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A new 100-m Digital Elevation Model of the Antarctic Peninsula derived from ASTER Global DEM: methods and accuracy assessment

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Abstract

A high resolution surface topography Digital Elevation Model (DEM) is required to underpin studies of the complex glacier system on the Antarctic Peninsula. A complete DEM with better than 200 m pixel size and high positional and vertical accuracy would enable mapping of all significant glacial basins and provide a dataset for glacier morphology analyses. No currently available DEM meets this specification. We present a new 100-m DEM of the Antarctic Peninsula (63–70° S), based on ASTER Global Digital Elevation Model (GDEM) data. The raw GDEM products are of high-quality on the rugged terrain and coastal-regions of the Antarctic Peninsula and have good geospatial accuracy, but they also contain large errors on ice-covered terrain and we seek to minimise these artefacts. Conventional data correction techniques do not work so we have developed a method that significantly improves the dataset, smoothing the erroneous regions and hence creating a DEM with a pixel size of 100 m that will be suitable for many glaciological applications. We evaluate the new DEM using ICESat-derived elevations, and perform horizontal and vertical accuracy assessments based on GPS positions, SPOT-5 DEMs and the Landsat Image Mosaic of Antarctica (LIMA) imagery. The new DEM has a mean elevation difference of +3 m (±26 m RMSE) from ICESat, and a horizontal error of less than 2 pixels, although elevation accuracies are lower on mountain peaks and steep-sided slopes. The correction method significantly reduces errors on low relief slopes and therefore the DEM can be regarded as suitable for topographical studies such as measuring the geometry and ice flow properties of glaciers on the Antarctic Peninsula. The DEM is available for download from the NSIDC website: http://nsidc.org/data/dems/datasets.html (doi:10.5060/D47P8W9D).

1 Introduction

The Antarctic Peninsula differs from the rest of the continent in that it is a complex mountainous glacier system: outlet valley glaciers flow from a high elevation plateau region, draining to the east and west of the peninsula, either flowing into ice shelves or terminating as grounded or floating marine glaciers. The Global Land Ice Measurements from Space (GLIMS) glacier inventory of the Antarctic Peninsula comprises over 1100 individual glacier systems, including isolated ice caps, mountain glaciers and ice piedmonts (Rau et al., 2006). The behaviour of neighbouring marine-terminating glaciers is complex as mass balance changes are affected not only by climate and oceanographic forcings but also by subglacial and surrounding topography. The tidewater glaciers throughout the Antarctic Peninsula have recently shown changes in extent, velocity and thickness (Cook et al., 2005; Pritchard and Vaughan, 2007; Pritchard et al., 2009) but the changes in the mass balance of specific systems have not yet been quantified. The response of glaciers to warming air-temperatures and ocean circulation changes in this region is critical for understanding future mass-balance changes, but the scale and inaccessibility of the region has hindered analyses both of the glacier system as a whole and of individual glaciers.

Digital Elevation Models (DEMs) are increasingly being used by glaciologists to investigate glacial features in regions that are difficult to access, and are commonly used to analyse spatial and temporal changes in the ice surface topography (e.g. Pope et al., 2007). A topographic model of the Antarctic Peninsula glacier system would enable measurements such as area, hypsometry, slope, aspect and flow direction, all of which are important in understanding ice dynamics, not only of individual flow units but of the complete glacier system. In recent years, DEMs of Antarctica have been produced using a range of source data including radar missions, stereo satellite image processing techniques and laser altimetry, but many of these elevation models have a spatial resolution of 1 km or greater and are optimised for coverage of the main Antarctic continent. This resolution is insufficient for the smaller glaciers and the steep-sided coastal regions of the Antarctic Peninsula, however, which would require a resolution of 200 m or less.

The ASTER Global Digital Elevation Model (GDEM) is a recently released nearly global high-resolution DEM, composed of elevation data generated automatically using photogrammetric principles and source data from the Advanced Spaceborne Emission and Reflection Radiometer (ASTER) stereo scenes (ASTER GDEM Validation Team, 2009). It is widely used globally but is generally not considered for use in Antarctica due to the well-acknowledged large anomalies in these regions, introduced as a direct result of high reflectance and lack of features on snow-covered plateaus. Although it is therefore unsuitable for much of the interior of Antarctica, the Antarctic Peninsula has significant areas of exposed rock, varying surface slope and texture that suggest it will be better suited to this region. ASTER GDEM has a cell size of 1-arc second (equating to ∼10 m east-west and ∼30 m north-south in the Antarctic Peninsula) and, if the errors on the plateau regions can be sufficiently reduced, it could be considered as a useful new dataset for glaciological applications. Figure 1a and b shows a sample region that illustrates the ASTER GDEM compared against the visible-band image, the Landsat Image Mosaic of Antarctica (LIMA). The smoother, low-relief slopes visible on LIMA contain large spikes/pits on GDEM, whereas the higher-relief and greater texture coastal regions closely match the features visible on LIMA.

In this paper we describe a method that we have used to improve the ASTER GDEM dataset in the Antarctic Peninsula, and an assessment of the accuracy of the new DEM produced by this method. We begin by comparing existing DEM datasets in the Antarctic Peninsula that have a pixel size of 200 m or better and assess the suitability of each for glacial topography studies. We discuss the problems and inherent errors of GDEM, and discuss the feasibility of reducing these errors to produce a significantly improved DEM. The method that we have used to remove the artefacts in the data involves interpolating between contour data and combining these corrected regions with the higher-accuracy regions of GDEM. This unconventional technique is only used because standard methods do not work in this region, and it is effective because GDEM outliers primarily occur on low surface slope regions, where the spikes and pits can be removed in order to smooth the surface. Accuracy tests reveal that the new DEM has errors that are significantly less than existing DEMs in the Antarctic Peninsula and it therefore has a broad applicability for glacier mapping and morphology studies. Indeed, the new DEM is already being widely used and included in Antarctic datasets, such as BEDMAP2.

2 High resolution gridded elevation data sets for the Antarctic Peninsula

In order to find a suitable DEM dataset for use in mass balance analyses in the Antarctic Peninsula, existing DEMs with a pixel size of 200 m or better were considered. Those with peninsula-wide coverage that are currently available to the international research community are the Radarsat Antarctic Mapping Project (RAMP) v2 model (Liu et al., 2001) and the ASTER Global Digital Elevation Model (ASTER GDEM Validation Team, 2009). Regional DEMs include those produced from SPOT-5 High Resolution Sensor (HRS) stereoscopic data (Korona et al., 2009), and from elevation data collected as part of Operation IceBridge using the NASA/GSFC Land, Vegetation and Ice Sensor (LVIS) (http://nsidc.org/data/icebridge/data_summaries.html#lvis). High resolution Tandem-X Interferometric Synthetic Aperture Radar DEMs are currently being generated (http://www.dlr.de/dlr/) and Cryosat-2 Synthetic Aperture Interferometric Radar Altimeter (SIRAL) data will be used for creating elevation grids (http://www.esa.int/SPECIALS/Cryosat/), but at the time of writing these DEMs are not yet available for the Antarctic Peninsula. The Landsat Image Mosaic of Antarctica (LIMA) has enabled identification of features at a spatial resolution of 15 m and although it is not an elevation data source, it provides a geospatially accurate base coastline (Bindschadler et al., 2008).

