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Report **March 2012**

RICS RESEARCH

Improving the Accuracy of ASTER Elevation Data for Glacial Change Assessment in Antarctica

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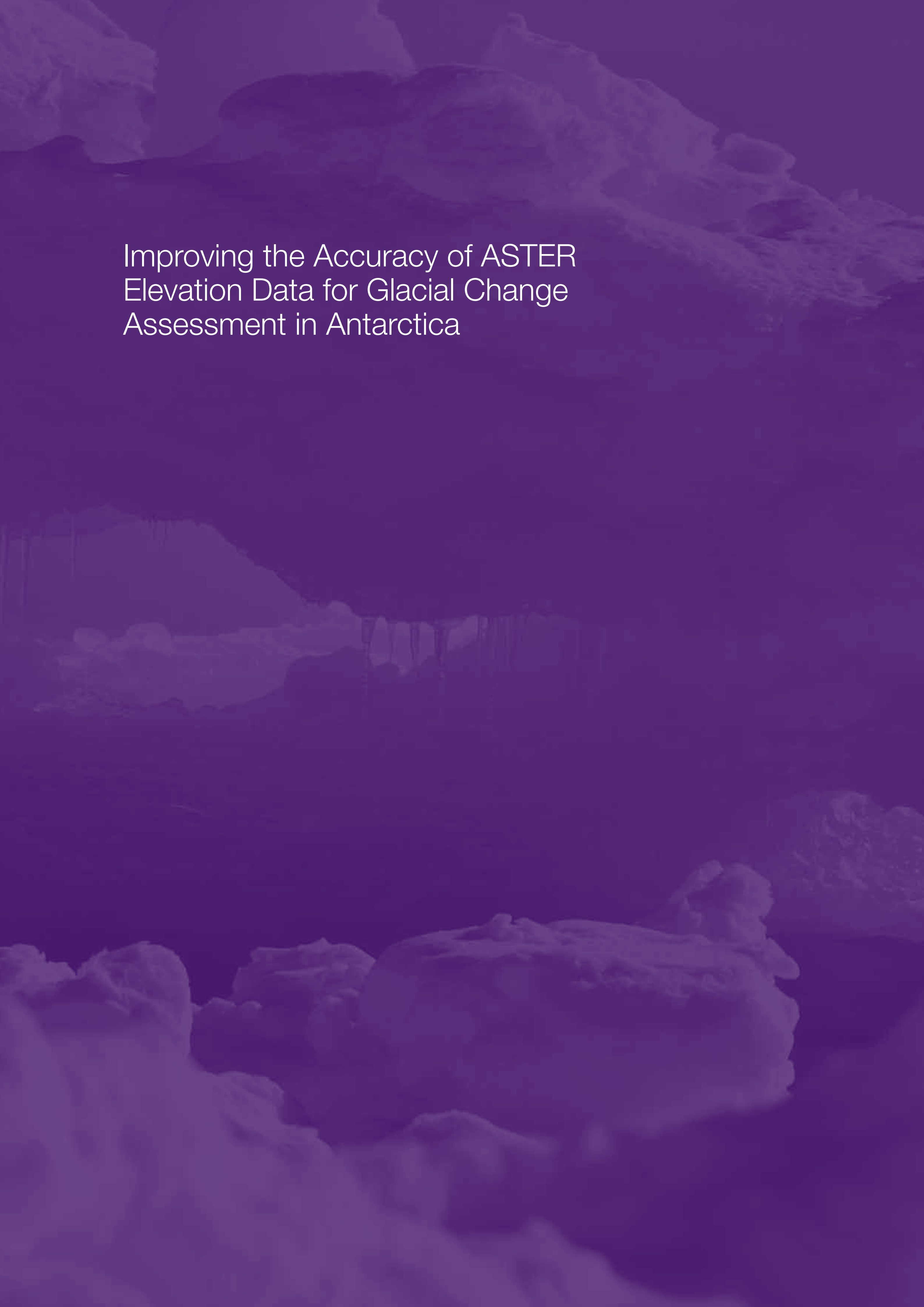
Improving the Accuracy of ASTER Elevation Data for Glacial Change Assessment in Antarctica



Report for Royal Institution of Chartered Surveyors

RICS the mark of property professionalism worldwide

A report for Royal Institution of Chartered Surveyors commissioned by London Regional Board of RICS.

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Contents

Introduction

In order to improve understanding of processes such as sea level rise and climate change, there is a requirement for enhanced assessment of historical and present-day glacial change in sensitive polar regions such as the Antarctic Peninsula. Vulnerable coastal societies such as the UK require better, more reliable estimates of sea level rise, and such information is essential in shaping government policy and mitigating impacts upon existing infrastructure. However, accurate assessment of glacial change in the remote and hazardous Antarctic Peninsula is not straightforward. A range of existing approaches for measuring elevation change exist. These include aerial photography, satellite laser altimetry (e.g. ICESat), and radar-based approaches (e.g. ERS-1/2). However, for a variety of reasons, nearly all suffer from drawbacks. Satellite-based stereo imaging offers perhaps the strongest solution, allowing the production of a digital elevation model (DEM) – a continuous surface which models elevation changes in a three-dimensional manner. Currently, DEMs derived from NASA's Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) senor offer greatest potential, with good coverage of polar regions and a spatial resolution of 30 metres. However, the potential of ASTER is limited by its relatively weak accuracy, with elevation measurements correct to only around 10-20 metres, and deteriorating further over steep terrain. Although this can be improved through the use of ground control points, which are acquired through field survey, such an approach is not possible in inaccessible and hostile polar environments. This research investigates an automated mathematical approach which instead performs statistical minimisation of a poorly-controlled DEM surface with respect to a DEM of higher accuracy. This approach, known as 'surface matching' offers significant potential for improving the accuracy of ASTER data and facilitating the wider application of the technique in order to quantify glacial change in a systematic manner across the Antarctic Peninsula.

Implementation

Through collaboration with the British Antarctic Survey (BAS) the research was applied to a test site located on the western Antarctic Peninsula at Pourquoi Pas Island. This encompassed a glacier system, extending over an area of 86 km^2, and providing a variety of terrain types over which to investigate the approach. In addition to an ASTER DEM, a high-accuracy DEM, derived from aerial photography captured at the same time as the ASTER data, was available for the site. This provided a strong basis for the validation exercise, as any systematic offsets between the datasets will be due to registration deficiencies rather than terrain change.

Three main aspects were evaluated through the project, and can be summarised as follows:

1. Assessment of ASTER DEM quality, specifically investigating elevation bias;
2. Development of an optimal surface matching strategy, adopting an experimental approach;
3. Evaluation of ASTER DEM quality in relation to terrain type.

Through the first stage of the project, the existing surface matching software was further developed to offer an enhanced capacity for eliminating any elevation-dependent errors in the ASTER DEM, a phenomenon which has been observed through other studies. The software was then applied to the research datasets, with the goal being to align the ASTER DEM to the photogrammetric DEM, thereby eliminating any systematic offsets between the DEMs. A number of different configurations were established, investigating matching of the entire DEM surface and also focussing on smaller individual regions. After establishing an optimal approach, the final phase of the project involved assessing the accuracy of the ASTER DEM in the context of different terrain types, including flat glacier surfaces, steep, rocky mountain slopes and icefalls (frozen waterfalls). This was expected to deliver valuable information on the reliability of the matching approach under different terrain types, allowing uncertainty estimates to be attached to glacial change measurements derived more widely across the Antarctic Peninsula.

Results

The results of the project clearly demonstrated that surface matching is able to enhance the accuracy of ASTER elevation data, achieving accuracies with a similar level of magnitude as could be expected through the use of ground control. Over relatively flat glacier surfaces, the technique was able to improve the agreement between the surfaces to within an average value of 2 m. Overall, the results revealed a significant improvement in the alignment of the ASTER DEM, providing strong evidence in support of the broader application of the technique across the Antarctic Peninsula. Investigation of various matching configurations suggests that an approach based on the sampling of multiple small patches within the DEM can provide an optimal solution. Furthermore, it is crucial that an optimal scale of application is established for the matching approach. Results suggest that this is best restricted over individual glacier extents, and that application over wider areas may see a drop-off in overall accuracy, as the solution becomes too generalised.

Outcomes and Conclusions

The primary outcomes of this research are summarised as follows:

- surface matching offers a valid technique for significantly improving the elevation accuracy of ASTER elevation accuracy;
- the research provides a basis for extending the application of this technique across the Antarctic Peninsula, and is expected to lead to enhanced estimates of glacier change and mass balance;
- the outcomes presented here are of broader relevance in the context of ASTER DEM data, and offer potential for improving the value of this dataset globally;
- surface matching is a generic, low-cost registration tool, of direct relevance to UK Geomatics practitioners for a diversity of applications;

The approach developed here is currently being applied more widely through an associated PhD project which is quantifying change at glacier sites across the Antarctic Peninsula. This neglects the need for a high-accuracy control surface, and instead registers historical United States Geological Survey (USGS) imagery to ASTER DEMs in a relative sense, removing systematic errors. Downstream benefits of this research will lead to enhanced estimates of sea level change, with direct implications for informing RICS best practice guidelines and UK government policy.

