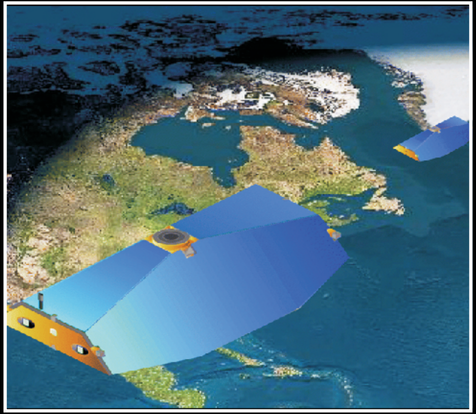
Mass Exchanges



The GRACE satellites

GOCE is an example of what is called a 'spatial gravity' mission. GRACE (GRavity And Climate Experiment) is a 'temporal gravity' mission which has lower spatial accuracy than GOCE but which can measure <u>changes</u> in gravity around the world over an extended period. These changes arise from variations in the density structure of the ocean, fluctuations in the mass of the ice caps, changes in water storage on land, and even variations in the mass of the atmosphere. Scientists are now learning how to decouple signals from these processes (all of which are relevant to understanding sea level changes) in the combined space gravity and altimetric data. GRACE was launched in 2002 and is expected to continue working for several years more, and one hopes for an on-going series of similar missions thereafter. However, it is not the only way one can infer mass exchanges. GPS data can also be used to monitor changes in loads on the solid Earth, while measurements of length of day and polar motion from geodetic satellite and lunar laser ranging provide further insights.

So how does Geodesy then help to understand Global Sea Level Change?

From tide gauge and altimeter data in combination, we believe that global-average sea level is rising presently at a rate of about 3mm/year. This appears to be due to a combination of factors: changes in the heat content of the ocean ('steric' changes), melting of continental glaciers, natural and man-made hydrological changes altering the exchange of water between land and ocean, changes in the great ice sheets in Greenland and Antarctica and other factors.

One can imagine Geodesy helping us understand what is going on in the following ways:

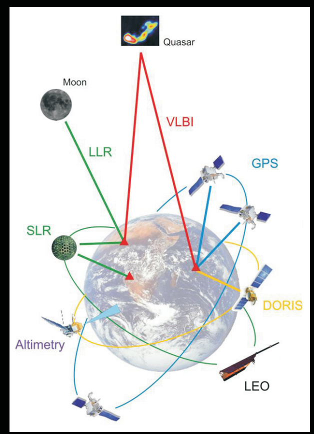
- Geodesy can enable effective monitoring of sea level change from tide gauges and altimetry (requiring GPS, AG etc.).
- It can provide an accurate determination of the geoid via spatial gravity missions such as GOCE.
- It can thereby constrain descriptions of the steady state ocean circulation included in the Atmosphere Ocean General Circulation Models (AOGCMs) used for climate and sea level predictions.
- Meanwhile, measurements of temporal changes in the spatial gravity distributions (together with altimeter data) can be used to infer changes in ocean thermal structure and the physical processes which result in ocean change. This leads to further AOGCM improvement.
- In addition, measurements of ice cap thickness and continental water storage can be inferred from their 'fingerprints' to be found in temporal gravity measurements. When combined with changes in the ocean, these processes result in the sea level changes observed by tide gauges and altimetry.
- The ultimate objective is provide sufficient data to confront the models, such that have significant gains in reliability in prediction of future climate and sea level change.

GPS and Oceanography

As well as GPS measurements related to sea and land level changes themselves, GPS is particularly important in related environmental monitoring. For example:

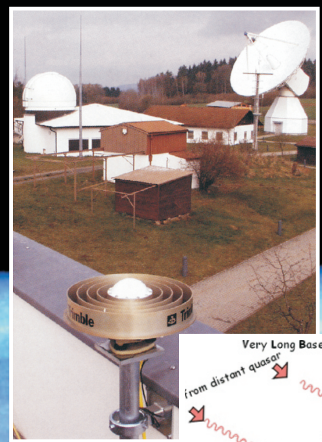
- GPS can be used to monitor the elevation and rates of flow of glaciers and ice sheets.
- GPS can provide precise positioning and timing for a range of ocean instrumentation (floats, buoys, bottom pressure recorders etc.) that inform us how the ocean works.
- GPS also has many practical applications in ocean science, in addition to the scientific ones. These include redefinitions of datums, active charting, and surface and sub-surface navigation.

