# Toward 1-mGal accuracy in global marine gravity from CryoSat-2, Envisat, and Jason-1

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More than 60% of the Earth's land and shallow marine areas are covered by > 2 km of sediments and sedimentary rocks, with the thickest accumulations on rifted continental margins (Figure 1). Free-air marine gravity anomalies derived from Geosat and ERS-1 satellite altimetry (Fairhead et al., 2001; Sandwell and Smith, 2009; Andersen et al., 2009) outline most of these major basins with remarkable precision. Moreover, gravity and bathymetry data derived from altimetry are used to identify current and paleo-submarine canyons, faults, and local recent uplifts. These geomorphic features provide clues to where to look for large deposits of sediments. While current altimeter data delineate large offshore basins and major structures, they do not resolve some of the smaller geomorphic features and basins (Yale et al., 1998; Fairhead et al., 2001). Improved accuracy and resolution is desirable: to facilitate comparisons between continental margins; as an exploration tool and to permit extrapolation of known structures from well-surveyed areas; to follow fracture zones out of the deep-ocean basin into antecedent continental structures, to define and compare segmentation of margins along strike and identify the position of the continent-ocean boundary; and to study mass anomalies (e.g., sediment type and distribution) and isostatic compensation at continental margins. In this article, we assess the accuracy of a new global marine gravity model based on a wealth of new radar altimetry data and demonstrate that these gravity data are superior in quality to the majority of publicly available academic and government ship gravity data.

## New radar altimeter data

Gravity field accuracy depends on four factors: spatial track density, altimeter range precision, diverse track orientation, and the accuracy of the coastal tide models. Recently three new nonrepeat altimeter data sets have become available:

1) CryoSat-2 was successfully launched in February 2010 and has routinely collected altimetry data over ice, land, and ocean since July 2010 (Wingham et al., 2006). The satellite has a long 369-day repeat cycle resulting in an average ground track spacing of 3.5 km at the equator.
2) The Envisat satellite, which has been in continuous operation since 2002, was running low on the fuel needed for maintaining a repeating ground track. In October 2010, Envisat was placed in a new partly drifting-phase orbit (~30 day repeat) to conserve fuel. Although the spacecraft failed in April 2012, it was able to collect 1.5 years of data along this new ground track. These data combined with 97 repeat cycles in the 35-day ground track make a significant contribution to gravity field improvement, especially in the Arctic where the closely spaced repeat tracks can collect data over unfrozen areas as the ice cover changes (Childers et al., 2012).
3) The Jason-1 satellite was launched in 2001 to replace the aging Topex/Poseidon satellite. To avoid a potential collision between Jason 1 and Topex, the Jason-1 satellite was moved into a lower orbit with a long repeat time of 406 days resulting in an average ground-track spacing of 3.9 km at the equator. The maneuver was performed in May 2012 and the satellite is collecting a tremendous new data set from a relatively lower inclination orbit of 66° that complements the higher inclination orbits of Envisat (81°) and CryoSat-2 (88°). The Jason-1 satellite failed just four days after completing its 406-day geodetic phase.

This article provides a progress report on our goal of achieving 1-milligal (mGal) accuracy for the global marine gravity field at a ½ wavelength spatial resolution of 7 km. The new gravity model (V21) is based on all the available altimeter data. This includes the older Geosat and ERS-1 data that were used to construct the V18 global marine gravity model widely used in the industry today (Sandwell and Smith, 2009) as well as newer, Envisat, CryoSat-2 (until December 2012), and Jason-1 (until January 2013). We first describe the improvements in range precision of the newer altimeters in comparison with the older altimeters. These results are published in Garcia et al. (2013). We then assess the accuracy of the V21 gravity model through comparisons with industry-quality gravity data as well as lower-quality data from the research cruises available at the National Geophysical Data Center (NGDC). Through these comparisons, we demonstrate the current accuracy is better than 1.7 mGal for

**Figure 1.** *Major offshore sedimentary basins around the world (green).*

latitudes less than 72° and somewhat lower accuracy (2–3 mGal) at higher latitudes depending on ice cover. Finally, based on this current analysis, we estimate the accuracy of altimeter-derived marine gravity in the year 2015, using additional data from the geodetic phase of Jason-1 and assuming that CryoSat-2 remains in operation, and predict that better than 1.4-mGal accuracy is attainable in areas such as the Gulf of Mexico.