1.0 Introduction

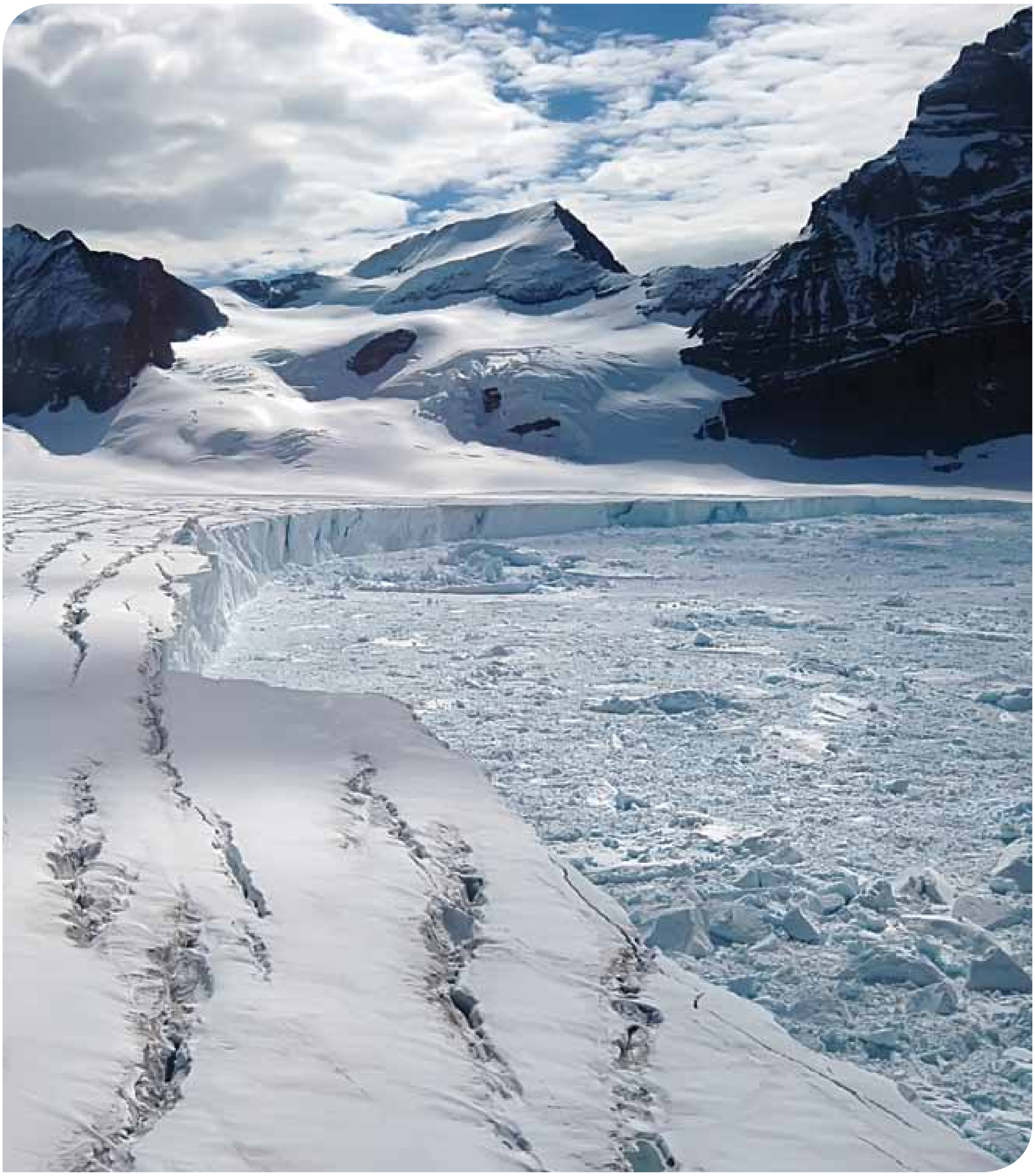
Improved quantification of glacial change is urgently required in order to better assess processes such as sea level rise, and associated impacts upon vulnerable coastal societies, such as the UK. An important contributor is the Antarctic Peninsula, which is reported to be one of the fastest-warming regions on Earth, exhibiting dramatic glacial retreat over the latter half of the 20th Century (Rignot and Thomas, 2002). Of 244 glaciers in the Antarctic Peninsula, more than 85 % have shown retreat over this period (Cook et al., 2005). This region is characterised by mountain glaciers, which globally are believed to have been the dominant glacial contributor to rising sea levels in the 20th Century (IPCC, 2007), and which are expected to contribute a further 0.124 ± 0.037 m of equivalent sea level by 2100 (Radić and Hock, 2011). However, these rapid changes and the recent mass balance history of glaciers in this region are a result of processes which remain poorly understood. Thus, any forward predictions (e.g.Radić and Hock, 2011) must be regarded as somewhat uncertain.

In order to address such uncertainties, there is a requirement for robust, spatially comprehensive quantification of both historical and present-day change. By assessing past trends in glacier dynamics over a number of decades, it is possible to derive predictions of future changes and impacts upon sea level. However, in high latitude regions such as the Antarctic Peninsula, reliable measurements are difficult to achieve. Ground based surveys are impractical due to the challenging terrain and difficulties in access, whilst airborne surveys (e.g. photogrammetry) are restricted by the short polar flying seasons. In reality, spaceborne techniques offer the only effective means of capturing change across broad extents. However, whilst satellite laser altimetry (e.g. ICESat) has enabled wide-scale, accurate sampling over the Antarctic and Greenland ice sheets, the large ground footprint (~70 m) is unsuitable for more mountainous terrain (Howat et al., 2008). Likewise, InSAR digital elevation models (DEMs), such as those derived from ERS 1/2, are of restricted value due to loss of coherence over ice and snow (Cziferszky et al., 2010).

A possible alternative can be found in satellite-based stereo imaging. However, photogrammetric approaches to DEM extraction can encounter difficulties in areas of very homogeneous terrain (e.g. ice, snow) where the lack of image texture can cause the image correlation process to fail. Whilst this is particularly problematic over the expansive, featureless ice sheets of interior Antarctica, areas such as the Antarctic Peninsula offer greater contrast and variation, increasing the potential for application of this technique. DEMs derived from the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) currently offer the most readily available source of this type of elevation data, with a resolution of 30 m and coverage to latitudes 82° N/S. However, the undoubted potential of ASTER cannot be completely realised. Off-the-shelf ASTER DEMs are specified accurate to within ± 25 m $RMSE_{XYZ}$ (LP DAAC, 2010). Yet, for mountainous high latitudes, this may deteriorate to as much as ± 35 m (Miller et al., 2009). Although accuracy can be improved by incorporating ground control points (GCPs), in hostile, polar environments this is not practicable. This restricts the value of ASTER DEMs, introducing unacceptable uncertainties into multi-temporal change analysis. In order to address this shortcoming, the research carried out here will demonstrate an efficient solution which significantly improves the accuracy of ASTER DEM data in high latitude environments through an automated surface matching technique.

Surface matching overcomes the requirement for GCPs and instead utilises a control surface (DEM) in order to register the ASTER DEM. This is achieved through statistical minimisation of offsets between the control DEM and the matching DEM. Surface matching has been applied to applications across a range of scales, but is particularly well suited to change detection studies (Mills et al., 2005). Previous Newcastle-based research has applied this technique to studies including coastal geohazard assessment (Miller et al., 2008), and initial investigations into glacial dynamics (Miller et al., 2009). This latter study confirmed the viability of the technique for analysis of glacial change. However, it was not possible to rigorously assess performance, due to a lack of validation data. The research carried out here will build from this, and through collaboration with the British Antarctic Survey (BAS), will exploit a unique validation dataset in order to fully assess the potential of this approach for accurate quantification of glacial change in the Antarctic Peninsula. This will contribute to ongoing PhD research, which is being undertaken by Mr Matthias Kunz, a co-investigator on this project. The PhD is addressing the wider implementation of the matching technique in order to facilitate unprecedented, extended time series analysis of glacial change at sites across the Antarctic Peninsula.

2.0 Aims and Objectives



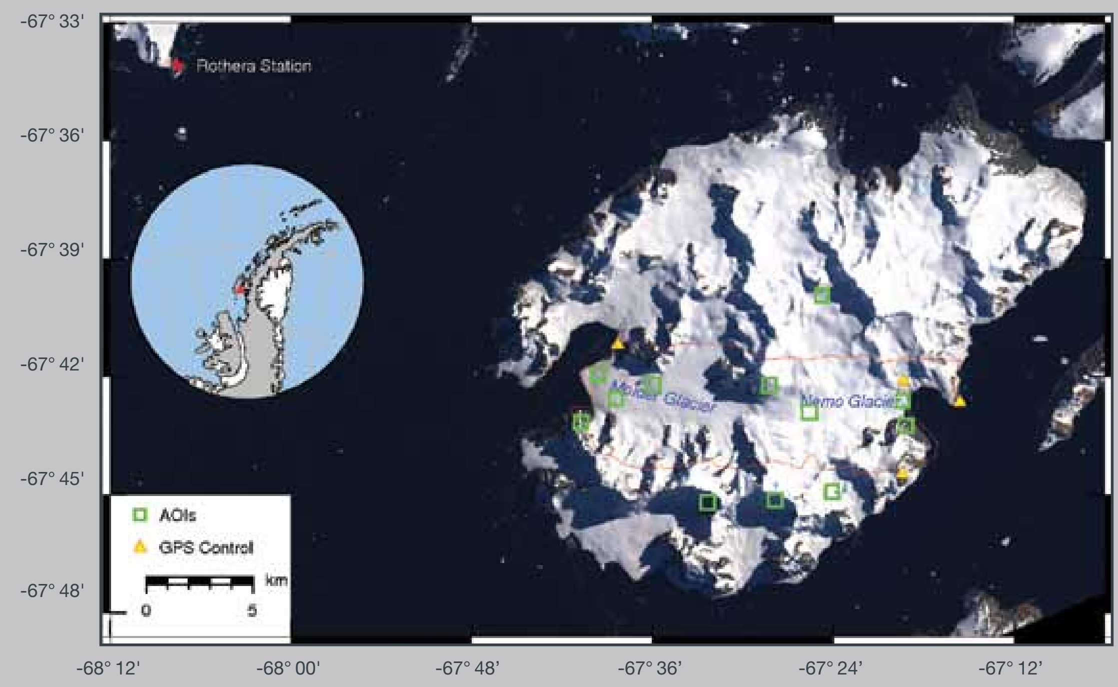
The aim of this research was to develop an approach for enhancing the positional accuracy of elevation data derived from the ASTER satellite sensor, thereby enabling enhanced quantification of glacial change in the Antarctic Peninsula. Ultimately, this will facilitate extended investigation of historical glacial change across the region, enabling assessment of mass balance change and contribution to future sea level fluctuations. The following objectives were proposed in order to address this:

1. extend the existing matching algorithm for optimal application to ASTER data;
2. identify an optimal approach for future application, by exploring a number of registration strategies and validating results through comparison to control data;
3. assess results in the context of terrain characteristics, quantifying performance prior to broader application of the technique across the Antarctic Peninsula.

3.0 Test Site and Datasets

The research was applied to a test site located on Pourquoi Pas Island, which lies on the western Antarctic Peninsula at 67° 40' S, 67° 30' W (Figure 1). Pourquoi Pas Island is composed of glaciated, mountainous terrain, characteristic of that found more widely across the Antarctic Peninsula. The test site straddles two glaciers. Moider glacier flows in a westerly direction, whilst Nemo glacier flows to the east. Figure 1 also indicates the close proximity of the test site to the BAS research station at Rothera.