Of the regional DEMs, SPOT-5 stereoscopic survey of Polar Ice: Reference Images and Topographies (SPIRIT) is an International Polar Year (IPY) project in which a large archive of SPOT-5 HRS stereoscopic images and 40-m DEMs of Polar Regions were made available to the scientific community (Korona et al., 2009). Certain regions were chosen and prioritised before acquisition and the SPIRIT digital terrain model (DTM) products were generated automatically from the optical stereo-images through a matching algorithm. The DTMs were validated by comparison with ICESat elevation profiles and for a highly-textured ablation region on the large outlet glacier in Greenland, Jakobshavn Isbrae, the SPIRIT DEM elevations were within ±6 m of ICESat elevations for 90 % of the data, although the errors were greater on flat accumulation areas (Korona et al., 2009). The DTM products are at a high resolution and have good geospatial accuracy, but they only cover certain regions of the Antarctic Peninsula, primarily along the western coast and northern regions, therefore coverage is currently not sufficient to produce an all-inclusive DEM of the Antarctic Peninsula.

Of the two products providing complete coverage, the Radarsat Antarctic Mapping Project (RAMP) v2 model (Liu et al., 2001), available from the NSIDC (http://nsidc.org/data/nsidc-0082.html), is a DEM with widespread usage. It was originally created for use in processing images for the RAMP AMM-1 SAR Mosaic of Antarctica and since then has been widely used to detect glaciological properties of the ice sheet (Jezek, 1999). The DEM accuracy varies according to the terrain and accuracy of the wide range of data sources, and uncertainties that are introduced through data integration. For the Antarctic Peninsula the geolocation accuracy is thought to be generally better than the horizontal resolution (200 m in this region), and the vertical accuracy lies between 100–130 m (Liu et al., 2001). This is a reliable and widely used surface topography dataset for scientific research and logistics operations throughout Antarctica. The vertical accuracy required, however, for glacier drainage basin delineation for mass balance analyses on the Antarctic Peninsula must ideally be greater than those specified in the RAMPv2 documentation.

The ASTER Global Digital Elevation Model (GDEM) is the most recently released nearly global elevation dataset and is based upon a composition of automatically generated DEMs from ASTER stereo scenes acquired from 2000 to the present. It was produced by the Ministry of Economy, Trade and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA) and was first released to the public in June 2009 (ASTER GDEM Validation Team, 2009). ASTER consists of nadir and backward looking sensors, enabling a stereoscopic DEM to be generated based on photogrammetric principles. An automated approach was used to produce a stereo DEM between 83° N to 83° S, in 1-degree tiles, with a pixel size of 1-arc second. Validation tests were performed by both the US and Japanese partners by calculating statistical accuracies based on reference DEMs and Ground Control Points for sample regions around the globe. Conclusions in the validation summary report (ASTER GDEM Validation Team, 2009) are that the overall vertical accuracy of the ASTER GDEM1, on a global basis, is approximately 20 m at 95 % confidence. With this pixel size and overall accuracy, GDEM could provide an attractive solution to a finding a suitable DEM on the Antarctic Peninsula.

3 ASTER GDEM: limitations and potential for use in the Antarctic Peninsula

Although the majority of ASTER GDEM tiles have vertical accuracies within 20 m "ASTER GDEM does contain residual anomalies and artifacts that most certainly degrade its overall accuracy" (ASTER GDEM Validation Team, 2009). No formal GDEM validation has been performed over Antarctica, but it is evident that there are significant errors within the tiles throughout this region. This is to be expected, as the snow-covered landscape results in low contrast and sparse repeat coverage, both of which contravene the essential criteria for stereo-image processing. Recent independent assessments of ASTER GDEM in Arctic regions (Hvidegaard et al., 2012; Rees, 2012; MacFerrin et al., 2012) have shown that the number of independent ASTER DEMs contributing to the final elevation value for any given pixel (known as the stacking number) is a good indicator of accuracy. In areas where this number is greater than ∼6, the GDEM root-mean-square-error (RMSE) is typically 5–10 m (Rees, 2012). At high elevations on the Greenland Ice Sheet however, where GDEM tiles are dominated by cloud and striping artefacts, the majority of points have low stacking numbers (Rees, 2012; MacFerrin et al., 2012). A study of GDEM accuracy in coastal regions of Greenland by Hvidegaard et al. (2012) showed that there was a bias of 10–20 m in the data and an RMSE elevation difference ranging from 15–65 m. Hvidegaard et al. (2012) attributed the large RMSE to: low stacking numbers; reduced correlation between images due to snow cover; mis-registration between GDEM and the test dataset due to high sloping areas on the coast; and seasonal changes in the ice sheet. ASTER GDEM2 was released on 17 October 2011 and although it is a significantly improved version on a global scale (ASTER GDEM Validation Team, 2011) a comparison of GDEM1 and GDEM2 in Greenland concluded that there was insignificant difference in overall accuracy between the two versions in that region (MacFerrin et al., 2012).

Until now, GDEM has not been considered as a reference DEM for glaciological projects in Antarctica. As the potential for ASTER DEMs to be used for glacier-change studies in the Antarctic Peninsula is becoming more recognised (Cziferszky et al., 2010; Glasser et al., 2011; Shuman et al., 2011; Scambos et al., 2011), it is important to consider how the GDEM artefacts can be reduced. For Greenland, recommendations for reducing errors include filtering regions where stacking numbers are low and cloud and striping artefacts are high, and either interpolating across remaining cells where the ice is relatively flat, or down sampling (MacFerrin et al., 2012). In some parts of the Antarctic Peninsula, however, if the “noise” was filtered, there would be too few remaining postings for interpolation to be viable and valid elevations would be lost with down sampling. Figure 2 illustrates the stacking numbers of ASTER GDEM for a sample region of the Antarctic Peninsula between 66–68° S, in which extensive regions with stacking numbers less than six can be observed. One suggestion is to insert other elevation datasets, such as NASA Ice, Cloud and land Elevation Satellite Geoscience Laser Altimeter System (ICESat GLAS) data or Shuttle Radar Topography Mission (SRTM) data. The Antarctic Peninsula is not covered by the SRTM however, and ICESat GLAS Elevation points are too widely spaced in this region to fill the extensive gaps.

The stacking number file that is provided with the elevation dataset however also indicates regions that could be considered as accurate and should be investigated further. When GDEM is contoured and placed over the LIMA, in some regions it fits closely to terrain features, particularly in coastal and feature-rich areas. Rock features, mountain slopes, crevasses and supraglacial water create texture for the image-matching algorithms, thereby increasing the stacking numbers of valid ASTER scenes per pixel. In other areas, often where the stacking numbers are low, the contours clearly do not fit terrain features and large pits and spikes appear. The contours are a way of visualising where the GDEM changes, often sharply, from good quality to poor. If the data are so noisy that they cannot be filtered or smoothed using recognised techniques, an alternative approach must be considered.

