How Sea Level is Measured

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Sea Level Measurements

• The concept of measuring sea level is simple.
• Its “simply” a distance measurement : a ruler!
• However there are many different types of rulers….
• The most well known methods are a tide gauge and satellite altimetry
• Values of sea level (or sea surface height) are either spot-measurements at regular time intervals, or averages (called integrations) over certain short time intervals.
• For most tidal, storm surge or Mean Sea Level work, time intervals of 5, 6, or 15 minutes are adequate.
• For tsunami work, time intervals of a minute or less are usually needed.
What We Will Cover

• Tide gauges
• Satellite Altimetry
• Alternative Methods
  Satellite Gravimetry and the Argo Float Network
  ‘Proxy’ measurements from Geological Techniques
  GNSS Technology
Types of Tide Gauge Measurement

- Tide poles (or tide staffs)
- Float tide gauges
- Acoustic gauges in tube (2 types)
- Pressure gauges (several types)
- Radar gauges (several types)
Tide Pole (or Tide Staff) Gauges

- The simplest possible system, and lowest cost
- Important common sense ‘reality check’ alongside modern black box digital tide gauge systems
- Of course, tide poles have not for many years been a primary source of sea level data.
- However, it is always worth having a simple tide pole at every gauge site as a check.
- Although they are simple, there is a need for datum control, just as there is for more expensive and complicated gauges
COLOUR KEY
Black shown shaded thus
Traffic yellow shown thus
Even numbers yellow on black ground
Odd numbers black on yellow ground
Falkland Islands 2009

Liverpool, UK

A tide pole at a UK stilling well/float tide gauge station
William Hutchinson measured heights and times of high water at Liverpool 1764-1793
Nileometers at Rawda Island, Cairo and Elephantine Island, Aswan
Classical Float Gauge

BASIC TIDE GAUGE

- Float wheel
- Pen
- Clock
- Recording drum
- Pen wire tensioners
- Counterweight
- Float
- Stilling well
- Conical inlet
- Orifice

Figure 3.1
Two Stilling Wells with Float Gauges at Holyhead, UK

Classical stilling well float gauge from a station with large tidal range in the USA
Importance of Float Gauges

• They still form a large part of the global network

• No need for paper charts now. They can be made digital with the use of shaft encoders

• Even if they are now being replaced with acoustic, pressure and radar systems, they were the source of most of the historical record
Pressure gauges

Measure the pressure at some fixed point below the sea surface and convert this pressure to a level by using the basic hydrostatic relationship

\[ P = P_A + \rho g D \]

- \( P_a \) atmospheric pressure
- \( \rho \) mean density of overlying column of sea water
- \( g \) is acceleration due to gravity
- \( D \) is the water level above the transducer

Different Types

- Bubbler gauges
- Transducer in the sea gauges
- ‘B’ (or ‘triple’) pressure systems

Schematic of a bubbler tide gauge
Transducer in the sea pressure system
Appropriate also for tsunami monitoring

Port Stanley, Falkland Is.
A Triple (or ‘B’) pressure gauge setup with 3 pressure transducers, can provide ongoing datum control to the ‘C’ data.

- **A** Atmospheric pressure point
- **B** Pressure point at ‘datum B’ which is approximately Mean Sea Level.
- **C** Sea pressure point below low tide

The diagram shows a setup where data is relayed via satellite, with a transmitter, barometer, data logger, and signal processor. The outer galvanized steel pipe with copper pressure sensor assembly is located below the low tide mark.
Acoustic gauges

Measure the two way travel time from the sensor to the sea surface using an acoustic signal and then convert this to distance

This travel time is given by:

$$t_p = \frac{2l_z}{C_a}$$

Corrections must be made for variations in $C_a$ (velocity of sound) with air temperature, pressure and humidity. So these parameters must also be recorded

• They became something of a GLOSS standard in many areas
• Acoustic systems in open air or inside the stilling wells of float gauges.
• Cheap but several groups have not been successful in operating them to good standards
Radar Gauges

The principal of timing a reflected signal may also be applied using a pulse of electromagnetic radiation. In this case the velocity is the speed of light and unlike acoustic measurements radar gauges are not affected by temperature or vertical temperature gradients.

