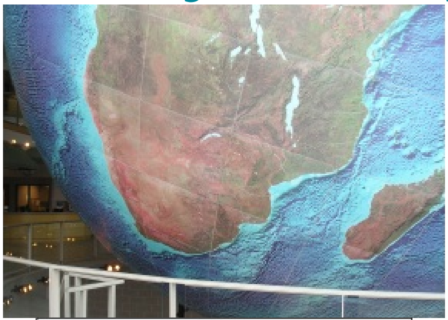
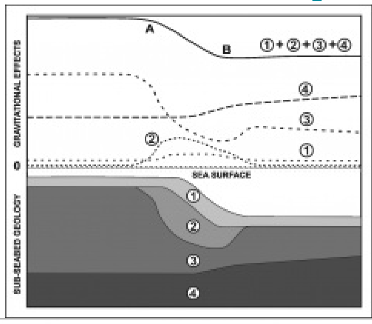
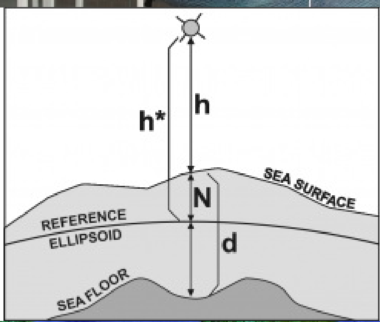
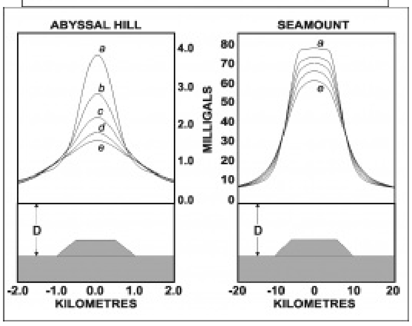
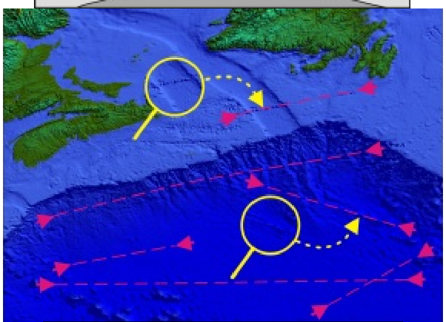
# Bathymetry From Space

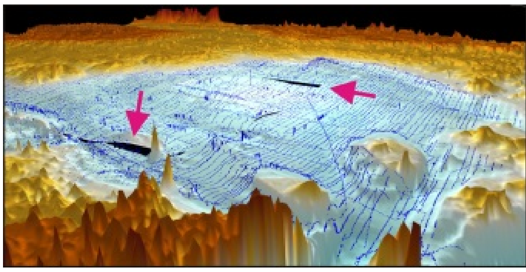


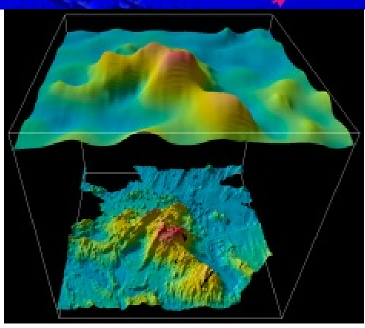


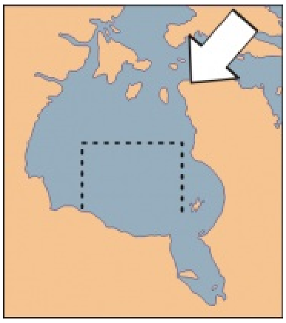









Global grids of synthetic bathymetry make it a simple matter to portray generalised ocean depths in all parts of the world, except the central Arctic Ocean. Derived from measurements of satellite height above the sea surface, synthetic bathymetry lacks the resolution and accuracy of acoustic soundings, plus it contains flaws that arise from measurement and computational processes. Users must therefore exercise care in the analysis and presentation of such information.