Figure 1 **Pourquoi Pas Island overview map, with inset highlighting location within Antarctic Peninsula**



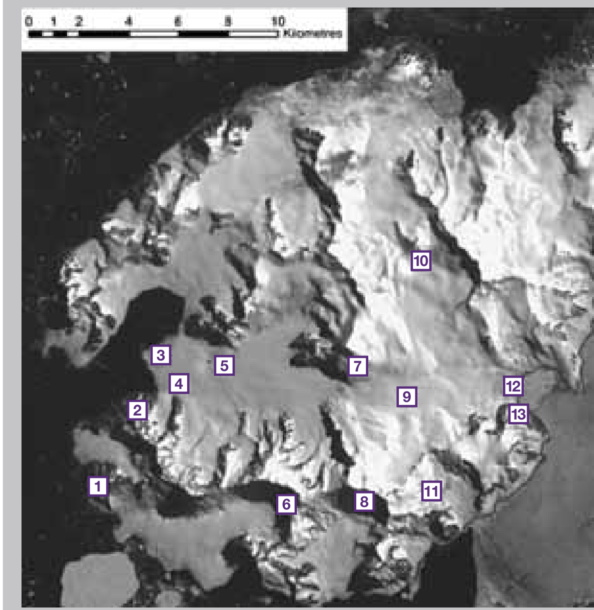
NASA's Terra satellite (launched in 1999 and formerly referred to as EOS AM-1) carries the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER). ASTER is an imaging sensor which provides information on land surface temperature, reflection and elevation. ASTER imagery and DEM data is utilised widely by the geoscience community for analysis of a diversity of earth surface processes including geology, glaciology, landslide assessment and soil science. ASTER is positioned in a near-polar, sun-synchronous orbit, with inclination of 98.2°, providing coverage between latitudes 82° N and 82° S. In comparison to other earth observation satellite sensors, ASTER offers particularly good coverage of the Earth's polar regions, and at relatively high spatial resolution. Through along-track nadir viewing (band 3N) and backward viewing (band 3B, 27.7° off-nadir) within the near-infrared (760 – 860 nm) portion of the spectrum, digital elevation models can be generated through standard photogrammetric techniques. Further details can be found on the LP DAAC website (LP DAAC, 2011).

In this research, the Level 1B data was downloaded from NASA's Land Processes Distributed Active Archive Center (LP DAAC) and processing was carried out using the *ENVI's* 'DEM Extraction Module' (ENVI, 2009). This utilises the stereo imagery in combination with an ASTER sensor model in order to extract a DEM. This is a relative product, which means that the DEM is generated using the satellite attitude and ephemeris data, without the use of ground control points. Findings reported in the literature indicate that an $RMSE_{XYZ}$ of 10 – 30 m can be expected for relative ASTER DEM products, although this is likely to deteriorate over particularly steep or rugged terrain (Eckert et al., 2005; Fujisada et al., 2005; Hirano et al., 2003; Toutin, 2008). The extracted DEM has a spatial resolution of 30 m and was produced from imagery acquired on the 30th December 2004.

An excellent validation dataset was available for the Pourquoi Pas Island test site through collaboration with BAS. Aerial photography was collected by BAS on the 20th January 2005, only three weeks after the ASTER acquisition, thus minimising any surface differences due to snow/ice melt/accumulation. The data was flown with GPS positioning of camera centres, thus eliminating the requirement for ground control points. The imagery offers a spatial resolution of 0.6 m and an absolute positional accuracy of better than 0.5 m_{XYZ}, as validated and reported by Fox and Cziferszky (2008). A DEM at a spatial resolution of 2 m was extracted for this project and refined through manual editing in *BAE Systems SocetSet v5.5.0* digital photogrammetric workstation. BAS also provided access to thirteen 500 m x 500 m areas of interest (AOI) which had been sub-sampled through manual measurement of the photogrammetric DEM. Figure 2 illustrates the distribution of these AOI across the test area.

Each AOI is individually homogeneous in terms of terrain type, but in combination the AOI offer a range of slope gradients, slope aspects and land-cover types, as indicated in Table 1. This will facilitate assessment of the registration solutions under a range of typical surface conditions. It should be noted that AOI 1 was not used in this research, as it was located outside the coverage of the ASTER and photogrammetric datasets. BAS also provided coordinates for four check points, with distribution as indicated in Figure 1. The check points were measured through GPS field survey and provide an independent source of validation for assessing the quality of the results.

Figure 2 Distribution of AOI across test site



2 AOI ID

Source: Cziferszky et al., 2010

Table 1 Pourquoi Pas Island AOI characteristics

Class	AOI ID	Terrain Type	Aspect	Height Range	Surface Texture
I	3	glacier tongue	west	low (49 m)	high
I	4	glacier	west	low (37 m)	high
I	5	glacier	west	low (92 m)	medium
I	9	glacier	east	low (31 m)	low
II	7	icefall	south	moderate (347 m)	high
II	10	glacier	south	moderate (137 m)	low
II	11	icefall	east	moderate (392 m)	high
II	12	glacier tongue	east	moderate (166 m)	high
III	1	rock/ice face (shadow)	west	high (606 m)	high
III	2	rock/ice face	north	high (617 m)	high
III	6	rock/ice face (shadow)	south	high (537 m)	high
III	8	rock/ice face (shadow)	south	high (732 m)	high
III	13	rock/ice face	north	high (652 m)	high

4.1 Surface Matching

As already discussed, ASTER DEM data is well-suited to quantifying and characterising change in polar environments. However, one significant drawback is the poor absolute positional accuracy of the data, which limits value in relation to multi-temporal change assessment. Previous work carried out by the authors performed preliminary analysis of the technique explored here for a similar, mountainous, glaciated environment in Svalbard, Norway (77° 59' N, 16° 20' E,) (Miller et al., 2009). Under these conditions, ASTER was found to be accurate to ± 35 m. Furthermore, previous investigation of the datasets under consideration here, indicates that the $RMSE_Z$ of the December 2004 ASTER DEM ranges from 5 – 160 m depending on the terrain type (Cziferszky et al., 2010). Clearly, errors of this magnitude will bias or obscure genuine terrain change which may exist between DEMs acquired at different periods in time (referred to here as multi-temporal DEMs). What is not clear from the work of Cziferszky et al. (2010), is whether any systematic offsets exist in the ASTER DEM. Some of the larger RMSE values will be due to gross errors, caused by difficulties in the DEM extraction process in areas of shadow or very steep terrain. However, the ASTER DEM may also contain systematic error, which must be removed before multi-temporal analysis can be undertaken. Conventionally, this is achieved through the use of ground control points (GCPs), which allow multiple DEMs to be accurately aligned to a common reference system, often a national or global coordinate system such as the UK National Grid (OSGB36) or WGS-84. This is normally achieved through field measurement (often by GNSS – i.e. GPS/GLONASS) of four or five distinct point features within the area of interest which can also be precisely identified within the DEM dataset (which in this case would be the corresponding ASTER imagery). For more accessible regions of the Earth, this approach would be applied in order to accurately register ASTER DEMs, thereby enabling their utilisation in monitoring or mapping studies. However, this is not feasible for polar environments due to the remote, inaccessible and inhospitable terrain.

Least squares surface matching is an automated registration technique which has been shown to offer a reliable alternative to the use of GCPs. The goal of surface matching is to recover the optimal transformation which registers a poorly-controlled floating surface (DEM), to a well-controlled fixed reference DEM (Miller et al., 2008). Essentially, this allows multiple overlapping DEMs to be transformed to a common coordinate system, removing any systematic errors between the datasets, and facilitating reliable change detection. The algorithm implemented in this research is based on a conformal coordinate transformation which enables conversion from one coordinate system to another by means of three translations (Tx, Ty, Tz), three rotations (ω, φ, κ) and a scale factor (s). This is a standard transformation in surveying and mapping, and corresponds to the approach which would be implemented if GCPs were utilised. The algorithm attempts to minimise the distance between each point on the matching surface (in this case the ASTER DEM) and a corresponding surface patch on the reference surface, where each point can be considered to provide control information (Mills et al., 2003). In standard least squares fashion, the differences are minimised globally across the matching surfaces, and the procedure iterates until convergence is achieved. A major advantage of the least squares matching technique is its inherent capacity for change detection; the final post-match least squares residual correspond to differences between the DEMs at individual point locations, which may arise due to terrain change over time.

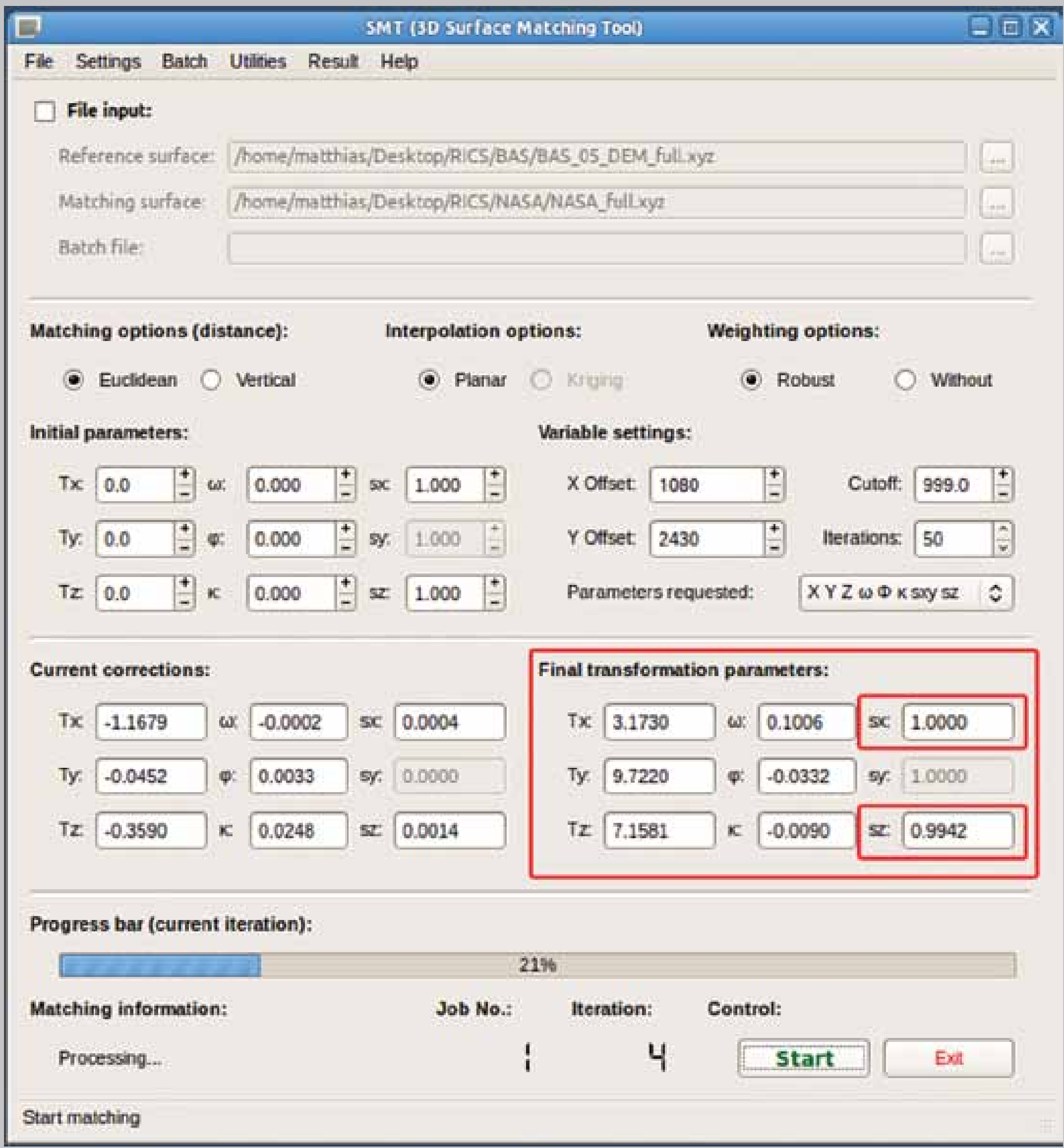
Whilst individual points may not offer the same confidence as a GCP measured by GNSS, the use of all points within the reference DEM provides significant redundancy, ensuring that a reliable solution is achieved. Furthermore, the algorithm has been refined in order to increase robustness to outlying observations. Typically, this may include gross error points (e.g. spikes in the DEM) or regions of terrain change in multi-temporal datasets. The introduction of local discrepancies between surfaces will influence the estimation of the transformation parameters, and where the effects are significant, conventional least squares approaches may fail to converge, or may converge to an erroneous solution (Li et al., 2001). In order to overcome this, a weighting function, based on a maximum-likelihood operator has been embedded in the software in order to down-weight points which display large residuals. This approach has been shown to deliver more accurate results than those achieved through the standard matching strategy, as detailed more fully in Miller et al. (2008). The robust capacity will be useful for this research, where it is likely that there will be unreliable regions within both DEMs, which may have arisen due to erroneous image correlation caused by poor surface contrast or shadow.

