C-Tides

GNSS Technology for the Determination of Real-Time Tidal Information

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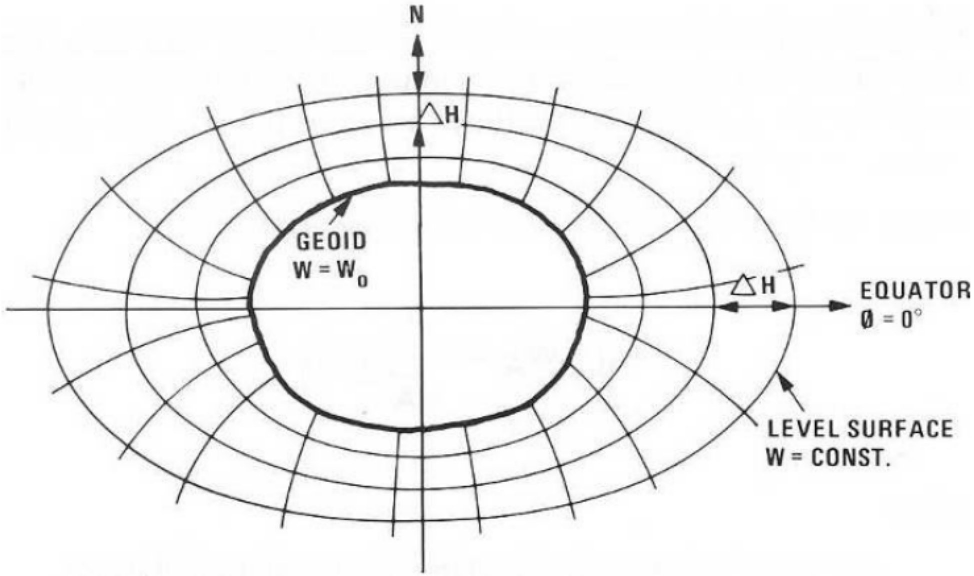
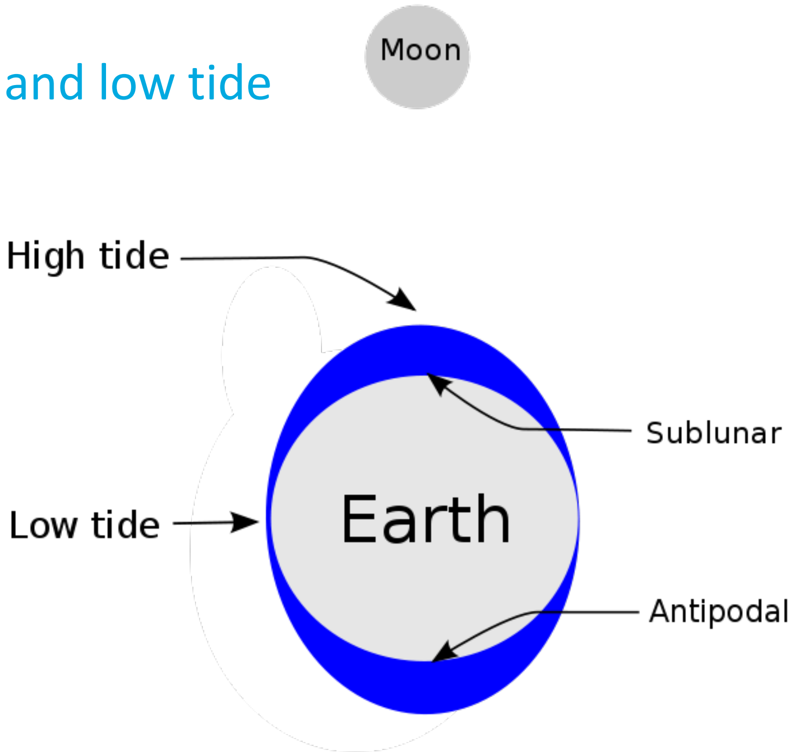
Offshore Survey & Positioning - 12th December 2013

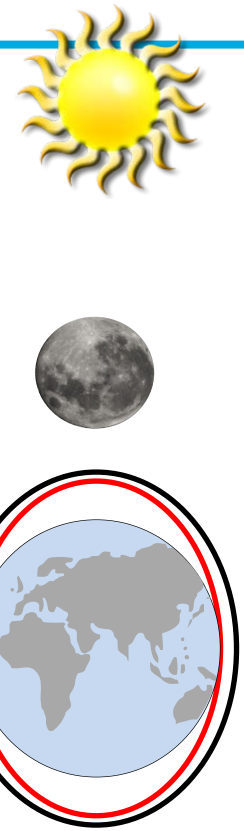
Stavanger, NORWAY

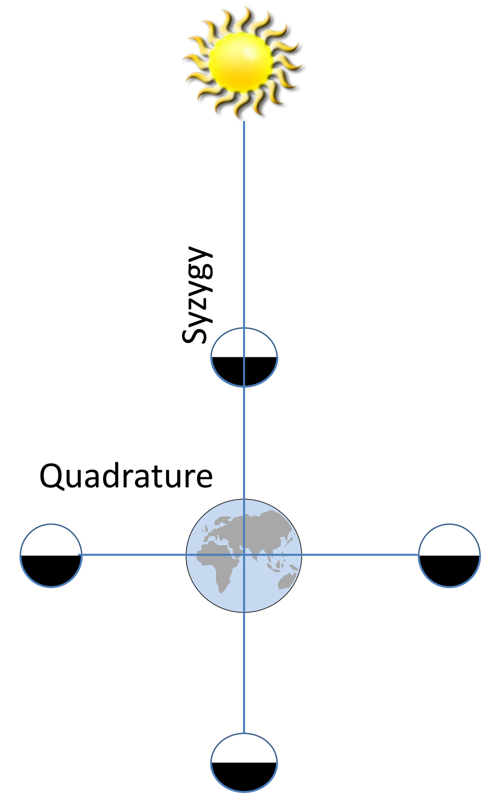


- Gravity defines the vertical in the real world
- Equipotential (geopotential) is constant (W)
- Neither parallel or equally spaced
- Vertical is perpendicular to the equipotential (gravity vertical is curved)
- Surface whose geopotential (W) is the same as the geopotential of MSL (W_0) is called the geoid

- Tides are very long-period waves that move through the oceans in response to forces exerted by the moon and sun
  - Gravitational forces of the moon and sun create areas of high and low water on the earth's surface
  - As the earth rotates the location of high and low tide changes
  - The moon has the greatest effect on the water compared with the sun due to it's proximity to the earth



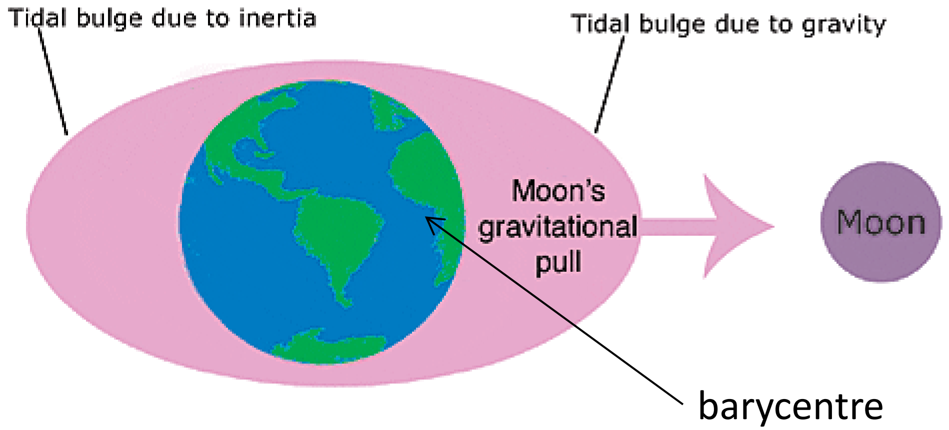



Syzygy
Quadrature

Introducing Tidal Datums

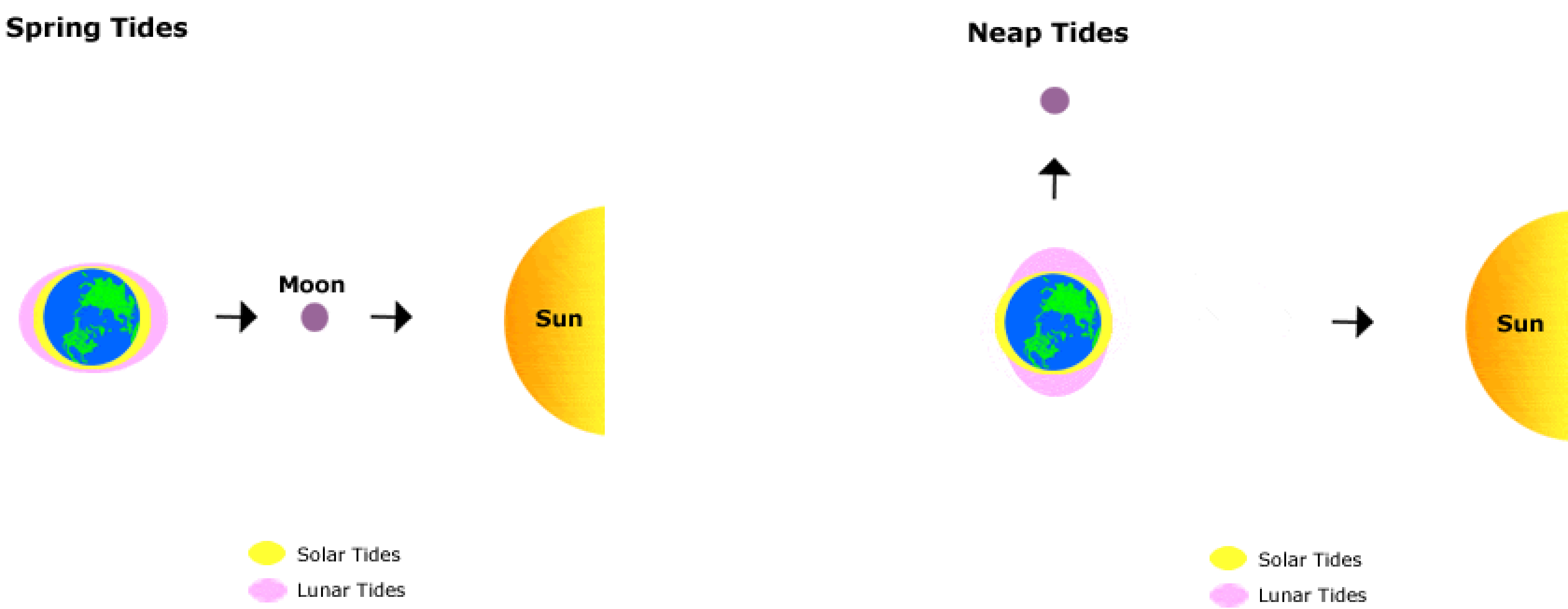
- The geoid is that horizontal equipotential surface that approximates Mean Sea Level (MSL), which, due to mean ocean dynamics is not horizontal
- MSL is a tidal datum. It is the average water level observed at a tide gauge over the 18.6 year precession of the lunar orbital plane w.r.t. The ecliptic 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

