The Impact of Using Jason-1 and Cryosat-2 Geodetic Mission Altimetry for Gravity Field Modeling

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Abstract

Since the release of the Danish Technical University DTU10 global marine gravity field in 2010, the amount of geodetic mission altimetry data has nearly tripled. The Cryosat-2 satellite have provided data along its 369 day near repeat since 2010 and as of May 2012 the Jason-1 satellite has been operating in a geodetic mission as part its end of life mission.

In this presentation, we perform an investigation of the impact of the Cryosat-2 and Jason-1 geodetic missions on high resolution marine gravity field mapping through comparison with recent high quality marine gravity measured by the United States Naval Ship Bowditch in the Western Pacific Ocean in 2006. Comparisons of pre and post Cryosat-2/Jason-1 gravity fields illustrated the importance of these new geodetic missions for altimeter marine gravity field mapping.

Altimetric gravity derived using 1 year of either Cryosat-2 or Jason-1 is nearly 10% better than gravity derived from retracked and reprocessed combined ERS-1 and Geosat in terms of lower standard deviation with marine gravity. The combination of data from all four geodetic mission data improves the agreement from around 4.1 mGal to around 3.1 mGal. Accounting for an error estimate of around 1 mGal in the marine gravity observations, it is concluded that for this particularly gravity survey region, the new gravity field from four geodetic missions has an accuracy of about 2 mGal.

Keywords

Gravity anomalies • Marine gravity • Satellite altimetry

1 Introduction

During 1985/1986 Geosat performed a 15 months geodetic mission resulting in an irregular roughly 6 km track spacing at the Equator. In 1994/1995 the ERS-1 satellite performed a similar geodetic mission lasting 11 months resulting in a regular 8 km across track pattern. Since 1995 various missions have be measuring along exact repeat track for oceanography (i.e., the 9.91 days repeat track by TOPEX/Poseidon and Jason). However, these exact repeat tracks are not particularly useful to gravity field determination, as they do not provide the essential dense track coverage. However with the availability of Cryosat-2 and the Jason-1 end-of-life missions, three times as many geodetic mission altimetric data have now become available to the scientific community.

Of equal importance is the fact, that the Cryosat-2 and Jason-1 are new generations of satellite altimeters offering increased range precision compared with the older ERS-1 and Geosat generation satellites. Increased range precision improves local mapping of the Ocean's height field which will improve local marine gravity field mapping. The Cryosat-2 pre-launch specifications indicated a factor of two in range precision compared with the older geodetic mission. This could in principle lead to a twofold improvement in

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C. Rizos, P. Willis (eds.), *IAG 150 Years*, International Association of Geodesy Symposia 143,
DOI 10.1007/1345_2015_95