This background, and the results presented in Miller et al. (2009) indicate that surface matching is a technique which is well-suited to assessment of glacial change, provided a suitable reference surface exists. Although this latter aspect may not always be straightforward, in the context of glacial change assessment in the Antarctic Peninsula, assessment of mass balance change is of prime importance. Mass balance change is derived from volumetric change, which in turn can be determined through multi-temporal DEM analysis. In this respect, the absolute accuracy of the DEM surfaces is irrelevant, as volumetric differences remain the same irrespective of absolute positioning. What is of greatest relevance is the delivery of a good relative registration of the DEMs, ensuring they have been registered to the same coordinate system, and that any systematic errors between the surfaces have been removed. In this case, surface matching is highly suitable, and the associated PhD project being carried out by Kunz is directly investigating this aspect. Specifically, this is assessing change over extended time periods, stretching back to the 1960s, for around a dozen glaciers distributed across the Antarctic Peninsula. This project is utilising ASTER DEMs as control surfaces in order to align archival photogrammetric DEMs (derived from BAS and United States Geological Survey (USGS) imagery). The research performed in this RICS project will also therefore contribute to the PhD research by establishing an optimal matching approach, and assessing performance across different terrain types.

4.2 Assessing Elevation Bias

Nuth and Kääb (2011) highlight the potential for elevation-dependent biases to arise in ASTER DEMs. This is attributed to an inadequate ASTER sensor model, but could also arise where there is a sub-optimal distribution of GCPs, leading to incorrect scaling of the z-component during DEM extraction (Nuth and Kääb, 2011). If present, this type of error has the potential to introduce significant uncertainties into subsequent glacial change measurements. It is therefore desirable that the surface matching algorithm has a capacity to address this aspect. This will also offer increased flexibility for future use with a range of ASTER, photogrammetric and other DEM surfaces. Consequently, the first phase of the research focussed on implementing this capacity within the software, and assessing the Pourquoi Pas ASTER dataset to determine whether any such bias could be detected. Nuth and Kääb (2011) suggest that the bias may in some cases be non-linear, and can be approximated to a polynomial function. However, extensive analysis of multiple ASTER DEMs, carried out by Kunz as part of his PhD research, has returned inconclusive results. Although some indications of elevation-dependent offsets were encountered, these were found to approximate to a linear distribution, and furthermore, were likely not related to the sensor geometry or GCP distribution. This is because many of the DEMs which were investigated contained mountainous terrain, and DEM errors are known to increase over steep slopes. Any small planimetric offsets, or differences in the spatial resolution of overlapping DEMs, will be exacerbated over steep terrain. Therefore, for the DEM data examined by Kunz, it seems more likely that any elevation-related effects are due to this phenomenon rather than the type of sensor-dependent aspect reported by Nuth and Kääb (2011).

Figure 3 Surface matching interface, with scale parameters highlighted



However, in order to investigate this for the ASTER dataset under consideration here, the existing version of the matching software was applied in order to register the ASTER DEM to the BAS photogrammetric surface. This existing version implements a conformal transformation, applying a uniform scale factor. This means that even if the ASTER DEM is scaled to fit the reference DEM, the shape of the surface will be maintained, with equal scaling in the *x*, *y*, *z* components. The matching allowed the ASTER DEM to be fully evaluated in terms of the distribution of the residuals, investigating correlation with terrain elevation. In addition, the algorithm was modified in order to introduce a capacity for adjusting any elevation dependent bias found either in this dataset, or through future research.

This involved introducing separate scaling parameters in plan (*x*, *y*) and elevation (*z*). Through this approach, the transformation solution is extended from seven to eight parameters. The revised graphical user interface is illustrated in Figure 3, with the scale parameters highlighted within the transformation solution set. Note that the software was also configured to solve for all three scale parameters separately (if desired) and consequently in the representation in Figure 3, planimetric *x-y* scaling is actually indicated by '*sx*' whilst '*sz*' represents the *z* parameter.

4.3 Devising an optimal matching approach

The glaciers under consideration in this research extend over large portions of terrain, with the complete study area comprising 86 km^2. Least squares surface matching minimises DEM offsets in a global manner, providing the 'best fit' for the matching area as a whole. However, previous experience has shown that over large areas (e.g. tens of km^2), this may provide a sub-optimal solution at a more localised scale. Furthermore, some studies have explored the use of patch-based matching (e.g. Gruen and Akça, 2005) in order to introduce computational efficiency by matching on the basis of multiple well-distributed surface patches, as opposed to the DEM surface in its entirety. This approach may be valid in the context of this research, where the glacier systems extend over tens of km^2, and where extended areas may be unreliable due to poor correlation in the DEM generation process, as already discussed. The research will therefore focus on evaluating this aspect. Initially, matching will be performed on a very local scale, utilising the individual 500 m^2 AOI. This will then be extended to multi-patch matching, whereby multiple AOI are aggregated to form a single matching surface, before finally implementing the matching over the entire study area. This leads to a number of matching strategies, which are presented in Table 2, and explained in greater detail below.

Under **Strategy A**, the matching and reference surfaces are comprised of small regions (500 m x 500 m), covering the respective AOI only. The reference surface was configured to cover a slightly extended region in all directions, on the assumption that offsets already existed between the surfaces prior to matching, and hence the algorithm may require points which had initially fallen outside the ASTER AOI location.

Table 2 Surface matching strategies

Strategy	Reference DEM	Matching DEM
A1	BAS AOI 2	ASTER AOI 2
A2	BAS AOI 3	ASTER AOI 3
A3	BAS AOI 4	ASTER AOI 4
A4	BAS AOI 5	ASTER AOI 5
A5	BAS AOI 6	ASTER AOI 6
A6	BAS AOI 7	ASTER AOI 7
A7	BAS AOI 8	ASTER AOI 8
A8	BAS AOI 9	ASTER AOI 9
A9	BAS AOI 10	ASTER AOI 10
A10	BAS AOI 11	ASTER AOI 11
A11	BAS AOI 12	ASTER AOI 12
A12	BAS AOI 13	ASTER AOI 13
B1	BAS all points*	ASTER AOI {2,3,4,5}
B2	BAS all points*	ASTER AOI {7,9,12,13}
B3	BAS all points*	ASTER AOI {2,3,4,5,7,9,12,13}
C1	BAS all points*	ASTER all points

* overlapping points from BAS DEM with 10 m spatial resolution

Strategy B provides a step up from the local matching scale of strategy A and examines the patch-based matching approach. The AOI are distributed across the test site, as shown in Figure 2. It is evident that whilst some AOI are relatively isolated (e.g. 6, 10), others are clustered more closely. This provided an opportunity to explore the patch-based matching approach over a range of scales. Three separate multi-patch schemes were devised. B_1 and B_2 consider Moider (western) and Nemo (eastern) glaciers separately, with the matching surface composed of the points falling within the AOI {2, 3, 4, 5} for B_1, and {7, 9, 12, 13} for B_2. The algorithm considers the individual points which are input as the matching surface file, and therefore is unaffected by the fact that large gaps exist across the surface between these points. In contrast, the reference surface is triangulated to form a surface mesh, which is then used to evaluate the overlapping points from the matching surface. Consequently, for B_1 and B_2 the BAS photogrammetric DEM, clipped to the area surrounding the relevant AOI, was used as the reference surface. This was sampled to a spatial resolution of 10 m, as this is still significantly better than the 30 m ASTER points used in the matching surfaces, and will offer faster execution of the code. Previous testing has indicated that under this type of scenario (low resolution matching surface), there would be no significant advantage to applying the BAS DEM at the highest resolution of 2 m. Finally, match B_3 extended this approach over the entire glacier system, encompassing the AOI patches from B_1 and B_2. This should provide some indication of the sensitivity of this approach to the scale of the region under consideration.

