POTENTIAL FOR IMPROVING GLOBAL MARINE GRAVITY FROM CRYOSAT AND JASON-1

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ABSTRACT

Marine gravity anomalies derived from radar altimeter measurements of ocean surface slope are the primary data for investigating global tectonics and seafloor bathymetry. The accuracy of the global marine gravity field is limited by the availability of non-repeat altimeter data. Current models, having accuracies of 3-5 milligals (e.g., S&S V18 and DNSC08), are based on the non-repeat data collected by Geosat (18 mo.) and ERS-1 (12 mo.) which use altimeter technology from the 70's and 80's, respectively. The next opportunities for significant improvements in marine gravity will come from Cryosat and perhaps Jason-1 if it is placed into a non-repeat orbit. In addition to complete ocean coverage, the three attributes needed for improved gravity are improved range precision, optimal satellite inclination, and long mission duration. We will use these methods to assess the range precisions of Cryosat and Jason-1 in relation to Geosat, ERS, Topex, and Envisat. We expect that the higher PRF's of the newer altimeters will provide a square root of 2 improvement in range precision. The low inclination of the Jason-1 orbit offers the best opportunity for improvement in the E-W variations in gravity, especially at low latitude. The hopefully, long mission duration of Cryosat provides the best opportunity for reducing the noise due to ocean surface roughness from swells. Data from these two missions may eventually result in a factor of two improvement in the accuracy of the marine gravity field and geoid at scales less than 100 km.

1. INTRODUCTION

Over the next 3 to 5 years, a wealth of new marine gravity data will be provided by three currently operating satellite altimeters CryoSat, Jason-1, and Envisat. With careful processing of the data, in combination with data from past Geosat and ERS-1/GM altimeter missions, we propose to improve the accuracy of the global marine gravity field by at least a factor of two and in some areas a factor of four. Our proposed research has 4 main components. The first is to develop retracking algorithms and computer codes for analysis of data from these three radar altimeters. The second is to construct new global marine gravity models at 1 minute resolution extending to a latitude of 88 degrees north. The third is to update global bathymetry grids at both 1 minute and 30 arc second resolutions using the new gravity field information for interpolating areas where there are no ship soundings. These first three activities will be performed in collaboration with Walter H. F. Smith at NOAA (see letter of collaboration). The fourth is to use these new data to estimate the bending moments needed to support the trench and outer rise topography of all subduction zones. In addition, the higher resolution gravity may reveal the orientation and amplitude of outer trench wall fractures associated with this bending. These measurements will be coupled to Benioff zone geometry and ultimately be used to infer the slab pull forces driving the plates. This work will be performed in collaboration with Dave Stegman at SIO.

2. NEW SATELLITE ALTIMETRY DATA FROM CRYOSAT, JASON-1 AND ENVISAT

The marine geophysics community has been waiting for 15 years for a new source of densely spaced radar altimeter measurements. Current gravity fields are based primarily on 18 months of Geosat/GM data collected in 1985-86 and 12 months of ERS-1/GM collected in 1995-96. Since then there have been several advances in radar altimeter technology but all the newer satellites have been placed in the repeat orbit configuration that is optimal for recovering changes in ocean surface height associated with currents and tides [1] but provide little new gravity information. The repeat orbit altimeters include Geosat/ERM 1986-1989, ERS-1 1991-1995, Topex/Poseidon 1992-2006, ERS-2 1995-2010, GFO 1998-present, Jason-1 2001-present, Envisat 2002-present, and Jason-2 2008-present. Over the past year there have been three developments related to radar altimeter missions with dense track spacing. First, CryoSat-2 was successfully launched in February of 2010 and has routinely collected altimetry data over ice, land, and ocean since July 2010 (Fig. 1 - upper). Second, the Envisat satellite, which has been in continuous operation since 2002, is running low on the fuel needed for maintaining a repeating ground track. Beginning in October, 2010 the orbit has been allowed to drift while still collecting altimetry data. Envisat will remain in this drifting orbit at least until the 2013 launch of the replacement satellite Sentenel-1. Third, the Jason-1 altimeter was replaced by Jason-2 in 2008 so to avoid a potential collision and to provide new gravity information, it will be maneuvered into an orbit with a 419-day repeat cycle (Fig. 1 - lower) in early 2013 which is optimal gravity field recovery [2]. In their normal operating modes all three of these "new" altimeter have range precision approximately the square root of two times better than Geosat and ERS because they operate at 2 times higher pulse repetition frequencies of about 2000 Hz. More important, the Cryosat altimeter can also be operated in a synthetic aperture radar mode over the oceans to achieve a perhaps factor of 2-4 improvement in range precision [3,4,5,6]. Fig. 1 shows the planned modes of operation for Cryosat as well as the actual standard-mode (LRM) data collected for the past 6 months. A zoom of the Caspian Sea area shows existing coverage as well as planned coverage from Cryosat and Jason-1. The planned Jason-1 trackline is too dense to see individual tracks on this figure.

