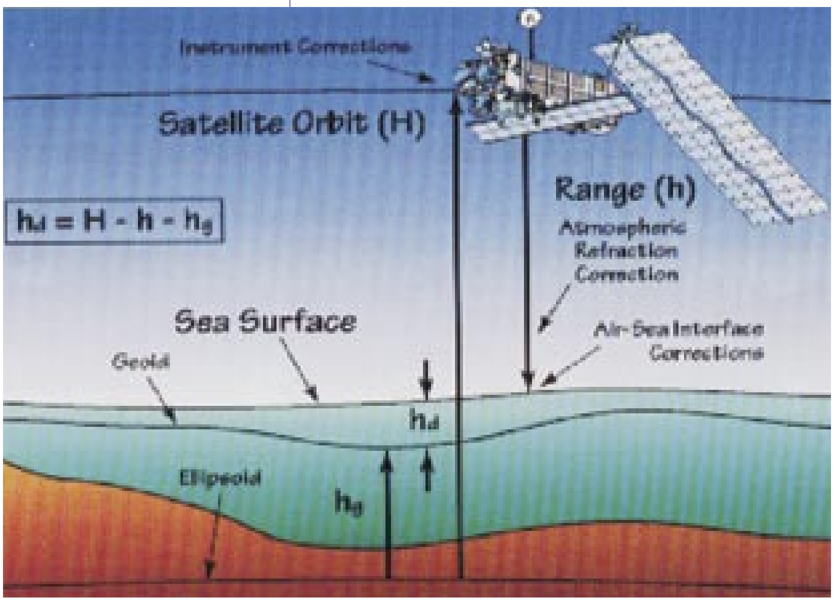
How altimetry works



All figures and pictures in this article: ESA

Earth – a misleading name

A few figures about the oceans below give some idea why "Ocean" would be a more appropriate name for our planet:

Total ocean surface area: 360 million km2, covering 71% of the planet. Total mass: 1.4 billion billion tonnes. Mean depth: 3,800 m (11,000 m at deepest point) Temperature: –4°C in polar regions to +30°C in tropical region. Age: 4.5 billion years. Current flow velocity: 1 mm/s to 1 m/s.

Altimetry theory

Altimetry measurements are acquired by an altimeter on a non-synchronous satellite in a repeating low-Earth orbit designed to fly over the same points at regular intervals. The altimeter is a radar instrument that emits a signal at very high frequency—typically 2,000 pulses per second—vertically beneath the satellite. This signal propagates until it meets an obstacle, which reflects radar "echo" back to the altimeter's antenna.

By calculating the round-trip time of the signal, one can determine the distance—or range—from the obstacle (in this case, the ocean or ice surface) to the satellite. This calculation is performed simply by multiplying the time by the speed of light, at which electromagnetic waves propagate.

One major drawback of ocean-observing altimeters is that radio waves cannot penetrate below the sea surface. Consequently, we have to estimate the sea-surface height with respect to an arbitrary terrestrial reference surface. In practice, to achieve the required level of accuracy, this theoretical measurement is corrected for perturbations of the satellite on its orbit and propagation of radio waves as they pass through the atmosphere.

From visible observations to satellites

Observation of the oceans most certainly began when the first sailors set out to sea. To begin with, observations would have been concerned with finding the best trade routes. Subsequently, as each new discovery by explorers raised new questions, the study of the oceans developed into a scientific discipline.

Data collected in situ over the centuries formed the foundation for modern oceanography by revealing the complex nature of ocean phenomena and helping to invent new measuring instruments. The same goes for the situation of the icy areas of the world. The polar explorers in earlier centuries were not only interested in becoming the first to come to the most inaccessible places of the world, they carried out very important scientific research too. However, the technology development has provided the scientists with possibilities to steadily more data in a simpler way.

Space technologies are a good example. Among the many instruments sent aloft on satellites, altimeters have changed our perspective of the oceans and ice-covered areas forever. Satellite altimetry measurements of altitude today can gather more data about ocean circulation in 10 days than ships and polar expeditions collected over several centuries. And not only do we have more data—they are also more accurate. Surprising though it may seem, an altimeter can detect a trough in the ocean and ice surface of no more than a few centimetres across an entire basin.

Sailors have studied ocean currents to find the best routes since ancient times. Benjamin Franklin was the first to chart the Gulf Stream in 1777, by measuring sea temperatures. He recommended following this warmer current to reduce the time it took to go between New York and London.

In 1849, Matthew Maury published the first global charts of winds and currents compiled from data collected by ships. Exploration of the oceans for purely scientific purposes really began in 1872, when the first Challenger expedition surveyed the oceans for 42 months, gathering data from the surface to the sea floor.

From the 1970s, space technologies revolutionized the way scientists study the planet. The technique of satellite altimetry was first presented at a symposium in Athens in 1965 and subsequently used on the U.S. satellites GEOS 3 (1975), SEASAT (1978) and GEOSAT (1985). The first large-scale altimetry mission was the French-U.S. satellite TOPEX/POSEIDON (1992), followed by JASON-1 (2001) and the European ENVISAT (2002). These missions have taken ocean and ice science to new heights.

