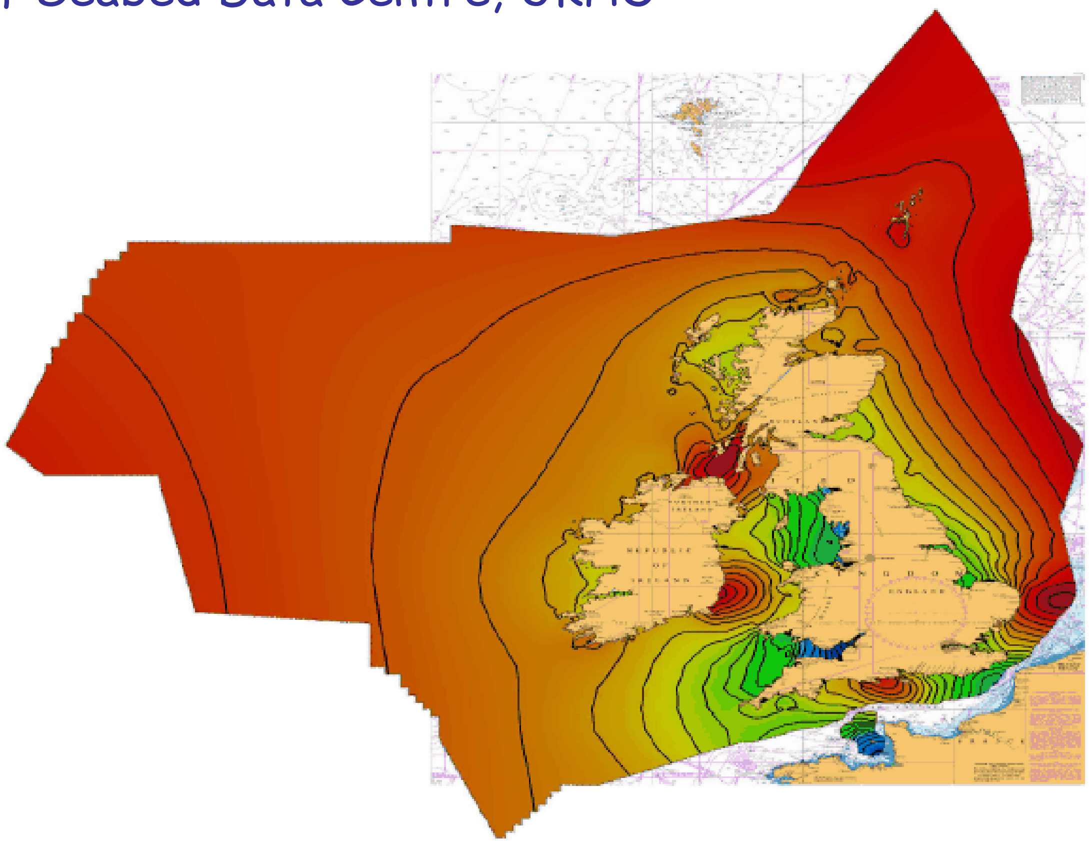
- Labrador 06-07
- Labrador 07-08
- Northumberland 07
- Fundy 07
- Fundy 08

Continuous Datums, Targets and Transforms

- Existing well considered and mature examples
  - NOAA (VDATUM)
  - UKHO (VORF)
- Canadian Continuous Vertical Datum Project
  - What approaches will be used?
  - Where are we?

