Uncertainty modeling of glacier surface mapping from GPS: An example from Pedersenbreen, Arctic

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Abstract: For accurately mapping a small glacier Pedersenbreen in Arctic, more than 3000 GPS records were taken on the ground. Mapping results produced by several widely used interpolation methods were compared. In addition, spatial distribution of errors and interpolation uncertainty were visualized and quantitatively analyzed with topograpic features of the glacier. Results show that all the interpolation methods produced acceptable accuracy within 10 m, and the best one RBF controlled both negative and positive difference within 3 m. The largest difference caused by different interpolations can even achieve 75 m between the study area boundary and surveying lines. Moreover, interpolated error increases as the slope goes steep or slope aspects are between 210° -30° . We conclude that the accuracy report relying on the randomly selected 30% check points overestimate the overall accuracy of the glacial map, and more test sampling are needed. Results in this study give both general and spatial-referenced suggestions about the important checking places in the next field surveying or from other data sources.

Keywords: Interpolation, GPS, glacier DEM, Arctic, uncertainty map

Introduction

In the light of global climate change, glacier surface mapping and the determination of glacier volume become important subjects of research (Binder et al. 2009). The accuracy of surface elevetion and bedrock mapping as well as the uncertainty propagation in the terrain estimation will directly influence the quality of future modeling such as in climate change, sea-level rise or montain hydrology (Fischer 2009, 2011). Does the surface elevation derived from limited GPS coordinates have sufficient accuracy to delineate the local terrain undulations? Do the slight volume decrease of a glacier and its terminus retreat that estimated from observations are reliable evidences for supporting the climate warming

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statement, rather than false alarms caused by large uncertainty embeded in the information extraction process? Bearing these questions in mind, data quality and uncertainty modeling should be placed in a crucial role in the glacier mapping activities.

Previous research on mapping glacier surface and rockbed terrain by digital elevation models (DEMs) have been concerning the error distribution in various applications (Ai et al. 2006; Binder et al. 2009; Fischer 2009, 2011). Glacial surface terrain can be generated using satellite-based techniques, photogrammetric methods from remote sensed data and interpolations from field surveying data. Generally, the quality of a glacier surface DEM depends on three main sources of uncertainty: (i) sampling strategy and accuracy of the source data; (ii) the elevation extraction and interpolation processes; and (iii) morphological characteristics of the glacier surface. The quality of the source data varies with sampling and collection techeniques, such as resolution of remote sensed images (sampling interval), density, size and sampling scheme of filed sampling spots, such as random, systematic or stratified. From limited source data, elevations are estimated to fill the no-value space and to cover the whole study area. Many interpolation methods exist but there is no unique best choice, the evaluation and comparesion of these methods and related error distributions are essential to understand the quality of the final derived DEM. Beside, interpolation algorithms are usually designed based on spatial configuration of the surface, thus characteristics of the terrain such as flatness, hilly or mountainous, and spatial autocorrelation will also infulence the final accuracy. Among the above sources of uncertainty, we can handle the uncertainty caused by different interpolation methods after GPS corrodinates have already been recorded at filed samples for a specific glacier. Although the source data cannot be changed after collection, we still can learn from the uncertainty modeling of interpolation and identify areas with large deviation of estimated elevations for better preparing the next data collection.

So far, only a few glaciological studies concerned about unceratinties produced in interpolation process and provided a careful assessment of interpolation accuracy over glaciated area using ground GPS data. This paper aims to first evaluate the suitability of various interpolation techniques to construct DEMs for glacier Pedersenbreen in Arctic, and to identify the spatial distribution of undertain areas and related topographic characteristics.

Study area and data

The glacier Pedersenbreen (12.175° E, 78.515° N) is located at Svalbard in Arctic, 10 km away from Chinese Arctic Yellow River Station. It is a small polythermal glacier with area around 5.6 km^2 and altitude between 90m to 650m, lying in the mountainous area with the highest peak reaching 1017m. Investigations conducted between 2005- 2009 revealed the surface of Pedersenbreen was relatively flat and covered with a small amount of debris.