Gravity, Inertia, and the Two Bulges



- Barycentre is the centre of mass of the earth-moon system
- Three quarters of an earth radius from the centre of the earth
- The moon rotates around the barycentre, not the earth centre
- The gravitational effect of the moon raises the tide on the side of the earth facing the moon
- Centrifugal force is greater on the side of the earth opposite the moon, this creates a second high tide

Tidal Variations



- Spring Tide when earth, sun and moon are aligned
- Neap Tide when earth-moon and earth-sun are perpendicualr

Meteorological and Local Effects

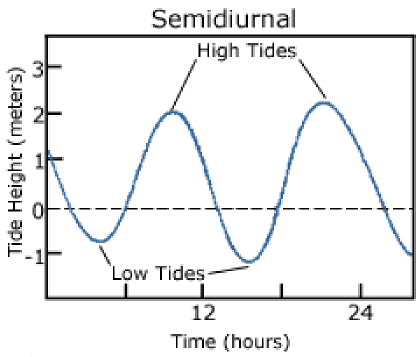
But nothing is ever simple at sea…
The so-called astronomical tide (the tide due to the tide raising forces of the Sun and Moon, Earth's gravity field etc) will at best be idealisations.

Additional to the astronomical forces are local and regional effects including:

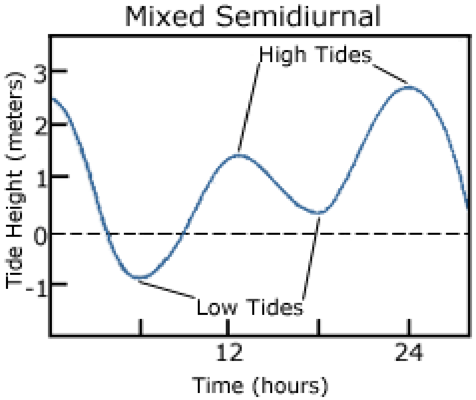
- Atmospheric pressure
- Pressure differentials
- Wind speed and direction (fetch)
- Water depth variations (friction)
- Coastal geography induced anomalies
- Basins and impounding features
- Amphidromes

The list is almost endless… its to allow for these complexities that knowledge of the tide regime is so important…

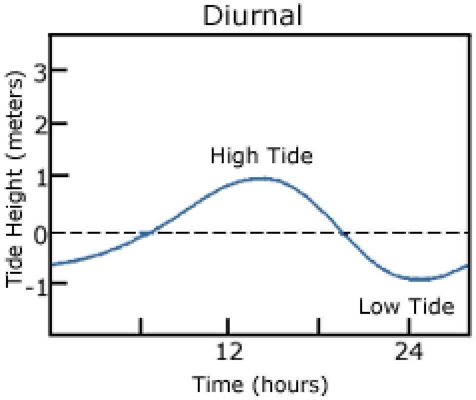
Tidal Phases



- Semidiurnal, two high tides per day



- Mixed Semidiurnal, high and low tides differ in height



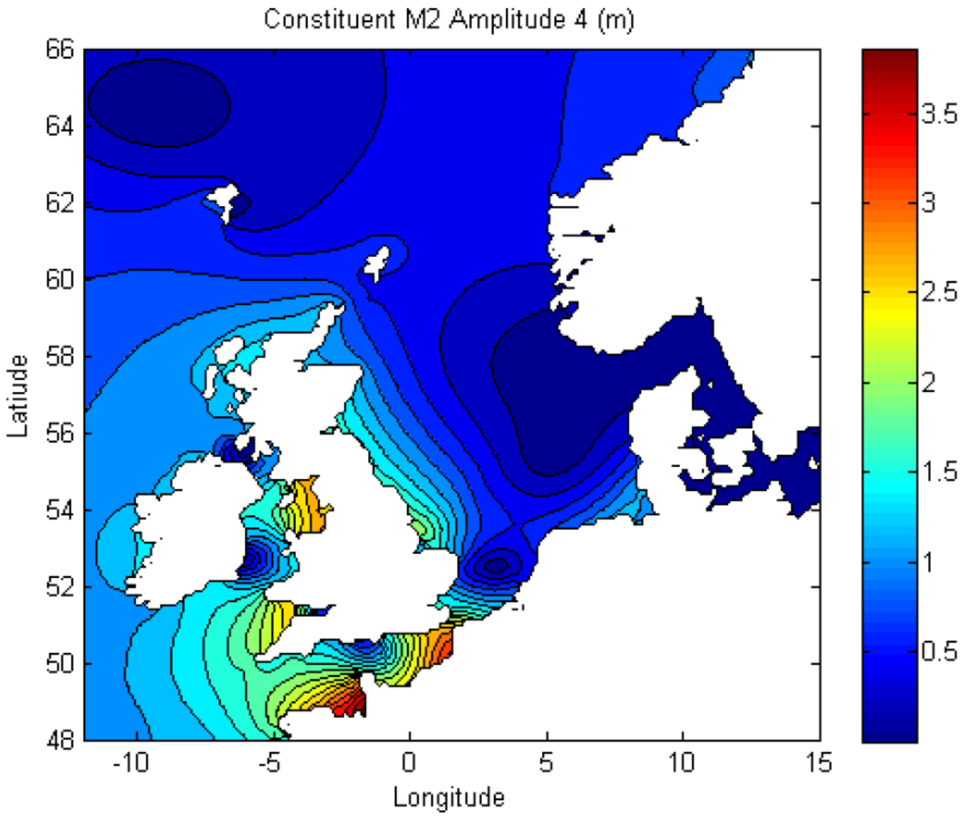
- Diurnal, one high tides per day

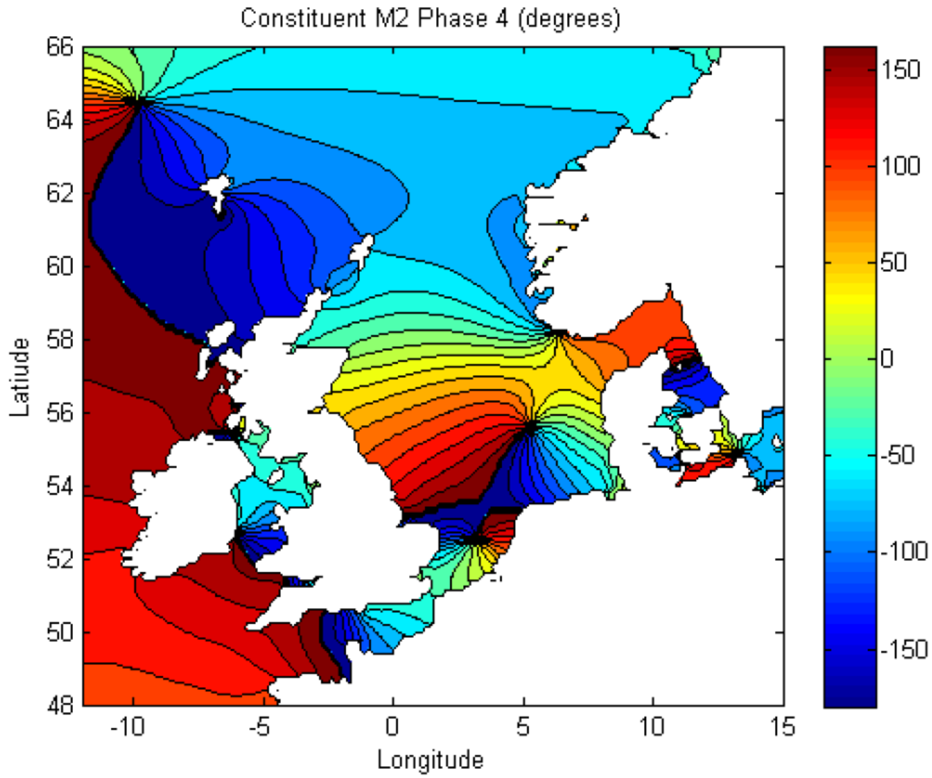
Tidal Constituents

- 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)

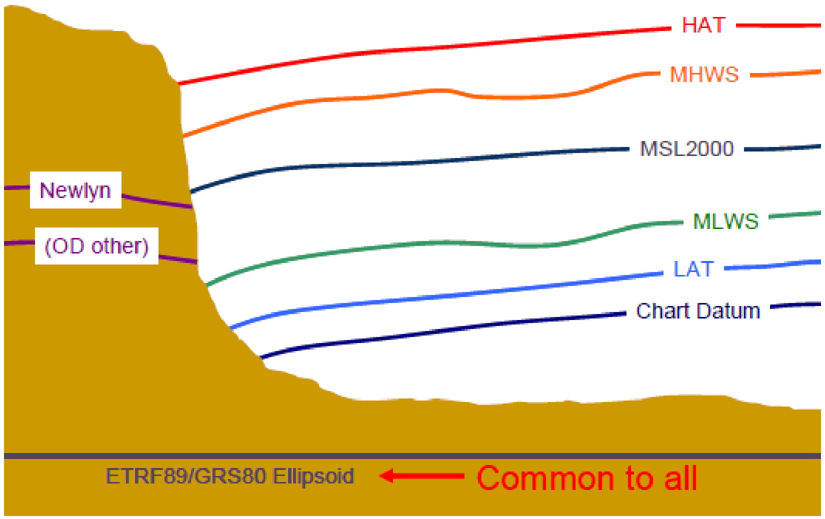
CONSTITUENT	CYCLES PER DAY	SPEED (DEGS PER HOUR)	TIME TO COMPLETE ONE CYCLE
M2	2	28.98	12hr 25min
S2	2	30.00	12hr 00min
K1	1	15.04	23hr 56min
O1	1	13.94	25hr 50min

