What's Up?
Tidal and Vertical Datums

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Motivation

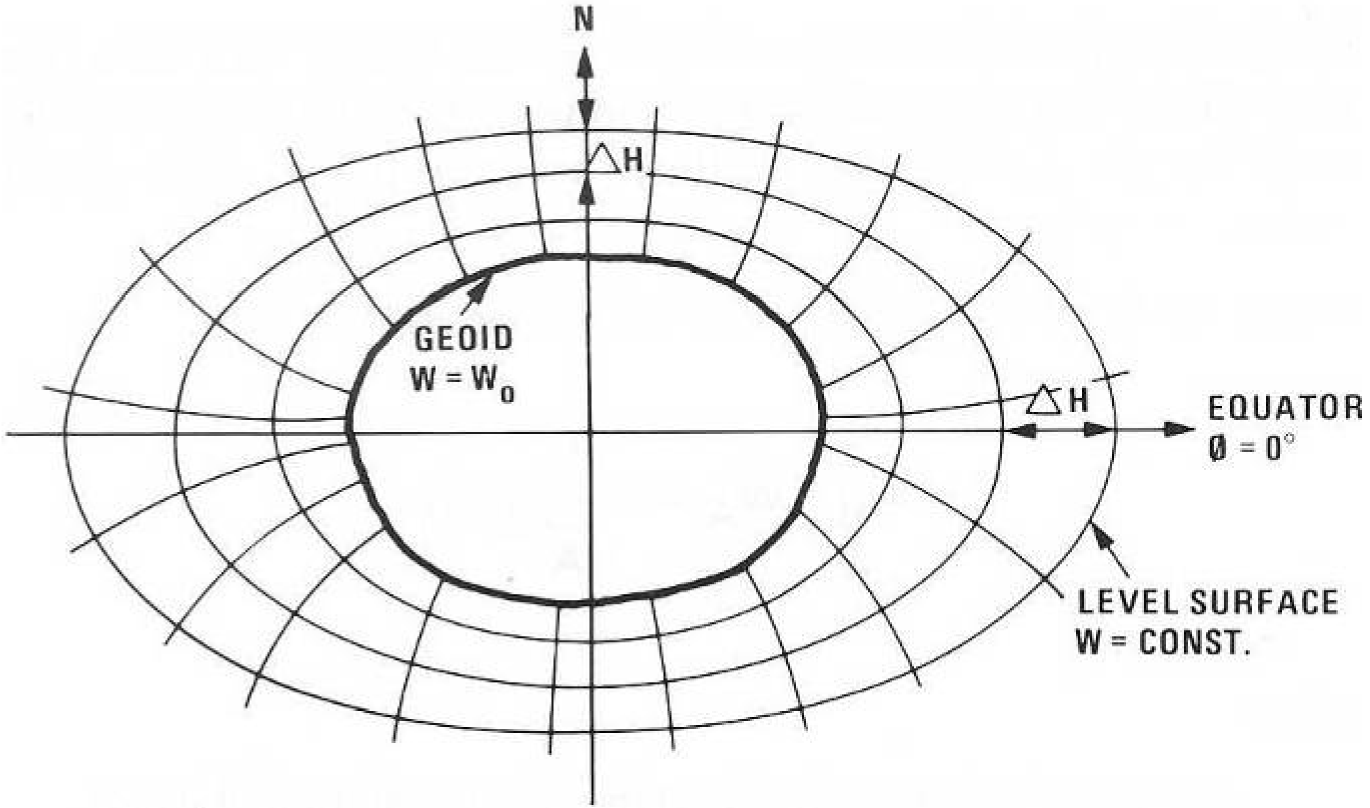
- The real world is three-dimensional, therefore, coordinates are necessarily 3-D
- In the oil patch we carefully qualify horizontal coordinates with geodetic datums, map projections, grid parameters, et cetera, but not so much in the vertical
- Gravity defines the vertical (up / down) dimension in the real (non-ellipsoidal) world
- Careful qualification is as required in the vertical as in the horizontal for many reasons, one of which is the integrity of 3D visualization

Ellipsoidal Vertical

Horizontal graticule of parallels and meridians, latitudes and longitudes, intersecting orthogonally on the ellipsoid.

The ellipsoidal vertical is measured along the normal, <u>the straight line perpendicular to the ellipsoid surface</u>.

Gravitational Vertical



Level equipotential surfaces are neither parallel nor equally spaced. Vertical lines (equipotential perpendiculars) are curved.

Elevation is measured with respect to the geoid, the surface whose potential (W) approximates that of Mean Sea Level ($W=W_0$).

Gravitational Geopotential (W)

If **$W = g \cdot D$**, where g is the acceleration of gravity (±9.78 m/s^2 on the geoid at the Equator) and D is the distance to the center of the Earth (±6,378,137 m on the geoid at the Equator), then

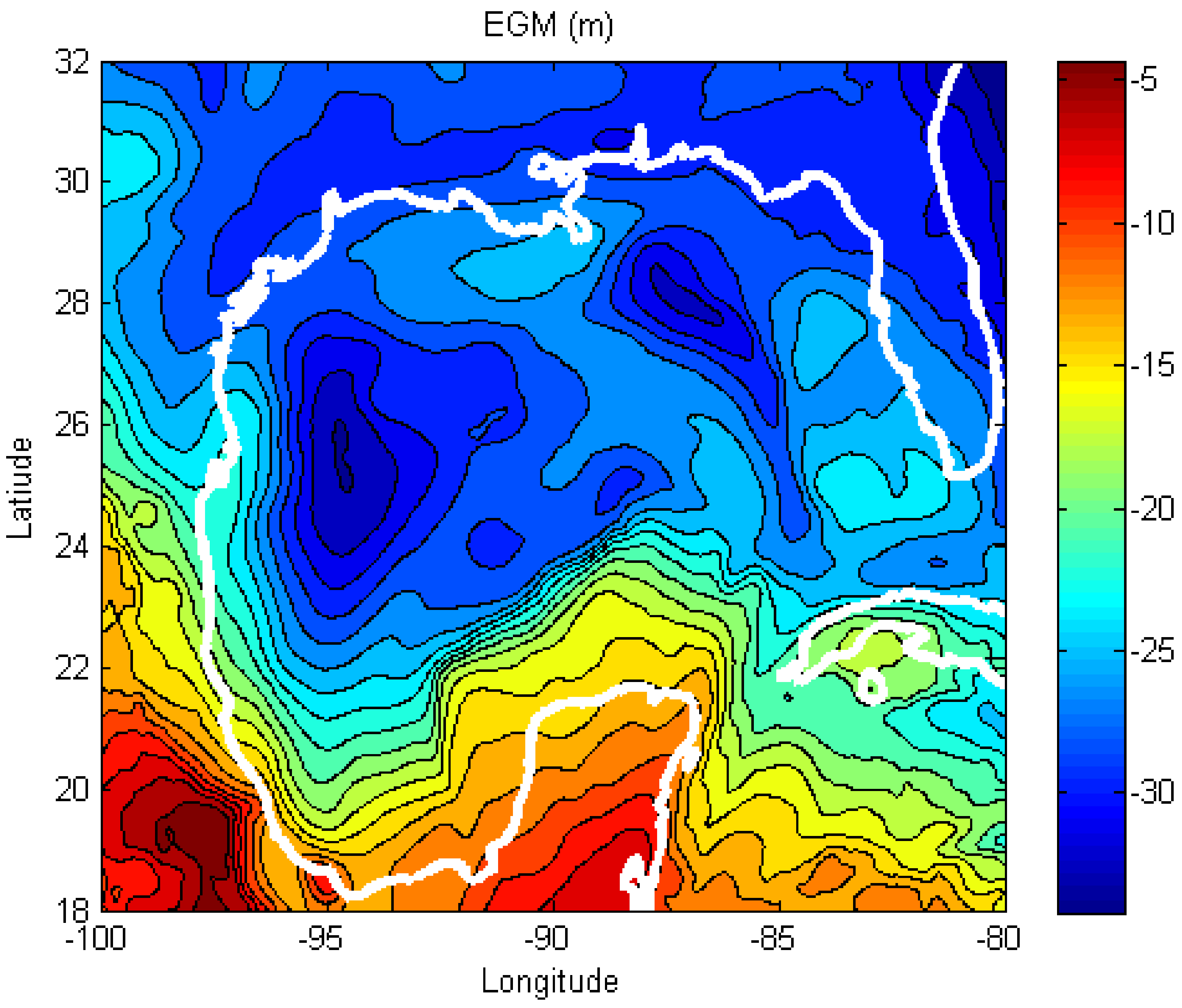
$W_0 \approx 62M\ m^2/s^2 = 62M$ Joules/kg
$= 6.2M$ kgal·m $= 6.2M$ GPU

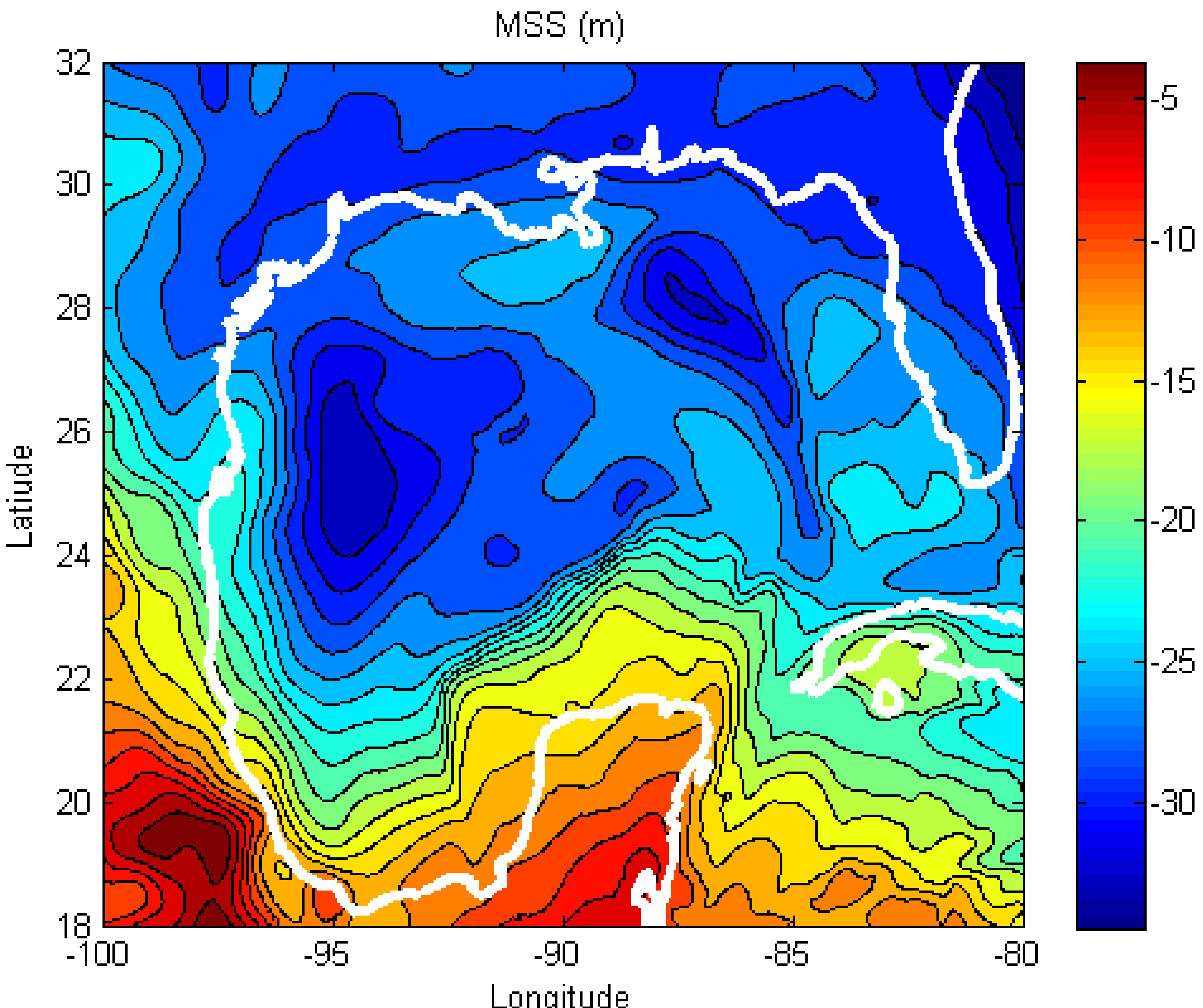
Geopotential (W_0) is everywhere constant on the geoid, but the acceleration of gravity (g) is not!