Princip for the satelites track over the surface.

Altitude and sea-surface height

Since the altimeter only measures the range from the satellite to the sea surface, one has to calculate the sea-surface height with respect to a terrestrial reference.

To do this, one must first define an arbitrary reference surface. Since the sea depth is not known accurately everywhere, one uses a regular, imaginary surface that is a raw approximation of the shape of the Earth, which is a sphere flattened at the poles. This surface is called the reference ellipsoid, which allows us to calibrate data precisely and uniformly.

The satellite's altitude with respect to the reference ellipsoid, is calculated with an accuracy of 3 cm using the satellite's orbital parameters, and precise positioning instruments.

The sea-surface height is thus the difference between the satellite's altitude relative to the reference ellipsoid and the altimeter range.

This height corresponds to the undisturbed sea level, called the geoid. The geoid is a model of the figure of the Earth that mirrors the shape of the sea surface in the absence of the effects of waves, winds, currents and other perturbations. It is a very irregular, undulating surface reflecting global variations in gravity. The dynamic topography (DT), is the difference between this unperturbed surface and the actual sea surface.

The antenna and hardware for the Radar Altimeter, RA-2 in the Envisat satellite. Photo: Alenia Aerospazio.

Radio waves transmitted and received by an altimeter do not travel in a vacuum. Signals passing through Earth's atmosphere may be subjected to path delays, thus introducing errors into measurements. For example, large amounts of electrons at altitudes near 400 km, dry air and water vapour all generate errors ranging from a few centimetres to more than 2 metres.

To achieve the extreme level of accuracy required, one has to identify the source of these perturbations and then calculate the necessary corrections. Special instruments on board the satellite are designed to measure physical parameters for this purpose. After corrections, the satellite-to-ocean range can be estimated with an accuracy of 2 centimetres.

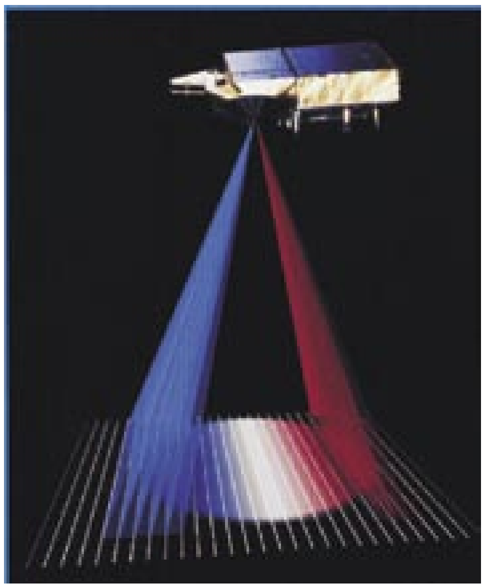
Since the aim is to estimate sea level precisely with respect to a terrestrial reference, measurements must also be independent of the satellite. For this reason, one needs to know the satellite's exact orbital position.

This is the role of the onboard orbit determination systems, supported by a network of ground location beacons and orbital trajectory models. Used in combination with GPS positioning instruments, these systems enable us to calculate the satellite's position very precisely relative to Earth, in terms of its altitude, longitude, latitude and orientation.