## Picking the arrival time

For recovery of the static marine gravity field, the critical measurement is the slope of the ocean surface. Laplace's equation combined with Bruns' formula shows that one microradian (μrad) of ocean surface slope roughly corresponds to 1 mGal of gravity anomaly. Therefore, achieving this 1-mGal threshold requires a radar altimeter to have a range precision of 7 mm over 7-km horizontal distance. This precision could be derived from a single profile or a stack of repeated profiles. Ocean surface slope can be estimated by differencing height measurements along satellite altimeter tracks so absolute range accuracy is largely irrelevant.

The largest error source in measuring the ocean surface slope is caused by errors in picking the arrival time of the return radar echo. The shape of this echo depends on three parameters: the arrival time; the rise time of the leading edge of the waveform, which depends on the height of the ocean waves; and amplitude of the waveform, which depends on the roughness of the ocean caused by short waves generated by the wind. Previous studies have shown (Maus et al., 1998; Sandwell and Smith, 2005) that the arrival time and rise time are highly correlated during the parameter estimation, resulting in less than optimal estimates of arrival time. One way to improve the arrival time is to perform a two-parameter adjustment where the rise time is held to a fixed value based on the along-track smoothed value (20–45 km) of the rise time from a three-parameter retracking. This double retracking approach improved the range precision of Geosat and ERS-1 data by a factor of 1.5 and reduces the adverse effects of increasing significant wave height (SWH).

We have performed the same double retracking approach on seven types of altimeter data including SAR and SARIN-modes data from CryoSat-2 (Garcia et al., 2013). The noise of the altimeter measurements is commonly reported as the standard deviation of the 20-Hz retracked height averaged over 1-s intervals. One-second along-track corresponds to ~7 km and one expects only a small variation in height over this distance. The results of the 20-Hz noise for each data type was computed for a large region in the North Atlantic (Garcia et al., 2013) and a summary is provided in Table 1. The noise level increases as the ocean roughness SWH increases. The most common significant wave height (SWH) is ~2 m and an extreme wave height is 6 m. The SARIN-mode data, which are designed for ice observations, are noisy and they are not used in our gravity analysis. At 2 m SWH, CryoSat-2 LRM has the lowest noise level of 42.7 mm while ERS-1 has the highest noise of 61.8 mm. We attribute this 1.45 improvement in range precision to the factor of nearly two increase in pulse rate of CryoSat-2 with respect to ERS-1. The second lowest noise level comes from the Jason-1 altimeter (46.6 mm at 2 m SWH). Also note that Jason-1 has the lowest noise level at a SWH of 6 m. In all cases, except for the SAR-modes, the noise level of the two-parameter retracking is about 1.5 times smaller than the three-parameter retracking. As the standard ocean products provided by the space agencies use the three-parameter approach, one must go back and retrack the raw altimeter waveforms to achieve the lower noise and thus the best range precision.

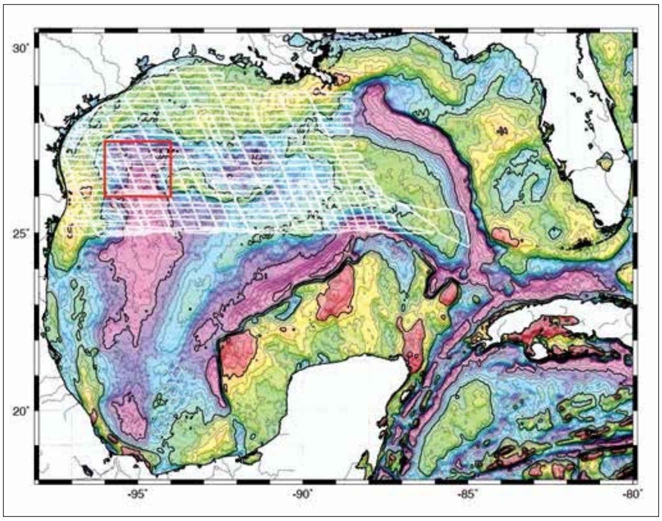

***Figure 2.*** *Free-air gravity anomaly for the Gulf of Mexico based on all available altimeter data until January 2013 (V21). Contour interval is 10 mGal with heavy contours at 50 mGal. Red box shows area of Alaminos Canyon where EDCON-PRJ has provided accurate shipboard-based gravity for assessment of our satellite gravity fields. White lines are the trackline of an academic fleet cruise where marine gravity data were collected.*

| Altimeter | 2-PAR @ 2m | 2-PAR @ 6m | 3-PAR/2-PAR |
|---|---|---|---|
| Geosat | 57.0 | 105.4 | 1.54 |
| ERS-1 | 61.8 | 111.8 | 1.51 |
| Envisat | 51.8 | 88.6 | 1.52 |
| Jason-1 | 46.4 | 64.2 | 1.63 |
| CryoSat-2 LRM | 42.7 | 71.7 | 1.51 |
| CryoSat-2 SAR | 49.7 | 110.9 | .996 |
| CryoSat-2 SARIN | 138.7 | 148.6 | .998 |

