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Assessment of Glacier Volume Change Using ASTER-Based Surface Matching of Historical Photography

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Abstract—Glaciated regions are known to be particularly sensitive to climate change. Historical archives of glacier volume change are important, as they provide context for present-day changes. Although photogrammetric archives exist for many regions, their usefulness is often limited by a lack of contemporary ground control. High quality digital elevation models (DEMs) underpin a range of change analysis activities. This paper presents a cost-effective solution which utilizes Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEMs as control for the scaling and orientation of archival data sets. Instead of relying upon ground-control points, a robust surface matching algorithm is employed to automatically determine the transformation required to register two overlapping DEMs. Through application to the Slakbreen glacier system in Svalbard, Norway, the strategy is assessed by first matching an ASTER DEM to a fixed lidar reference surface. This demonstrates that ASTER DEMs are effectively correct in scale, supporting their use as a control surface. The second stage of the research implements this by matching an aerial photogrammetric DEM to an ASTER reference surface. Resultant volumetric and annual elevation change rates are compared to those derived from lidar data, which are considered in this paper as a truth data set. ASTER-based matching produced a mean annual elevation change rate of -4.12 ma^{-1}, compared to a value of -4.11 ma^{-1} derived from the lidar data. In volumetric terms, this equates to a difference of 0.6%. A major advantage of this approach is the near-global coverage offered by ASTER data and the opportunity that this presents for remote glacial change analysis over regional extents.

Index Terms—Geodesy, remote sensing, terrain mapping.

I. INTRODUCTION

GLACIER ice loss has been the dominant mass contributor to sea level change during the twentieth century [1]. However, the presently available record for glacier mass change is far from complete, both in terms of the number of glaciers

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sampled and the available time series extent and sampling frequency. A number of national and international projects are underway in order to recover the missing information from historical archives (e.g., [2]). One important step toward assessing glacier mass change (which affects sea level) is a more complete understanding of glacier volume change.

Historical archives of aerial photography are now recognized as being an extremely valuable source of this information. However, one of the greatest barriers to reliable change detection and analysis is the effective registration of multisensor multitemporal digital elevation models (DEMs) to a common reference frame. This is an essential task, as registration errors between DEMs will propagate into estimates of elevation or volume change, rendering any subsequent results or conclusions unreliable. However, the successful registration of DEMs in remote and hostile environments is not a straightforward process, with the complicating step that comparison with modern-day elevations requires the establishment of often expensive ground control in order to scale the stereoscopic images. In many cases, this information was never collected or not available in a reference frame that is consistent with modern techniques. Conventional approaches require the use of identifiable ground-control points. However, a variation on this is the technique proposed by [3], whereby ground-control points are manually extracted from modern-day DEMs based on lidar data controlled by global positioning system (GPS) data. An alternative method is presented by [4], who orient archival photography through the use of control points derived from modern aerial photography which has been accurately controlled via direct GPS positioning of the camera stations. However, both these approaches can be troublesome in the case of relatively featureless glaciated terrain, and the costs and time associated with such exercises are often prohibitive.

Where suitably well-controlled historical DEMs are available, these are now routinely differenced with DEMs from the Shuttle Radar Topography Mission, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), or airborne lidar data in order to compute ice volume change (e.g., [5]–[8], among others). ASTER is particularly attractive, as it offers near-global coverage at relatively high spatial resolution and accuracy and with low cost. Regardless of the modern-day data source, however, care is needed when differencing with historical DEMs since mission-specific biases may exist (e.g., [9]) even after accounting for differences in reference frame and/or reference ellipsoid. Differences in scale, translation, and rotation between the different data sets are assumed negligible
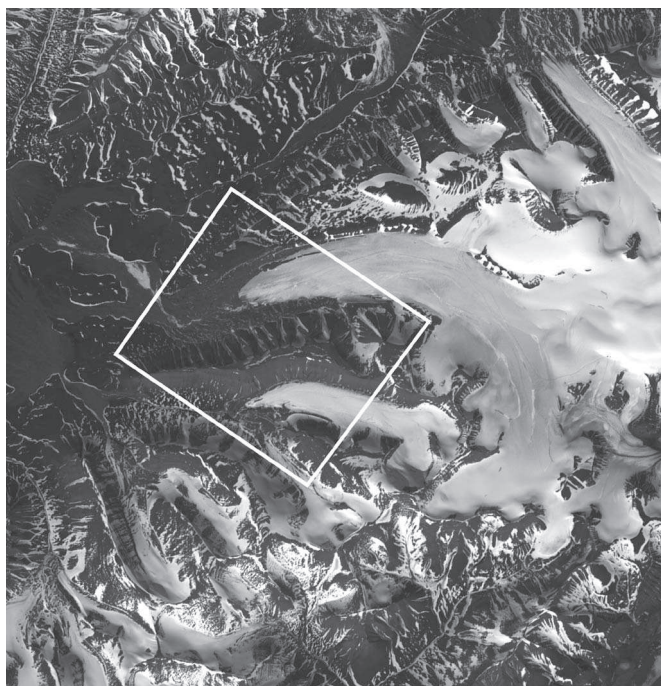
Fig. 1. Subset of ASTER scene (June 13, 2002), highlighting the study area within the Slakbreen glacier system.

