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Satellite gravity – enhancements from new satellites and new altimeter technology

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ABSTRACT

This paper reviews the impacts of new satellite altimeter data sets and new technology on the production of satellite gravity. It considers the contribution of the increased data volume, the application of new altimeter acquisition technology and the potential for future developments. Satellite altimeter derived gravity has provided gravity maps of the world's seas since the 1980s, but, from 1995 to 2010, virtually all improvements were in the processing as there were no new satellite data with closely spaced tracks. In recent years, new data from CryoSat-2 (launched in 2010) and the geodetic mission of Jason-1 (2012–2013) have provided a wealth of additional coverage and new technology allows further improvements. The synthetic aperture radar mode of CryoSat-2 uses a scanning approach to limit the size of the altimeter sea surface footprint in the along-track direction. Tests indicate that this allows reliable data to be acquired closer to coastlines. The synthetic aperture radar interferometric mode of CryoSat-2 uses two altimeters to locate sea-surface reflection points laterally away from the satellite track. In a study to generate gravity for freshwater lakes, this mode is found to be valuable in extending the available satellite coverage. The AltiKa altimeter uses higher frequency radar to provide less noisy sea-surface signals and its new orbit mode gives potential for further improvements in satellite gravity. Future developments include the potential for swath mapping to provide further gravity improvements.

Key words: Gravity, Acquisition, Imaging.

INTRODUCTION

Satellite altimeter gravity has seen several phases of enhancement since the 1980s, with a number of developments in satellites and instrumentation since 2010 which are the focus of this contribution. Satellite altimetry involves mapping the height of the sea surface using a radar altimeter mounted on a satellite – generally at 700–1300 km elevation. The sea surface approximates an equipotential surface of the gravity field and hence a grid of its height variation can be converted to a grid of gravity variation.

Satellite altimeter gravity came to general prominence with the global gravity map of Haxby (1985), which used SeaSat data to illustrate the gravity field and tectonic structures of the world's oceans with a consistency not seen before. However, SeaSat was a short-lived mission with wide track spacing – its 22-day repeat cycle (known as an exact repeat mission) giving a track spacing of ~125 km at the equator. Over the years, global satellite altimetry data sets were enhanced by the addition of repeat mission data from GEOSAT, ERS-1 and Topex/Poseidon satellites, which improved on both quantity of data and overall spacing of tracks. However, the

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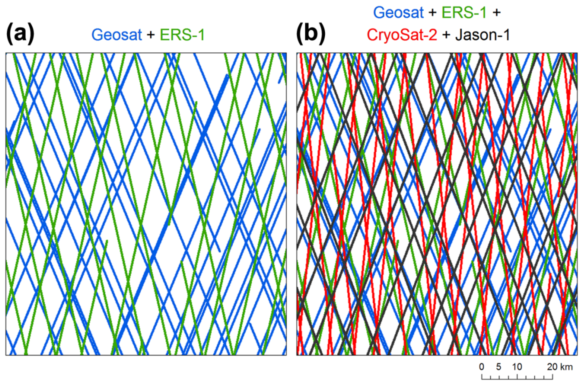

Figure 1 Improved satellite altimeter track coverage for an area in the Caribbean: (a) geodetic missions available up to 2010 – GEOSAT and ERS-1 and (b) geodetic missions up to 2017 – CryoSat-2 and Jason-1 have doubled the track coverage.

track spacing was still a major constraint (ERS-1 had the best coverage, with a 35-day repeat cycle giving track spacing of ~80 km at the equator), and although various methods were devised to extract gravity signal (e.g. Sandwell and McAdoo 1990; Olgiati *et al.* 1995), the result was still limited by the coverage of available data. The geodetic mission (satellite mission with closely spaced tracks) of ERS-1 (1994–1995) and subsequent release of the geodetic mission of GEOSAT led to a big reduction in track spacing: ~8 km for ERS-1 and ~5 km on average for GEOSAT (Fig. 1a). This improvement in track spacing is achieved by satellite manoeuvres to achieve a much longer repeat cycle or no repeats (a single 336-day mission for ERS-1, whereas the GEOSAT orbit was allowed to drift such that improved coverage was achieved in a less regular way – note irregular spacing of GEOSAT tracks in Fig. 1). A number of higher resolution gravity data sets were generated (e.g. Sandwell and Smith 1997; Fairhead, Green and Fletcher 2004; Andersen, Knudsen and Berry 2010). Despite some significant processing advances, there were no new altimeter geodetic missions from 1995 until 2010.