In April 2009, GPS points were obtained using a GPS unit in navigation mode attached on pulseEKKO PRO GPR. The main purpose of the survey is to measure the thickness of Pedersenbreen as well as map the surface and bedrock DEMs. Therefore, the GPR attached GPS was preferred over a more accurate GPS unit which can be differentially corrected. As a rule of thumb, we consider the vertical accuracy of the GPS unit to be about 10 m. In total, 3150 sampling GPS points were collected in the field (Fig 1). The GPS data referenced to the WGS84 geographic coordinate were projected to the North Pole Stereographic system. Considering the sampling interval is about 3-5 m and the accuracy level of GPS, the final DEM raster is set to 10 m resolution to avoid meaningless interpolation at too detailed scale.

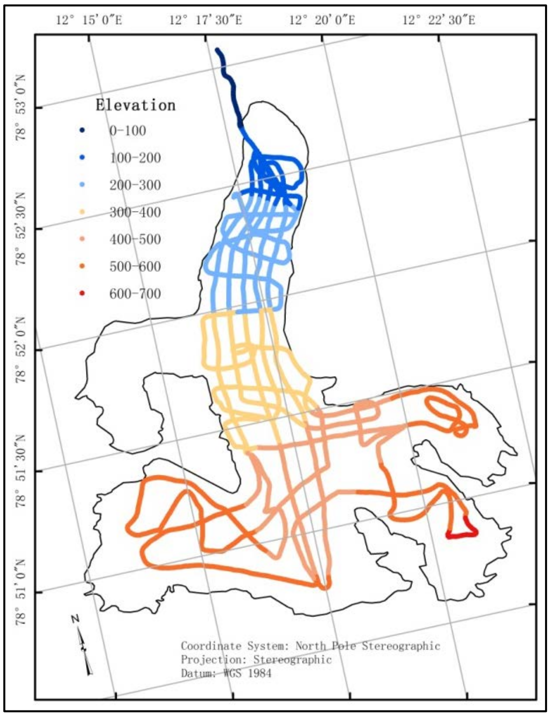

Fig. 1 Study area and ground GPS data

Method

Four widely used interpolation methods were examined, namely inverse distance weighting (IDW), Radial Basis Functions (RBF), local polynomial interpolation (LPI), universal Kriging (UK) and Triangular irregular networks (TIN). The first three belong to the deterministic method, which assign values to locations based on specified mathematical formulas that determine the smoothness of the resulting surface from the surrounding measured values. UK is a typical geostatistical method, which is based on statistical models that include autocorrelation. We chose UK instead of other Kriging method, mainly due to the mean of the input data is not constant across the entire study area and an obvious trend exists. TIN is a form of vector-based geographic data to represent surface morphology. Delaunay triangulation method is used to interpolate GPS points to form TIN and then linearly resampled to raster DEM. TIN is typically used for high-precision modeling of smaller areas, since it preserves all the precision of the input data while simultaneously modeling the values between known points.

70% of the total GPS points were randomly selected as training data for interpolating DEM and the rest are used as testing data. The Geostatistical analyst module of ArcGIS 10.0 is used in two steps. First, the training data were checked with exploratory data analysis tools for dependency, stationarity and statistic distribution. Then five interpolation methods were carried out and all the paramters in the interpolation processes were automatically optimized using cross validation by the software.

The errors at testing points were evaluated by subtracting interpolated values from ground records of vertical coordinates. Root mean square errors (RMSE) are calculated for every interpolation method to assess their performance. The absolute values of errors were grouped to find out the topographical characteristics in terms of altitude, slope and aspect. In addition, range of all interpolated values (maximum-minimum) at each cell were mapped to visualize the spatial configuration of uncertainty caused by interpolation. Interpolation differences at testing points were especially colored on a map to analyze whether the testing points were sufficient and the target check area in the next field surveying.

Results

The vertical accuracy of DEMs derived from five interpolation methods were examined by 920 testing points. All the methods produced acceptable accuracy within 10 m, and the best one controls both negative and positive difference within 3 m. All the mean errors are close to zero but be negative, which indicates averaged interpolated values are larger than ground values, and thus suggests all the interpolations tend to overestimate slightly. The statistics of the errors (Table 1) show that RBF, UK, TIN outperform LPI and IDW in general. RBF and UK have similar results, but RBF run first due to the lowest RMSE and Range and the closest mean error to zero. Both LPI and IDW show extreme maximum and minimum values and results in larger RMSE than other methods.

