What are the limitations of satellite altimetry?

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Radar altimeter measurements of the marine geoid collected during the Seasat altimeter mission gave geophysicists hope of uncovering the gravity field over all the ocean basins. However, because of insufficient track density, it has taken 16 years for the full potential of the satellite altimeter to be realized. The high-density coverage obtained by ERS-1 during its geodetic mapping phase (April 1994-March 1995) prompted the U.S. Navy to declassify all of the Geosat altimeter data in June 1995. The combination of these two high-density data sets provided the first global view of all the ocean basins at a wavelength resolution of 20-30 km.

Here we assess the future of satellite altimetry for exploration in relation to other measurements and the types of structures that need to be imaged. We address the following questions: What are the physical limitations of satellite altimetry? Can satellite-derived gravity be improved using more measurements or better processing? How well does satellite-derived gravity compare with more accurate local surveys, especially near land? And finally, what is the best way to merge satellite-derived gravity with more accurate local data?

Satellite altimetry methods and limitations. A satellite altimeter uses pulse-limited radar to measure the altitude of the satellite above the closest point of the sea surface. Global precise tracking coupled with orbit dynamic calculations provide an independent measurement of the height of the satellite above the ellipsoid. The difference between these two measurements is equal to the height of the sea surface (~geoid height) minus any delays in the propagation of the radar echo due to the ionosphere and troposphere. There are many errors in these measurements but most occur over length scales greater than a few hundred km. For exploration or detailed marine geophysical studies which focus on shorter wavelengths, the major source of error is the roughness of the ocean surface due to waves (1-6 m). The radar pulse reflects from an area of ocean surface (footprint) that grows with increasing wave height. The superposition of the reflections from this larger area stabilizes the shape of the echo, but it also smooths the echo so that the timing of its leading edge is more uncertain. By averaging many echoes (1000 Hz) over multiple repeat cycles, precision of 10-20 mm can be achieved. Over 4 km (i.e., 1/4 wavelength) this corresponds to a sea-surface slope error of 4-µrad. Laplace's equation provides the mapping from sea surface slope to gravity anomaly, so a 4-µrad slope error maps into a gravity error of about 4-mGal. Thus the only way to improve the resolution is to make many more measurements or stop the ocean waves!

The situation is even more hopeless in the deep oceans (~4000 m) because upward continuation of the gravity field from the ocean floor to the ocean surface provides a strong high-cut filter to the gravity signal. Consider an anomaly on the ocean floor with a 16-km wavelength and a 15-mGal amplitude (i.e., a typical value for oceans). On the surface this anomaly will be reduced to 3.1 mGal by upward continuation. Of course on the shallow margins, the upward continuation effect is minimal so there will be important signals having wavelengths down to a few hundred meters (Table 1). Global satellite gravity grids are optimized for the dominant deep-ocean situation by high-cut filtering the data. For shallow-water exploration, one may ask if the resolution can be pushed to shorter wavelengths. We think there are some minor improvements to be made through more careful treatment of the data, but there won't be a breakthrough.

Gravity anomaly resolution — the thresholds of survey reliability. Gravity anomaly resolution can be measured both objectively and subjectively. The objective approach is to establish the wavelength where the noise level and signal levels are equal. In the case of satellite altimetry, this can be done in the Gulf of Mexico where the true gravity signal is known from more precise shipboard measurements. More commonly, a subjective approach is used where one identifies the smallest anomaly apparent in a gravity map. The danger is that a group of people will provide a variety of estimates, and many estimates may be optimistic. Nevertheless, it is important to understand the likely noise threshold for a map so that you can know which anomalies can be trusted and which should be evaluated with suspicion. The following opinions are meant to help with that understanding:

- The size of an anomaly is a combination of its amplitude in mGal and its width or apparent wavelength