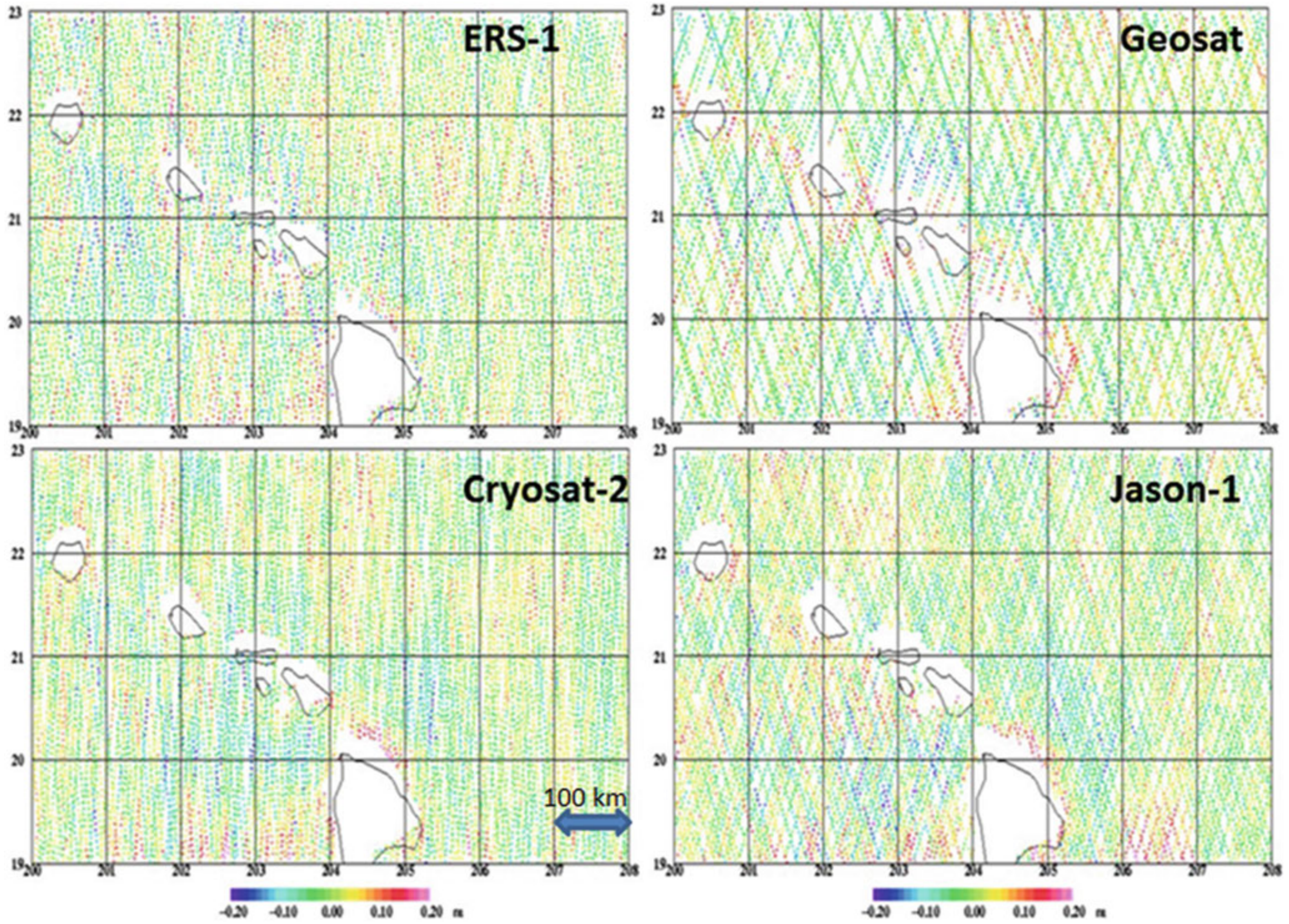

Fig. 1 Residual geoid height relative to EGM2008 (in meters) derived from 1 year of various geodetic missions around the Hawaiian island chain in the Pacific Ocean. *Upper left*: ERS-1 (11 month); *Upper right*: Geosat; *Lower left*: Cryosat-2; *Lower right*: Jason-1. One degree in longitude on the x-axis corresponds to roughly 100 km at the given latitudes, as illustrated in the lower left figure. An old version of the NGDC coastline is shown to outline the Hawaiian island chain

gravity field modeling (Sandwell et al. 2013). However, retracking of the old geodetic mission data (Sandwell and Smith 2005; Andersen et al. 2010) has significantly improved the range precision of these older missions by a factor of 1.5 (Sandwell et al. 2009) which means that the expected improvement with Cryosat-2 and Jason-1 will be less than a factor of two.

Here we will assess the improvement in gravity field determination that these new data offers through a comparison with highly accurate marine gravity observations in the Pacific Ocean. The structure of the paper is such that the next session describes the new altimeter data. The following section describes the marine gravity data and the comparison between marine gravity observations and altimetric gravity field prediction.

2 Altimetry Data

2.1 Conventional ERS-1 and Geosat Geodetic Missions

The ERS-1 and Geosat geodetic missions had for 15 years been the only available geodetic missions for gravity field determination. Consequent, these have been extensively investigated, reprocessed (Lillibridge et al. 2004) and retracked with respect to gravity field determination (i.e. Andersen et al. 2010; Maus et al. 1998; Sandwell and Smith 2005). Figure 1 shows the so-called along track residual geoid height for each geodetic mission relative to EGM2008. The residual geoid height is derived from the corrected and crossover adjusted data following the method of Andersen and Knudsen (1998). In the upper left the ERS-1 GM data are shown and in the upper right the Geosat GM data are shown.