Table 1 Errors of interpolation results by different methods

	RBF	UK	TIN	LPI	IDW
Mean	-0.02	-0.03	-0.07	-0.06	-0.07
RMSE	0.41	0.42	0.52	0.91	0.95
Max	1.60	1.55	1.82	5.12	4.47
Min	-2.66	-2.77	-3.31	-9.03	-8.29
Range	4.26	4.32	5.13	14.15	12.77

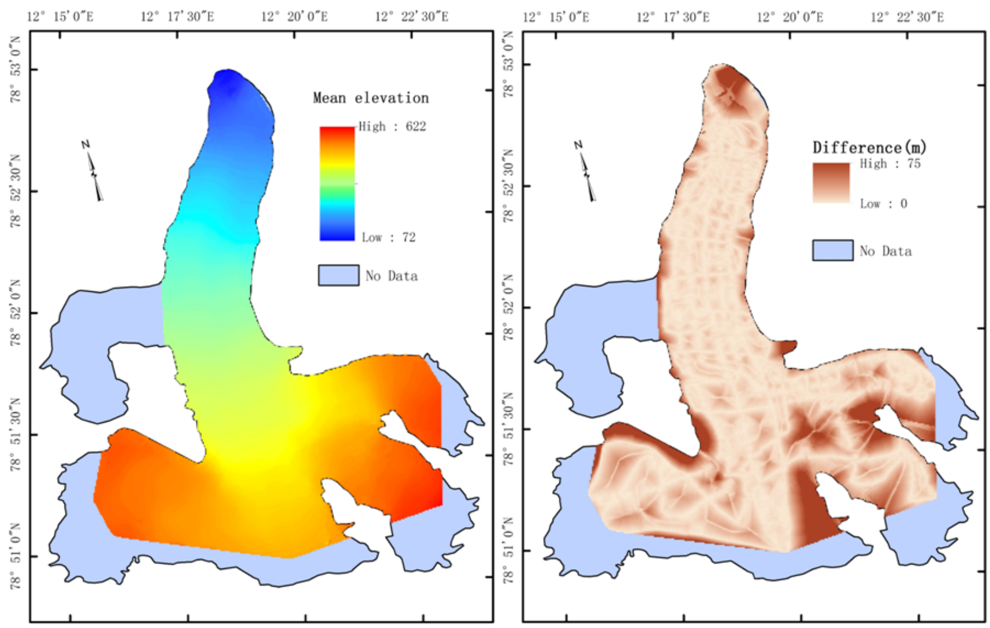

Fig. 2 Mean DEM averaged from all the interpolations (left:a) and range of interpolated difference (right:b)

By averaging the five DEM from different interpolations, we finally obtain the glacial surface map of Pedersenbreen (Fig.2). As expected, the glacier has a smooth surface and gently inclines upwards to the south. The lowest elevation around 70 m, appears at the northernmost point of the glacier tongue. While the peak around 620m at the southeast source, is the farthest place we can reach with the GPR equipment during the field surveying.

The spatial pattern of interpolation differences were illustrated in Fig.2. Interpolation methods produce more similar results at densely sampled places. It means that if the input data have sufficient density, then the influence from interpolation will be minimized. The largest difference only caused by different interpolations can even achieve 75 m in extreme case. The most uncertain areas locate between the study area boundary and surveying lines, because no samplings outside the boundary to control the quality of interpolation in these zones.