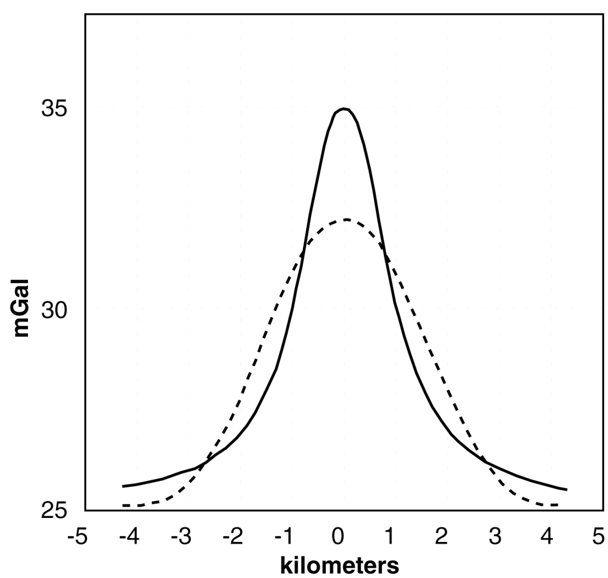

Figure 1. In the course of processing, both signal and noise are filtered together in the effort to suppress noise. The dashed curve shows the effect of a 5-km-wavelength, high-cut filter on the signal of an anomaly source with a depth of 1 km. At this scale, a 1-km-wavelength, high-cut filter has no discernible effect.

Target	Wavelength	Amplitude
Buried cavities, tunnels, tanks	1 - 10 m	5 - 100 μGal
Pediment and seismic weathering layer thickness, shallow gas pockets, karst	10 - 200 m	.05 mGal - 0.2 mGal (200 μGal)
Shallow salt domes and cap rock	200m - 1 km	0.1 - 0.3 mGal
Anticlines, faults, deep salt dome flanks and overhang	500m - 4 km	0.2 - 2.0 mGal
Deep sedimentary basin structure	2 km - 20 km	5 mGal
Sedimentary basin outlines and boundaries, plate tectonic structures	10 km - 100 km	10 mGal

Table 1. Wavelength and amplitude resolution required for typical geologic targets.

where wavelength typically amounts to something less than twice the anomaly width.
- Shorter wavelength anomalies tend to have shallower sources and smaller amplitudes.
- Wavelengths longer than depth to source dominate the gravity anomaly signal; i.e., a high-cut filter that cuts only wavelengths shorter than the depth to source will have practically no effect on anomaly half-widths and anomaly gradient measurements typically used for depth estimation. Any greater degree of filtering or smoothing will have a marked impact on anomaly shape and will distort interpretation results. Figure 1 is an example.

Wavelength resolution is limited by sampling interval and ultimately by wavelength filtering used to reduce noise and enhance signal (Figure 2). Typically station gravity data are not filtered, including underwater and microgravity surveys. So, in the case of station data, wavelength resolution is taken to be twice the station spacing, and station repeatability gives an estimate of amplitude resolution.

In the case of satellite gravity and dynamic gravity (marine and airborne), practically continuous data are available along acquisition tracks so that it is the level of filtering used in processing that determines wavelength resolution; line spacing is important, but it is the level of filtering that limits spatial resolution. Filtering is necessary to suppress short-wavelength, high-amplitude noise that would otherwise obliterate the signal. Remarkably, submilligal signal is routinely extracted from dynamic-gravity background noise levels of tens of thousands of milli-

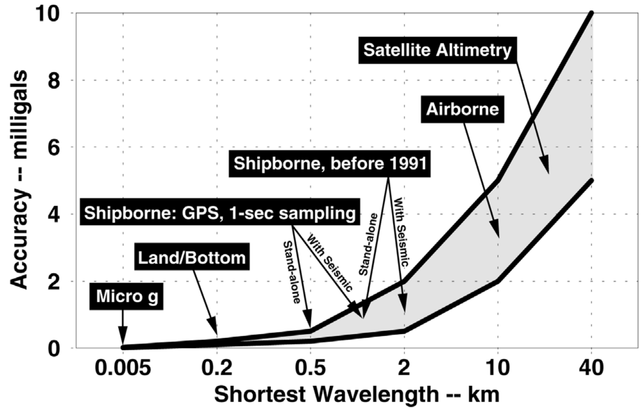

Figure 2. A collection of opinions on the resolution of a range of gravity surveying methods from microgravity surveying to satellite altimetry. For every problem, target size, and depth, there is an appropriate surveying tool that will deliver the resolution we need. The wavelength resolution of station-based data is limited by sampling. Shipborne, airborne, and satellite altimetry are limited by the filtering that is required in processing. Stand-alone shipborne surveys benefit from less active Eötvös corrections and better average weather corrections than typical for conditions on board seismic vessels.

