Satellite-derived gravity having an impact on marine exploration

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Converting sea-surface height variations, derived from satellite altimetry, to free air gravity is not new. In the early 1980s William Haxby (Lamont Doherty Geological Observatory) produced the first global marine gravity map from SeaSat satellite altimeter data using interorbital track spacing of about 180 km. Haxby's map had a significant impact on plate tectonic theory because marine free air gravity data were able for the first time to uniformly image the tectonic fabric of the earth's oceanic crust. Since that time, much effort has been applied to improving satellite-derived gravity resolution. A major advance occurred in 1995, when the altimeter data from Geodetic Missions (GM) of GeoSat and ERS-1 satellites were released. Table 1 gives details of these satellites.

By combining their orbital tracks, a track density of ~3 km was achieved at the equator with increasing track density toward the poles. This resulted in a spectacular global marine gravity model developed by David Sandwell and Walter Smith based on the sea-surface height data provided by NASA (GeoSat) and Eurimage (ERS-1). Despite the spatial coverage of orbital tracks being ~3 km, it was surprising that the overall resolution of this new data set was no better than ~25 km. Could better resolution be achieved?

In 1996, GETECH working with the International Gravity Bureau (Toulouse, France) showed that, even after improving and refining processing procedures, only marginal improvements on the ~25 km resolution were possible if prepicked sea-surface height data were used. Visual inspection of ERS-1 repeat track data indicated a significant noise envelope. GETECH decided the only way to significantly improve resolution was to repick the sea-surface heights from the "raw" waveform data. This had not previously been done for GM data, due in part to the large data volumes (e.g., ERS-1 GM waveform data alone filled 130 exabytes!). An industrial consortium study was undertaken to determine what was possible.

Methodology. Figure 1, a simple example of a radar waveform, is made up from the progressive return of reflected energy from a single satellite radar pulse. Determining sea-surface heights requires the precise measurement of the onset time of each returning radar pulse located at 50% of the total power along the leading edge. Sea roughness shapes the leading edge such that calm and rough seas generate steep and slanting leading edges, respectively. Since these returning radar echoes are weak and are repeated every ~1/1000 s, the satellite was programmed to stack 50-100 of the reflections and return to earth reflection signals at 1/20-s intervals for ERS-1 (~350 m along track) and every 1/10-s for GeoSat (~700 m along track). The waveforms were sampled at 3-ns intervals, thus generating huge volumes of data. The European agency responsible for picking the ERS-1 waveforms used five parameters to define its shape. The tail of the radar waveform is generally very noisy but important for oceanographers studying air-sea interactions. The use of five parameters to locate and define the shape of the waveform has invariably degraded the onset "geodetic" parameter and is viewed as a major contributing factor to the uncertainty of the onset time.

Table 1. Specifications of the Geodetic Missions (GM)

GM details	GeoSat	ERS-1
Year	1985/86	1994/95
Height	~800 km	~800 km
Latitude range	∓72?	∓82?
Radar frequency	13.5 GHz	13.8 GHz
Pulse repetition	1020 Hz	1020 Hz
Echo sampling	10 Hz (100 fold)	20 Hz (50 fold)
Data sampling	3.125 ns (~45 cm)	3.03 ns (~45 cm)

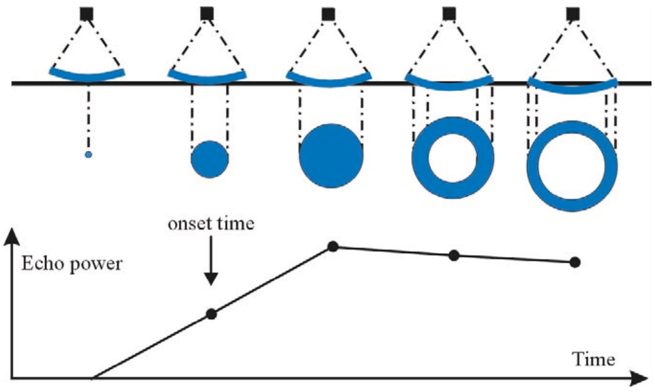

Figure 1. Time-lapse intersection of an altimeter pulse with the sea surface.

