Digital Elevation Model of Polygonal Patterned Ground on Samoylov Island, Siberia, Using Small-Format Aerial Photography

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Abstract

Accurate land cover, such as meso-scale to high-resolution digital elevation models (DEM), is needed to obtain reliable inputs for modeling the hydrology and the exchange between the surface and atmosphere. Small format aerial photography can be used to acquire high-resolution aerial images using balloons and helicopters. This method presents a low-cost, efficient method to construct a DEM of the polygonal patterned ground on Samoylov Island in the Lena Delta, Northern Siberia (72.2°N, 126.3°E). The DEM should be the foundation for modeling meso-scale hydrological processes on the island and identifying locations of discharge. The whole island could be covered with images taken from heights between 600 m and 800 m. All points of the DEM, with a resolution on the ground of 10 m, have a horizontal and vertical accuracy better than 1.0 m. This accuracy and the resolution depend on the survey height, the resolution of the camera system, the number and the quality of the images, and the algorithms used in the analysis. All listed parameters are explained and discussed in the paper.

Keywords: aerial photography; balloon; digital elevation model; polygonal patterned ground; Samoylov Island.

Introduction

The application of small format aerial photography to acquire high-resolution aerial images is still challenging. Balloons, kites, and helicopters are interesting and valuable tools for aerial photography. Several techniques with their advantages and disadvantages are briefly introduced and discussed in Bigras (1996) and Henry et al. (2002). Boike and Yoshikawa (2003) showed the successful use of balloon aerial photography for mapping snow, ice, and periglacial landforms around Fairbanks and Ny-Alesund, Svalbard. Recently, Vierling et al. (2006) successfully employed a tethered balloon with an altitude up to 2 km to acquire remotely sensed data. Further application fields are briefly explained in Aber and Aber (2002).

The goal of our work was to generate a digital elevation model (DEM, regular or irregular distributed points) of the polygonal patterned ground on Samoylov Island in the Lena Delta, Northern Siberia (72.2°N/126.3°E). The DEM should be the foundation for the modeling of meso-scale hydrological processes on the island for answering questions like: where are polygonal seas, how big are they, and where does the water drain into the Lena?

The landscape of the island is shaped by the micro topography of the wet polygonal tundra. The development of low-centered ice-wedge polygons results in a prominent micro relief with the alternation of depressed polygon centers and elevated polygon rims with elevation differences of up to 0.5 m over a few meters distance. Satellite images with resolutions between 15 m and 30m, such as Landsat (Aber & Aber 2002), do not represent this micro relief sufficiently. Difficulties of using satellite images are discussed in detail by Dare (2005). It is, however, the most important factor for small-scale differences in vegetation type and soil moisture, and is therefore a major variable when considering heat and trace gas fluxes on the meso-scale.

Depending on the general conditions, feasible equipment, cost, and available measurement time, the required horizontal and vertical accuracy of the DEM should be better than 1 m. Since remote-control-aircraft and drones are not permitted in Siberia, we used a tethered helium balloon. In addition it was also possible to take images from a helicopter. The photogrammetric equipment consists of a Nikon D200 with a 14 mm lens, 26 fabric-made targets for ground control points (GCPs), and additional geodetic equipment (tachymeter Elta C30).

This paper presents a low-cost, efficient method to acquire high-resolution aerial images using helium filled balloons. It discusses (1) different steps of obtaining aerial images from a balloon and a helicopter, (2) data analysis, (3) advantages and disadvantages of different assimilation platforms and (4) further improvements to increase the resolution of the DEM and the horizontal and vertical accuracy of the coordinates of each point.