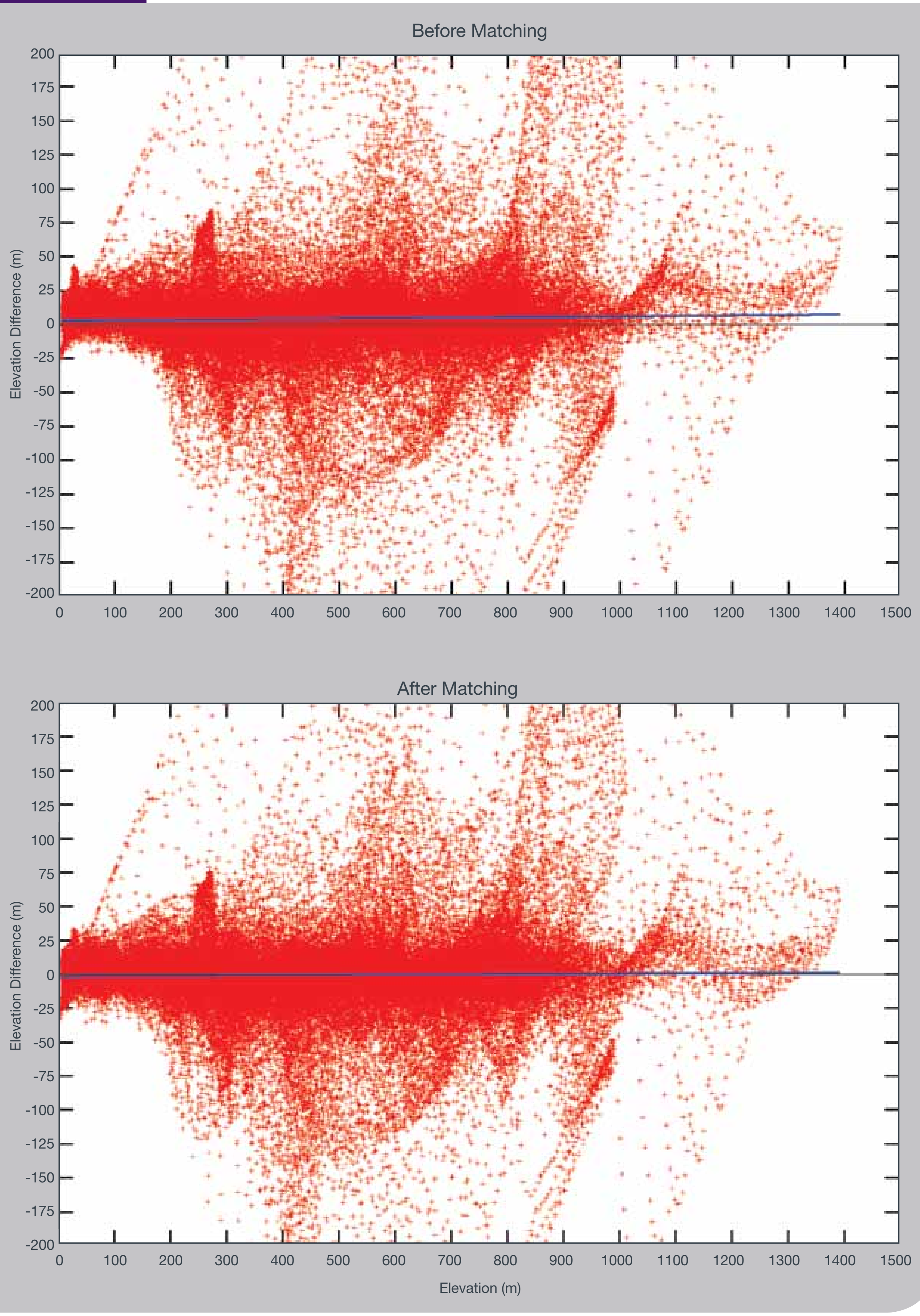
The final approach, **Strategy C**, explored matching performance under the more conventional scenario whereby the surfaces were matched in their entirety, across the entire region of interest. Again, the 10 m version of the BAS photogrammetric DEM was applied, in order to increase speed of execution.

In all of the above cases, the quality of the matching solution was assessed through inspection of the output matching statistics (number of iterations, final transformation parameters, etc). In addition, the vertical distances between the surfaces were calculated based on the matching residuals. This is the distance between the ASTER points and the intersecting surface patch (triangle) from the reference BAS DEM. This then enabled determination of the mean elevation offset and an $RMSE_Z$ value, where the photogrammetric elevations are taken as the 'correct' values. The two DEMs will contain differences due to random error and possible gross errors (e.g. spikes). In addition, differences will exist due to the disparate spatial resolution of the two datasets. As the DEMs are only separated by a period of three weeks, discrepancies due to terrain change should be minimal. Therefore it can be expected that differences in the results obtained from the three matching strategies will be principally due to the different approaches, with some manifestation of the DEM differences (random error, spikes, etc).

4.4 Evaluating Performance with Respect to Terrain Type

In order to facilitate broader application of the research approach through the associated PhD project, it is important to assess the quality of the results in the context of the different terrain classes as outlined in Table 1. This research validates the methodology in comparison to a well-controlled reference DEM, with additional assessment in comparison to check points. This should allow conclusions to be drawn with respect to the performance of the algorithm in an absolute sense. However, the post-match differences between the photogrammetric and ASTER surfaces should be similar even in circumstances where the reference surface is less well-controlled – i.e. in the case of the PhD research, where the ASTER DEM forms the reference surface for registration of archival aerial photogrammetric DEMs. Thus, evaluating the performance of the algorithm with respect to different terrain types as a part of this project should provide valuable information on the reliability of the approach, allowing uncertainties to be more accurately quantified with respect to broader application across the Antarctic Peninsula. This was achieved by assessing final post-match surface differences with respect to the different terrain categories.

Figure 4 **Elevation offsets before and after matching, with linear trend fit (blue line)**



5.1 Assessing Elevation Bias

An initial match was performed using the existing version of the software, in order to register the ASTER DEM to the BAS photogrammetric DEM. Following this, the vertical distances between the ASTER and reference DEM, before and after matching, were plotted on a point-by-point basis against terrain elevation (Figure 4, top). This reveals that a small systematic elevation offset appears to exist between the surfaces prior to matching. Although a small correlation with elevation does appear to exist, this is most likely due to the previously discussed deterioration in DEM quality over steep slopes, leading to increased errors in the ASTER DEM at high elevation. Following application of the matching algorithm, this offset has been successfully eliminated (Figure 4, bottom), indicating that for the ASTER DEM used in this project, application of a single scale parameter is sufficient. To confirm this, the updated version of the software was applied to the datasets, recovering separate scales for *x-y* and *z*. However, no significant deviation from unity was detected in plan or elevation, and on this basis, it was decided that the research should be implemented using a single scale factor.

5.2 Determining an Optimal Matching Strategy

The surface matching registration technique was implemented following the three strategies outlined in Table 2 and producing a total of sixteen sets of results. The results can be assessed on a strategy-by-strategy basis as follows.

5.2.1 Strategy A

The final transformation parameters and post-match statistics for strategy A are presented in Table 3 and Table 4. Solutions were obtained for A_2, A_4, A_{10}, A_{11} and A_{12}, whilst the other seven configurations failed to converge. Examination of the pre-match surface differences as shown in Table 4 indicates that the seven failures contained relatively large surface differences, as highlighted through the pre-match RMSE, minimum and maximum difference values. This would indicate that within these AOI, the ASTER DEM may be relatively weak, containing some error points. It is likely that across these specific AOI, the 500 m x 500 m extent is simply not large enough to contribute enough reliable points from which the matching could establish a solution. In the five cases where the matching converged, initial inspection suggests that good solutions have been achieved, as evidenced through significant improvements in the mean and RMSE surface differences. However, the scale factors of 0.8453 and 0.8872, recovered for A_4 and A_{10} respectively, show a significant and unlikely departure from unity. This suggests that whilst the post-match differences may indicate an acceptable result for these configurations, in fact, the algorithm has most likely converged to an erroneous solution. Based on these concerns and the fact that strategy A has failed for more than 50 % of cases, it can be concluded that the approach is not particularly successful, and is highly sensitive to the quality of the DEM within the localised AOI.

Table 3 Strategy A transformation solutions

Strategy	Transformation Solution							
	Iterations	T_X (m)	T_Y (m)	T_Z (m)	ω (°)	φ (°)	κ (°)	s
A_1	No convergence							
A_2	6	-6.05	-6.29	10.79	-0.0290	0.5576	0.4540	0.9588
A_3	No convergence							
A_4	34	-21.10	4.71	22.75	0.1130	-0.8787	-1.5755	0.8453
A_5	No convergence							
A_6	No convergence							
A_7	No convergence							
A_8	No convergence							
A_9	No convergence							
A_{10}	21	26.67	-41.75	43.32	0.9307	3.4265	-2.8959	0.8872
A_{11}	20	24.50	-12.80	1.95	-0.0779	-0.2831	-2.7664	0.9618
A_{12}	22	3.16	-6.95	45.86	1.3682	2.5681	4.2156	0.9167

Table 4 Strategy A matching statistics

Strategy	Pre-Match Differences (m)					Post-Match Differences (m)				
	Mean	σ	RMSE	Min.	Max.	Mean	σ	RMSE	Min.	Max.
A_1	33.68	79.45	86.26	-110.49	324.27					
A_2	9.18	5.23	10.56	-12.36	27.27	-0.05	4.69	4.69	-18.44	17.09
A_3	0.32	15.15	15.15	-67.26	52.53					
A_4	2.10	5.27	5.67	-22.51	21.04	-0.13	4.46	4.46	-31.24	15.19
A_5	-112.76	117.77	163.02	-426.65	91.55					
A_6	25.37	23.93	34.87	-97.48	81.24					
A_7	3.68	55.46	55.56	-193.78	137.30					
A_8	-4.55	38.21	38.46	-100.53	93.94					
A_9	9.69	41.05	42.16	-143.84	177.99					
A_{10}	29.55	19.97	35.66	-39.44	109.56	0.13	15.39	15.39	-190.15	65.05
A_{11}	4.70	6.42	7.95	-12.12	30.79	0.13	5.20	5.20	-19.96	22.05
A_{12}	9.95	18.61	21.10	-90.06	96.08	0.12	18.60	18.60	-87.45	95.04

5.2.2 Strategy B

The transformation solutions and difference results for strategy B are shown in Table 5 and Table 6. In this case, all three matches have successfully converged, and inspection of the transformation parameters suggests that acceptable solutions have been achieved. There is little notable difference between the results obtained through the more restricted patches of B_1 (western area) and B_2 (eastern area), and that obtained by combining all of these patches (B_3) to bridge the broader glacier system. Inspection of the matching differences confirms that significant improvements have been achieved over the pre-match alignment of the DEMs. For example, in the case of B_2, the mean elevation difference has been improved from + 8.87 m (pre-match) to -0.26 m (post-match), indicating that a significant systematic offset has been removed. Although the RMSE and σ values are still relatively high following the matching, this is likely due to the presence of outlier points. Under strategy A, the mean elevation offsets for the successful matches all fell under 0.15 m, whilst the RMSE was within 20 m. As can be seen from Table 6, the results of the patch-based matching approaches are poorer than this. This can be attributed to the fact that whilst the software finds the best global alignment for the matching patches, this will not necessarily provide the optimal registration for an individual patch (AOI). However, clearly strategy B is more reliable in terms of achieving successful convergence than strategy A.