2.2 Cryosat-2 "Geodetic Mission" Data

CryoSat-2 was successfully launched by ESA in February 2010 focusing on collecting altimetry over the cryosphere (Wingham et al. 2006). However several studies have demonstrated its importance for ocean and land as well (i.e., Stenseng and Andersen 2012). The satellite has a near 369-day repeat cycle resulting in an average ground track spacing of 7 km at the equator. Such long repeating cycle make it extremely useful for geodetic purposes and hence it's called a geodetic mission. The altimeter onboard Cryosat-2 is capable of operating like other nadir looking altimeters (called LRM or low resolution mode). It can also operate in SAR mode where the along track resolution is increased from 7 km to around 300 m and in SAR-in mode (Wingham et al. 2006) where two antennas are applied. The operation mode changes dynamically with time and is defined by the mode mask found at earth.esa.int. For this investigation we have solely used the Cryosat-2 LRM taken from the Radar Altimetry Data System (RADS) processed with the standard set of range and geophysical corrections (Andersen and Scharroo 2011). The processed Cryosat-2 data for 1 year (2011) are shown in the lower left part of Fig. 1. Cryosat-2 measures all the way to 200 km from the North Pole (inclination of 88°). Consequently, the tracks will be more north–south going than any of the other geodetic missions and consequently the satellite will have fewer crossing point locations at low latitude. Cryosat-2 has now been operating more than 3 years performing three complete repeats of 369 days data. More years of Cryosat-2 data will naturally continue to improve gravity field further in the future by the increased number of observations. In this investigation we have treated each track individually and not examined the potential of averaging of repeat tracks to lower sea surface variability and its effect on gravity field modelling.

2.3 Jason-1 End of Life Geodetic Mission

The Jason-1 satellite was launched in 2001 to replace the aging TOPEX/Poseidon satellite. After many years of successful observations, the satellite was taken out of normal operation and put into an End-of-Life orbit in 2012. 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 7 km at the Equator. Jason-1 has the lowest inclination of all satellites (66°). This nicely complements the higher inclination orbits of i.e., ERS-1 (82°) and Cryosat-2 (88°), as it creates a high number of crossing locations for the cross-over adjustment. Jason-1 failed just 4 days after completing its 406-day geodetic phase in June 2013. The Jason-1 data are shown in the lower right part of Fig. 1.

Figure 1 illustrates the residual geoid signal (relative to EGM2008) derived from roughly 1 year of each geodetic missions. This signal is subsequent used for the gravity field computation. For the given region this signal varies between −15 and 15 cm, as the Hawaiian island chain is a region of very large gravity anomalies. It illustrates that ERS-1 and Geosat data has higher noise than particularly the newer Cryosat-2 and Jason-1 satellites (more salt and pepper type noise). A careful inspection the figure illustrates, that the different inclination for the different satellites result in slightly different cross-over adjustment, which in turn will result in slightly different gravity anomalies. As an example, a region of higher residual geoid is seen bounded by 19–19.5° N and 206–207° E for Jason-1). This highlights the importance of having more satellites to stabilize the cross-over adjustment as this consequently leads to a more accurate marine gravity field.

3 Impact of New Altimeter Missions

A direct way of assessing the improvement in accuracy gained by introducing the two new geodetic missions is through a comparison with accurate marine gravity observations. We have used a recent survey by the United States Naval Ship (USNS) Bowditch in the western Pacific Ocean. This marine gravity survey was carried out to map the western insular margins and the 2,500-m isobath of Guam and the northern Marianas islands. The northern part of the survey used here is outlined in blue in the left part of Fig. 2 and bounded by latitude 15° N to 22° N and longitude 141° E to 144° E. Location of the southern survey is outlined with yellow colors. A total of 66.291 marine gravity observations along 74 tracks were measured with a maximum gravity anomaly reaching 148 mGal. The survey used GPS navigation and the BM-5 gravity instrumentation. So, the accuracy is expected to be around 1 mGal (Gardner 2006) though it might be higher. The data have been downloaded from the National Ocean and Atmosphere Administration (NOAA) National Geophysical Data Center (NGDC) web site.

