Introduction to Tidal Theory

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Tidal Theory

" The tide is the periodic vertical movement of water on the earth's surface."

Admiralty Manual of Navigation

- Introduction
- Short history
- Who uses tidal information
- Definitions
- Tidal theory
- Simple planetary motion
- Tide raising forces
- Tidal patterns – types
- Factors affecting tide form
- Installing a Tide Gauge
- Types of tide gauges

A Brief History

"Tide was just the sea advancing and retreating once or twice a day"

- Legends explained the movement of the sea
  - Whales breathing cycle
- Greeks and Romans not bothered by tide
  - Mediterranean tides are imperceptible
  - Caesar lost war on the English shores

- 3rd Century
  - Aristotle first to make reference to tidal motion
- 10th Century
  - Arabs related tide to the cycles of the moon
- 13th Century
  - First tide table complied by an English Monk
- 17th Century
  - Sir Isaac Newton and his universal theory of gravitation (1687)
  - Gravitational theory became the established theory for all tidal theory
- Baron Kelvin/ George Darwin
  - Developed harmonic analysis
    - Kepler, Newton and Laplace

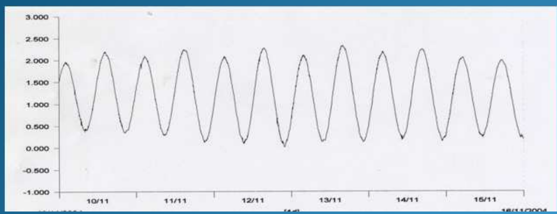
Who Uses Tidal Predictions

- The Hydrographic Surveyor
  - To reduce soundings to a common datum
- The Navigator
  - Safe navigation of estuaries and coastal waters
- Harbour and coastal engineers
  - Construction of harbours, bridges etc.
- The general public
  - Fishing, sailing, hiking etc.

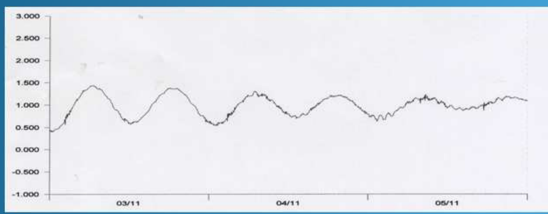
Definitions

- Tide
  - Vertical rise and fall of the oceans and other large bodies of water in response to the gravitational attraction of the moon and sun.
- Tidal stream
  - The horizontal movement that accompanies the rise and fall (vertical) movement of the tide
    - In the USA known as tidal current

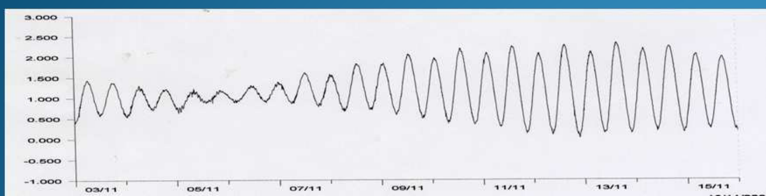
- Spring tide
  - Highest high tide and lowest low tide



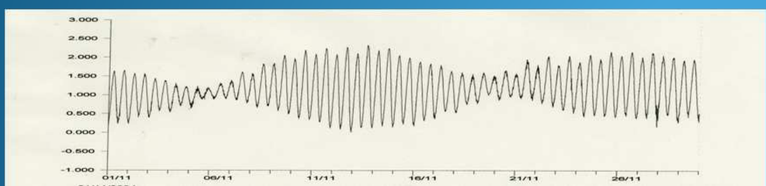
- Neap tide
  - Lowest high tide and highest low tide



- Tide progressing from neaps to springs



- Tide over one month

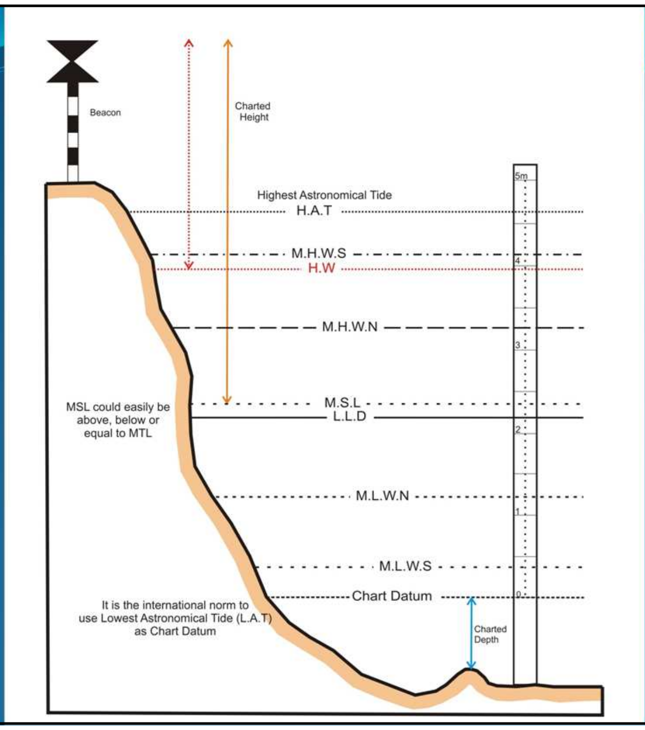


- Chart Datum (CD)
  - The datum to which all soundings on large scale navigational charts of an area are reduced
  - Lowest Astronomical Tide (LAT) in RSA
- Land Leveling Datum (LLD)
  - The datum to which all altitudes above sea level and all depths below it are referred
  - Sometimes referred to as Mean Sea Level (MSL)
  - Ordinance Datum

- MHWS
  - Mean high water springs
  - The average HEIGHT of the HIGH water SPRING tides
- MLWS
  - Mean low water springs
  - The average HEIGHT of the LOW water SPRING tides
- MHWN
  - Mean high water neaps
  - The average HEIGHT of the HIGH water NEAPS tides
- MLWN
  - Mean low water neaps
  - The average HEIGHT of the LOW water NEAP tides

- MHW
  - Mean high water
  - Average height of high water levels at a given location over a period of 19 years.
- MLW
  - Mean low water
  - Average height of low water levels at a given location over a period of 19 years.
- Mean Sea Level (MSL)
  - The average position of the sea level across all tidal periods during a 18.6 year interval
  - This is different to Land Leveling Datum/ Ordinance Datum
- These levels vary with change in MSL, from year to year in a cycle of 18,6 years.
- When the average maximum declination of the moon is 23½°, the range of the tide is at it's greatest.

- Declination
  - Inclination from the vertical
  - Angular distance from celestial equator
- Apogee
  - The point at which the moon's orbit is the furthers from the earth's gravitational center
- Perigee
  - The point at which the moon's orbit is the closest to the earth's gravitational center
- Syzygy
  - Occurs when the right ascension of the sun and moon are co-incident to one another (in line) when the moon is full or new
- Lunitidal Interval
  - Interval between the moon's transit (upper or lower) over the local time meridian (Or Greenwich meridian) and the following high or low water.
    - Upper transit: crosses the time meridian near the tide gauge
    - Lower transit: crosses the meridian that is 180º from the tide gauge



Tide Raising Force

- Newton’s law of motion and gravity
- The earth- moon system
- The earth - sun system
- The gravitational force
- Earth’s rotation
- Declination
- The lunar orbit
- The earth-sun-moon system

Gravitation

Newton's laws of motion and gravity

- 1st LAW
  - Every body continues in a state of rest or uniform motion in a straight line unless acted upon by an external force
- 2nd LAW
  - When a body is acted upon by an external force, it's acceleration is directly proportional to that force and inversely proportional to the mass of the body. Acceleration is in the direction in which the force acts

- 3rd LAW
  - If a body exerts a force on a second body, the second body exerts a force that is equal in magnitude and opposite in direction to the first force.
  - For every action there is an equal, but opposite reaction.

- Newton's universal law of gravitation states that for any two heavenly bodies, a force of attraction is exerted by each one on the other:
  - Proportional to the product of their masses

  Inversely proportional to the square of the distance.

$$F_g = G \frac{m_1 m_2}{r^2}$$

- Tides are caused by the gravitational pull of a heavenly body on the earth and the water lying on the earth's surface

Basic Tidal Theory

- Equilibrium tidal theory
  - Imaginary earth that is totally covered in water
  - **No** land masses/ continents
  - **No** declination
  - **Nothing** like real tide theory
- Real tide theory
  - The real earth
  - Has land masses
  - Has declination
  - Has rotation
  - More dynamic

Equilibrium Theory

- Gravitational attraction between sun/earth and earth/moon
  - Mass of sun= **27 million** times mass of moon
  - Distance between sun and earth = **390** times the distance between moon and earth
    - $\frac{Fg(sun)}{Fg(moon)} = \frac{27 \times 10^6}{(390)^2}$
    - Fg (Sun) = **178** times that of the moon
- The moon's tide producing force is **2x** the sun's gravitational effect
- Moon's gravitational effect is 1/10 000 000th of the earth's gravitational effect

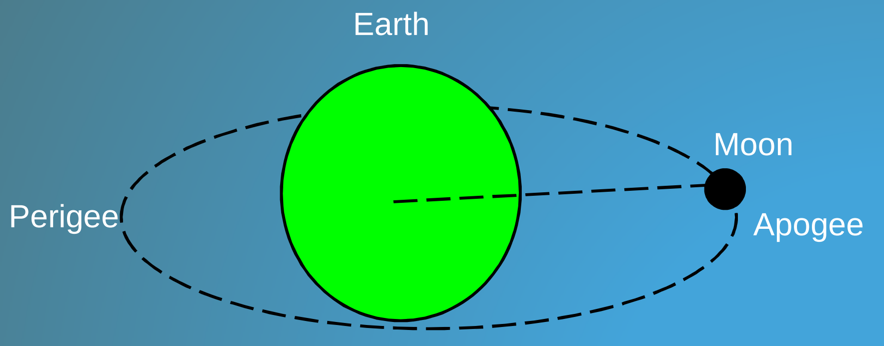
Tide Producing Force

it's all about mass and distance

Tide Producing Force ~ (M1*M2)/ Distance (cubed)

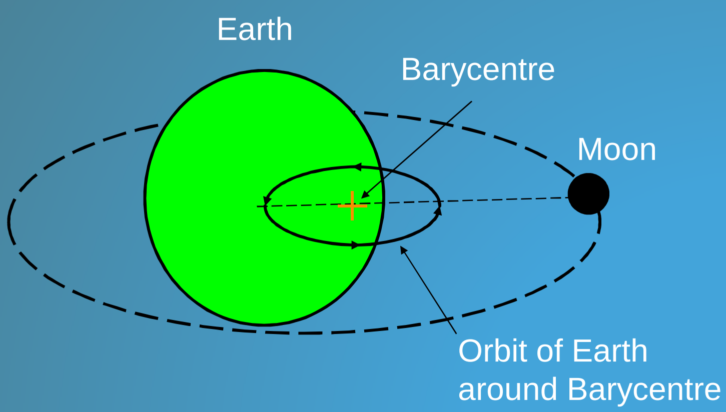
	MASS	DISTANCE From Earth	TIDE PRODUCING FORCE
Sun	3.33X10e5 > earth's	147.1 x 10e6 km	0.46 of Moon's
Moon	0.01 of Earth's	0.36 x 10e6 km	1.00
Mars	0.11 of Earth's	55.7 x 10e6 km	2.9 x 10e-6 of Moon's

The Earth-Moon System

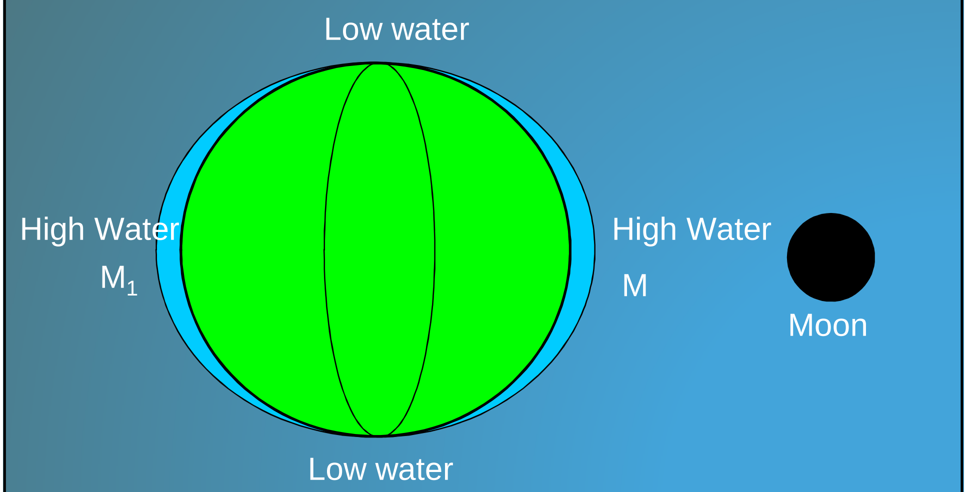


- The earth/moon rotate around a common centre of gravity
- Known as the barycentre
  - Approx. 1700km below the surface of the earth
- (Earth and the sun both rotate around a common centre of mass which is less than 500km from the centre of the sun)