A preliminary analysis, discussed below, shows that CryoSat altimeter has better range precision than Geosat by a factor of 1.4. If Cryosat operated for 3 years or longer, then the combined gravity field improvement will be a nearly factor of 2 as shown in Fig. 2. One negative feature of CryoSat is that the high orbital inclination results in mostly N-S track orientation so at low latitudes the E-W component will not be resolved as well as the N-S component. At low latitudes, the data from Jason-1 will be important for gravity field improvement. The tracks will be very dense if the satellite can operate for a full 419 day repeat cycle.

3. WHY RETRACKING IS ESSENTIAL FOR CRYOSAT AND JASON-1

Satellite altimetry data are provided to the user community at different levels of processing. Most users begin with the level-2 products where the raw waveform data has been retracked and averaged into 1 Hz or 7 km along-track spacing. Standard waveform retracking estimates 3 to 5 parameters, the most important being arrival time, rise time, and the return amplitude [7,8]. Through calibration, these 3 parameters are transformed into sea surface height, significant wave height, and wind speed respectively. Most users of level-2 data, average these parameters for about 30 km in the along-track direction to further reduce noise. However, this standard processing is inadequate for optimal recovery of the marine gravity field. The marine gravity field is a measure of ocean surface slope so high range precision over the shortest possible along-track distance is needed.

The accuracy of the recovered gravity field depends only on the accuracy of the arrival time parameter. One way of improving the gravity field is to retrack the raw altimeter waveform using an algorithm that is optimized for arrival time estimation. Arrival time and swh are inherently correlated because of the noise characteristics of the return waveform [9,10]. Two previous studies have demonstrated up to 40% improvement in range precision by optimizing the retracking algorithm to achieve high range precision at the expense of recovering small spatial scale variations in significant wave height [9,10]. For this proposal, we have modified the ERS-1 retracking software to work with CryoSat LRM data. Our preliminary analysis based on 8 profiles across the Indian Ocean reveal the following (Fig. 3). First the quality of the raw waveform data are excellent. The EGM2008 model was used to assess the accuracy of slope estimated from retracked CryoSat. The standard 3-parameter retracking has a median absolute deviation (MAD) of 3.14 *m*rad. The optimized 2-parameter retracking reduces the MAD to 2.48 *m*rad. A similar analysis using retracked Geosat and ERS-1 data shows MADs of 3.19 *m*rad and 3.56 *m*rad respectively. **We attribute the 1.4 reduction in noise level of CryoSat with respect to the previous altimeters to its 2 times higher pulse repetition frequency. This preliminary analysis suggests that a factor of 2 improvement of global marine gravity is feasible with 3 years of data and optimized waveform retracking.** The European Space Agency has no plans to retrack CryoSat data using this optimized approach. Our proposal is to develop optimal retracking methods for CryoSat, Jason-1, and Envisat. One year of CryoSat data has 500 million waveforms so the retracking algorithms must computationally efficient.

