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Generation of High-Resolution Precise DEMs Through Airborne LIDAR Surveys on Huge Antarctic Regions

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Abstract

NASA, NSF and USGS jointly conducted airborne LIDAR surveys to acquire numerous surface points with high densities over the Antarctic Dry Valleys and its vicinity. The huge set of these points retains two characteristics undesirable for DEM generation, which are unusually high blunder ratio and large variation of the local point densities. Hence, in order to not only reduce the undesirable effects due to these characteristics but also process the huge number of points within reasonable limits of time and resources, we developed an efficient, robust, nearly automatic approach to DEM generation. This paper reports about the application of this approach to generating high-resolution precise DEMs from the Antarctic LIDAR surveys and the evaluation of their accuracy.

Keywords : *DEM, LIDAR, Antarctica, Dry Valleys, Robust, Efficient*

1. Introduction

NASA (National Aeronautics and Space Administration, USA), NSF (National Science Foundation, USA) and USGS (United States Geological Survey) jointly conducted LIDAR surveys in December 2001 to acquire high-resolution elevation data over several sites in the Antarctic Dry Valleys and its vicinity. Elevation of the topographic surface was measured at numerous points by NASA's Airborne Topographic Mapper (ATM) conical laser scanning altimetry system. Details on the ATM system and its application for change detection on beaches and polar ice sheets are presented by Krabill (1995, 1999, 2000).

The analysis on the unprocessed data indicated high blunder ratio, and the conical scanning pattern resulted large variation of the point densities. These characteristics would significantly degenerate the quality of a DEM generated using a conventional interpolation method. Hence, to reduce the undesirable effects due to these characteristics and process the huge number of points with reasonable time and resources, we developed an efficient, robust, nearly automatic approach to DEM generation. This paper reports about the application of this approach to generating high-resolution precise DEMs from the Antarctic LIDAR surveys and the evaluation of their accuracy. This paper is mainly based on two past papers presented by one of the authors about this topic, an application-oriented one (Lee et. al., 2003) and an algorithm-oriented one (Lee and Choi, 2004).

2. Project Sites and Data Acquisition

The selection of the sites was based on the priorities of on-going scientific research and the requirements for calibration and validation of surface elevations measured by NASA's Geoscience Laser Altimetry System (GLAS). GLAS consists of both LIDAR and altimetry subsystems and it is the sole sensor of the ICESat, the Ice Cloud, and Land Elevation Satellite that was launched in January 2003. Details on the ICESat mission are presented by Zwally et. al (2002). The ATM surveys acquired more than 1 billion points

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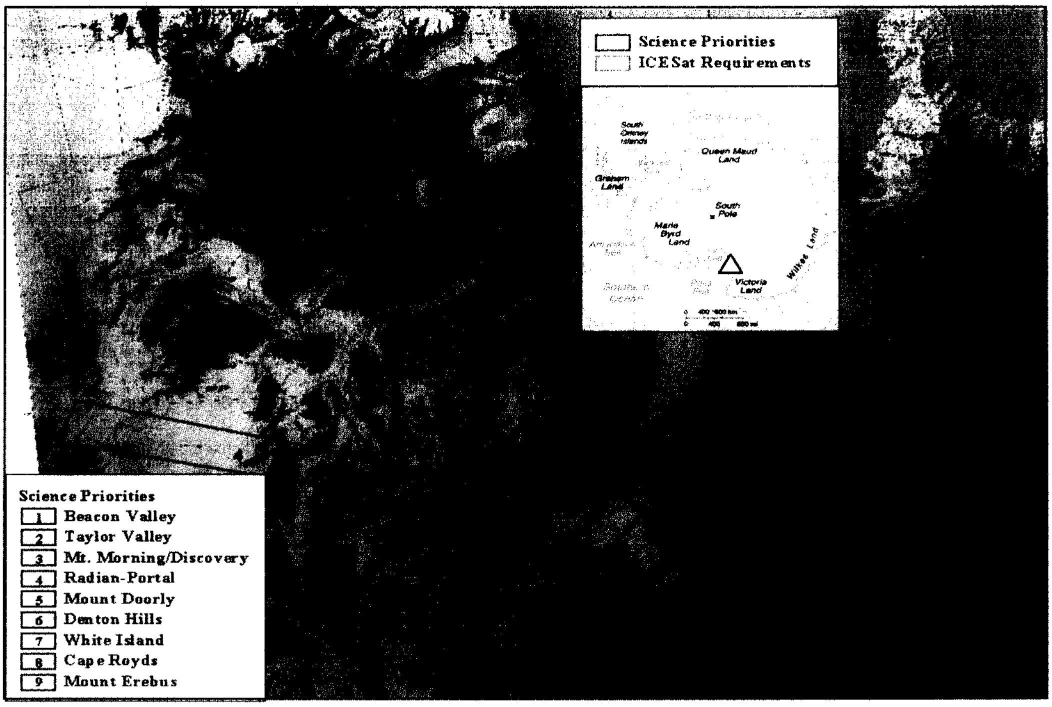