***Table 1.*** *20-Hz altimeter noise (mm). Standard deviation of retracked 20-Hz height estimates. The data are from a region of the North Atlantic with relatively high sea state. The values represent the median of thousands of estimates over a 0.4-m range of SWH. The 10-Hz Geosat estimates were scaled by 1.41 to approximate the errors at 20 Hz. Note in all cases except for the CryoSat-2 SAR and SARIN modes, the 3-PAR to 2-PAR noise ratio is close to the 1.57 value derived from a least-squares simulation (Sandwell and Smith, 2005).*

Prior to gravity model construction, we smooth the data along the satellite track using a filter that has a 0.5 gain at a wavelength of 14 km. Over a ½ wavelength of 7 km, the noise level should be reduced by about the square root of 20 to an average value of 11.5 mm. This range precision is approaching the desired precision of 7 mm over a 7-km distance needed to achieve a slope accuracy of 1 µrad, which will provide a 1-mGal accuracy gravity model. Reducing the noise by the needed factor of 1.64 could be achieved by repeating each slope measurement by 2.7 times on average. The outstanding questions are: Does this simple back-of-the-envelope calculation hold with the real observations? Will we reach the 1-mGal accuracy goal before the Jason-1 and CryoSat-2 satellites fail?

## Gravity field assessment

Sea-surface slope profiles from all the altimeter data available to January 2013 were used to construct a new global marine gravity model to a latitude of 85°. The method is described in a previous publication (Sandwell and Smith, 2009) and a brief summary follows. Along-track slopes from the 20-Hz-retracked profiles are low-pass filtered at 14-km wavelength (0.5 gain) and a lower-resolution sea-surface height model [EGM2008, Pavlis et al., 2012] is removed from each profile. The residual slopes and direction are gridded using a biharmonic spline in tension (0.25) to form global maps of residual north and east slope. Using Laplace's equation in the 2D Fourier domain, the north and east slopes are converted to a residual gravity anomaly. A second 2D low-pass filter is applied to the residual gravity having a 0.5 gain at 16-km wavelength; for latitudes greater than the maximum latitude of Envisat of 81.5°, a 18-km filter is used. Much of this Arctic area has seasonal and permanent ice cover, so the residual gravity is noisy and thus needs more filtering. Finally, the EGM2008 gravity model is restored to construct the full-amplitude free-air anomaly. We are still experimenting with low-pass filters that depend on latitude as well as ocean depth to maximize the signal-to-noise ratio.

To assess the accuracy of the final gravity model, we first focus on the Gulf of Mexico region where high-accuracy gravity data have been assembled by EDCON-PRJ for industry applications. The free-air gravity model (V21) is shown in Figure 2 with thick contours at 50-mGal intervals; it extends onto land where the grid is based on the EGM2008 model. Over the ocean, the familiar gravity signals are apparent such as the sharp gravity changes at the Florida and Campeche escarpments. This gravity model is based on a significant amount of new altimeter data, as shown in Figure 3.