In Part II of his satirical account Gulliver's Travels into Several Remote Nations of the World, Jonathan Swift described his protagonist's thoughts after a close-up observation of the flawed complexions of the gigantic women of Brobdingnag: *"This made me reflect upon the fair skins of our English ladies, who appear so beautiful to us, only because they are of our own size, and their defects not to be seen but through a magnifying glass; where we find by experiment that the smoothest and whitest skins look rough, and coarse, and ill-coloured."*

Whatever this passage may have lacked in political correctness (considering it was written nearly three centuries ago), it articulated nicely the sense of disappointment arising from the discovery that something that appears flawless from a distance may on close inspection reveal itself to be less than perfect.

To an observer wielding a 'magnifying glass' in the form of display software that allows an operator to zoom into a gridded data set for a closer look, current portrayals of synthetic bathymetry derived from observations of satellite altimetry may also "look rough, and coarse, and ill-coloured".

The above analogy is not as far-fetched as it may seem: upon entering the headquarters of the DeLorme Company in Maine (USA), visitors immediately encounter a giant rotating globe known as Eartha. With a diameter of 12.5 metres, Eartha has been certified by the Guinness Book of World Records as the 'World's Largest Revolving/Rotating Globe' (you can read about Eartha on the DeLorme website, 8 1). Commissioned in the late 1990s, Eartha offers a global portrayal of land topography and seabed morphology – but the generalised presentation of the latter with its unattractive orange-peel texture contrasts sharply with the detailed view of the former (see Figure 1), offering an unspoken yet telling commentary on the poor state of contemporary ocean mapping.

## Basic Principles of Satellite Bathymetry

While the synthetic bathymetry that comes packaged in a global grid such as ETOPO2 has undeniable value for certain applications in marine science and map-making, users need to be aware of the grid's limitations in order to avoid drawing false or misleading conclusions. To help create a better understanding of those limitations, we briefly discuss the technique of estimating ocean depths from observations of satellite altimetry in the following sections.

Satellite bathymetry refers to ocean depths derived from orbiting radar altimeters that observe variations in sea surface height relative to the reference ellipsoid. These variations are caused by several factors, including oceanographic (tides and currents) and climatological (wind and atmospheric pressure) factors. However, the major causative factor by far is gravitational, i.e. local variations in the Earth's gravityfield over the ocean. These are caused by morphological irregularities and density transitions that occur beneath the ocean's surface: in the seabed itself, in the sediment layers that underlie the seabed, in the assemblages of igneous rock beneath the sediment and in the deeper layers of crustal rock.

By treating the undulating sea surface as an equipotential surface where the value of gravity is constant everywhere, geodetic theory can be invoked to convert sea surface heights into variations of gravity, known as anomalies. Gravity inversion theory – which is an inexact procedure – then enables the transformation of these anomalies into approximations of ocean depth, i.e. the vertical distance between the sea surface and the seabed.

## Uncertainties in the Measurement and Derivation Processes

There are several uncertainties inherent in the measurement and manipulation of satellite altimetry observations in order to estimate ocean depth.

An important initial uncertainty is introduced by the width of the observing satellite's radar beam, which does not return an exact measurement of altitude over a specific point: instead, it integrates altitudes over an area illuminated by the radar beam, known as the 'footprint'. If the sea surface within the footprint is rough or markedly sloped, the margin of error and the apparent flattening will be greater than if the sea surface is smooth or horizontal.

Once the sea surface height has been converted to gravity, the question arises: just what does the gravity show? The contents of the gravity field vary according to several physical factors and they reflect some things better than others. An inverse square law causes the gravitational attraction of a source object to decrease exponentially with distance. Consequently, the gravitational attraction of a minor source object on the deep seabed (for example, an abyssal hill) will have less effect at the sea surface than will a major object (for example, a seamount). In practice, the inverse square law acts as a filter that reduces or even neutralises the effect that a minor seabed source can have on the height of the sea surface. Satellite altimetry cannot circumvent this law of physics, which is why the technique is capable of mapping only the more significant components of seafloor topography.

Often, density and topographic variations within and below the seabed are unknown, so they are not taken into account in the inversion process – which is a reasonable computational shortcut under some circumstances, considering that the gravitational influences of deeper structures may be less than those caused by the density contrast between water and sediment at the seabed. This again is a function of the inverse square law of gravity.