Geopotential is important later in the presentation.

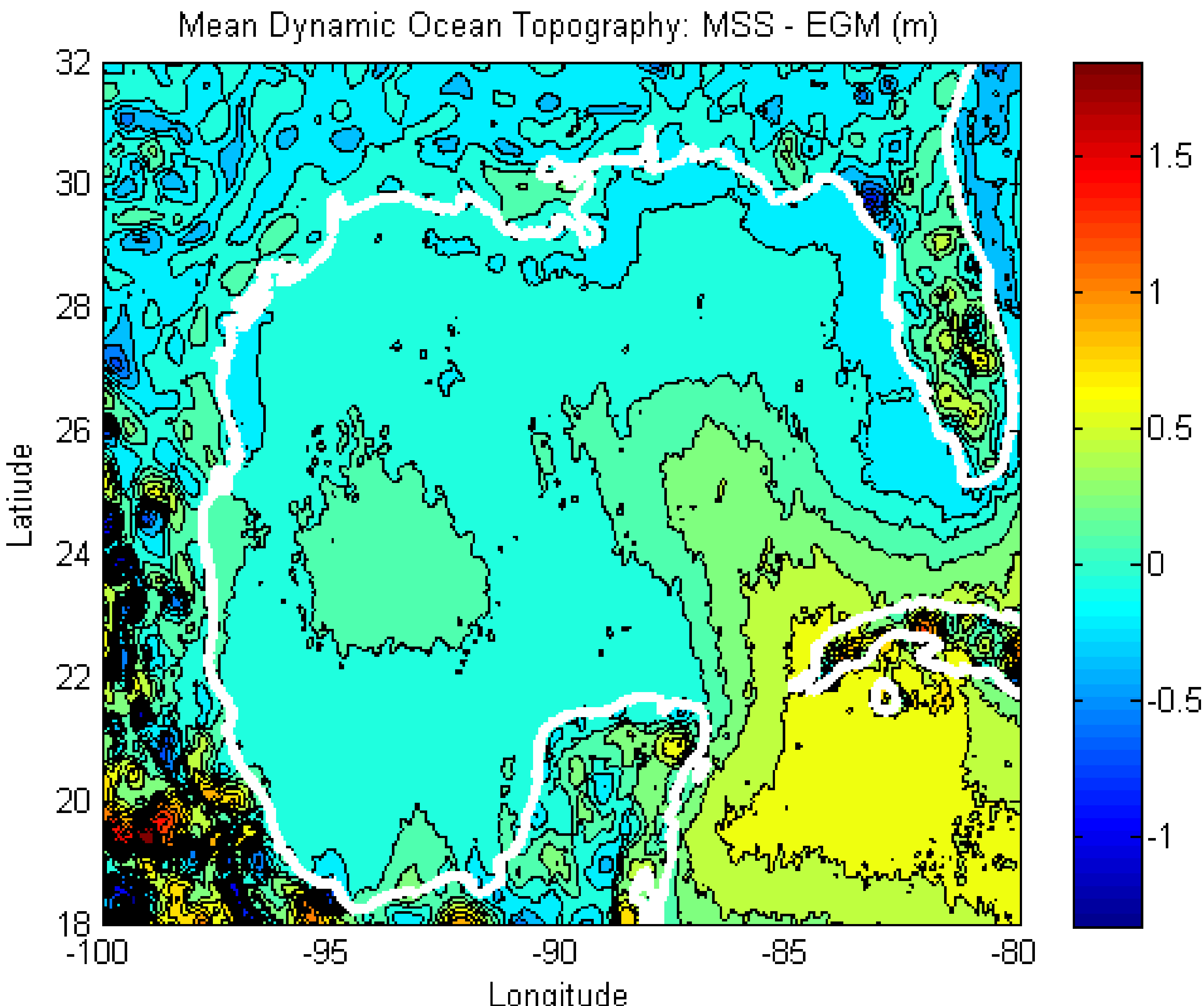
Introducing Tidal Datums

- The geoid is that horizontal equipotential surface that approximates Mean Sea Level (MSL), which, due to mean ocean dynamics, is not horizontal
- MSL is a tidal datum. It is the average water level observed at tide gauge over the 18.6 year precession of the lunar orbital plane w.r.t. the ecliptic plane
- A Mean Sea Surface (MSS) extends MSL over the entire sea surface by combining tide gauges with satellite altimetry
- Mean Dynamic Ocean Topography (DOT) is the difference between the geoid and MSS


EGM (m)
Latiude
Longitude
32
30
28
26
24
22
20
18
-100
-95
-90
-85
-80
-5
-10
-15
-20
-25
-30



MSS (m)
Latiude
Longitude
32
30
28
26
24
22
20
18
-100
-95
-90
-85
-80
-5
-10
-15
-20
-25
-30



Mean Dynamic Ocean Topography: MSS - EGM (m)
Latiude
Longitude
32
30
28
26
24
22
20
18
-100
-95
-90
-85
-80
1.5
1
0.5
0
-0.5
-1

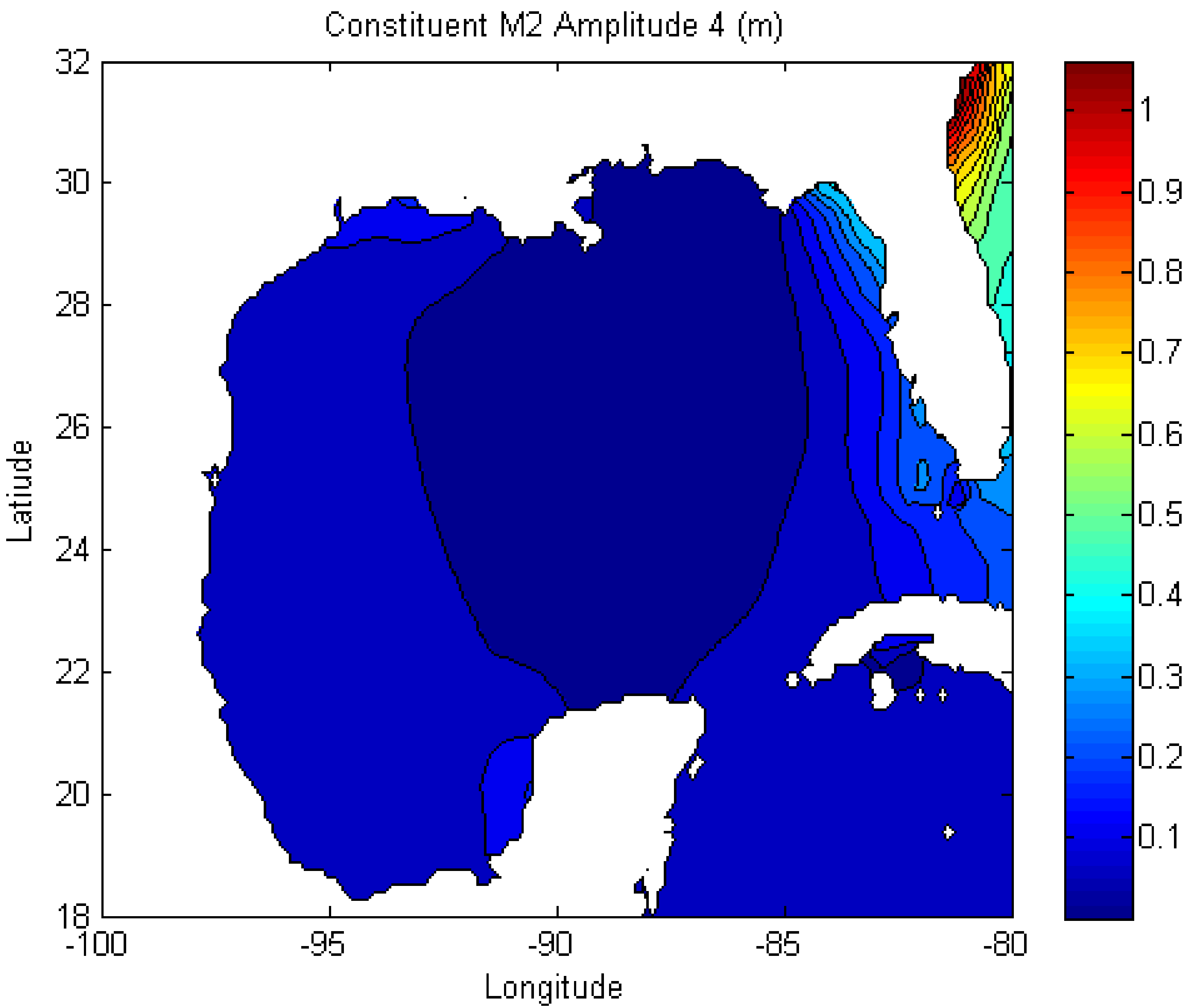
Tidal Constituents

- Tides are generated by the gravitational forces of the moon (68.5%) and the sun (31.5%)
- A constituent is a repeatable geometry in the positions of the earth, moon and sun expressed as a period (hours) and speed (degrees/hour)
- The tidal effect of a constituent at a specific place has an amplitude and phase shift w.r.t. some initial time
- The constituents with the greatest amplitude are:
  - M2, principal lunar semi-diurnal
  - S2, principal solar semi-diurnal
  - K1, diurnal lunisolar declination
  - O1, diurnal lunar declination