and hence are not typically taken into account; any errors of this kind will produce systematic errors in glacier volume change. Clearly, what would be ideal is an approach that took advantage of the spatial coverage and low cost of ASTER DEMs but included the rigor of [3] and [4] applied in an automated fashion.

This paper proposes a solution which employs an ASTER DEM as a control surface for the registration of archival DEMs, facilitating subsequent glacial change analysis. This approach dispenses with the requirement for conventional ground-control points and instead employs a least-squares-based surface matching algorithm. The first section of this paper assesses the quality of the ASTER DEM and illustrates the viability of utilizing ASTER as a source of control for scaling of archival photogrammetric DEMs. The second section implements the ASTER-based control approach, assessing the quality of the results through analysis of glacial volumetric change. In both stages of the experiment, a lidar DEM of superior quality is used to assess the accuracy of the ASTER-based results. This strategy is applied to part of the Slakbreen glacier system on Spitsbergen, Svalbard.

II. STUDY AREA AND DATA SETS

A. Slakbreen Study Area

The Slakbreen study area (Fig. 1) is located at $16°20'$ E, $77°59'$ N on Spitsbergen, which is the largest island of the Svalbard archipelago, Norway. Svalbard lies at the northern reach of the warm North Atlantic Drift current, and consequently, it is anticipated that this region may be relatively sensitive to the effects of climate change [10]. This is supported by a significant trend of $+0.16$ °C warming per decade between 1911 and 2004 [11]. As a result, the Svalbard archipelago is considered an important site for climate and glaciology studies.

Svalbard is comprised of mountainous and complex terrain, and the study area, which includes part of the Slakbreen glacier system, typifies this, with elevations ranging from 79 to 1254 m. The study area includes the front of the main Slakbreen glacier and a smaller glacier to the south. As shown in Fig. 1, the glaciers are separated by a mountain range extending from east to west. The glaciers are composed of relatively gentle slopes, largely below 10°, while the mountain area incorporates slopes ranging from 25° to 45°. As the terrain surface is primarily glaciated, the majority of geomorphologic change can be expected to occur as a result of glaciological processes and glacier melt. Tundra vegetation is dominant, and taller species such as shrubs and trees do not occur.

B. Data Sets

1) ASTER Data: The ASTER sensor, mounted on the TERRA satellite platform, provides multispectral imagery, and derived DEMs of the Earth's surface for latitudes between 82° N and 82° S. ASTER DEMs are available from the NASA-U.S. Geological Survey Land Processes Distributed Active Archive Center (LP DAAC), where they are produced through an automated stereo-correlation method [12]. Users can also generate their own DEMs by ordering stereo images directly, as described by [13]. The production of ASTER DEMs is based on photogrammetric principles, and therefore, image matching is a fundamental aspect. However, glaciated terrain can be susceptible to correlation difficulties, particularly in areas of snow cover, where image texture is poor [14], and this can have a detrimental effect on the quality of the resultant DEM. It is therefore important to fully assess image/DEM quality in this regard, prior to any analysis activities.

ASTER DEMs are relatively inexpensive compared to alternative techniques such as lidar or aerial photogrammetry, and ASTER provides good near-global coverage, with a revisit period of five days. ASTER DEMs offer a vertical accuracy of ± 7 m at best, but this varies greatly, depending on the nature of the terrain, the quality of the imagery, and the processing strategy employed [13], [15]. ASTER data are well suited to a range of environmental applications, and ASTER DEMs have been utilized in a number of recent studies relating to Earth surface processes (e.g., [16]–[18]) and glaciological analysis [19]. However, for some forms of geomorphological analysis, the accuracy of the DEM product can be a limiting factor [16], and very little research has thus far focused on investigating this aspect. In this paper, an ASTER DEM scene from June 13, 2002 was obtained from LP DAAC. This DEM offers a spatial resolution of 30 m and an $rmse_{xyz}$ of better than 25 m [20]. As shown in Fig. 1, the ASTER scene exhibits no cloud cover and presents near nadir viewing.