UKHO VORF

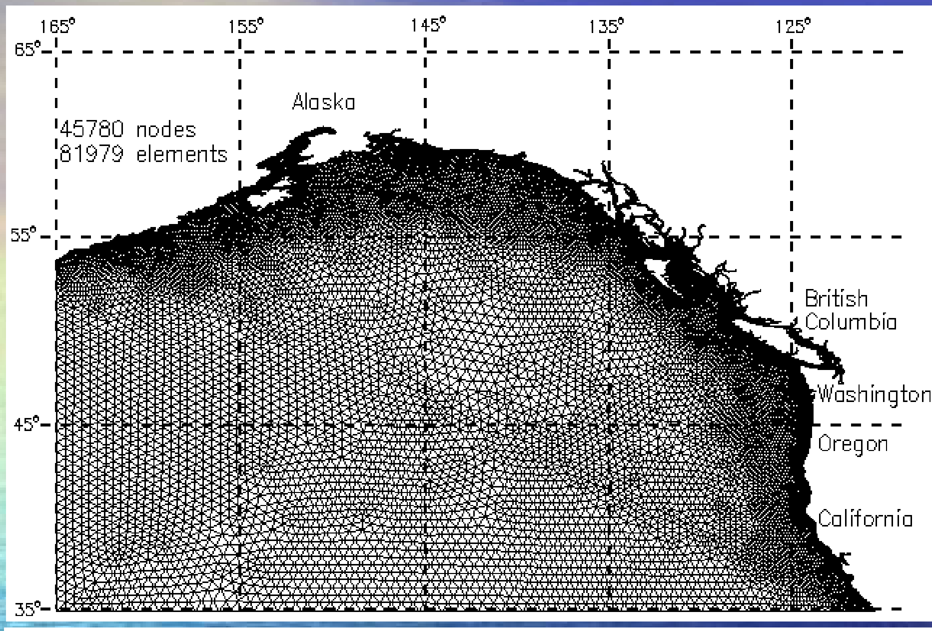
Chris Howlett
Head of Seabed Data Centre, UKHO