CryoSat-2 was launched in 2010 into a near-polar geodetic orbit, which means that it has coverage of all ice-free marine areas of the world with track spacing at the equator of ~7.5 km. Moreover, CryoSat-2 operates in three different modes designed for different surface conditions, but also offering new data types over marine areas. In 2012, Jason-1 was moved into a geodetic mission for the last year of its 11-year life – further enhancing coverage (Fig. 1b). In 2013, the AltiKa altimeter started to collect data with a higher frequency altimeter; initially this was in the same repeat orbit as ERS-1, but recently the satellite has started to drift – generating coverage with closer tracks (see later section and Fig. 6). All these new satellites and new missions have contributed new data to be integrated with the previously available data from GEOSAT and ERS-1 and giving opportunities to develop new higher quality satellite gravity data sets. New data modes and altimeter types offer further possibilities.

In addition to enhancements in satellite altimetry, there have been new data from gravity-measuring satellites, such as GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity Field and Steady-State Ocean Circulation Explorer). GRACE (2002–2017) and GOCE (2009–2013) measured gradients of the gravity field on-board the satellites, which allowed very accurate mapping of the gravity field at satellite altitude. However, due to the elevations of the satellites (250–500 km), the spatial resolution of gravity anomalies from the Earth's surface and sub-surface is limited – to about 150 km or more and, hence, the data are of limited value for local exploration problems. The GRACE/GOCE data are, however, very valuable and have been incorporated into global geopotential models – for example EGM2008 (Pavlis *et al.* 2012) included GRACE data to control long wavelengths of the gravity field, together with terrestrial and satellite altimeter data to control short wavelengths. They have also been built into a range of satellite-only gravity models; Fig. 2(c) shows a part of the EIGEN-6S4 model (Förste *et al.* 2016) – one of a number of models available (Drewes *et al.* 2016). GRACE and GOCE also show seasonal and longer period variations of gravity. It should be noted that these data from gravity-measuring satellites are fundamentally different from satellite altimetry, which measures the sea-surface height and, hence, images the gravity at the sea surface. Figure 2(b,c) shows the difference in resolution between the two measurement types: satellite altimeter gravity shows gravity offshore at wavelengths down to below 20 km, whereas the gravity model from Laser Geodynamic Satellite, GRACE and GOCE shows longer wavelengths over land and sea.

In this paper, we review the impacts of the new satellite altimeter data and data types. We consider the impact of the greatly enhanced coverage, the advantages of synthetic aperture radar (SAR) mode CryoSat-2 data in coastal areas, the use of SAR interferometric (SARIn) mode CryoSat-2 data over lakes and the potential improvements of AltiKa altimeter data.

NEW SATELLITE MISSIONS

CryoSat-2 was launched in late 2010. Its primary focus was radar altimeter measurements of ice and, hence, it is in a

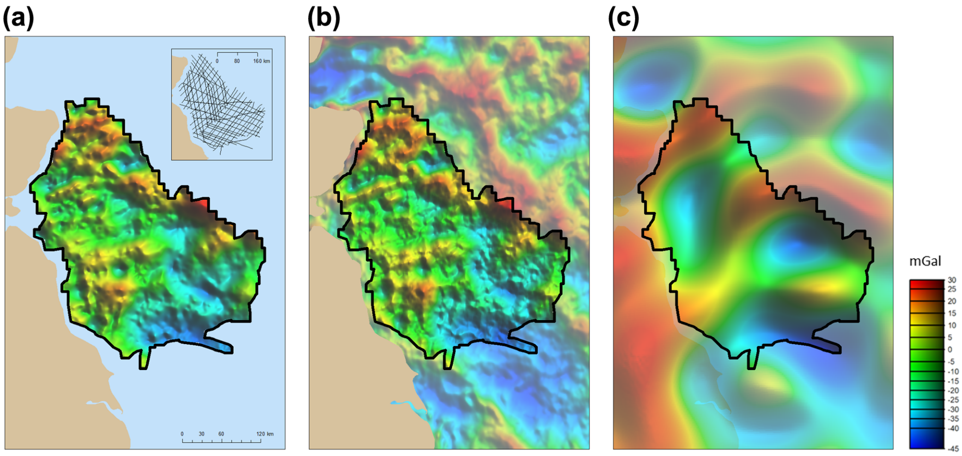

Figure 2 Comparison of gravity data types in North Sea area (same colour range for each image): (a) shipborne gravity (free air anomaly) observations collected by EDCON on behalf of the UK Oil and Gas Authority in 2015; (b) satellite altimeter gravity (Getech Multi-Sat); (c) satellite-only gravity model (EIGEN-6S4 based on LAGEOS [Laser Geodynamic Satellite], GRACE [Gravity Recovery and Climate Experiment[and GOCE [Gravity Field and Steady-State Ocean Circulation Explorer]).