In order to initially evaluate the impact of the "new generation" Cryosat-2 and Jason-1 satellites, altimetry from 1 year from each individual geodetic mission (except for 11 month for ERS-1) was processed and used to compute altimetric gravity field for the region. The altimetric gravity was computed using the methods described in Andersen (2010), Andersen et al. (2010), and Andersen and Knudsen

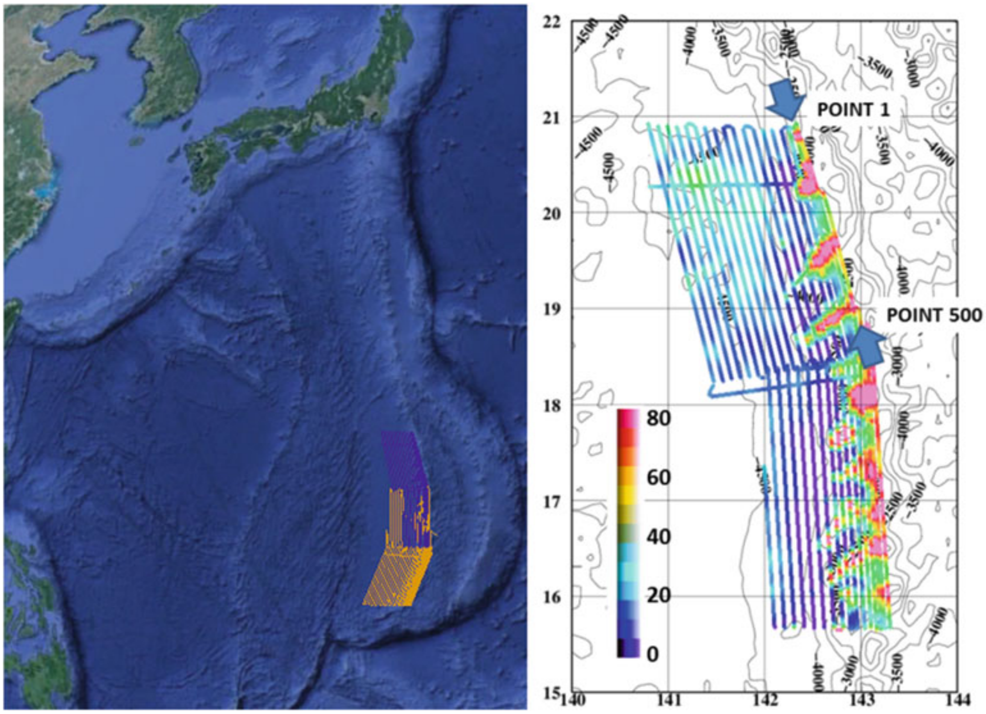

Fig. 2 The USNS Bowditch marine gravity survey. The *left part* of the figure illustrates the location of the northern and southern parts of the survey (in *blue* and *yellow*) and the *right part* of the figure illustrates the measured gravity anomalies (scale is in mGal) for the northern survey. The profile used for the detailed gravity comparison is marked with *arrows*

(1998) using altimetric sea surface height observations. The process of deriving gravity from the sea surface height applies a remove-restore technique relative to EGM2008 and the dynamic topography DOT07A (Pavlis et al. 2012) to account for the long wavelengths. Iterative local editing of the altimetric data is performed to ensure that there will be no outliers present. Subsequently a crossover adjustment is applied to remove ocean variability. This is followed by optimal interpolation onto a regular 1 min grid using a covariance function with a correlation length of 6.5 km. Finally, gravity is computed using Fast Fourier methods. As the conversion from geoid height to gravity enhances short wavelengths, a Wiener filter is applied to filter out wavelength shorter than 7 km. The setup is similar to that used for the derivation of the DTU10 gravity field. However, two important differences are implemented. The correlation length in the interpolation of geoid residuals (values shown in Fig. 1) was lowered from 9 to 6.5 km and the Wiener filter cut-off wavelength where the filter reaches 0.5 was lowered from 12 to 7 km. These values were determined empirically where the resulting gravity fits the best with the Bowditch marine gravity observations. The lowering of the correlation length and the cut-off wavelength will allow significantly shorter wavelength gravity signal to be present in the new gravity field which again increases the fit with marine gravity. The ability to lower the filtering is a consequence of the increased number of data and less noise in the new Cryosat-2 and Jason-1 sea surface height observations.