Tidal Constituents



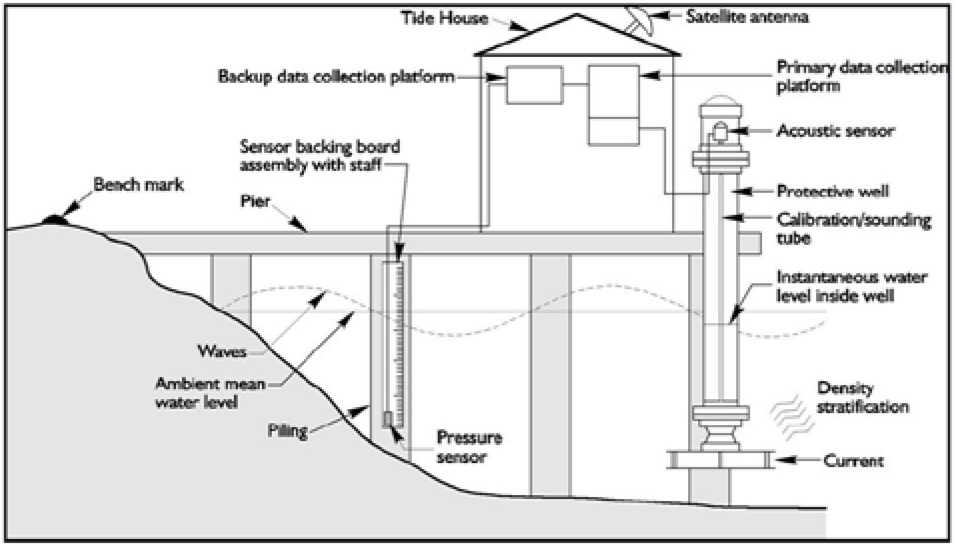


C-Tides



- HAT/LAT – the highest and lowest levels respectively which can be predicted under average meteorological conditions
- MHWS/MLWS – the average of the height of two successive high waters during those periods of 24 hrs (approx. once per fortnight)
- MSL – the average level of the sea surface over a long period, normally 19 years
- CD – often defined as by the LAT observed over a certain time period. A common outcome from a survey is a chart showing depth of water below Chart Datum.
  The chart seeks to express the minimum depth of water available to the mariner for the purposes of navigation

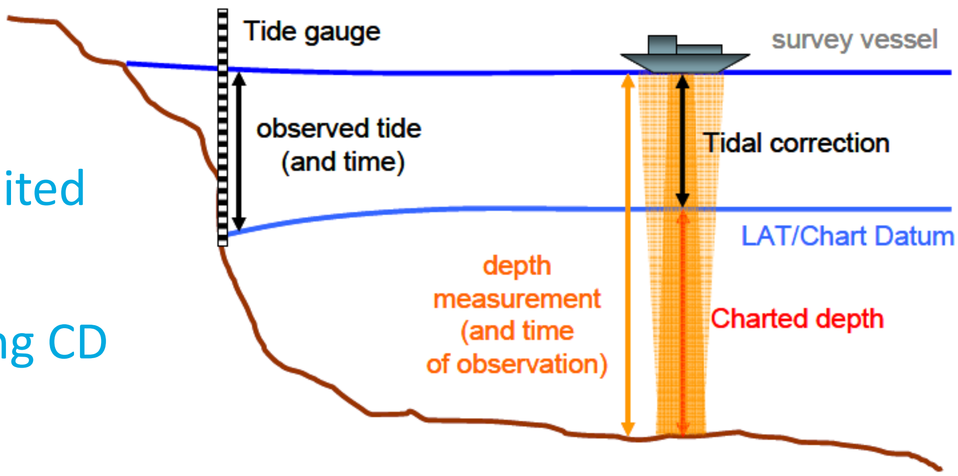
- Tide poles or tide staffs
- Mechanical Float and Stilling Well gauges (self-recording)
- Pressure gauges (bubbler gauges)
- Acoustic gauges
- Radar gauges



- Pressure sensor (not requiring a fixed datum)
  - Easiest use offshore
  - Robustness and validity of measured tide
  - Any acquisition problems only highlighted after recovery
  - High risk of loss of the instrument
- Tide gauges used indirectly through tidal predictions
  - Can't account for local environment (surge, atmosphere)
- Tidal prediction software (e.g. POLPRED)
  - Can't account for local environment (surge, atmosphere)
  - Only access regional portions of predicted tides per license
  - Easy to operate

Conventional Bathymetric Processing

- Tidal correction must be applied to reduce the soundings to CD
- Coastal tide gauge and co-tidal charts
  - Co-tidal chart to correct the observed coastal tide variations for change in phase and amplitude of tide between the station and the survey vessel
- Drawbacks
  - Synchronised operations
  - Latency (two observation sets married together)
  - Accuracy (co-tidal charts have a limited resolution, paper product)
  - Inconsistency (survey practices using CD are poorly defined)

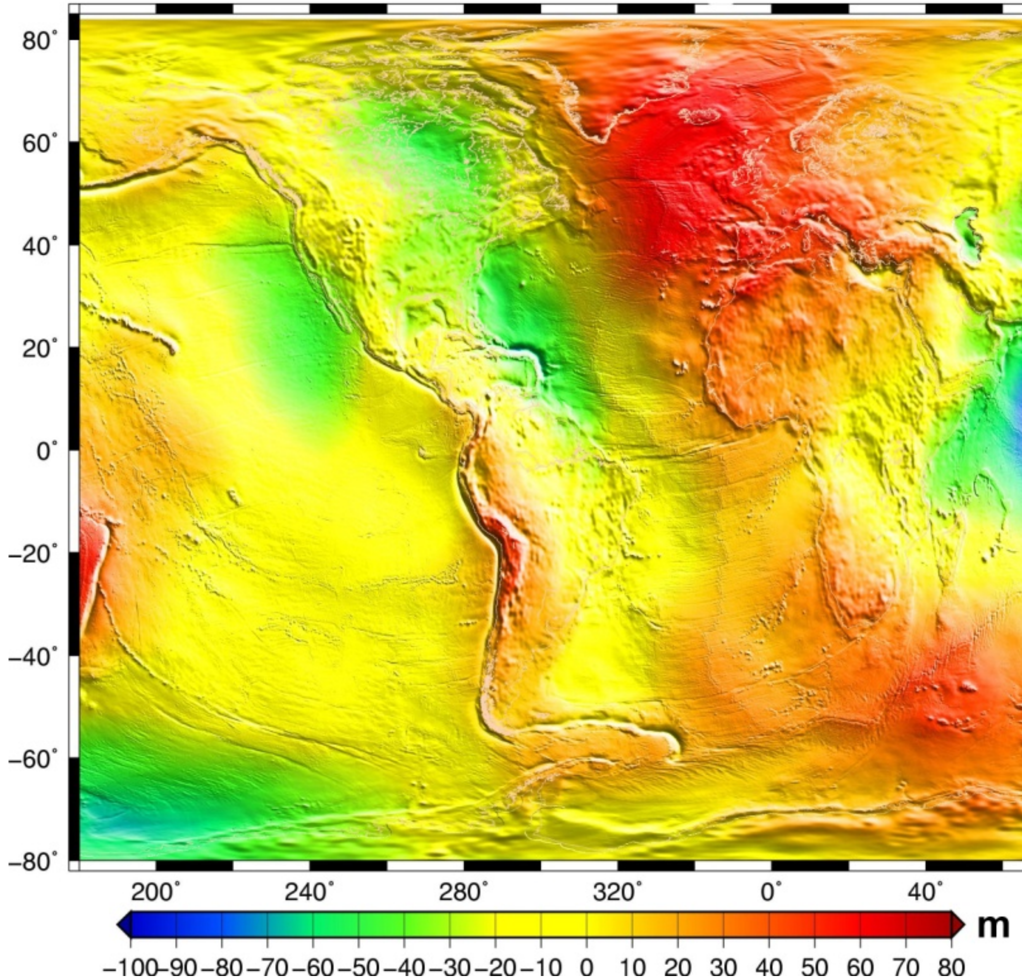


Sea Level from Space

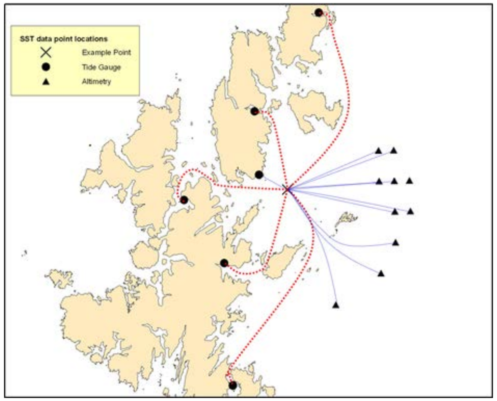
- Using satellites, we can measure sea level over almost the entire ocean
- Two kinds of measurement are needed to determine sea level
  - Position of sea surface (radar altimetry using two way travel time and precise tracking of the satellite)
  - Accurate measurements of the Earth's gravity field or height associated with Gravity to find the position of a level surface known as the geoid