The International Terrestrial Reference Frame

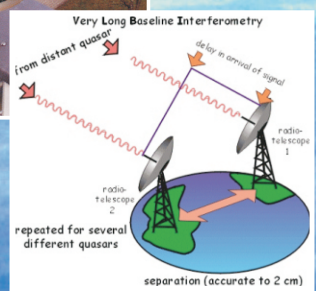


The combination of many techniques makes up the ITRF

The International Terrestrial Reference Frame (ITRF) is defined by measurements from networks of different types of geodetic instruments, including SLR, VLBI, DORIS and GPS. Measurements are made at many sites worldwide (inland as well as at the coast) with as far as possible co-located measurements by different techniques. The ITRF defines the 'ruler' with which the changes in sea or land levels are measured subsequently, and a rule-of-thumb is that the 'ruler' should be ten times more stable than the quantity being measured (i.e. 0.1mm/year compared to the typical signals of 1mm/year of sea and land movement). The permanence, stability and accuracy of the ITRF is fundamental to all of our measurements of position whether on the Earth's surface, or in the air or in space.



GPS and VLBI co-location



VLBI description

The Herstmonceux Satellite Laser Range

Sea Level Science and Geodetic Techniques

A contribution to the Global Geodetic Observing System of the International Association of Geodesy

This brochure was produced by the Proudman Oceanographic Laboratory for the Global Geodetic Observing System of the International Association of Geodesy

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NATURAL ENVIRONMENT RESEARCH COUNCIL

Background image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center. STS057-73-75 (http://eol.jsc.nasa.gov)

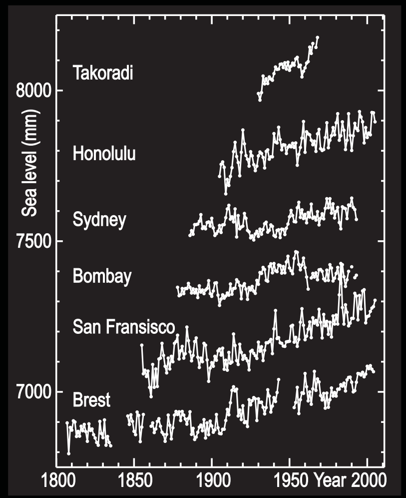
Sea Level Science and Geodetic Techniques

Sea Level Science and Geodesy (the science of the shape of the Earth) are closely related subjects – indeed the sea surface defines the shape of the Earth over two-thirds of the globe. In determining the shape of the Earth precisely, geodesists have developed techniques for measuring small changes in position. Sea level research has come to depend upon a number of these new techniques for the measurement of sea level changes worldwide. They are fundamental to fulfilling our objectives of understanding how fast and why global sea level rise is occurring. This leaflet provides several examples of the importance of geodetic techniques to Sea Level Science.

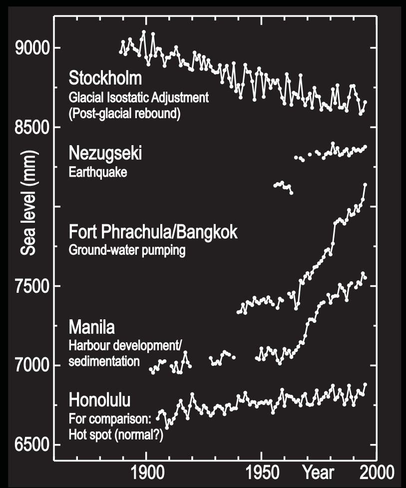
Tide Gauges and GPS

Sea level measurements have been made for hundreds of years with instruments called tide gauges. These devices measure changes in coastal sea level relative to that of a marker (benchmark) on nearby land. The Global Positioning System (GPS) provides an excellent example of how a new geodetic technique has transformed a conventional measurement practice. Many tide gauges are now equipped with GPS receivers which enable:

