How deep is the ocean?

Scientists have long sought to measure the ocean, and how far down it goes. **James Hanley** presents a brief history of attempts to get to the bottom of it – statistically speaking

The ongoing search for Malaysia Airlines flight MH370, which disappeared and is thought to have crashed somewhere in the southern Indian Ocean in March, reminded many of the fact that the depths of the Earth's oceans remain one of the great unknowns.

Initial searches for the aircraft had to be called off when investigators discovered that the area of water they were exploring was actually deeper than anticipated. The Bluefin-21, an unmanned submersible sent to detect signs of the missing airplane, had an operating limit of only 4500 metres but soon encountered depths far exceeding that.

This would come as little surprise to anyone with even a passing interest in oceanography. Gene Feldman, a NASA Earth Explorer, remarked in 2009 that "even with all the technology that we have today – satellites, buoys, underwater vehicles and ship tracks – we have better maps of the surface of Mars and the moon than we do the bottom of the ocean. We know very, very little about most of the ocean" (1.usa.gov/1B37K47).

Given our limited knowledge of the seabed – less than 10% has been mapped with shipborne instrumentation – it is no mean feat to measure the depth of the ocean at a specific location. But specific locations aside, estimating the mean depth of the ocean has tormented scientists and thinkers throughout history.

Several ancient philosophers weighed in on the subject, including Posidonius of Rhodes (135–51 BC) who stated that the Mediterranean, near Sardinia, had been sounded to 6000 feet, which he considered the greatest depth that had ever been attained.

Fast-forward to the eighteenth century, and Luigi Ferdinando Marsili challenged the opinion of those who held that the sea had no bottom in some places, and argued instead in his *Histoire Physique de la Mer* that there was symmetry between the heights of the land and the depths of the ocean. Similar views prevailed during the early nineteenth century. In *Mécanique Céleste*, the noted mathematician and statistician Pierre-Simon Laplace arrived at the conclusion, from theoretical considerations, that the mean height of the dry land was 3280 feet, and that the mean depth of the ocean was, likewise, 3280 feet.

Before Marsili and Laplace, the explorer Ferdinand Magellan attempted to sound the open ocean while crossing the Pacific in the years 1520–1521. When his short line failed to reach the bottom, he concluded that he had reached the deepest part.

Sharing Magellan's technological shortcomings, fellow explorers such as James Cook, the Ross cousins, and Robert FitzRoy, captain of HMS *Beagle*, had taken reasonably accurate soundings in the open ocean in the eighteenth and early nineteenth centuries, but in really deep locations they were hampered by inadequate instruments.