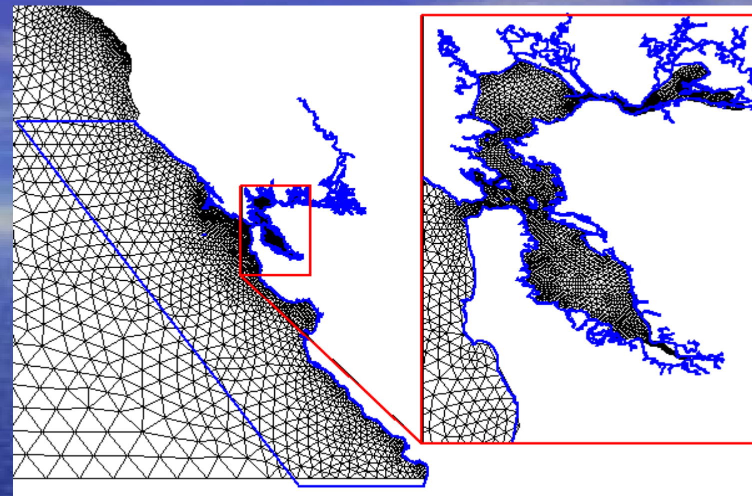


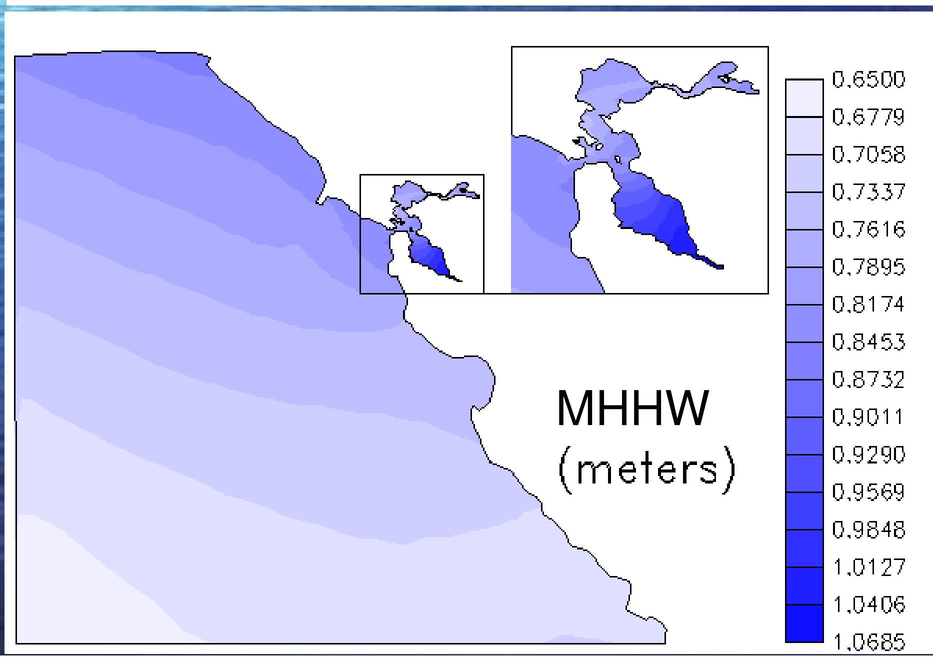
VORF Approach

- mean sea-surface model in the open oceans derived from satellite altimetry
- Geoid model OSGM05, derived from OSGM02 model combined with long-wavelength gravity-field data from the GRACE
- tide-gauge data from the UK Permanent Service for Mean Sea Level (PSMSL) for all UK primary tide-gauges, circa sixty datasets; data comprising monthly mean sea-level, typically spanning ten years or longer
- tide-gauge data from Admiralty Tide Table (ATT) stations, comprising some seven hundred datasets; observations typically span short periods of time (one to twelve months) and go back as far as 1855
- GPS-derived ellipsoidal heights at specific tide-gauge locations
- bathymetric models for use with dynamic tidal modelling.

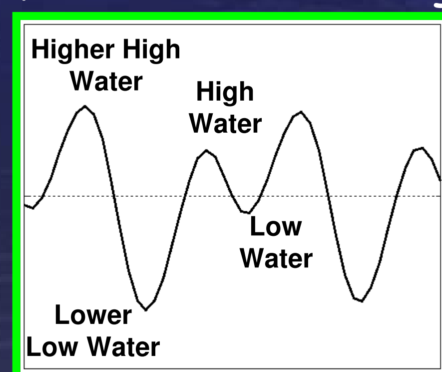
NOAA, VDATUM: Modeling + Data, Generation of Tidal Datum Surfaces







- MHW tidal datum fields (as well as MHHW, MLW, MLLW, MSL, MTL, DTL) from calibrated hydrodynamic models
- *Analysis of model-produced time series, then adjusted to provide a best fit to datums at NOS gauges.*



Transformations available on VDatum Grids

Tidal Datums

MLLW	**Mean Lower Low Water**
MLW	Mean Low Water
LMSL	Local Mean Sea Level
MTL	Mean Tide Level
DTL	Diurnal Tide Level
MHW	Mean High Water
MHHW	Mean Higher High Water

Orthometric Datums

NAVD 88	North American Vertical Datum 1988
NGVD 29	National Geodetic Vertical Datum of 1929