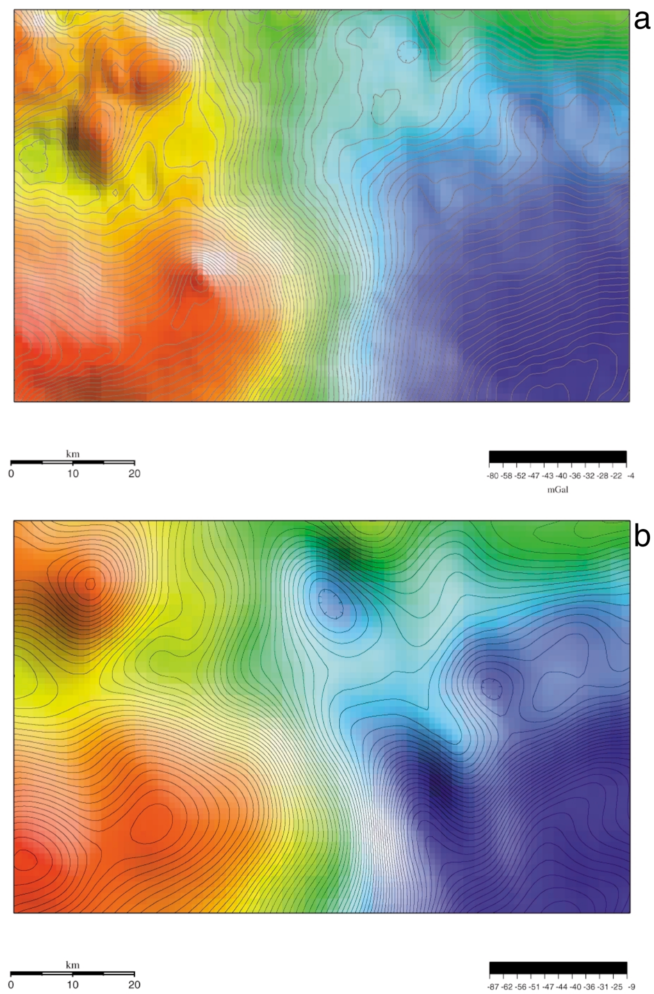

Figure 3. Free-air gravity anomaly (1-mGal contour interval) based on (a) ship surveys, (b) satellite altimetry optimized for deep ocean.

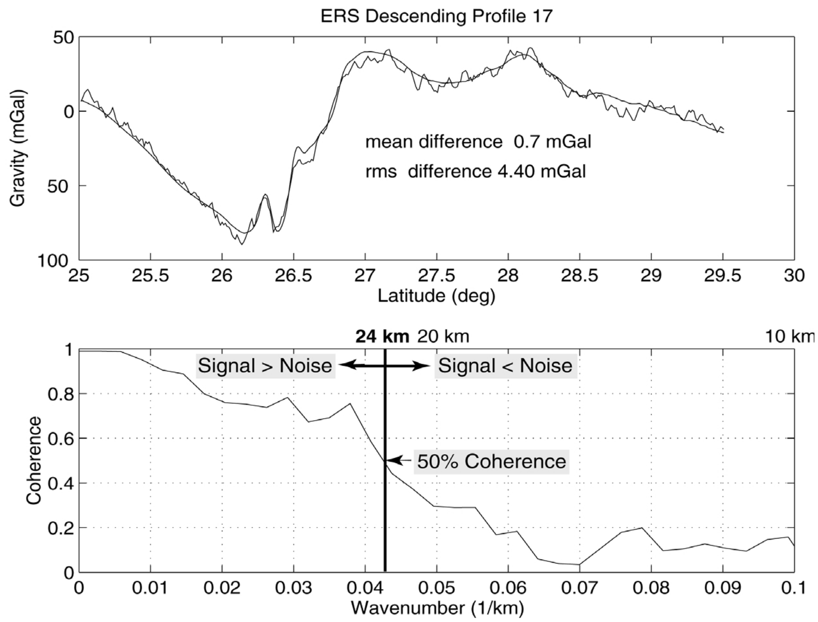

Figure 4. (top) Comparison of shipboard (smooth) and satellite-derived (noisy) gravity in the Gulf of Mexico. The satellite-derived gravity profile is a stack of up to 43 repeat profiles and represents a best-case example. There is good agreement at wavelengths greater than about 50 km except in a few locations. At small scales the altimeter-derived gravity contains both signal and noise (a 10-km wavelength high-cut filter was applied). (bottom) Coherence between stacked ERS altimetry and the ground truth ship (25 profiles across northern Gulf) data provides a quantitative resolution of 24 km at 0.5 coherence where signal-to-noise equals 1. This slight improvement in resolution over deep ocean comparisons (23-30 km) may be due to the higher signal strength of the shallower water in the Gulf.

gals. Dynamic gravity resolution has improved over the past few years mainly because of improved GPS positioning and the consequent improvements to instrumentation and processing. The present state-of-the-art, under the very best conditions, seems to be stuck at a wavelength resolution of about three minutes of sailing or flight time, which corresponds to about 500 m at typical ship speeds and 9 km at a typical 90-knot survey aircraft speed. Gravity gradiometry seems to hold the most promise for a further breakthrough in resolution.