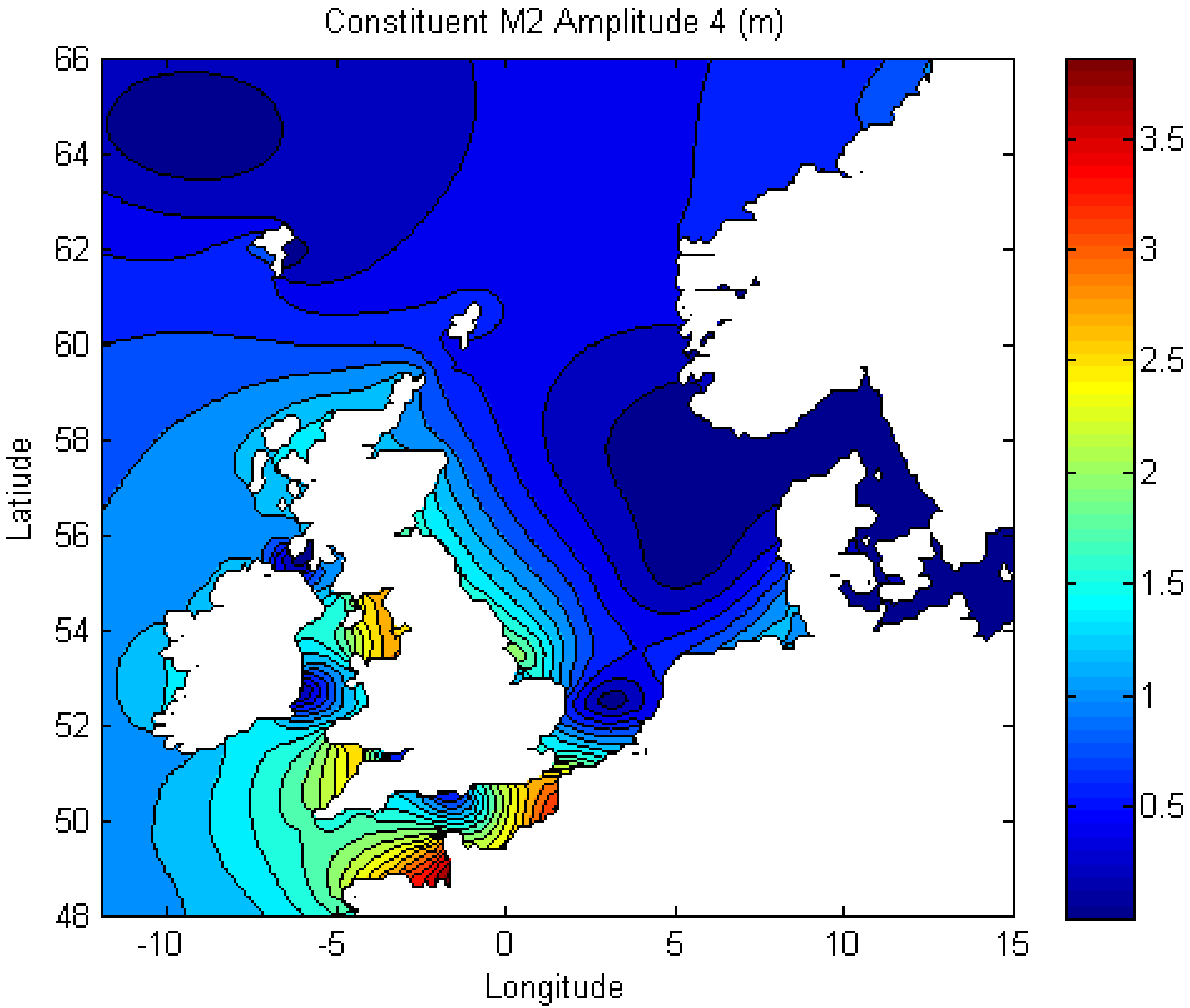
A List of Tidal Datums

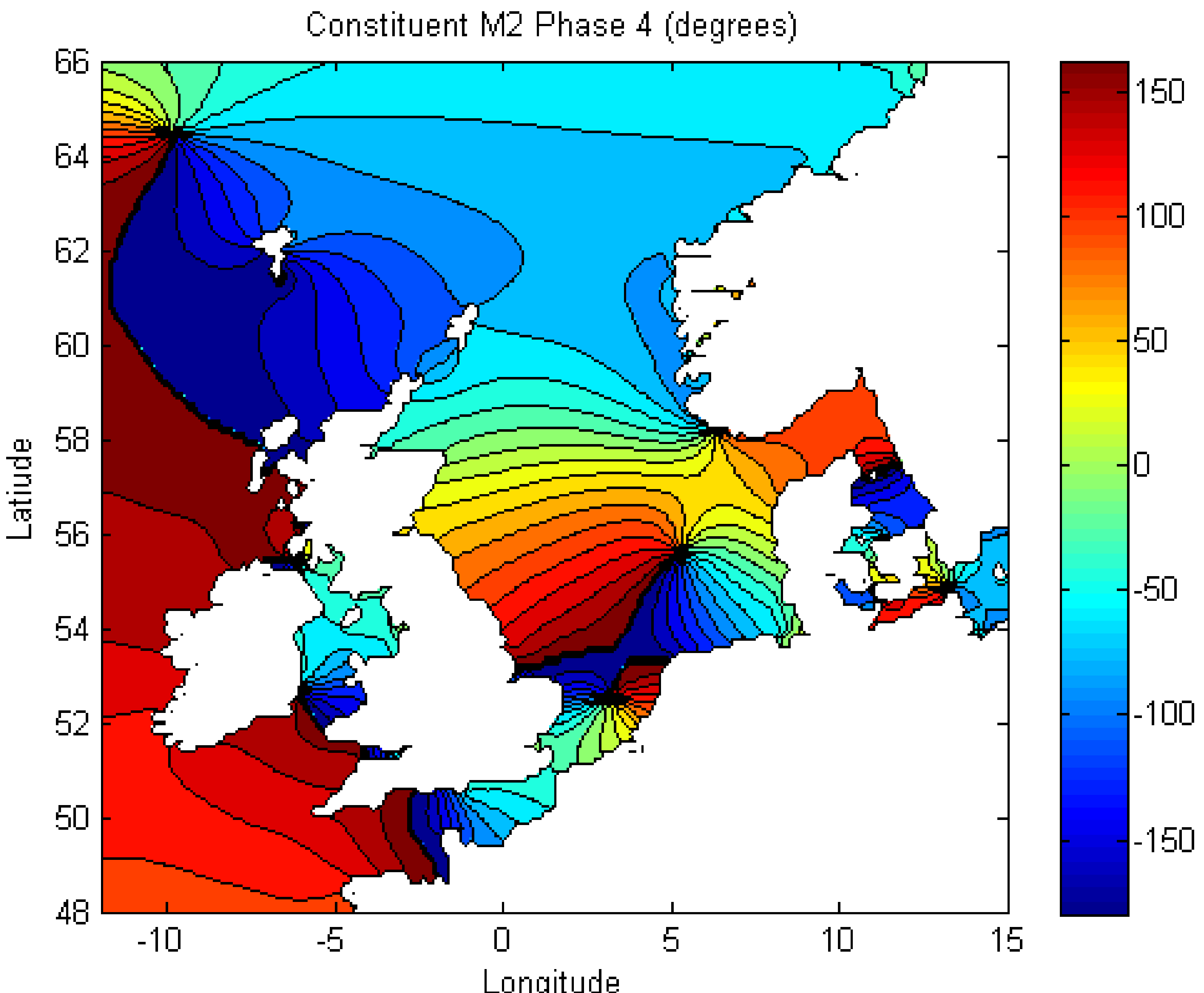
Approximate Lowest Astronomical Tide
Approximate Mean Low Water Springs
Approximate Mean Low Water Tide
Approximate Mean Low Water
Approximate Mean Sea Level
Equinoctial Spring Low Water
Half Tide
Highest Astronomical Tide
Higher High Water Large Tide
Highest Normal High Water
Higher High Water
Highest High Water
High Water
High Water Springs
Indian Spring High Water
Indian Spring Low Water
Lowest Astronomical Tide
Lower Low Water Large Tide
Lowest Low Water Springs

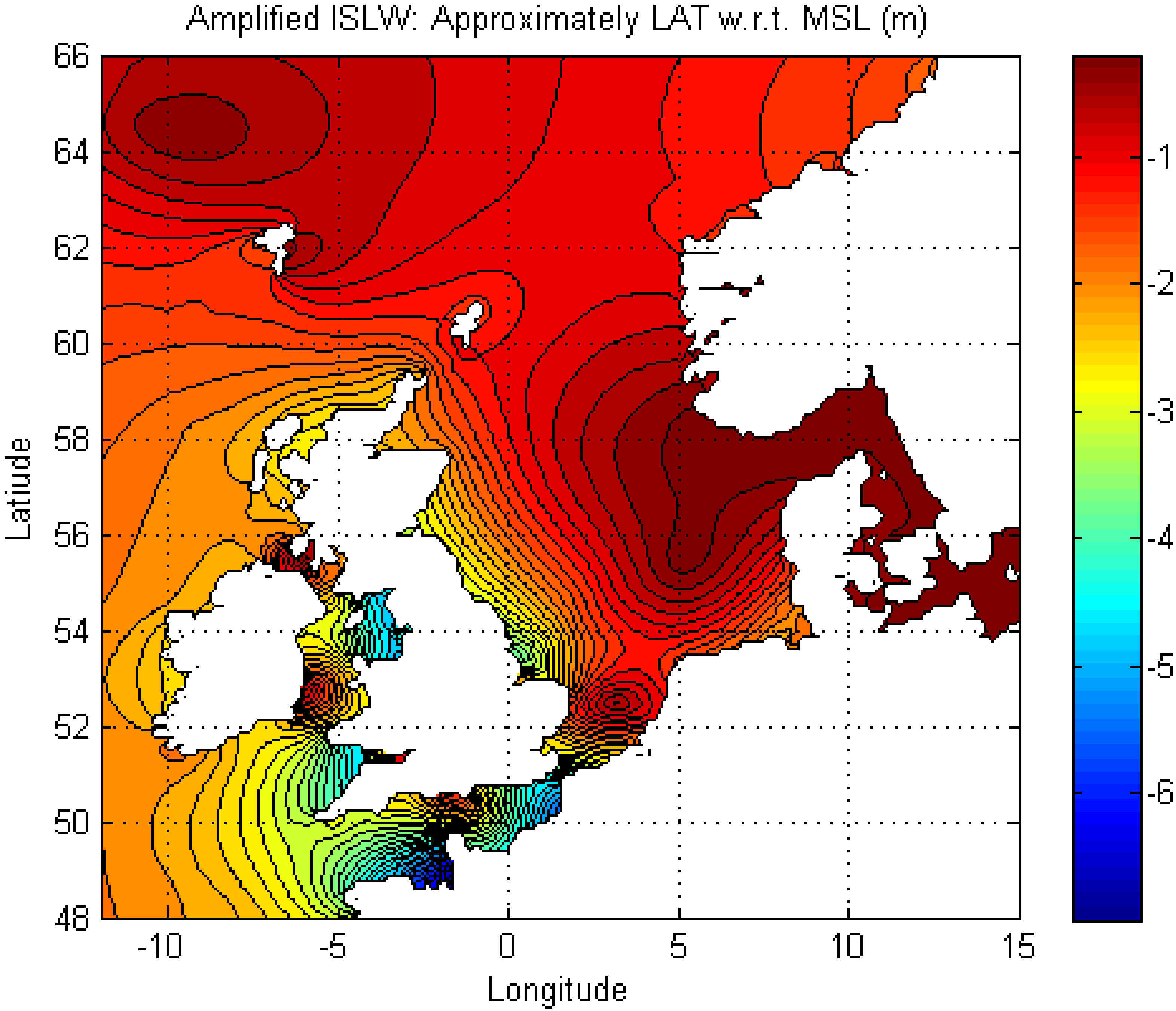
Lower Low Water
Lowest Low Water
Low Water
Low Water Springs Low Water Springs
Mean Higher High Water
Mean Higher Water
Mean High Water
Mean High Water Neaps
Mean High Water Springs
Mean Lower Low Water Springs
Mean Lower Low Water
Mean Low Water
Mean Low Water Neaps
Mean Low Water Springs
Mean Sea Level
Mean Tide Level
Nearly Lowest Low Water
Neap Tide
Spring Tide