MSS/MSL

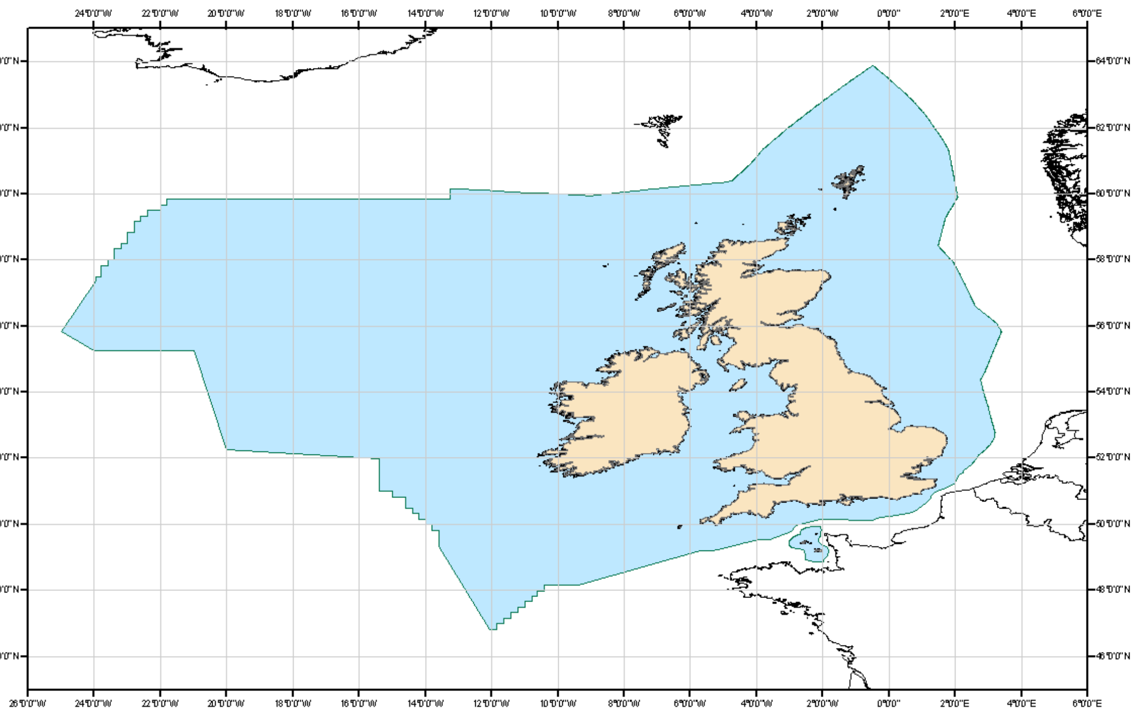
- Relationship between local vertical levels (CD, LAT or MSL) and the ellipsoid (GNSS)
- Two kinds of surface models can be used worldwide
  - **Geoid** – equipotential surface of the Earth's gravity field tending to coincide with MSL. Coincidence is exact if the oceans and the atmosphere were in a complete state of equilibrium
  - **MSS** – derived from altimetry, the height of the free surface of the oceans. Average level of ellipsoid corresponding to observation period of the model.
    - Altimetry values only valid a respectable distance from the coast ~10km
    - Integrate Geoid models in to the calculations
    - Affected by currents, wind and atmosphere – Dynamic Ocean Topography (DOT)
    - DOT mathematically corresponds to the difference between the Geoid and the MSS
    - Globally, changes in DOT are generally between -2 m and +2m


80°
60°
40°
20°
0°
−20°
−40°
−60°
−80°
200°
240°
280°
320°
0°
40°
80°
120°
160°
m
−100 −90 −80 −70 −60 −50 −40 −30 −20 −10 0 10 20 30 40 50 60 70 80

- Offshore reference frames represented as a continuous surface relative to ETRF89 (GRS80)
  - Use GNSS to precisely determine ellipsoidal height of each tide gauge
  - Tide gauge observations used to derive ellipsoidal height of MSL at tide gauge
  - Satellite altimetry measures MSL of open oceans from space >> ellipsoidal height of MSL at tide gauge **AND** in open oceans now known
  - Geoid to derive DOT (MSL – Geoid) >> use DOT to interpolate between open ocean and tide gauge >> gives continuous MSL surface
  - Use tidal modelling to derive other surfaces
  - 17 times denser than either the MSS or EGM08 surfaces



VORF Coverage

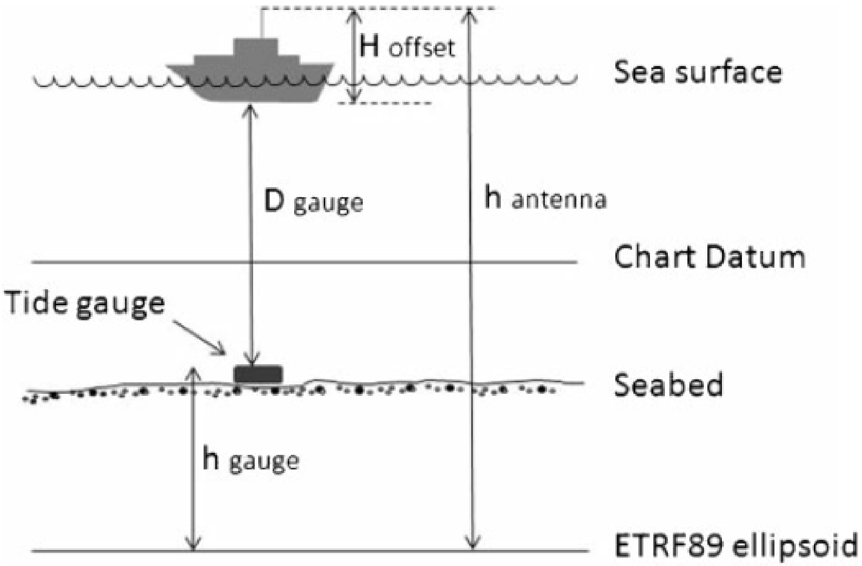


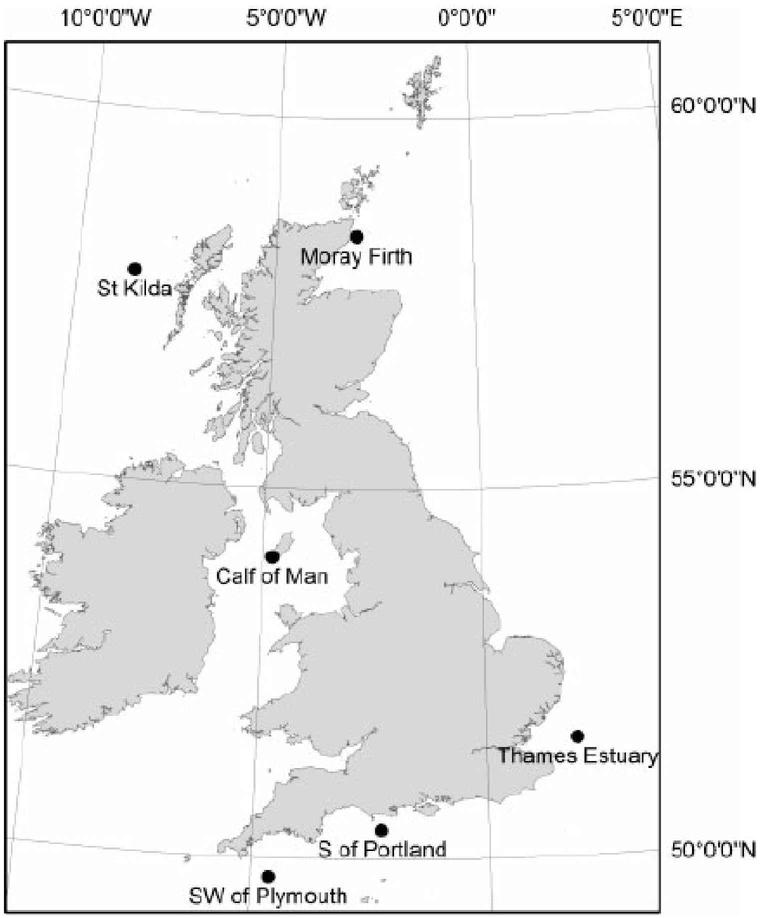
VORF Validation

- 245 checks on datum connections at coastal points
- 63 comparisons between VORF-corrected tidal levels observed with GNSS and tide gauge data
- 6 specially commissioned offshore tide gauge deployments
- Ellipsoidal height of the gauge established by a vessel equipped with GNSS and echo sounding equipment making measurements over a period of 8-10 hours
- Target accuracies 0.10m inshore and 0.15m offshore (1σ)

Point	Difference between observed value and VORF/m	Formal VORF uncertainty value/m	Distance offshore, measured to nearest land/km
Calf of Man	0·11	0·12	0·25
South West of Plymouth	0·11	0·12	45
South of Portland	0·69	0·18	20
Thames Estuary	0·23	0·14	45
Moray Firth	0·37	0·12	8
St Kilda	−0·16	0·06	0 (or 65 km from Outer Hebrides)

VORF Validation



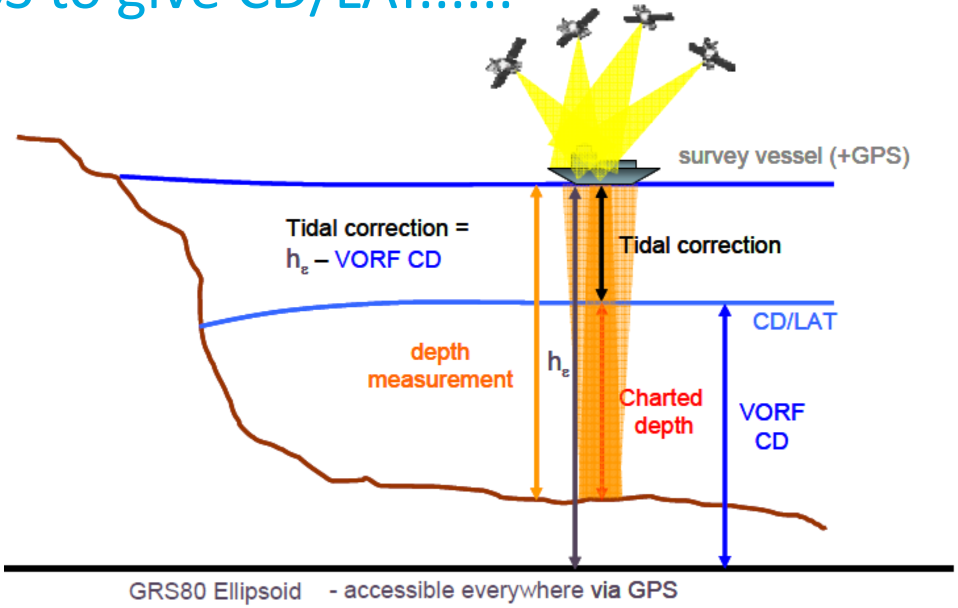


Bathymetric Processing using GNSS

- Survey vessel equipped with GNSS delivers ellipsoidal height at an accuracy ~10cm (1σ)
- GNSS enables calculation of the ellipsoidal height of the echo sounder (h_ε) (assuming corrections for offsets and attitude)
- Lat/Long used to query VORF/MSS to give CD/LAT......