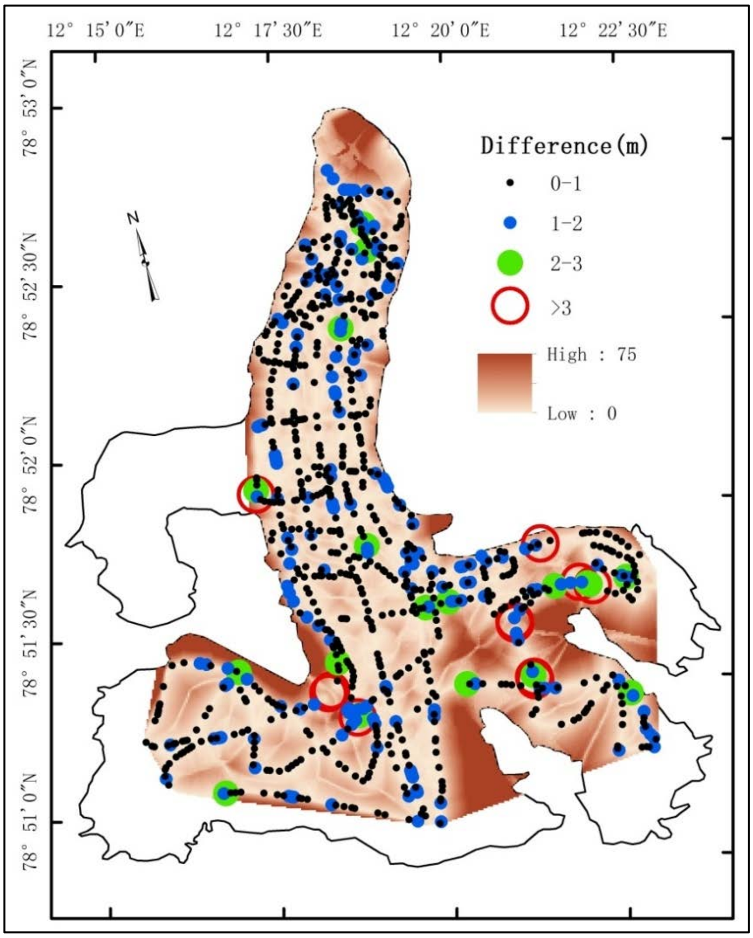

Fig. 3 Vertical ranges between all the interpolated values at testing positions

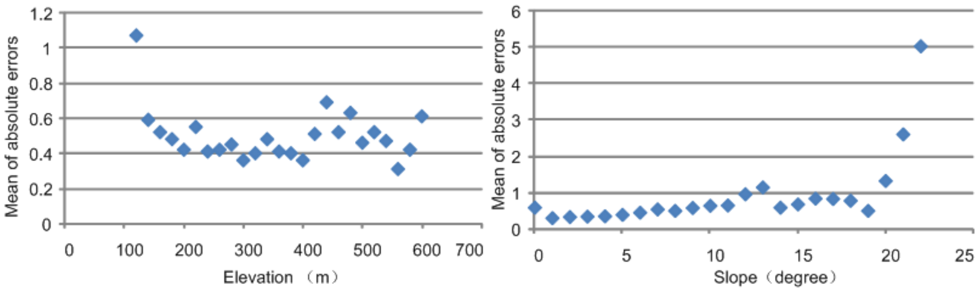

Fig. 4 Relationships between mean absolute errors and elevation (left) and slope (right)

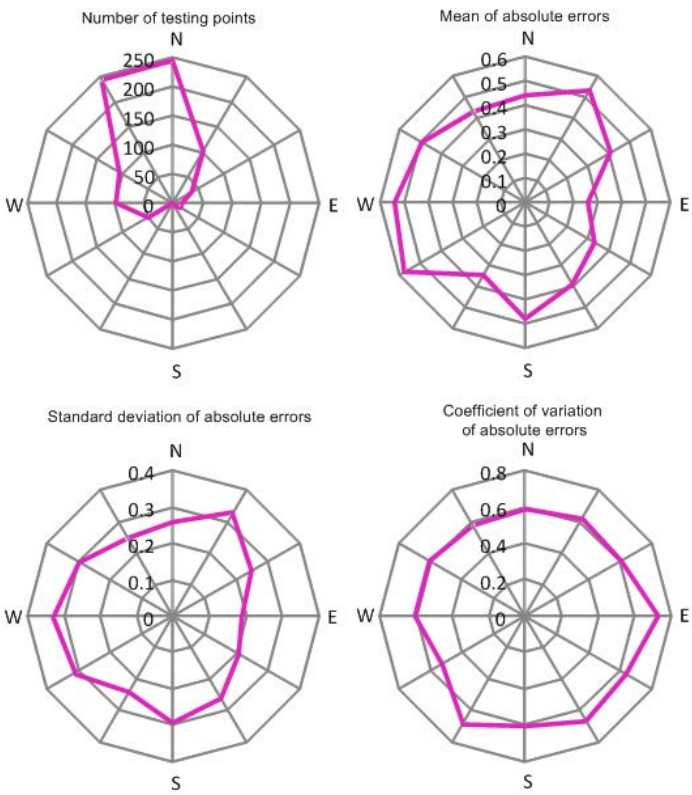

Fig. 5 Radar charts of mean absolute errors, observation points as a function of slope aspect

Differences between all the interpolated values at testing samples were illustrated to reveal the spatial covering of uncertain areas by the randomly selected 30% check points in Fig. 3. Vertical differences within 2 m distributed randomly across the whole surveying area.