2) Lidar Data: Lidar is an airborne laser ranging technique capable of producing dense and accurate digital topographic models [21]. The data are normally acquired from either a fixed or rotary wing aircraft and georeferenced directly using an in-flight system which combines GPS and inertial measurement unit (IMU) measurements in order to determine aircraft position and orientation. As the technology and

associated processing algorithms continue to mature, lidar is becoming increasingly applicable for a diversity of applications, including flood plain modeling, forestry, coastal monitoring, transport corridor mapping, city modeling, and bathymetric applications. As a direct sensing technique, lidar is unaffected by the correlation problems associated with image-based DEMs and consequently offers significant potential for monitoring of glaciated terrain [22].

The lidar data set for the Slakbreen study area was acquired on August 8, 2003 by the U.K. Natural Environment Research Council's Airborne Research and Survey Facility (NERC ARSF). The data were acquired using an Optech ALTM 3033 instrument, mounted on a fixed wing aircraft. This sensor offers a specified vertical accuracy of better than ± 0.15 m from a flying height of 1000 m [23]. This error is dominated by GPS positioning errors, although these could be reduced by employing more sophisticated GPS analysis strategies [24]. In this paper, the data were acquired from a flying height of 2800 m. This suggests that the vertical accuracy may be poorer than the specified value of ± 0.15 m. Despite this, the accuracy of the lidar DEM will remain an order of magnitude higher than the ASTER DEM. Planimetric accuracy is dependent on the quality of the GPS-IMU solution; previous experience with this system suggests that this is likely to be within ± 0.20 m. The study area, which comprises 120 km^2, was flown in nine strips, at a spatial resolution of approximately 2 m. This resulted in over 46 million lidar points. The data set consisted of first and last pulse returns, but due to the lack of surface vegetation, no difference existed between the two pulses; thus, first pulse returns were discarded.

3) Aerial Photography: Aerial photography is an important resource for the interpretation of landscape change. However, where metric photography is available, photogrammetric measurements can also be carried out, thus enabling quantitative analysis of change. As discussed in Section I, archival aerial photography is relatively abundant for many glaciated regions. Advances in digital photogrammetry over the last ten to fifteen years have resulted in highly automated standardized workflows for photogrammetric DEM extraction. As a result, photogrammetry is now relatively accessible to nonexperts, offering earth scientists improved opportunities for the utilization of archival photogrammetric data sets in change detection studies. However, while a number of scientists have exploited such opportunities (e.g., [25] and [26]), the uptake is disproportionately low in comparison to the extensive archival collections which exist. As highlighted by [4], this is partly due to factors such as nonstandard imagery, a lack of camera calibration information, and poor image quality. However, as discussed in Section I, one of the primary limitations relates to the difficulties associated with obtaining reliable ground control.

For purposes of validation, a relatively recent epoch of aerial photography was used in this paper. This was acquired on August 8, 2003, which is contemporaneous to the lidar data set. The imagery was flown at a scale of 1 : 16 000 and scanned at a resolution of 11 μm, resulting in a ground sample distance of 0.18 m. The images were then processed in a *BAE Systems Socet Set* digital photogrammetric workstation [27] to extract a 10-m grid DEM for the Slakbreen study site.

III. METHODOLOGY

When integrating multiple data sets, registration to a common reference frame is of fundamental importance [28]. This is also a critical aspect of change detection analysis, as it is essential to ensure that differences due to registration error are minimized. However, the registration process is not always straightforward. Conventionally, common control points can be used to register multiple data sets in preparation for difference detection. However, in remote and challenging terrain, such as that found in the Slakbreen study area, establishing control points in the field can be both costly and logistically challenging. Furthermore, due to the relatively low spatial resolution of the ASTER data and the "blind" nature of lidar (in the sense that terrain data are captured in an indiscriminate manner, and specific features are not directly recorded), it can be difficult to improve registration through the use of control points. In addition, in the case of archival aerial photography, landscape change can severely hamper the identification of control points in the field. This paper presents a solution to the basic registration problem, which is independent of the data collection technique, and the spatial resolution of the source DEMs.