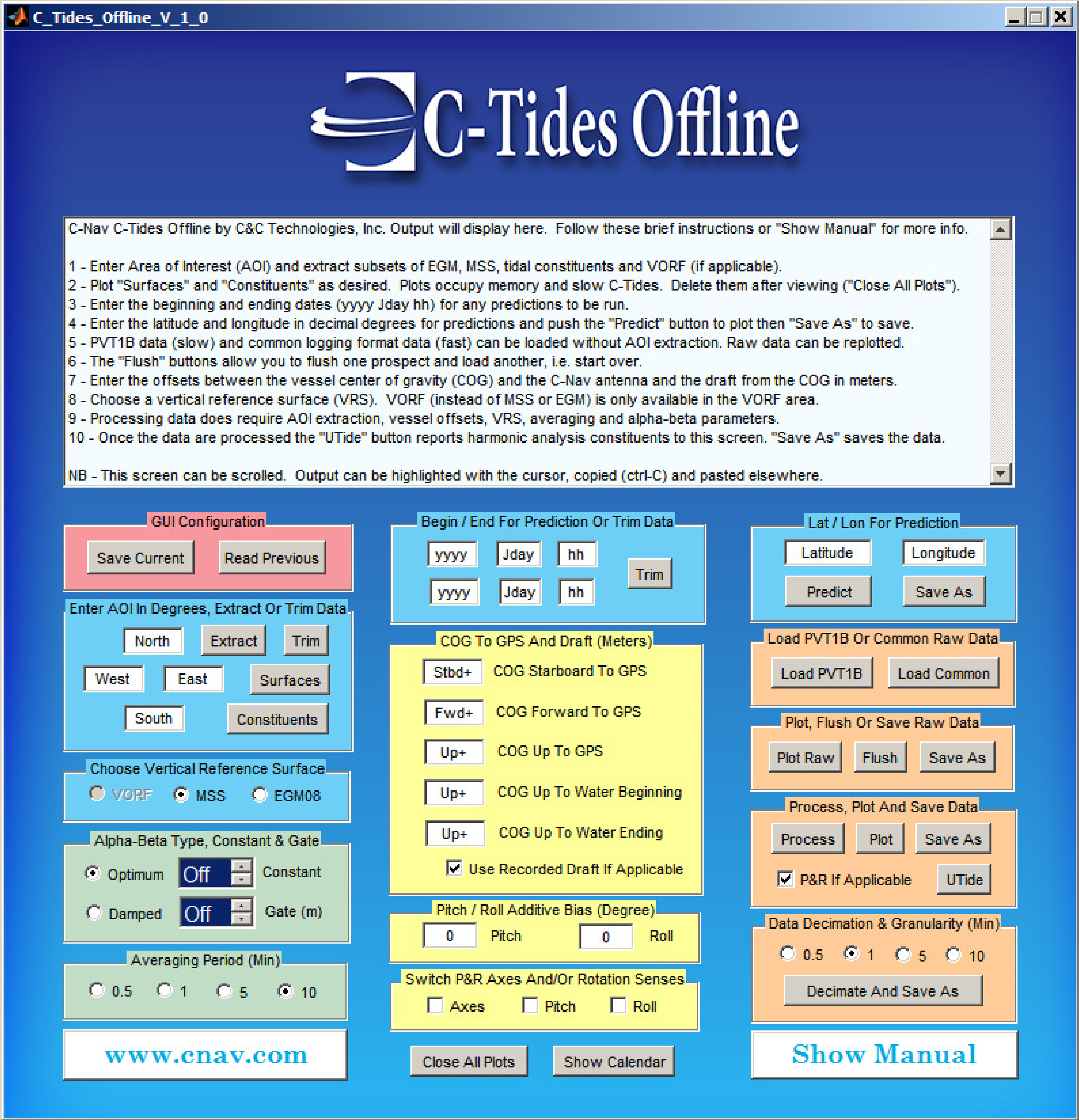


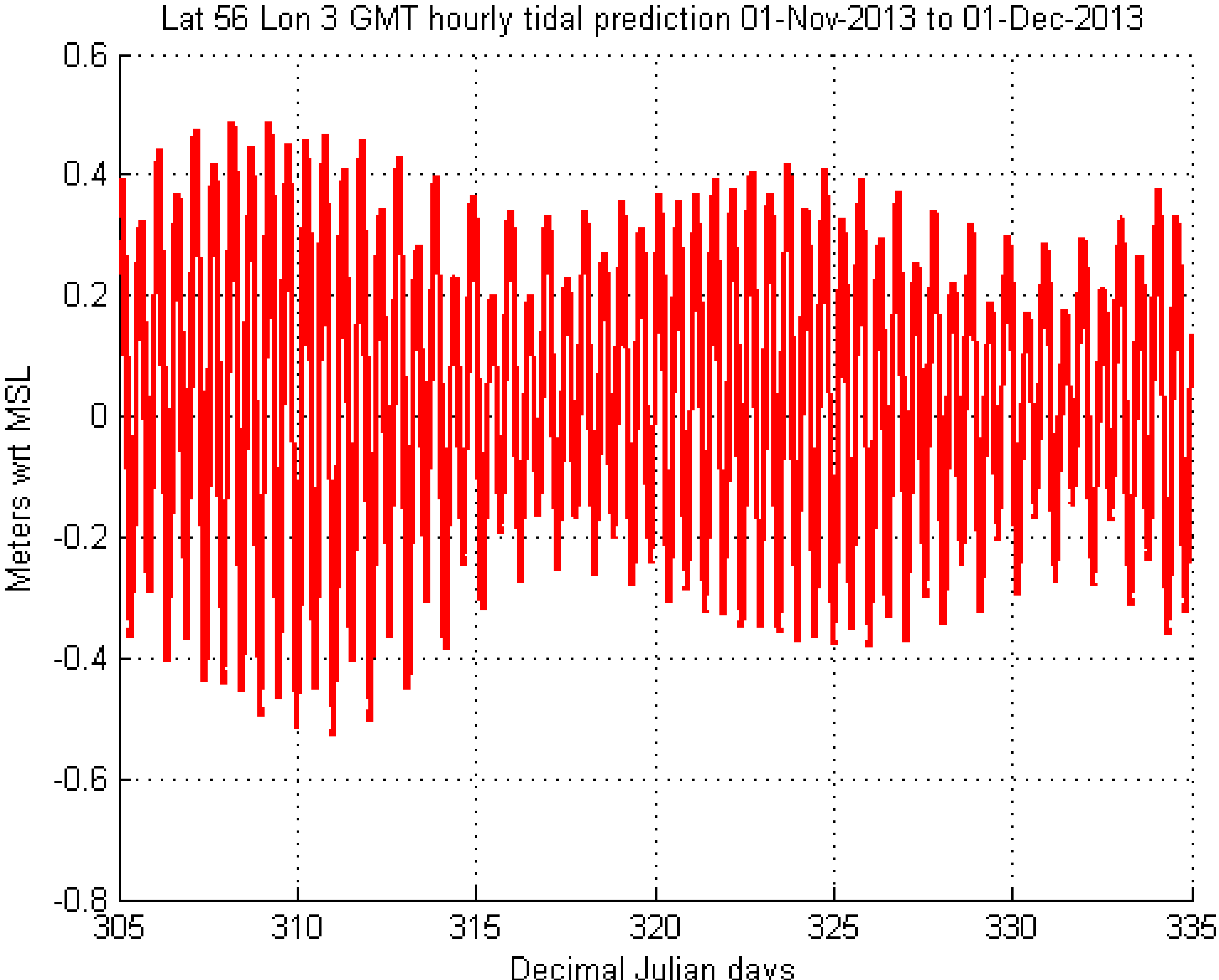
Constituent M2 Amplitude 4 (m)
32
30
28
26
24
22
20
18
Latiude
-100
-95
-90
-85
-80
Longitude
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1


Constituent M2 Amplitude 4 (m)
Latiude
Longitude
66
64
62
60
58
56
54
52
50
48
-10
-5
0
5
10
15
3.5
3
2.5
2
1.5
1
0.5


Constituent M2 Phase 4 (degrees)
Latiude
Longitude
66
64
62
60
58
56
54
52
50
48
-10
-5
0
5
10
15
150
100
50
0
-50
-100
-150

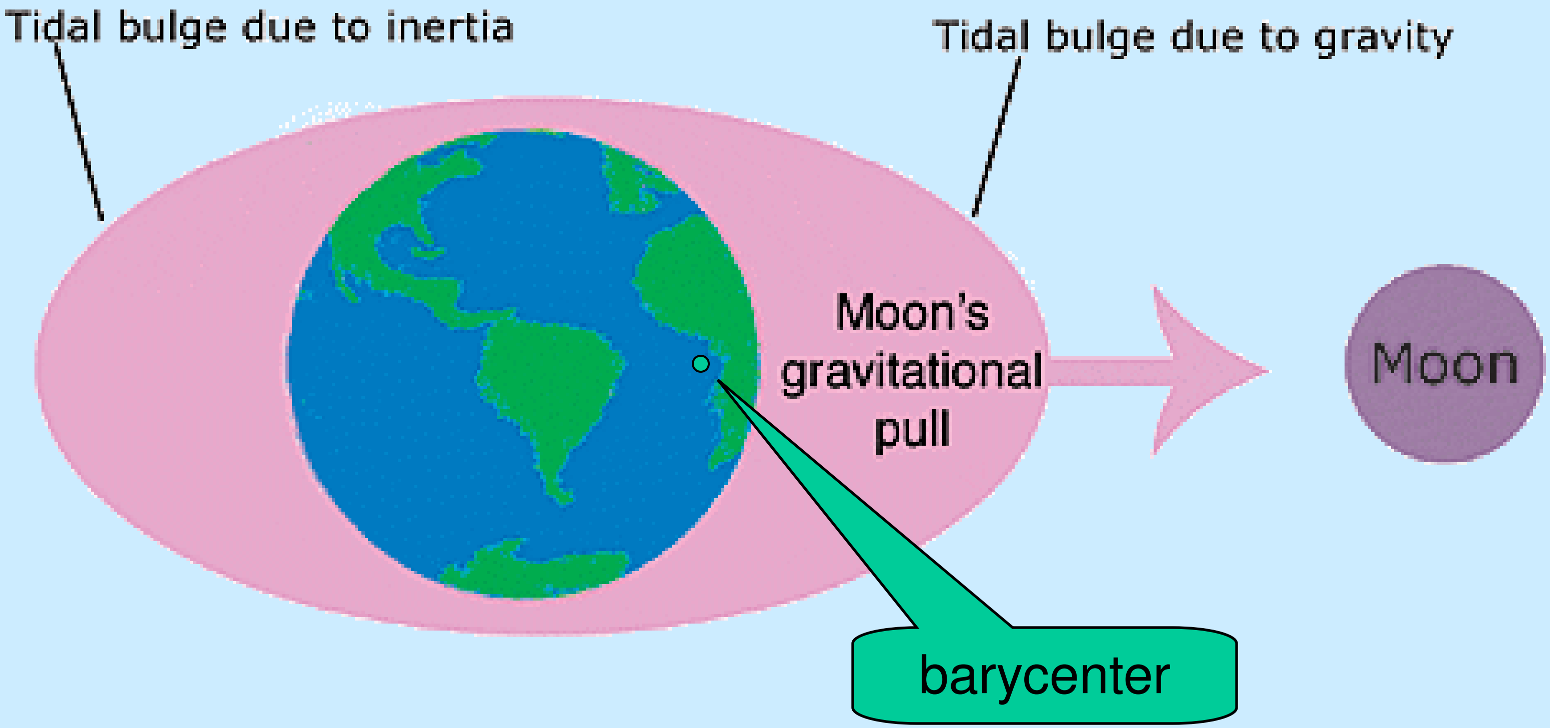

Amplified ISLW: Approximately LAT w.r.t. MSL (m)
66
64
62
60
58
56
54
52
50
48
Latitude
-10
-5
0
5
10
15
Longitude
-1
-2
-3
-4
-5
-6