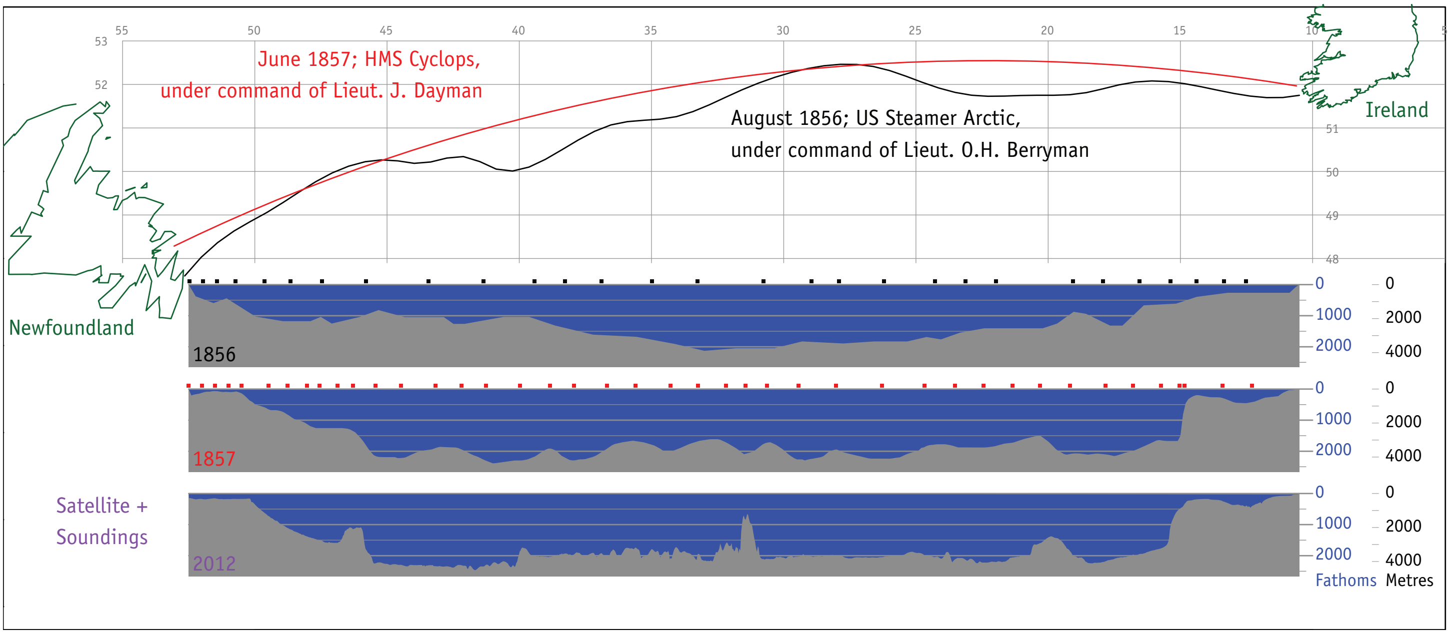

Figure 1. Early ocean measurements, prompted by commercial interests, contrasted with modern ones. Vertical section of the bed of the Atlantic Ocean, from Valentia, Ireland, to Trinity Bay, Newfoundland, based on soundings (made at the indicated spacings) for the laying of the transatlantic telegraph cable (1856 and 1857), and based on (great-circle) data extracted from the global 30 arc second grid (source: SRTM30PLUS V8.0 of the 2012 database)

However, mid-nineteenth-century efforts to lay an underwater telegraph cable between Europe and North America led to rapid improvements in the practicality and accuracy of depth measurements. Even so, there were some notable arguments about the depth and smoothness of the seabed.

The American oceanographic pioneer Matthew Maury held fast to his idea of a "telegraphic plateau", which he initially based on soundings made in 1853. "From Newfoundland to Ireland," he wrote, "the distance is about 1600 miles, and the bottom of the sea between the two places is a plateau which seems to have been placed there especially for the purpose of holding the wires of a submarine telegraph and of keeping them out of harm's way."[1]

The section or "depth profile" corresponding to the first series of depth measurements made along the planned route between Newfoundland and Ireland in 1856 (Figure 1) was quickly added to promotional and other news material and widely circulated. Since Maury and his counterparts in England were concerned about the quality of these data, a new set was made the next year, just ahead of the first cable-laying attempt. From what we now know (Figures 1 and 2), it is not surprising that it took three tries to successfully lay a cable over such an incompletely charted seabed.

A new *Challenger*

Measurements of the mean ocean depth took a step forward with the arrival of Sir John Murray (1841–1914), a pioneering oceanographer and marine biologist. In 1872, he joined the British *Challenger* expedition, a four-year journey to explore the deep oceans, as an assistant to the expedition leader, Charles Wyville Thomson. The expedition travelled 70 000 nautical miles and laid the foundation for oceanography. When Thomson could no longer endure the stress of publishing the work of the expedition, Murray took over, and edited and published over 50 volumes of reports, which were completed in 1896.

In his writings, Murray used the "fathom" as the unit of depth, and 1 fathom is equivalent to 6 feet. In his subsequent accounts Murray claimed that "deep soundings, even in 4000 fathoms, carefully taken … are believed to be correct within 25 fathoms".[2] For the purposes of this article, we rechecked that Murray did indeed write 4000 fathoms, since it came as a surprise that he claimed such accuracy (less than 50 metres) at this depth of approximately 7.3 kilometres (or 4.5 miles).

By 1888, armed with "the records of travellers, of deep-sea expeditions, and the hydrographic surveys of various nations", Murray was sufficiently confident to attempt to give "a numerical expression to the areas of land at different levels above, and of the ocean's floor at different depths below the surface of the sea, as well as to the bulk of the dry land, and the bulk of the waters of the ocean, with their mean height and depth".[3]

To do so, he employed a planimeter – a device for measuring the area of a two-dimensional shape. Referring to Figure 3 as an example, we can see how Murray used the planimeter to mark out regions on a map, with the boundary lines of each representing different height and depth contours. Murray used the areas of these regions and their heights/depths to create cylindrical representations from which he could estimate the bulk of the land and the volume of the ocean.