A timing accuracy of $1 \times 10^{-10}$ seconds is required to resolve a level difference of 0.01 m

Several Different Types

- Open-air pulsed radars – measures the time of flight of many radar pulses
- Open-air FMCW (frequency modulated continuous wave)– uses continuous frequency and measures the phase shift between the transmitted and received waves
- Radar in a sounding tube
- Guided Wave Radar (down a wire)
Many examples of open-air pulse and FMCW radars.
Satellite Altimetry
Basic principles of satellite altimetry

Radar altimeters transmit signals at high frequency to Earth, and receive the echo from the surface.

By timing it, we measure the distance between satellite and sea (range).

We know the position of satellite (precise orbit) from models and measurements.

Hence determine height of sea surface w.r.t. reference ellipsoid.

Altimeters also measure waves and wind.

Conceptually simple
Technically challenging!!
(required accuracy ~1 cm from ~1000km)
Atmospheric corrections

• Ionospheric correction: 2-20 cm [± 3 cm]
  Caused by the presence of free electrons in the ionosphere

• Dry tropospheric correction: 2.3 m [± 2 cm]
  Caused by oxygen molecules

• Wet tropospheric correction: 5-35 cm [± 3-6 cm]
  Caused by clouds and rain
The bias is typically 2% to 5% of the significant wave height.

There is no theoretical method for estimating the sea state bias, hence we use empirical methods.
Retracking of the radar waveforms

= fitting the radar echoes (waveforms) with a waveform model,
→ we estimate the three fundamental parameters

Maximum amplitude: related to wind speed

“Epoch”: gives range (therefore height)

Slope of leading edge: related to significant wave height

Open-ocean waveform model: Brown, 1977

Normally done at 18-20 Hz (~350 m along-track) and then averaged at 1-Hz (~7km) to improve precision

Figure from J Gomez-Enri et al. (2009)
Reference surfaces

The **reference ellipsoid** is a rough approximation of the Earth’s shape.

The **geoid** is an equipotential surface that coincides with the shape that the sea surface would take in the absence of perturbing forces (currents, wind, etc.).

- The **mean dynamic topography (MDT)** is the stationary component of the ocean dynamic topography (not given by altimetry).
- The **mean sea surface (MSS)** is the sum of the geoid and the MDT.
- The **sea surface height** is the sea surface height wrt the reference ellipsoid.
- The **sea level anomaly (SLA)** is the sea surface height wrt the MSS.
The Geoid

Geoid height (EGM2008, nmax=1000)
The mean sea surface (with respect to the reference ellipsoid)

The MSS departs from the standard ellipsoid by ± 100 metres because of the density composition of the solid Earth
Altimetry is “along-track”

10-day repeat (T/P, Jason-1,-2,-3)
35-day repeat (ERS, Envisat, AltiKa)

Data SIO, NOAA, U.S. Navy; NGA, GEBCO
Image Landsat
The Tsunami of 26 Dec 2004
Global mean sea level from altimetry

Overall trend: 3.10 mm/yr
Altimeter data up to 66° latitude
Corrected for GIA
Annual signal removed
Altimetry in the coastal zone

Traditionally, data in the coastal zone are flagged as bad and left unused (coastal zone: as a rule of thumb 0-50 km from coastline, but in practice, any place where standard altimetry gets into trouble as waveforms are non-Brown and/or corrections become inaccurate).

In recent years a vibrant community of researchers has started to believe that most of those coastal data can be recovered.

http://www.coastalt.eu/community
Satellite gravimetry and the Argo float network
The Gravity Recovery and Climate Experiment (GRACE)

GRACE consists of two satellites separated by a few hundred kilometers.

Changes in their separation are used to infer the gravity field.

GRACE provides a horizontal resolution of about 500 km.