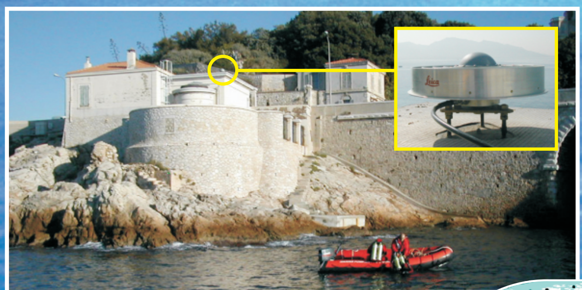
- Accurate time-tagging of the tide gauge data (clock errors were common before GPS).
- Precise location of the position of coastal sea level in a geodetic reference frame, enabling combination of tide gauge and off-shore altimeter sea level data and a calibration of altimeter data relative to tide gauge information (see opposite for altimetry).
- Estimates of the rates of vertical land movement so enabling a decoupling of the signals due to sea and land level changes in the tide gauge records.



Long sea level records – global sea level is rising

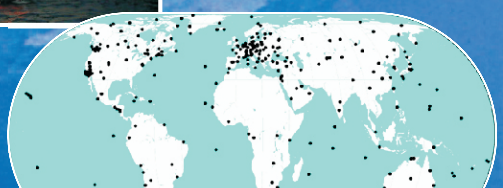


Geophysical influences on sea level records (post-glacial rebound, water extraction etc.)



Marseille tide gauge and its GPS

The GPS constellation



The global GPS network of the International GNSS Service

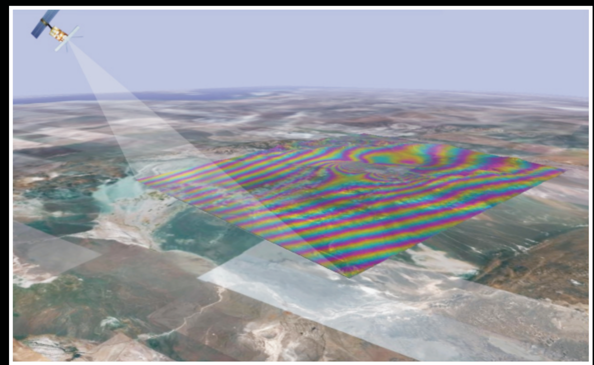
Absolute Gravity

Land levels at some gauges are also monitored with geodetic instruments called absolute gravimeters. These measure small changes in gravity from year to year at the same location. If gravity increases (or decreases) it implies that the land is nearer to the centre of the Earth i.e. the land is subsiding (or emerging).

An absolute gravimeter

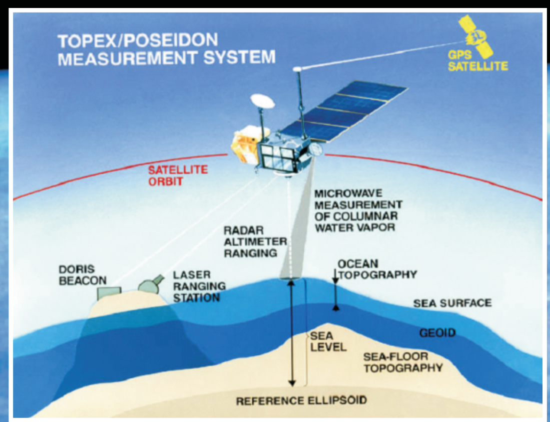
InSAR

GPS and AG provide measurements of land level changes at particular points and, in principle, one would like to know how land levels are changing in a wide area around a tide gauge station. Interferometric Synthetic Aperture Radar (InSAR) can measure small shifts in the position of the Earth's surface by differencing the phase (as opposed to amplitude) information from two radar images. Typically, SAR images from satellites cover an area of 100km x 100km. With an individual pixel size of around 20m x 20m there is potential for millions of estimates of land movement in the satellite line-of-sight direction.