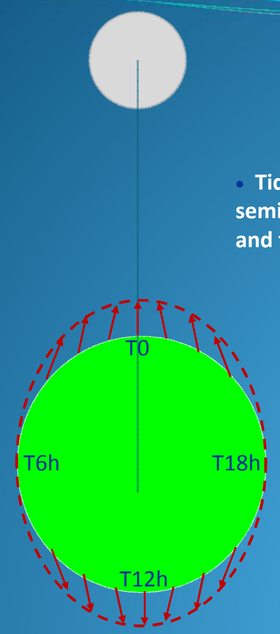
The Barycentre



Lunar Equilibrium Tide

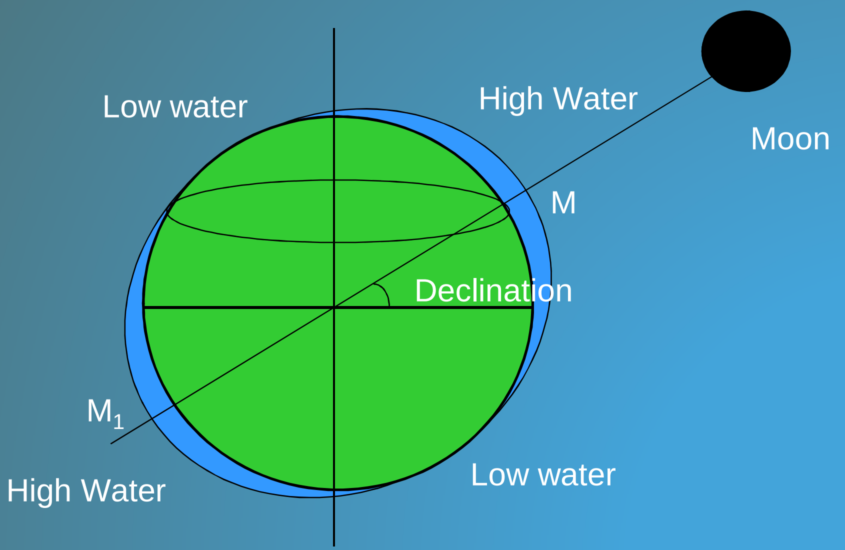


Earth-Moon System: Overhead view

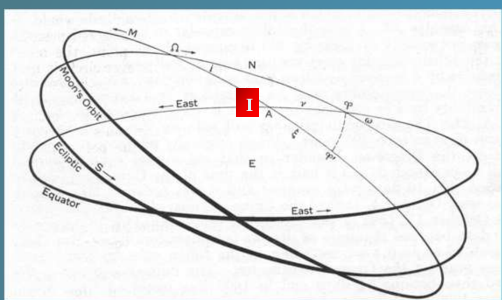


- **Tide producing forces drive the semidiurnal signal (two high tides and two low tides per day)**

Effects of declination (diurnal tide generation)



Lunar Orbit

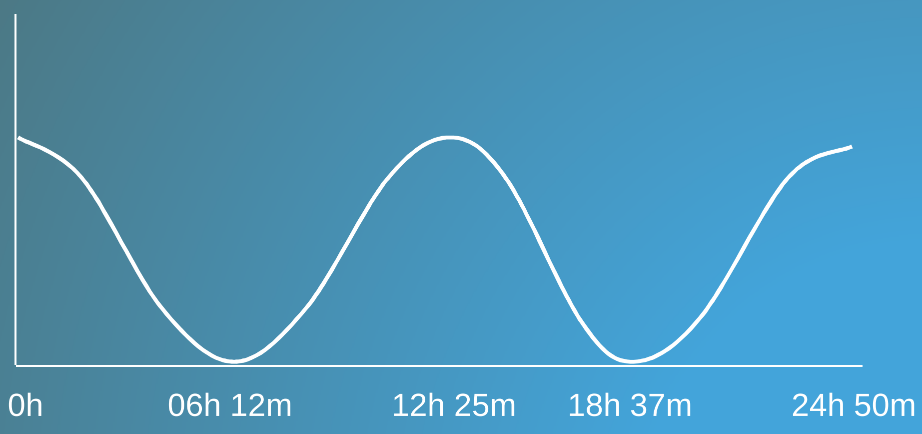


- Angle I is angle between the plane of moon's orbit and Earth's equatorial plane
- I varies over an 18.6-yr period between 28.5° to 18.5°)
- Cycle called the *lunar nodal regression*
  - Has a ±4% effect on M_2 and a ±11% on diurnal frequencies

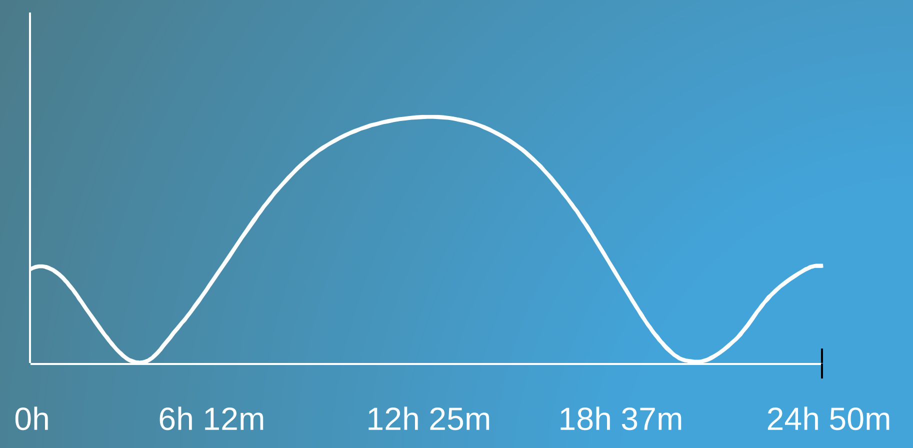
Tidal Patterns

- Semi- diurnal tides
  - Two high tides
  - Two low tides
    - Approximately 6 hours apart
- Diurnal tides
  - One high tide
  - One low tide
    - Approximately 12 hours apart
- Mixed tides
  - Characteristics of semi- diurnal and diurnal tides

Semi-Diurnal Tides



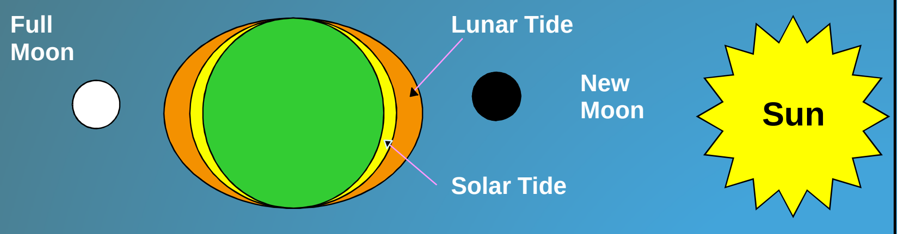
Diurnal Inequality



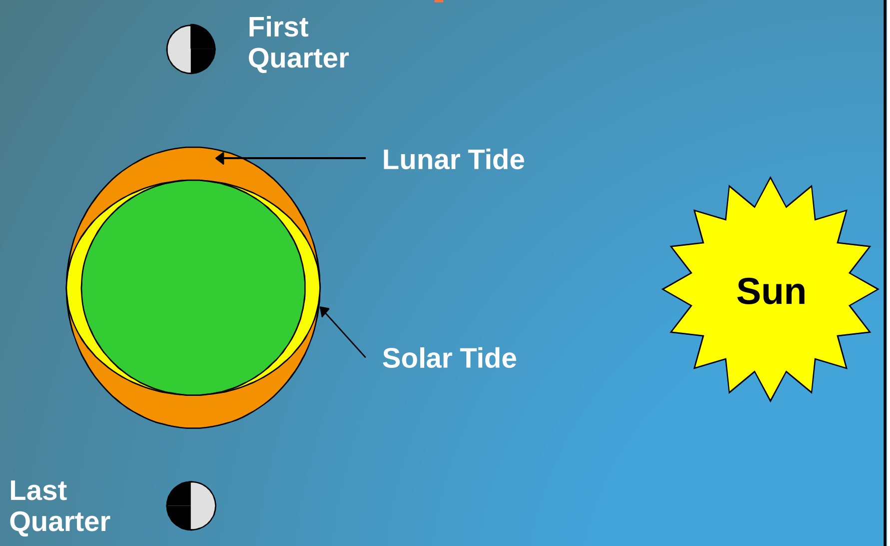
- Spring tides
  - Highest high tide
  - Lowest low tide
    - Large range
  - Occurs 1 to 2 days after full and new moon
- Neap tides
  - Lowest high tide
  - Highest low tide
    - Small range
  - Occurs 1 to 2 days after first and last quarter

- Approximately every 7 days alternates between springs and neaps.

Spring Tides



Neap Tides



Real Tide

- Dynamic tide theory
  - Real tide
  - Has land masses and declination
  - Earth's rotation taken into account
  - Tide is represented as a wave "forced" by tide producing forces

Factors Effecting Tide Form

- Real ocean basins have very complicated coastal and bottom topography.
- The sun/ moon
  - Varies the amplitude and timing of the tide
- Geography
  - Land masses impede and deflect water movement
- Friction
  - Retards movement
- Basin oscillation
  - Natural period of oscillation
- Lunar and terrestrial orbits
  - Shape and plane of earth's orbit around the sun and that of the moon's around the earth
- Natural Resonance
  - Determines how water will behave

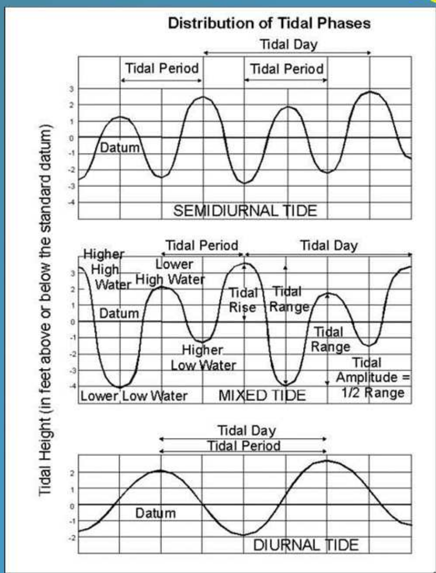
- The earth's orbit
  - Eccentric ellipse
  - Perihelion
  - Aphelion
- The earth's tilt/ declination
  - Relative position of the sun and moon in relation to the earth
- The moon's orbit
  - Eccentric ellipse
  - Varying apogee and perigee
- The weather
  - Prevailing winds
  - Frontal movements
  - Atmospheric pressure
  - Storm surges

Natural Resonance

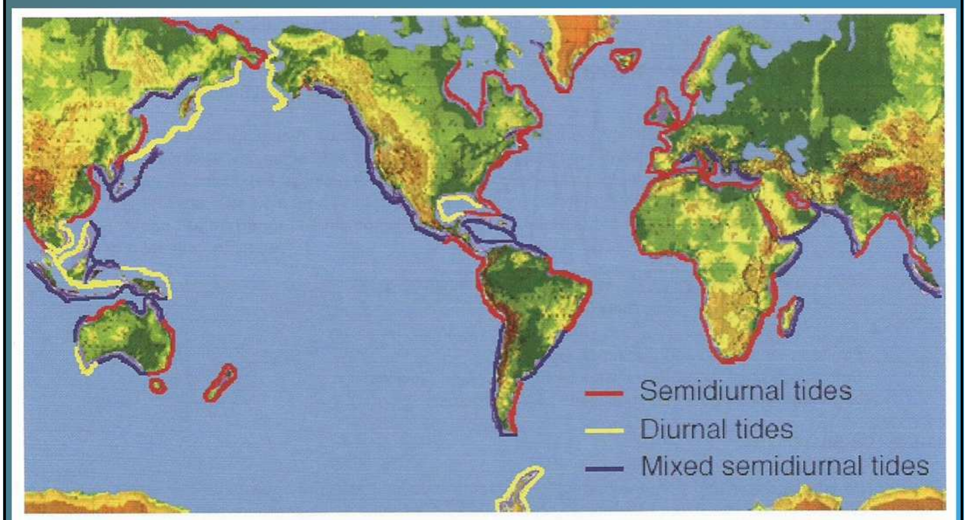
- Every body of water, of any size, has a natural frequency of oscillation
  - Dependent on size and depth of the body of water
- When natural frequency of the oscillation = (or is very nearly the same) the frequency of an imposed force, resonance occurs
  - Wave has similar frequency to the oscillation the wave becomes amplified.
  - Very large movements result from very small applied forces.
- Decisive factor in determining whether the water will respond to diurnal, semi- diurnal or mixed tide raising forces

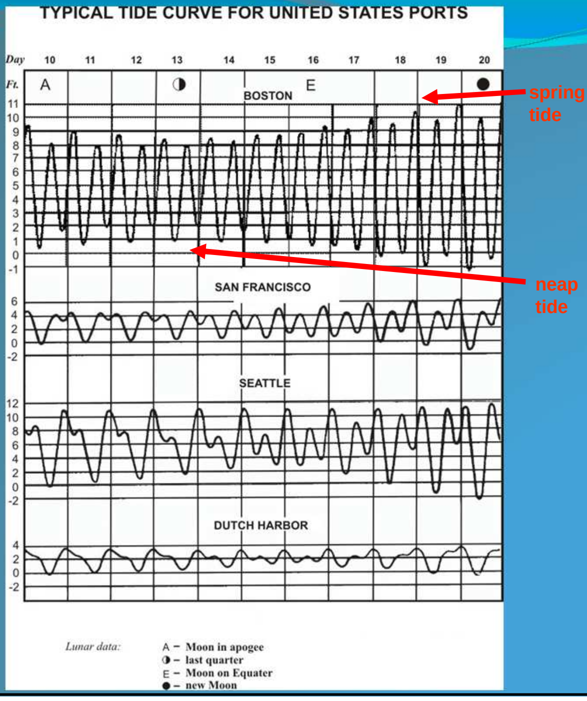
- Semi-diurnal
  - The Atlantic tends to be more responsive to semi-diurnal forces
  - More influences by the phases of the moon than by declination
    - Largest tide of the year: at springs near the equinox
      - Sun and moon are at the equator
- Diurnal
  - The Pacific tends to be more responsive to diurnal forces
  - Large diurnal component
  - Largest tides are associated with the greatest declination of the sun and moon
    - Summer and winter solstices

- Mixed
  - Where the diurnal and semi-diurnal tide raising forces are both important
    - Tends to be characterized by large diurnal inequalities