The temporal gravity variations measured by GRACE can be used to monitor changes in water storage on continents, ocean bottom pressure (i.e., mass changes), mass loss of ice sheets, etc.
The Argo float network

Argo floats measure the temperature and salinity of the upper 2000 m of the ocean as they freely drift with the ocean currents.
How do Argo floats work?

6-12 hours at surface to transmit data to satellite

Descent to depth – 6 hours

1000m – drift approx. 9 days

Total cycle time –10 days

Temperature and Salinity profile recorded during ascent –6 hours

Float descends to begin profile from a greater depth –2000m
How do we use gravimetry and Argo float observations for sea level?

The sea surface height anomalies observed by an altimeter can be viewed as the sum of two terms (after removal of atmospheric pressure effects):

\[ h = h_{steric} + \frac{P_{bottom}}{g_0} \]

- \( h_{steric} \) represents expansion/contraction of the seawater associated with T/S changes.
- The second term represents sea level variations associated with mass addition or redistribution.
An example of using GRACE/Argo data for regional sea level

Mediterranean Sea mean sea level and its components

Observed estimates from altimetry, Argo, and GRACE in black.

Grey curves represent estimates obtained by adding or subtracting the other two observational components.

Calafat et al., 2010
An example of using GRACE/Argo data for global mean sea level
Geological Techniques
Three important points to start

1. Sea level has changed throughout the geological record, is changing now and will change in the future

2. The many timescales and rates of change imply many different measurement techniques

3. All the ‘sea level’ we discuss using geological techniques is what we call Relative Sea Level

Relative means sea level relative to the height of the nearby land (like for tide gauge data).
'Proxy' means non-instrumental. We have tide gauges and altimetry for studying sea level changes over years to centuries. But for longer timescales we have to make use of 'proxy' techniques involving study of:

• Landforms

• Stratigraphy

• Fossils
Beach ridges above present-day sea level

- Beach ridges are wave-swept or wave-deposited ridges running parallel to a coastline
- They essentially record the height of storm wave run-up
- Beach ridges above present position could suggest MSL change
- They can be carbon dated using entrapped material (e.g. driftwood, mollusc shells)

Present-day beach ridges, north coast of Estonia (Many beach ridges in Scandinavian beach mapped extensively by N-A. Mörner and others)
Wave cut notches

- Prolonged wave action causes a notch in a cliff to be eroded.
- A displaced notch (above or below present water level) is an indication of a former sea level, often due to tectonic change.
- Dated by inference, or sometimes barnacles, or using nearby corals if available.
- Any significant rising or falling trend doesn't have sufficient residence at a given elevation to produce a notch.
Corals

A micro-atoll forms when the top of a coral head breaks water (e.g. due to sea level fall) and becomes visible at low tide. The top dies but growth continues laterally. Micro-atolls are primarily Porites. (Photo. Maui Nui Marine Resource Council, Hawaii).
Oxygen Isotope Analysis

- Many of the methods we have discussed so far apply only to study of sea level since the LGM.
- To go further back, one can use landforms or other techniques such as oxygen isotope analysis of shells of tiny marine organisms (foraminifera or 'forams').
- During extended Warm Periods, when ice sheets small or absent (e.g. Cretaceous to Pliocene), the $^{18}O$ variations in benthic forams largely reflect temperature (the forams take up less $^{18}O$ when they are warmer).
- $^{18}O$ in a sample can be readily measured using a mass spectrometer.
Salt marshes

- Salt marshes develop in the intertidal zone in sheltered lagoons behind coastal barriers, river estuaries etc.

- Upward growth of the marsh and of peat largely follows sea level as long as sediment supply is sufficient.

The differing frequency of salt water inundation leads to differing plants (and foraminifera) at different heights on the marsh.
Salt marshes and the transfer function

- A ‘transfer function’ expresses the heights of forams on the present marsh surface as heights above Mean Tide Level. These heights are obtained from a set of surface samples whose heights are measured by levelling and with the use of a temporary tide gauge to determine MTL.
- Accuracy typically 10-20% of the local tidal range.
- Assumption then is that the marsh environment has not changed, such that a particular mix of forams at a certain height above MTL now will tell us what the height above MTL was for a sample in a core.