How will improved gravity enable new science? One of the main drivers for an improved gravity field is the ability to resolve new structures on the ocean floor (Fig. 4). The scientific rationale for such a mission is mature and a set of papers related to this topic was published in a special issue *Oceanography* [11], entitled *Bathymetry from Space*. The global ocean floor could be mapped to about 200 m horizontal resolution acoustically by ships carrying multi-beam echo-sounders, at an investment of around 200 years of ship time [12]. A global ocean mapping program by a satellite altimeter operated in SAR mode would be cheaper by an order of magnitude, but would also have a more limited resolution (about 6 km). This limitation is imposed by physical law (upward continuation of gravity anomalies from the sea floor to the sea surface) and not by altimeter technology. Studies by the ABYSS science team, [13] found that an altimeter mapping sea surface slope to 1 microradian with a half-wavelength resolution of 6 km would be sufficient to resolve the abyssal hill fabric of the oceans. Although not as detailed as acoustic bathymetry, mapping to this resolution threshold would be a critical advance for a large number of basic science and practical applications, including: determining the effects of bathymetry and seafloor roughness on ocean circulation [14], mixing [15], climate [16], tides [17], and biological communities, habitats, and mobility [18]; understanding the geologic processes responsible for ocean floor features, such as abyssal hills, seamounts, microplates, and propagating rifts [19,20]; improving tsunami hazard forecast accuracy by mapping the deep ocean topography that steers tsunami wave propagation [21]; assessing potential territorial claims to the seabed under the United Nations Convention on the Law of the Sea [22].

These studies of the new science are related to a gravity accuracy of better than 1 mGal. Note that 1 mGal accuracy in gravity translates into 1 microradian accuracy in ocean surface slope. Current gravity models have accuracies of 3-5 mGal over a 9 km length scale. With CryoSat we hope to reduce this error to 1.5-2.5 mGal over a 9 km length scale (Fig. 2). Achievement of better than 1 mGal over a 6 km length scale will require an altimeter operating in SAR mode. So we see CryoSat as an important milestone in demonstrating the ultimate accuracy and resolution threshold. Moreover, as shown in Fig. 1, CryoSat will be operated in the SAR mode over the Arctic Ocean as well as some small test regions in the lower-latitude oceans. As part of this proposal we will assess the gravity improvement that can actually be achieved by operating in the SAR mode and will incorporate these SAR-mode data in our global gravity models.

4. PROPOSED TASKS

We have an investigation, approved by the European Space Agency, to obtain all the CryoSat waveform data (LRM, SAR, and InSAR) over the oceans at no cost. These LRM data have similar characteristics to Geosat waveform data records WDR or the ERS waveform product (WAP). Our 4-year plan is:

Year 1 – We will modify our waveform retracking software and altimeter processing software to be used with the CryoSat waveform data product. We have obtained a few passes of CryoSat over ocean areas to evaluate the signal-to-noise characteristics of the multi-looked waveform data. Through comparisons with high-resolution geoid models we will refine waveform tracking algorithms that are optimized for the open ocean and sea ice areas. We expect that the algorithm development will continue into the second year of the investigation.

Year 2 - We will construct a new global gravity grid (1-minute resolution) based on all available satellite altimeter data. The methods and computer codes for constructing the vertical deflection, gravity anomaly, and geoid height grids are published in [23,3]. If we can automatically re-track CryoSat data in areas of sea ice, we will extend the grid to +88˚ latitude. The gravity field construction will be repeated at 1-year intervals until the end of the CryoSat mission (3 – 5 years). The long-wavelength reference field for this grid will be based on the best available spherical-harmonic gravity models from CHAMP, GRACE, and GOCE. The altimeter-derived gravity models are most accurate between wavelengths of 20 km and 2000 km while the satellite-derived models are most accurate between wavelengths of 400 km and 40,000-km. The overlap part of the spectrum will be used to validate both approaches as well as to isolate the false gravity signals that will be apparent in the altimeter-derived gravity along the fronts of the major currents.