Only few points have interpolation differences larger than 2 m and they mainly occur in the south part of the glacier where have higher altitudes. Moreover, greatest differences (>3 m) tend to locate on the outline of the sampling area. All the value of differences at testing points was less than 5 m, which is much less than the 75 m for the whole interpolated area.

Absolute values of errors were summarized by topographical characteristics. From the scatter plots in Fig.4, we observe that the errors have no obvious relationship with the elevation. Degree of errors spreads more or less the same in lower and higher places. Absolute errors tend to increase with the slope goes up and errors greater than 1 m occur on steep slopes (>20 degree). In terms of the slope aspect, 86% testing samples were on N- or NW -facing slopes and located between 270° -30° . Mean absolute errors range from 0.26 m on E-facing slopes to 0.58 m SWW-facing slopes. Relatively larger mean errors occur between 210° -30° . The standard deviation of mean errors has similar radar shape, which means larger mean errors correspond with greater deviation also. Coefficient of variation, which is defined as the ratio of the standard deviation to the mean of the errors, therefore, does not depend on slope aspect.

Conclusions and Discussion

Glacier surface DEMs construted from five widely used interpolation techniques for Pedersenbreen in Arctic were compared and evaluated. All the methods produced acceptable accuracy and RBF, UK, TIN outperform LPI and IDW in general. The unsatisfied estimation from IDW in this study confirms the results from other research (Erdogan 2009, Racoviteanu et al. 2007). One possible reason could be the weight in IDW relies simply on the inverse of the distance and IDW never predict values above the maximum measured values or below the minimum measured values, which do not match the characteristics of the glacier surface. LPI is best suited to data that exhibits short-range variation and thus works not well for the relatively smooth surface of Pedersenbreen. In contrast, RBF, being an exact interpolator, requires the surface pass through the measured points and produces good results for gently varying surfaces. UK also do good job considering spatial autocorrelation, and captures the structure and random components of the surface during interpolation.

The largest difference only caused by different interpolation methods can achieve 75 m between the study area boundary and surveying lines. The user of this DEM, therefore, should be aware of the artificial interpolated elevations when no data available in surrounding area. Compared with the large uncertainty between different interpolated values, vertical differences between interpolated values and elevations from testing points were much smaller. This suggests that the accuracy report on these randomly selected 30% check points overestimate the overall accuracy of the glacial map (Fig 2a), and only can represent the uncertain distribution within the outline of surveying areas (excluding the interpolated areas between the study area boundary and surveying lines).

By exploring the topographic characteristics of error distribution, we found that glacialated areas tend to have increasing interpolated error as the slope goes steep or slope aspects are between 210° -30° . This result gives general suggestion about the important checking places in the next field surveying or elevation data collection from other sources. The invisible reslationship between errors and altitude of mapping area is out of our expectation. One possible reason is that Pedersenbreen has an overall flat surface, and no steep slope or roughness on high altitude that may influence the mapping accuracy.

We conclude that the accuracy report relying on the current check points overestimate the overall accuracy of the glacial map, and more test sampling are needed. Results in this study give both general and spatial-referenced suggestion about the important checking places in the next field surveying or elevation data collection from other sources.

Acknowledgement

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References

Ai ST, E DC, Yan M and Ren JW (2006). Arctic glacier movement monitoring with GPS method on 2005. Chinese Journal of Polar Science, 17(1):61-68

Binder D, Brückl E, Roch KH, Behm M, Schöner W and Hynek B (2009) Determination of total ice volume and ice-thickness distribution of two glaciers in the Hohe Tauern region, Eastern Alps, from GPR data. Annals of Glaciology 50(51):71–79

Fischer A (2011) Comparison of direct and geodetic mass balances on a multi-annual time scale. The Cryosphere 5:107-124

Fischer A (2009) Calculation of glacier volume from sparse ice-thickness data, applied to Schaufelferner, Austria. Journal of Glaciology 55(191):453-460

Erdogan S(2009) A comparision of interpolation methods for producing digital elevation models at the field scale. Earth Surface Processes and Landforms 34: 366-376.

Racoviteanu AE, Manley WF, Arnaud Y and Williams MW(2007) Evaluating digital elevation models for glaciologic applications: An example from Nevado Coropuna, Peruvian Andes. Global and Planetary Change 59: 110-125.