- The Mediterranean Sea and Baltic
  - Resonant period of a few hours
  - To small to enable any appreciable tide to be generated
- Strait of Gibraltar
  - Too restricted to allow Atlantic tides to have any appreciable effect other than on the extreme western side



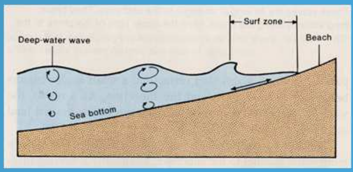


Friction

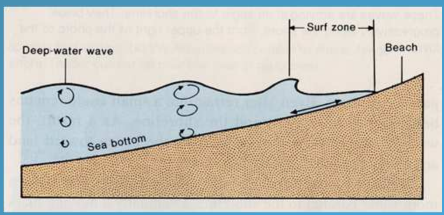
- Friction
  - As with all fluids there is internal drag between water molecules
  - Frictional drag exists between water and the sediments on the sea floor
- Frictional influence extends upwards towards the surface of the water
  - Effect of friction is to slow water flow
    - Actual speed of water is much greater than that occurring near the seabed.
- The lower part of the flow experiencing frictional retardation is known as the *boundary layer*

Land and Shallow Water Effect

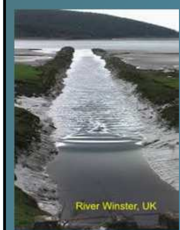
- Land
  - Location and shape of various land masses
    - Local conditions of resonance
    - Effect on tidal conditions
- Shallow water
  - When a wave travels into shallow water
  - Its shape is changed
  - Friction causes a distortion
  - Of the tidal curve.
    - The curve steepens
    - The circular motion of the water
    - Particles become elliptical



- As waves approach a shelving shore
  - Orbital motion becomes flattened to an ellipse
  - Wave slows down
  - Crests pile up and eventually wave breaks to form surf



- Incoming tide and river estuaries
  - The amplitude of the tide wave increases as it travels up an estuary
  - Forcing from a wide entrance to a narrower channel
    - Distorts the tidal height
- These distortions can become of great importance
  - Results in very large tides.

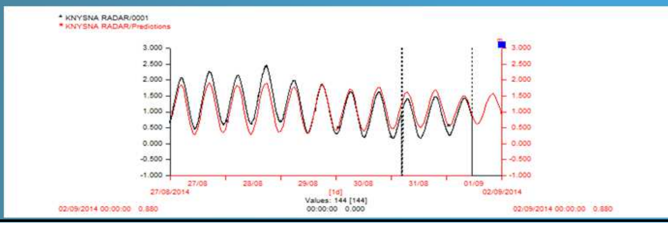


- Bores
  - Extreme case of shallow water effect when a tide with a large range is funneled into a river or estuary with a steeply shelving bottom.

Meteorological Effects

- Meteorological conditions which differ from the average will cause corresponding differences between actual and predicted tides
- Variations are mainly caused by strong/prolonged winds and unusually high or low barometric pressures
- Differences between predicted and actual tide heights are mainly due to wind
- Statistical analysis indicates
  - 1 std deviation of differences between predicted and actual heights and times = 0.2m and 10 minutes respectively

- Barometric pressure
  - Tidal predictions are calculated for average atmospheric pressure
  - Low pressure = tendency for sea level to rise
  - High pressure= tendency for sea level to drop/be depressed
- Water level does not adjust immediately to pressure change.
  - It responds to the average change over a considerable area
- Water level seldom exceeds an adjustment of 0.3m due to barometric pressure change



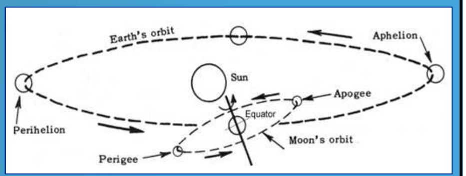
- Effect of wind
  - Very variable and depends largely on the topography of the area
- In general ⟶ the wind will raise sea level in the direction towards which it is blowing
  - A strong onshore wind will pile up water ∴ high water will be higher than predicted
  - Winds blowing offshore will have the opposite effect
- Winds blowing along a coast
  - Set up long waves that travel along the coastline
    - Wave crest raises the sea level
    - Wave trough lowers the sea level

Positive and negative surges

- A change in sea level often caused by wind and barometric pressure.
  - A ***rise*** in sea level = ***positive*** surge
  - A ***fall*** in sea level = ***negative*** surge
- A ***storm surge*** is an unusually severe positive surge
- Positive surge
  - Greatest effect in confined area
  - rarely increases general sea height by more than 1m
- Negative surge
  - NB for large vessels navigating with small under-keel clearances
  - Most evident in estuaries and areas of shallow water
  - Falls of up to 2m have been recorded.

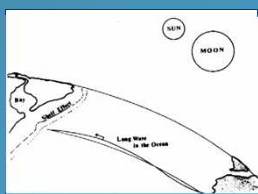
So far…

- Tides are the result of the gravitational forces of the Earth, moon & sun and the centrifugal forces created by the orbit of the moon around the Earth & the Earth around the sun
- Tidal frequencies (constituents) are created due to changes in the moon's orbit around the Earth.
    - Consequently the same applied to the earth's orbit around the sun
- It is the ***astronomical forcing*** of the tide that is the basis for the tide's predictability.



and…

- **hydrodynamics** ***determines:***
    - the size of the tide range,
    - the timing of high and low waters
    - the type of tide
    - the speed and timing of the tidal current
    - etc.



- The range and timing of the tide (and thus the speed/ direction/ /timing of the tidal stream) are affected by
    - Length, width & depth of the bay
    - Friction
    - And Storm surges
        - (The hydrodynamics)
- Because of hydrodynamics, the tide (and tidal stream) characteristics vary with horizontal (geographic) distances throughout a waterway.

Questions?

Tidal Streams

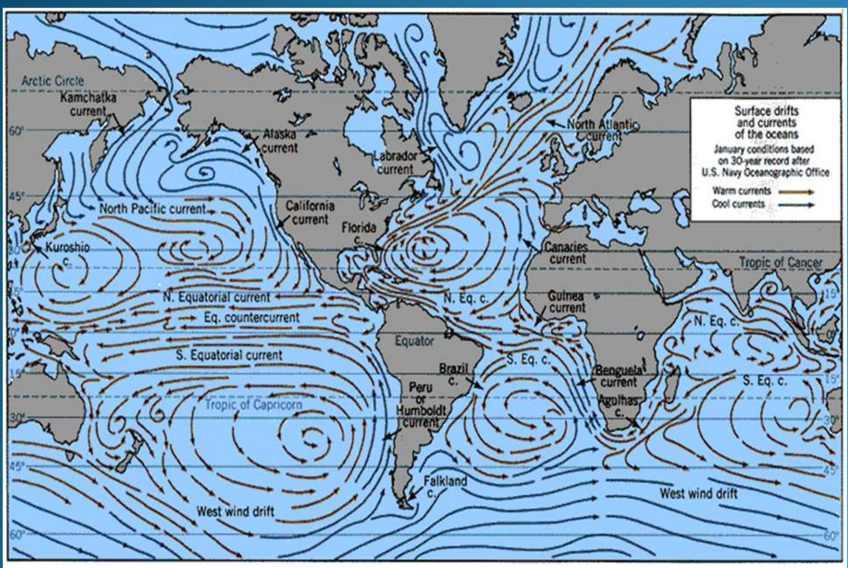
- Influence of water movement on maritime operations
  - Influenced over the whole column from surface to sea bed
- Deep draught vessel navigation
  - Water movement ⊥ to the course of the ship will influence the course to steer
  - In relatively shallow areas (20-40m) water movement will be largest
  - Friction will cause variation in speed and direction with increasing depth

- Submarine navigation
  - Surface water is of little importance, submarines are subject to deep water movement
- During naval exercise - surface and sub-surface vessels are subject to different movements
  - Same courses to steer result in different courses over the "ground"

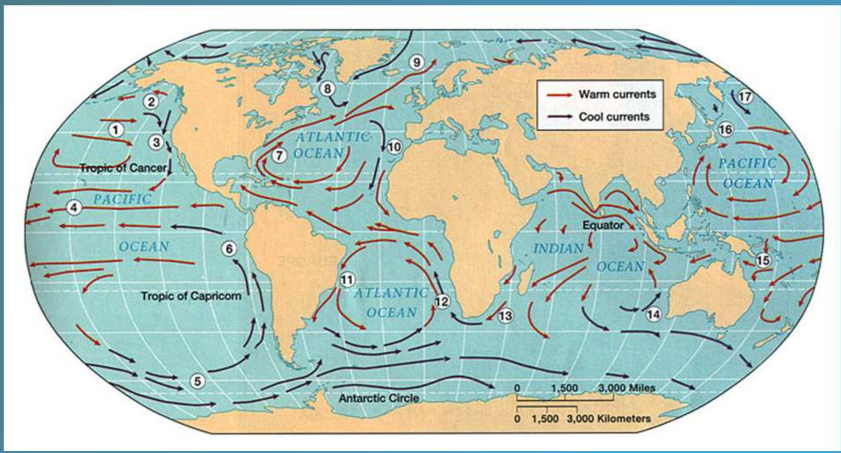
- What is a tidal stream?
  - It is the motion of the water particles *caused by the tide-generating forces **only***.
  - And it is the horizontal movement of water particles associated with the vertical movement of tide.
- Tidal streams can be modified by meteorological changes, and the effects of any other currents present.
- Tidal streams change direction and strength as a result of man-made structures
  - The direction and rate of the stream may vary, at any instant, with depth below the water surface.
  - **NB** to know the depth at which readings are taken.

- Total flow is the actual movement experienced.
  - Includes the effects of weather, tidal currents and random errors of measurement
  - Expressed as a rate towards a certain direction
    - eg: 1.4 knots, (towards) 137
- Non- tidal currents are mainly meteorological in origin and often involve density changes
  - Approximately constant in rate and direction from day to day
  - May change from month to month in an annual cycle
- The surveyor conducting tidal stream observations wants to measure tidal stream without the effect of weather and current
  - In reality all measurements include some form of non-tidal component
  - When accepting tidal stream measurements assume that the other effects are negligible

Oceanic Current Circulation

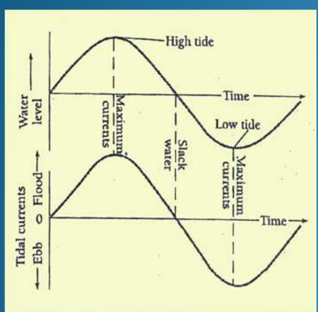


Oceanic Currents

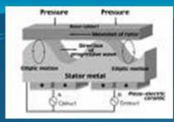


Progressive and Standing waves

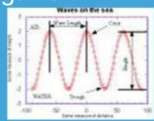
- For tide waves, depth is small compared with wavelength
- As progressive wave moves past some fixed point
  - Successive high and low sea levels are observed



- **At local high water there is a maximum current in the direction of the wave propagation, but at low water there is a current in the opposite direction.**

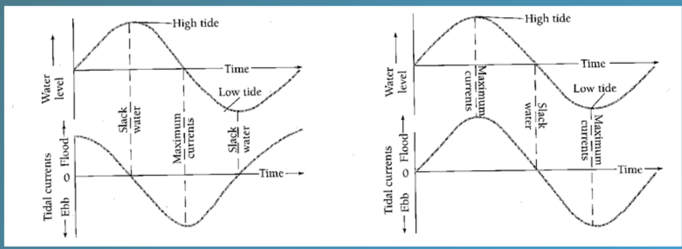


- Tides cannot propagate endlessly as progressive waves.
- Tides undergo reflection at sudden changes of depth and at local coastal boundaries.
- The reflected and incident waves combine together to give the observed tide.
- Reflection produces a fixed pattern of *standing waves*
  - Has alternative **nodes :** position where amplitude is 0, and **antinodes:** where amplitude is at a maximum
  - Separated by a distance of $\lambda/4$ (λ is the wavelength of the original progressive wave)



- At the **nodes** there is **no net change of water level**
  - Currents have maximum amplitude

- At the **antinodes** there is **a maximum change of water level**
  - No currents



- This is the theoretical relationship between tidal height and tidal stream in the case of progressive and standing waves
- In reality neither of these waves occur alone

Nature of Tidal Streams

- It is known from observations that tidal streams in most cases do not simply flow to and fro in one direction
    - Change direction and *rotate* in the tidal period.
- Tidal streams in the open are, by their very nature, **rotary**
    - They only tend to flow back and forth (rectilinear) when constrained by land masses and shoals
- The sense of rotation is controlled by many factors
    - Tide raising forces
    - Coriolis accelerations
        - Coriolis deflects currents to the **left** in the **south**ern hemisphere and to the **right** in the **north**ern hemisphere.
    - Shelving coast
    - Combinations of oscillations and progressive waves
    - Bathymetry.

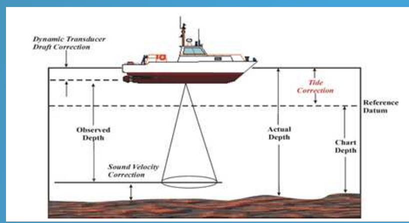
Nature of Oceanic Currents

- Currents in the deep oceans are set up by a number of mechanisms
  - Astronomical tide generating forces
  - Coriolis
  - Prevailing winds (wind generated gravity waves)
  - Atmospheric pressure gradients
  - Density gradients
    - Density varies with salinity, temperature and pressure (depth)
  - Cooling in the polar regions

Questions?

Tidal Levels and Datums

- When conducting a survey, the surveyor needs to measure heights & depths above or below certain fixed levels - **datums**
    - Either given to you by tidal department (CD)
    - Choose your own (SD)
  - Must be fixed connected to a fixed land datum
- In RSA, LLD = MSL = 0
  - This is only when MSL is a reference level with no value attached to it.