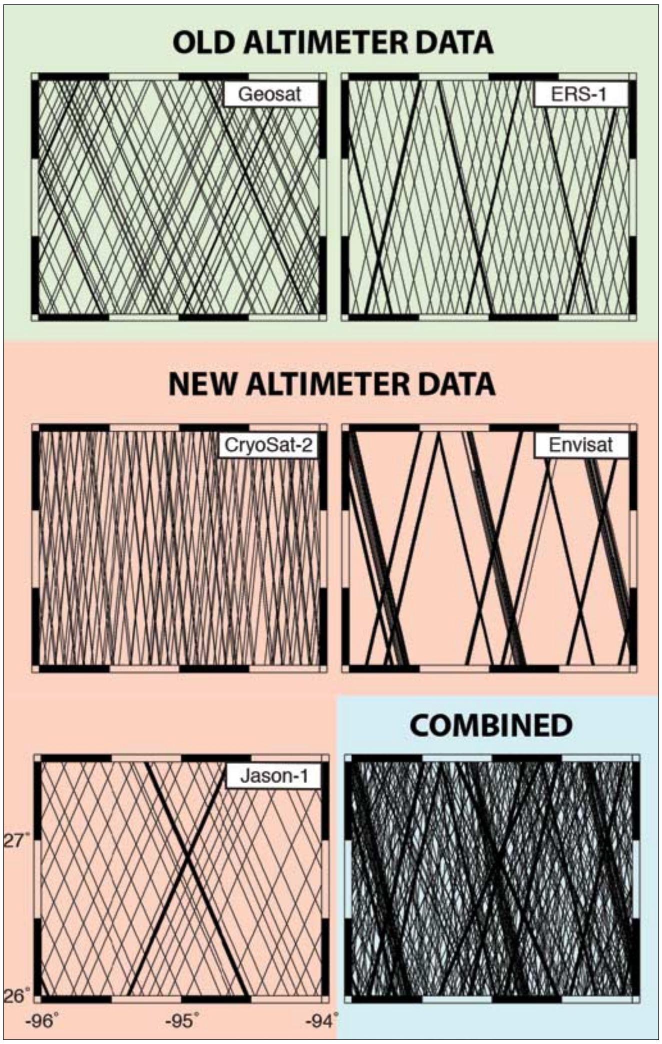

***Figure 3.*** *Examples of satellite altimeter track density (red box in Figure 1) used for this gravity construction. An older published gravity model (V18) is based on old tracks from Geosat and ERS-1. This newer gravity model (V21) is based on the combined tracks from all five altimeters. The heavier tracklines represent phases of the data coverage where there are tens to hundreds of tracks that don't repeat exactly resulting in swath coverage.*

Assessing the accuracy of the satellite gravity requires a comparison with more accurate data. The most straightforward analysis is simply a point-wise comparison of the satellite gravity (SAT) and the EDCON gravity for the small region of the Alaminos canyon (red box in Figure 2). The mean and rms differences between the satellite gravity and EDCON gravity in mGal are: V18, mean = 2.23, rms = 2.03 and V21, mean = 2.45, rms = 1.68. The EDCON gravity has a precision of ~0.5 mGal so the rms difference mainly reflects errors in the satellite gravity. The addition of the new data from Envisat, CryoSat-2, and Jason-1 has resulted in a variance reduction of 31%. The question is over what part of the spatial spectrum does most of this improvement occur? A 2D coherence between the satellite gravity (V18 and V21) and the EDCON data is shown in the lower part of Figure 4. As expected, the coherence falls below the statistically significant level of 0.2 at a wavelength of ~14 km because the satellite gravity grids are low-pass filtered at this wavelength. The coherence is close to 1 for wavelengths greater than 40 km. Most of the improvement in the coherence going from V18 to V21 occurs in the 40-km to 14-km wavelength band. This is the band of interest for applications such as identification of remote sedimentary basins on continental margins as well as mapping the deep ocean floor in areas where depth soundings are unavailable.

To establish the noise contributions from these two data sets, we use independent data from a shipboard gravity survey archived at NGDC, shown as the white track in Figure 2. The satellite and EDCON grids were sampled at the ship gravity locations resulting in 46,467 points for the three-way comparison. (A few hundred extraneous ship-gravity values were hand-edited because they showed large deviations from both the satellite and EDCON gravity.) The NGDC to SAT (V21) rms $\sigma_{NS}$ is largest at 2.59 mGal followed by the NGDC to EDCON rms $\sigma_{NE}$ at 1.97 mGal followed by EDCON to SAT rms $\sigma_{ES}$ at 1.83 mGal. In all cases the mean difference was removed. Assuming the error sources in each data set are statistically independent, one can write the variance of the rms differences in terms of the individual variances as follows:

$$\begin{bmatrix} \sigma_{NS}^2 \\ \sigma_{SE}^2 \\ \sigma_{NE}^2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sigma_N^2 \\ \sigma_S^2 \\ \sigma_E^2 \end{bmatrix}$$

An inversion of this 3 x 3 system provides estimates of the individual standard deviations of $\sigma_E$ = 0.51 mGal; $\sigma_S$ = 1.75 mGal; $\sigma_N$ = 1.91 mGal. The analysis shows that the EDCON data are much better than the other two data sets. Moreover, the satellite gravity data have slightly better precision than the ship gravity data.