The land was divided into areas representing 600, 1500, 3000, 6000, 12 000, 18 000 and 24 000 feet. For the ocean, Murray marked out areas representing 100, 500, 1000, 2000, 3000 and 4000 fathoms. He estimated that these seven segments contained, respectively, 7.4%, 5.4%, 4.7%, 21.3%, 56.6%, 4.5% and 0.1% of the ocean area.

He concluded that "the area of the dry land is estimated at 55,000,000 square miles,

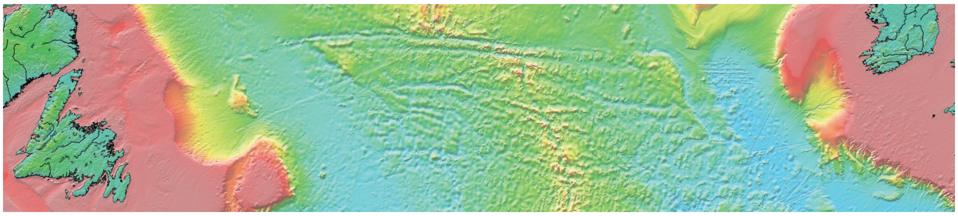

Figure 2. Modern data pertaining to the region between Ireland and Newfoundland, traversed by the transatlantic telegraph cable. Topography version 14.1, July 2011. Note the red-flecked yellow patch that runs through the middle of the image, approximately north to south. This is part of the Mid-Atlantic Ridge, which contains a fracture known as the Charlie–Gibbs Fracture. This fracture has shifted the southern part of the ridge eastward relative to the northern part, making the east–west location of the peak in the profile (shown in the 2012 data in Figure 1) a strong function of latitude. Image courtesy of the Scripps Institution of Oceanography, University of California San Diego (bit.ly/1xLQ5NT)

the area of the ocean at 137,200,000 square miles. The bulk of the dry land above the level of the sea is 23,450,000 cubic miles, and the volume of the waters of the ocean is 323,800,000 cubic miles. The mean height of the land is 2250 feet; the mean depth of the whole ocean is 12,480 feet (2080 fathoms)."

He admitted that "such a uniformity as we have supposed in the slope of the land nowhere exists in nature", and that "the valleys and hills existing between contours render any exact estimate out of the question". However, Murray considered it "unlikely that the bulk estimate is too high a number; it is probably less than the truth".

In the case of the waters, he first divided them into 30 oceans, seas and gulfs. When calculating the volume of the segments, he used a multiplier of one-half the depth in the zones 0–100 fathoms (0–600 feet) and 100–500 fathoms (600–3000 feet), and a multiplier of two-thirds of the depth for all other zones. "The reason for this is obvious," he wrote, "for just as the slope of the land increases as we approach mountains, so does the slope in general decrease as we get into deeper water."

Better tools

The turn of the twentieth century brought with it acoustic echo sounders, which were first patented in 1913 by Alexander Behm as tools for detecting icebergs. Originally developed in response to the *Titanic* disaster of 1912, these devices actually proved more useful and effective as a means of surveying the sea-floor, and they quickly led to greater bathymetry coverage and to hitherto undiscovered seamounts and ocean ridges – geographical features that may have led to overestimates of the overall ocean depth.

Another boon for oceanographers was the 1995 declassification of the US GEOSAT satellite radar altimetry data. This allowed scientists to determine ocean depths from gravity anomalies. In 1997, Walter Smith, of the National Oceanic and Atmospheric Administration (NOAA), and David Sandwell, of the Scripps Institution of Oceanography (SIO), combined these with quality-controlled ship depth soundings to derive a high-resolution grid of sea-floor topography.[4]

But, surprisingly, mean ocean depth – a key component of the "global water budget", the balance of the volume of water coming and going between the oceans, atmosphere and continental landmasses – had not been recalculated using the latest satellite-derived ocean bathymetry until Matthew Charette, of the Woods Hole Oceanographic Institution, and NOAA's Smith did so in 2010.[5] To make their calculation, they relied on version 5 of the SRTM30PLUS bathymetry database, which resulted from Smith and Sandwell's earlier work, but which had been updated to include the Arctic Ocean as well as retracked altimetry and new single- and multi-beam echosounder data from US and international agencies, and academic and industrial sources.