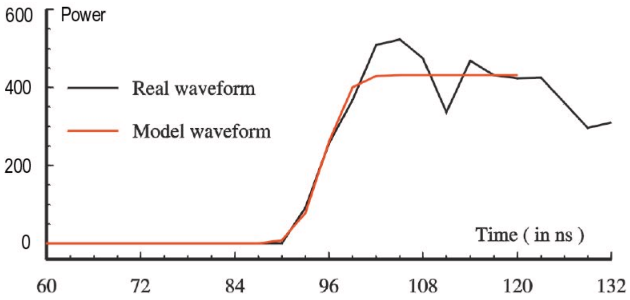

Figure 2. Fitting a model to the radar waveform.

GETECH has repicked the onset times using a technique used in seismic picking. This involves matching individual waveforms with a varying model waveform whose emergent onset (slope of the leading edge) is controlled by the varying sea-state parameter (Figure 2).

This technique significantly reduced the along track noise particularly in the wavelength range 50-10 km. Figures 3a and 3b show ERS-1 agency picks (black) and our repicked waveforms (red). Due to the 3-ns sampling interval, the leading edge commonly only contains 3-4 data points, resulting in an uncertainty of the onset time which manifests itself as high frequency noise (red in

Editor's note: This article updates TLE*'s 1998 article "Satellite-derived gravity: Where are we and what's next."*

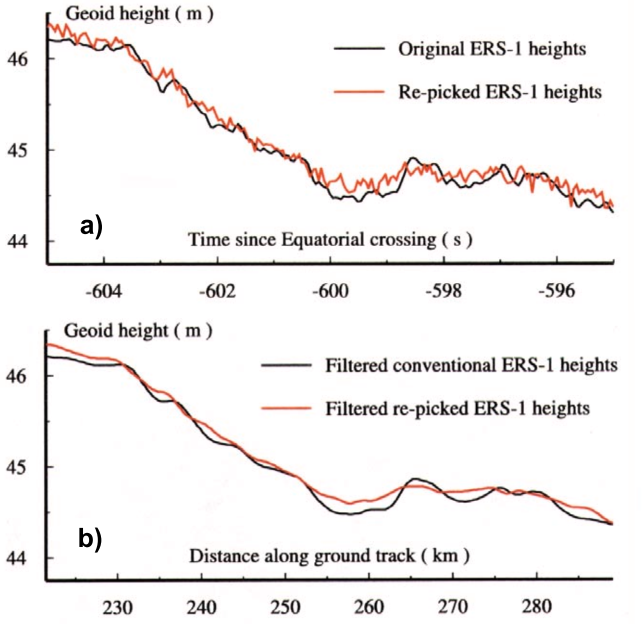

Figure 3. (a) Profile of the sea-surface height picks. (b) Height profile with 5-km low-pass filter.

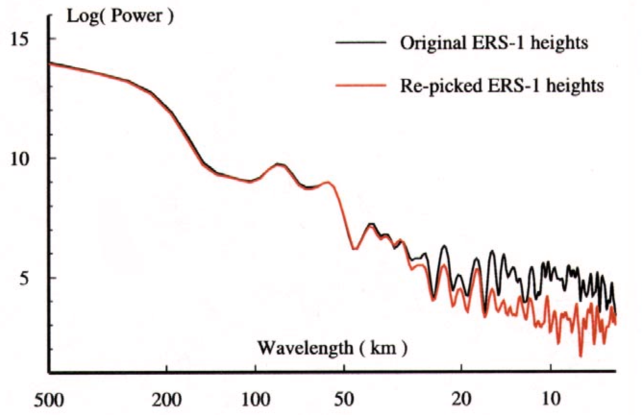

Figure 4. Power spectrum of the sea-surface height profiles.

Figure 3a). Application of a low-pass 5-km filter removed this noise (Figure 3b).

Comparison of our repicks with the agencies picks revealed that GeoSat data has been consistently better picked than ERS-1 data. The GETECH repicked GeoSat waveforms did not improve on the agency along track resolution. This was not the case for ERS-1 data where we consistently and significantly improved the resolution by repicking. Figure 4 compares along track power spectra of ERS-1 altimeter data. The agency data (black) exhibit the onset of white noise below 25 km; for the repicked data (red), white noise commenced below 10 km. Our conclusion was that the ERS-1 data had been poorly picked by the agency and degrade the combined satellite gravity solution. The next task was to investigate how the repicked waveform data could improve spatial resolution.