$$\Delta tide = h_\varepsilon - h_{VORF\ MSL}$$

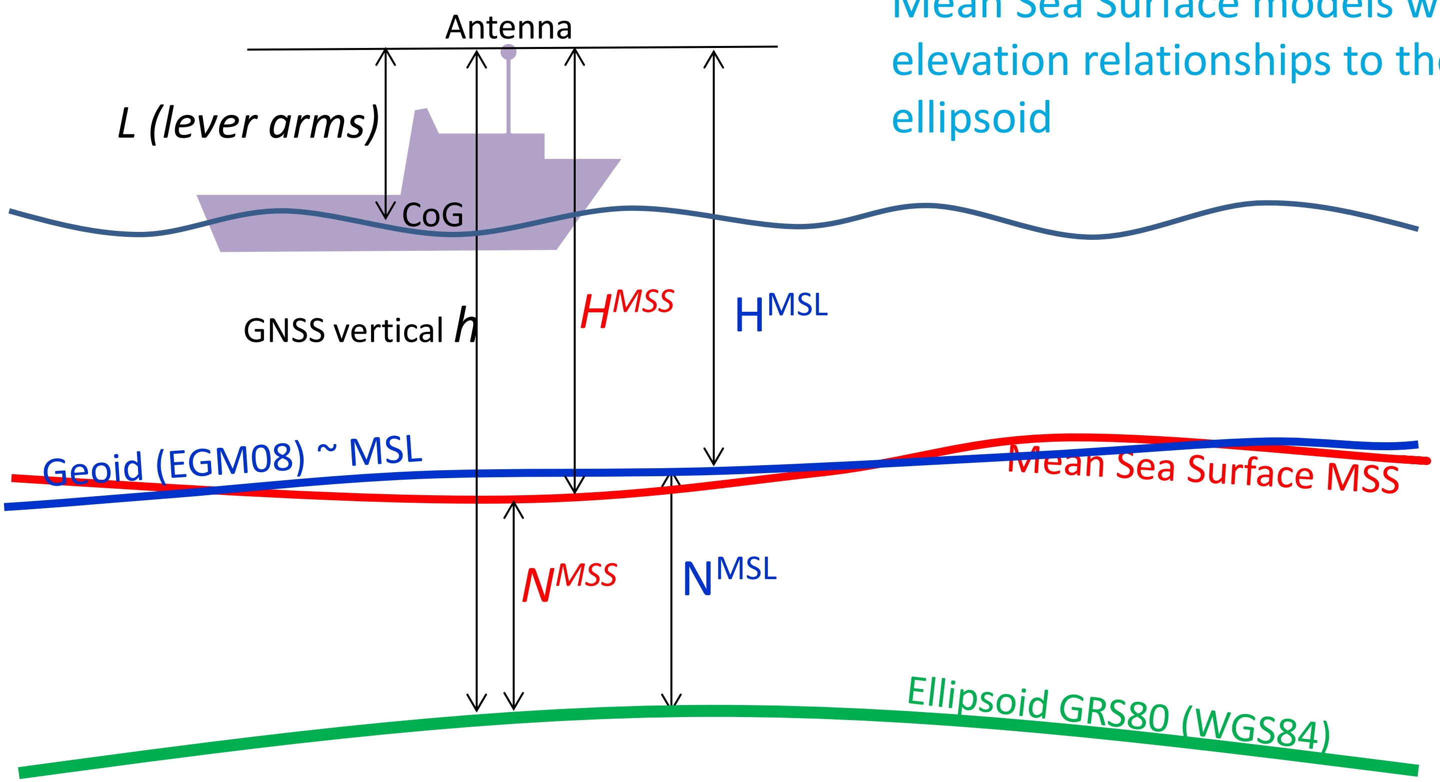
- Gains
  - No reliance on tide gauges
  - Consistency (all contractors using same reduction methods
  - QC (error budget controlled by GNSS and bathymetry – both user based)
  - Speed (data available on board the ship)



C-Tides

C-Tides Principle

C-Tides uses global and local Mean Sea Surface models with elevation relationships to the ellipsoid

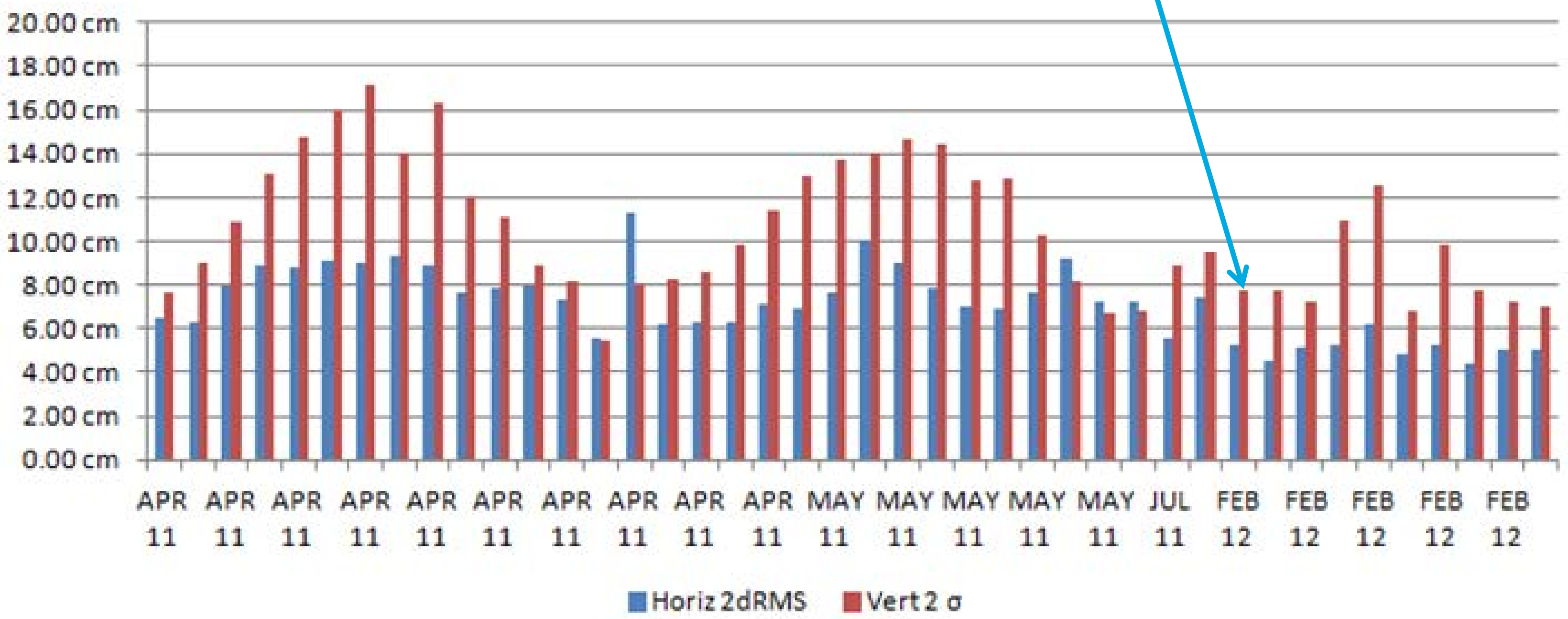


$CoG = h - N^{MSS} - L$

OR

$H^{MSS} - L$

- Correctors for GLONASS constellation (C2)
- Improved GNSS PPP algorithms (*iCORE*)
- GPS & GLONASS improved convergence time



C-Nav C2 Vertical Performance

- C-Nav C2 vertical accuracy is significantly more precise than the legacy C1 (GPS only service)
- Upgrade included implementation of proprietary network of C-Nav3050 equipped reference stations
  - Improved modelling using homogeneous network of receivers
- New PPP algorithms
- 10.3 cm ± 2.4 cm (2σ)

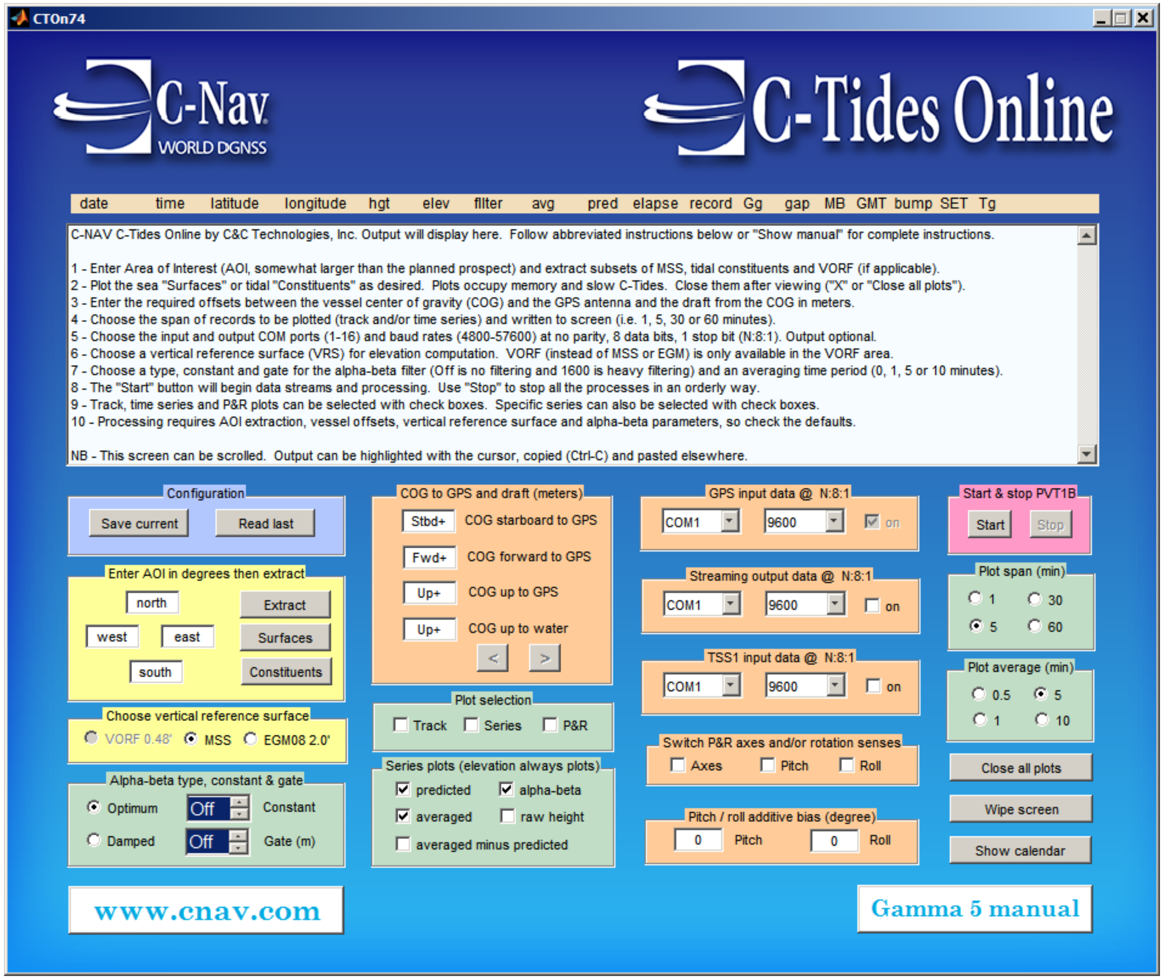
Station: CRCS Singapore	Observed Mean Position
Latitude: 1.330909528 Longitude: 103.951987028 Height: 51.597	Latitude: 1.330909442 Longitude: 103.951987105 Height: 51.601