- **Mean Sea Level**
  - Natural reference level of the geoid
    - Average level taken up by the sea over a 19 year interval (over all tide readings)
    - Best vertical reference level ∴ basic reference level for tides

- Observed MSL subject to change:
    - Polar melting / glacial activity
    - Meteorological effect (frequently not local)
    - Short period effects (sea, swell, surges)
    - Tectonics
    - Astronomical effects

- MSL can only be found by observation:
  - Mean of all tide readings over long period (30days - 19 years)
  - Mean of 39 hourly observations (method involves applying filters)
  - Mean of 25 hourly observations (very poor method)
- **MSL is considered a level surface over a long stretch of coast, mean tide level which varies from place to place.**
- In this case: MSL ≠ LLD

- **Mean Tide Level (MTL)**
  - Mean of all the HW's and LW's over a period of time and is area specific
  - MSL cannot be converted to MTL (or vise versa)
- **DO NOT CONFUSE ACTUAL MSL, WHEN MSL = LLD and MTL**

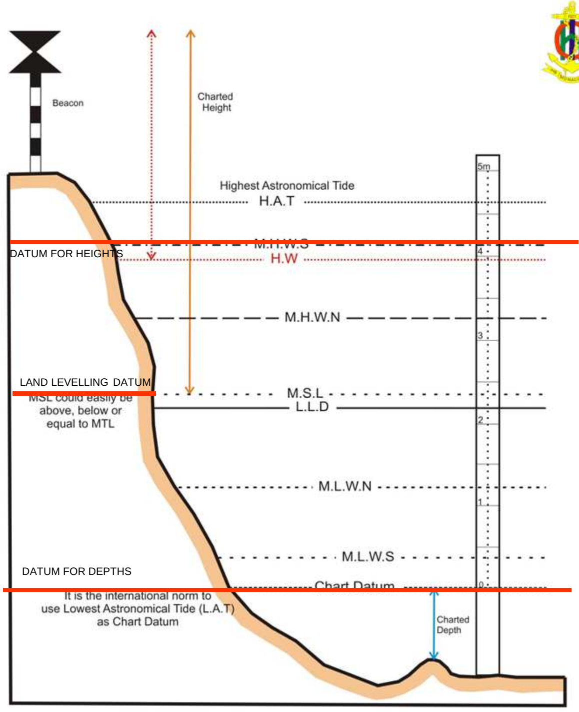
- When tide is mainly diurnal the values of MHHW & MLLW are used in place of MHWS & MLWS
- MHHW
  - Mean higher high water
    - Average height of the higher of the two daily high water levels experienced over a period of time at a given location. When only one HW occurs in a day, this is taken as the higher high water.
- MLLW
  - Mean lower low water
    - Average height of the lower of the two daily low water levels experienced over a period of time at a given location. When only one LW occurs in a day, this is taken as the lower low water.

- Symbols used:
  - Z_{oo} = value of MSL relative to CD
  - Z_o = height of MSL above CD from individual analysis
  - S_o = height of MSL above zero of the tide gauge from an individual analysis
  - A_o = height of MSL above arbitrary datum, other than CD or the zero of observation

- Sounding datum (SD)
  - The low-water plane to which soundings are reduced and above which drying heights are given on a bathymetric sheet.
    - Datum that is established in the field by the surveyor
- Chart datum (CD)
  - The datum to which all soundings on large scale navigational charts of an area are reduced
  - The datum to which tidal heights are referred
  - Lowest astronomical tide in RSA
  - The water level will seldom fall below this level
  - Should vary gradually from area to area
    - Avoid errors of discontinuities with adjoining charts
- The surveyor does not establish CD in the field

- Lowest Astronomical Tide (LAT)
  - The lowest level of tide that can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions.
    - This level may not be reached every year.
    - Calculated from 19 years worth of tidal predictions
- In RSA and United Kingdom: CD = LAT and is port dependent
- In USA: MLLW for Sounding and Chart Datum
- In Canada: CD= surface of Lower Low Water, Large Tide (LLWLT)
- THE IHO Has adopted LAT as Chart Datum

TIDAL HEIGHTS AND DATUMS

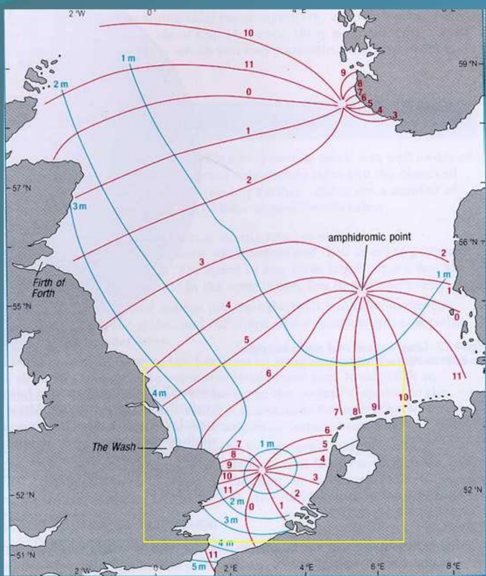


Co-Tidal Charts

- Chart showing lines joining places having (say) HW at the same time, & joining places having equal tidal ranges.
  - Published co-tidal charts cover critical areas
  - Surveyor may construct his own from tide tables or own observations.
- Used to establish a datum at a point off-shore that is relative to a datum at a port ashore
  - Soundings obtained offshore can be reduced using tidal observations from the port ashore.
- Shows both co-tidal and co-range lines

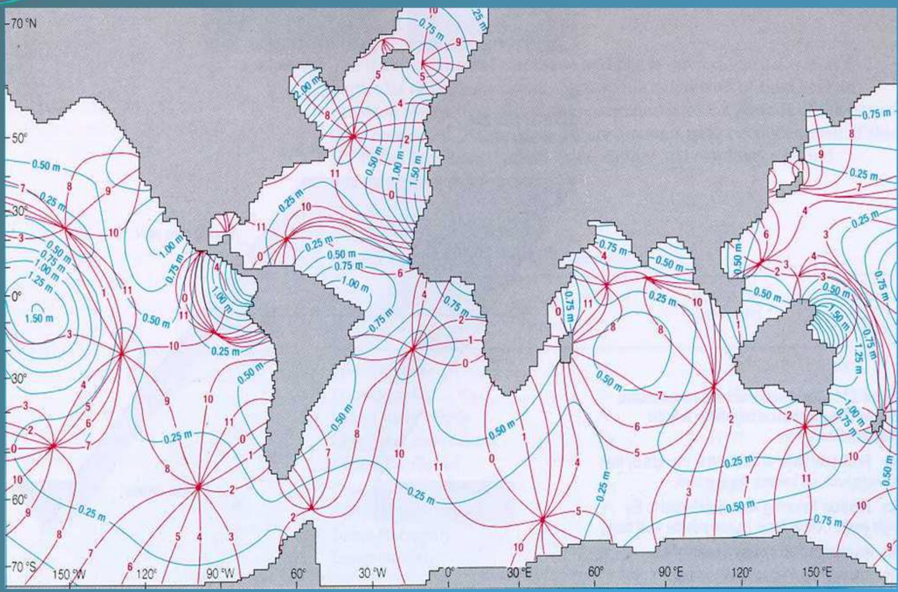
- **Co-tidal** lines
  - Joins places at which HW (or LW) occurs simultaneously.
  - Needs careful definition (**read the fine print!!**)
    - Some charts show the line at intervals of 30° in the phase lag of the average tide (m_2) - hours of lunar time (lunitidal interval)
    - Some charts are in solar time
- **Co-range** lines
  - Joins places of equal range
  - Can be split to show lines of mean spring range and mean neap range.

SEMI-DIURNAL CO-TIDAL CHART



Amphidromic Points, Co-Tidal Lines and Co-Range Lines in the North Sea

Worldwide Co-Tidal Chart



Questions?

Observations
Equipment and Procedures

Tides and Tidal Streams

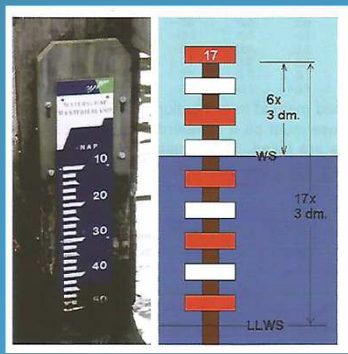
Types of Tide Gauges

- A tide gauge (TG) is an instrument for measuring the height of the tide. Basic classification
- TG's divided into two groups:
  - Non-registering gauges which require the presence of an observer to take and record the height of the tide.
  - Self-registering or automatic gauges which automatically record the rise and fall of the tide while unattended.
- **Nowadays, manual readings by tide staff, probes and tapes are mainly used for frequent gauge/staff comparisons during deployment to assist in assuring measurement stability and minimizing processing type error**

Types of Tide Gauges

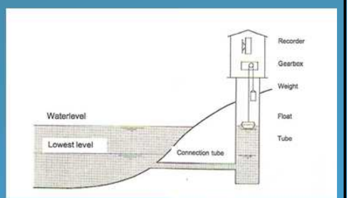
Level/ Tide Pole:

- Most commonly used in Surveys
- Read Manually by an observer
- Zero local Chart Datum
- Advantages:
  - Cheap, easy to install
  - Extremely common
  - Harbours, sluices, bridges
- Disadvantages:
  - Not automated
  - Needs to be near a tide gauge
  - Generally checked infrequently
    - Degrades level of accuracy



Float Actuated:

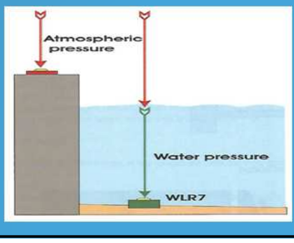
- Vertical tube with a float inside attached to a recording device.
  - Movement of float recorder by a stylus on paper or on an electronic sensor.
- Zero local Chart Datum
- Advantages:
  - reliable
  - accurate
- Disadvantages:
  - Biological and non- biological fouling
  - Regular cleaning required
  - Temperature variations
    - Inside and outside the tube



Pressure Gauge:

- Quartz pressure sensor or manometer
  - Measures height of water column above the sensor.
- Zero local Chart Datum

- Advantages:
  - Can be used in areas that have inaccessible locations and greater water depths
    - No structure above the water level
- Disadvantages:
  - Measured data MUST be corrected
    - Variations in atmospheric pressure and sea water density
    - Ambient atmospheric pressure
      - Separate pressure sensor on the surface
    - Source of errors.



Altimeter:

- Measures height of water level from a known point above the waterline
- Two types:
  - Measures up (Placed on sea bottom)
    - Inverted echo sounder
  - Measures above water to waterline
    - Laser, radar or acoustic.
- Zero local Chart Datum
- Advantages:
  - Can be constructed relatively easily
- Disadvantages:
  - Susceptible to noise.

Capacity type tide gauges:

- Measures height of water level in-between two iron bars
- Voltage applied over both bars
  - Creates resistance (capacity)
- The resistance (capacity) is different depending on if the bars have water or air between them.
  - Can be used to calculate water height
- Disadvantages:
  - Susceptible to salinity variations
  - Requires regular calibration and cleaning
  - Biological fouling.

My Tide Gauge

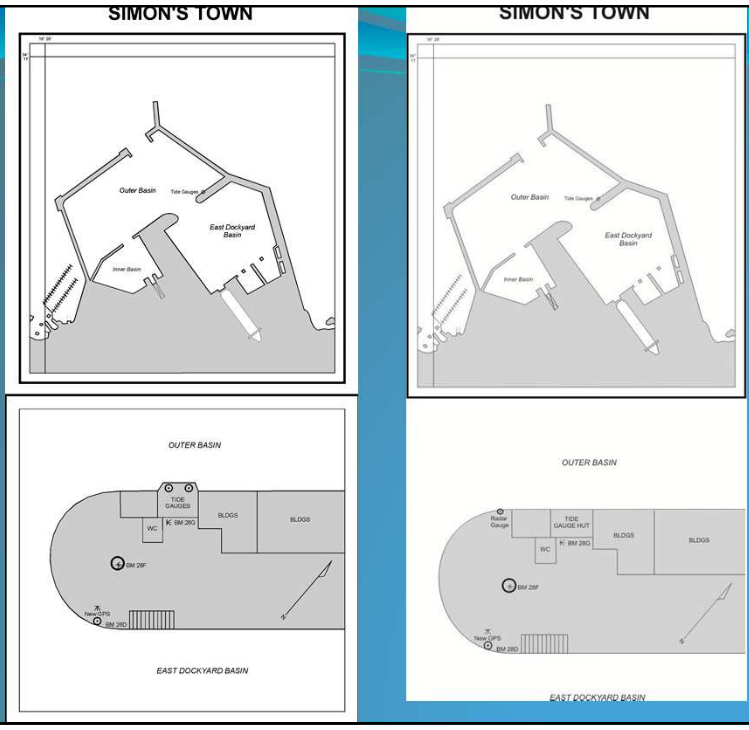
- How do I decide what gauge is best for me?
  - Research the different gauges on the market,
  - Speak to /email colleagues about their experiences,
  - Decide what type of gauge will be best for your environment,
  - Budget – expensive is not always better!
- If possible, try and bench test the equipment you want to buy
- Consider the costs of maintenance, upgrades/replacement, peripherals.