Fig. 1. Project sites selected under the consideration of the science priorities and the ICESat requirements. The small triangle indicates the location of the sites in a low-resolution index map of Antarctica.

with an average point density of about 0.3 point/m^2 in 14 days, starting 18 December 2001. Fig. 1 shows the project sites.

3. The DEM Generation Approach

The proposed approach consists of five main tasks, that is, 1) constructing spatial databases from a given point set, 2) verifying the quality of the data, calibrating them if necessary and eliminating any identifiable blunder point, 3) generating preliminary DEMs by establishing a grid and determining the elevation of each grid post based on a robust interpolation method, 4) refining the DEMs by filtering out any blunder elevation, inspecting visually and editing the DEMs if necessary, and 5) evaluating the quality of the DEMs. Details of each task are explained in the following sections.

3.1 Spatial Database Construction

A spatial database provides an efficient means to storage, retrieve, update and search in a set of spatially labeled entities such as points. If we organize a huge set of points into a spatial database, the database can significantly accelerate many spatial queries arising during the DEM generation. Such queries can be extracting all points locating inside a specified area of interests, finding the nearest point to a point, and other processes, for examples.

We first determine the spatial coverage of a given data set before the database construction. The coverage can be represented as a set of polygons that include the entire points of the set with reasonably small area. Such coverage can be computed using the alpha-shape algorithm (Edelsbrunner et. al., 1983) with the alpha value appropriate to the average point spacing. An example is demonstrated in Fig. 2.

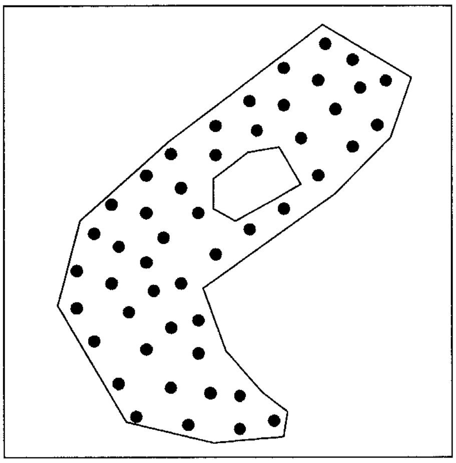


Fig. 2. A spatial coverage computed using the alpha shape algorithm assigned with a reasonable alpha value.

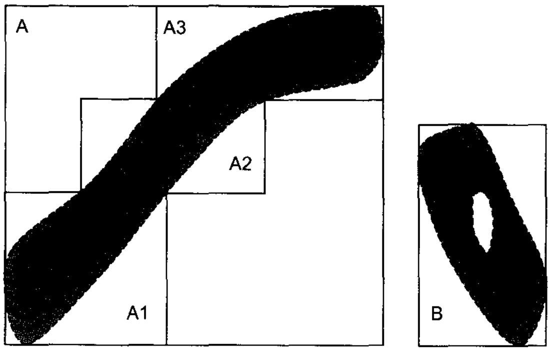


Fig. 3. Examples of coverage and spatial extents.