4 A new approach to ASTER GDEM correction

A DEM generation approach already implemented in Antarctica used spatial interpolation algorithms within a Geographic Information System (GIS) environment to interpolate a surface between different vector data sources. The Radarsat Antarctic Mapping Project (RAMP) used a comprehensive collection of digital topographic source data, including cartographic data, remotely sensed data and survey data, which were then integrated and merged to produce the RAMP DEM (Liu et al., 1999). One data type that was used was contours digitised from paper topographic map sheets, included in the Antarctic Digital Database (ADD) (BAS et al., 1993). Contour-specific interpolation algorithms were tested by Liu et al. (1999), who found that the TOPOGRID-based method (Hutchinson, 1989; ESRI, 1991) was the most effective technique in terms of the consistency with the source contour data and preservation of the fine surface structures. With this method, linear interpolation is enforced along ridge and stream lines, which are automatically derived from points of maximum curvature on contour lines (Liu et al., 1999). Although originally developed for use in ArcInfo, similar algorithms are now available in many GIS software packages.

The principle of the new method we present in this paper is that when GDEM is converted into contours and the erroneous contours are removed, a smooth and realistic new DEM can be produced from the remaining contours. If this is applied only to regions with spurious contours, the resulting DEMs can be merged with the unaltered high-quality GDEM regions. The method is made possible by the fact that the high-artefact regions are those where the real surface slope is significantly less than ~20° (and therefore fewer contours are required to derive the new surface topography) and contours that are short in length can be removed from these regions since these represent spurious spikes and pits where the real-surface (as observed on LIMA) is smooth. The remaining contours occur where the DEM has consistent elevation values between the anomalies and can be used to reconstruct the surface topography by interpolation. This method has already been successfully applied in producing topographic maps (BAS, 2010a, b).

5 Methodology for ASTER GDEM correction

ASTER GDEM tiles were downloaded from http://www.gdem.aster.ersdac.or.jp/ and mosaicked according to each latitudinal degree across the Antarctic Peninsula. Each mosaic was projected onto a reference system suitable for minimising distortions in scale and for preserving angles locally. In this case, Lambert Conformal Conic (LCC) projection was used with standard parallels and other parameters according to latitude. The mosaic was converted to a 32-bit continuous floating point raster to minimise elevation errors at each stage of data processing. The subsequent methodology was then applied separately to each latitudinal degree raster between 63–70° S.

Using a GIS, contours were generated automatically from the GDEM at 20 m intervals. A new file was then created by digitising around regions of erroneous contours. The stacking number file was used to generate the initial outline of poor quality regions (where the stacking number is less than 6), but manual corrections were necessary using visible band imagery (in this case, LIMA) to assess terrain contour-fit (Fig. 3a). These “noisy” regions of the DEM were then extracted and resampled to 200 m to simplify and remove gross errors and, using GIS hydrology and filtering tools, “sinks” in the DEM were filled and smoothed. Contours at 20 m intervals were then created for this generalised DEM. In order to correct these contours two methods were applied. The first involved creating a slope model and removing contours that fell within a slope angle of greater than 20° (this angle was chosen after testing various slope values). The second step involved deleting contours less than 1 km in length (chosen as the best indication of a spurious contour at this DEM cell size, after testing a range of values). In order to minimise discontinuity between the corrected regions and the high-quality regions, we created a 200 m overlap or "buffer" zone for all error-regions. The contours could then be manually checked and any remaining spurious contours deleted or improved based on the terrain visible in the LIMA image. It was then possible to generate a new DEM for the error-regions using the edited contour file. We did this using the Topo to Raster interpolation tool in ArcGIS, with a 100 m output cell size.

The outer limit we chose for the new DEM is the coastline that is visible on LIMA (or the grounding line where there is ice shelf), plus a buffer of 500 m offshore. This means that all of GDEM is included, even where the horizontal positioning does not directly match LIMA. The high-quality GDEM (i.e. the original GDEM with the erroneous regions erased) was resampled to 100 m, and "filled" to remove minor pits. A cell size of 100 m was determined to be optimal for the intended purpose of the final DEM: if the grid size is smaller, artefacts remain on the high-quality regions and the data volume increases, whereas sufficient topographic detail can be obtained at this spacing for the complexity of terrain in the Antarctic Peninsula.

Finally, the corrected error-region DEM was mosaicked with the high-quality GDEM, using a blend method to ensure a topographically consistent DEM across the buffer zones (Fig. 3b). Once these steps were completed for each individual latitudinal degree tile, a common reference system was selected before the tiles were integrated. For the Antarctic Peninsula, Polar Stereographic projection with a standard latitude of 71° S and a central meridian of 0° was chosen. As the ASTER GDEM is referenced to the WGS84 ellipsoid and adjusted to the EGM96 geoid model, the new DEM is also on this reference system and therefore gives height with respect to the geoid. The final step of the process involved mosaicking all tiles by blending, and filtering to smooth. The filtered mosaic was clipped to remove any remaining artefacts along the coast to create the finished DEM (Fig. 4).

6 Error analysis

In order to validate the new DEM we carried out tests to assess vertical and horizontal positional accuracy. In Antarctica, assessing the quality of the derived surface can be problematic, as high-accuracy ground-control points are limited and poorly distributed throughout the modelled area. A first assessment of ASTER GDEM tiles was undertaken by Reuter et al. (2009), in which ICESat elevations were used for absolute accuracy tests and SRTM was used for relative accuracy for 5 GDEM tiles from around the globe. We applied a similar methodology here. We first addressed vertical accuracy, where we used ICESat as an absolute reference and created profiles along ICESat tracks to compare elevations of existing DEMs. Vertical accuracy of improved regions only was also assessed in order to detect any significant differences from the mean errors or whether a systematic bias was introduced during editing. ICESat elevation points cannot be used for horizontal accuracy tests for the DEM, so we calculated absolute geospatial accuracy using 10 peaks in one small sample region based on GPS points and a photogrammetric DEM. Peaks obtained from SPIRIT DEMs gave relative accuracies across a wider region to test for consistency across the model. Finally, horizontal differences from LIMA were calculated, for when the DEM is used alongside LIMA.

6.1 DEM accuracy

6.1.1 Absolute vertical accuracy obtained from ICESat elevation values

The NASA Ice, Cloud and land Elevation Satellite (ICESat) mission from 2003–2009 consists of semi-continuous profiles of elevation points acquired using the on board Geoscience Laser Altimeter System (GLAS) and provides consistent, near-repeat surface elevations (Zwally et al., 2002; Shuman et al., 2006). ICESat has a footprint of ~70 m with an along-track spacing of 170 m and an across-track spacing of about 20 km at 70° S. The high precision and sub-decimetre accuracies of the along-track elevation values on low-slopes (Shuman et al., 2006) are ideal for measuring absolute-errors and determining the accuracy of other elevation products (e.g. Korona et al., 2009; Nuth and Kaab, 2011).

The sample region we chose for ground-truthing errors using ICESat elevation values is between 66–68° S. This is the central region of the Antarctic Peninsula and includes a wide range of terrain types, from high plateau, to mountains with varying slope angles and low coastal regions. The error regions are representative of those across the rest of the DEM. We used Release 531 GLAS/ICESat L1B Global Elevation Data (GLA06), available from NSIDC (Zwally et al., 2003), for accurate surface altimetry across the range of terrain. The GLAS accuracy in horizontal geolocation is ∼15 m and for clear skies and low-slopes the surface elevation is accurate to ±14 cm (Shuman et al., 2006). We chose 5 ICESat tracks from 2007 (Fig. 5), to correspond with the year that SPIRIT scenes in the same region were acquired. GDEM however, is compiled from ASTER scenes from a range of dates between 2000 and 2009 and, due to ice surface elevation change over time, this must be taken into account when assessing relative elevation differences. We created elevation profiles along each track and calculated the surface elevation values of GDEM, the new DEM, a SPIRIT DEM (where available) and the RAMPv2 DEM for each point (Fig. 6). Each DEM is referenced to the EGM96 Geoid, so relative differences are based on mean heights with respect to the geoid. Although ICESat/GLAS uses a different ellipsoid (TOPEX/Poseidon), it results in elevation values only 70 cm higher than those obtained using the WGS84 ellipsoid. The ICESat values have been corrected to the EGM96 Geoid.