Table 5 Strategy B transformation solutions

Strategy	Transformation Solution							
	Iterations	T_X (m)	T_Y (m)	T_Z (m)	ω (°)	φ (°)	κ (°)	s
B_1	11	27.10	-1.63	5.99	0.2066	0.1633	0.8946	0.9872
B_2	13	71.00	-29.25	1.83	0.0622	-0.0129	0.3519	0.9837
B_3	19	58.95	-13.84	2.52	0.4062	0.0257	0.0458	0.9979

Table 6 Strategy B matching statistics

Strategy	Pre-Match Differences (m)					Post-Match Differences (m)				
	Mean	σ	RMSE	Min.	Max.	Mean	σ	RMSE	Min.	Max.
B_1	11.37	38.63	40.27	-110.49	324.27	3.05	28.07	28.23	-142.65	224.41
B_2	8.87	28.28	29.64	-104.23	105.42	-0.26	24.14	24.14	-138.71	103.38
B_3	10.08	33.72	35.19	-110.49	324.27	1.31	26.75	26.79	-143.33	215.59

5.2.3 Strategy C

Under the final matching strategy, C, the entire ASTER DEM was matched to the 10 m BAS photogrammetric DEM, producing the results detailed in Table 7 and Table 8. This delivered a small improvement in the RMSE and standard deviation, but the mean elevation offset has slightly deteriorated overall. There are clearly large disparities between the surfaces in places, as evidenced previously under strategies A and B through the large minimum and maximum values. Under strategy C, which includes all surface points, the extremes of difference are in the order of 500-600 m both before and after matching.

Table 7 Strategy C transformation solution

Strategy	Transformation Solution							
	Iterations	T_X (m)	T_Y (m)	T_Z (m)	ω (°)	φ (°)	κ (°)	s
C_1	8	62.40	-22.93	2.36	0.0655	0.0068	-0.0488	1.0002

Table 8 Strategy C matching statistics

Strategy	Pre-Match Differences (m)					Post-Match Differences (m)				
	Mean	σ	RMSE	Min.	Max.	Mean	σ	RMSE	Min.	Max.
C_1	1.16	54.72	54.73	-594.22	472.60	-1.48	50.02	50.04	-579.56	467.96

In comparing the three matching strategies, it would seem that strategy A should be discarded, as the AOI are too limited in size to guarantee a successful match. Further exploration of strategies B and C is required before any final conclusions can be drawn. It is evident that the ASTER and photogrammetric surfaces contain significant disparities in places. Therefore in order to directly compare the results of the two strategies, the differences will be analysed only for the AOI. This will also enable analysis of differences in relation to surface type.

5.3.1 Patch-Based vs. Global Matching

The surface differences for strategies B and C were evaluated for individual AOI. In considering the results for Strategy B_1 (Table 9), it can be seen that whilst the post-match differences for AOI 3 and 5 show significant improvement, the results for AOI 2 and 4 are less dramatic. AOI 4 appears to exhibit a small deterioration in the mean offset, from + 1.45 m (pre-match) to 2.03 m (post-match). There is no clear explanation for this, as AOI 4 is falls within terrain class I, and is described as relatively flat, with good surface texture, indicating that the ASTER DEM should be reliable for this area. Inspection of Table 9 reveals particularly poor results for AOI 2. Although a distinct improvement in the registration solution has been achieved for AOI 2, the post-match differences remain several orders of magnitude greater than for the other AOI, with high post-match RMSE, and large extreme values, ranging from 142.65 m to + 224.41 m. AOI 2 falls within terrain class III and is described as a rock/ice face, with a large elevation range (617 m). This likely indicates that large disparities may exist between the ASTER and photogrammetric surfaces due to the effects of the steep slopes in exacerbating differences in the spatial resolutions of the DEMs. Such effects would not be so evident over the flatter glacier surfaces covered by AOI 3, 4 and 5.

Table 9 AOI difference statistics for Strategy B_1

AOI	Pre-Match Differences (m)					Post-Match Differences (m)				
	Mean	σ	RMSE	Min.	Max.	Mean	σ	RMSE	Min.	Max.
Combined	11.37	38.63	40.27	-110.49	324.27	3.05	28.07	28.23	-142.65	224.41
2	33.52	73.54	80.80	-110.49	324.27	15.24	53.33	55.45	-142.65	224.41
3	9.89	5.42	11.27	-12.36	29.79	-0.12	5.22	5.22	-22.05	16.58
4	1.45	14.73	14.80	-66.76	53.21	-2.03	14.61	14.75	-69.70	49.00
5	2.48	5.51	6.04	-35.17	22.70	-0.09	5.80	5.80	-33.33	22.30

It is likely that the effect of these discrepancies in AOI 2 has reduced the quality of the overall solution. In order to explore this assumption, strategy B_1 was repeated, but with AOI 2 omitted. The results are shown in Table 10. This reveals a stronger overall solution, with the mean post-match surface offset reduced from + 3.05 m (Table 9) to – 0.75 m. The post-match RMSE has been reduced from + 28.23 m to + 9.57 m through the removal of AOI 2. The results for the remaining AOI (3, 4, 5) based on this new solution are similar to those obtained initially, although there is a small overall deterioration. This is likely due to the fact that the matching is now based on fewer points, and hence may not offer the same redundancy.

Table 10 AOI results for strategy B_1 with AOI 2 removed

AOI	Pre-Match Differences (m)					Post-Match Differences (m)				
	Mean	σ	RMSE	Min.	Max.	Mean	σ	RMSE	Min.	Max.
Combined	4.62	10.24	11.23	-66.76	53.21	-0.75	9.54	9.57	-71.29	49.59
3	9.89	5.42	11.28	-12.36	29.79	0.04	5.29	5.29	-21.94	19.33
4	1.46	14.73	14.80	-66.76	53.21	-2.23	14.67	14.84	-71.29	49.59
5	2.48	5.51	6.04	-35.05	22.70	-0.10	5.60	5.60	-35.61	21.82

Similar analysis was also performed for strategy B_2, with results as shown in Table 11. In this case, all AOI show a clear improvement in the mean elevation offset after the matching, achieving similar magnitudes to those obtained through B_1. In the case of AOI 9, 12 and 13, the mean offset has been reduced to less than 0.20 m. AOI 7 does not quite attain this level of agreement, although there is still a significant improvement from the pre-match mean offset of + 23.28 m to – 1.20 m.

Table 11 AOI results for strategy B_2

AOI	Pre-Match Differences (m)					Post-Match Differences (m)				
	Mean	σ	RMSE	Min.	Max.	Mean	σ	RMSE	Min.	Max.
Combined	8.87	28.28	29.64	-104.23	105.42	-0.26	24.14	24.14	-138.71	103.38
7	23.28	26.81	35.50	-100.72	100.27	-1.20	18.55	18.59	-138.71	81.50
9	-3.34	38.18	38.32	-104.23	100.40	0.16	37.31	37.31	-98.20	103.38
12	6.29	7.84	10.06	-21.37	34.79	0.10	6.61	6.60	-23.40	27.28
13	10.60	22.07	24.48	-95.64	105.42	-0.11	21.17	21.17	-106.94	87.42

The results for strategy B_3 are detailed in Table 12. Again, AOI 2 exhibits particularly high offsets post-match, which lends further credence to the assumption that the ASTER DEM is particularly poor over this region. For the remaining AOI, the post-match mean offsets do not attain quite the same level of agreement as through strategy B_1 and B_2, but nevertheless, still display significant improvement in most cases, indicating that a successful registration solution has been achieved. In a small number of cases (AOI 4, 9) strategy B_3 results in a small deterioration in elevation offset. For AOI 4, this observation is consistent with the outcomes of B_1. It is likely that these results arise from the algorithm determining the best 'global' fit for the eight patches, which will return strong solutions for the majority, but potentially poorer solutions in a small number of cases.

Table 12 AOI results for strategy B_3

AOI	Pre-Match Differences (m)					Post-Match Differences (m)				
	Mean	σ	RMSE	Min.	Max.	Mean	σ	RMSE	Min.	Max.
Combined	10.08	33.72	35.19	-110.49	324.27	1.31	26.75	26.79	-143.33	215.59
2	33.53	73.54	80.80	-110.49	324.27	15.13	53.34	55.43	-143.33	215.59
3	9.89	5.42	11.28	-12.36	29.79	-0.95	5.81	5.89	-21.81	16.91
4	1.45	14.73	14.80	-66.76	53.21	-2.05	15.08	15.22	-70.90	49.02
5	2.47	5.51	6.04	-35.05	22.70	-1.06	5.44	5.54	-42.95	17.61
7	23.28	26.81	35.50	-100.86	100.27	4.47	20.44	20.92	-126.73	60.31
9	-3.34	38.18	38.32	-104.23	100.40	-3.72	38.21	38.39	-103.36	98.72
12	6.28	7.85	10.05	-21.37	33.29	-3.50	7.48	8.26	-26.28	31.08
13	10.58	22.06	24.46	-95.64	105.42	3.72	21.37	21.68	-105.45	88.83

In comparing the results of B_1/B_2 and B_3 – i.e. localised patch-based matching versus a more global patch-based matching, Table 9, Table 10, Table 11 and Table 12 reveal that for the individual AOI, a stronger solution is clearly achieved through the localised patch-based approach of B_1/B_2. Under B_1/B_2, it has been possible to reduce the mean offset to less than one metre for the majority of AOI.

The next step was to compare the individual patch-based results for strategy B to those returned through strategy C, where matching was performed across the entire DEM datasets. The results for the individual AOI for strategy C are shown in Table 13. The results appear to be rather variable, with some areas showing improvement (e.g. AOI 7, 10, 11 and 13), whilst others have significantly deteriorated (e.g. AOI 5, and 8). This is likely because instead of focussing only on the AOI, strategy C considers all points in the ASTER DEM and attempts to find the best overall fit to the photogrammetric DEM.