near-polar orbit which covers most of the cryosphere. As such, the satellite tracks also cover all of the ice-free seas of the world and because of the satellite's close track spacing, it provides a substantial increase in the total available geodetic mission altimeter database. Moreover, CryoSat-2 is continuing in this orbit and has now completed seven full repeat cycles with track spacing at the equator of ∼7.5 km. In 2012, Jason-1 moved to a 406-day geodetic mission 'end-of-life' orbit, which it had almost completed when the satellite failed – thus generating another altimeter data set with ∼7.5 km track spacing at the equator. Figure 1 shows the increase in satellite altimeter track coverage from 2010 to late 2013; the network of tracks has effectively doubled and the range of track orientations has also increased. This wider range of track orientations means that features with a wider range of trend directions can be mapped with confidence. Altogether, these additions to the data volume have given the opportunity for production of new satellite gravity data sets which have better accuracy (grid values are closer to the actual value of gravity at that point), better resolution (geological features of smaller size can be imaged) and better reliability (gravity grids have fewer artefacts and erroneous features). The quality of the final gravity data set depends on the editing and processing schemes, as well as the data quality; of particular concern is the approach to integrating satellite track data with a wider range of track directions into coherent geoid or geoid gradient grids for conversion to gravity without generating artefacts in the data. There are various approaches to this problem and thus resulting products differ, but have been developed and applied to geological interpretation and exploration purposes (Sandwell *et al.* 2014; Andersen *et al.* 2017; Getech 2017).

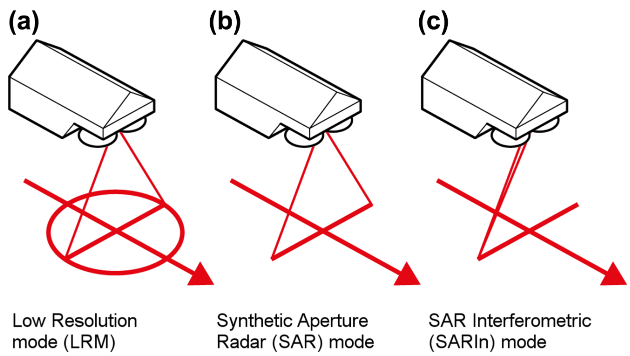

Figure 3 The three modes of CryoSat-2 operation: (a) low-resolution mode (LRM) produces a roughly circular footprint ∼5 km across – this mode is used by most of the satellite altimeters discussed in this paper, (b) SAR (synthetic aperture radar) mode gives reflections from strips ∼250 m along track by ∼5 km across track and (c) SARIn (SAR interferometric) mode uses the two cross-track mounted altimeters to identify the reflection point for the altimeter surface reflection.

SYNTHETIC APERTURE RADAR MODE OF CRYOSAT-2 – GETTING CLOSER TO THE COAST

Unlike other satellites discussed here, CryoSat-2 operates in three altimeter modes (only one at once); arrival times for each signal type can be calculated from the return waveform in a process commonly known as 're-tracking'. Each mode has different properties (Fig. 3):

- *Low-resolution mode (LRM)*. This is the conventional mode used by all other altimeters mentioned in this paper. The altimeter signal is pulse limited and images an isotropic circular footprint on the sea surface with an effective diameter of ~5 km, depending on sea state. The return altimeter waveform can be readily re-tracked based on a simplified version of the classic Brown (1977) model waveform.
- *Synthetic aperture radar (SAR)*. This employs a delay-Doppler approach which effectively illuminates cross-track strips of the sea surface ~0.25 km along track and ~5 km across track, depending on sea state. The return waveforms are sharper than the LRM waveforms and depend on sea state in different ways. However, they can be readily re-tracked using an approach such as that described by Garcia, Sandwell and Smith (2014); some numerical simplification is possible in practice.
- *SAR interferometric (SARIn)*. This mode uses the two altimeters of CryoSat-2 mounted perpendicular to the flight direction to identify the precise point of the reflection received at the satellite. In both LRM and SAR modes, the reflection point is close to the nadir point – directly below the satellite; in the SARIn mode, the reflection point can be some distance off-track (Fig. 5). The waveforms are similar to SAR waveforms and can be re-tracked using a similar approach.