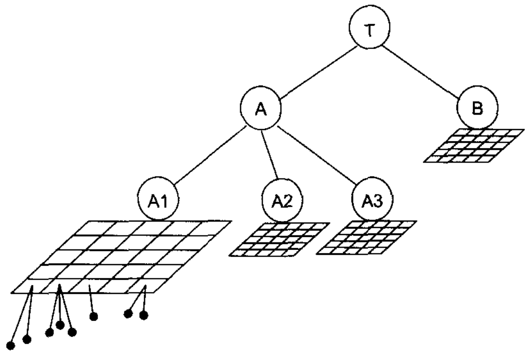


Fig. 4. Examples of data structures based on the hierarchical binning scheme.

The coverage is then used to determine the spatial extents of entities to be organized into a spatial database, as shown in Fig. 3. A spatial database usually has a maximum limit to its manageable data size and hence to the spatial extents. This leads to dividing a large extent into several manageable extents, for example, extent A consisting of three extents. Every point is classified into an appropriate extent and then stored in the spatial data structure linked to the extent. This structure can be implemented with two different types of databases, that is, a home-made one based on a hierarchical binning scheme, and a commercial one, "Oracle Spatial" based on quad and range tree schemes. For example, the structure based on the hierarchical binning scheme can be illustrated in Fig. 4. A leaf node of this graph structure is combined with a grid structure in which each cell is linked to the points locating within the cell.

3.2 Data Verification, Calibration and Cleaning

ALS data generally include systematic and gross errors in some degree for various reasons. The verification process is to assess the quality of the data by measuring the degrees of the systematic and gross errors in the data. To check the systematic errors, we compare two different data sets acquired from the same overlapping area but on different swathes, times or dates. A set of elevations over the area are independently computed from each set using a robust method. The discrepancy between both elevation sets indirectly indicates the significance of the systematic errors. If it is high, we should perform a calibration process consisting of

- establishing error models associated with the data acquisition,
- estimating the systematic parameters embedded in the models by minimizing the elevation discrepancy, and
- correcting the data based on the estimated parameters and error models.

Readers can refer to details on error modeling (Schenk, 2001) and calibration (Filin, 2001, Lee, 2003).

The cleaning process aims to eliminate the gross errors (or blunders). Every point was tested and labeled as a blunder if one of the following conditions is fulfilled.

- The point is significantly deviated from the regular scanning pattern; normally, a linear scanner produces a linear pattern and a conical scanner an elliptical pattern on the ground during a scanning period.
- The point is spatially incompatible with its neighborhood points; proximate points normally tend to retain similar elevations.
- The point is significantly deviated from a low-resolution reference DEM; in some cases, a coarse DEM is already available and a newly surveyed point is normally consistent with it.