Methods

The motivation mapping of the patterned ground on Samoylov Island was achieved using photogrammetric methods on aerial images with overlapping areas, allowing the determination of 3D coordinates (stereoscopy). There are different methods available ranging from simple stereoscopic methods with two images to a bundle block adjustment (Henry et al. 2002) over all taken images. Here

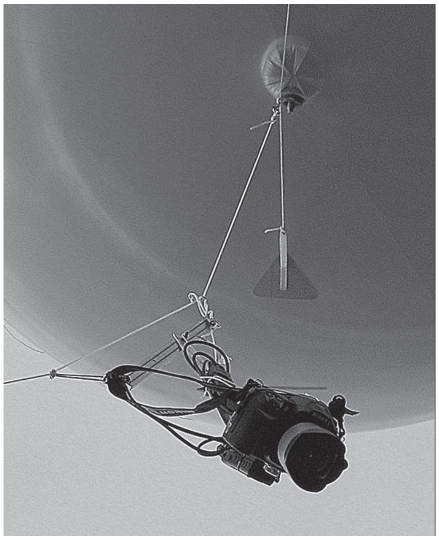

Figure 1. Camera system: Nikon D200, hanging at the tethered helium filled balloon.

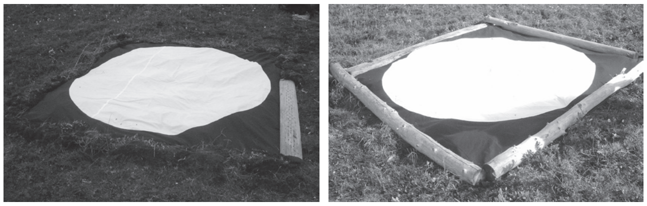

Figure 2. Fabric-made targets used as ground control points with a diameter of 2.5 m.

the former method was used, since the flight path, height, and orientation of the balloon and thus the resulting images were somewhat unpredictable. The data analysis then consisted of two important steps: firstly a separate backward intersection for the calculation of the image orientation and secondly a forward intersection for the calculation of the 3D coordinates of the points of the DEM.

Before the fieldwork was carried out, the optimal camera system and the number of the GCPs was determined. The pre-condition for the DEM was a resolution on the ground better than 10 m with an accuracy in coordinates better than 1 m. Thus prior calculations were done on flight height, the size of the GCPs, the distance between them, and the required number of images covering the whole island. The survey height and the number and size of the GCPs finally were a compromise between the available time for measurement, the investment for the camera system, and the mentioned optimal conditions for resolution and accuracy.

Equipment

The equipment for the aerial photography consists of a Nikon D200 camera with a 14 mm lens (Fig. 1) and 26 fabric-made targets used as GCPs (Fig. 2). The Nikon D200 is a digital mirror reflex camera with a CCD sensor of 10.2 megapixel. With the calculated flight height of 800 m, one pixel maps an area of ~0.12 m² on the ground.

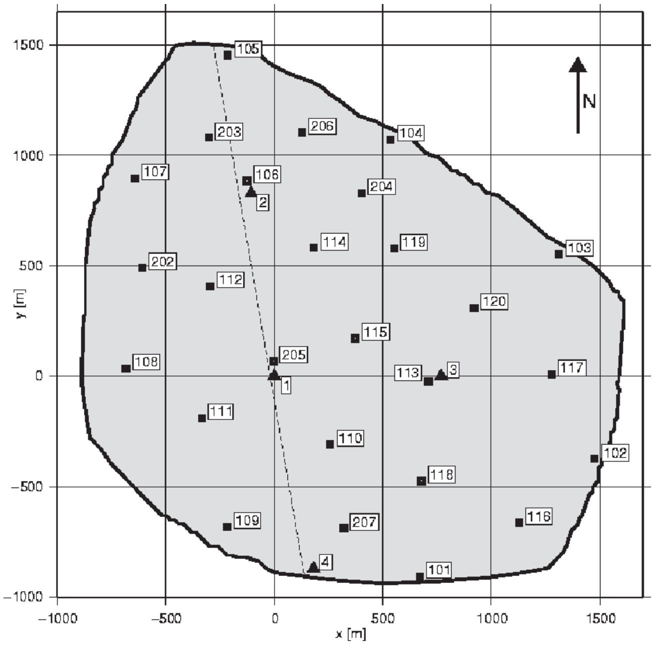

Figure 3. Schematic illustration of Samoylov Island: Network of 26 ground control points (squares); The coordinate (0,0) shows the origin of the local coordinate system with a fixed height of 100 m. The 4 datum points are displayed as triangles. The dashed line separates the flood plain (western part) and the plateau (eastern part).