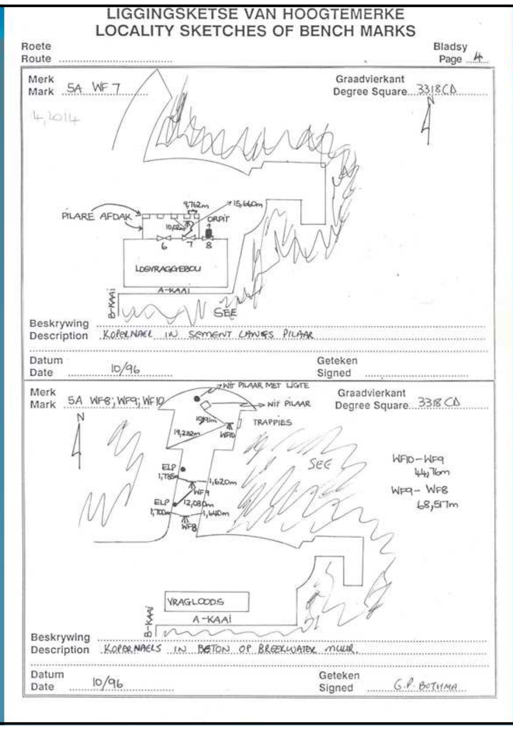
- Decide on a location for installation.
  - Effective planning and field reconnaissance is very important.
    - Physical Environment:
      - Is there swash/ oscillations?
      - Is there a benchmark network or will one need to be established?
        - Availability of benchmark data.
      - Are there existing structures I can use or will these need to be built?
      - Is there power available?
        - Local stability/ solar/ batteries
      - How will data be retrieved?
        - Landline/ 3G to an FTP site/ Manually

- Security of the equipment and the data?
  - Will access be restricted?
  - Are people able to tamper with the equipment

- Calibration and routine maintenance
  - How easy/ difficult will it be to service, calibrate, maintain?
  - Can this be done with one or two people or is a boat and crew required.
  - Is specialized equipment needed?
  - Lifespan of the equipment
    - Corrosively of the water/air
  - How often should the gauge be leveled and calibrated?
    - Minimum of once a year
  - High or low biological fouling?

- Each station must have its own file
  - Tide station report
  - Nautical chart section
  - Benchmark Sketch
  - Photographs of component parts and location
  - “To Reach” description
  - Benchmark descriptions and photographs
  - Leveling Records
  - Calibration records
  - Maintenance records





LIGGINGSKETSE VAN HOOGTEMERKE
LOCALITY SKETCHES OF BENCH MARKS

Roete / Route ....

Bladsy / Page 4

Merk / Mark 5A WF 7

Graadvierkant / Degree Square 3318CD

4,2014

Beskrywing / Description KOPERNAEL IN SEMENT LANGS PILAAR

Datum / Date 10/96

Geteken / Signed ....

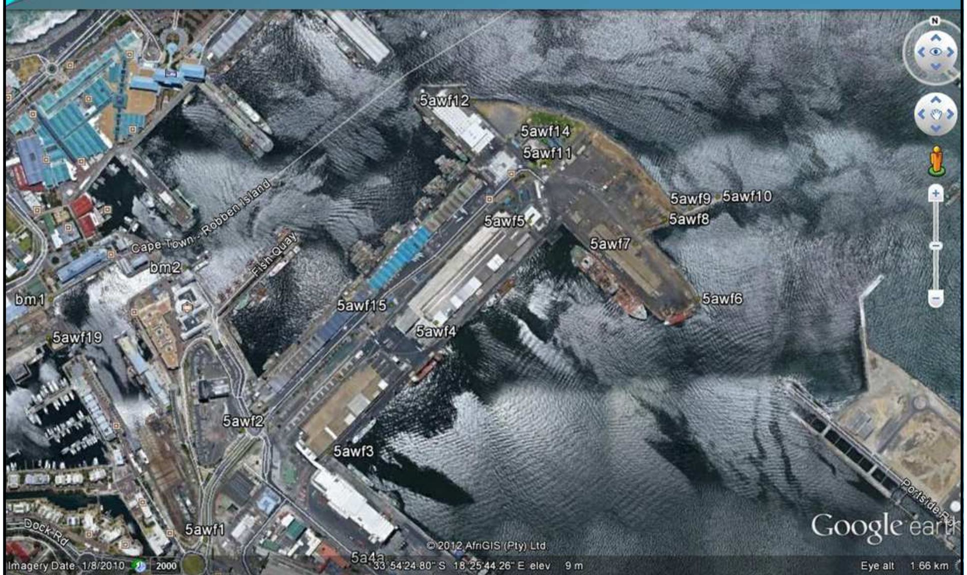
Merk / Mark 5A WF8; WF9; WF10

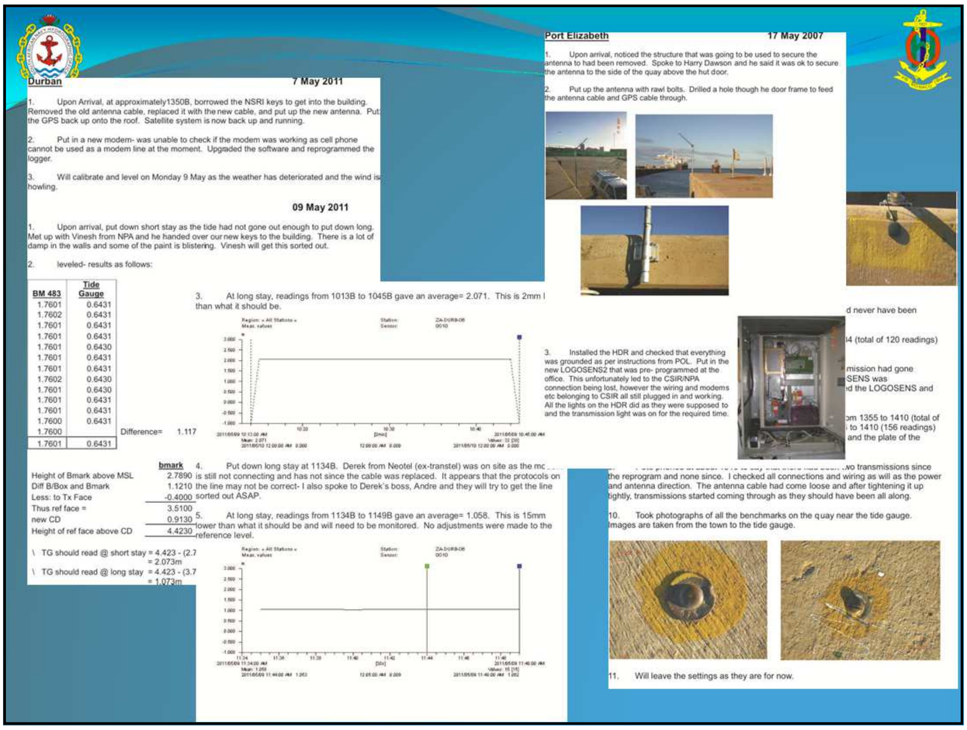
Graadvierkant / Degree Square 3318 CD

Beskrywing / Description KOPERNAELS IN BETON OP BREEKWATER MUUR.

Datum / Date 10/96

Geteken / Signed G.P. BOTHMA





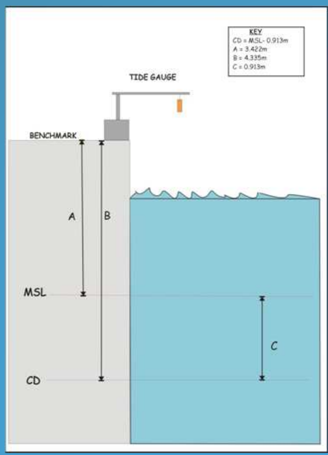
Installing A Radar Type Tide Gauge

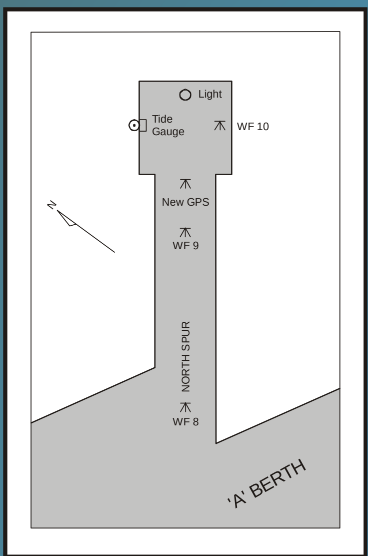
Leveling the Transducer

- The transducer needs to be level on the davit
  - Spirit level

- After Installation:
  - Gauge must be levelled into local benchmark network and a reference level programmed into the logosens.
  - Must know
    - Exact height of benchmarks above LLD
    - what LLD is.
- In RSA LLD = MSL = 0
  - Anything above MSL is height or elevation
  - Anything below MSL is a depth.
- Thus benchmarks are heights above MSL
- CD is LAT ∴ CD is a value below MSL
  - Durban CD is MSL – 0.913

- So a benchmarks height can be converted to a height above CD
  - Height of benchmark above MSL + CD for the port
  - A + C = B

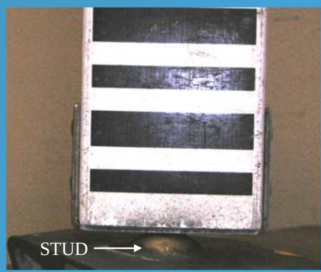




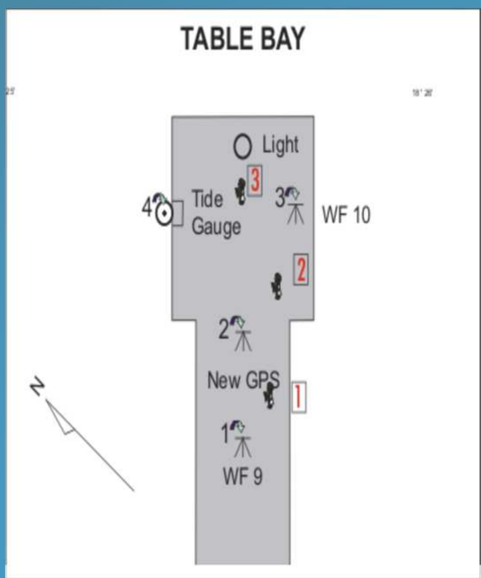
- Identify benchmarks and check their location with a site map (left)
- Benchmark heights can be obtained from
  - *Land Surveyor*
  - *Town Planners Office*

- WF9 = MSL + 2.331m
- WF10 = MSL + 2.343m
- NEW GPS = MSL + 2.329m

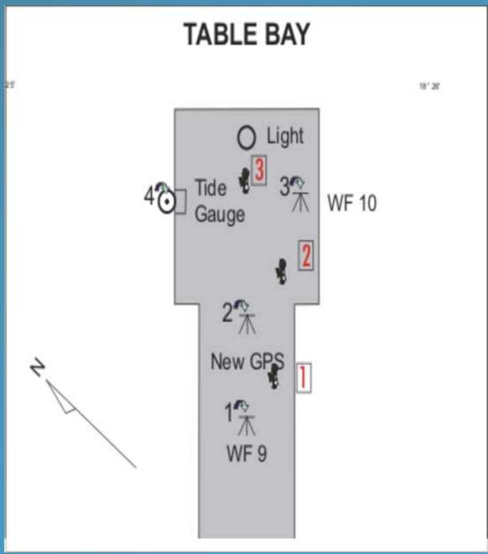
- The tripod, with dumpy, must be positioned ½ way between each benchmark.
- The tach staff will be placed (level) on the benchmark stud



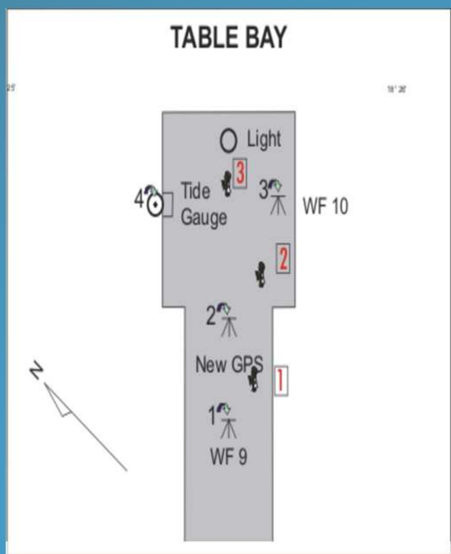
- Surveyor stands at positions 1, 2 & 3
- Person holding the tach staff places it on the benchmarks marked 1, 2, 3 & on the tide gauge transducer at 4



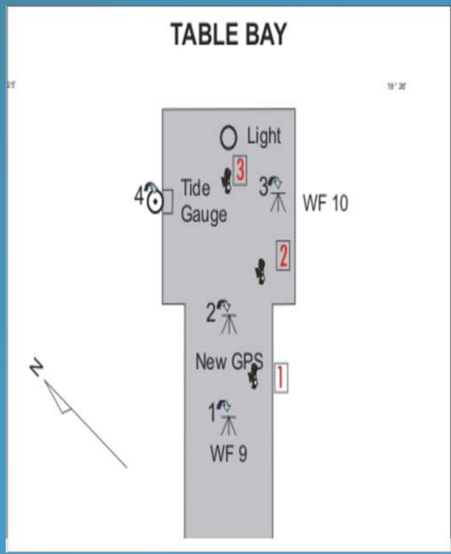
- You stand at 1
  - Assistant at 1
    - Take readings
  - You turn, without moving the tripod, to 2
  - Assistant moves to 2
    - Take readings
- You move to 2
  - Assistant stays at 2, turning to face you without lifting the tach staff off the benchmark stud
    - Take readings.



  - You turn, without moving the tripod, to 3
  - Assistant moves to 3
    - Take readings
- You move to 3
  - Assistant stays at 3, turning to face you without lifting the tach staff off the benchmark stud
    - Take readings.