A. Robust Surface Matching

Surface matching offers a software-based solution to data set registration, removing the requirement for specific ground-control points and, instead, deriving control from the geometry of the DEM surfaces. In this paper, a robust least squares-based surface matching algorithm was used [29]. In general terms, the goal of surface matching is to recover the optimum transformation which aligns a poorly controlled "floating" surface to a well-controlled fixed reference surface. However, essentially, surface matching can be considered as a tool which enables multiple overlapping data sets to be transformed to a common reference system, as defined by the reference DEM. The algorithm implemented in this paper is based on a standard 3-D conformal coordinate transformation, which enables conversion from one 3-D coordinate system to another, by means of three rotations (ω, φ, and κ), three translations (Tx, Ty, and Tz), and a scale factor (s) [30].

Each DEM point on one surface can be considered to provide control information, and the algorithm attempts to minimize the vertical difference between a point on the matching surface and a corresponding surface patch on the reference surface [31]. In standard least squares fashion, these differences are minimized globally across the surfaces, and the procedure is iterated until convergence is achieved. A key advantage of this approach is its inherent capacity for difference detection; the final postmatch least squares residuals correspond to vertical differences between the two surfaces, which may arise due to terrain change over time. An overview of the basic algorithm is provided in [31] and [32], and [33] describes the implementation of this for monitoring of dynamic coastal terrain. The mountainous terrain of the Slakbreen study site is well suited to surface matching, offering strong surface gradients, which help to constrain the matching solution.

The basic surface matching algorithm has been further developed in order to increase robustness to outlying observations.

Due to differing acquisition techniques and temporal differences between collection epochs, DEM surfaces will never be identical. Moreover, in dynamic environments, such as that under study here, there is potential for more significant differences to arise as a result of processes such as glacier melt. The introduction of local discrepancies between the surfaces will influence the estimation of the transformation parameters, and where the effects are significant, conventional least squares approaches may fail or converge to an erroneous solution [34]. To overcome this, a weighting function based on a maximum likelihood estimator (M-estimator) was embedded in the software. The M-estimator analyzes the least squares residuals following each iteration and assigns weights to individual observations on the basis of the magnitude of their associated residuals. This enables those observations (individual DEM points) which produce large residual values to be automatically down-weighted accordingly [35]. Thus, the influence of outlying points, or regions of surface difference, can be mitigated, and a more accurate solution is likely to be achieved. Similar approaches, based on the incorporation of robust estimation functions, have been shown to produce good results with experimental data sets [34], [36]. It is beyond the scope of this paper to provide a detailed account of the algorithm utilized here. Full details can be found in [29] and [37], where robust surface matching is implemented for coastal geohazard monitoring, demonstrating the improved accuracy of the robust algorithm over the basic version.

B. Data Preparation

The region corresponding to the study area (Fig. 1) was clipped from the source DEMs. Prior to matching, the lidar data set was thinned using *TerraSolid's TerraScan* software [38]. This was necessary in order to avoid excessively long processing at the matching stage. In the future, computational efficiencies are expected, and for very large regions, computational cluster technologies could be employed. The original resolution of the ASTER and photogrammetric DEMs (30 and 10 m, respectively) was preserved. The data sets were referenced to UTM Zone 33 North.

After matching, the final transformation solution can be applied to the full resolution data set if the matching DEM was thinned beforehand (although this was not the case here). *LSS* terrain modeling software [39] was used in order to calculate elevation differences between the DEM surfaces before and after matching. This enables elevation differences to be determined at every point on both surfaces. These values can then be output for further statistical analysis. For visualization of the elevation differences and volumetric change analysis, *ArcGIS* software [40] was used.

IV. RESULTS

A. Part I: ASTER Accuracy Assessment

The first phase of the experiment involved establishing the accuracy of the ASTER DEM. Given the superior quality of the lidar DEM, this was designated as the reference surface, and the ASTER DEM was matched to this. The resultant transfor-

TABLE I
TRANSFORMATION SOLUTION FOR ASTER-TO-LIDAR MATCHING

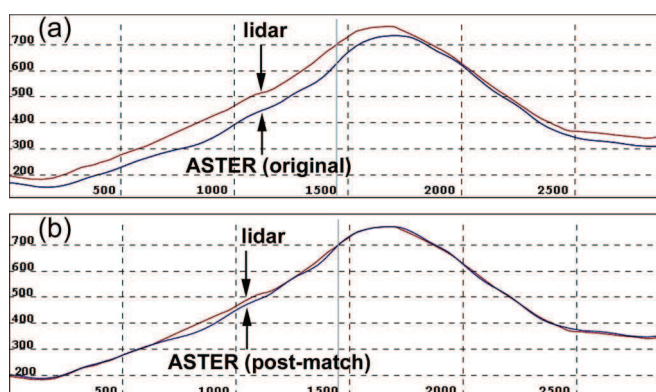| Parameter	Value
ω°	0.01796
φ°	-0.01766
κ°	-0.03622
Tx (m)	-30.528
Ty (m)	30.002
Tz (m)	33.496
s	1.00205
No. Iterations	19