C_Tides_Offline_V_1_0
C-Tides Offline
C-Nav C-Tides Offline by C&C Technologies, Inc. Output will display here. Follow these brief instructions or "Show Manual" for more info.
1 - Enter Area of Interest (AOI) and extract subsets of EGM, MSS, tidal constituents and VORF (if applicable).
2 - Plot "Surfaces" and "Constituents" as desired. Plots occupy memory and slow C-Tides. Delete them after viewing ("Close All Plots").
3 - Enter the beginning and ending dates (yyyy Jday hh) for any predictions to be run.
4 - Enter the latitude and longitude in decimal degrees for predictions and push the "Predict" button to plot then "Save As" to save.
5 - PVT1B data (slow) and common logging format data (fast) can be loaded without AOI extraction. Raw data can be replotted.
6 - The "Flush" buttons allow you to flush one prospect and load another, i.e. start over.
7 - Enter the offsets between the vessel center of gravity (COG) and the C-Nav antenna and the draft from the COG in meters.
8 - Choose a vertical reference surface (VRS). VORF (instead of MSS or EGM) is only available in the VORF area.
9 - Processing data does require AOI extraction, vessel offsets, VRS, averaging and alpha-beta parameters.
10 - Once the data are processed the "UTide" button reports harmonic analysis constituents to this screen. "Save As" saves the data.
NB - This screen can be scrolled. Output can be highlighted with the cursor, copied (ctrl-C) and pasted elsewhere.
GUI Configuration
Save Current
Read Previous
Enter AOI In Degrees, Extract Or Trim Data
North
Extract
Trim
West
East
Surfaces
South
Constituents
Choose Vertical Reference Surface
VORF
MSS
EGM08
Alpha-Beta Type, Constant & Gate
Optimum
Off
Constant
Damped
Off
Gate (m)
Averaging Period (Min)
0.5
1
5
10
www.cnav.com
Begin / End For Prediction Or Trim Data
yyyy
Jday
hh
Trim
yyyy
Jday
hh
COG To GPS And Draft (Meters)
Stbd+
COG Starboard To GPS
Fwd+
COG Forward To GPS
Up+
COG Up To GPS
Up+
COG Up To Water Beginning
Up+
COG Up To Water Ending
Use Recorded Draft If Applicable
Pitch / Roll Additive Bias (Degree)
0
Pitch
0
Roll
Switch P&R Axes And/Or Rotation Senses
Axes
Pitch
Roll
Close All Plots
Show Calendar
Lat / Lon For Prediction
Latitude
Longitude
Predict
Save As
Load PVT1B Or Common Raw Data
Load PVT1B
Load Common
Plot, Flush Or Save Raw Data
Plot Raw
Flush
Save As
Process, Plot And Save Data
Process
Plot
Save As
P&R If Applicable
UTide
Data Decimation & Granularity (Min)
0.5
1
5
10
Decimate And Save As
Show Manual



Lat 56 Lon 3 GMT hourly tidal prediction 01-Nov-2013 to 01-Dec-2013
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Meters wrt MSL
305
310
315
320
325
330
335
Decimal Julian days

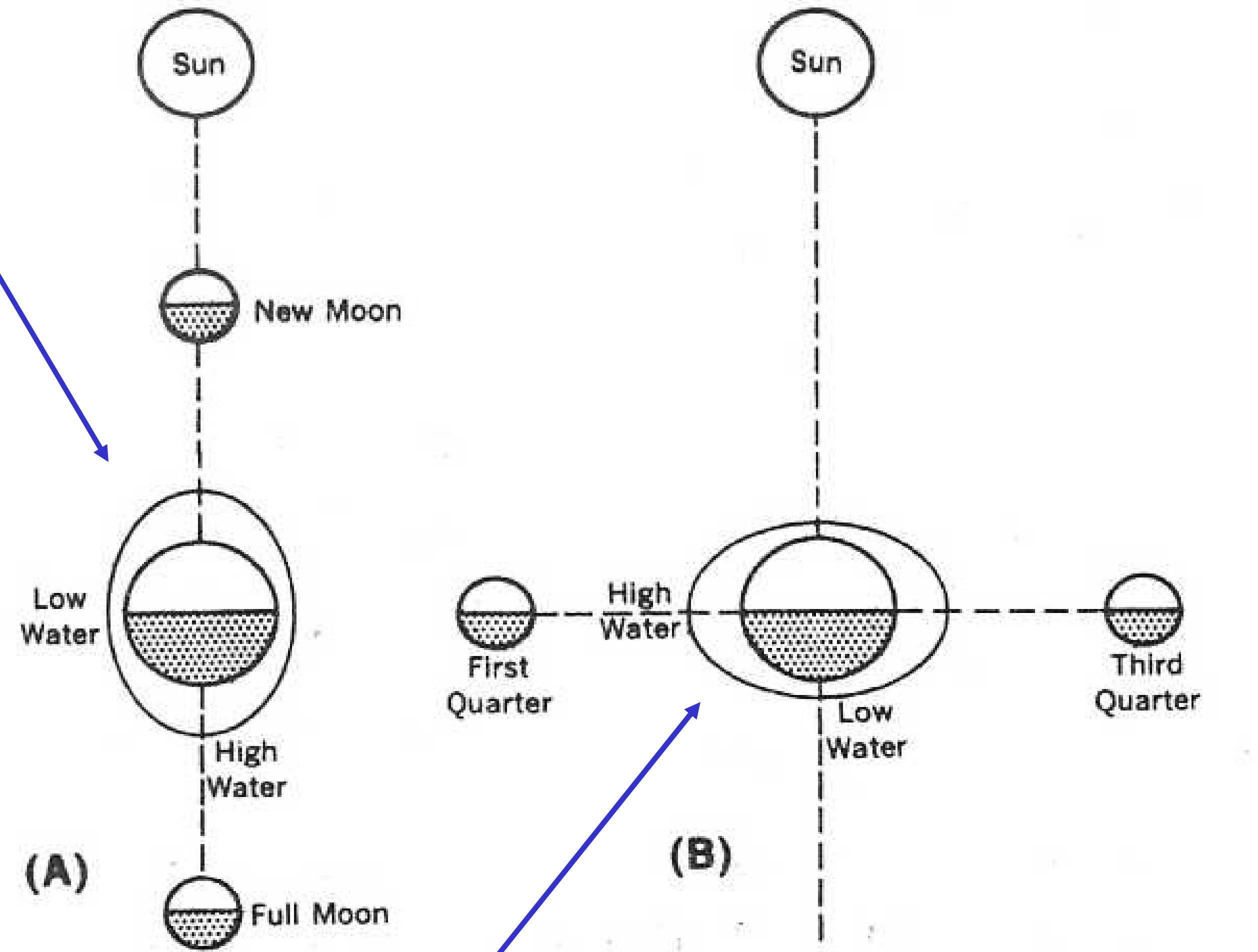
Tidal Hydrography



Because the earth-moon barycenter of rotation is not at the earth's center (actually 3/4 earth radius from the center), water accelerates toward the moon at the sub-lunar point and away from the moon at its antipode, as shown, thus producing two high tides per day.

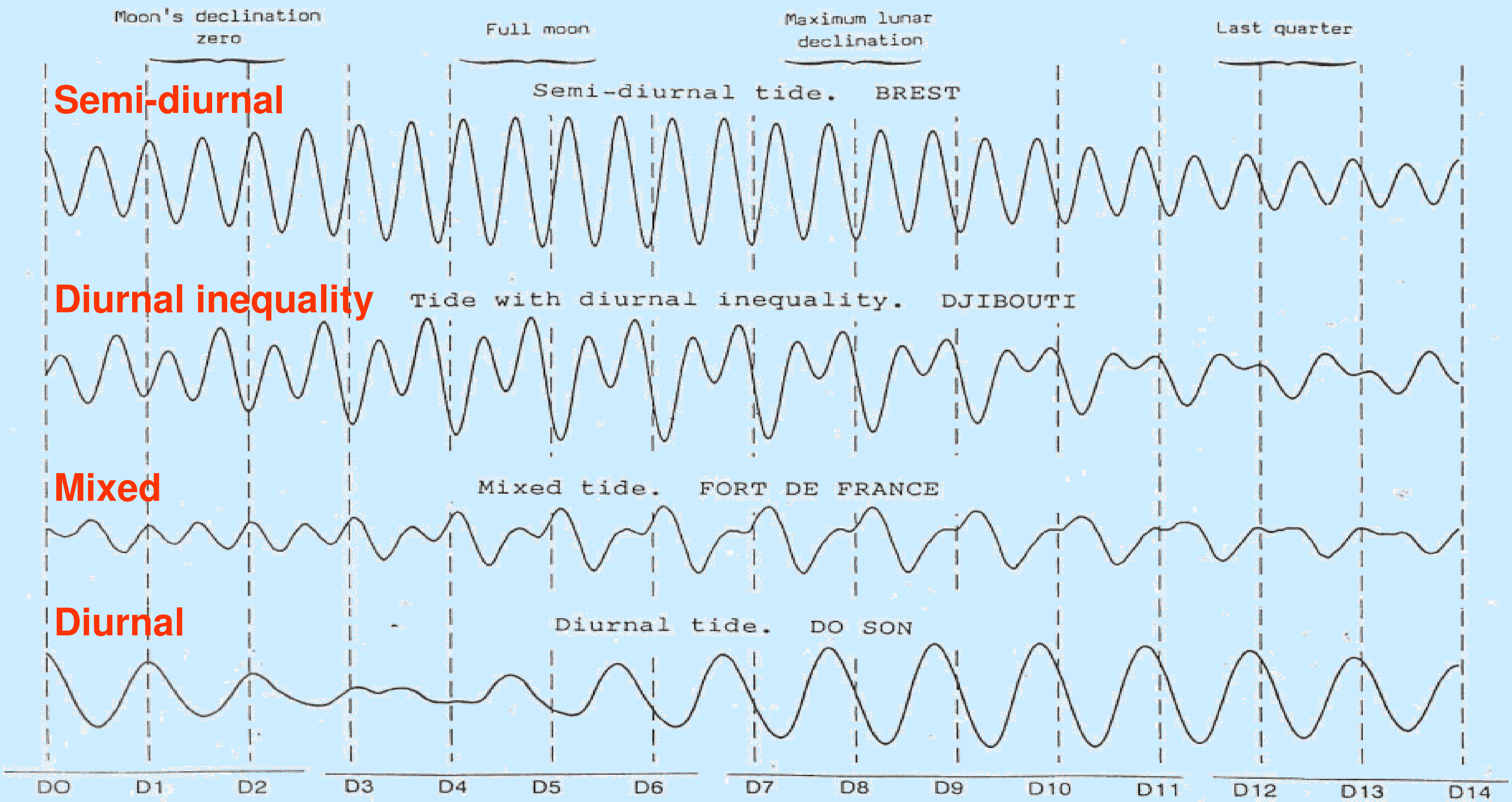
Tidal Hydrography

Spring tides (higher high water / lower low water) occur when the earth and moon are aligned at new moon or full moon (A).