To determine if these are typical ship data, we have performed an initial statistical analysis of the median absolute deviation of the satellite gravity data with respect to 1700 shipboard gravity cruises from the academic fleet as provided by the NGDC. The NGDC data were processed using the procedures of Chandler and Wessel (2008) prior to the analysis. The results show that one half of the cruises have median absolute deviations of 4.0 mGal and the most likely median absolute deviation is 2.75 mGal. Therefore this ship gravity data from the Gulf of Mexico has a standard deviation that is significantly better than 95% of the ship gravity from the academic fleet. The implication is that the precision of the gravity data from the academic fleet is now significantly worse than the satellite gravity. Therefore, academic fleet gravity data are no longer adequate for assessing the accuracy of the satellite gravity.

## Arctic gravity

The accuracy of the marine gravity field also depends on a number of environmental factors such as the typical significant wave height in the region and the prevalence of sea ice; both of these factors degrade the altimeter range measurement. In addition, ocean surface height variability caused by small-scale currents and coastal tides can introduce errors in the ocean surface slope measurement. The Gulf of Mexico represents perhaps the optimal area for marine gravity recovery because the adverse effects of these factors are minimal. In contrast, we next consider one of the worst cases of the Canadian Arctic where ice, waves, and coastal tides introduce large errors in the ocean surface slope measurement (Figure 5). This region also contains adequate marine gravity coverage available from the Geologic Survey of Canada (GSC) for quantitative analysis of the satellite gravity data.

Using the three-way variance approach described earlier for the Gulf of Mexico, we assess the standard deviation of three independent marine gravity data sets for the Canadian Arctic. The first is from the Geologic Survey of Canada where we used data from ocean areas where the depth is greater than 200 m. This resulted in 24,618 gravity measurements shown as white dots in Figure 5. The second data set

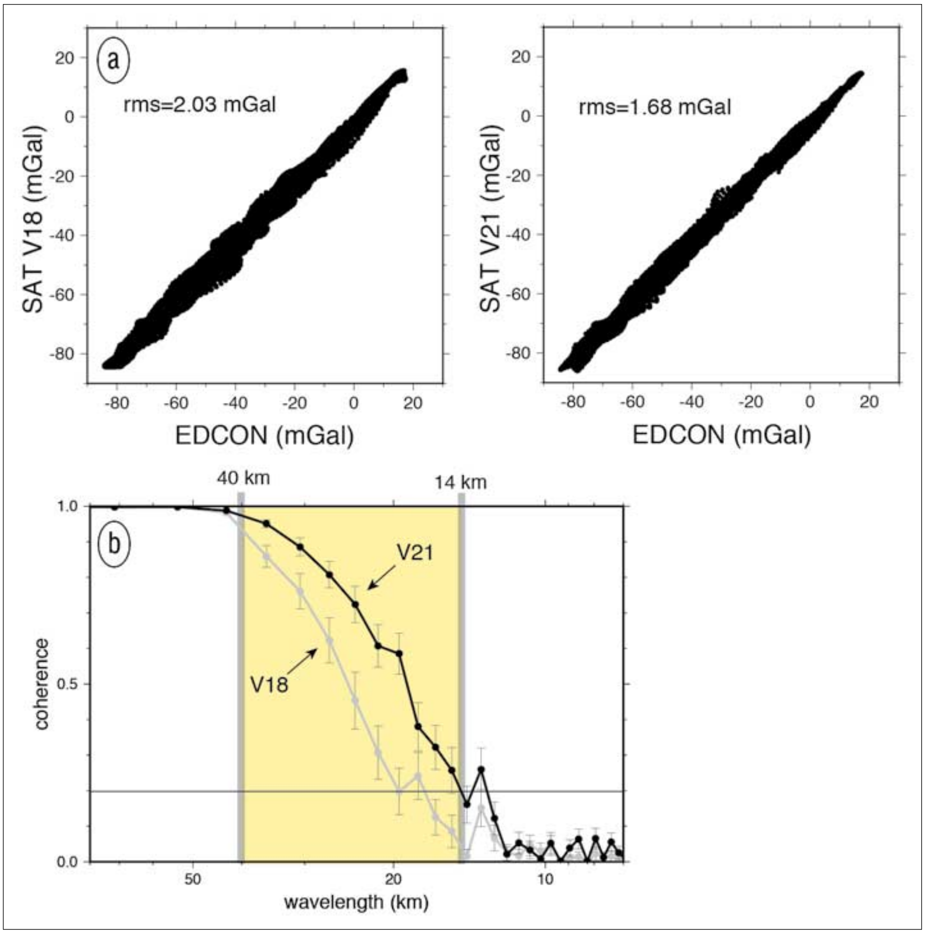

***Figure 4.*** *(a) Satellite gravity anomalies from V18 and V21 plotted versus shipboard gravity from Alaminos Canyon (EDCON-PRJ). (b) Coherence between satellite gravity and EDCON gravity over the area of the Alaminos Canyon (red box in Figure 2). The coherence falls to 0.5 at a wavelength of 27 km for V18 and a wavelength of 20 km for V21. Adding the new altimeter data from Envisat, CryoSat-2, and Jason-1 provides improvement in the 14-km to 40-km wavelength band.*