Fig. 2. Cross section through DEMs (a) before and (b) after matching. Units are in meters.

mation solution is presented in Table I. This shows that, while the rotation parameters are relatively small, the translations are of a much larger magnitude, suggesting that the ASTER DEM may have contained systematic errors in plan and height. This is supported by visual inspection of the data sets, as shown in Fig. 2, which shows a typical cross section through the DEMs, before [Fig. 2(a)] and after [Fig. 2(b)] matching. Simple DEM differencing would clearly produce erroneous volume change estimates.

The results suggest that robust surface matching has markedly improved the absolute accuracy of the ASTER DEM, through registration to the lidar DEM. Modifications to the scale parameter were relatively minor (Table I). Crucially, this shows that, while the absolute accuracy of the ASTER DEM may be poor, the product is relatively stable in scale. The ramifications of this will be discussed as follows.

In order to further assess the quality of the matching solution, the pre- and postmatch elevation differences between the ASTER and lidar surfaces were analyzed, with results as presented in Table II. On average, the more recent lidar surface lies nearly 38 m above the ASTER DEM prior to matching. This is a highly unlikely scenario, even if no melting or erosion occurred between 2002 and 2003, and lends further support to the presence of systematic error in the ASTER DEM. The postmatch elevation difference statistics (Table II) strongly suggest that the accuracy of the ASTER DEM has been improved through surface matching. The mean difference between the surfaces is close to zero, and the rmse value is five times

TABLE II
PRE- AND POSTMATCH LIDAR–ASTER ELEVATION
DIFFERENCE STATISTICS

Elevation Difference Statistics	Pre-match	Post-match
Mean (m)	37.770	0.224
Standard Deviation (m)	13.640	7.626
RMSE (m)	40.158	7.629
Maximum (m)	110.611	46.458
Minimum (m)	-22.657	-43.945

TABLE III
TRANSFORMATION SOLUTIONS FOR ASTER-BASED
MATCHING ASSESSMENT

Parameter	(i) Photo to lidar	(ii) Photo to ASTER	(iii) ASTER to lidar
ω°	0.00040	0.00196	0.00325
φ°	-0.00085	0.00567	-0.01116
κ°	-0.00200	-0.03721	0.01205
Tx (m)	0.350	29.057	-27.631
Ty (m)	0.122	-29.922	29.993
Tz (m)	0.079	-34.064	34.715
s	0.99990	0.99720	1.00180
Iterations	6	20	16

better than the prematch value. This postmatch rmse of 7.629 m is due to a combination of differences arising due to terrain change, the differing resolutions of the ASTER and lidar surfaces, and random errors in each of the techniques. The mean postmatch difference between the surfaces remains positive $(0.224 \pm 7.626 \text{ m})$, and the visual inspection of the postmatch surface differences suggests that almost equal erosion (or melt) and deposition (or accumulation) have occurred over the 14-month period.

B. Part II: Multitemporal Change Assessment

1) ASTER-Based Surface Matching: For the majority of glacier regions, lidar data will be unavailable, due to the relative scarcity and limited coverage of this data source. Crucially, however, the results presented in Section IV-A demonstrates the scale stability of the ASTER DEM. This is highly relevant in the context of glaciology, where the most valuable aspect of change analysis relates to volumetric change, and measurements derived from this. Volumetric change remains constant irrespective of the absolute orientation of the surfaces, instead being reliant on the correct relative orientation and scaling of the surfaces. This would suggest that ASTER DEMs may be capable of providing a control surface for registration and scaling of aerial photogrammetric DEMs.

In order to explore this theory, matching was carried out using the photogrammetric DEM introduced in Section II. This 10-m DEM had been derived from imagery acquired at the same time as the 2003 lidar data, and consequently, the photogrammetric and lidar DEMs can be considered as being near identical, although minor differences will exist due to the differing acquisition techniques and spatial resolutions. The photogrammetric surface had been oriented using pseudo-control points, which were extracted directly from the lidar data set. This satisfied the requirement that the surfaces be approximately aligned prior to matching, which is essential to ensure that good approximations are supplied for the unknown transformation parameters.