The database, provided by the SIO, is publicly available and consists of over 933 million entries over a rectangular grid (see Figure 4), with a resolution of 30 arc seconds – half of one-sixtieth of 1 degree – in longitude and latitude.

Charette and Smith do not give details of how they calculated the average depth, but if we had a computer large or powerful enough to hold or process all of the 650 million data points that are considered in the ocean, we might simply take a weighted average of them – with weights proportional to the cosine of their latitude, so as to offset the progressively greater overrepresentation of locations further and further from the equator.

Once Charette and Smith had calculated their modern estimates of the depth, area and volume of the world's oceans, they were surprised and impressed by the closeness of Murray's 1888 estimates. Murray's

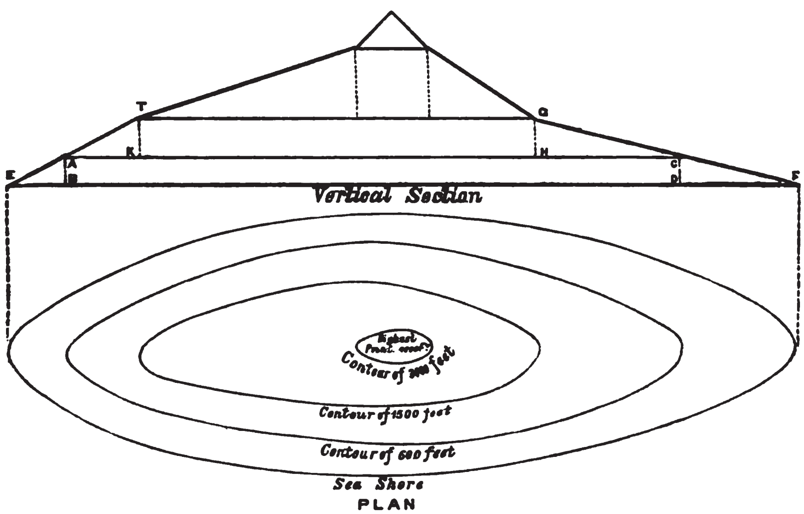

Figure 3. Model used by oceanographer John Murray in 1888 to calculate the bulk of the dry land above the level of the sea, and the volume of the waters of the ocean.[3] The diagram represents a large island or continent. The bulk was estimated as the sum of the volumes of cylinders, such as ABCD, and the "quoit-like" masses of the type ABE and CDF. The contents of the highest zone are ascertained by multiplying the area by one-third of the height of the highest mountain in that zone above the last contour line