The distribution of these three modes conforms to a pre-determined plan, based largely on the type of ice coverage expected in a given area. Most ice-free marine (and land) areas are covered by LRM mode data, but significant areas (including much of SE Asia and NW Europe) are covered in SAR mode data and some patches in the oceans have SARIn data. Thus, SAR mode data will be incorporated in any satellite gravity map of global continental margins.

In theory, the SAR mode provides more precise altimetry measurements than the LRM mode (Raney 2012). It has a smaller footprint and, hence, could potentially give better along-track resolution of sea-surface heights. However, the smaller footprint also makes the SAR mode more susceptible to noise – such as is expected in high sea states – thus, it is not immediately clear whether SAR data are likely to be better or less good than LRM. In practice, in most cases, SAR data are observed to provide good quality results. A particular issue arises close to coasts, where marine altimeter signals often show interference produced by reflections from adjacent land (Deng *et al.* 2002). In this case, it is to be hoped that SAR data will be less contaminated as the satellite track approaches or departs from the coastline, as the rectangular SAR footprints are more likely to lie parallel to the coast and not overlap the onshore area compared to the circular LRM footprints.

This can be tested in a coastal area where CryoSat-2 was in LRM mode one year and SAR mode the next – such as the coast of India (Fig. 4a). In this study (Dawson, Green and Fletcher 2015), return waveforms along each track were analysed to identify the waveform closest to the coast which could be reliably re-tracked. The distances from the coast of these closest reliable waveforms are shown in histogram form in Fig. 4(b,c). Although there is some spread in each histogram, the SAR waveforms are generally found to be usable 1 km closer to the coast (or two-thirds the distance to the coast) compared to the LRM waveforms. This indicates that SAR waveforms should give better sea-surface height and gravity data close to coasts and – more broadly – that the SAR waveform data can be reliably re-tracked in general.

LAKE ALTIMETER GRAVITY – INCLUDING SYNTHETIC APERTURE RADAR INTERFEROMETRIC MODE OF CRYOSAT-2

The surfaces of lakes also represent an equipotential surface of the gravity field, although the absolute height may be some distance above or below the geoid (sea surface) height. On this basis, we calculated gravity anomalies for large lakes (Cheyney *et al.* 2017) around the world. This raised some difficulties: ERS-1 data were not acquired in the correct mode in these areas, CryoSat-2 was in a variety of modes within lakes and significant proportions of the areas of most lakes are close to the edges of the lake and subject to land contamination.

Because of the lack of ERS-1 data, the addition of CryoSat-2 has provided a huge increase in the available data volume; previous lake gravity data based on the irregular tracks of GEOSAT often had significant gaps and the results were variable and unreliable. One notable challenge is working with satellites over several decades, during which time lake heights may have changed significantly; thus, depending on the processing approach taken, particular care is required over lakes to generate a coherent network of along-track adjusted lake height values. CryoSat-2 was in SARIn (synthetic aperture radar interferometric) mode for many lakes, which presents a challenge and an opportunity. The challenge was met by adapting the re-tracking algorithm used for SAR (synthetic aperture radar) data and it was discovered that the resulting sea-surface profiles have similar noise levels to the SAR and low-resolution mode (LRM) data. In terms of opportunity, it was noted that reflection points were often observed to be off-track and that this was particularly the case in some