The artefacts on the original GDEM are visible on the profiles, particularly on the ice plateau regions, and it is clear that the new DEM closely matches the ICESat values in almost all sections of the profiles. The points are used to calculate elevation differences along each track (Table 1a) and the total elevation differences are summarised in Table 1b. Although the SPIRIT DEM has a relatively low mean offset from ICESat (−14 m), it has a relatively high RMSE (±61 m). The new DEM has a mean offset of +3 m, with an RMSE of ±26 m, which is a small improvement on the RMSE of the original GDEM (mean +1 m, RMSE ± 35 m). The raw GDEM accuracy values are perhaps better than expected, but may be because ICESat points rarely fall directly on the pits and spikes. The new DEM elevations are within the RMSE value for 85 % of the data. From these absolute error values we can conclude that the new DEM is a significant improvement on existing surface topography models of the Antarctic Peninsula.

6.1.2 Vertical accuracy for corrected regions compared with unaltered regions

Figure 5 also shows the delineated erroneous regions within the sample area. The ICESat tracks have been intersected with the file to give points only within the corrected regions, and as described above, the analysis gives a comparison of each DEM with the ICESat points (Table 1c). The differences from ICESat in the corrected regions are similar to the differences from ICESat in total. The error-regions are generally on low surface slopes, where there are only small differences in elevation between adjacent cells and therefore the effects of mis-registration and positional accuracy are minimised. Within the error-regions, the new DEM absolute mean difference of +4 m, and the RMSE (±25 m) is less than the RMSE for the raw GDEM (±54 m) due to the removal of pits and spikes in these regions. We can deduce that there is no systematic bias introduced as a result of the correction process.

6.1.3 Horizontal accuracy for 10 peaks in one small sample region, based on GPS points and a photogrammetric DEM

Ryder Bay on Adelaide Island (67.5° S, 68° W) (Fig. 7) was chosen as a sample region from which to ground truth geodetic height and horizontal positions, as it has been GPS surveyed and a DEM at 2.5 m resolution produced from aerial photographs. The GPS positions are better than 0.1 m in both horizontal and vertical accuracy and the photogrammetric DEM has a vertical accuracy of better than 0.5 m. Only positions from peaks can be used for ground truthing, as they are easily detectable on each DEM. The SPIRIT model does not cover this region, so only GDEM and the new DEM were compared to the Ryder Bay DEM. Although the sample region is small and only 10 peaks are used, the positions can give absolute-error values (Table 2). The horizontal mean difference from the pixel centres for the raw GDEM is 40 m, and for the lower-resolution new DEM it is 64 m (i.e. below the 100 m pixel size). The mean vertical differences however are considerably greater than those calculated along the ICESat tracks. The mean peak difference for GDEM is 38 m lower, and for the new DEM is 77 m lower than the absolute value. Previous studies have shown that ASTER DEM accuracy is highly correlated to the steepness of the terrain, where gross errors are likely to occur at steep slopes and high peaks (Kaab et al., 2002; Cziferszky et al., 2010). Peak elevations on the new DEM have been further reduced during the resampling and filtering process. This may give a misleading result as this only occurs on peaks whereas the ICESat tracks cover a wide range of terrain types.

6.1.4 Horizontal and vertical relative accuracy and consistency tests across the DEM using positions of peaks obtained from SPIRIT DEMs

A wider assessment of geopositional accuracy can be carried out using SPIRIT DEMs, as they are well distributed across the new DEM. The SPIRIT products are likely to be better suited to the Antarctic Peninsula than ASTER GDEM as the HRS resolution is higher than ASTER and the sensor gain settings were optimised for collection of data over snow and ice. Although SPIRIT DEMs have inaccuracies of their own (Korona et al., 2009) they can be used as a suitable reference dataset for relative accuracy and consistency tests across the new DEM.

Figure 8 shows the location of SPIRIT tiles and the sample regions that we chose for relative error tests. Within each sample region, a number of peaks were identified on the SPIRIT DEMs, and the same peaks were then identified on the GDEM and the new DEM. The results are summarised in Table 3a and b. Firstly, using all 60 points from across the Antarctic Peninsula we show differences between GDEM and the new DEM relative to the SPIRIT DEMs. In each case the centre of the pixel is used as the geodetic position. The positions of the peaks on ASTER GDEM have a mean horizontal difference from their positions on the SPIRIT DEMs of 75 m (RMSE ± 48 m) and the new DEM has a mean difference of 130 m (RMSE ± 59 m). The peaks on ASTER GDEM have a mean vertical difference from the SPIRIT models of −8 m (RMSE ± 24 m) and those on the new DEM a difference of −51 m (RMSE ± 25 m). As explained above, there is a reduction in height of peaks during the DEM editing process but this does not occur on lower relief slopes. To assess the consistency of the new DEM from north to south, the three regions can be compared (Table 3b). The mean horizontal difference is less than 2 pixels for each region (between 106–161 m), and there is little variation in vertical errors, with mean heights ranging from 40 to 64 m below the SPIRIT DEM values.

6.1.5 Horizontal differences from the Landsat Image Mosaic of Antarctica (LIMA)

LIMA, at 15 m resolution, is often used as a base image for many glaciology studies so its geospatial accuracy relative to the DEMs must also be taken into account. The horizontal positions of the peaks on the SPIRIT DEMs were compared with their positions on LIMA. In addition to the Ryder Bay points, 25 positions along the coast of Ryder Bay were measured from LIMA and compared to the coast digitised from the photogrammetric DEM. The raw GDEM was used against which to compare LIMA as it has a higher resolution than the new DEM. LIMA has offset values from each dataset ranging from 81 to 110 m, although it must be noted that the direction of offset is not consistent between datasets (Table 4).

6.2 Methodology errors

Some of the inaccuracies in the new DEM have been introduced through data processing methods. From the original GDEM tile, each process introduces the following horizontal differences:

- Reprojecting the original GDEM to LCC projection introduces a difference of ∼15 m
- Resampling to 100 m reduces the precision by up to ∼50 m
- Each tile was on an LCC projection with different parameters, so when re-projected onto Polar Stereographic before mosaicking, a further difference of up to ∼50 m was introduced
- The filter process caused "expansion" of up to 140 m at edges but did not change horizontal positioning within the DEM.

These processes can explain horizontal differences, but the principal vertical differences occur during the resampling and filtering processes. Filtering was necessary to smooth the DEM to remove small artefacts on low-moderate relief slopes and to reduce inconsistent topography at tile overlaps. The average heights in regions of low-moderate relief were unaffected by smoothing, but the peaks and steep slopes were reduced in height (however the topography was preserved). Filtering was used as it gave the fewest anomalies across the range of terrain on the Antarctic Peninsula at the final resolution of the DEM. The new DEM is an improvement on existing surface topography models of the Antarctic Peninsula, but it comes with a few caveats. It has been corrected for the purpose of measuring glacier geometry, but it is not suitable for elevation change studies or accurate positional measurements of mountain peaks. This is largely because GDEM is from ASTER scenes spread between 2000–2009, meaning that seasonal and climatic differences in the ice surface are inherent in the data, and the RMSE value is too large to allow for precise surface measurements. Some anomalies along the coast have been removed, resulting in small gaps, and the DEM has a small number of remaining artefacts. It only covers regions included in ASTER GDEM, in which there are inherent gaps and some missing islands.