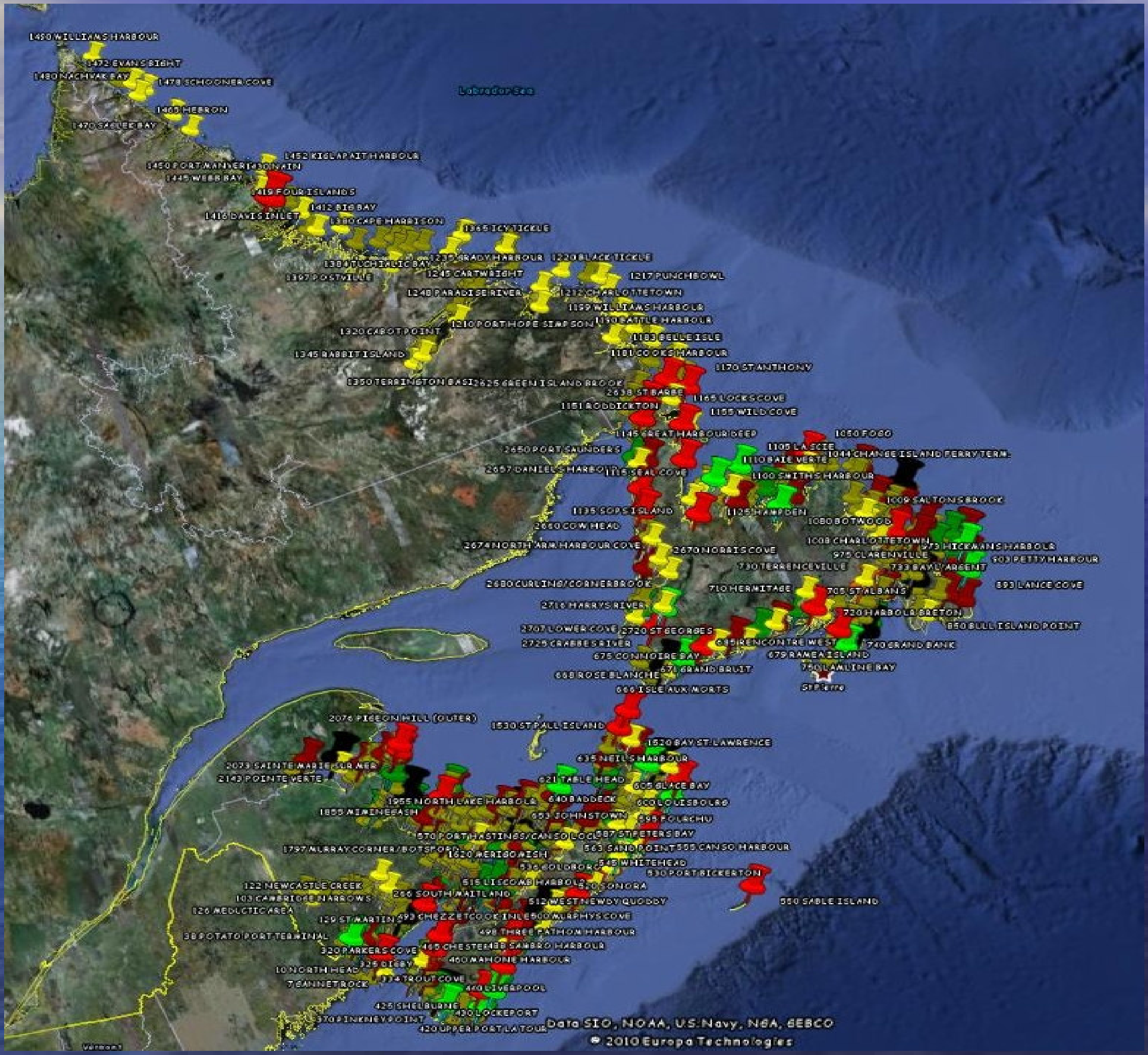
3-D/Ellipsoid Datums

NAD 83 (NSRS)	North American Datum 1983
WGS 84(G873)	World Geodetic System 1984 (G873)
WGS 84(G730)	World Geodetic System 1984 (G730)
WGS 84(orig)	World Geodetic System 1984 (original system -- 1984)
WGS 72	World Geodetic System 1972
ITRF	International Terrestrial Reference Frame 1988-94, 1996-98, 2000
SIO/MIT 92	Scripps Institution of Oceanography / Mass. Inst. of Tech. 1992
NEOS 90	National Earth Orientation Service 1990
PNEOS 90	Preliminary Nat'l Earth Orientation Service 1990