Neap tides (lower high water / higher low water) occur during the first and third quarters of the moon (B).

Tidal Hydrography



Example tides resulting from these celestial mechanics and local geography for different locations in the world over a 14-day period.

WebTide

Usage Instructions

WebTide News!

Data Sets

Arctic

Halifax Harbour

Hudson Bay

Northeast Pacific

Northwest Atlantic

Quatsino Sound

Scotia-Fundy-Maine

Bras d'Or

Upper Fundy

Global

Log Files

Change Log

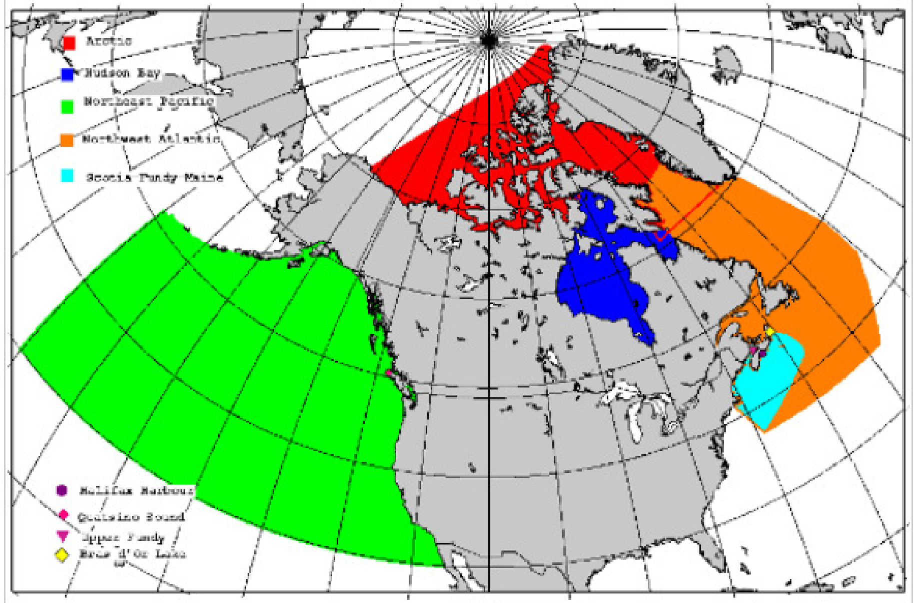
Windows Trouble Shooting

Linux/Unix Trouble Shooting

WebTide Tidal Prediction Model (v0.7.1)

WebTide is a graphical user interface for a tidal prediction program. Predictions can be obtained for any point inside a selected model domain and are based on analyses of ocean model output.

Potential users should be aware that this is still a research product and exercise due caution. This product should not be used for navigation purposes.



	includes Java VM	without Java VM	Instructions
Windows	Download (26.2M)	Download (10.6M)	View
Linux	Download (30.8M)	Download (10.5M)	View

Download Data Sets:

- Arctic
- Bras d'Or Lake
- Halifax Harbour
- Hudson Bay
- Northeast Pacific
- Northwest Atlantic
- Quatsino Sound
- Scotia - Fundy - Maine
- Upper Fundy
- Global Data

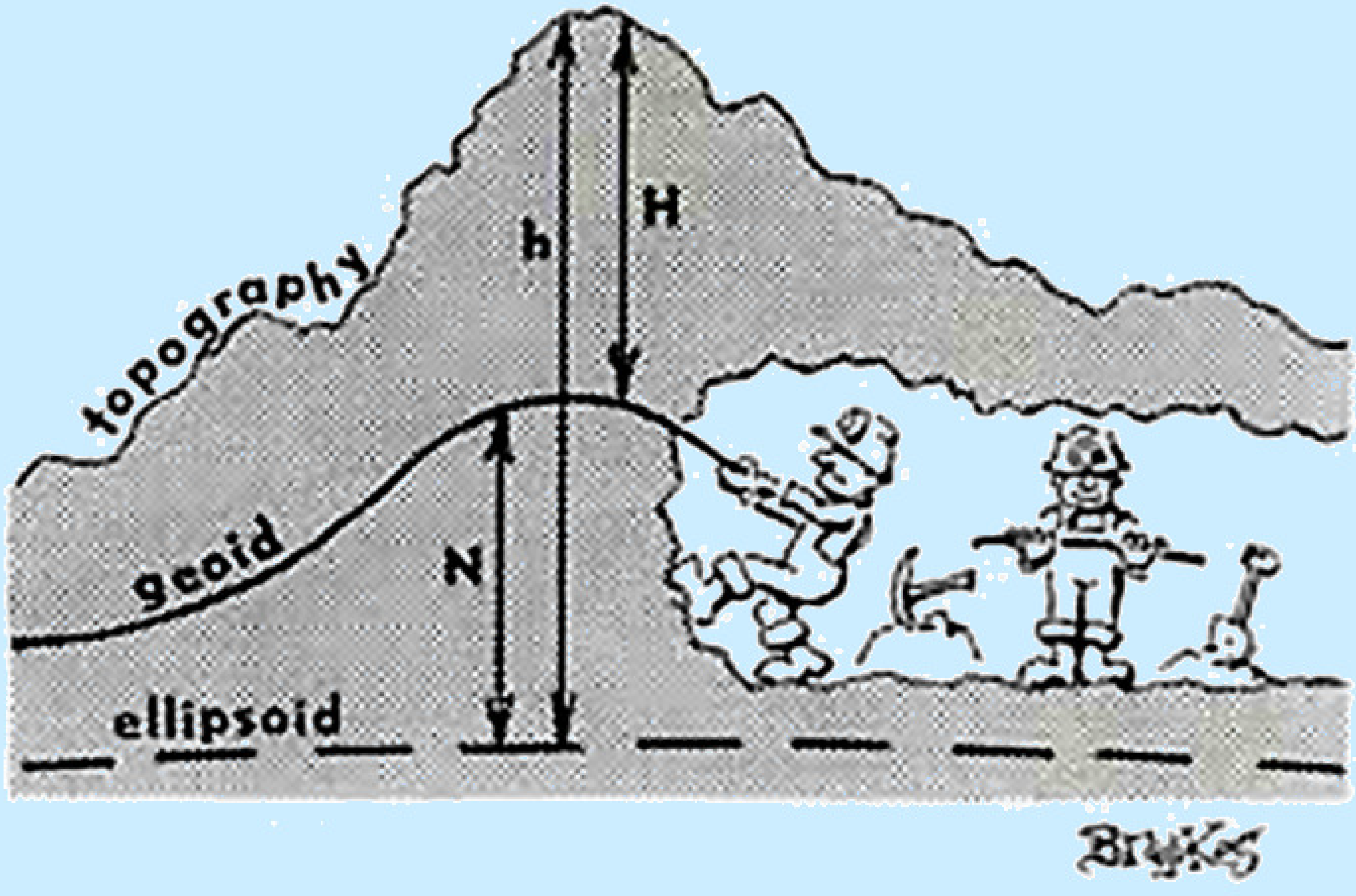
Download Log Files:

- Change Log
- Windows Trouble Shooting
- Linux/Unix Trouble Shooting

MSL to Geoid to Vertical Datum

- The geoid (W_0) approximates as Mean Sea Level
- On land the geoid is the level that MSL would take "if tunnels were bored through the land"
- The geoid is realized as a vertical datum on land
- A vertical datum is defined by the elevations of benchmarks (monuments) embedded in the land

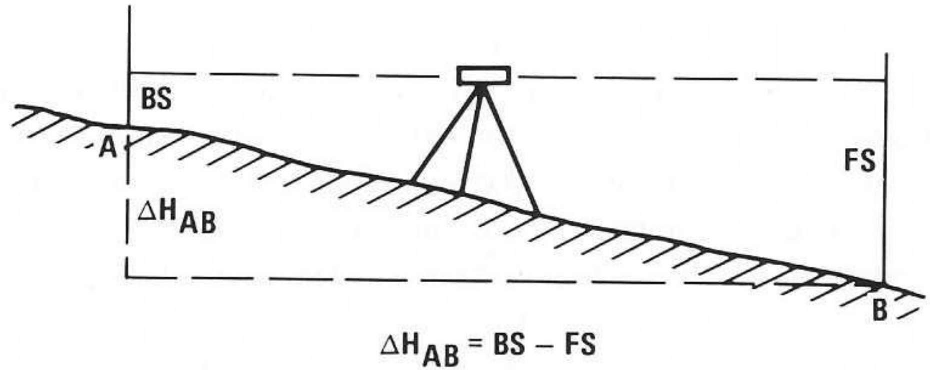
Tunneling Along the Geoid

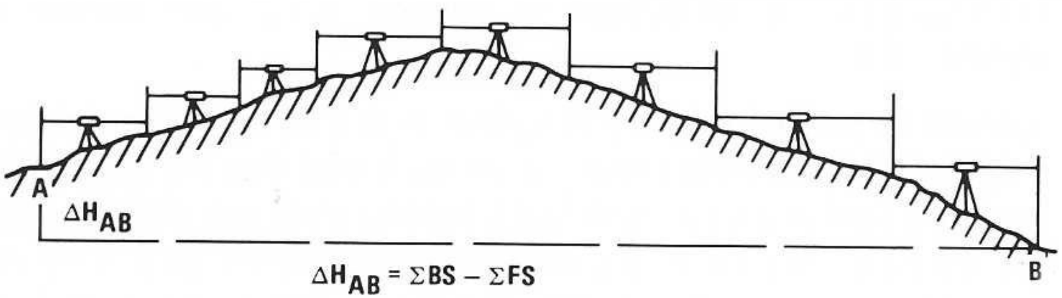


Vertical Datum Benchmark

A benchmark is a brass cap embedded in concrete, the physical embodiment of a vertical datum. A benchmark will have different elevations depending upon the vertical datum referenced.