Nevertheless, some deep sedimentary and igneous structures can be substantial enough to have an observable effect, so their exclusion from the inversion process may introduce uncertainty in estimates of ocean depth. Conversely, their inclusion may introduce a comparable uncertainty: often, the depths and configurations of buried source bodies are unknown, in which case it is necessary to make assumptions or to rely on partial information in order to define these parameters. In fact, gravity inversion can in principle yield an infinity of possibilities and so it is critical that realistic limiting conditions be selected.

Cumulatively, the uncertainties outlined above limit the technique'sability to map finer seabed structuresto a resolution of 5 to 10 kilometres, with inaccuracies that in places exceed a 100 metres.

## Calibrating Satellite Results with Acoustic Observations

One approach for dealing with the uncertainties inherent in synthetic bathymetry is to adjust the derived sea surface according to depth values that have been measured acoustically. Selected sounding profiles can be assigned an increased weight in the gridding process, thereby forcing the level of the synthetic sea surface to better match the acoustic depths. In areas where the seabed has been thoroughly and systematically sounded, the process can be taken one step further, which is to extract patches of synthetic depths and to replace them with acoustic observations.??In principle, the use of acoustic data to calibrate synthetic bathymetry should result in better representations of depth, as long as clean and coherent sets of soundings are used in the process. Unfortunately, this is not always the case: a substantial portion of the soundings used for this application appear to consist of disparate data sets that have been submitted to public-domain data centres without the benefit of rigorous quality control and without a concentrated effort to rationalise their contents. Consequently, there is a significant potential for many errors to creep into the process. These errors arise from several causes: poor navigation, wrong sound velocities, bad sound velocity corrections, etc. These can be difficult to identify and correct, usually entailing a series of time-consuming and labour-intensive procedures, although automated techniques are now available that facilitate the process considerably. Sounding tracks that are so afflicted appear as noticeable artefacts on the seabed.

The adjustment technique described above may not be systematically applied everywhere. Figure 6 illustrates ETOPO2 synthetic bathymetry in Hudson Bay, where the edges of a 5° by 10° 'flap' trace abrupt depth changes of up to 130 metres relative to the surrounding surface. This is an area criss-crossed by systematic survey lines, but those observations do not appear to have been used for matching depths across the edges of the flap. A wider-ranging investigation might reveal similar scenarios in other regions.

## Conclusions

There are various justifications for using portrayals of global synthetic bathymetry: the information coverage is nearly worldwide and reasonably uniform; the acquisition of basic altimetry data by orbiting satellites is relatively cheap and fast compared with conventional depth sounding by ships; it is adequate as a reconnaissance tool over large unmapped features; and it is useful for regional tectonic investigations.

However, there are some significant disadvantages to synthetic bathymetry: with limited resolution and accuracy, it cannot match the detailed seabed perspectives that are obtainable with echosounding (see Figure 7); inclined orbital planes rule out observations in the central Arctic Ocean; derivations of depth can be significantly biased by unknown sub-bottom geology beneath the point of observation; and the ubiquity of posters and publications that feature brightly coloured renditions of the global seabed create a misleading illusion that the world's oceans have already been fully mapped by satellite – which provides little or no motivation for government and intergovernmental agencies to take steps that improve the situation.

There is ample reason for seeking clearer and more detailed maps of the global seabed: among other things, these parameters are needed to establish a context for understanding climate change and rising sea levels; to predict the transport of water through deep, intermediate and shallow regions; to explain the occurrence and distribution of bottom-dwelling species; and to predict the propagation of tsunamis throughout the world's oceans. At present, the acoustic echosounder represents the only effective technology for mapping ocean depths with the accuracy and resolution needed for these and other types of scientific investigations. True advances in ocean mapping will not occur by placing more altimeters in orbit, but by sending more survey vessels to areas where the seabed needs to be sounded.

In the field of ocean mapping, rocket scientists have had their day. Now is the time to give hydrographic surveyors the mandate and the resources they need to do the job properly.

## References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## Additional Information with the Figures

The author has provided more information than the captions can hold. For this purpose, please find additional information related to the imagery below.