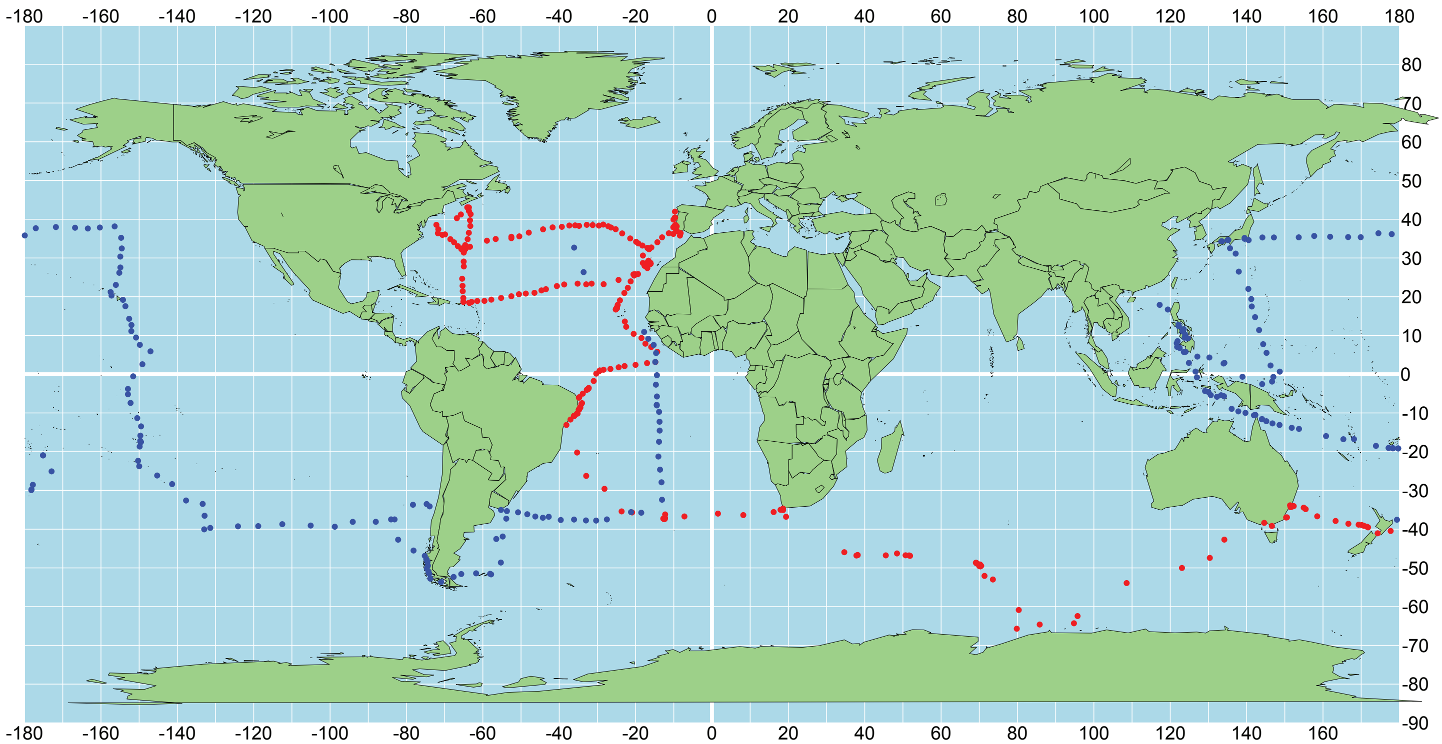

Figure 4. Schematic representation of the rectangular grid of 933 million recordings in the SRTM30PLUS database, along with the locations of the soundings taken during the outward (red) and return (blue) parts of the *Challenger* expedition of 1872–1876. The soundings ranged from 4 to 4475 fathoms: mean approx. 1400 (2700 metres, 1.6 miles). The locations, and the recorded depths, of all 500 soundings can be found online (bit.ly/1GOyN8R)

measurements, in metric terms, were a mean depth of 3797 metres, an area of 355 million square kilometres and a volume of 1.349 billion cubic kilometres. Charette and Smith's comparable figures were 3682 metres, 361 million square kilometres and 1.332 billion cubic kilometres.

The fact that Murray's estimates were so closely in line with Charette's and Smith's is indeed "remarkable", as the pair note. Some of Murray's success may have come from subdividing the overall task into 30 smaller ones, and using a simple geometric model to go with his limited resolution data. Had his American counterpart Maury lived to see the data in the SRTM30PLUS database, he would surely have continued to remind us that the vertical and horizontal scales in Figure 1 give an exaggerated impression of the real gradients: in the big picture, the ocean floor and the above-water terrain are quite smooth, mathematically speaking. In any case, Murray's estimates are a (retrospective) victory for small data and small models.

Data-mining challenge

Significance readers are invited to use the SRTM30PLUS database to make their own estimates of the mean depth, the ocean area and the volume of water. However, since the database is indeed colossal, those with mere personal computers are unlikely to have enough bandwidth of their own to download it, or space to store it, or the resources to unpack it, even though it is also provided in 33 tiled segments.

Readers can, however, sample small rectangles or points, using the internet application provided by the Scripps Institution. And if they do not wish to do everything from scratch, the following website has links to ways of selecting random points on a sphere, and provides R code for automating the internet queries: bit.ly/1wLquVd.

Queries have to be submitted, and the answers received back, one location (or rectangle of locations) at a time. Thus, casting a wide net takes a noticeable amount of time to obtain several hundred observations, and failed queries need to be resubmitted. Thus, teachers might wish to use this challenge in student projects designed to simulate real-life research constraints such as choosing a sampling design and data-collection plan that (i) stays within a statistical budget, (ii) accepts certain statistical margins of error, and (iii) makes several efforts to get an observation.

References

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James Hanley is a professor in the Department of Epidemiology, Biostatistics and Occupational Health, McGill University, Canada. This work was supported by grants from the Natural Sciences and Engineering Research Council of Canada, and le Fonds Québécois de la recherche sur la nature et les technologies