is V18 of the altimeter-derived gravity, which is based on ERS-1 data between latitudes of 72° and 81.5° and both Geosat and ERS-1 data for lower latitudes (Sandwell and Smith, 2009). The third data set is the new altimeter-derived gravity where Geosat and ERS-1 data were not used; we call this V21b. Visual comparisons of gravity maps from V18 and V21b show that V18 is much noisier. This is largely confirmed through rms comparisons with the GSC gravity data. The SAT (V18) to SAT (V21b) rms is largest at 7.22 mGal followed by the GSC to SAT (V18) rms at 6.96 mGal followed by GSC to SAT (V21b) rms at 4.96 mGal. An inversion of this 3 × 3 system provides estimates of the individual standard deviations of GSC rms = 3.24 mGal, SAT (V21b) rms = 3.75 mGal, and SAT (V18) rms = 6.17 mGal. In this case, we find that the new satellite gravity (V21b) has similar precision to the shipboard gravity from the GSC. One more important, but expected, result is that the V21b satellite gravity is 1.6 times more precise than the V18 gravity. This large improvement in the Arctic area is expected because the CryoSat-2 and Envisat altimeters have about 1.4 times better range precision than Geosat and ERS-1 and also higher data density. We expect that the V21 gravity, which included the Geosat and ERS-1, has an accuracy of about 3 mGal in this Arctic area.

## Discussion

An important issue not yet highlighted in this report is that the accuracy of the gravity field derived from this combination of satellite altimeters is uniform over all ocean areas and large inland bodies of water. As noted, the accuracy depends on spatial-track density, altimeter-range precision, diverse-track orientation, and the accuracy of the coastal-tide models. We have discussed the improved range precision and coverage from these new altimeters. However, a diversity of trackline orientations is also important. In particular, the new high-spatial density data from CryoSat-2 provides exceptional recovery of the NS component of gravity (Figure 6a). CryoSat-2 also contributes to the improvement in the EW component but as shown in Figure 7, the EW component is still about 1.5 times less accurate than the NS component. We are fortunate that the lower-inclination tracklines of the Jason-1 altimeter are rapidly improving this EW component especially in equatorial areas (Figure 6c). As an example the rms difference between V21 and the EDCON gravity in the Gulf of Mexico is 1.87 mGal when the Jason-1 data are not used in the solution as compared to 1.68 mGal when they are used. To date Jason-1 has completed only half of its 406-day geodetic phase. If the satellite survives until July 2013, the Jason-1 track density will double, providing an additional 0.4-mGal improvement of the EW component of gravity resulting in a 0.2 average

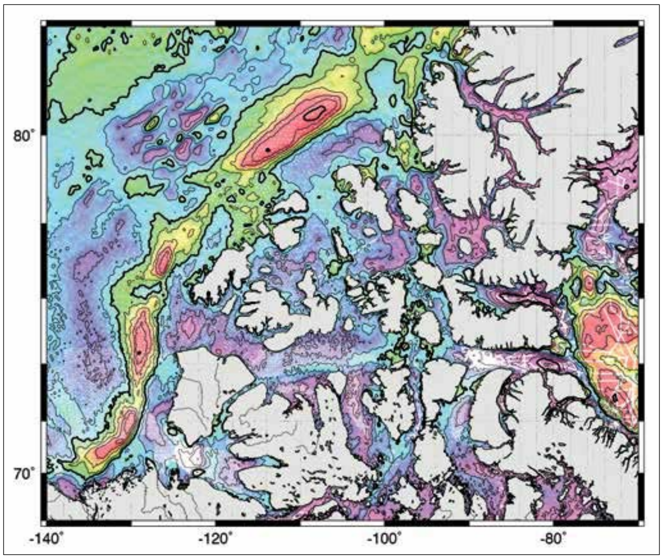

***Figure 5.*** *Free-air gravity anomaly for the Canadian Arctic based on all available altimeter data until January 2013 (V21). Contour interval is 10 mGal with heavy contours at 50 mGal. White points show locations of marine gravity measurements available from the Canadian Geological Survey (ocean depth < 200 m). The 88° maximum latitude of CryoSat-2 extends the range of the Arctic gravity beyond the 81.5° latitude from ERS-1 and Envisat. The maximum latitude of Geosat is 72°.*