The comparison with the USNS Bowditch gravity observations and the derived gravity field from each geodetic mission and combination of various geodetic missions are shown in Table 1. Gravity derived from the 1 year of ERS-1 or Geosat both show a standard deviation with the marine data of around 4.2 mGal. By combining these two old geodetic mission datasets the standard deviation is lowered to 4.05 mGal. This number hereinafter called the “Old GM limit” (GM = geodetic mission), as these are the data that were available for the derivation of the DTU10, Sandwell and Smith (SSV18.1) and EGM2008. For reference these fields compare with the Bowditch data at 4.16, 4.09 and 4.21 mGal for DTU10, SS 18.1 and EGM2008.

The comparisons with Bowditch using gravity derived from 1 year of either Cryosat-2 or Jason-1 missions are considerably lower at around 3.7 mGal. The conclusion is, that altimetry from only 1 year of either Cryosat-2 or Jason-1 already lowers the standard deviation with the Bowditch data by 7% compared with the “Old GM limit” of gravity from the combined ERS-1 and Geosat missions. The maximum difference between observed and estimated gravity also decreases, supporting that the Cryosat-2 and Jason-1 derived gravity is actually getting closer to the measured marine gravity.

Table 1 Comparison with the USNS Bowditch 66219 marine gravity observations and interpolated gravity field from each geodetic mission and from a combination of various geodetic missions

	Std. dev of difference (mGal)	Maximum difference (mGal)
ERS-1	4.23	49.1
Geosat	4.21	49.0
ERS-1 + Geosat (DTU10)	4.05	46.9
Cryosat-2 (1 year)	3.77	41.8
Jason-1 (1 year)	3.73	41.5
Cryosat-2 (3 year)	3.42	39.8
C2 (3Y) + J1 (1 year)	3.30	37.6
All (DTU13)	3.14	36.1