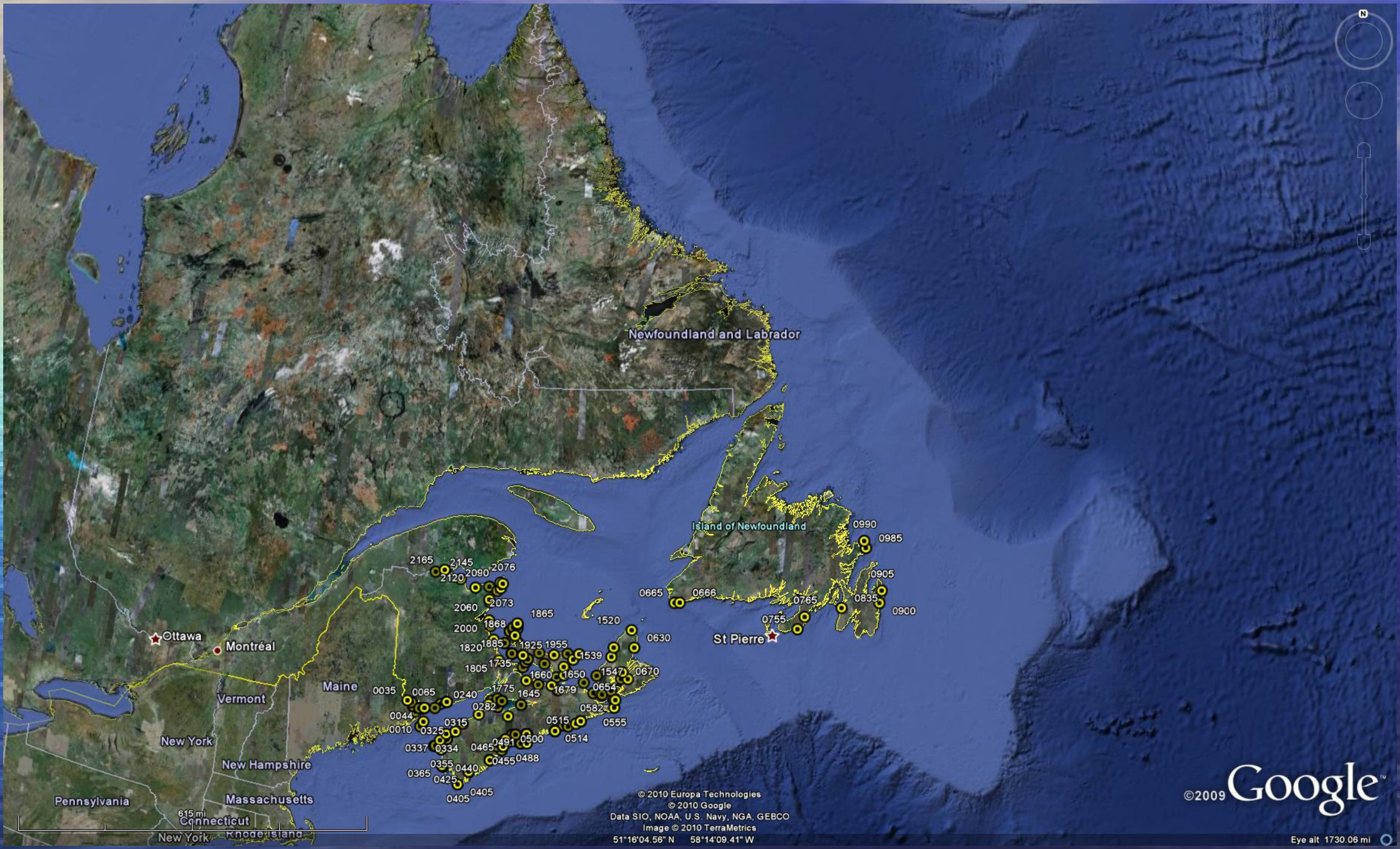
Canadian Continuous Vertical Datum Project

- National in scope: develop common strategies for all CHS regions (Pacific, Central and Arctic, Quebec and Atlantic)
- Present Status:
  - Planning methods
  - Collecting, collating and improving shore based data and control
  - Obtaining funding (this will ultimately determine timescale)
- Suggested Strategy:
  - Clean up shore based datum and target holdings and establish solid links to reference systems, NAD83(CSRS)xxxx, CGVD28
    - In Progress, 24 hr occupations, NRCan PPP processed, references to NAD83(CSRS)2006 and CGVD28 (modeled HTv2.0)
  - Mean water level in open ocean or far from land from satellite altimetry
  - Open ocean and far from land transformations MLW_CDxxxx and to LATxxxx, HHWLTxxxx … (Ocean Modeling)
  - Link offshore to shore based data (methods still under discussion May 2010, combination of VDATUM and VORF methods)