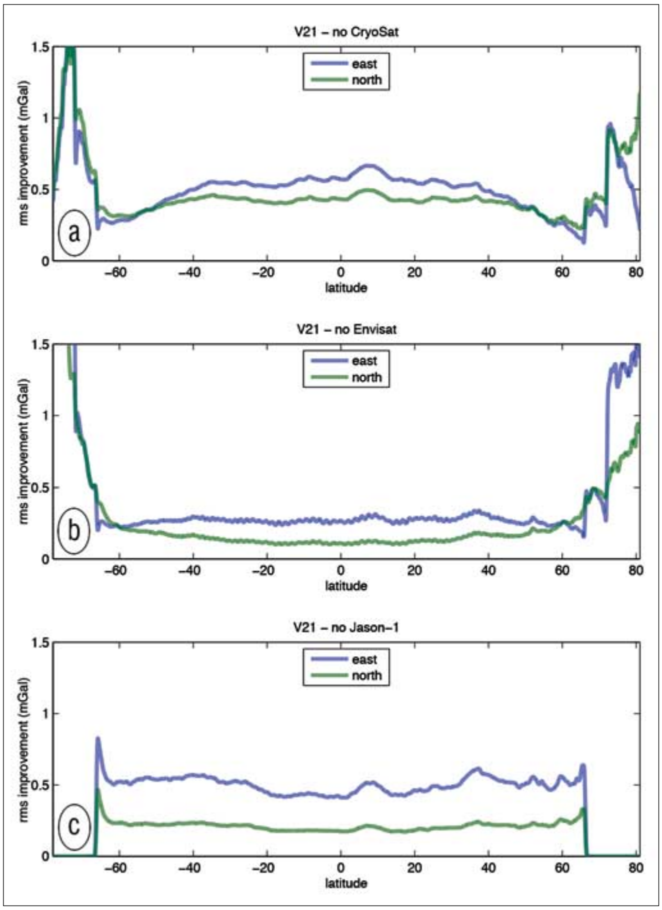

***Figure 6.*** *Improvement in rms accuracy for east (blue) and north (green) components of the marine gravity because of the addition of CryoSat-2 (a), Envisat (b), and Jason-1 (c) data. CryoSat-2 has the highest orbital inclination and highest track density so provides the greatest improvement overall. Envisat has nearly repeating tracks but excellent high-latitude coverage where it provides the greatest improvement. Jason-1 has the lowest orbital inclination, so mainly improves the EW gravity component for latitudes < 60°.*