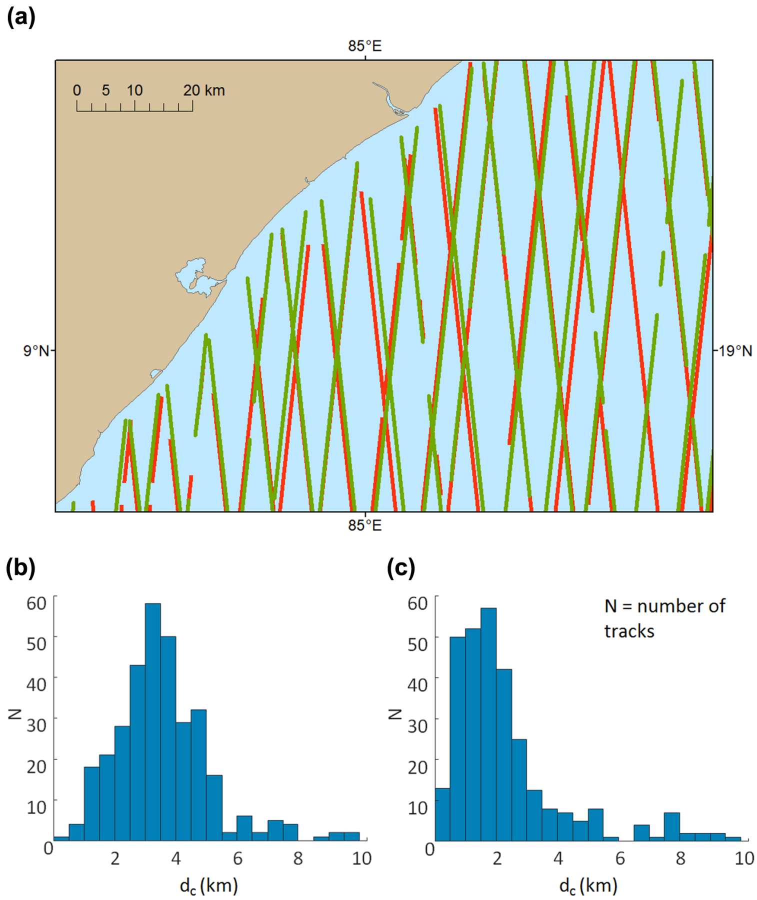

Figure 4 Differences in low-resolution mode (LRM) and synthetic aperture radar (SAR) modes of CryoSat-2 close to the coast. The test was carried out over an area of the coast of India. (a) A subset of the area; CryoSat-2 was in LRM mode (red) in 1 year and SAR mode (green) in another year. (b) The histogram of the closest point to the coast on each LRM track where a reliable sea-surface reflection was observed. (c) The same histogram for SAR tracks.

areas where the nadir point of the satellite was on land and the reflection point was off-track to one side – close to the edge of the adjacent body of water (Fig. 5a). Thus for SARIn CryoSat-2 data, coverage was enhanced compared to what might have been expected – from a narrow focused nadir reflecting altimeter. Figure 5(b) shows the resulting gravity grid for Lake Tanganyika – illustrating that overall calculation of gravity over the lakes and incorporation of CryoSat-2 SARIn mode data have both been a success.

HIGHER RADAR FREQUENCY – AltiKa

The SARAL (satellite with Argos and AltiKa) satellite incorporating the AltiKa altimeter (Bonnefond *et al.* 2018) was launched in 2013 with the aim that it would follow a high-latitude 35-day repeat orbit – following the same tracks as the repeat mission of ERS-1 (and the subsequent ERS-2 and ENVISAT satellites which had no geodetic mission) (Fig. 6). Most of the altimeters mentioned in this article operate in the k_u band with radar frequencies ~13.6 GHz and wavelengths of ~2 cm; AltiKa operates in the k_a band with radar frequency 33.75 GHz and wavelength ~9 mm. AltiKa has a narrower radar beam and therefore, in principle, produces a smaller footprint on the sea surface, whilst the sampling of the return waveform is also smaller – making for potentially higher precision sea-surface height estimation. One downside is that k_a band altimeters are more affected by rain and the altimeter will not collect data in some cases where the k_u band altimeter will deliver satisfactory data.

AltiKa waveforms can be readily re-tracked based on algorithms similar to those used for other low-resolution mode (LRM) altimeter waveforms. The results show relatively little noise and provide a generally cleaner solution than for other satellites – in good weather – which should provide more accurate, higher resolution sea-surface heights.

Whilst SARAL remained in its repeat orbit, it had little impact on gravity calculation except at high latitudes where it was able to greatly enhance the available track coverage in areas where the prevalence of ice meant that available data are patchy. Since July 2016, the orbit of SARAL has drifted and is