7 Conclusions

We have presented a methodology in which anomalies inherent within ASTER GDEM have been significantly reduced to produce a new DEM for the Antarctic Peninsula between 63–70° S. Although the technique is unconventional, it has enabled a new 100-m DEM to be produced that is a demonstrable improvement on existing surface topography models on the peninsula. This new representation of the surface could prove to be useful for many glaciological applications and is already being widely used and included in datasets. In this paper, we have validated the DEM by carrying out five accuracy tests, which highlight that whilst it is imperfect, it is the first DEM with the spatial coverage, resolution and accuracy suitable for glacier morphology studies in the region. Absolute vertical accuracies from ICESat show that across a representative range of terrain on the Antarctic Peninsula the new DEM has a mean vertical error of +3 m, with an RMSE of ±26 m. Absolute accuracies within the edited regions are similar (mean +4 m, RMSE ± 25 m) so there is no apparent bias introduced through the editing process. Vertical values on peaks however are significantly below real-values. This was found when using 10 positions obtained from GPS and a photogrammetric DEM in Ryder Bay, where the positions on the new DEM are, on average, 77 m lower than real positions. This was also found to be the case for 60 widely distributed peaks, when measured relative to SPIRIT DEMs. The peaks on the new DEM were found to be on average 51 m lower (RMSE ± 25 m) than their positions on SPIRIT, with little variation in error across the dataset. Although the peaks were lower, the topography was preserved. The ICESat tracks give a broader representation of vertical accuracy across the various types of topography. Horizontal accuracies for the new DEM are below 2 pixels, as found in all error tests. For the 10 peaks in Ryder Bay, the mean horizontal difference is less than 1 pixel (64 m), and for the 60 peaks across the wider region, the mean difference from the new DEM to the SPIRIT position is 130 m (RMSE ± 59 m). The difference between the new DEM and LIMA is also less than 2 pixels. The DEM is available for download from the NSIDC website: http://nsidc.org/data/dems/datasets.html (doi:10.5060/D47P8W9D) and a low resolution version of the new DEM is available from BEDMAP2: http://www.antarctica.ac.uk/bas_research/our_research/az/bedmap2/index.php.

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Table 1a. Mean elevation differences from ICESat for each DEM along 5 individual ICESat tracks (see Figs. 5 and 6). ASTGTM is the unaltered ASTER GDEM dataset. *N* is the number of ICESat points. The mean difference from each ICESat point is measured at height with respect to the geoid and the root mean square error (RMSE) is shown in metres.

	ICESat-New DEM	ICESat-ASTGTM	ICESat-SPIRIT	ICESat-RAMP
GLA06_0144				
N	614	614	295	614
Mean	−4	−2	−11	−46
RMSE	±21	±24	±28	±270
GLA06_0167				
N	371	371	31	371
Mean	−8	4	54	162
RMSE	±31	±56	±190	±263
GLA06_0286				
N	559	559	179	559
Mean	−1	2	−27	141
RMSE	±23	±28	±71	±258
GLA06_0382				
N	556	556	0	556
Mean	2	4		268
RMSE	±31	±41		±229
GLA06_0405				
N	685	685	268	685
Mean	−6	−3	−17	47
RMSE	±25	±25	±35	±235

Table 1b. Mean elevation differences from ICESat (total from 5 ICESat tracks).

	ICESat-NewDEM	ICESat-ASTGTM	ICESat-SPIRIT	ICESat-RAMP
N	2785	2785	773	2785
Mean	−3	1	−14	105
RMSE	±26	±35	±60	±273

Table 1c. Mean elevation differences from ICESat: error-regions only.

	ICESat-NewDEM	ICESat-ASTGTM	ICESat-SPIRIT	ICESat-RAMP
N	891	891	140	891
Mean	−4	5	−6	132
RMSE	±25	±54	±40	±228

Table 2. Absolute errors in the Ryder Bay region. The table shows the mean differences from the Ryder Bay DEM and GPS points for 10 peaks (metres).

	ASTGTM	New DEM
Horizontal	40	64
Vertical	−38	−77

Table 3a. Relative errors. Values are a summary of the differences relative to SPIRIT DEMs for ∼60 points distributed across the Antarctic Peninsula (in metres).

		ASTGTM	New DEM
Horizontal	Mean	75	130
	RMSE	±48	±59
Vertical	Mean	−8	−51
	RMSE	±24	±25

Table 3b. Consistency tests, based on points obtained from SPIRIT DEMs in north, mid- and south Antarctic Peninsula regions (see Fig. 9). Values are mean differences in metres.

	ASTGTM	New DEM
63–64° S: 17 points		
Horizontal	55	131
Vertical	−6	−44
67–68° S: 25 points		
Horizontal	67	106
Vertical	−16	−64
69–70° S: 17 points		
Horizontal	106	161
Vertical	4	−40

Table 4. Horizontal differences (in metres) from the Landsat Image Mosaic of Antarctica (LIMA).

	Ryder Bay (55 points)			SPIRIT (60 peaks)			ASTGTM (70 peaks)		
	x	y	distance	x	y	distance	x	y	distance
Mean	−81	−69	110	−25	4	94	18	−10	81
RMSE	±39	±39	±41	±70	±84	±62	±59	±77	±56

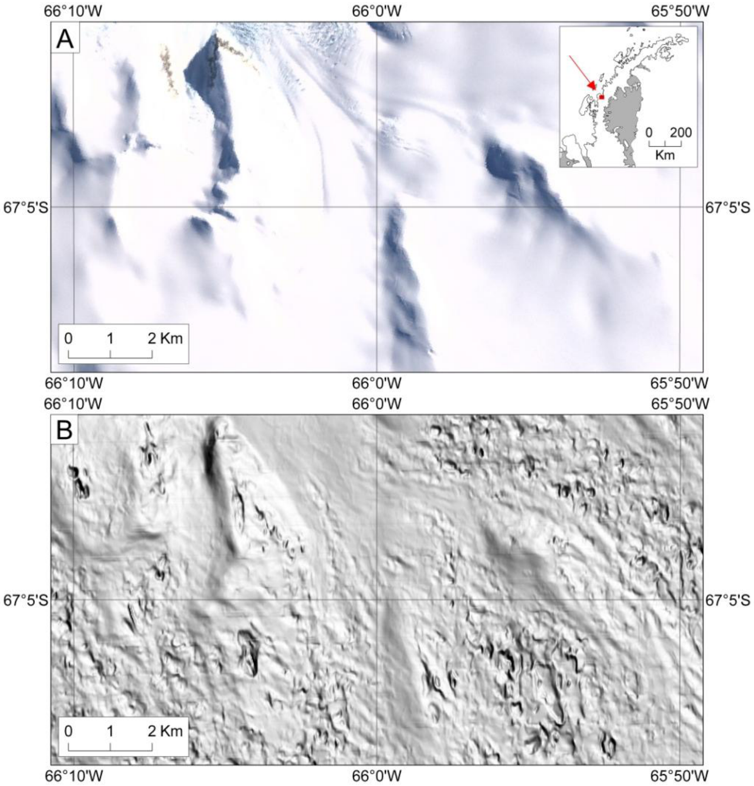

Fig. 1. Sample area showing features visible on LIMA satellite image, displaying crevassed high-texture regions, rock outcrops and smooth surface low-relief slopes **(A)**. The raw ASTER GDEM has been hillshaded to show the problems in the dataset such as pits/spikes, which primarily occur on the featureless surface slopes **(B)**.