Years 3 and 4 – If Jason-1 is still operational after it is placed into it 419-day repeat cycle phase in mid-2012 we will develop a waveform retracker that is optimized for gravity recovery. We hope to receive a 419 days of Jason-1 data from the planned Geodetic mission by mid-2014. We will add these data to the gravity field to improve the lower latitude gravity accuracy by another milligal. The major benefit of Jason-1 data will be to better constrain the E-W gravity field so N-S features such as the East Pacific Rise can be better resolved. In addition to Jason-1 we expect some new gravity information from the drifting phase of Envisat. However, the extent and duration of this drifting phase are not well known. ESA hopes to keep the envelope of the drifting Envisat tracks to less than 20 km so repeat-track InSAR and altimetry is still sometimes possible.

5. REFINEMENT OF GLOBAL BATHYMETRY

The third aspect of our proposed research is to continue the construction of global bathymetry models at 1-minute and 30-arc seconds. lobal cleaned bathymetry data will be used with the improved CryoSat and Jason-derived gravity model to make a new global bathymetric prediction. The accuracy of the prediction degrades with distance to the nearest depth sounding [24] so our focus will be to locate existing data that will fill the largest data gaps. These "new" data do not come from the normal archives such as NGDC or the Marine Geosciences Data System. For example, the National Geospatial Agency has accumulated an archive of 1376 cruises that are not included in the NOAA GEODAS distribution [25]. In general the quality of these data are poor and unsuitable for constructing grids even at 1 minute resolution. Some of these tracks cover remote seafloor where there are large gaps. Approximate 50% of these sounding data have significant blunders in depth or navigation. Undergraduate students in our lab visually examine every trackline using a tool that displays the sounding depth along with the predicted depth. Blunders and questionable data are flagged and not used in the next update of the global bathymetry. This is an iterative process where a new global map is constructed, the SID of conflicting points is recorded and the trackline is re-edited. Over the past 7 years we have assembled and cleaned 6800 files of bathymetry data from perhaps 100 different sources. Some of these data are proprietary but most have no restrictions and have been provided to other investigators.

6. BROADER IMPACTS

This work will support the training of a graduate student and 2 - 3 undergraduate students. We will continue to: participate in media activities, give talks at Museums and Science Centers, and give presentations at local schools. In addition we will continue to distribute our data products and scientific results at our web site http://topex.ucsd.edu. To determine the effectiveness of our web outreach activities, one could Google search on the following keywords and our web site topex.ucsd.edu will be near the top of the sites listed: *marine gravity* (1st/6.4 million), *global topography* (2nd/8.6 million), *bathymetry* (4th/0.3 million), *seafloor* (3rd/0.8 million). The key to the success of these pages is long-term stability and consistency. The gravity and bathymetry data are distributed at three levels to help fill the needs of expert, intermediate, and novice users as described in the section Data Management Plan.

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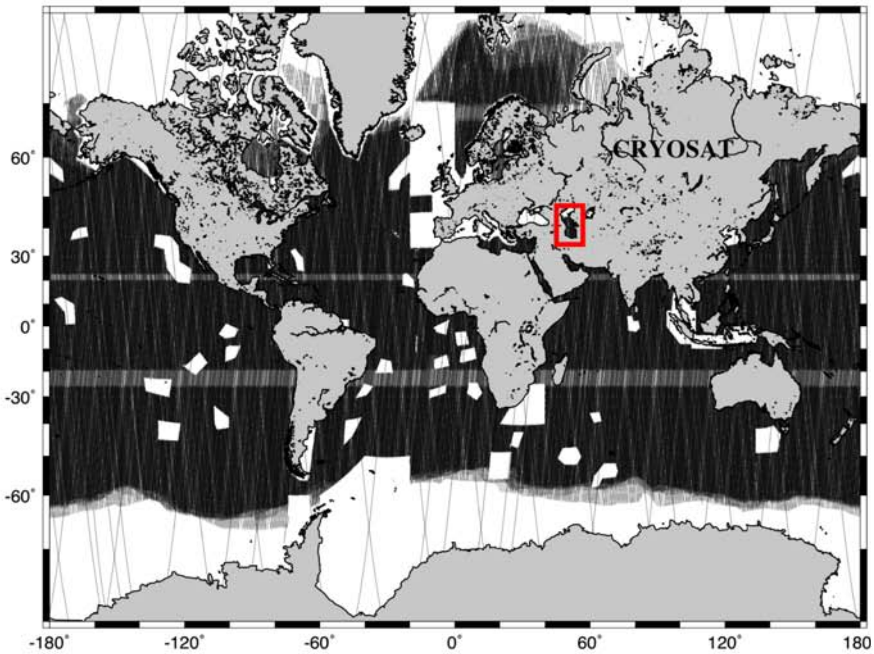