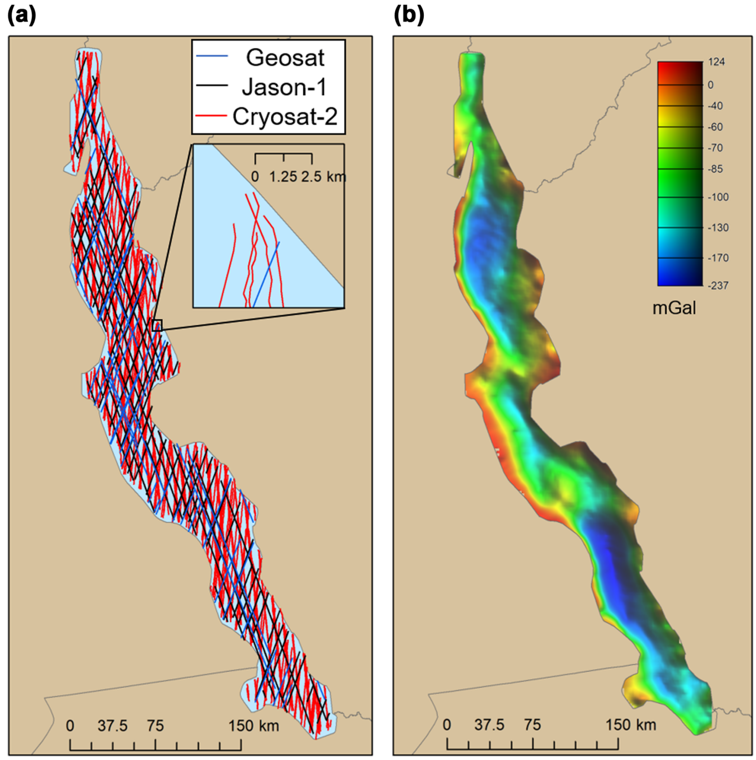

Figure 5 (a) Satellite track coverage over part of Lake Tanganyika shows how CryoSat-2 SARIn (SAR interferometric) mode provides additional coverage where the surface reflection point follows the open water, whilst the nadir point approaches and crosses on to land. (b) Satellite altimeter-derived gravity (free air anomaly).

now starting to provide improved track spacing, such that the AltiKa data can be incorporated into generation of satellite gravity globally. Figure 6 shows a sample of AltiKa coverage up to the end of 2017; by comparing Fig. 6(a,b), it is apparent that AltiKa coverage was already approaching that offered by each of the existing four geodetic mission satellites. The apparent high quality of the AltiKa track data indicates that geodetic mission track spacing could lead to further advances in resolution of satellite altimeter gravity. In the shorter term, a more complete coverage of AltiKa data could remove the requirement to integrate the lower resolution ERS-1 data as the pattern of tracks is essentially the same.

ASSESSMENT OF DATA ACCURACY

It is possible to assess the accuracy of the gravity data derived from satellite altimetry, by comparing to shipborne data where the gravity field has been measured directly. Here, the data have been analysed against the UK Oil and Gas Authority survey for the Mid-North Sea High, offshore United Kingdom, presented previously in Fig. 2(a). This survey consisted of approximately 12,000 km of gravity data.

To assess the accuracy of the satellite-altimetry derived gravity data at different wavelengths, both shipborne and satellite data have been filtered using a Butterworth bandpass filter of order 8. A 20 km wavelength band was chosen and applied at a range of central wavelengths – for example the band described as 50 km was bandpass filtered 40–60 km. The Pearson correlation coefficient (R) was then calculated between the filtered ship profile gravity data and the satellite gravity data (Fig. 7). The results show very high correlations at longer wavelengths ($>$30 km), with values $>$0.98 for the longest wavelengths. For wavelengths shorter than 30 km, there is a drop in the correlation between the two data sets, with a correlation coefficient of 0.5 obtained at $\sim$15 km wavelength. This correlates approximately to the low-pass filter applied to the altimetry sea surface height grid to remove short wavelength noise during the process of conversion to gravity. It should be noted that these comparisons assume the accuracy of the shipborne data set to be very high; this is likely to be valid at shorter wavelengths as the gravity meter measures the gravity field reliably at wavelengths $<$1 km, although the stability of longer wavelengths is likely to depend on statistical levelling processes.

DISCUSSION

There are a range of improvements now available, based on the new (since 2010) satellite altimeter data, the improvement