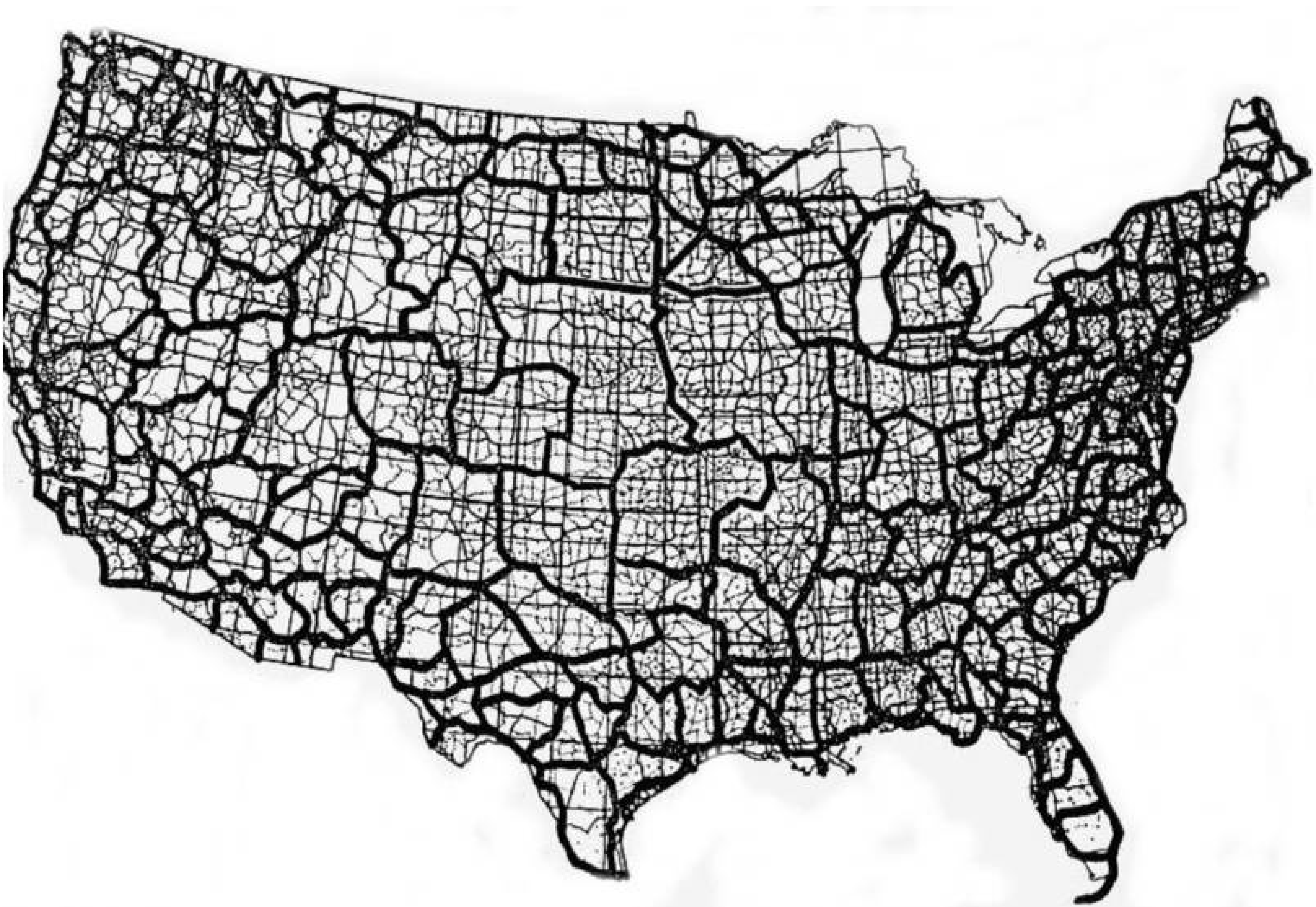
Spirit Leveling



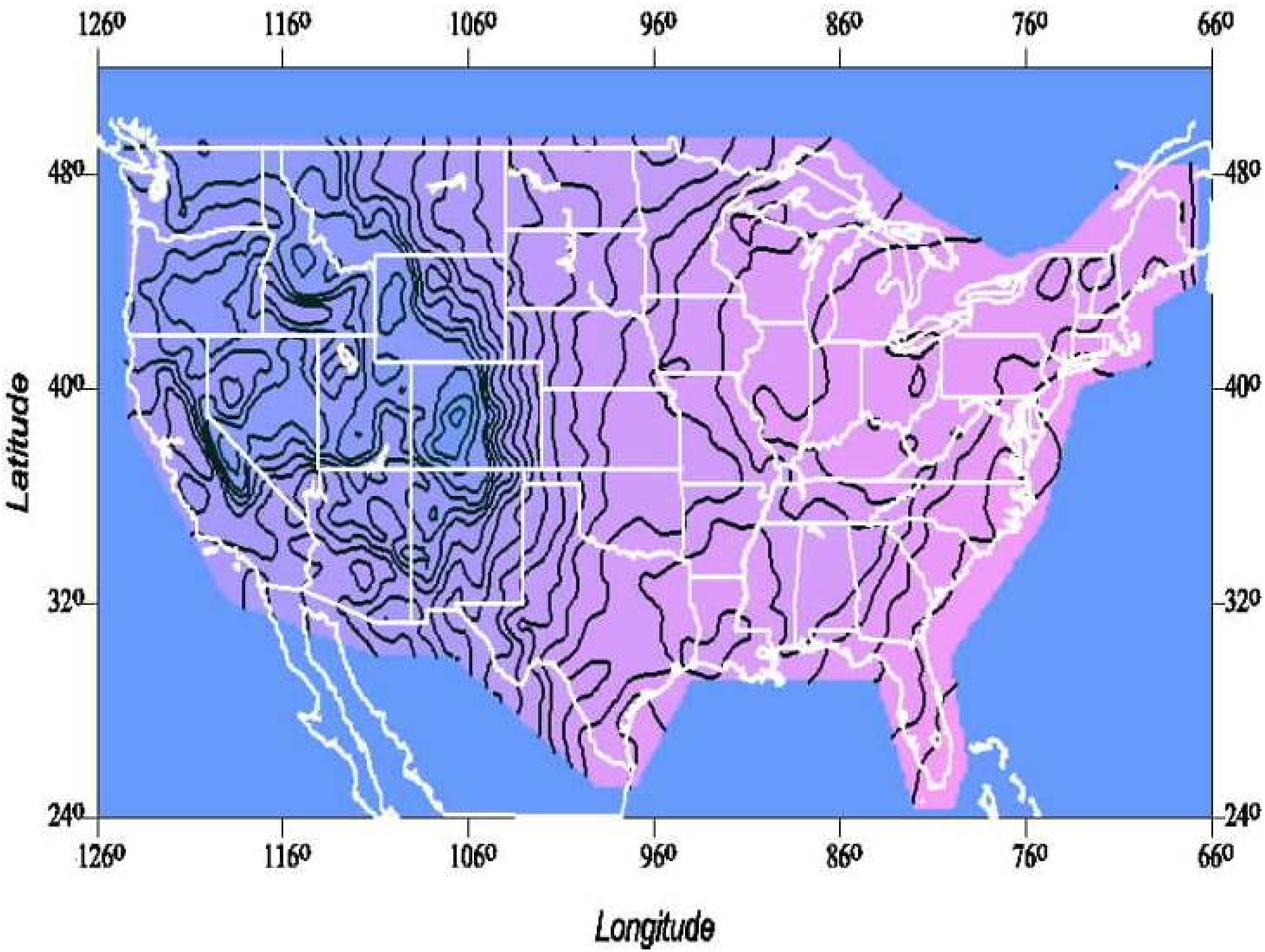


Spirit leveling is surveying in the vertical with an instrument (called a spirit level) that transfers elevations from tidal stations on one coast over the land to a tidal station on another coast in a "level net" of "level lines" with benchmarks in the ground. At key benchmarks gravity measurements are also made.

NAVD88 Level Lines



NAVD88 minus NGVD29



NGVD29 and NAVD88 define heights differently

Some Vertical Datums Elsewhere

- Australian Height Datum
- Bandar Abbas, Fao (Iran)
- Caspian (Azerbaijan, etc.)
- DHHN85 & 92 (Germany)
- EGM2008 (Whole World)
- EVRF2000 (Europe)
- IGLD 1985 (Great Lakes)
- KOC WD (Kuwait Wells)
- Kuwait PWD (Kuwait)
- Lagos 1955 (Nigeria)
- Lerwick (UK)
- MSL (Oceans of the World)
- NGVD29, NAVD88 (USA)
- NN54 (Norway)
- Normaal Amsterdams Peil (Netherlands)
- PDO Height Datum 1983 (Oman)
- Yellow Sea, Yellow Sea 1956 & 1985 (China)
- The EPSG dataset lists more than 128 vertical datums worldwide. Some countries have more than one vertical datum.

Vertical Datum Modeling

- The US National Geodetic Survey provides software applications to transform among NGVD29, NAVD88, the geoid, tidal datums and NAD83 ellipsoid height
  - VERTCON, GEOID09, GEOID03, USGG2003, GEOID99, G99SSS, G99BM, CARIB97, MEXIC097, DMEX97, VDatum and **GRAV-D (2022)**
- Other governments provide similar software for their vertical datums
- In the absence of country-specific modeling software, Earth Gravity Model 2008 (EGM08) can be applied to orthometric heights to produce WGS84 ellipsoidal heights … or vice versa

Vertical Datum Types

- The vertical is defined differently in different vertical datum types
- Common definitions are:
  1. Geopotential number C_P in GPUs
  2. True orthometric heights (a variation of C_P)
  3. Dynamic heights (a variation of C_P)
  4. Normal orthometric heights (a variation of C_P)
  5. Helmert orthometric heights (a variation of C_P)
  6. Normal heights

(1) Geopotential Numbers

- Geopotential numbers (C_P) are expressed in geopotential units (GPUs) seen earlier
- If W_0 is the geopotential of the geoid, W_A the geopotential of point A, *h* the height of point A and *g* is the acceleration of gravity, the geopotential number of point A is:

$$C_P = W_0 - W_A = \int_0^A g(\phi, h) \cdot dh$$

(1) Geopotential Numbers

- The geopotential unit (GPU) of C_P is:
  - 1 GPU = 10 meter^2/second^2 = 1 kgal·meter
- Advantages:
  - All points on water have the same GPU
  - Spirit leveling loops will "close" regardless of route
- Disadvantages:
  - GPU differs numerically from elevations by 2%
  - GPU is an unusual unit (kgal-meter)

(2) True Orthometric Heights

- But … true orthometric heights result by dividing the C_P by mean gravity along the plumb line from the topography to the geoid
- But … since mean gravity cannot be measured, in most vertical datums the C_P is divided by some estimate or function of surface gravity in order to approximate an orthometric height

(3) Dynamic Heights

- Dynamic heights result by dividing geopotential numbers by the same standard gravity value
- For example, the International Great Lakes Datum of 1985 (IGLD 1985, US and Canada) uses dynamic heights and an acceleration of gravity of 9.806199 m/s^2 defined at 45° North on the GRS80 ellipsoid (NAD83)
- Dynamic heights preserve water levels, but they differ slightly from orthometric heights