Horizontal Statistics (meters)	Vertical Statistics (meters)
Minimum deviation: 0.000 Maximum deviation: 0.087 2dRMS: 0.051 Mean: 0.026 Standard Deviation: 0.026	Minimum deviation : -0.265 Maximum deviation : : 0.185 2 σ: 0.101 Mean: 0.004 Standard Deviation: 0.056

Station CRCS Kalvåg	Observed Mean Position
Latitude: 61.767820250 Longitude: 4.879132750 Height: 62.873	Latitude: 61.767820158 Longitude: 4.879132926 Height: 62.898

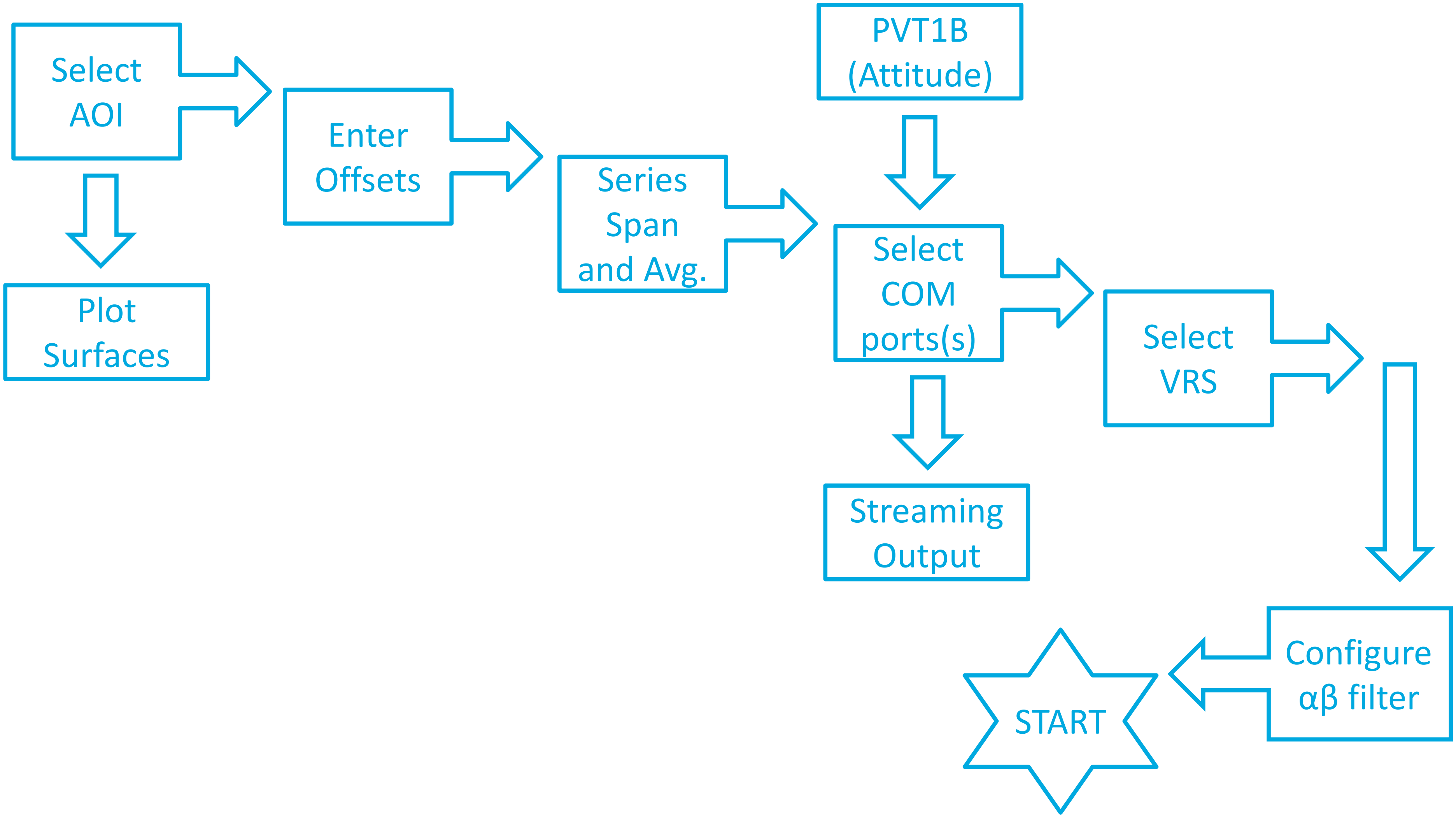
Horizontal Statistics (meters)	Vertical Statistics (meters)
Minimum deviation: 0.000 Maximum deviation: 0.112 2dRMS: 0.065 Mean: 0.032 Standard Deviation: 0.033	Minimum deviation : -0.138 Maximum deviation : 0.182 2σ: 0.094 Mean: 0.025 Standard Deviation: 0.042

C-Tides Online



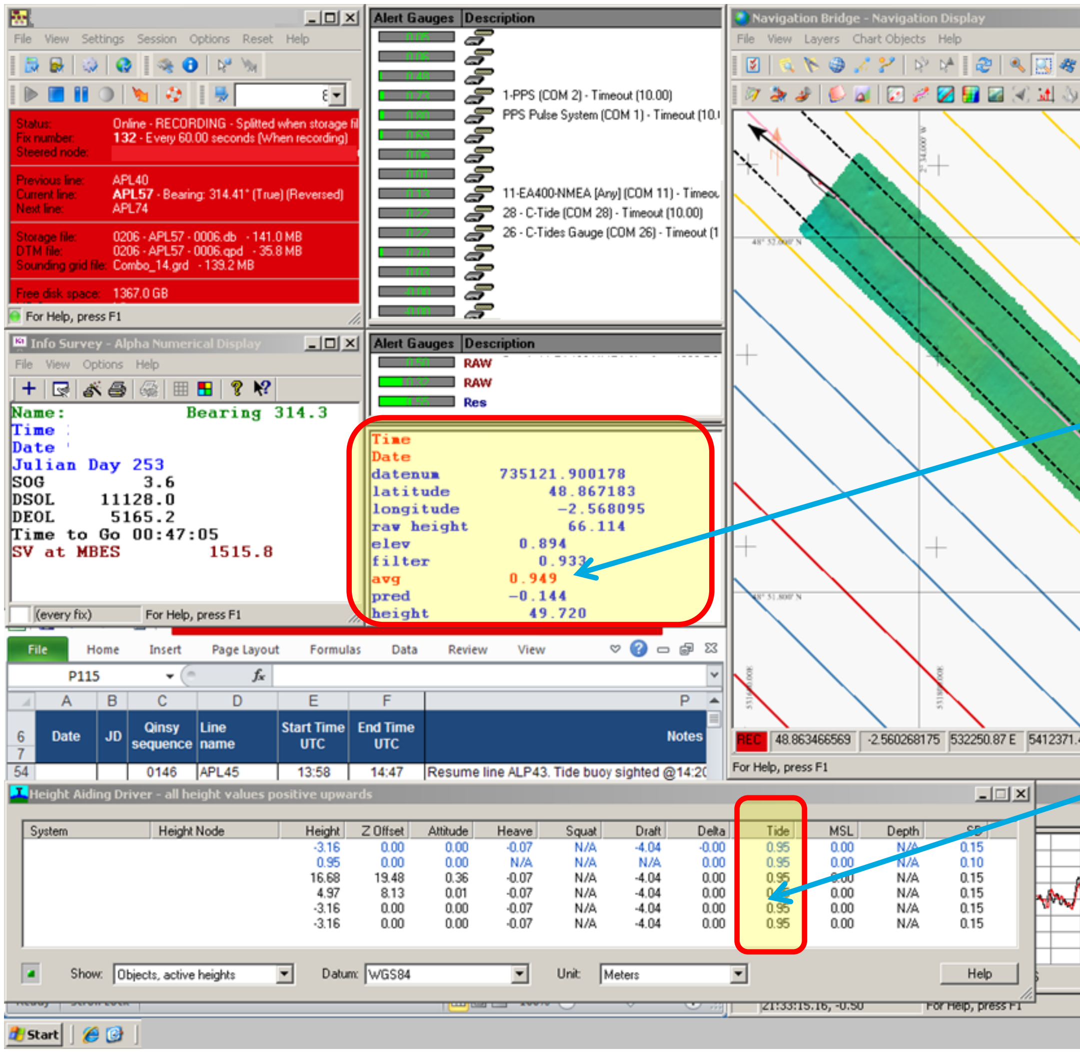
- Stream and process C-Nav3050 PVT1B data
- Instantaneous Tide relative to to MSS (Global), VORF MSL (UK), or EGM08
- Real-time tide output not dependent on 39-hour time delayed estimate
- Real-time attitude input
- Allows for tidal reduction (antenna offsets, draft changes) at any point in operation
- Output formats: time series plots, RS232 streams, ASCII log files, or difference contours