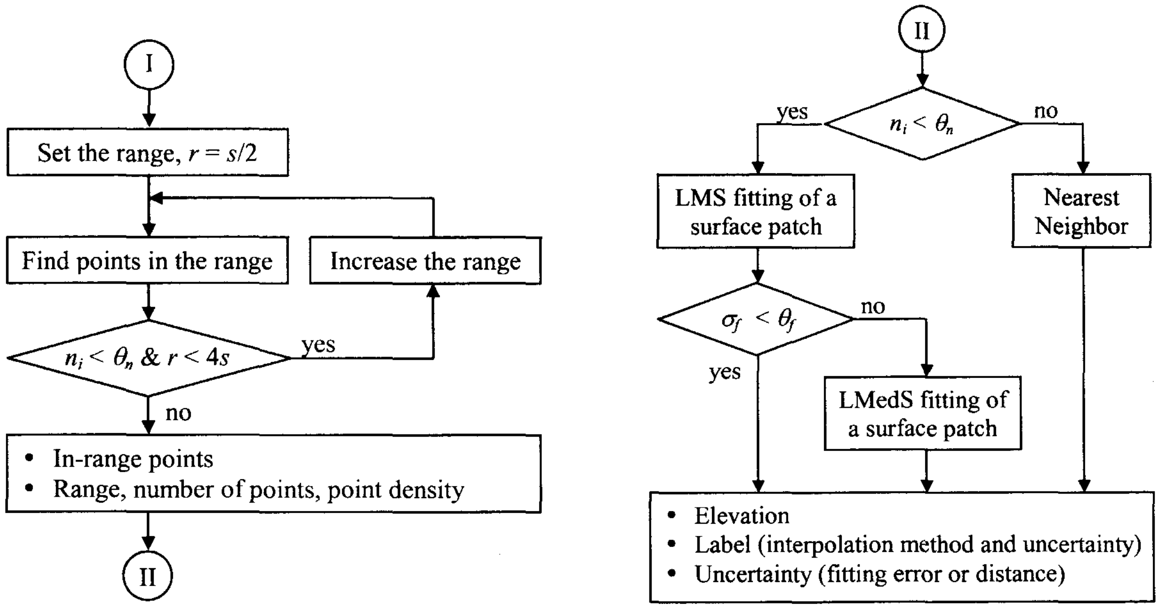
3.3 Grid Setup and Interpolation

The extent of a grid is determined so that it can include the entire data coverage. The spacing interval (or the spatial resolution) of the grid is based on the point density so that a cell of the grid can include a point in average. The value can be represented as:

$$s = \sqrt{1/D_p} = \sqrt{A_c/n_p}, \qquad (1)$$

where s is the grid interval, D_n the average point density, A_c the area of the data coverage, and n_p the number of points.

A preliminary DEM is then computed by determining the elevation of every grid post. This determination process involves two main steps, finding in-range points, that is, the points within a certain range from the post



(a) (b)

Fig. 5. Determination of an elevation for a grid post, finding in-range points (a) and deriving an elevation from the in-range points (b).

and deriving an elevation from the in-range points. The first step is illustrated in Fig. 5(a), where r is the range and n_i the number of in-range points. The range varies according to the local point density. It is initially assigned to the half cell size (s/2) and gradually increased to the four times cell size (4s) in maximum until the number of the in-range points reaches a certain number, θ_n. This number is the minimum number of points required to determine a surface patch during the second step. The range, number of in-range points and the local point density are also computed. The second step or called interpolation is shown in Fig. 5(b). If the in-range points are enough to determine a surface patch, the elevation is determined from a surface patch fitting to the in-range points. We first attempt to fit a surface patch based on Least Mean Squares (LMS) estimation. If the associated fitting error σ_f is greater than a certain threshold θ_f, then the in-range points are assumed to include some outliers. In this case, the least median squares (LMedS) estimation (Koster and Spann, 2000) known to be theoretically immune to 50% outliers is utilized instead. The type of the surface patch can be selected according to the topography of the area of interest. A planar patch is preferred if the local area around a post is sufficiently smooth. If the in-range points are not enough, the elevation is determined from the elevation of the nearest point to the post. A label is also assigned to each elevation, indicating the type of the interpolation method and the level of precision. The fitting error of a surface patch or the distance to the nearest point is used to indicate the uncertainty associated with the elevation.

3.4 Filtering, Inspection and Editing

The preliminary DEM may still include some blunder elevations. Some of them are made of a few peak elevations while others appear as a large cluster. The elevation of every post is tested and identified as a blunder if one of the following conditions is satisfied.

- The elevation is significantly different from the median elevation of the neighboring cells.
- The elevation is significantly deviated from a low-resolution reference DEM.

Furthermore, the DEM is visualized as 3D surface plots or shaded-relief plots with various view angles and coloring schemes. Based on visual inspection on such plots, the remaining blunders are identified. A refined DEM is then created by eliminating or correcting the elevations identified as blunders based on the neighboring posts.

3.5 Evaluation

The refined DEM is then evaluated with reference data, which usually contains 3D control points. The elevation differences of the control points from the DEM are computed; their mean and root mean squares are the typical measures to assess the quality of the DEM. Moreover, the analysis on the histogram and spatial distribution of the differences can localize some abnormalities, which indicate the existence of outliers still remaining in the DEM.

4. The DEM Generation and Evaluation Results

4.1 DEM Generation

We constructed spatial databases from the huge point set, which occupying several hundred G-bytes in hard disks. Although the database based on "Oracle Spatial" retains many advantages such as convenient user interfaces, it tends to spend larger overhead size and time in the storage and access of the data than the home-made database. From the analysis on the unprocessed data, we found that the data had insignificant systematic errors but abnormally many blunders. A main factor for the blunders is considered as the high variation of the surface reflectance due to mixtures of rocks and snows appearing in many areas. Most blunders were successfully eliminated by the cleaning process, but some of them still remain. We established 20 grids with resolutions of 2 or 4 m over the surveyed area and generate DEMs with the grids. The names and extents of the generated DEMs are shown with the trajectories of the LIDAR surveys in Fig. 6.