(4) Helmert Orthometric Heights

- Helmert orthometric heights result by dividing geopotential numbers by an estimate of the mean gravity along the plumb line
- The estimate is called Prey reduction and it is based upon surface gravity (*g*) and an assumed crustal density and free-air gravity gradient

$$H = C_P / (g + 0.0424 H)$$

- NAVD88 is in Helmert orthometric heights

(5) Normal Orthometric Heights

- Normal orthometric heights result by dividing geopotential numbers by "normal gravity"
- Bomford gives this formula (with modified units) for normal gravity as a function of latitude, height and the radius of the earth (*R*):

$$\gamma_h = 9.78(1 + 0.0053\sin^2\phi - 2h/R)m/s^2$$

- NGVD29 is in normal orthometric heights

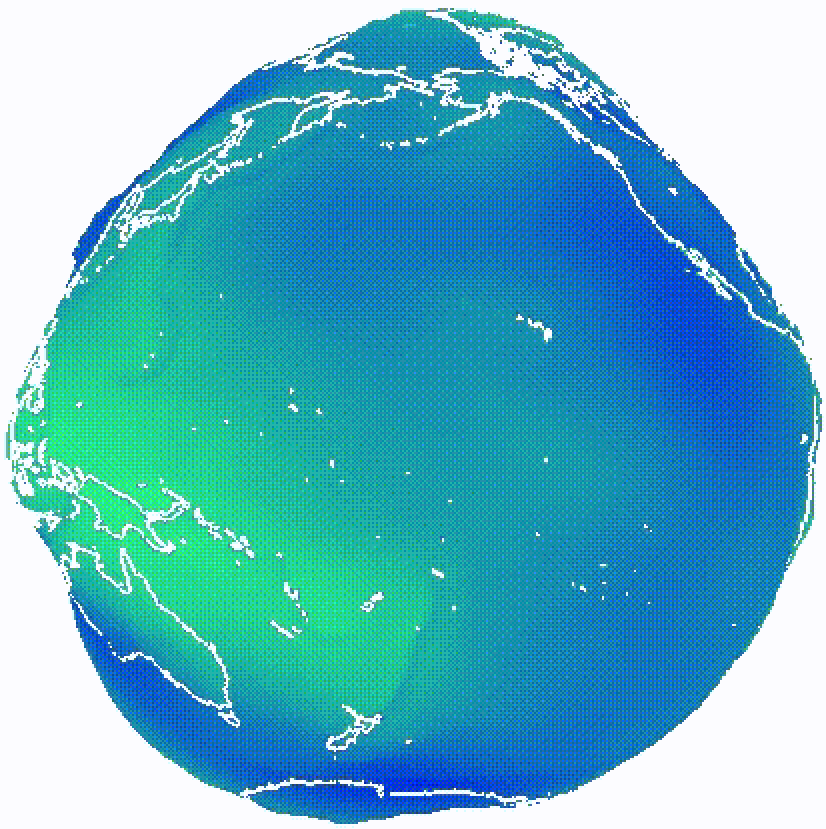
(6) Normal Heights

- Normal heights are based upon the gravity theory of Molodensky and upon two additional earth surfaces, the quasi-geoid and the telluroid
- Normal heights are used in the former Soviet Union countries, in Eastern Europe, and are being adopted in Western Europe
- Normal heights correspond to orthometric heights over the oceans and at low elevations, but differ by up to 2 meters in high elevations

Why Should I Care?!?

- Sun/Moon ⇨ Tides ⇔ Geoid ⇔ Vertical Datums
- Vertical datums types are well described
- Including vertical datum audits along with horizontal datum audits is desirable in the oil patch
- Modeling software transforms between orthometric and ellipsoidal heights
- Ellipsoidal height, latitude and longitude are just a conversion from ECEF (Earth-Centered Earth-Fixed)
- ECEF supports undistorted visualization in 3D

Here’s Why: Undistorted 3D Visualization

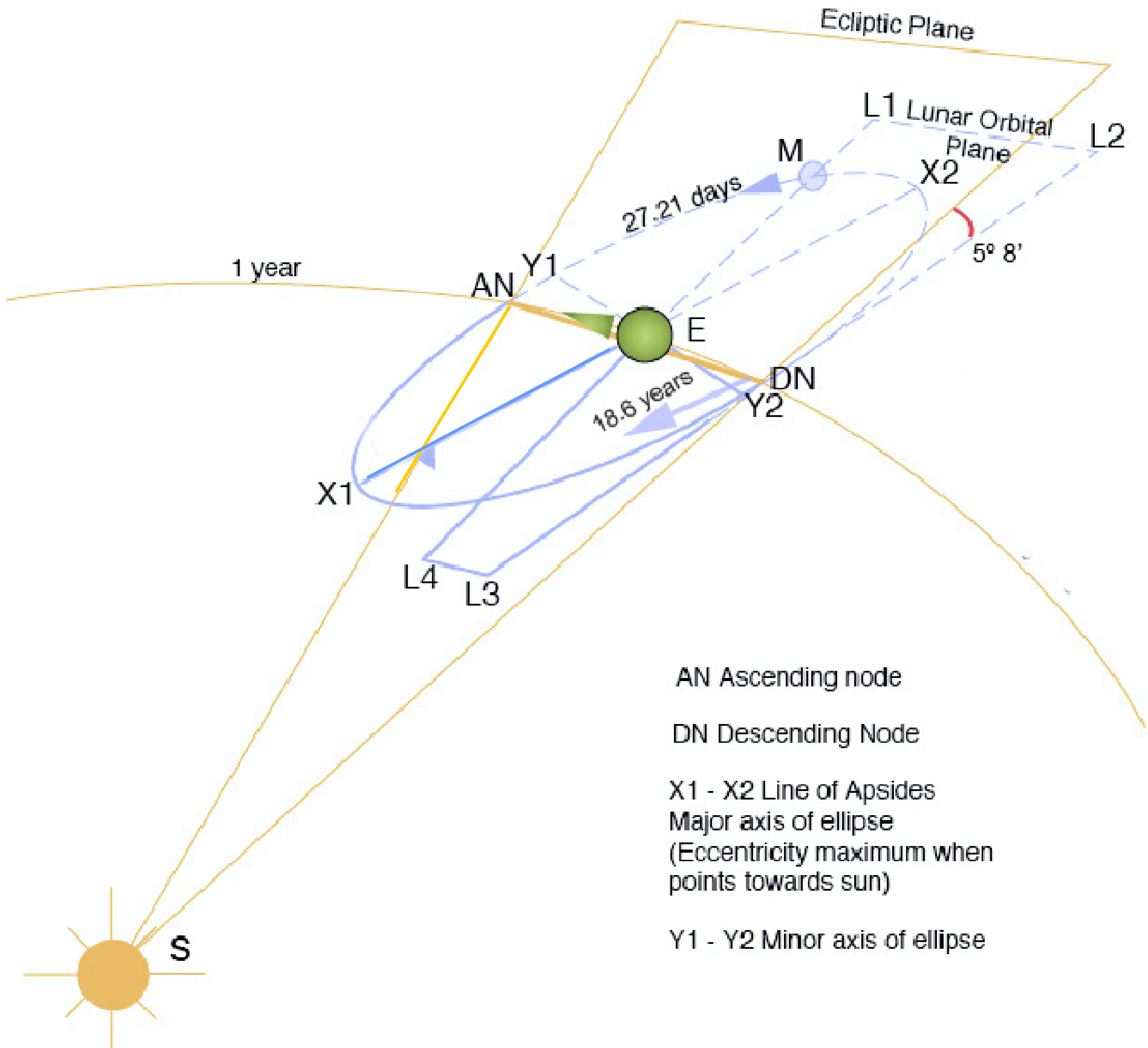


References

- Bomford, “Geodesy”, 1980
- Bowditch, “American Practical Navigator”, 1977
- Hoar, “Satellite Positioning”, Magnavox, 1982
- Service Hydrographique et Oceanographique de la Marine, “Manual of Hydrography”, 1984
- Vanicek and Krakiwsky, Geodesy: The Concepts, 1987
- Wikipedia
- Graphics from various DMA/NIMA/NGA and NOAA/NGS presentations on the web
- WebTide: http://www.bio.gc.ca/science/research-recherche/ocean/webtide/index-eng.php

Extra Slides

Lunar Nodal Period of 18.6 Years



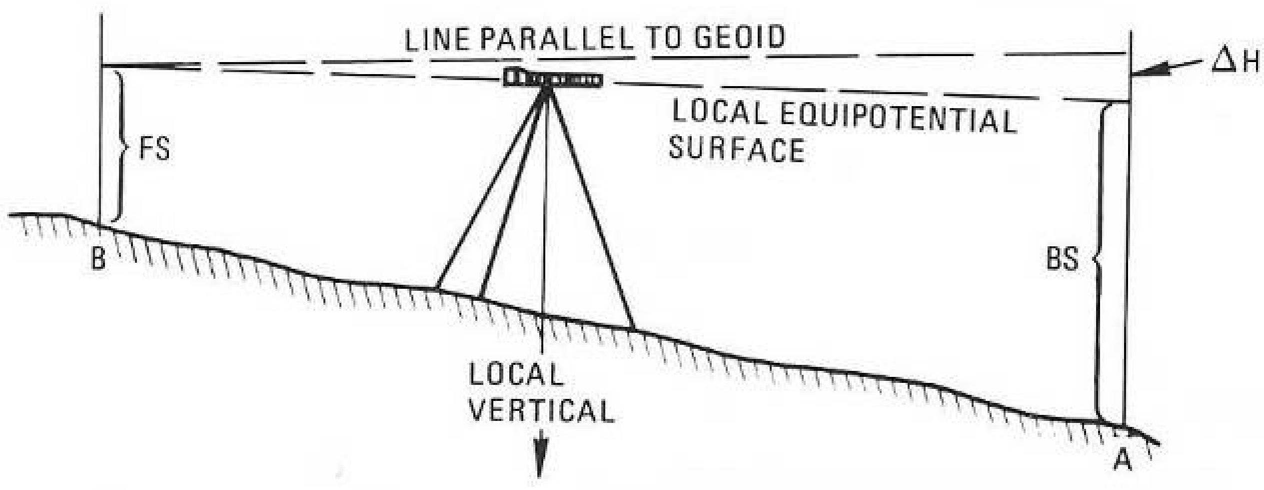
The Lunar Orbital Plane (LOP) is inclined with respect to the Ecliptic Plane (EP) by 5°8'. The LOP rotates inertially with respect to the EP in an 18.6 year period.

Therefore, to catch all possible positions of the moon, one must observe the tides for 18.6 years.

Normal Orthometric Heights: An Alternative Approach

- In the absence of geopotential numbers, normal orthometric heights can be computed by applying the "orthometric correction" to a spirit level line from a known benchmark
- The orthometric correction is also based upon normal gravity and is exhibited in the next slide

Orthometric Correction



Hoar gives the following for the orthometric correction (ΔH), where H is the average elevation of the line, ϕ is the average latitude of the line and $\Delta\phi$ is the difference in latitude in radians

$$\Delta H = H(0.0053 \sin 2\phi)\Delta\phi$$

Vertical Datums in North America

National Geodetic Vertical Datum of 1929 [NGVD 1929]
A fixed reference adopted as a standard geodetic datum for elevations determined by leveling. The datum was derived for surveys from a general adjustment of the first-order leveling nets of both the United States and Canada. In the adjustment, mean sea level was held fixed as observed at 21 tide stations in the United States and 5 in Canada. The year indicates the time of the general adjustment. A synonym for Sea-level Datum of 1929. The geodetic datum is fixed and does not take into account the changing stands of sea level. Because there are many variables affecting sea level, and because the geodetic datum represents a best fit over a broad area, the relationship between the geodetic datum and local mean sea level is not consistent from one location to another in either time or space. For this reason, the National Geodetic Vertical Datum should not be confused with mean sea level.

North American Vertical Datum of 1988 [NAVD 1988]
A fixed reference for elevations determined by geodetic leveling. The datum was derived from a general adjustment of the first-order terrestrial leveling nets of the United States, Canada, and Mexico. In the adjustment, only the heights of the primary tidal bench mark, referenced to the International Great Lakes Datum of 1985 (IGLD 1985) local mean seal level height value, at Father Point, Rimouski, Quebec, Canada was held fixed, thus providing minimum constraint. NAVD 1988 and IGLD 1985 are identical. However, NAVD 1988 bench mark values are given in Helmert orthometric height units while IGLD 1985 values are in dynamic heights.