Table 13 AOI results for strategy C

AOI	Pre-Match Differences (m)					Post-Match Differences (m)				
	Mean	σ	RMSE	Min.	Max.	Mean	σ	RMSE	Min.	Max.
Comb.	1.16	54.72	54.73	-594.22	472.60	-1.48	50.02	50.04	-579.56	467.96
2	33.53	73.54	80.80	-110.49	324.27	16.34	54.76	57.13	-135.96	235.26
3	9.89	5.42	11.28	-12.36	29.79	8.94	5.78	10.64	-11.10	27.83
4	1.45	14.73	14.80	-66.76	53.21	1.02	14.99	15.02	-67.05	53.33
5	2.47	5.51	6.04	-35.05	22.70	5.14	5.67	7.65	-38.10	23.61
6	-152.94	120.53	194.66	-94.15	424.63	-92.76	91.62	130.32	-87.09	338.37
7	23.28	26.81	35.50	-100.86	100.27	6.57	20.29	21.32	-127.14	66.81
8	-6.21	59.47	59.71	-129.21	201.44	-43.89	58.55	73.11	-90.19	201.81
9	-3.34	38.18	38.32	-104.23	100.40	-8.03	38.05	38.88	-107.65	96.58
10	15.75	34.02	37.44	-135.41	140.50	-4.74	33.96	34.24	-131.68	167.57
11	29.84	18.94	35.32	-108.41	18.93	-0.27	16.34	16.32	-57.75	50.23
12	6.28	7.85	10.05	-21.37	33.29	-8.12	8.28	11.59	-32.91	27.36
13	10.58	22.06	24.46	-95.64	105.42	1.38	22.24	22.27	-105.49	89.88

The results presented in this section allow some conclusions to be drawn regarding optimal matching approach and scale. It would seem that patch-based matching over restricted extents offers a good solution for the AOI. In the case of the Pourquoi Pas Island study site, strategy B_1 covered part of the western glacier (Moider), whilst B_2 encompassed the eastern-flowing glacier (Nemo). This would suggest that matching could be successfully applied on a glacier-by-glacier basis in order to obtain the optimal solution for a specific region of interest. Further, the associated PhD project has highlighted the difficulties in extracting a continuous DEM from archival aerial photography, due to poor image texture across glaciated terrain, and difficulties caused by shadows in mountain regions. The patch-based matching approach is well-suited to this scenario, as there are only limited regions of the DEM which can be considered stable (unchanged over time) and reliable in terms of DEM quality.

Table 14 Check point analysis for strategy B_3

Check Point	GPS Height (m)	Elevation Offsets (m)			
		Pre-Match	Δ Pre-Match	Post-Match	Δ Post-Match
Nemo Cove 1	597.08	499.00	-98.08	534.40	-62.68
Nemo Cove 2	252.80	226.00	-26.80	235.00	-17.80
Nemo Cove 3	45.15	25.00	-20.15	26.10	-19.05
Dalgleish Bay	24.62	13.00	-11.62	30.90	6.28

5.3.2 Validating the matching results

By assessing the individual AOI results, it was also possible to investigate the results in relation to terrain type. As strategy B delivered the strongest performance for the AOI, this approach has been used to investigate whether there is any correlation with terrain class. Although B_1 and B_2 delivered the best results, these matches do not encompass all the AOI. Therefore the results from B_3 were used to assess this aspect. As a preliminary step, and in order to ensure the reliability of the solution produced through B_3, the absolute accuracy of the results were assessed by applying this transformation solution to the entire ASTER DEM and then comparing this surface to the GPS check points. The results of this analysis are presented in Table 14, where they are also compared to the original (pre-match) position of the ASTER DEM. With the exception of the first check point (Nemo Cove 1), the pre-match results generally agree with NASA design specifications for the relative ASTER DEM product, which indicate an off-the-shelf $RMSE_{XYZ}$ of within ± 25 m (LP DAAC, 2010). However, following matching, the overall elevation accuracy of the ASTER DEM has been further improved. With the exception of the first point (Nemo Cove 1), the remaining points all offer post-match accuracies of less than a pixel (30 m), and generally show improvement in comparison to the pre-match offsets. Nemo Cove 1 is located at a relatively high altitude (597 m) in comparison to the other check points. This implies that it may be located in the vicinity of steeper, more mountainous terrain, and therefore the quality of the ASTER DEM may be poorer in this locale.

These results are extended through visual analysis, as presented in Figure 5, where pre- and post-match (B_3) elevation differences are plotted graphically across the central part of the study area, encompassing the main region of interest (including the glaciers). The most obvious features in both plots are the large elevation differences over the mountains which fringe the north and south of the glacier systems. This is to be expected, and has already been explained in relation to correlation with increased DEM error. However, following the matching, some other differences can also be noted. Prior to matching, notable green regions (positive elevation difference) exist, predominantly around the eastern part of the study area (Nemo glacier), but also around the front of Moider glacier in the west, where it meets the ocean. As the surfaces were captured only three weeks apart, this type of offset makes little sense, and is likely a systematic error in the alignment of the ASTER DEM. This would agree with the trend indicated in Figure 4 (top), which reveals a small positive pre-match systematic error in elevation. Following the matching procedure, there are fewer green areas across the central region, which encompasses the glaciers. However, the areas of positive change now appear more concentrated along the southern part of the study area. The reason for this is not clear, although it may be that strategy B_3 offers a sub-optimal solution in this area, as the utilised AOI patches were all more centrally located within the glaciers. The pattern of differences across the glacier surfaces is now more random and closer to zero (represented by yellow in the plot). There are notable areas of negative change (red) located between AOI 3 and 5, near the front of Moider glacier. An explanation for this is not immediately obvious, but one possible cause may be that this region corresponds to weak areas in the ASTER DEM where image matching has failed due to lack of image texture across the featureless ice surface. Overall however, Figure 5 demonstrates an improvement in the registration of the ASTER DEM following matching strategy B_3, and provides an indication of how the technique can be extended in order to quantify glacier change over time.

5.3.3 Investigating correlation with terrain type

The ASTER DEM transformed under strategy B_3 was used to investigate whether any correlation existed between DEM quality and terrain type. Analysis of this aspect by BAS, using the same datasets and AOI, has indicated a deterioration, particularly under class III terrain, although differences between class I and II appear to be less clear cut (Cziferszky et al., 2010). However, the study performed by BAS utilised the original datasets in their pre-match alignment. Hence it is possible that this interpretation of DEM quality in relation to terrain type may be clouded by the presence of unresolved systematic error. It is expected that the results presented here, following matching, will allow more robust conclusions to be drawn with respect to the influence of terrain. The AOI, which this time included all AOI, are organised under terrain class and presented in Table 15, detailing the surface differences following application of strategy B_3. The results show a strong correlation between terrain type and mean surface offset. AOI 3, 4, 5 and 9, which fall within class I, generally display the best agreement. The offsets deteriorate in class II, and are slightly poorer again in class II. Although there are exceptions to this (e.g. AOI 13), there is a clear trend in relation to terrain type.

Figure 5 Elevation differences before matching (top) and after matching through strategy B_3 (bottom)

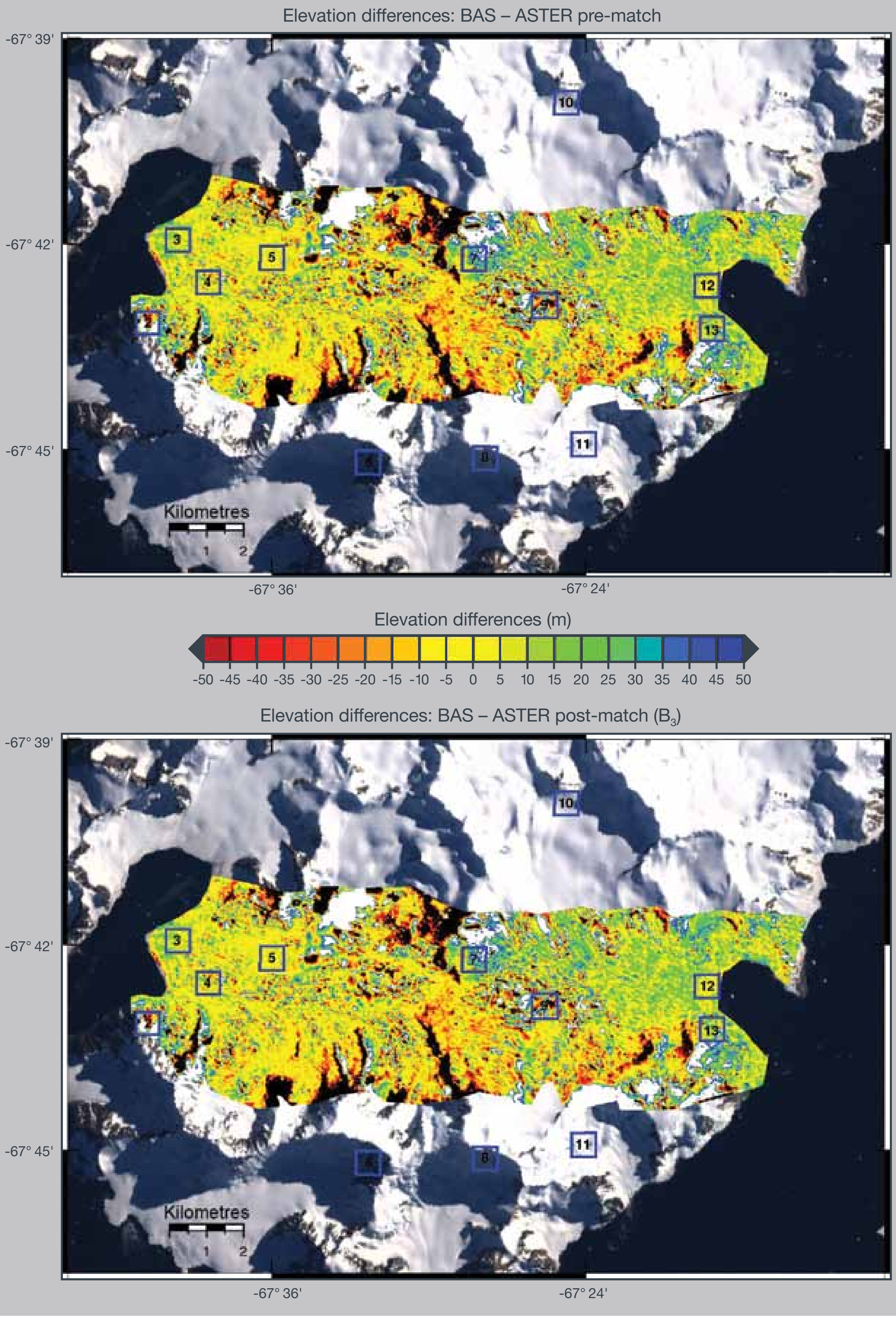
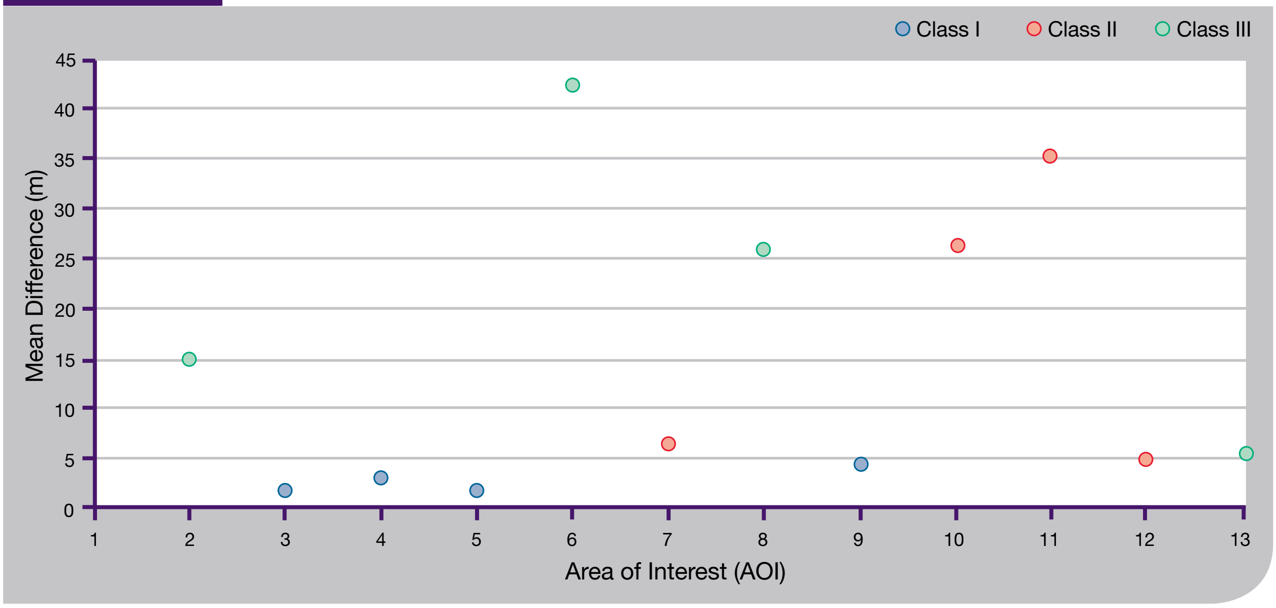