Depending on the flight height, the focal distance of the lens, and the condition that each GCP should represent an area of at least 6 x 6 pixels in the digital images, their diameter had to be greater than 2.0 m (Fig. 2).

To precisely calculate the image orientation, it was necessary to set up enough GCPs on the island to get a minimum of 4 points within each image. Considering the calculated flight height of 800 m, this resulted in at least 20 GCPs (called 101–120) with a spacing of about 500m to get an optimal coverage of Samoylov Island (~5 km²). Six control targets with a diameter of 1.0 m were additionally laid out to condense the point network (point IDs 202–207). The entire network of GCPs is shown in Figure 3.

A local coordinate system on Samoylov Island was fundamental to the photogrammetric fieldwork. Therefore 4 datum points (Fig. 3, point IDs 1–4) were set up, each marked with a 1m iron pipe in the permafrost soil. The distances between these points reached from 800 m to 1200 m. In Figure 3 the coordinate (0, 0) shows the origin of the local coordinate system with a fixed height of 100 m. For setting up the coordinate system we used the tachymeter Elta C30. The repeatability of the coordinates of the datum points was better than +/-2 cm.

Fieldwork

The fieldwork was divided into two parts. Firstly, GCPs were laid out, and their coordinates were surveyed in the local coordinate system. Secondly, aerial photographs were taken using a tethered balloon and a helicopter.

After laying out the GCPs, their registration was conducted

Figure 4. Tethered balloon, filled with helium, diameter 2–3 m.

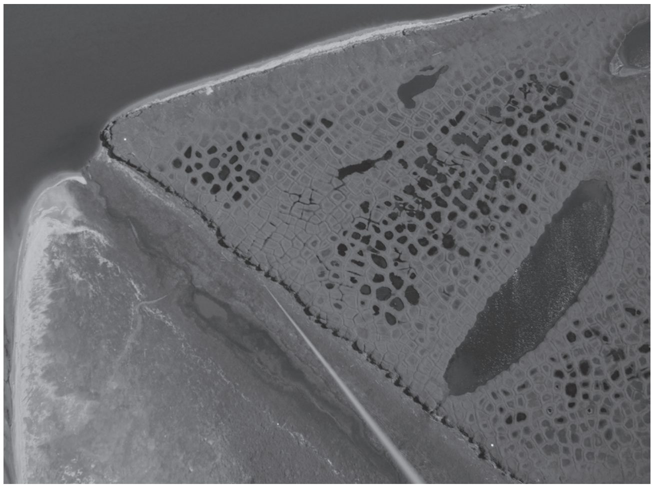

Figure 5. Polygonal patterned ground admitted from a height of ~750 m, in front the rope to the balloon.

in the local coordinate system with help of the tachymeter. The accuracy of the distances between the datum points and the GCPs was better than 1 cm. The coordinates of all GCPs had an absolute accuracy better than +/-5 cm. These accuracies depended on the determination of the center of the GCPs, the accuracy of the angle measurements with the tachymeter, and the distances to the survey points.

The balloon used in mapping the patterned ground on Samoylov Island is depicted in Figure 4, and an example image is given in Figure 5. The interval timer of the camera was adjusted to 1 minute, so the camera could take images for nearly four hours. Using the tethered balloon, one third of the entire island (western part, flood plain, Fig. 3) could be covered from a height of about 800 m.

Additionally, images were captured from a helicopter from altitudes between 600 m and 900 m. Using the helicopter, the middle part of the island could be covered with a flight height of ~600 m, the eastern part with flight heights of nearly 800–900 m.

Table 1. Nikon D200, interior parameters.