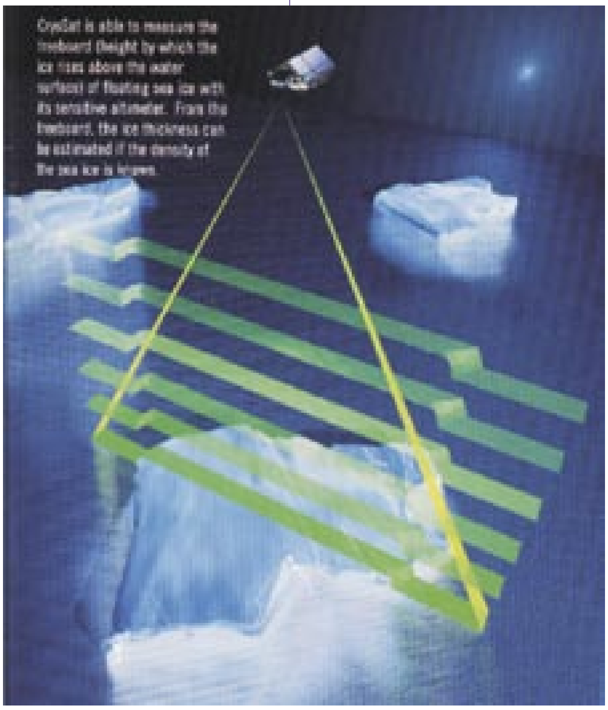
The SIRAL Radar Altimeter

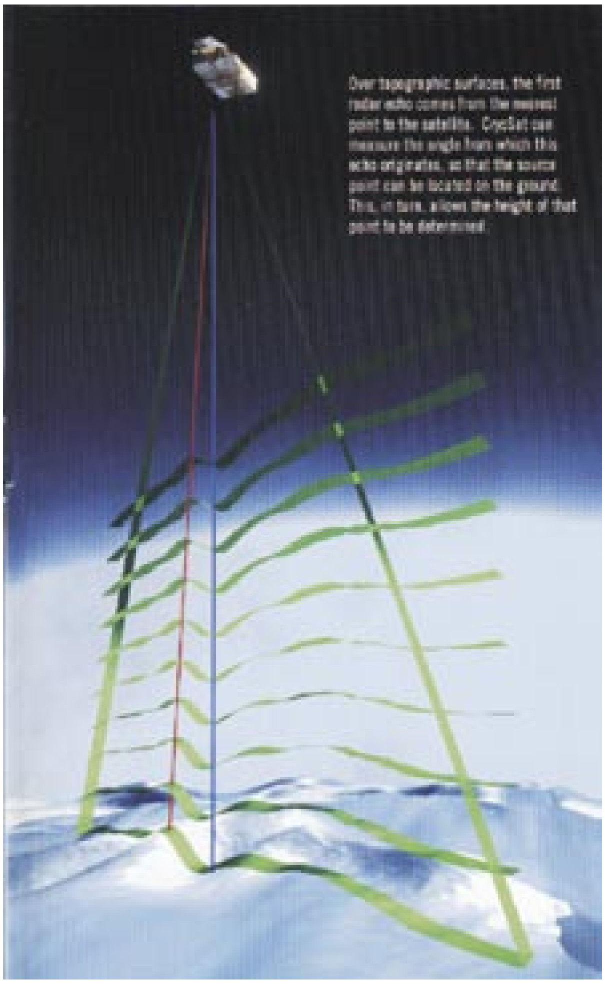
CryoSat's primary payload is the SIRAL radar altimeter with its extended capabilities to meet the measurements requirements for ice sheet elevation and sea ice freeboard.

Conventional radar altimeters send radar pulses with a large enough interval between them that the echoes are uncorrelated; many uncorrelated echoes can be averaged to reduce noise. At the typical satellite orbital speed of 7 km/sec the interval between the pulses are about 500 my/sec. The Cryosat altimeter sends a burst of pulses with an interval of only about 50 my/sec between them. The retuning echoes are correlated, and by treating the whole burst at once, the data processor can separate the echo into strips arranged across the track by exploiting the slight frequency shifts (caused by



The footprint of the radar beam on the ground and the princip for the Doppler effect. Figure: ESA.





the Doppler effect) in the forward- and aft-locking parts of the beam. Each strip is about 250 m wide and the interval between burst is arranged so that the satellite moves forward by 250 m each time. The strips laid down by successive bursts can therefore be superimposed on each other and averaged to reduce noise. This mode of operation is called the Synthetic Aperture Radar, or SAR mode.

In order to measure the arrival angle, a second receive antenna is activated to receive the radar echo with two antennas simultaneously. When the echo comes from a point not directly beneath the satellite there will be a difference in the path-length of the radar wave, which is measured. Simple geometry then provides the angle between the baseline, joining the antennas, and the echo direction. The difference in path length is tiny – up to a wavelength of the radar wave ((2.2 cm) – and has to be accurately determined in a range measurement of 720 km.

In addition to the altimeter, the knowledge of the precise orientation of the baseline of the two receiving antennas is essential for the success of the mission. CryoSat measures this baseline orientation using the oldest and most accurate of references: positions of the stars in the sky. Three star trackers are mounted on the support structure for the antennas. Each of these devices contains an electronic camera, with takes five pictures per second. Each image is analysed by the star tracker's build-in computer and compared to a catalogue of star positions.

The altimeter makes a measurement of the distance between the satellite and the surface. But this measurement cannot be converted into the more useful measure of the height of the surface until the satellite position is accurately known. These days the orbital position of altimetry satellites can be determined to a few centimetres, but this requires the satellite to carry some specific equipment. CryoSat has two such devices.

- A radio receiver called DORIS (Doppler Orbit and Radio Positioning Integration by Satellite) detects and measures the Doppler shift on signal broadcast from a network of over 50 radio beacons spread around the world. Although the full accuracy of this system is the only obtaining after ground processing. DORIS is able to provide a real time estimate onboard, good to about a half meter The DORIS system has been in operation for over a decade, and is used on many satellites, included Envisat.
- A small laser retro reflector is attached to the underside of Cryosat. This little device has seven optical corner cubes, which reflect light back in exactly the direction it came from. A global network of laser tracing stations will fire short laser pulses at Cryosat and time the interval before the pulse is reflected back. These stations are relatively few, but because their position is very accurately known from their routine work of tracing geodetic satellites, they provide a set of independent reference measurements of Cryosat's position.

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