Table 15 **AOI offsets by terrain class**

Terrain Class	AOI	Pre-Match Differences (m)				
		Mean	σ	RMSE	Min.	Max.
I	3	-0.95	5.81	5.89	-21.81	16.91
I	4	-2.05	15.08	15.22	-70.90	49.02
I	5	-1.06	5.44	5.54	-42.95	17.61
I	9	-3.72	38.21	38.39	-103.36	98.72
II	7	4.47	20.44	20.92	-126.73	60.31
II	10	26.86	34.18	43.44	-131.58	183.49
II	11	-34.07	17.27	38.19	-98.60	16.01
II	12	-3.50	7.48	8.26	-26.28	31.08
III	2	15.13	53.34	55.43	-143.33	215.59
III	6	41.51	90.21	99.23	-132.50	317.14
III	8	-26.77	64.90	70.12	-144.25	136.76
III	13	3.72	21.37	21.68	-105.45	88.83

The results are also displayed graphically for the three terrain classes in Figure 6. This clearly indicates the strong agreement within class I and the progressive deterioration of mean offset under class II and then class III terrain types. These results agree logically with the terrain types found within the three classes. Class I relates to relatively flat glacier surfaces, with low elevation change across the AOI. Within class I, AOI 9 is recorded as offering low surface texture (Table 1), and this may explain the slightly poorer result for this AOI. Class I terrain would be expected to return the strongest results, and provides a valuable indication of the reliability of the matching technique, which can be carried forward in the associated PhD work in order to gain a better understanding of uncertainties associated with the measurements.

Figure 6 Mean elevation difference for the AOI, organised under terrain class



Class II generally encompasses slightly steeper terrain, with moderate elevation range across the AOI (Table 1). This type of steeper terrain will exacerbate any minor offsets between the surfaces, and this is likely to explain the generally poorer results. Figure 6 and Table 16 highlight that poorest results are returned for class III overall, although within this class AOI 13 can be considered an exception. Class III terrain covers the AOI with the greatest elevation range (up to 723 m). Additionally, these AOI also include rock faces and shadow areas, which are likely to result in weak correlation through the DEM extraction process, possibly resulting in gross errors within the ASTER DEM.

This analysis provides valuable insight into the correlation between terrain type and DEM quality. Furthermore, the results allow performance to be assessed specifically for those AOI covering only glacier surfaces, and therefore not influenced by the detrimental effects of the steeper, mountainous terrain. The individual AOI results can be summarised by terrain class, as detailed in Table 16 where the mean absolute values over the four AOI per class are reported. This clearly reveals the progressive deterioration in the ASTER-photogrammetric DEM agreement as the terrain becomes increasingly rugged, and the quality of the ASTER DEM likely decreases.

Table 16 Mean differences by terrain class

Terrain Class	DEM Differences (m)		
	Mean	σ	RMSE
I	1.94	16.14	16.26
II	17.23	19.84	27.70
III	21.78	57.46	61.62

6.0 Research Outcomes

The primary outcome of the research has been the identification of an optimal registration approach for assessment of glacial change in the Antarctic Peninsula. The following can be highlighted as the main findings:

1. Least squares surface matching has been shown to provide a cost-effective registration solution and a reliable alternative to the use of GCPs;
2. A patch-based matching approach, limited to individual glacier scale, was found to offer the strongest solution;
3. The ASTER DEM is likely to be less reliable over steep terrain and shadow regions;
4. The matching approach can be expected to offer a mean relative agreement between DEMs of around 2 m over glacier surfaces.

In elaborating on these findings, the research has shown that the surface matching approach is capable of eliminating systematic error associated with the ASTER DEM. Over the glacier AOI, the localised patch-based matching approach consistently aligned the ASTER surface to within a mean value of ± 0.20 m of the BAS photogrammetric DEM. However, in carrying this finding forward, it must be borne in mind that this agreement will be sensitive to the spatial resolution of the DEMs under consideration. Figure 4 and Figure 5 effectively illustrate the overall improvement in the alignment of the ASTER DEM following the application of the matching technique. Overall, this evidence confirms the value of surface matching for registration of satellite-derived DEMs, facilitating subsequent assessment of multi-temporal glacier change, including mass balance fluctuations.

This research has established surface matching as a reliable mechanism for registration of multi-temporal DEMs, and has demonstrated this in the context of ASTER DEM data for the Antarctic Peninsula. This provides a benchmark more extension of this technique through the associated PhD research. This has already enabled DEMs extracted from archival USGS imagery to be aligned to present-day ASTER DEMs through the patch-based matching approach. In turn, this is currently enabling quantification of relative elevation change over periods of more than 40 years. Existing results indicate the emergence of notable trends in glacier change at around a dozen sites across the Antarctic Peninsula. The work carried out through this research has supported this broader application, and alongside more extensive error analysis, will allow quantification of uncertainty in the change measurements.

7.0 Beneficiaries

Through this research, surface matching has been demonstrated as a reliable technique for improving the elevation accuracy of ASTER DEM data. This has implications which extend beyond glacial science, as the developed registration approach provides a low-cost, automated mechanism which is of relevance to a diversity of ASTER-based studies globally and in the UK. This offers the potential to increase the value of ASTER data, driving down uncertainty, and potentially opening up new application fields.

The approach is also of relevance in a more generic context, and can be extended to other DEM surfaces, including new, enhanced products, such as TanDEM-X, which will offer a 12 m DEM, with global coverage. This offers exciting new opportunities to quantify glacial dynamics with previously unattainable levels of detail and accuracy over broad extents. As is the case with ASTER and other satellite-derived DEMs, TanDEM-X will be of value to a variety of applications on a global basis. In the context of UK Geomatics practitioners, surface matching provides a flexible, automated and robust registration approach which could be applied to a range of scenarios. The technique is directly relevant to projects where it is necessary to align a number of DEM datasets prior to performing subsequent analysis. For example, in the case of flood modelling, it is essential to ensure that any systematic errors between datasets have been eliminated prior to undertaking analysis. However, although DEMs may be delivered from a data provider in a particular coordinate system, it is often the case that systematic offsets still exist. Surface matching avoids the expense of undertaking a labour intensive field survey to collect GCPs, and instead provides a completely software-based solution which normally takes only a matter of minutes to execute. Furthermore, as already explained, the technique simultaneously delivers change information on a DEM point-by-point basis, enabling instant mapping of elevation change. This provides a valuable and low-cost resource for landslide monitoring, analysis of mining subsidence, coastal change, and even automated detection of urban development/change.

The research undertaken here, and more broadly implemented through the associated PhD project will lead to specific downstream benefits, which will be of relevance to RICS members. As already explained, changes to mountain glaciers across the Antarctic Peninsula are thought to generate a significant contribution to sea level change. Therefore, being able to more accurately quantify this aspect is of prime importance, and contributes towards refining the complex jigsaw of Antarctic glacial change. The surface matching approach offers a mechanism which reduces uncertainties associated with these changes, and which will, through future work, enable improved assessment of glacier mass balance trends, in turn delivering enhanced projections of sea level change. This is of direct relevance to coastal communities around the world, and including island nations such as the UK. Like many other countries, a large portion of UK infrastructure and population is concentrated at or near the coast. The work carried out through this project will be fundamental in contributing towards improved UK-specific estimates of sea level change, at reduced levels of uncertainty. This information will be vital to RICS members working in a diversity of fields, allowing the implementation of sustainable engineering practices, and contributing towards best practice guidelines.

8.0 Conclusions

This project investigated the potential of least squares-based surface matching as a technique for improving the elevation accuracy of ASTER DEM data in the Antarctic Peninsula. The goal of the research was to unlock the potential of ASTER data for delivering enhanced quantification of glacial change in the Antarctic Peninsula, a region which is thought to be particularly sensitive to climate change. In order to achieve this, the research investigated the presence of elevation biases in the ASTER DEM, and introduced a capacity within the matching algorithm for evaluating and correcting for any such errors. In the dataset under consideration here, no such bias was found to exist. Following this, the prime focus of the project was in establishing an optimum matching strategy for registering an ASTER DEM to a well-controlled photogrammetric DEM. The surfaces were acquired only three weeks apart in time, therefore minimising any terrain-related changes, and facilitating rigorous validation of matching performance. Local, patch-based and global matching strategies were explored over the 86 km^2 extent of the glacier system. The patch-based approach delivered significantly better performance for the selected areas of interest than the two alternative approaches, providing strong evidence to support the broader application of this strategy at other glacier sites across the Antarctic Peninsula. Following validation of these results through comparison to GPS check points, ASTER DEM quality was explored with respect to terrain type. This revealed strongest agreement between the ASTER and reference DEMs over relatively flat glacier surfaces, with significant errors occurring over steep terrain and in regions of shadow. These findings will be particularly useful in quantifying uncertainties associated with glacial change, through the extension of the research to other similar sites. The outcomes of this research are expected to lead to enhanced estimates of glacier mass balance change across the Antarctic Peninsula, which in turn, will reduce uncertainties associated with the contribution of this component to sea level. Ultimately, this will inform UK government policy on climate change impacts and the mitigation of the effects of rising sea levels, shaping RICS best practice guidelines in relation to sustainable engineering.

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