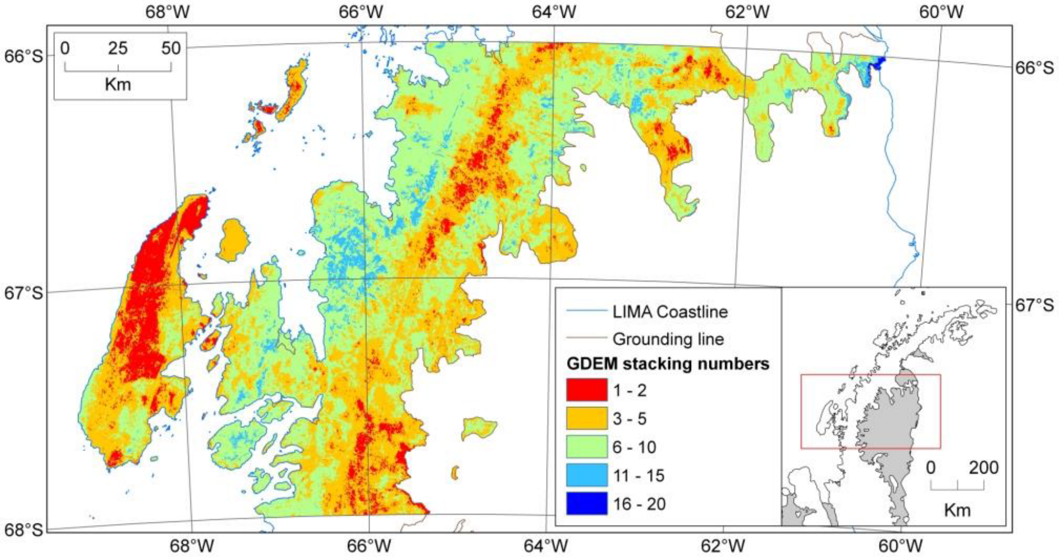

Fig. 2. Number of stacked local DEMs (stacking number) used to calculate each GDEM elevation value, for tiles between 66–68° S. Stacking numbers of ~6 or higher are an indicator of higher DEM accuracy.

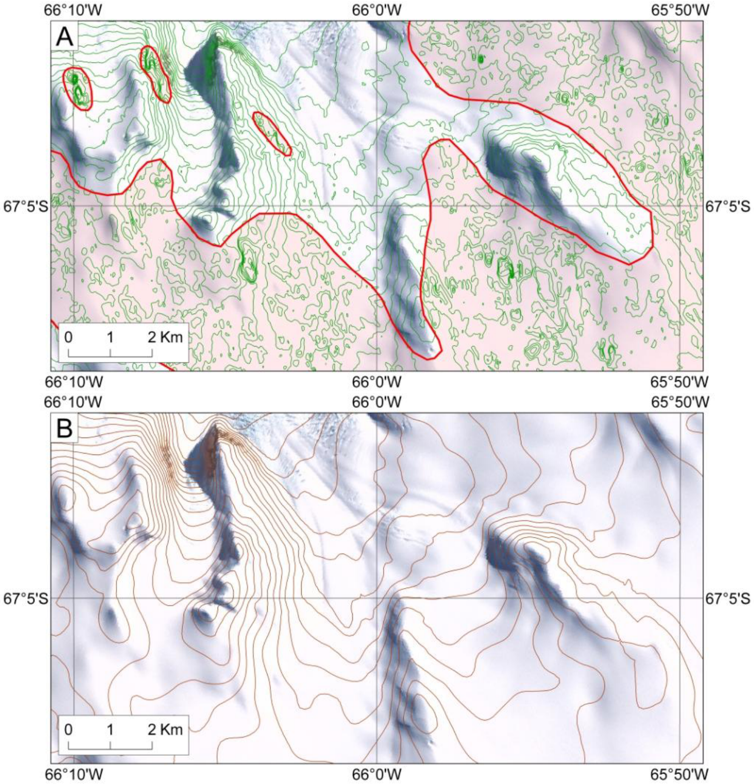

Fig. 3. Sample area displaying 50 m contours generated from raw ASTER GDEM and error-region polygons (in pink) **(A)**. This illustrates the first stage of the methodology: delineation of erroneous regions using contours draped over LIMA as a guide. The end-product has been contoured to illustrate the improvement in the DEM from the original and also the consistency of the topography at error region boundaries **(B)**.

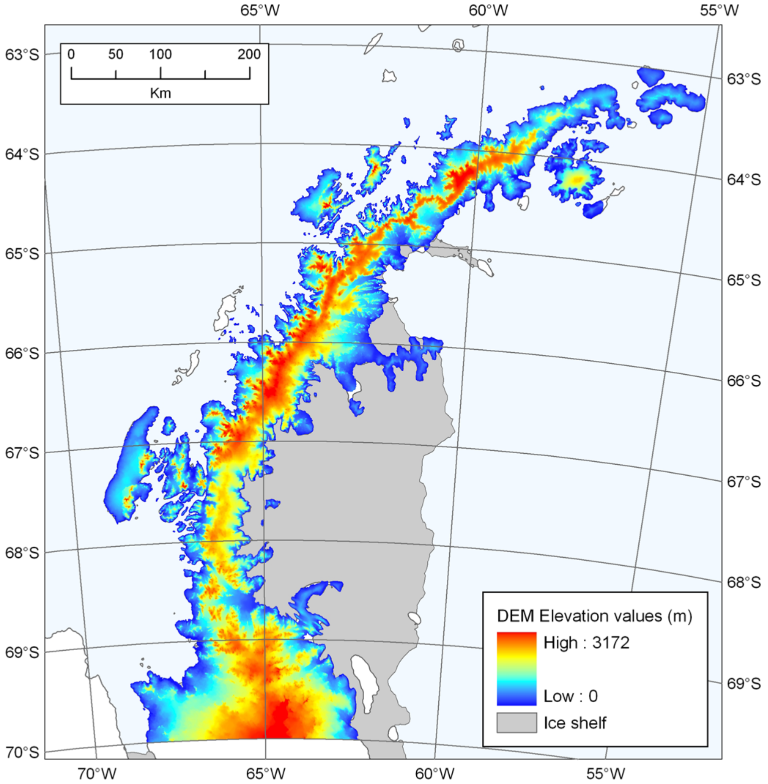

Fig. 4. The new 100 m-DEM of the Antarctic Peninsula.