Salt marsh data (black crosses) and corresponding tide gauge information (coloured lines).
Relative Sea Level

When we use a tide gauge to measure sea level it is relative to the TGBM on land

This is called Relative Sea Level and (when averaged over months and years) is the same as the Mean Sea Level archived at the PSMSL

Land Level as well as Sea Level Changes

- A problem is that Relative Sea Level can contain information on land level change as well as true sea level change

- The land could be submerging (e.g. Bangkok) or emerging (e.g. Sweden) relative to the centre of the Earth at a rate faster than sea level itself is changing

- So we also need to monitor the land level changes using modern geodetic techniques – this will give us Geocentric Sea Level
Some records are clearly affected by land movements

The effects of earthquakes (Japan), ground water extraction (Thailand) and glacial isostatic adjustment (Sweden)
Geocentric Sea Level

For science we would like to adjust the sea level measured by the gauge for the effects of land movements.

One way to do this is to monitor the vertical movement of the TGBM (or a BM near to it) using GNSS (GPS).

In practice the GPS may be installed exactly at the tide gauge or some distance from it.

Global Navigation Satellite System (GNSS) Includes

- GPS (US)
- GLONASS (Russia)
- Galileo (Europe)
- China (BeiDou)
- Japan (QZSS)
Tide gauge and GPS in Indonesia
Tide gauge and GPS in Tasmania
GNSS Technology

GNSS on buoys or Waveglider

GNSS Multipath Reflectometry

N.B. These need technical expertise and are not (for Buoys or Waveglider) capable of providing science-quality long-term sea level records.
Japan GPS buoy used for tsunamis

3 Buoy from French Researchers being tested

UVic. Tasmania, Australia

GFZ, Potsdam

Japan GPS buoy used for tsunamis
Waveglider Deployed in Loch Ness for Testing
GNSS Buoy/Waveglider

Concept is relatively straightforward, measure the GNSS Buoy height relative to a nearby base station.

This however meant that they were limited to within say 100 km of the coast.

New processing methods (called PPP) now allow us to do this globally.
GNSS Multipath Reflectometry

Concept of using reflected GNSS signals for environmental sensing was introduced by Martin-Neira in 1993.

Consider a direct GNSS signal to the receiver and also the reflected signal from nearby objects (including the sea). These interfere and we usually call it multipath and attempt to filter it out.

Newlyn tide gauge station, note the GNSS antenna on the lighthouse used for GNSS reflectometry test.
GNSS Signal Strength Data in a Multipath-Free World

Observed Composite Signal

- rising satellite
- setting satellite

Hours (UTC)

dB-Hz
What real signal strength data may look like

Reflected Signal for a 2m signal
What drives those oscillations?

Your GPS site becomes an interferometer

RH = reflector height
Peterson Bay, Alaska, ~30 km from NOAA/Seldovia tide gauge
Seldovia, Alaska

Traditional Implementation of a GLOSS CORE Network Site

**GNSS required to…:**
- Establish the measurements in a global geodetic reference frame
- Altimetric calibration
- World Height Datum
- Studies of Mean Dynamic Topography
- Measure Vertical Land Movement
Current known GNSS water level sites
Longest current GNSS tide gauge record!

Over 10 years of monthly data, with a RMS of around 1.5 cm compared to the PSMSL record
GNSS Multipath Reflectometry

• The technique is presently mainly a technical demonstration of using, and understanding, GNSS reflections
• But may be useful as a real tide gauge in certain circumstances
• One advantage is that you need only the one receiver to measure sea and land levels

+ The tide gauge is defined in ITRF.
+ Straight-forward to operate.
+ No moving parts in (salty or frozen) water.
+ Cost of operations can be shared.
+ Could be niche tide gauge for polar regions.
+ Can be far from the shore.

- Not designed for this purpose.
- It does not like high winds/waves.
- Snow on top of ice.
Please read