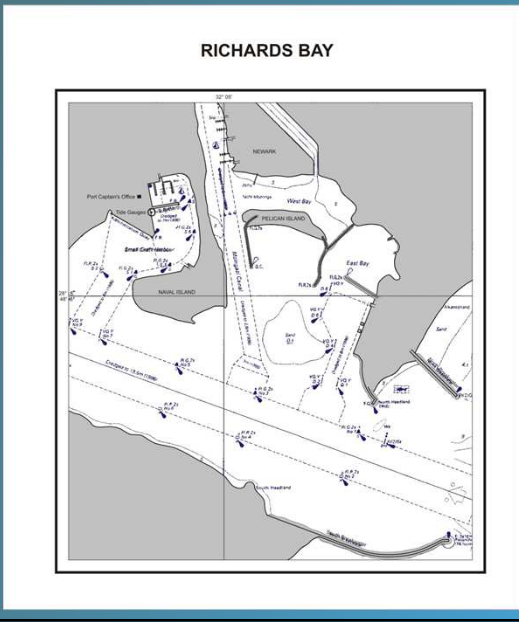


- You turn, without moving the tripod, to 4
- Assistant moves to 4
  - Take readings
- Repeat this process "leap-frogging" back to where you will be taking reading with the tach staff on position 1
- If correctly done:
  - Forward = backward
    - ∑ forward readings –
    - ∑ backward readings = 0



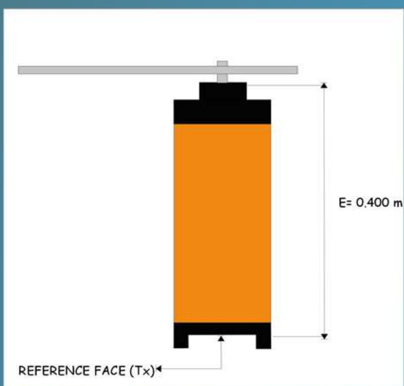
- When placing the tach staff on the transducer
  - Always place it on the "black box"
  - Never on the bracket.

- You can get the STD tach staff (1)
  - Graduations that can be read off manually
- And the electronic tach staff (2)
  - barcoded



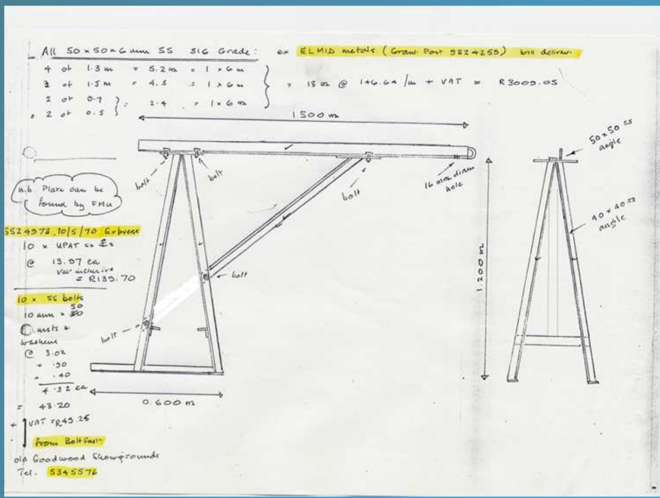
Example of survey results
For Richards Bay,
Northern Kwazulu Natal

MEASUREMENTS OF THE "KALESTO" RADAR GAUGE



- From top of "black box" to the transducer face (tx) is 0.400m

SURVEYING AND CALIBRATION

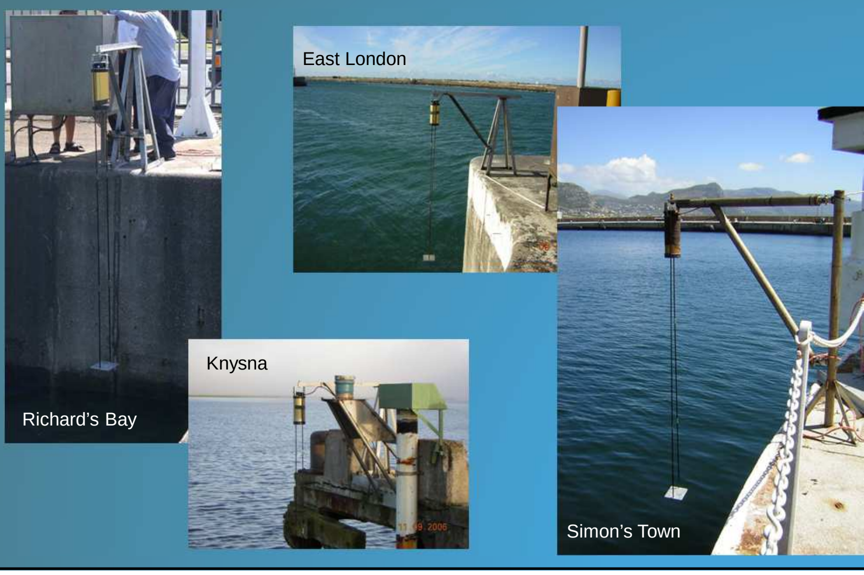


"KALESTO" RADAR GAUGE IN SITU (Richards Bay)

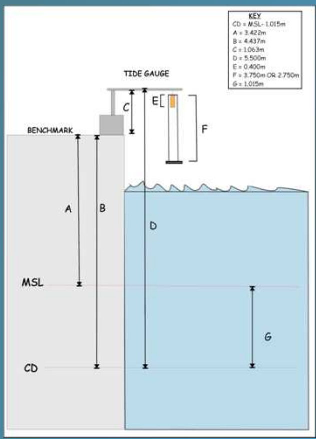
"KALESTO" RADAR GAUGE

Platform For Easy Access To Gauge During Leveling And Calibration. (Richards Bay)

Calibration rods



Calibrating a Radar Gauge



- Example of a calculation for check calibration of radar gauge, if
  A= 3.422m (known value for local benchmark)
- Av. A above CD = Av B

Av A	=MSL + 3.422
∆ (D-B)	= + 1.063
less E to Tx	= - 0.400
∴ Ref Face	=MSL + 4.085
CD	=MSL - 1.015
	+5.100

∴ Ht of Tx = 5.100m above CD

∴readings @ short stay:
5.100 - (2.750 - 0.400) = 2.750m

∴ readings @ long stay:
5.100 - (3.750 - 0.400) = 1.750m

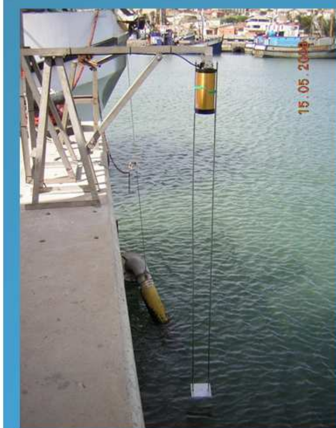
SCH3	SAN84.2	Tide Gauge
1.7207	1.7271	0.6649
1.7207	1.7271	0.6649
1.7207	1.7271	0.6649
1.7208	1.7271	0.6649
1.7207	1.7271	0.6649
1.7207	1.7271	0.665
1.7207	1.7271	0.6649
1.7206	1.7271	0.6649
1.7207	1.7270	0.6649
1.7207	1.7271	0.6649
1.7207	1.7271	0.6649
1.7207	1.7271	0.6649
1.7207	1.7271	0.6649

Difference A2	1.0558
Difference A1	1.0622

	SCH3	SAN84.2
Height of Bmark above MSL	3.4290	3.4220
Diff B/Box and Bmark	1.0558	1.0622
Less: to Tx Face	-0.4000	-0.4000
Thus ref face =	4.0848	4.0842
new CD	1.0150	1.0150
Height of ref face above CD	5.0998	5.0992
AV=	5.0995	

∴ TG should read @ short stay = 5.0995 - (2.750-0.400)
= 2.7495m

∴ TG should read @ long stay = 5.0995 - (3.750-0.400)
= 1.7495m



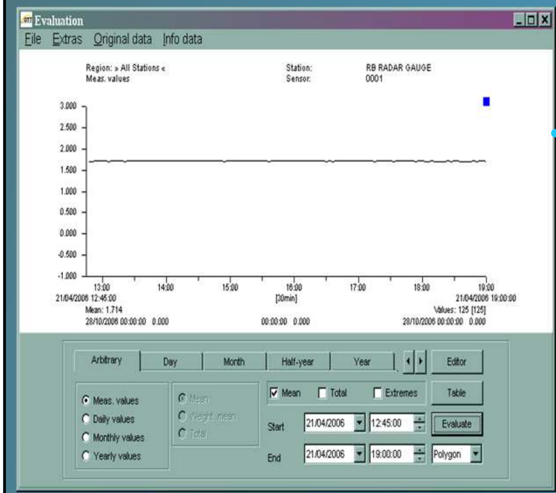
Tide G	Tide Gauge		
1.7383	0.6498		
1.7383	0.6498		
1.7384	0.6498		
1.7383	0.6498		
1.7383	0.6492		
1.7382	0.6492		
1.7382	0.6498		
1.7382	0.6498		
1.7383	0.6498		
1.7386	0.6497		
1.7383	0.6497		
1.7383	0.6497		
1.7384	0.6497	Difference=	1.0886
1.7383	0.6497		

	Tide G	
Height of Bmark above MSL	2.8120	
Diff B/Box and Bmark	1.0836	(minus 5mm for calibration plate)
Less: to Tx Face	-0.1170	
Thus ref face =	3.7786	
new CD	0.9130	
Height of ref face above CD	4.6916	

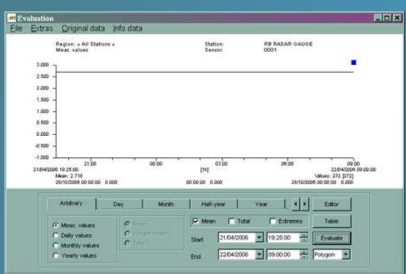
∴ TG should read @ short stay = 2.0586m
≈ 2.059m
∴ TG should read @ long stay = 1.0586
≈ 1.059m

CALIBRATING THE "KALESTO" RADAR GAUGE

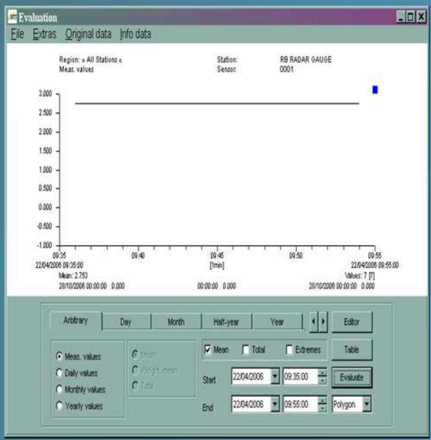
- Program the reference level into the LOGOSENS
  - With USB or RS232 cable
  - Create station in the office before departure to the installation site.
- "Play" with the software



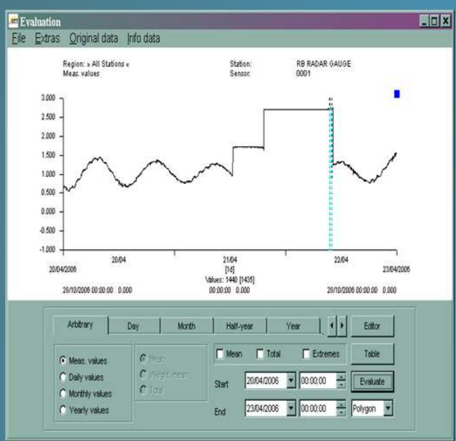
- At short stay:
  - From 1300B to 1900B
  - No values: 125
  - Mean: 1.715m above CD
  - This is 0.035m **LOW**
    - Add 0.035m to ref in LOGOSENS



- At long stay:
  - From 1925B to 0900B next day
  - No values: 272
  - Mean: 2.718m above CD
  - This is 0.032m **LOW**
    - Add 0.032m to ref in LOGOSENS



- After resetting the reference level in the LOGOSENS
- At long stay:
  - From 0935B to 0955B
  - No values: 7
  - Mean: 2.753m above CD
  - This is 0.003m **HIGH**
    - This 3mm is perfectly acceptable to be out by.



- This is how the previous information would be displayed once it is downloaded for a longer period of time.
- Calibration records are digitally stored in this method.

SOME USEFUL TIPS

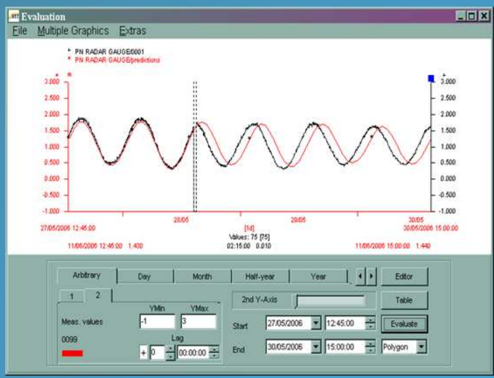
- Always print weekly graphics.
  - Errors can be noted and corrected timeously
    - Battery not working
    - No power
    - Telephone lines down
  - Assists with analysis of tides
    - Shows "spikes" very clearly.
- Insert your predictions into the software program, if possible
  - Check accuracy of your predictions
    - Overlay actual and predictions
  - Can pick up time/ clock errors timeously

EXAMPLES OF HYDRAS3 GRAPHICS

- No power, battery has not "kicked" in
  - Data lost.