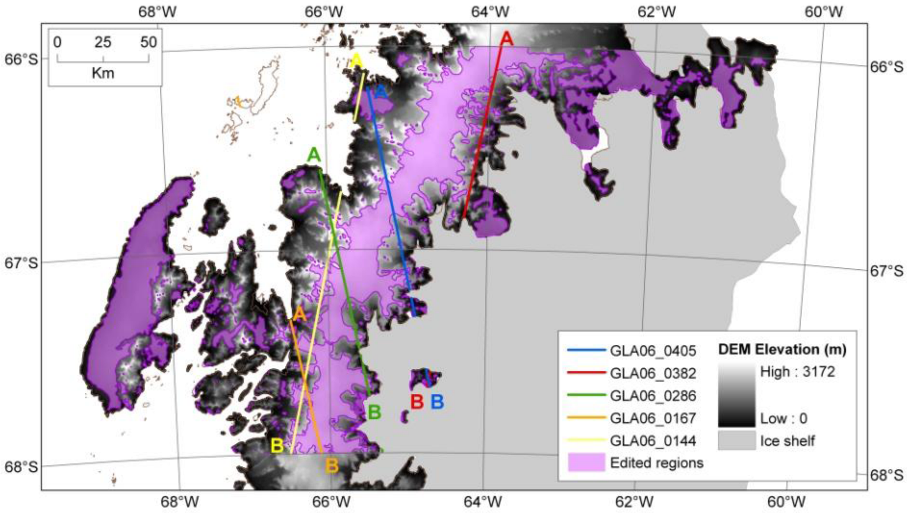

Fig. 5. ICESat tracks in the region 66–68° S, transecting the new DEM. The purple areas (with a transparency and hence different shading according to elevation) are the erroneous regions that have been edited, as described in the methodology. The ICESat track numbers relate to the following data downloaded from NSIDC (Zwally et al., 2003): GLA06_0144: XYGLA06_531_2121_002_0144_3_01_0001 (17/10/2007), GLA06_0167: XYGLA06_531_2121_002_0167_3_01_0001 (19/10/2007), GLA06_0286: XYGLA06_531_2121_002_0286_3_01_0001 (27/10/2007), GLA06_0382: XYGLA06_531_2121_002_0382_3_01_0001 (02/11/2007), GLA06_0405: XYGLA06_531_2121_002_0405_3_01_0001 (04/11/2007).

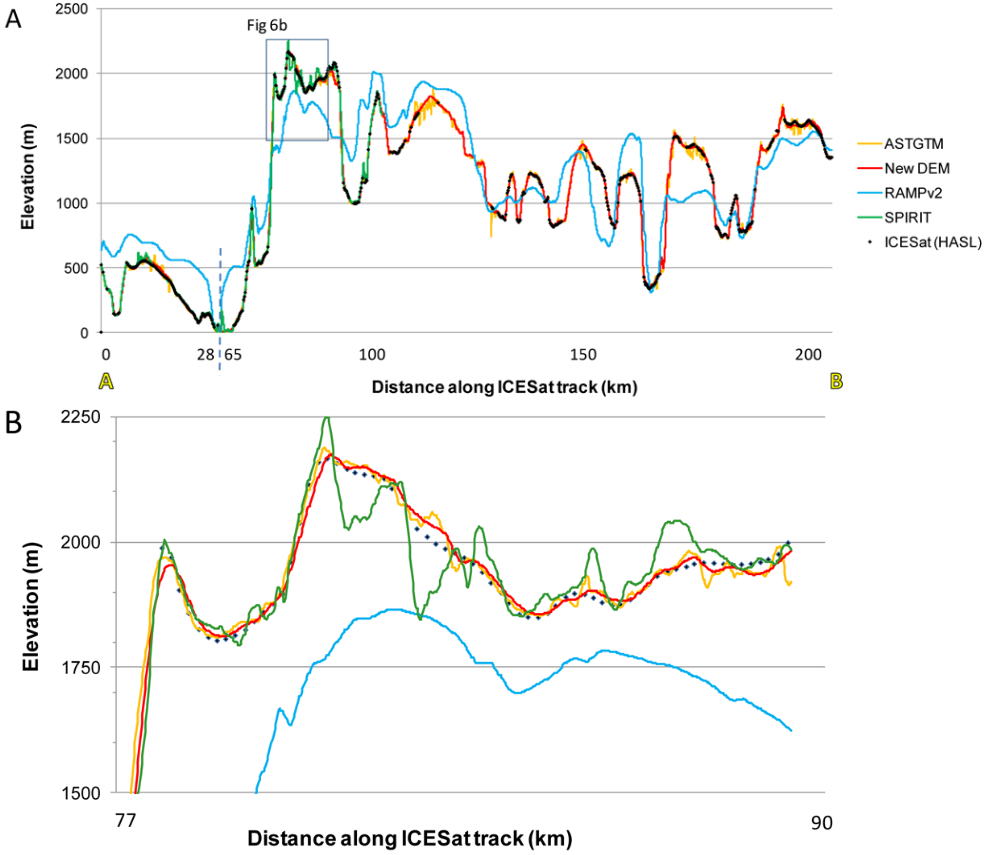

Fig. 6. (A) shows the profile for ICESat track GLA06_0144, illustrating relative differences between each DEM. The inset **(B)** shows the differences in greater detail. The profiles for the other 4 ICESat tracks are **(C)** GLA06_0167, **(D)** GLA06_0286, **(E)** GLA06_0382 and **(F)** GLA06_0405. See Fig. 5 for the ICESat track locations and Table 1 for results.

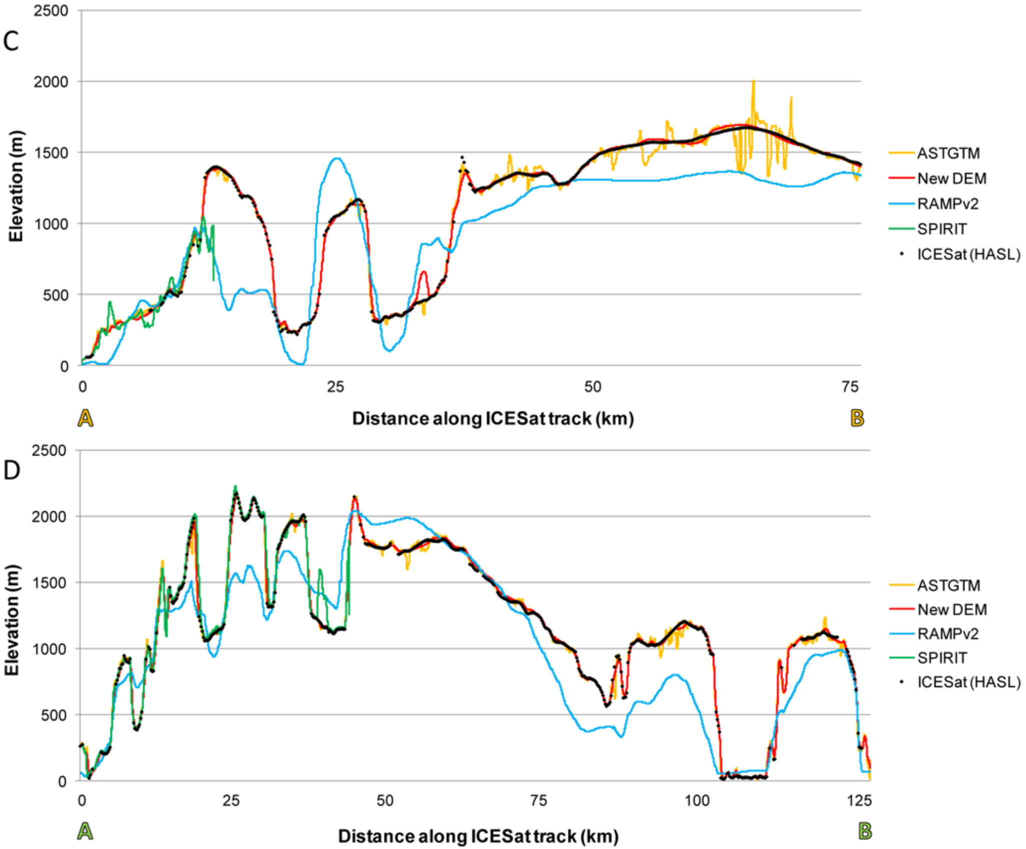

Fig. 6. Continued.