C-Tides Online Work Flow



C-Tides

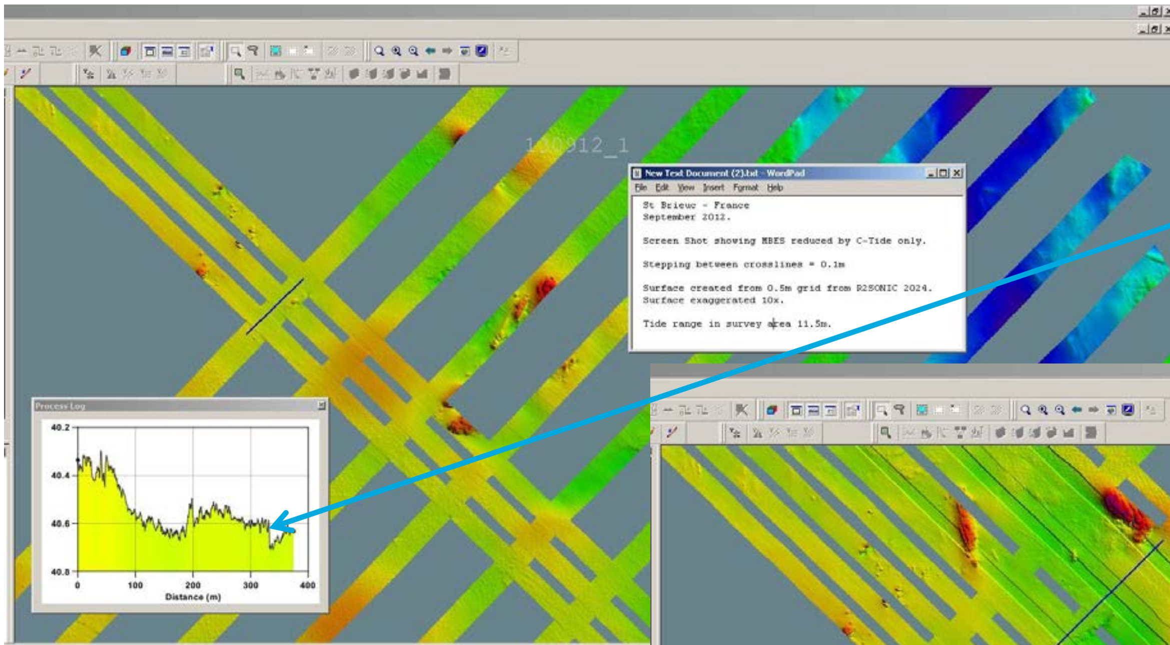
Real Time Bathymetry Reduction using C-Tides Online



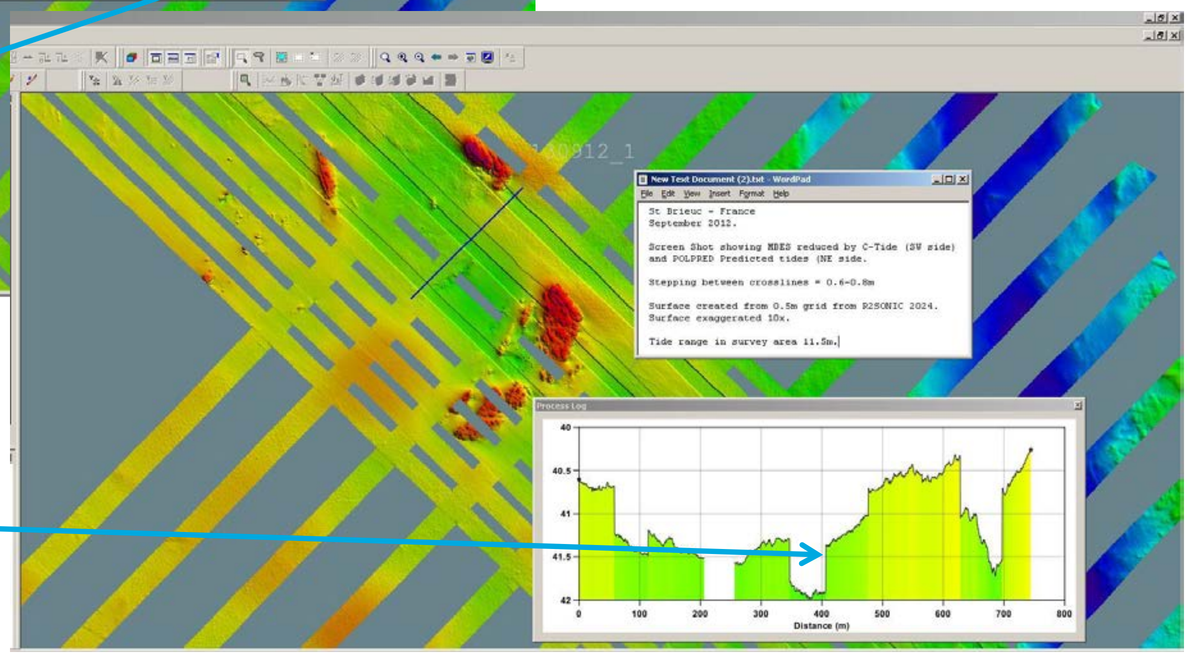
Data from C-Tides Driver

Height from C-Tides Driver

Real Time Bathymetry Reduction using C-Tides Online

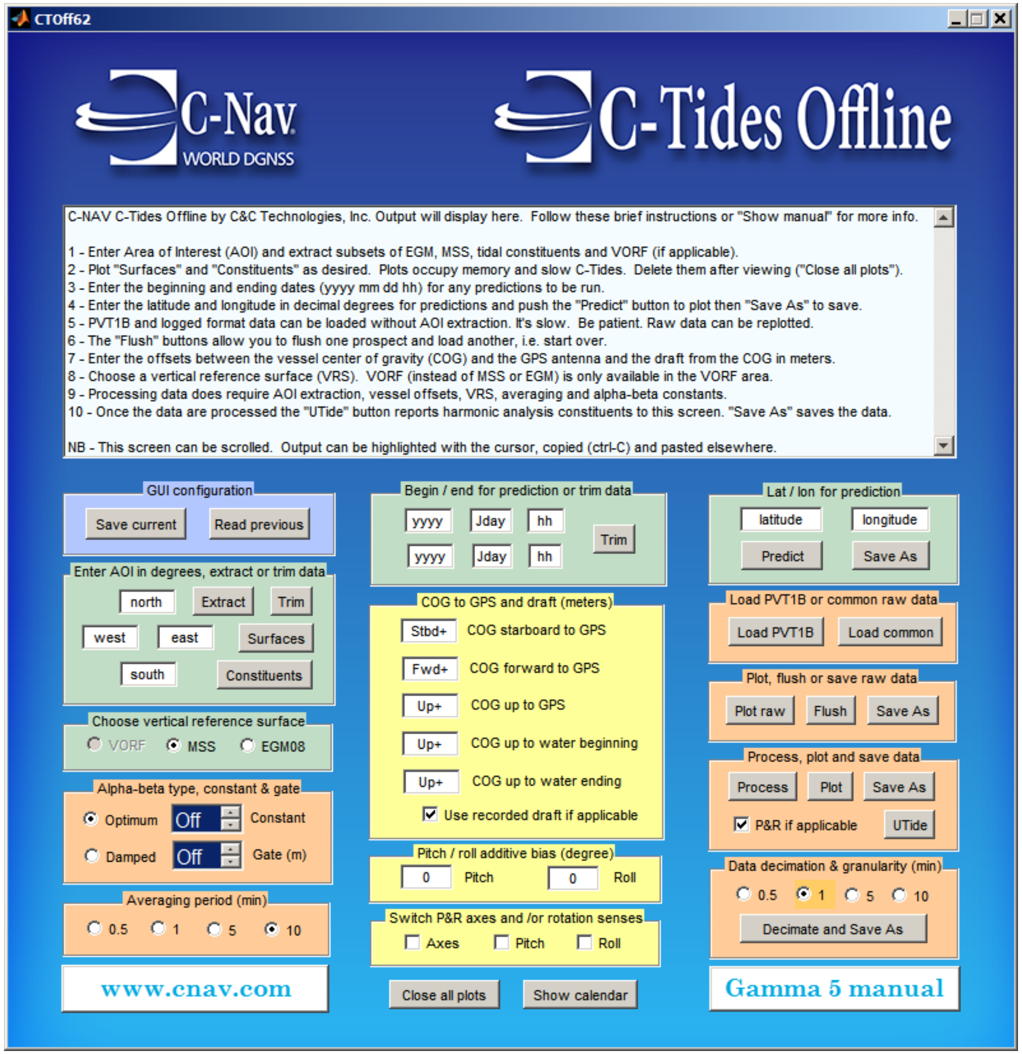


- MBES data reduced using C-Tides
- Cross section across overlapping swath lines
- Stepping ~ 10cm



- MBES data reduced using C-Tides and POLPRED
- Stepping up to 1m

C-Tides Offline



- Process C-Nav3050 recorded binary data or C-Tides Online data
- Processed tide relative to MSS (Global), VORF MSL (UK) or EGM08
- Allows for tidal reduction (antenna offsets, draft and squat)
- Tidal predictions for any Area of Interest in any time period
- Doodson X0 filter derived MSS estimate
- Tidal harmonic analysis using GNSS data to derive tide constituents using UTide

The Doodson X0 filter was designed in the 1930s to provide oceanographers with an empirical but accurate method for damping out the main tidal constituent frequencies.

It works by taking 19 averaged hourly values either side of a moving central value to which weights are applied as follows:

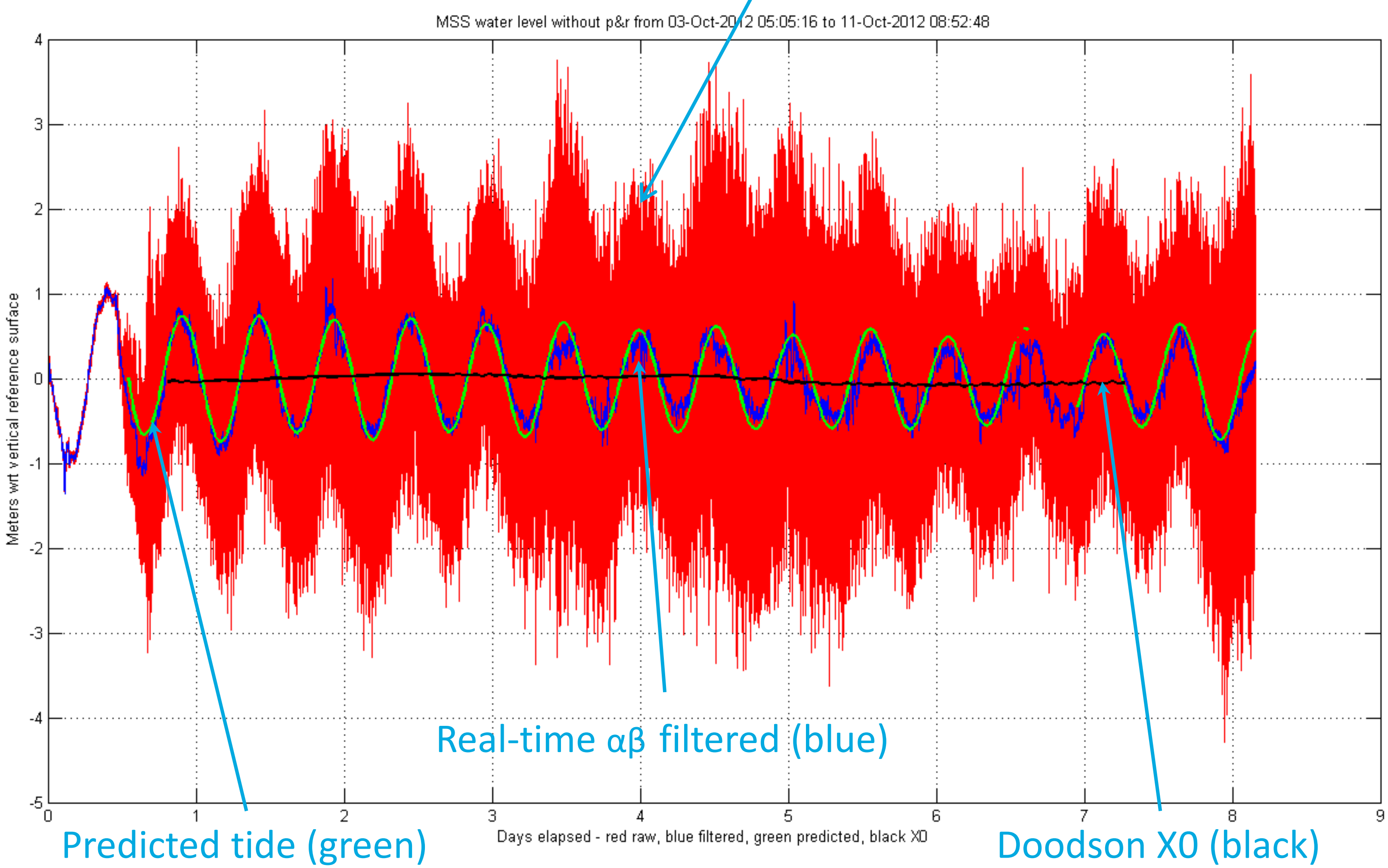
{1|0|1|0|0|1|0|1|1|0|2|0|1|1|0|2|1|1|2|0|2|1|1|2|0|1|1|0|2|0|1|1|0|1|0|0|1|0|1}

39

19 hours — Central Value — 19 hours

Real-time vessel motion (red) – heavy seas

C-Tides Offline

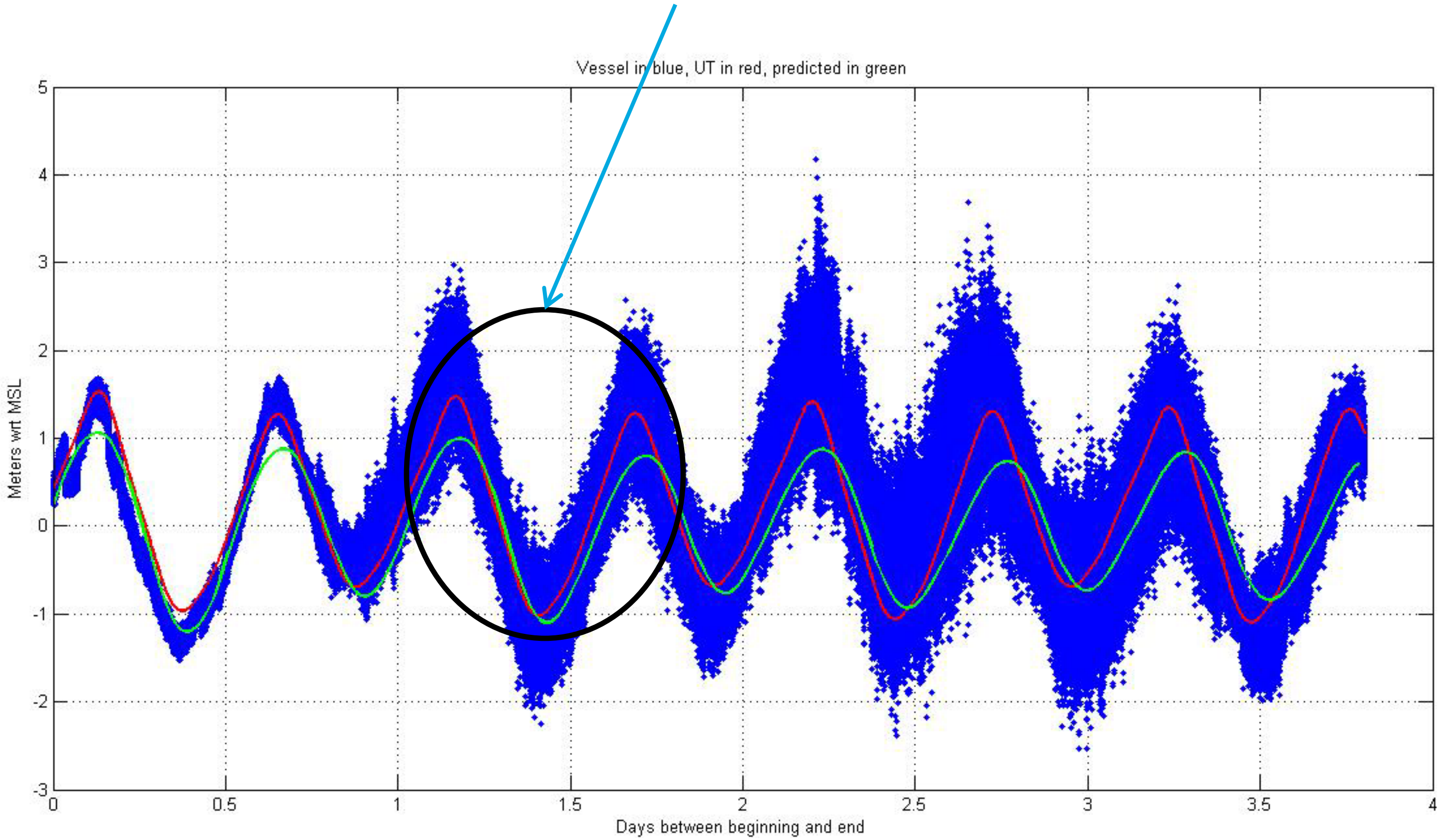


C-Tides

C-Tides Development Trial

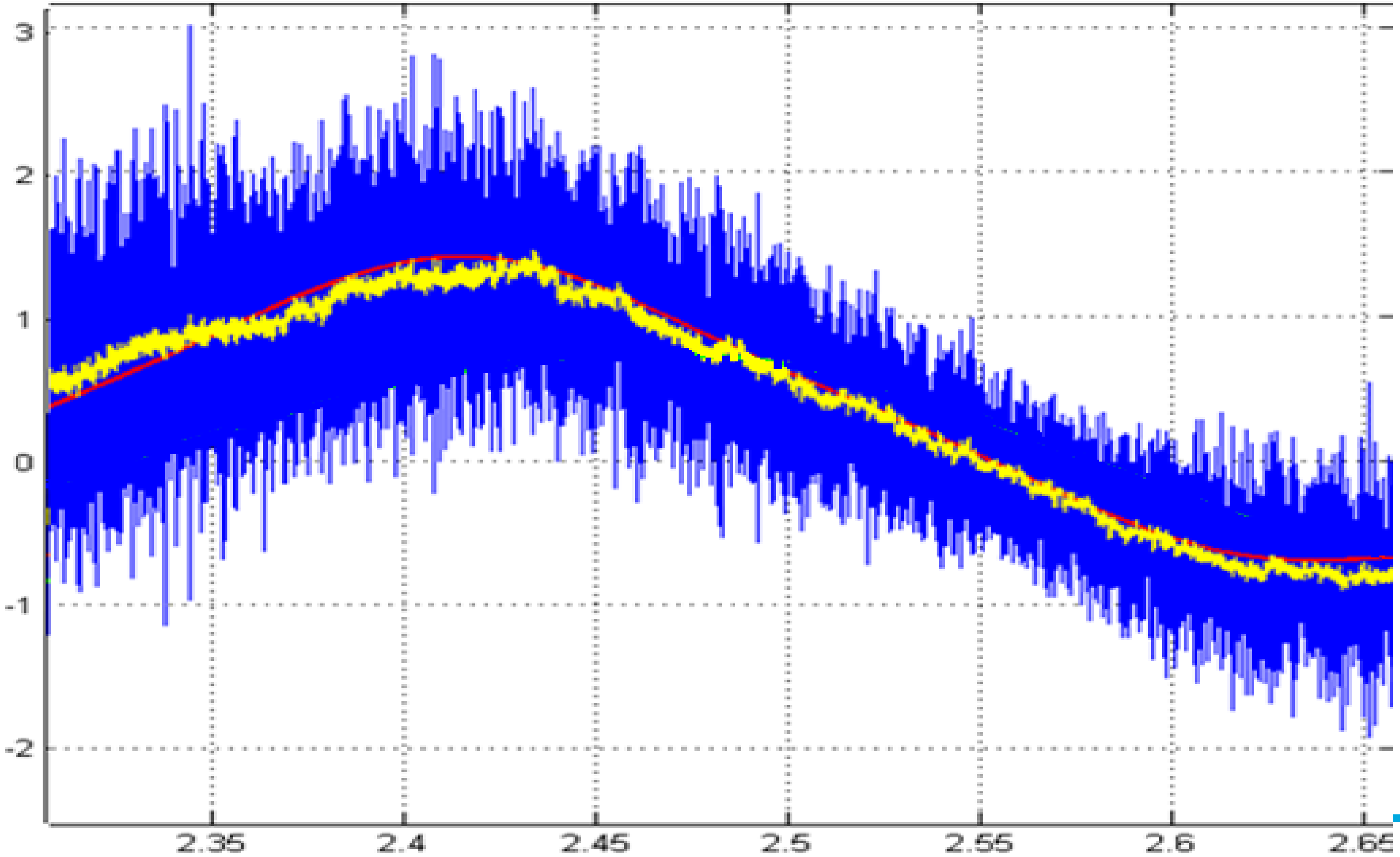
VORF + FES predicted (green) + harmonic fit (red)

Offset between predicted and observed due to lever arm errors



C-Tides

Real-time Raw
Real-time α-β filtered
PP harmonic curve



C-Tides

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http://www.hydrometronics.com/