4.2 DEM Evaluation with GPS Surveyed Points

We evaluated the DEMs with GPS surveyed control points by analyzing the elevation differences between the control points and the DEMs. The differences originate not only from the errors associated with the data acquisition and the DEM generation but also from the inaccuracy of the control points and the roughness of the topographic surfaces. In reality, it is extremely difficult to acquire many control points of high qualities particularly in polar areas due to the poor accessibility to these areas. We managed to acquire 88 control points of various qualities and compared them with the DEMs. 16 points among them show large deviations (> 1 m), thereby being considered as blunders and excluded. These blunders are thought to mainly come from the poor quality of the control points and (or) the high roughness or slopes of the surfaces. Based on the remaining 72 points, the average and standard deviation of the elevation differences are computed at ± 26 cm and ± 38 cm, respectively. In general, it is noticeable that the differences mostly show the positive values as the average also indicates. This must be because the ALS system measures the surface itself but the GPS

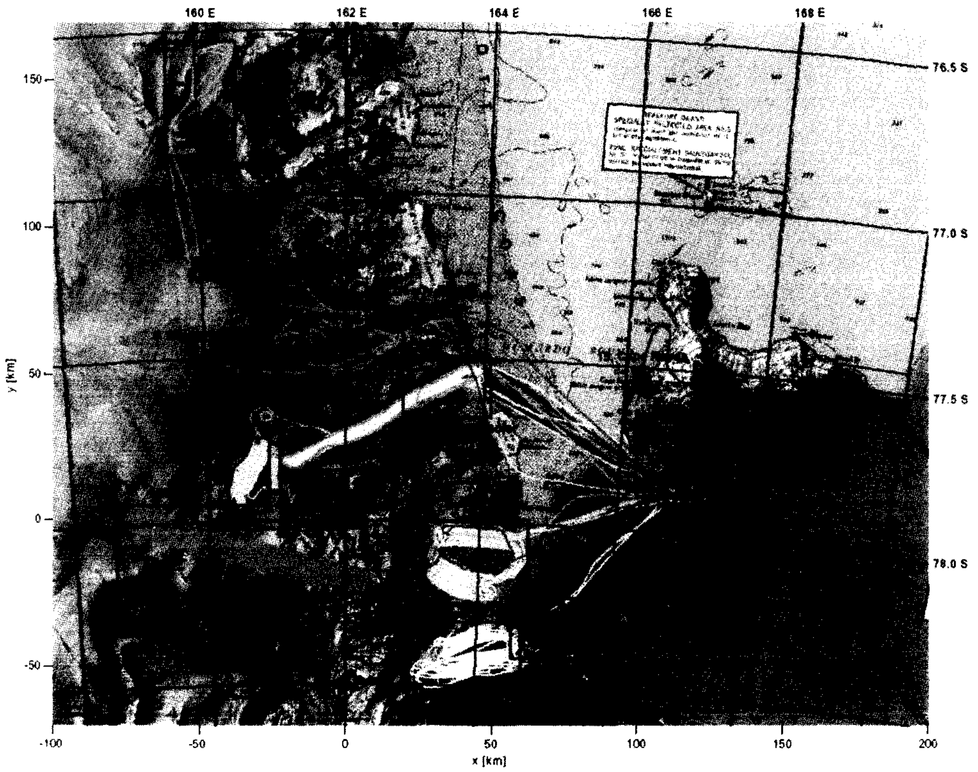


Fig. 6. The names and extents of the DEMs and the trajectories of the LIDAR surveys.

sometimes measures at the top of objects on the surfaces, such small boulders. The absolute accuracy represented as root mean squares can be conservatively concluded with better than ± 50 cm. In some areas like the Beacon valley where the surfaces are relatively smooth and the control points of better qualities are available, the accuracy of better than ± 20 cm can be achieved.