Three separate matches were carried out. The photogrammetric DEM was first matched to the lidar DEM. Following this, the raw photogrammetric DEM was then matched to the original ASTER data set, and then, the ASTER DEM was matched to the lidar DEM. In all three cases, the glacier regions were masked out of the matching surfaces. This was done in order to exclude these large dynamic bodies, thus minimizing potential for erroneous interepoch surface change. The robust matching software is designed to mitigate the impact of such

differences and, as discussed in Section III, has previously been shown to be effective in doing so. However, in the absence of checkpoint data, it was essential to optimize the conditions which contribute to a successful match, as the experiment hinges on ensuring that the photogrammetric-to-lidar match is reliable. The three matching solutions are detailed in Table III.

Relatively minor transformations were required in order to match the photogrammetric DEM to the lidar DEM, and the solution was obtained relatively quickly, after only six iterations [Table III (i)]. These results confirm the assumption that the photogrammetric and lidar surfaces are near identical, thus supporting the use of the lidar surface in validating the results of the photogrammetric-to-ASTER matching. Crucially, the parameter solutions for the ASTER-to-lidar match [Table III (iii)] are similar to those obtained in Part I of this section, where the complete surfaces were utilized in matching (Table I). Although some minor differences do exist, experience has shown that slightly different parameter combinations can often result in near-identical solutions—an observation supported by [41]. This suggests that the robust matching algorithm, as employed over the complete surface in Part I, has been effective in mitigating the effects of any change over the glacier areas. The results of the photogrammetric-to-ASTER matching [Table III (ii)] and ASTER-to-lidar matching [Table III (iii)] are broadly similar, but in reverse. This is particularly evident through the inspection of the translation values and provides further confirmation that the photogrammetric and lidar DEMs were initially in good agreement. The relatively minor scale modification required to match the photogrammetric DEM to the ASTER DEM confirms that the ASTER DEM supplies a relatively stable basis for the scaling of photogrammetric DEMs. Consequently, this would suggest that the strategy presented in this paper is a valid approach for reliable determination of volumetric change in glaciated terrain. This is investigated further in the following section, which utilizes the results of matches (ii) and (iii) in order to evaluate the success of this approach.

Fig. 3 shows the elevation differences between the ASTER DEM and the matched photogrammetric DEM. The surfaces display marked differences over a period of a little more than one year. From visual inspection, the largest changes occur over the mountain slopes. From a geomorphological perspective, such a pattern is possible, and there is some evidence of eroded
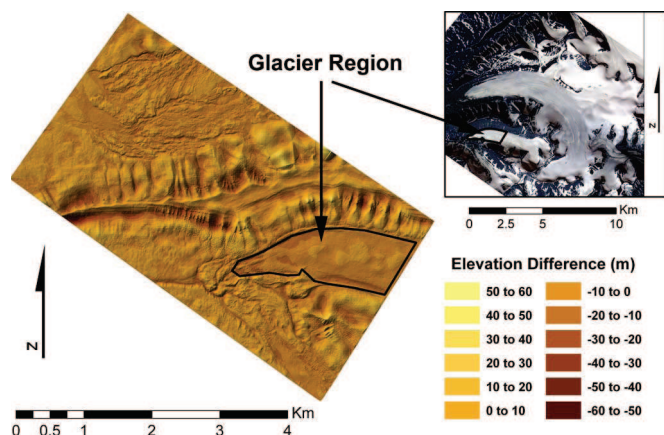
Fig. 3.   Elevation differences; postmatch 2003 photogrammetric DEM minus 2002 ASTER DEM. Glacier margin is highlighted.

TABLE IV
ANALYSIS OF VOLUMETRIC CHANGE FOR GLACIER REGION

Matching Strategy	Photo to ASTER	ASTER to lidar
Surface Area (m^2)	1,499,325.86	1,494,077.44
Gain (m^3)	289,931.02	255,908.80
Loss (m^3)	-8,292,605.14	-8,208,785.76
Net change (m^3)	-8,002,674.12	-7,952,876.96
Difference (m^3)	49,797.16	
Difference (%)	0.63	

material deposited at the foot of the mountains. However, the magnitude of these changes (up to 60 m in places) may be exacerbated by the differing spatial resolutions of the ASTER and lidar DEMs, particularly over steep terrain. Even more significant though is the influence of steep slopes combined with dark shadows, which will have degraded the quality of image matching and subsequent DEM production in the case of both the ASTER and photogrammetric DEMs in these areas. This represents an inherent limitation of image-based DEM creation. Over the highlighted glacier front, primarily negative change has occurred, suggesting glacier melt.