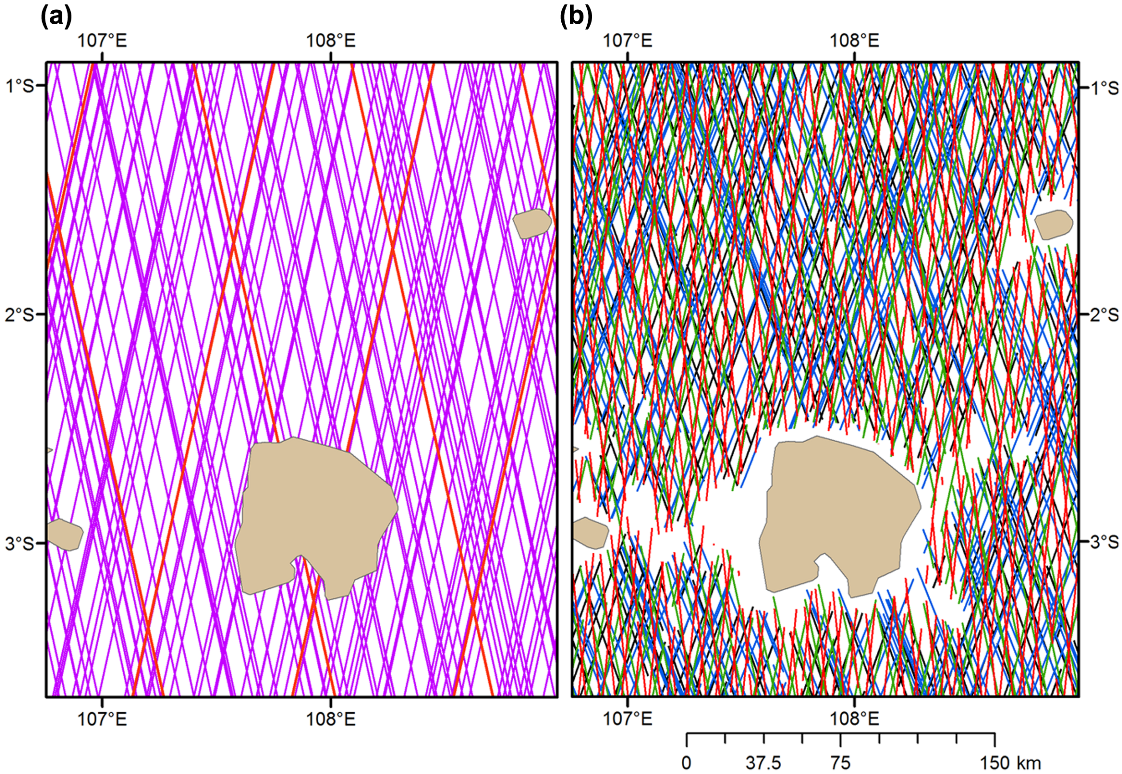

Figure 6 (a) The coverage of recent AltiKa tracks (before any editing); the satellite in drift mode (purple) is now providing a dense network of tracks, compared to the original constrained (repeat mission) orbits (red). (b) The coverage of the other satellites for the same area – GEOSAT (blue), ERS-1 (green), CryoSat-2 (red) and Jason-1 (black).

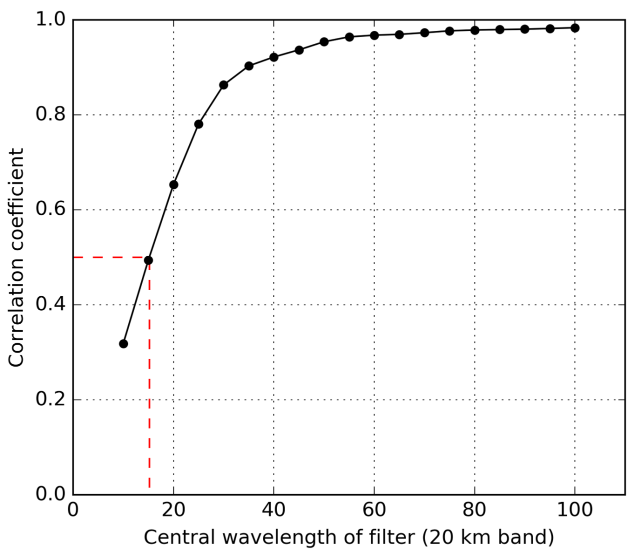

Figure 7 Analysis of the correlation coefficients between bandpass filtered versions of both shipborne gravity and satellite-altimetry gravity for a range of filter wavelengths. The data are from the area in the North Sea shown in Fig. 2.

in the resolution of the data can be seen in the comparison between the pre-2010 gravity data which used just two satellites, ERS-1 and GEOSAT, compared with the new gravity data using the additional Cryosat-2 and Jason data (Fig. 8). The arrows in Fig. 8 indicate features which can be mapped with improved confidence on the new data especially close to shore where the data were previously less reliable and now the features extend closer to the shore. Satellite gravity data are commonly used for a range of purposes including structural mapping, 2D and 3D modelling and inversion and tying together other gravity data sets; the applications have, to some extent, different requirements. Accuracy and resolution are clearly important for the modelling and inversion, but reliability is also very important – particularly for structural mapping; it is the reliability of the data that has probably benefitted the most from the increased data coverage and wider range of satellite track orientations.