Schematic of InSAR

Altimetry

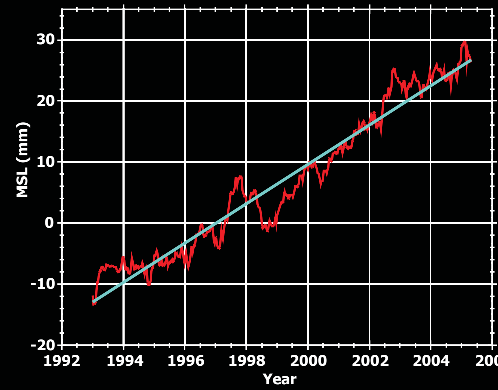


Altimetry measurement system

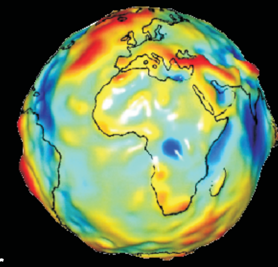
Sea level measurements are also made from space using satellite radar altimeters. These work by measuring the time for radar pulses transmitted from the satellite to be reflected from the sea surface back to the satellite. Then, if the position of the satellite is known, one knows the position of the sea surface. GPS and other techniques (e.g. Satellite Laser Ranging and DORIS) can now be used to monitor continuously the orbital position of the satellite with accuracy of around 1cm. Orbital accuracy is also improved if one has information on the Earth's gravity field at the satellite's altitude: this information comes from many years of tracking of special geodetic satellites (e.g. LAGEOS, Starlette).

LAGEOS

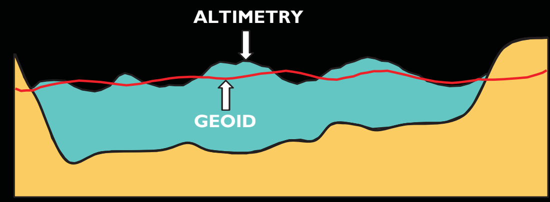
Altimetric measurements over an extended period provide a measure of the Mean Sea Surface (MSS), the shape of the Earth over the ocean referred to previously. This shape departs from a simple sphere or even an ellipsoid (a 'squashed sphere', which more closely describes the flattening at the poles due to rotation of the otherwise spherical Earth) because of the non-uniform nature of the density distribution of the solid Earth and of the topography of the sea bed. Sea water is a fluid and is free to move, and consequently every location on the MSS will (in the absence of other factors) be at the same gravitational potential. This results in an Earth shape which reflects features of the solid Earth which contribute to the gravity field. These spatial differences in solid Earth density and topography result in departures of this geopotential surface (called the 'geoid') from an ellipsoid of 100m. Spatial differences in the density structure of the water in the ocean result in additional departures of the observed MSS from the geoid of 1m.



Sea level rise seen by TOPEX/Poseidon



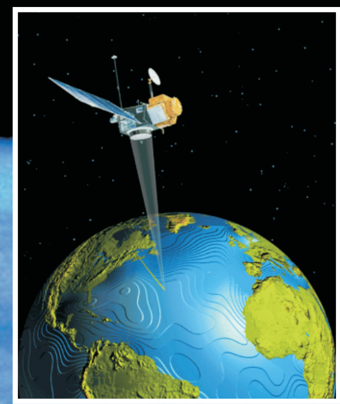
Geoid variations around the world



Departures of the sea surface from the geoid due to ocean currents

Radar altimetry can also be used to measure the elevations of ice sheets and land surfaces, while altimeter measurements using lasers (e.g. ICESAT) can provide higher spatial resolution over land and ice.

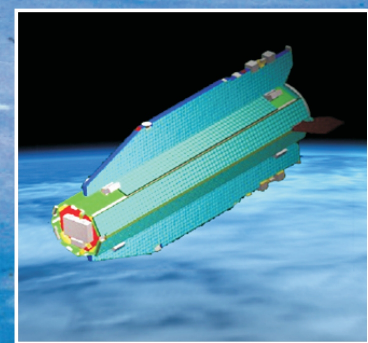
The Ocean Topography



Satellite altimetry provides the MSS

Oceanographers would dearly like to know the [MSS minus geoid] surface in some detail, because then they would have a good insight into the steady state ocean circulation, which can be measured at the moment only from ships or other in-situ ocean instrumentation. They do know the global MSS to excellent accuracy (typically 1–2cm) but at distances of several much less than 1000km the structure of the geoid surface is inadequately known.

Since GRACE date became available, we have had a much better idea of the geoid surface. However, in 2008, a geodetic space mission called GOCE (Gravity Field and Steady State Ocean Circulation Explorer) will be launched which will enable measurement of the geoid to an accuracy comparable to that of the MSS at wavelengths of most interest to oceanographers.



GOCE satellite