The quality of the photogrammetric-to-ASTER match was initially evaluated through analysis of the resultant surface elevation differences. A number of areas, away from the glaciers and mountain slopes, were selected on the basis that they were assumed to have remained stable over the period of study. Under such circumstances, there should be no significant differences between the surfaces at these locations. The analysis of these areas indicated that the matched surface was precise (in relation to the LiDAR surface) to approximately ±3 m on a point-by-point basis. This discrepancy is likely to be mainly due to the differing spatial resolutions of the input data sets (10 m for the photogrammetric DEM, compared to 30 m for the ASTER data set), and this would therefore reduce with spatial averaging.

2) Glacier Change Results: The most effective means of assessing the success of the ASTER-based matching strategy is to compare volumetric differences between the photogrammetric-to-ASTER match and the ASTER-to-lidar match, in both cases corresponding to change between June 2002 and August 2003. The latter can be considered as providing the most accurate solution, akin to a "control" data set. With modern GIS systems, the computation of volumetric change is a relatively straightforward process. However, there are several factors which must be considered if representative mass change results are to be achieved in glaciology—for instance, the difference between the densities of snow or ice is a factor of approximately three. In this paper, a relatively straightforward approach is adopted, in order to concentrate solely on evaluating the potential of the ASTER-based matching strategy for volume change assessment.

As highlighted in Fig. 3, marked negative changes were observed over the glacier region. *LSS* was used to determine volumetric change between the original ASTER DEM and the matched photogrammetric DEM, and between the lidar DEM and the matched ASTER DEM, for the glacier region only. The results are presented in Table IV. The values derived from the two matching strategies differ by around 50 000 m^3, which equates to an error of 0.63%, as calculated from the ASTER-to-lidar matching. In terms of elevation change across the glacier area as a whole, this represents an average elevation difference of only 3 cm and indicates encouragingly strong agreement between the two matching strategies.

In total, there has been a net volumetric loss of 8 million m^3 over an area of 1.5 million m^2. This is a relatively large change for a 14-month period, and it is important to highlight that the matching and analysis were carried out over a relatively small part of the glacier system. Following this, estimations of mean annual elevation change (water equivalent) were calculated for the glacier front. The calculations are based on the following relationship:

$$Mean\ elevation\ change\ rate = \frac{(Vol_{\mathrm{diff}} \times \rho)}{Area} \times \frac{12}{t_{\mathrm{diff}}} \quad (1)$$

where

Vol_{diff} the volumetric change in cubic meters;
$\rho = 0.9$ the density correction factor;
$Area$ the total surface area in square meters;
t_{diff} the time difference in months.

For the highlighted glacier region (Fig. 3), the mean annual elevation change rate for June 2002–August 2003 is approximately -4.12 ma^{-1} (-4.11 ma^{-1} for lidar-based matching; 0.24% difference). This elevation change rate compares favorably with the results from other studies (e.g., [42]).

V. DISCUSSION

The results presented in this paper have demonstrated the potential of surface matching as a technique for facilitating accurate glacier change analysis. It has been shown that ASTER DEMs are capable of providing a reference surface for accurate scaling of photogrammetric DEMs. This offers tremendous potential for greater exploitation of archival aerial photography, as well as DEMs derived from other sources.

A growing number of studies are applying remote sensing imagery to the critical issue of glacier mass balance (e.g., [43]).

Airborne- and satellite-based remote sensing methods offer the most effective means of assessing mass balance, particularly over regional extents [44]. However, Howat *et al.* [45] also comment that the requirement for ground control is currently a major limiting factor, particularly in relation to greater exploitation of photogrammetric data. The technique presented here provides an efficient means of overcoming this problem. Furthermore, while this research does not directly estimate glacier mass balance, the strategy supplies a reliable and effective mechanism for doing so. As a result, this approach offers a novel and flexible methodology for glacier change assessment, with implications for climate change analysis. As glaciated regions are generally considered as being particularly sensitive to the effects of climate change, continued assessment and retrospective analysis of change are essential.

The ASTER-based surface matching strategy offers several key advantages over existing approaches to glacial change assessment. Foremost, this approach removes the requirement for establishing ground control, which has thus far been a significant limiting factor in many image-based change detection studies. In addition, DEMs facilitate detailed examination of specific features, and the continuous spatial nature of this data source supports analysis which is superior to approaches reliant on point samples or transect data alone [45]. Finally, the use of ASTER data enables this technique to be applied over near-global extents. Where suitable historical DEMs are unavailable for comparison, multitemporal ASTER data sets (or DEMs derived from other spaceborne sensors) can be used for analysis of more recent change. These may also benefit from the outlined surface matching approach.