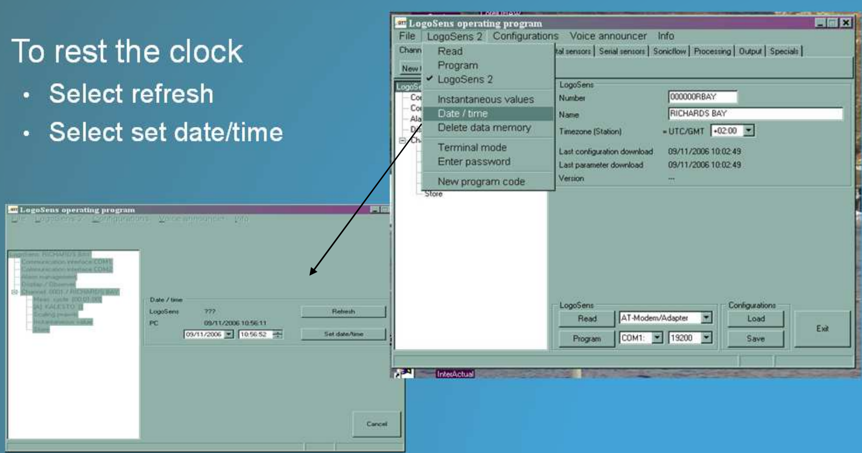
EXAMPLES OF HYDRAS3 GRAPHICS

- No power, battery has not "kicked" in
  - Data lost.
  - Clock stopped ∴data out of phase
- Reset clock immediately!
- Data will have to be manually moved back into phase

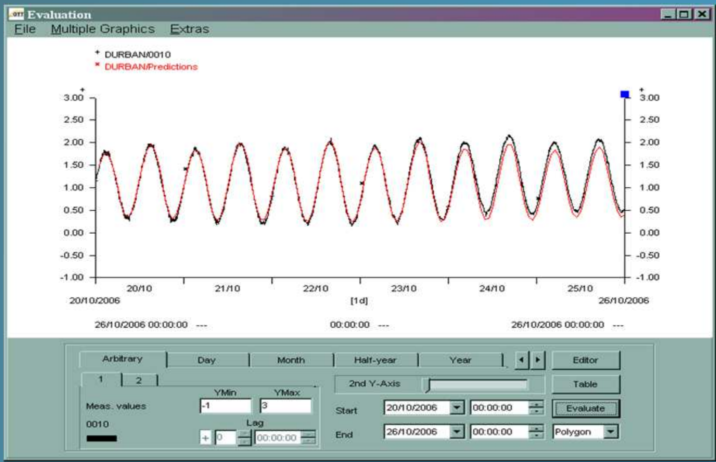


EXAMPLES OF HYDRAS3 GRAPHICS

- To rest the clock
  - Select refresh
  - Select set date/time

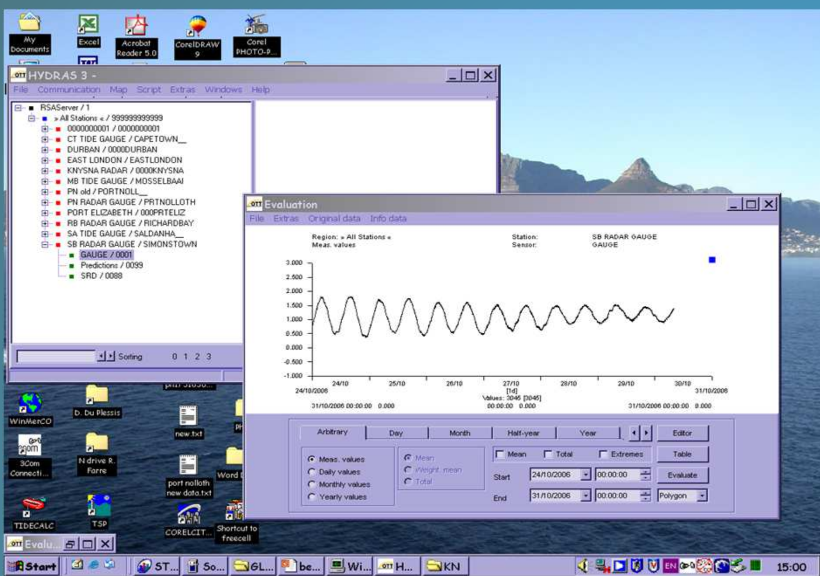


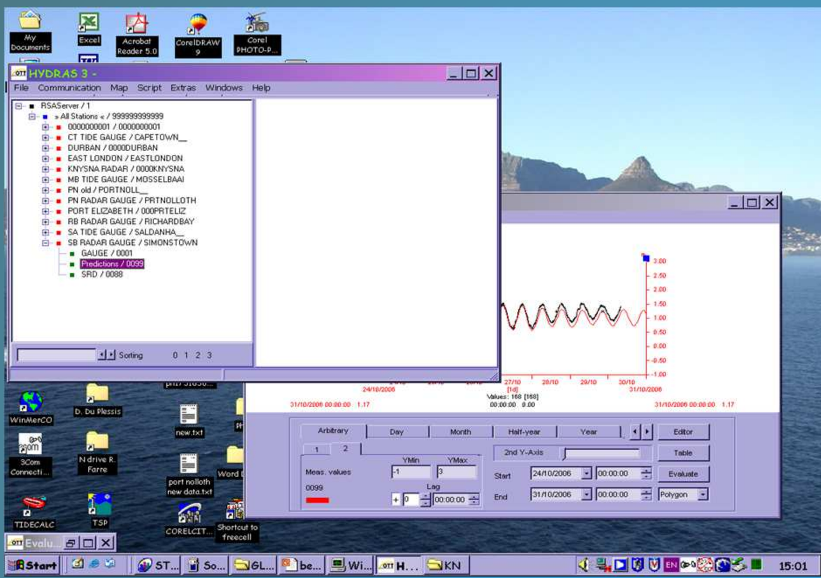
EXAMPLES OF HYDRAS3 GRAPHICS



- Predictions vs Actuals for Durban

MULTIPLE GRAPHICS




HYDRAS 3
File Communication Map Script Extras Windows Help
RSAServer / 1
CT TIDE GAUGE / CAPETOWN
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KNYSNA RADAR / 000KNYSNA
MB TIDE GAUGE / MOSSELBAAI
PN RADAR GAUGE / PRTNOLLOTH
PORT ELIZABETH / 000PRTELIZ
RB RADAR GAUGE / RICHARDBAY
SB RADAR GAUGE / SIMONSTOWN
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Predictions / 0099
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Arbitrary
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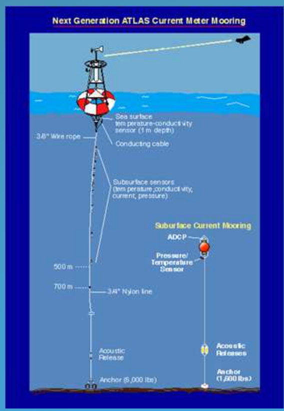
Questions?

Measurement of Tidal Stream

- Tidal stream or current observations require careful planning and application if the results are to be reliable
- Traditionally
  - Tidal stream measuring is uneconomical
  - Even if the greatest care is taken, the resulting stream prediction will **never** be as accurate as vertical tide predictions
- Trend in equipment is towards instruments that permit continuous data with the ship underway
  - Buoy-moored current meter



- Ideally
  - Measurements made hourly or ½ hourly for lunar month (29 days)
    - This is for buoy moored current meters
- In practice
  - Obtain a minimum of 25 hour/ ½ hour intervals
  - Weather should be good (i.e. several days of low winds)
  - At springs (streams are strongest and errors will be minimized)
  - Repeat at a time other than springs

- Measurement techniques fall into two categories
- Lagrangian
  - Labeling and tracking a volume of water
  - Physical observation data
  - Moving with the stream
    - Pole logship. Dyes, drift cards
- Eulerian
  - Monitoring flow past a point
    - Current meter

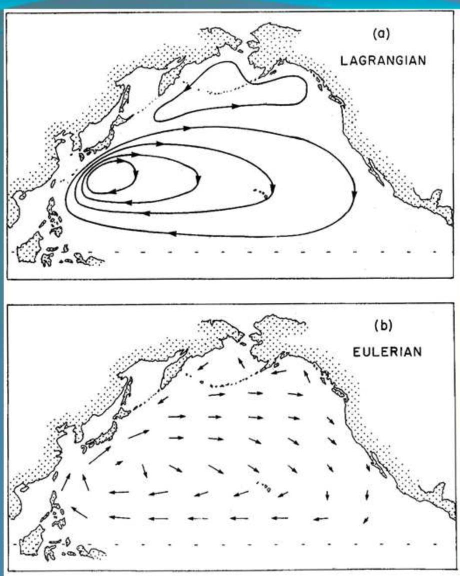
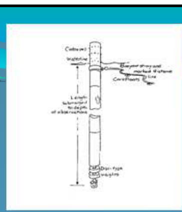


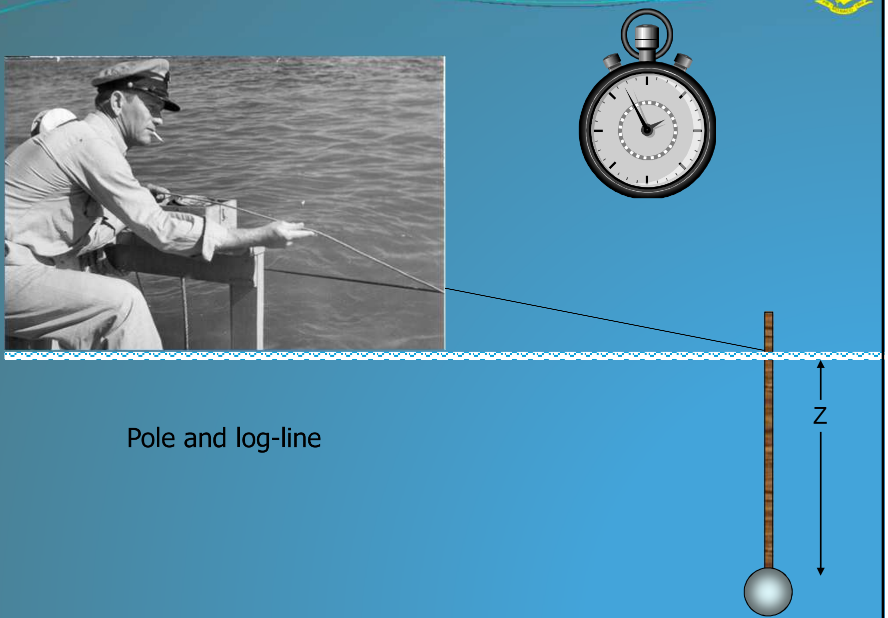
FIG. A.4 *Flow pattern described in (a) Lagrangian manner (flow lines), (b) Eulerian manner (velocities at points).*

Lagrangian v. Eulerian Descriptions

Pole Logship



- Pole logship can be either free-floating or tethered
  - Gives average flow rate
  - Direction over pole depth
- Disadvantages:
  - Immobilizes ship or boat and personnel for long periods of time
  - Handling problems
  - High accuracy fixing required
  - Inaccurate results
- Logship usually 15-30 ft long
  - Weighted so that it floats upright (only a few inches above surface to reduce wind resistance)
  - Top of pole fitted with small light and cats eyes (for tracking at night)



Tethered logship

- Pole attached to ship by buoyant line (first 15-30m unmarked, rest marked as for a lead-line)
- Precise method for measuring vessels position required
- Allow logship to drift away from vessels influence
- At zero of logline, start stopwatch, fix vessel
  - Note bearing of logship, ship's head and amount of line out
- After 1-2 min, stop stopwatch, fix vessel
  - Note bearing of logship, ship's head and amount of line out
- Obtain 3 sets of observations in quick succession
  - Note meteorological conditions
- Plot all 3 runs and combine to obtain mean rate and direction of flow

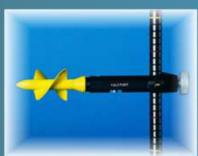
Free-floating logship

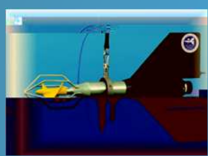
- The same pole can be used, without the distance line and marked with a small buoy
- The logship is released and it's position fixed.
  - NB the boat must not approach the logship to closely
- Re-fix the logship 2 or 3 times at regular intervals
  - Take time to the nearest second
- Recover the logship and repeat the sequence once or twice more.
  - Note the meteorological conditions
- Plot fixed positions of the logship
  - Calculate the rate and direction for each run and average
  - Refer average to mean time of observations
- Can be tracked by high-definition radar

Flow Meters

- A current meter is the most versatile method of measuring rate and direction of flow at any depth (even in deep oceans)
- May be ship-tethered, bottom- or structure- mounted or buoy-moored
- Readout is either direct to a control unit on the ship, or remotely recorded within the meter
- Meters in use today employ one of 3 methods for measuring rate and direction
  - Impeller or rotor
  - Electromagnetic current meter
  - Acoustic Doppler Current Profiler (ADCP)

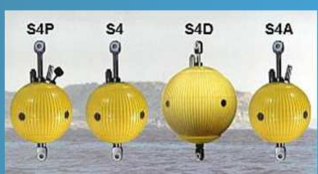
- Impeller or rotor
  - The impeller rotates in the current at a speed proportional to current rate
    - Vane on the instrument keeps it facing current flow.
- Pulses sent to the control unit
  - Current rate displayed in knots or m/s
  - Direction is sensed by aircraft type magnetic compass
- Dnc-3n current meter
  - Measures direction and velocity
  - Underwater unit consists of 3 parts
    - Nose cone
    - Rear tube
    - Fin/ impeller guard assembly



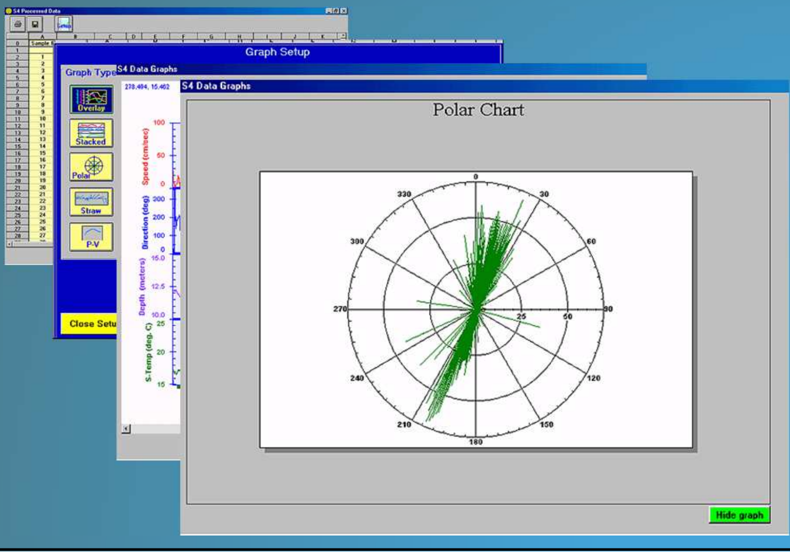


- Surface unit consists of
  - All electronics and display units
- Interconnecting cable is of oceanographic type
  - Combines function of strain cable and data transfer
- DNC-3N individual parameters
- Direction
  - Determined by precision double mounted compass
    - Sample rate 3X/second
  - Resultant digital signal converted to analogue, transmitted to surface
- Velocity
  - Impeller magnetically coupled to an optical sensing mechanism which converts the rotation to an electrical signal
- For greater accuracy atmospheric pressure compensations should be applied to all readings

- Electromagnetic current meter
- No moving parts
  - No risk of interference by floating debris
- Use faraday's law of electromagnetic induction
  - Law of relating the electromotive force (emf) induced a circuit to the change in magnetic flux threading it
    - $\varepsilon = -D\varphi/dt$
    - ε: Electromotive force, φ: Magnetic flux, t: Time
- A polar co-ordinate vector is obtained which represents the flow rate and direction



Electromagnetic current meters



- Acoustic Doppler Current Profilers (ADCPs)
- There are no moving parts
- Can measure up, down or sideways
- Configuration of transducers to examine doppler frequency shifts

- Doppler effect
  - The apparent change in frequency of a sound wave received, with respect to the frequency emitted, when the source and receiver are in relative motion
    - Example: train whistle

- ADCP uses the doppler effect by transmitting sound at a fixed frequency and listening to echoes returning from sound scatterers in the water
  - Sound scatterers are small particles or plankton that reflect sound back to ADCP.
  - On average they move at the same horizontal velocity as the water
- Sound scatterers scatter sound in all directions
- Most of the sound goes forward
- The small amount that reflects back is analysed for its doppler shift.