Atlantic Shore Based Control

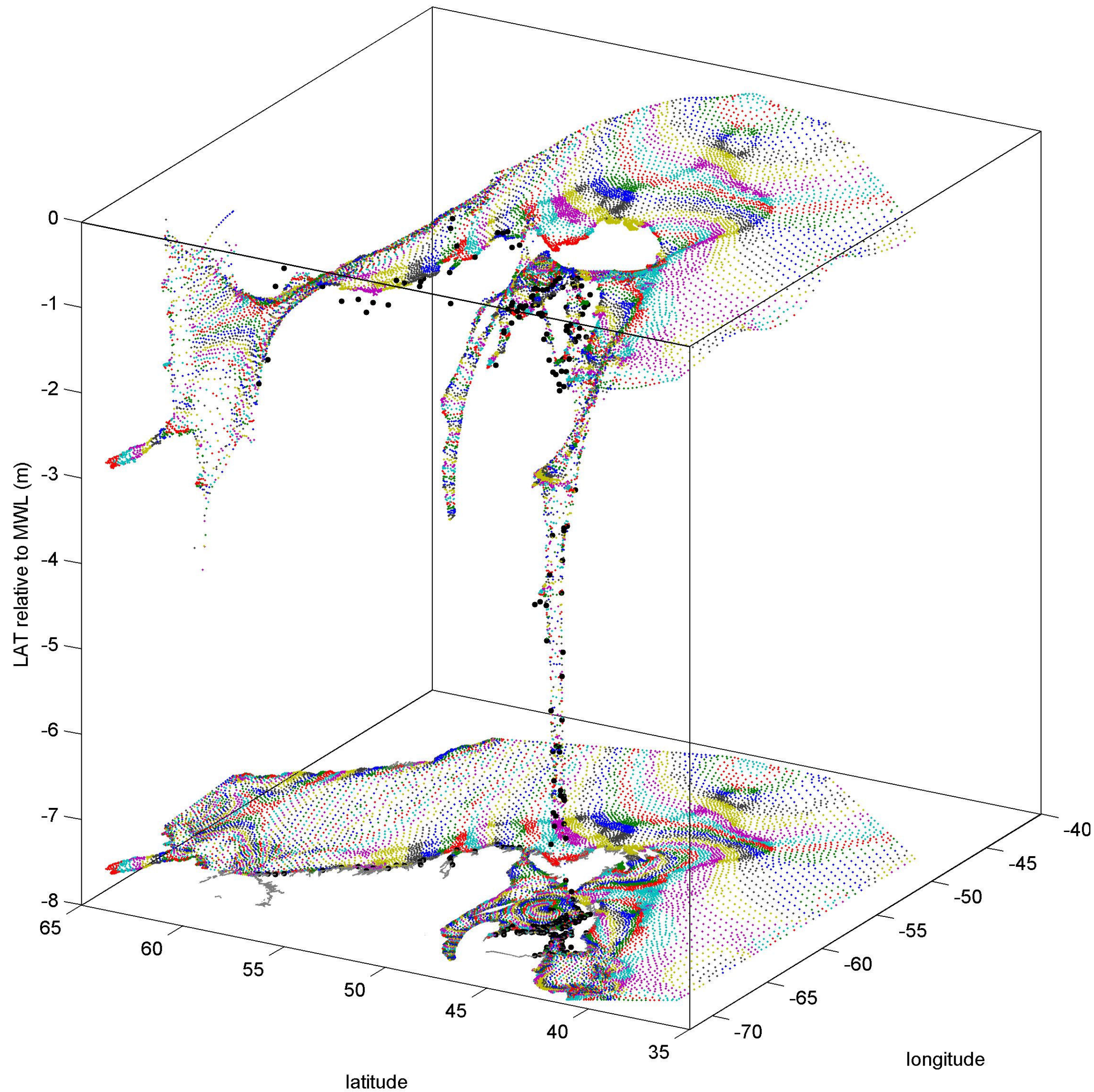


2009-2010 Occupations



What does a Continuous Atlantic Low Water Datum target Look like? (MWL_LAT based on Webtide)

- Example of a theoretical gridded target surface based on model data (i.e. for LAT some percentage of the sum, say 95-105%, of the WebTide constituent amplitudes).
- High water datum target surface defining land_sea boundary MWL_HHWLT would be similar but inverted.

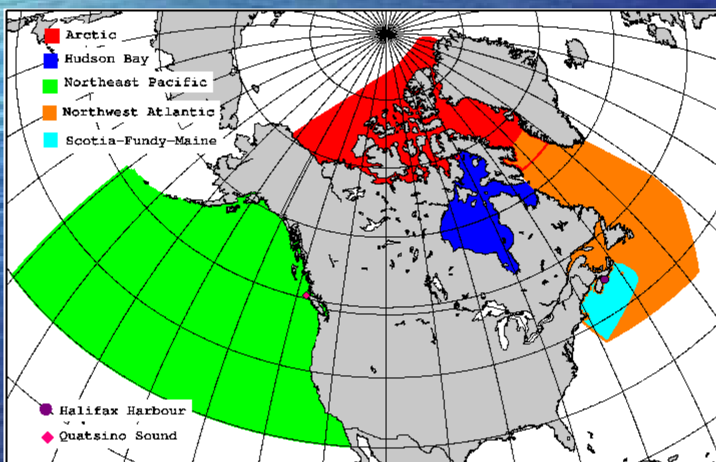


Highlights (Things to remember)