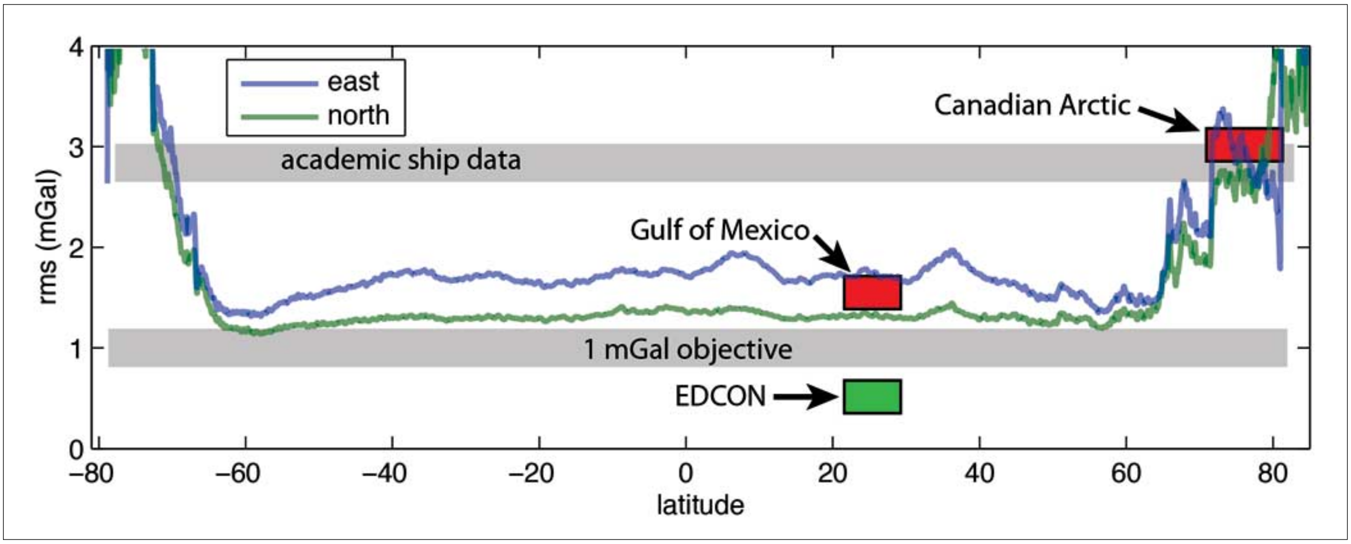

***Figure 7.*** *Jackknife estimate of the accuracy of the east (blue) and north (green) components of the marine gravity derived from satellite altimetry. Red boxes show the Gulf of Mexico and Canadian Arctic validations. Green box shows the precision of the EDCON gravity data. Marine gravity profiles collected by the academic fleet typically have gravity precision of 2.75 mGal. Our accuracy objective is 1 mGal. At latitudes less than 60°, the north component of gravity is better determined than the east component because altimeter tracklines are preferentially oriented NS. The availability of Jason-1 with its more EW track orientation will continue to improve the accuracy of the gravity field, especially the east component. The steps in gravity accuracy at latitudes of 66°, 72°, and 81.5° reflect the sharp changes in track density associated with the maximum latitudes of the Jason-1, Geosat, and ERS-1/Envisat satellites, respectively.*

improvement in the gravity field; we predict an accuracy of 1.48 mGal in the Gulf of Mexico.

It is also interesting to note that the greatest improvement in the Arctic gravity accuracy is provided by Envisat (Figure 6b). Although Arctic gravity is measured by both CryoSat-2 and Envisat, the 10 years of data accumulated from Envisat provides enough repeat coverage to sample most of the Arctic ocean during ice-free time windows and thus sample the gravity.

## Conclusions and outlook

An overview of the findings from this initial analysis of the new altimeter data sets is summarized in Figure 7.

- New altimeter data from CryoSat-2, Envisat, and Jason-1 have 1.25 times better range precision than the older data from Geosat and ERS-1. In addition, the newer satellites contribute 60 months of new data compared with the 31 months of data provided by the older satellites. These two improvements result in nearly a factor of 1.5 improvement in gravity accuracy at lower latitudes and a factor of 2–3 improvement in Arctic and Antarctic regions where seasonal ice cover has prevented high-precision altimeter measurements.
- Most of the improvement in the altimeter-derived gravity field occurs in the 14-km to 40-km wavelength band, which is of interest for investigation of sedimentary basins as small as 7 km.
- The current version of the altimeter-derived gravity field has an accuracy of 1.7 mGal in the Gulf of Mexico and 3.75 mGal in the Canadian Arctic. Unlike terrestrial gravity where coverage is uneven, these accuracies are available over ALL marine areas and large inland bodies of water so this gravity provides an important resource for exploration of remote sedimentary basins.
- The altimeter derived gravity field is about two times more accurate than the shipboard gravity collected by the academic institutions. However, some shipboard data, more carefully collected by industry (e.g., EDCON), is three times better than the altimeter-derived gravity and has much better spatial resolution.
- The Jason-1 altimeter satellite died just four days after completing its 406-day geodetic phase. Data collected between February and July 2013, not used in the V21 gravity, will provide an additional improvement in the EW component of gravity. Moreover, CryoSat-2 has enough capacity to collect altimetry data for another 5–7 years. This will provide significant improvement in gravity accuracy, especially over ice-covered ocean regions.
- New global gravity models derived from GRACE and GOCE will improve the accuracy of the gravity models at longer wavelengths (i.e., > 200 km).
- The construction of the gravity model discussed in this report does not yet involve trackline adjustments. Future models will be improved in areas of large mesoscale ocean variability and coastal tides through trackline adjustments.
- Our current gravity processing uses low-pass filters that only change with latitude and range in cutoff wavelength from 16 km to 24 km. We plan to develop spatially variable filters having cutoff wavelengths as low as 10 km in areas where the gravity signal to noise is high.
- Based on expected future data acquisitions and improved processing, we expect the accuracy of the gravity field to be better than 1.4 mGal but perhaps not attain our 1 mGal objective. **TLE**

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