Converting the repicked sea-surface heights to their gravity equivalent is a complex process initially involving the application of a range of corrections to individual picks (Table 2). The resulting heights can be considered as geoid heights. We have used the "geoid to gravity" method rather than the "along track gradient" method used by Sandwell and Smith. The reasons were our need to generate a reliable geoid model and that geoid grid interpolation is more robust than derivative grid interpolation in the presence of noise and where data coverage is irregular.

Table 2. Corrections applied to individual picks

Altimeter range corrections	Ionospheric correction Dry tropospheric correction Wet tropospheric correction Doppler range correction Spacecraft centre of gravity correction
Tidal corrections	Ocean tide model Solid Earth tide model Ocean loading tide model

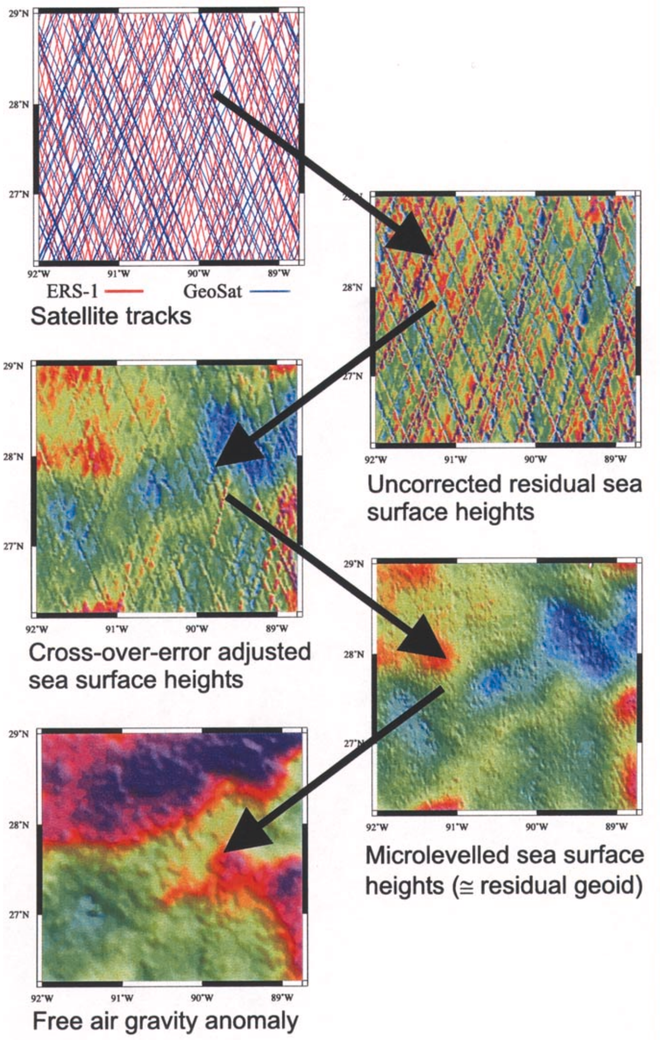

Figure 5. 'Geoid to Gravity' processing sequence.

Figure 5 illustrates the geoid to gravity method after the removal of the 0.50 EGM96 reference geoid model. The errors in orbital height are reduced initially by least squares adjustment prior to microleveling. The resulting surface is then converted to gravity by a Fourier domain operation. In its simplest form this involves the vertical derivative of the geoid surface and restoring the gravity equivalent of the EGM96 reference model.