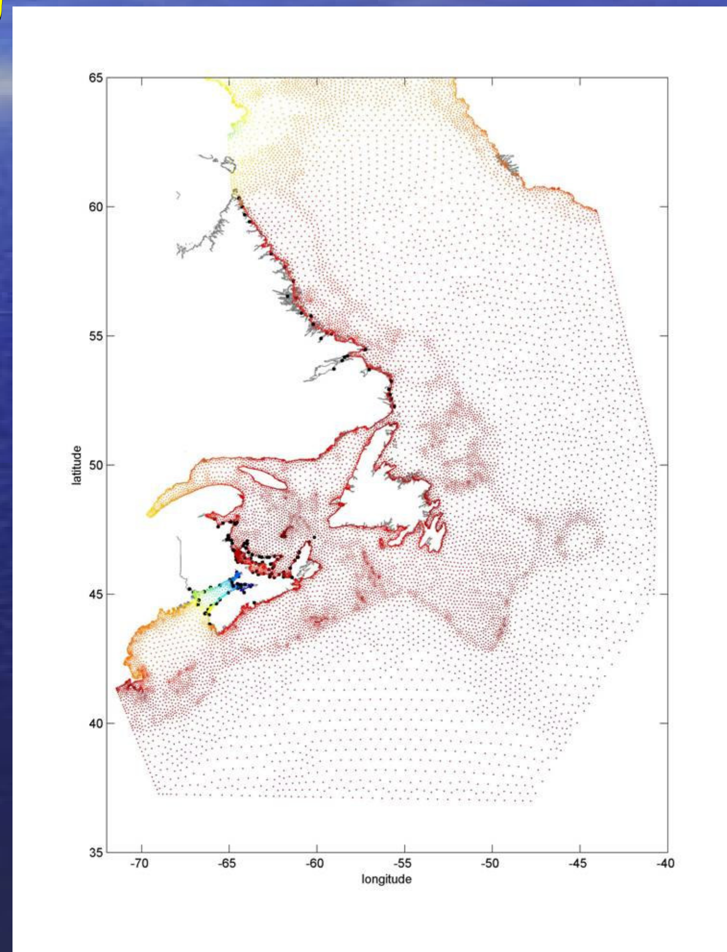
- Datums:
  - CD, SD, Zo, DE, DC, IGLD
- Datum Targets:
  - LAT, LLWLT, MWL, HHWLT, HAT
- References and reference surfaces
  - Benchmarks
  - CGVD28 (vertical reference frame built from leveling with modeling adjustments with 3 fixed reference points: near Halifax, Rimouski, Vancouver?)
  - NRCan height modernization and new Canadian vertical datum
  - Ellipsoids: WGS84, NAD83 (what are they, a few details)
- Datum Adjustments
  - Relative sea level rise
  - LAT migration
- Datum Epoch naming CDxxxx and Transform conventions MWLxxxx_CDxxxx
- Canadian Continuous Vertical Datum Project

What is Webtide?

- Webtide is a tool that accesses the results of dynamical ocean modeling efforts. The models are run based on appropriate forcing often including assimilation of satellite altimetry data. Model output is analyzed for constituents (just like tide gauge data) at the model grid points. Constituents are saved and accessed by the web tide tool to make predictions of water level relative to the model's floating MWL.



WebTide



Constituents derived from a Hydrodynamic Barotropic Ocean Model Assimilating Topex Posieden Altimeter data

Dupont, F., C.G. Hannah, D.A. Greenberg, J.Y. Cherniawsky and C.E. Naimie. 2002. Modelling system for tides for the North-west Atlantic coastal ocean. [online]. [Accessed 21 April, 2008]. Available from World Wide Web: http://www.dfo-mpo.gc.ca/Library/265855.pdf