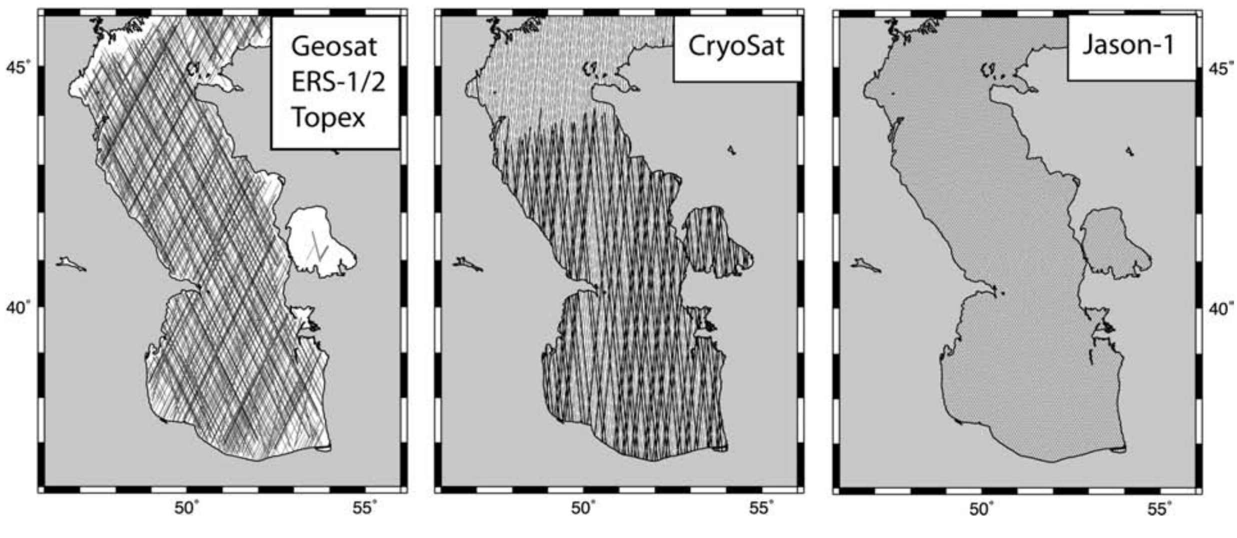

Figure 1. (upper) planned radar operating modes for CryoSat; LRM – standard mode used by all previous altimeters; SAR – synthetic aperture radar mode may provide 2-4 times better range precision. SARIN – uses two receive antennas to also measure cross-track slope over ice. We propose to process the data from all three modes for complete ocean coverage.

(middle) Actual CryoSat data collected in the LRM mode for the past 6 months basically follows the acquisition plan. Missing bands at +/- 22 latitude will be added in the second distribution of the data.

(lower) Ground tracks for the Caspian Sea region (left) actual tracks used in V18.2 global gravity [*Sandwell and Smith*, 2009]. (center) CryoSat tracks for the past 6 months (dark lines) as well planned 1-year tracks (light lines). (right) planned Jason-1 tracklines (light lines).