Figure 1: A close-up view of Eartha, at 12.5metres certified by the Guinness Book of World Records as the 'World's Largest Revolving/Rotating Globe', which contrasts the portrayals of land and oceanic areas. The land areas reflect the highly detailed knowledge that has been accumulated in past decades by continental mapping programs, whereas the representation of the oceanic areas suffers through recourse to low-resolution descriptions of the seabed, which have been derived from observations of satellite altimetry.

Figure 2: Cross-section of an idealised continental margin, portraying variations of shape and density in the sub-seabed geology, along with corresponding gravitational effects that can cause undulations in the sea surface (not shown here for the sake of clarity). The geological elements consist of: (1) unconsolidated sediment; (2) consolidated sediment; (3) crustal bedrock; and (4) upper mantle material. Their densities increase with depth. The gravitational effect of each element is illustrated by a dashed profile. The cumulative effect of all elements is indicated by the solid profile, which is a composite of the individual profiles and which approximates what an orbiting satellite would perceive as the gravity field at the sea surface. The composite profile mimics the general shape of the seabed; however, its inflection points at A and B are offset from the locations of the continental shelf break and the foot of the continental slope. Without knowing the densities and configurations of the sub-seabed geology, it would be impossible to re-create the true shape or depth of the seabed from the composite profile alone.

Figure 3: The computational alchemy of bathymetry from space. An observation of satellite altimetry is not a direct measurement of water depth: in reality it is a measurement of the height of the satellite above the sea surface (h). The satellite's orbit is well known, so its height above the reference ellipsoid (h*) can be readily derived. The difference (h* – h) between these measured and derived heights is known as the geoid height N, which closely matches the instantaneous height of the sea surface relative to the ellipsoid. The amplitude of this height is largely a function of the cumulative gravitational effect of the local seafloor and sub-seafloor, so it can be used to approximate a variation in the local gravity field, known as an anomaly. Applying certain assumptions and computational procedures, a gravity anomaly at the sea surface can then be treated to derive an estimate of the underlying ocean depth (d).

Figure 4: Attenuation with depth of the gravity signature of a seabed feature, due to the inverse square law of gravity. Left: an abyssal hill, 2km wide at its base and 200m high, where D ranges from 1,000 to 3,000 metres. Right: a seamount, 20km wide at its base and 2,000m high, where D ranges from 2,000 to 4,000 metres. The gravity signal from the abyssal hill ranges from 1.5 to 4mGal; levels that are easily lost in the measurement and computational noise that is inherent in the estimation of bathymetry from observations of satellite altimetry. In contrast, the gravity signal from the seamount ranges from 60 to 75mGal and readily overcomes the effects of noise.

| Profile | D, metres (abyssal hill) | D, metres (seamount) |
|---|---|---|
| a | 1,000 | 2,000 |
| b | 1,500 | 2,500 |
| c | 2,000 | 3,000 |
| d | 2,500 | 3,500 |
| e | 3,000 | 4,000 |

Figure 5: A view of ETOPO2 off the east coast of Canada. Arrows and dashed lines illustrate the locations of some noticeable seabed artefacts (e.g. spurious ridges and channels, examples magnified) that arise from the use of erroneous soundings to adjust synthetic ocean depths derived from observations of satellite altimetry.

Figure 6: A ‘flap’ in the ETOPO2 synthetic bathymetry of Hudson Bay, measuring about 5° latitude by 10° longitude, and with edges (indicated by red arrows) that trace abrupt changes in depth relative to the surrounding area; the discrepancy along the eastern edge of the flap reaches 130 metres. The location of the flap and the viewing angle are shown in the accompanying locator diagram. The blue dots portray locations of soundings acquired during systematic hydrographic surveys in Hudson Bay, and which do not appear to have been used to adjust the level of the flap.

Figure 7: Two views of Eltanin Seamount: the upper, generalised image was derived from satellite measurements of sea surface altimetry; the lower, more detailed image portrays depth values collected by a multi-beam echosounder (Figure adapted from Wille (2005); multi-beam data described by Krocker and Schenke (2006)).