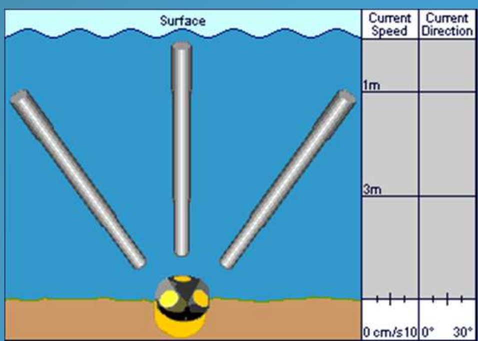
Acoustic Doppler Current Profilers

Example shows the display of data corresponding to the various depth cells within the water column. Each depth cell contains the average of the data collected by a series of transmitted sound pulses ("pings").

(a) Several pings are transmitted by the ADP each second.

(b) Pings are reflected back to the ADP after bouncing off particulate matter in the water.

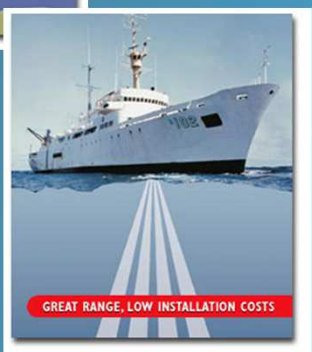
(c) Pings are processed (i.e. "averaged") by the ADP for recording and display.



Velocity accuracy:
- 1200, 600: ± 0.25% of the water velocity relative to the ADCP ± 2.5mm/s
- 300: ± 0.5% of the water velocity relative to the ADCP ± 5 mm/s

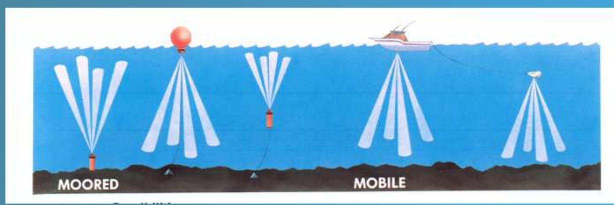
Velocity resolution: 1mm/s
Velocity range: ± 5m/s (default); ± 20m/s (maximum)

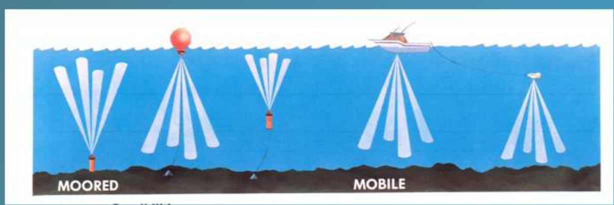
Compass (fluxgate type, includes built-in field calibration feature)
- Accuracy: ± 2° *
- Precision: ± 0.5° *
- Resolution: 0.01°



Frequency	Range	Cell Size
38 kHz	800-1000m	24m
75 kHz	560-700m	16m
150 kHz	380-425m	8m

- Multiple Beams
- ADCP using multiple beams pointed in different direction it senses different velocity components
- Trigonometric relations can convert current speed into compass components
  - One beam is required for each current component
  - ∴ To measure 3 velocity components (eg E, N, + UP), there must be at least 3 acoustic beams
- Four beams are used in the "Janus Configuration"

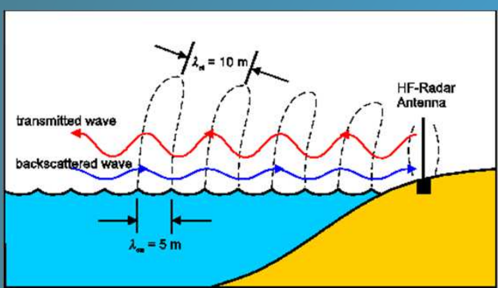


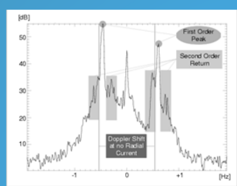


- Deployment possibilities for ADCP
- Fixed on a stationary platform
- Suspended on a mooring
- Housed in bottom frames
- Attached to surface buoys
- Towed behind or mounted on a vessel (surface or submerged)

- Remote sensing
- Radar backscatter
  - Commercial VHF and HF radar backscatter system
- Experimental systems- military radar
  - Shows benefits of a long range horizontal coverage possible
- Variety of systems available
- Interpretation is not simple
  - Inter-comparisons between radar and drifter measurements are important
- Radar yields excellent information
  - Only surface movement is detected
    - Wind-driven surface currents can be obscured by tidal flow

- Satellite observation
  - Of ocean currents and wind have long been sought
- Laboratory developments of radar backscatter models to satellite measurements needs more observations.





Questions?

So What Happens to the Data?

- The data is used for creating predictions
  - Bi-Lateral Agreements
    - More experienced
- Data sent to Sea-Level Rise research organisations
  - PSMSL (UK)
  - JASL (Hawaii)
  - Tsunami warning centres
- Data sharing

Tidal Analysis and Predictions

- The term tides can be defined as being **periodic** movements, which are directly related in **amplitude and phase** to some **periodic** geophysical force.
  - The emphasis of the definition being on the **periodic** and **regular** nature of the motion.
  - Each tide reading can be thought of as an observation for which an equation can be written.
- The unknowns are the values of mean sea level , h and g for each constituent.
  - Provided that there are more observations than unknowns it would be possible to solve the set of simultaneous equations by least squares analysis and derive values for the unknowns.
  - In theory a solution for MSL and the four primary constituents should be possible from ten or more tide readings.
  - In practice this would be the equivalent of fixing a position with three virtually parallel position lines, so data for a much longer period is required.

- Movements due to the regular movements of the moon-earth and earth-sun systems are called **gravitational tides.**
- The smaller movements due to regular meteorological forces, which are called **radiational tides** because they occur at periods directly linked to the solar day.
- Any sequence of measurements of sea level will have a tidal component and a non-tidal component.
- The non-tidal component which remains after analysis has removed the regular tide is called the **meteorological surge residual** (usually referred to as a surge).

- Tidal analysis of data collected by observations of sea levels (and currents) has two purposes:
  - A) A good analysis provides the basis for predicting tides at future times.
  - B) The results of an analysis can be interpreted scientifically in terms of the hydrodynamics of the seas and their responses to tidal forcing.

- The process of analysis reduces many thousands of numbers, eg: a year of hrly sea levels consists of ± 8760 values, which contain the soul or quintessence of the record (Godin 1972).

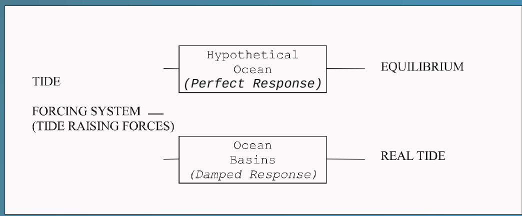
- In tidal analysis the aim is to reproduce significant time stable parameters which describe the tidal regime at the place of observation.
  - Should be in a form suitable for prediction,
  - Should be related physically to the process of tide generation
  - Should have some regional stability.

- The parameters are often termed **tidal constants** on the implicit assumption that the responses of the oceans and seas to tidal forcing do not change with time.

- Also implicit in the use of this term is the assumption that if a sufficiently long series of levels is available at a site, then a true value for each constant is obtained by analysis.

- The longer the period of data available for analysis, the better will be the approach to the true value,
  - Except in places subject to natural or man-made changes in the topography.
    - At such places the tidal "constants" obtained from analysis of a long period may have changed during that period.
    - An extreme example is the building of the causeway connecting Singapore to Johore, which actually reversed the direction of streams in the Johore Strait.
    - Less dramatic, but still significant, changes can occur as a result of dredging or natural shifting of sand banks.

- The close relationship between the movements of the moon and sun, and the observed tides, makes the lunar and solar co-ordinates a natural starting point for any analysis scheme.
- The **equilibrium tide** defines a tidal level at each point on the earth's surface as a function of time and latitude.
- The observed tides differ very markedly from the equilibrium tide
  - Real depth and boundaries.
  - In shallow water the tides are further distorted by the loss of energy through bottom friction and the preservation of the continuity of water flow.
- However, LaPlace's principle**,** states that: "the frequencies inherent in a forced system, however damped, show the same frequencies as the forcing system".



- The observed real tides have their energy at the same frequencies as the equilibrium tide.
  - The NB of the equilibrium tide lies in its use as a **reference** to which the observed phases and amplitudes of harmonic tidal constituents can be related, when preparing models for tidal prediction.
  - It also gives an indication of the important harmonic constituents to be included in a correct tidal analysis model.

- **Typically performed on observed hourly height time series to obtain amplitude and phase of each tidal constituent**

- **Four basic processes**

  - **Initial separation of individual constituents from the observations**
  - **Orientation of the constituent tides with the astronomical elements (tidal potential**
  - **Nodal factor adjustment**
  - **Elimination from each constituent the effects of other nearby tidal constituents**

- **Two types typically used:**

  - **Fourier Analysis – usually used for short time series (less than 29 days)**
  - **Least-squares Analysis – usually used for time series>180 days**

Analysis of Tidal Stream Data

- Two methods for analysis of tidal stream data
- Harmonic analysis
  - Similar to that used for the vertical movement of tides
  - 25 or 50 hourly observations have been obtained only the four main tidal constituents can be determined
- Semi-graphic methods
  - Maintain an empirical relationship between tidal stream at a place and the tide at a suitable std port.
  - Cannot handle diurnal inequalities in tidal stream
  - Assumes the stream is purely semi-diurnal

Prediction

- This is the easy part…
- Where the tide has been analysed it is possible to predict the tidal height at any time by evaluating the tidal equation for all known constituents.
- The tide tables publish data for mean sea level, the four primary constituents, M_2, S_2, K_1 and O_1 and quarter and sixth diurnal shallow water constituents, in part iii.
- The astronomical data from table vii is an adjustment of the pure data for the four primary constituents to take account of the effect of a further 20 constituents.
- The shallow water data is not for true constituents but describes the effect in relation to the amplitude and speed of the combination of M_2 and S_2.

Questions?

References

- Bowditch, N (LL. D.): *American Practical Navigator.* Defense Mapping Agency Hydrographic Centre. 1977
- Von Arx, W.S: *Introduction to Physical Oceanography.* Addison-Wesley Publishing Company, 1967
- Emiliani, C: *Dictionary of the Physical Sciences: Terms, Formulas, Data.* Oxford University Press 1987
- Hatfield, HR (Cdr RN): *Admiralty Manual of Hydrographic Surveying: Volume 2 Chapter 2: Tides and Tidal Streams.* The Hydrographer of the Navy, Taunton Somerset. 1969
- Forrester. W.D. :*Canadian Tidal Manual.* Canadian Hydrographic Services, Ottawa 1983
- University of Cape Town Ocean and Atmospheric Sciences course notes 1997-2001
- Plummer/McGreary: *Physical Oceanogreaphy 7th Edition,* Wm. C. Brown Publishers 1996
- W.G. van Dorn: *Oceanography and Seamanship 2nd Edition*, Cornell Maritime Press 1993
- Skilltrade BV, 2011 *Handbook of Offshore Surveying, Volume II Positioning and Tides*,
- Hicks, S.D.2006. *Understanding Tides*, CO-OPS, NOAA/NOS
- Parker, B.B., 2007. *Tidal Analysis and Prediction*, NOAA Special Publication NOS CO-OPS3, CO-OPS, NOAA/NOS
- Schureman, P., 1958. *Manual of Harmonic Analysis and Prediction of Tides,* Special Publication No. 98, Reprinted 1988, U.S DOC/ Coast and Geodetic Survey
- Boon, J.D., 2004. *Secrets of the Tide, Tide and Tidal Current Analysis and Applications,* Storm Surges and Sea Level Trends, Horwood Publishing Chichester, UK
- Admiralty Tide Tables
- TWLWG Tide Course notes and presentations