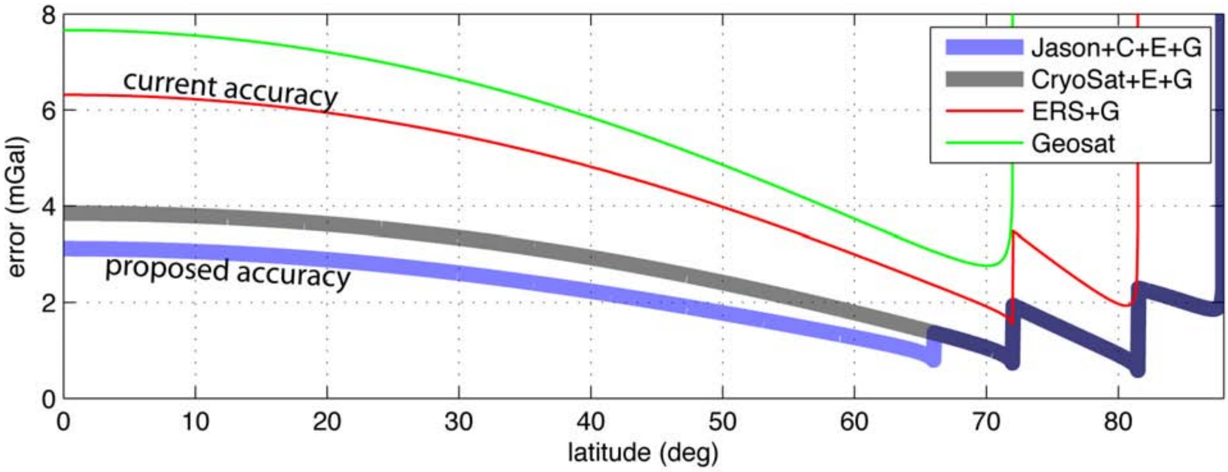

Figure 2. Theoretical gravity field accuracy versus latitude showing relative improvements as new altimeter data become available. Green curve shows gravity field accuracy based on retracked Geosat only which has a maximum latitude of 72˚. Accuracy improves with latitude to 72˚ as tracks become more orthogonal and track density increases. Red curve shows the present-day gravity accuracy from V18.1 [*Sandwell and Smith*, 2009], which also includes retracked ERS-1 data which has a maximum latitude of 81.5˚. The thick black and blue curves show improvements by adding Cryosat (3 years retracked) and Jason (1.15 year retracked).

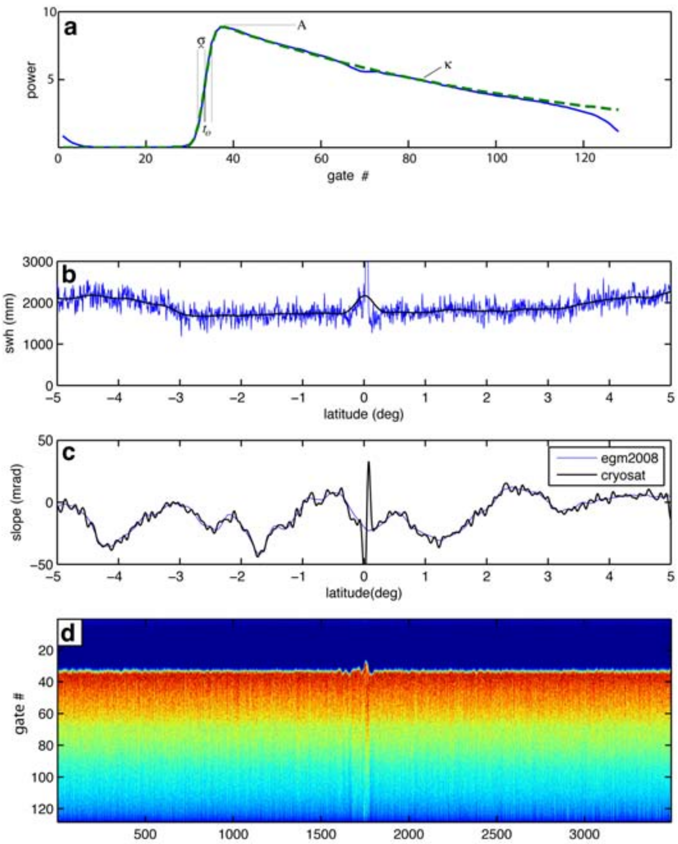

Figure 3. Short segment of a CryoSat LRM track across the Indian Ocean.