Values are given in mGal

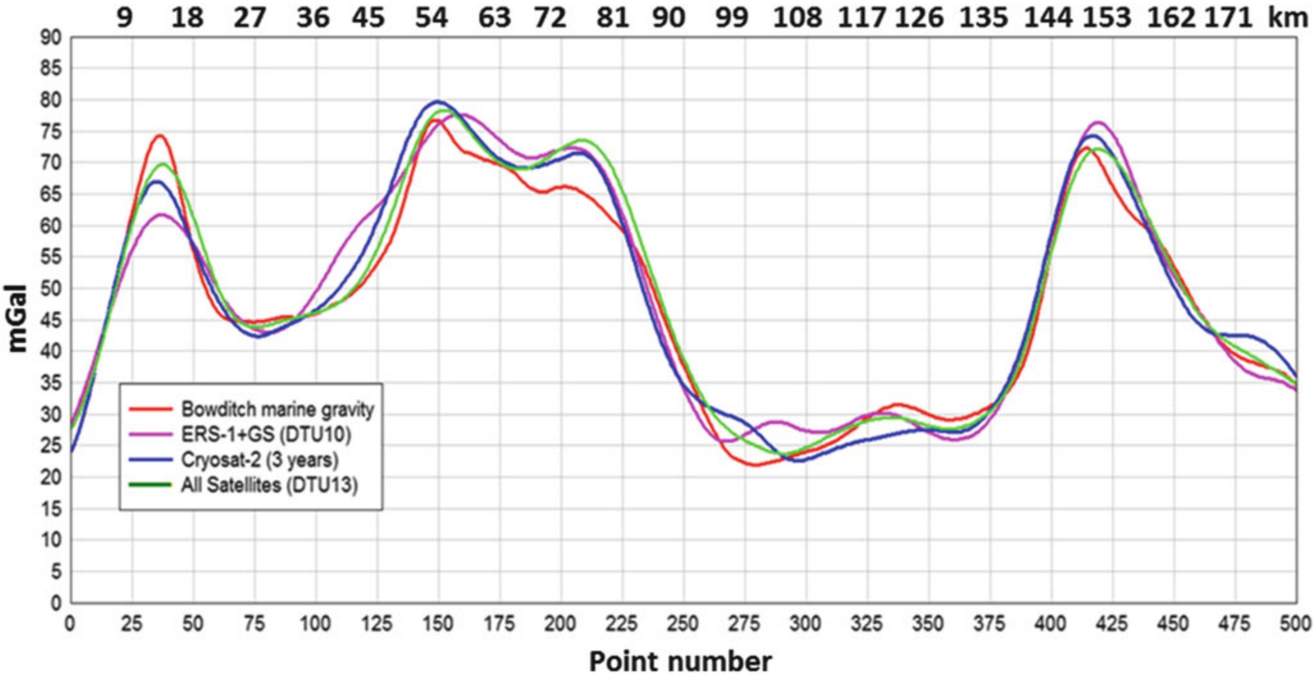

Fig. 3 A direct comparison with one of the Bowditch marine gravity tracks shown in Fig. 2 going from 20.9° N, 142.3° E to 18.6° N, 142.9° E. The Bowditch marine gravity is shown in *red*, the ERS-1/Geosat gravity delineated in *purple*. Cryosat-2 derived gravity field is shown in *blue* and the gravity field from all four geodetic missions is delineated in *green*. The scale in the *upper part* of the picture is the equivalent distance in km assuming a constant speed of the ship

By increasing the number of Cryosat-2 data to 3 years further increases the agreement to 3.42 mGal, and by introducing 1 year of Jason-1 data the number is further lowered to 3.30 mGal. Again, the conclusion is supported by a similar decrease in maximum deviation with the observed marine gravity. The result is even more impressive when the assumed 1 mGal error in the marine gravity data is accounted for. The final inclusion of all four geodetic missions lowers the standard deviation to 3.15 mGal being almost 1 mGal better than the "Old GM limit".

It is interesting, that the inclusion of the old geodetic missions, still improves the gravity field compared to a combined Cryosat-2 and Jason-1 gravity field. This is most likely a result of the additional data stabilizing the crossover adjustment and at the same time increasing the number of data. By accounting for an error of around 1 mGal in the marine gravity observations, it can be concluded, that for this particularly gravity survey, the new derived altimetric gravity field has an accuracy of about 2 mGal.

A detailed investigation along a profile consisting of 500 points in the marine gravity file going northwest to southeast from (20.9° N, 142.3° E to 18.6° N, 142.9° E) is shown in Fig. 3. For reference, the values are labeled 62,911,903 to 62,920,830 and the profile is marked with arrows in Fig. 2. In Fig. 3, both the point-number and the associated distance along the profile are shown assuming a constant speed of the vessel.

The Bowditch marine gravity is shown in red, the ERS-1 + Geosat gravity is delineated in purple. The Cryosat-2 alone gravity field from 3 years of data is shown in blue and the gravity field from all four satellites is delineated with green. The first peak in the figure occurs at point 40 and the measured gravity reaches 75 mGal. The pre "old GM limit" gravity derived from ERS-1 and Geosat data only reaches 60 mGal and hence was nearly 15 mGal of the measured gravity. However, the gravity field using all four geodetic missions reaches 70 mGal being less than 5 mGal of the measured gravity field anomaly. As data have been processed using identical setup, this illustrates how shorter wavelengths in the gravity field are significantly better mapped with the inclusion of the two new geodetic missions.

Significantly differences are particularly seen between point number 150 and 225 where the differences exceed 6 mGal at several locations. A comparison with the DTU10 and SSV18.1 gravity fields showed similar consistent differences. This discrepancy is currently under investigations, but it leads to the conclusion that the assumption of a 1 mGal error on the Bowditch data is most likely too optimistic.