4.3 DEM Evaluation with ICESat GLAS Measured Points

Furthermore, we evaluated the DEMs with a set of points measured by ICESat GLAS. Since ICESat was launched on 12 January 2003, GLAS has generated 2239 points overlapped with the DEMs, which were used for this evaluation. Fig. 7 represents the ICESat GLAS points over the mapping trajectories in green, where the point color indicates its elevation deference from the DEM. The average and standard deviation of the elevation differences are computed as 5 cm and ± 6.82 m, after the 1% extreme values considered to be outliers being excluded. It is very remarkable that such smaller average difference is achieved, since it indicates that the DEMs are very consistent with the GLAS points in average, where GLAS is designed to achieve a nominal absolute elevation accuracy of better than ± 10 cm. Since the size of a laser footprint in the GLAS is 30-40 times larger than in the ATM, the surface roughness in a single footprint of GLAS is much larger than that of ATM, resulting in the high standard deviation.

5. Conclusions

We presented an efficient and robust approach to the DEM generation from a huge set of LIDAR data. This approach has been applied to generating huge high-resolution precise DEMs and the results demonstrated its prominent performance. Consequently, the high efficiency in the approach is achieved by managing a huge point set with the spatial data base and the robustness to blunders by employing the sophisticated blunder detection processes and robust interpolation method.

Furthermore, the generated DEMs themselves can provide great contributions to many on-going scientific studies on the Antarctic areas since they retain much better resolutions (2 to 4 m) than the old ones (> 30 m). This study also has shown that a LIDAR survey can be a cost and time efficient method to acquire precise DEMs over polar areas.

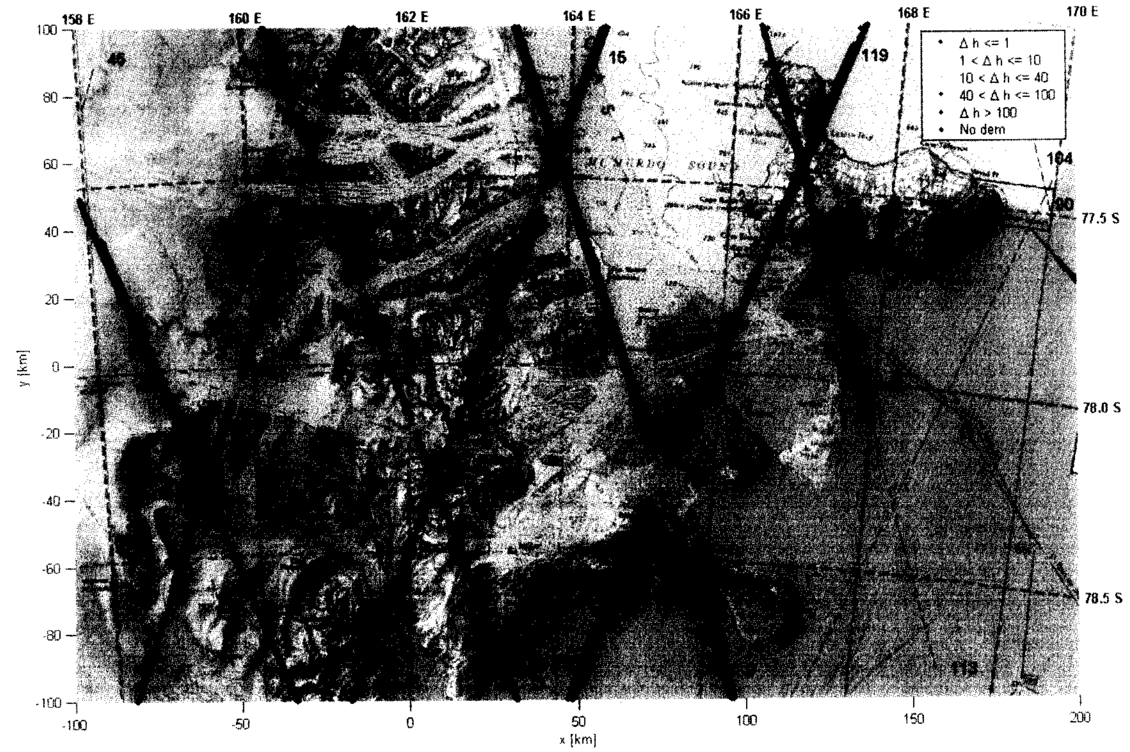


Fig. 7. ICESat GLAS points over the aircraft trajectories of the LIDAR surveys.

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