(a) Average of 27,000 CryoSat radar waveforms (solid) and a simplified model (dashed) with four adjustable parameters: A-amplitude, t_o – arrival time, σ – rise time, and κ – trailing edge decay.

(b) Significant wave height (swh) derived from 4-parameter retracking model (blue curve) has unrealistic short wavelength jitter. Smoothed swh (black curve) was provided to a 2-parameter retracker to constrain the shape of the leading edge of the waveform so the arrival time is more accurately estimated.

(c) Arrival time converted to along-track slope (black curve) compared with slope from the EGM2008 model (blue curve, essentially V18.1 gravity). Both were low-pass filtered at 18 km wavelength for direct comparison with a previous analyses of Geosat and ERS-1 data. The slope differences have a median absolute deviation of 2.48 microradian – part of this difference is gravity signal and part is altimeter noise.

(d) CryoSat waveforms used for the analysis. The anomaly at the equator is perhaps due to a rain cell. Further algorithm development is needed to identify and remove these bad data.

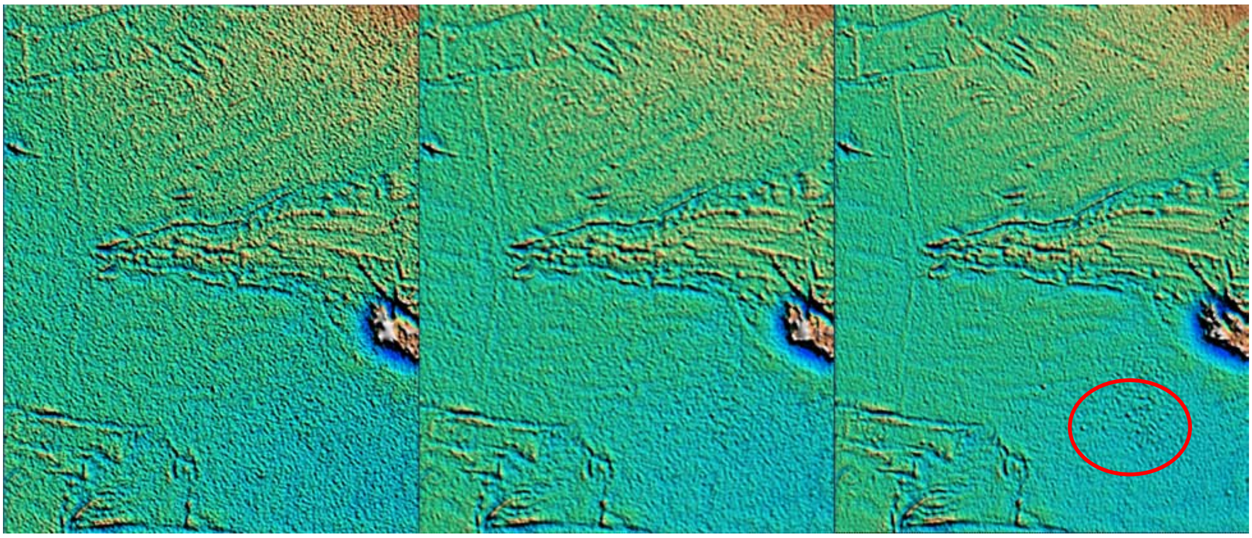

Figure 4 Shaded gravity anomaly for a large region in the Central Pacific Ocean centered at the Galapagos Triple Junction (latitude 11˚ to –8˚, longitude 255˚ to 270˚). Colors saturate at +/- 60 mGal. The visual noise level decreases as one moves from V9.1 (left) to V11.1 (center) to V18.1 (right). The axis of the East Pacific Rise is well defined in V18.1 but more difficult to trace in V9.1 because of the higher noise level. The red oval outlines a patch of small uncharted seamounts not apparent in V9.1. The evolution from V9.1 to V18.1 corresponds to a factor of 2