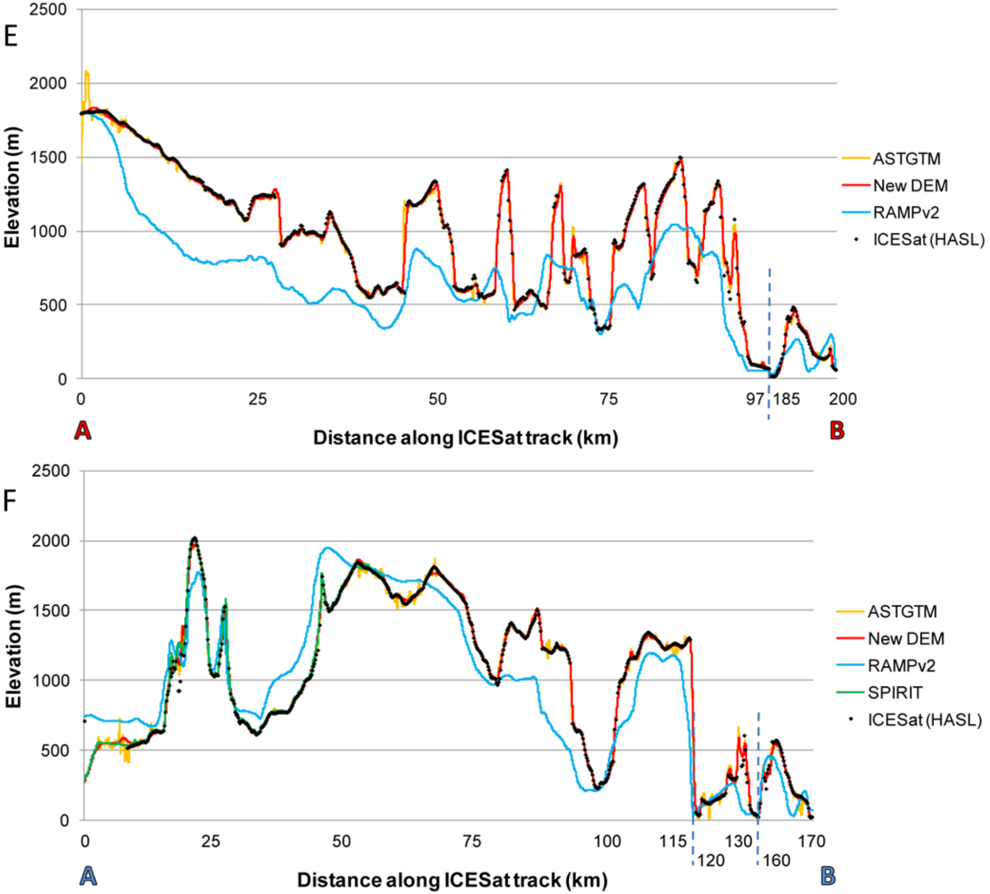

Fig. 6. Continued.

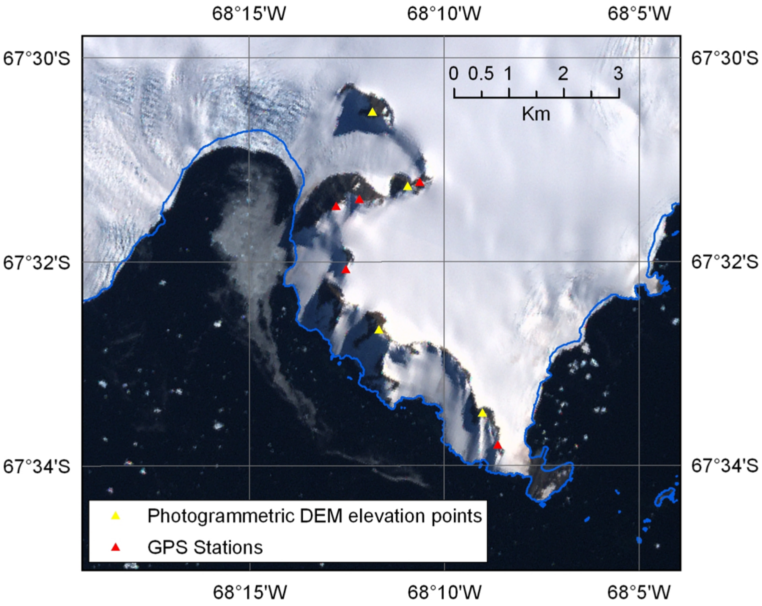

Fig. 7. Ryder Bay on Adelaide Island (67.5° S, 68.2° W) sample region, displaying the location of GPS points and elevations derived from the high-accuracy photogrammetric DEM.

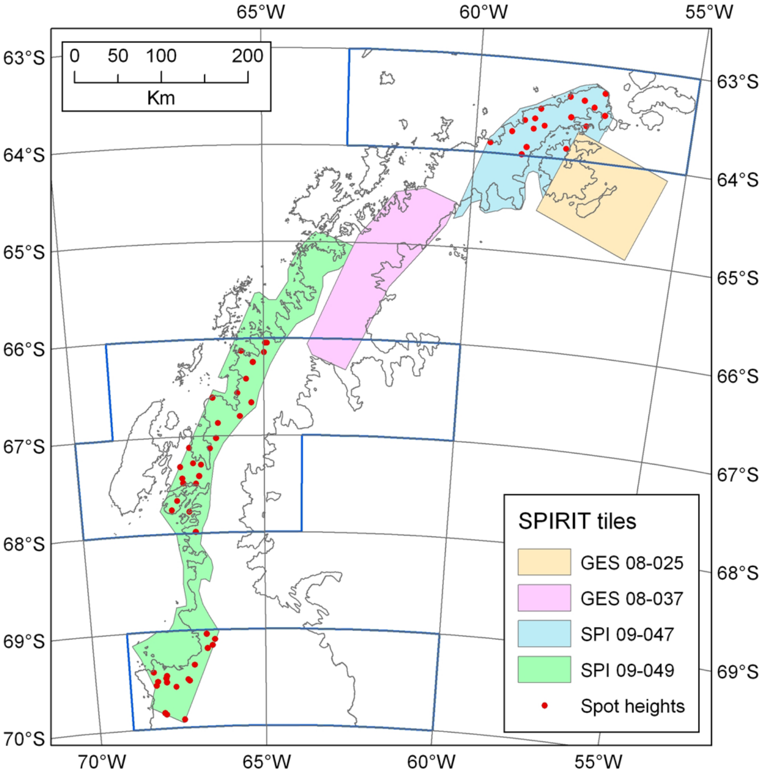

Fig. 8. SPIRIT tile limits and the location of spot heights chosen for consistency and relative error tests.