4 Summary

With the launch of Cryosat-2 and the Jason-1 end-of-life geodetic mission two new geodetic missions have become available to marine gravity field determination. The impact of these new geodetic mission data on global marine gravity field is highlighted through comparison with high quality recent ship borne gravity onboard the USNS Bowditch in the Western Pacific Ocean. Altimetric gravity derived using 1 year of either Cryosat-2 or Jason-1 is nearly 10% better than gravity derived from retracked and reprocessed combined ERS-1 and Geosat in terms of lower standard deviation with marine gravity. This improvement increases further if one accounts for the internal error in the marine gravity of around 1mGal.

The final inclusion of all four geodetic missions (ERS-1, Geosat, Cryosat-2 and Jason-1) lowers the standard deviation to 3.15 mGal being almost 1 mGal better than what could be achieved using ERS-1 and Geosat. It is found that the inclusion of the old ERS-1 and Geosat geodetic missions with the new geodetic mission still improves gravity compared with a field derived using the new geodetic missions alone. This is explained by the fact that the old geodetic missions stabilize the crossover adjustment and also increase the number of data. Detailed comparison with the Bowditch survey along a profile illustrates the importance of the new geodetic mission data but also highlighted potential significant errors in the survey.

Ongoing investigations can and will improve the gravity field further in the near future. One improvement is expected from the retracking of the Cryosat-2 and Jason-1 geodetic mission as this previously significantly improved the older ERS-1 and Geosat geodetic missions. A second improvement might come from the use of more years of Cryosat-2 as the mission continues to operate for hopefully many years.

Acknowledgements The authors would like to thank the RADS (rads.tudelft.nl) team for making altimetric data as well as corrections readily available to the user. Also the authors would like to acknowledge the NOAA National Geophysical Data Center for making the Bowditch marine gravity data available to the scientific community.

References

Andersen OB (2010) The DTU10 global gravity field and mean sea surface – improvements in the Arctic. Presented at the 2nd international gravity field service symposium, Fairbanks, Alaska

Andersen OB, Knudsen P (1998) Global marine gravity field from the ERS-1 and GEOSAT geodetic mission altimetry. J Geophys Res 103:8129–8137

Andersen OB, Scharroo R (2011) Range and geophysical corrections in coastal regions: and implications for mean sea surface determination. In: Vignudelli S et al (eds) Coastal altimetry. Springer, Berlin, pp 103–145. doi:10.1007/978-3-642-12796-0_5

Andersen OB, Knudsen P, Berry PAM (2010) The DNSC08GRA global marine gravity field from double retracked satellite altimetry. J Geod 84:191–199. doi:10.1007/s00190-009-0355-9

Gardner JV (2006) Cruise report, USNS Bowditch: U.S. Law of the Sea cruise to map the western insular margin and 2500-m isobath of Guam and the Northern Marianas Islands: Cruise BD06-1, UNH-CCOM/JHC Tech Rep 06–100

Lillibridge JL, Smith WHF, Scharrroo R, Sandwell DT (2004) The Geosat geodetic mission 20th anniversary data product, AGU, 85(47), Fall Meet. Suppl., Abs SF43A–0786

Maus S, Green CM, Fairhead D (1998) Improved ocean-geoid resolution from retracked ERS-1 satellite altimeter waveforms. Geophys J Int 134(1):243–253

Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2012) The development and evaluation of the earth gravitational model 2008 (EGM2008). J Geophys Res 117:B4

Sandwell DT, Smith WHF (2005) Retracking ERS-1 altimeter waveforms for optimal gravity field recovery. Geophys J Int 163:79–89. doi:10.1111/j.1365-246X.2005.02724

Sandwell DT, Smith WHF (2009) Global marine gravity from retracked Geosat and ERS-1 altimetry: ridge segmentation versus spreading rate. J Geophys Res 114:B01411. doi:10.1029/2008JB006008

Sandwell DT, Garcia E, Soofi K, Wessel P, Chandler M, Smith WHF (2013) Towards 1-mGal accuracy in global marine gravity from Cryosat-2, Envisat and Jason-1. The Leading Edge, Houston, pp 892–898

Stenseng L, Andersen OB (2012) Preliminary gravity recovery from CryoSat-2 data in the Baffin Bay. Adv Space Res 50(8):1158–1163

Wingham D et al (2006) CryoSat-2: a mission to determine the fluctuations in Earths land and marine ice fields. Adv Space Res 37(4):841–871