Satellite altimeter gravity data sets have always been well controlled at long wavelengths, due to the global network of satellite tracks, but short wavelengths are less accurate; as shown in Fig. 7, accuracy decreases rapidly below 20 km

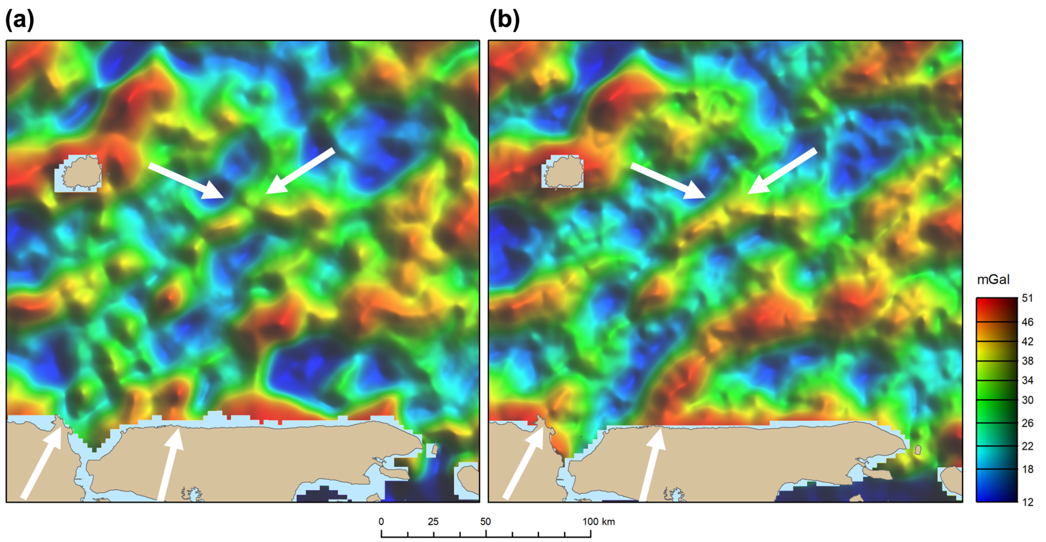

Figure 8 (a) Gravity (free air anomaly) produced pre-2010 using altimetry data from just two satellites, ERS-1 and GEOSAT, for comparison with (b) new free air anomaly gravity data produced using data from ERS-1, GEOSAT, CryoSat-2 and Jason-1. White arrows indicate features which can be mapped with greater confidence in the new gravity data.

wavelength. In recent years, it has been commonly noted that new satellite gravity data are as good as ship gravity data in many cases (Sandwell *et al.* 2013), but that necessarily depends on the ship data available over the area. Many available academic and government shipborne gravity data sets are old; Wessel and Watts (1988) show that the peak of acquisition of such data was the early 1970s. These gravity data had analogue recording and data were often sparsely sampled along track; the navigation was generally poor by today's standards. Generating a gravity grid from a disparate group of surveys is thus problematic and the results have limited accuracy, resolution and reliability. Current gravity surveys are digitally recorded, well sampled and have good navigation and corrections; for many years, accuracy of 0.2 mGal and resolution of 0.25 km have been achievable (Fairhead and Odegard 2002). Thus, along-track resolution of contemporary shipborne data will always be better than satellite altimeter gravity. When comparing grids of shipborne and satellite gravity, the ship track spacing is critical. In general, we consider satellite gravity to have better resolution than shipborne surveys with line spacing >10 km. However, below 20 km wavelength, signal-to-noise ratio reduces rapidly and the satellite data become less reliable. We observe that anomalies smaller than 10 km in size are still imaged in satellite gravity in places, but they can be less reliably identified.

In the next few years, increased coverage of close-spaced AltiKa data, together with a growing database of CryoSat-2 data, offer scope for satellite gravity data improvements. New processing of the SAR (synthetic aperture radar) and SARIn (SAR interferometric) modes of CryoSat-2 – including utilization of cross-track gradients from CryoSat-2 SARIn mode – holds promise for further improvements – especially if the geographic coverage of these modes can be increased or re-located.

The success of both new modes of CryoSat-2 and the higher frequency signals of AltiKa indicate the scope for different satellite missions to make improvements to gravity field generation. A particularly interesting future plan is the Surface Water and Ocean Topography (SWOT) mission – see, for example Biancamaria, Lettenmaier and Pavelsky (2016). The SWOT SAR interferometer would measure wide swaths of the Earth's surface at high accuracy and resolution; over water areas, the satellite will map the gravitational equipotential surface. Although there will undoubtedly be challenges in utilizing this much larger volume of data for gravity calculation, the result has the potential to greatly improve the accuracy and resolution of offshore gravity data, compared to current altimeter-based results.

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