The method was initially applied to a test area in the northern Gulf of Mexico (Figure 5) where extensive shipborne and seabed gravity data exist and can be used to

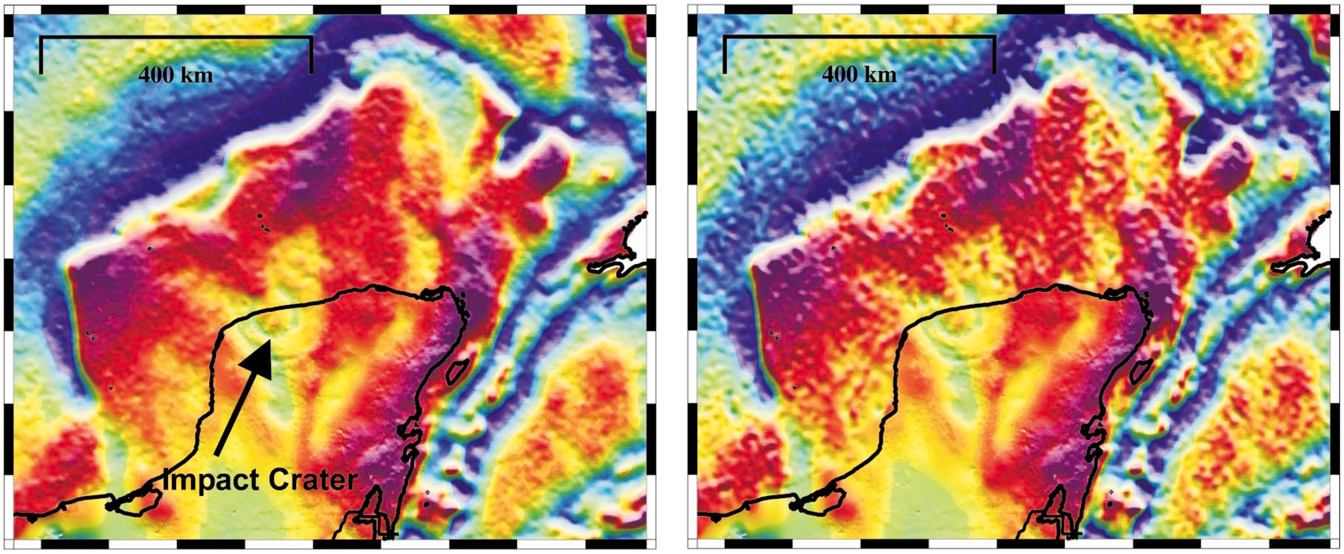

Figure 6. Gravity image of the Chicxulub impact crater. (a) GETECH data and (b) Sandwell data.

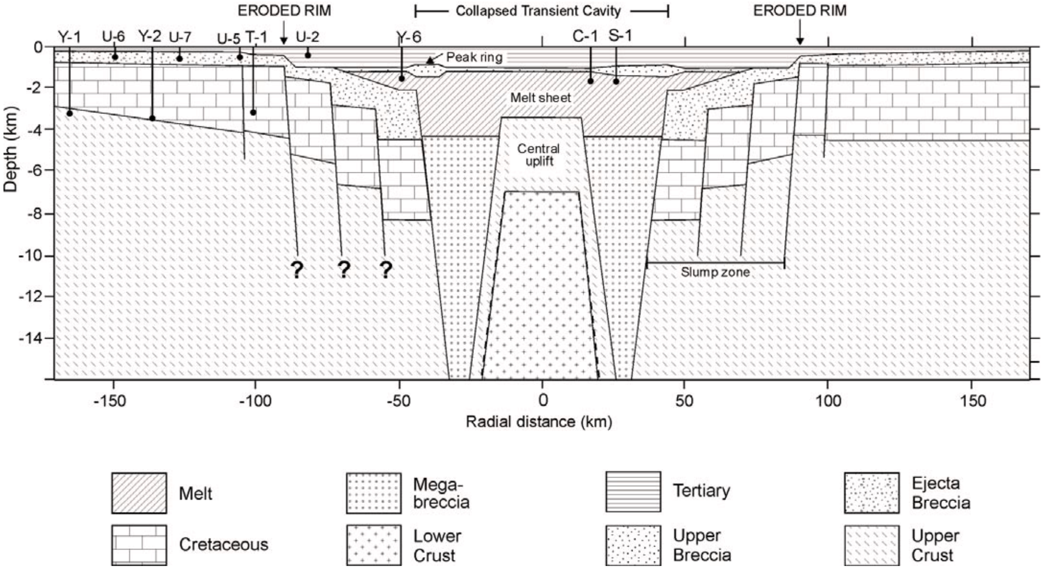

Figure 7. Cross-section of the Chicxulub impact crater by Pilkington and Hildebrand.