A number of specific points can be highlighted in relation to the performance of the surface matching algorithm. It is an advantage of the algorithm that not all points are required to achieve an optimum solution; testing has shown that it is possible to reduce the spatial resolution of the surfaces without compromising the quality of the solution. The final transformation parameters can then be applied to the complete data set and subsequent analysis carried out at full resolution. However, matching must be performed over the entire area of interest—it is not advisable to match only a small subset of the DEM and then apply the solution to a wider extent. In this case, it has been found that the quality of the solution will deteriorate as distance from the matched area increases. In order to match over large extents, as may be necessary when analyzing entire glacier systems, the performance of the software requires improvement through the implementation of spatial indexing strategies, such as an octree-based approach (e.g., [46]). This would allow the point correspondence search time to be reduced, thus increasing the capacity of the algorithm to handle larger data sets.

While pseudocontrol points extracted from the lidar DEM were used here to approximately orient the photogrammetric model prior to matching, this does not limit the wider applicability of this technique. Control points derived from large-scale topographic mapping would have been equally effective in this respect.

Prior to applying this technique over wider extents, it would be desirable to carry out a robust assessment of the accuracy of the matching solutions, using GPS checkpoints acquired in the field. This would also allow for an investigation of the errors associated with the differing spatial resolutions of the ASTER, lidar, and photogrammetric DEMs. Ultimately, errors introduced by the relatively low spatial resolution of the ASTER DEM (30 m) are likely to limit the accuracy of the results. In addition, the approach proposed in this paper is entirely image based, and it is important to acknowledge that image matching problems may affect the quality of the DEMs. Furthermore, the challenges associated with successful photogrammetric processing of archival imagery should not be overlooked. However, notwithstanding these factors, the results presented in this paper have demonstrated that this technique is capable of facilitating accurate volumetric change analysis of glaciated terrain. Indeed, without application of translation and rotation parameters, biased volume change measurements would have resulted.

The ASTER DEM supplied by LP DAAC is produced without the use of ground-control points, relying instead on the sensor's ephemeris and attitude data. The consistent quality of this should ensure that the scale stability of the ASTER DEM is maintained on a global basis. In terms of overall volumetric change, the ASTER-based matching technique was found to be accurate to within 0.6% of the lidar-based solution. This performance is highly encouraging and importantly suggests that this approach should remain comparatively sensitive to the detection of low-magnitude trends.

Although this paper analyzed glacier change over a relatively short period of 14 months, the data sets were acquired at similar times of year (June 2002 and August 2003), therefore minimizing changes which could be attributed to seasonally induced snow accumulation or melting. The results provide a strong indication that the glacier is losing mass and present a compelling case for continued monitoring of this region. Future work will involve further verification of the approach presented here. This will include assessing the matching strategy using ASTER DEMs for different regions of the Earth's surface, including regions of steeper topography. In addition, testing will be carried out in order to establish the accuracy and limitations of the technique for surfaces which are primarily composed of snow or ice and to examine how the spatial distribution of stable terrain influences the quality of the solution. While the predominance of ice-covered terrain would not necessarily preclude the application of surface matching, it is essential that potentially unstable or dynamic areas are down weighted through the robust features of the algorithm. In the longer term, efforts will be concentrated on implementing this strategy in order to extract change information from archival aerial photography stretching back over several decades. This will lead to an improved understanding of glacier behavior in response to climate change and will involve further analysis of the Svalbard archipelago.

VI. CONCLUSION

This paper presents a novel solution for the reliable determination of volumetric change in glacial environments. At the core of the strategy lies a least-squares-based surface matching algorithm, facilitating the robust registration of multisensor

multitemporal DEMs. Focusing on part of the Slakbreen glacier system on Spitsbergen, Svalbard, this paper has demonstrated that ASTER DEMs are essentially correct in scale. This property underpins their value as a reference DEM for surface matching, thus providing an automated solution for scaling of archival photogrammetric data sets. Crucially, this approach removes the requirement for ground control and supplies an effective mechanism for data set registration and volumetric change assessment. Results suggest that the ASTER-based matching approach is capable of determining volumetric change to within 0.6% of a truth data set. For the glacier region analyzed over the 14-month study period, there was a net volumetric loss of 8 million m^3 over an area of 1.5 million m^2, providing a strong indication of glacier mass loss. Given the near-global coverage of ASTER data, and the relatively extensive archives of aerial photography, which exist for many glaciated regions, this technique has the potential to make a significant and timely contribution to change analysis in climatically sensitive environments.

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