Satellite gravity also seems to have practical limits of resolution with a threshold around 20-40 km, depending on the level of noise that you think you can see through. Marginal data often show intriguing, but false, anomaly patterns. These can be misleading and costly. Figure 3a is a free-air anomaly map taken from an area in the Gulf of Mexico and based on a high-quality marine gravity data with a line spacing of 1 mile. For purposes of comparing with satellite-derived gravity maps, this represents the true gravity field. The corresponding free-air gravity field based on satellite altimetry shows the same broad features but lacks important details (Figure 3b).

Ground truth accuracy and resolution of satellite-derived gravity. The Gulf of Mexico provides a unique opportunity to assess the accuracy and resolution of satellite-derived gravity because of the high-accuracy marine gravity coverage available in EDCON's archives. In an effort to improve gravity field resolution, up to 43 profiles from the repeat phases of the ERS-1 and ERS-2 missions were averaged using the methods described by Yale et al. in the *Journal of Geophysical Research* in 1995. Along-track sea-surface slopes from the V7.2 gravity field were subtracted from the stacked profiles, resulting in residual profiles containing both signal and noise not captured in the V7.2 gravity grid. A 1-D Hankel transform was used to convert these along-track residual slopes into residual gravity, and finally the V7.2 gravity was added back to form a full bandwidth gravity profile. We then extracted the ground-truth gravity along 40 of these stacked profiles in the northern Gulf from the EDCON data. An example is shown in Figure 4 (top) where satellite gravity (noisy) is plotted along with ship gravity (smooth). The mean and rms differences of -0.7 and 4.4 mGal are representative of the other 39 profiles (the mean of all of the rms's is 4.7 mGal). An examination of all of the profiles reveals a number of common features:

- Mean differences are generally less than 1 mGal.
- There is usually good agreement for gravity features greater than 50 km across, but there are some differences (Figure 4, top).
- There is good agreement for some of the smaller-scale features but poor agreement for others. A 10-km high-cut filter does not suppress all of the altimeter noise, but a 20-km filter may be too strong in shallow areas.
- About 1/2 of the profiles show high noise levels within about 20 km of the coastline, suggesting some stray echoes are effecting the radar and/or our processing has introduced significant edge effects.
- Less filtering combined with stacking more profiles can improve ERS resolution from 30 km to the 24-km resolution (Figure 4 bottom).
- The comparison of ship and satellite gravity in the Alaminos Canyon area (Figure 3) reveals other important features. In this case the satellite-derived gravity was filtered (~22 km wavelength) to suppress the noise. However, it is clear that this filtering eliminates small-scale structure that is apparent in the shipboard gravity.

The value of satellite gravity. These figures illustrate the value and limits of satellite gravity. A broad view of the gravity field over most of the world's oceans is available to anyone at practically no cost (http://topex.ucsd.edu). The locations of sedimentary basins along with regional structural relationships can be reliably interpreted from satellite gravity. Satellite gravity provides regional background control for detailed marine surveys. In fact, satellite gravity is usually more valuable and reliable than widely spaced public and commercial marine data that were acquired 20 or 30 years ago.

On the other hand, structural features within basins, including salt domes, anticlines, and fault blocks at a petroleum-prospect scale of interest (Table 1), usually require resolution at much shorter wavelengths than can be reliably taken from satellite measurements. It is obviously perilous to pursue a prospect based on a fictitious anomaly.

Summary. So here are brief answers to the original questions:

Ocean surface waves are the primary factor that limits the accuracy and resolution of the satellite-derived gravity. A factor of 2 improvement will require 4 times more data. Since ERS and Geosat data span 10 years, we would need another 30 years of data collection.

In the case of ERS data, better processing of the raw waveform data may lead to significant gains in accuracy, but the improvement will be less than a factor of 2. Geosat and Topex altimeter data do not suffer from the noise problems of the ERS onboard tracker, so don't expect much overall improvement in the global gravity models.

A number of independent studies show satellite-derived gravity has accuracies of 3-7 mGal and resolution of 20-30 km depending on such factors as typical sea state and proximity to land.

The best way to use satellite-derived gravity for exploration is to augment the more accurate local surveys. The satellite-derived gravity can provide the big picture needed for the local interpretation. This is especially true in areas where large-scale tectonics has had an important influence on basin development. LE

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