"ground truth" the satellite-derived gravity data. The spectral content of the satellite-derived (2 km) grid indicates a spatial resolution down to 10 km full wavelength (or 5 km at half wavelength). Independent analyses of the satellite gravity by two consortium sponsors have confirmed this value which is consistent with the 3-km track density of the combined GM data sets.

Implications for oil exploration. It is important to remember that the spatial resolution of the data is at sea level not at the satellite height of ~800 km. The spatial resolution allows concession scale gravity anomalies to be reliably measured, albeit not at the resolution of 0.1 mGal and 0.5 km currently achieved by gravity meters on seismic vessels. Thus the niche market that the new higher resolution satellite data can exploit is their ability to assess new exploration areas, particularly deepwater parts of the continental margins where seismic imaging is either sparse or expensive.

Reprocessing the whole of the Gulf of Mexico has revealed improvements over the agency-based solutions for subtle structure greater than 50 km wavelength as well as anomalies from 50 km down to 10 km. The repicked altimeter data can also yield gravity data closer inshore than previously possible, thus minimizing the interpolation needed to link with onshore gravity data. The improvement in resolution in the wavelength range 50-10 km permits better and more reliable derivatives to be constructed, which by their very nature are sensitive to the shallow Tertiary geologic structures such as sedimentary pathways, depositional centers, and basins. This leads to better interpretation.

Figure 6 is an example of the enhanced satellite data linked to onshore data for the Mexico region centered on the Chicxulub impact crater on the northern shore of the Yucatan Peninsula. Recent investigation by Pilkington and Hildebrand (*Journal of Geophysical Research*, 2000) generated the cross-section in Figure 7. The enhanced satellite gravity data offshore allows structures emanating from the impact crater to be traced across the continental margin.

Conclusions. We have advanced the resolution of currently available altimeter data to its spatial limits resulting in recoverable signal down to 10 km (Figure 8). To map and interpret geological structures from satellite data requires a bathymetry model of similar resolution since the seabed interface generates a major gravitational effect that often dominates the marine free air gravity anomaly. The higher

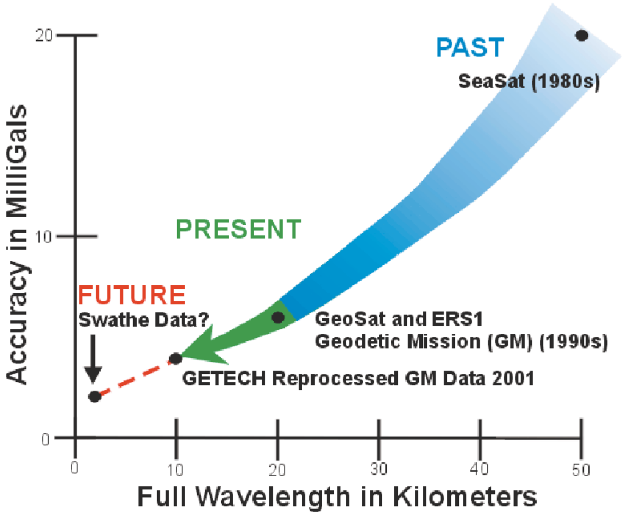

Figure 8. Satellite gravity spatial resolution trend—past, present, and future.

resolution satellite gravity data will play an important role in global exploration due to their low cost and global availability. *So what next?*

Current satellite technology suffers from the law of diminishing returns in that: *Sea-surface height (cm) = 0.016 × wavelength (km) × gravity anomaly (mGal)*

To improve further the spatial resolution of satellite gravity will require a quantum increase of data and an ability to reliably define sea-surface heights to less than a centimeter with corrections (Table 2) to match. This is unlikely to occur using acquisition methods previously used. One possible way to overcome these limitations is repeat satellite swathe mapping similar to that carried out by U.S. National Imagery and Mapping Agency (NIMA) as part of the Shuttle Radar Topographic Mission (SRTM) in February 2000 (Figure 8). Unfortunately such data over the marine areas of the world's continental margins remain classified. **LE**

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