Parameter of inner orientation:	
Horizontal size Vertical size	3872 Pixel 2592 Pixel
Pixel size	0.0058mm
Principal point	x_0 = 0.10424mm y_0 = -0.19185mm
Principal distance	c = -13.32284mm
Parameter of distortion dx, dy (without units):	
Radial	a_1 = -0.000495642 a_2 = 1.65615e-006 a_3 = 0.0
Assymetric distortion Tangential distortion	b_1 = 1.72277e-005 b_2 = -1.51355e-005
Affinity Shear	c_1 = 0.000149996 c_2 = 2.72591e-005
r_0 - parameter	r_0 = 8.44

Calibration of the camera system

For the subsequent data analysis it was necessary to determine the parameters of the inner orientation of the camera system (interior parameters: principal distance c, coordinates of the principal point x_0, y_0, parameter of distortion dx, dy). The calibration of the camera system as specified in Luhmann (2000) was conducted before the fieldwork at the Institute of Photogrammetry at the Dresden University of Technology (Table 1).

To verify these camera parameters, a calibration-field was set up on Samoylov Island. Using the Elta C30, the coordinates of these points were measured with a relative accuracy of a few millimeters. The parameters of the inner orientation, that were consecutively determined, were nearly the same as in the laboratory, so the relation between the body of the camera and the objective can be assumed as stable.

Data Analysis

To analyze the collected data, a program was generated based on the algorithms of Luhmann (2000) and Schwidefsky & Ackermann (1976). The program includes the collinearity equations, which correlate the image coordinates (x,y) and the object coordinates (X,Y,Z) for each point:

$$x = x_0 - c \cdot \frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)} + dx \qquad (1)$$

$$y = y_0 - c \cdot \frac{r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)} + dy \qquad (2)$$

First, a backward intersection was calculated for each single image to determine the outer orientation (perspective center (X_0, Y_0, Z_0) and rotation matrix $\underline{R}$). Approximated parameters of the outer orientation were necessary and could be calculated applying a special algorithm developed by Schwidefsky and Ackermann (1976). The calculation of the outer orientation was successful for all images, which had minimized 4 GCPs.

Second, approximated coordinates for the points of the DEM were determined with help of a regular raster with a step size of 10 m based on the local coordinate system. The height of each point was set up to the average height of all GCPs. With the known outer orientation of the images a backward intersection could be determined for each preliminary point of the DEM, so the approximated positions could be found in the images. Then a search patch was defined around these locations and a matching-algorithm (with sub pixel accuracy) was implemented to locate precisely the same patch in other images. The matching algorithm was calculated with a cross-correlation:

$$k = \frac{\sum_{x'}\sum_{y'} g_1(x',y') \cdot g_2(x+x', y+y')}{\sum_{x'}\sum_{y'} g_1(x',y')^2 \cdot \sum_{x'}\sum_{y'} g_2(x+x', y+y')^2}$$

$$-1 \le k \le 1$$

At each position (x', y') a correlation coefficient k was determined depending on the gray scale value g of each pixel. The output consisted of a correlation image with all calculated values of k. Then, an algorithm was implemented which fitted an ellipsoidal paraboloid in the correlation image to find the exact position of the correlation maximum. At the end a forward intersection was calculated as a least square adjustment to get the exact 3D-coordinates for the points of the DEM.

The output dataset consists of all calculated coordinates, the standard deviation, and the correlation factor for the matching of one point between different images. If the correlation factor is greater than 0.7, and if the accuracy of the coordinates (horizontal and vertical accuracy) is better than 1 m, the point is stored as a point of the resulting DEM of Samoylov Island.

Results

Figure 6 shows the triangulated DEM. The horizontal and vertical accuracy of the coordinates of each point is better than 1.0 m (1σ, i.e., confidence interval of 68%). Polygonal lakes are easy to distinguish, because the algorithm was not able to match over the uniform water surface. Also, areas with bad data coverage are recognizable, for example in the southeastern part of Figure 6. The main reason for this is that the helicopter height changed very fast during the taking of the subsequent images, resulting in changing scaling factors of these images and smaller correlation factors. Other reasons for degraded correlation are poor illumination conditions and insufficient contours. As a result, only few points were found with a correlation larger than 0.7, whereas for most points the correlation factor was lower than 0.5. The island's center and the western and northern part have the best coverage of points. The helicopter was flying over the center at a nearly constant height of 600 m. In addition, the height of the tethered balloon over the flood plain (western part, Fig. 6) was nearly constant, which made the calculations (in particular the matching algorithm) really successful. The estimated points from both datasets could be matched with correlation factors up to 0.99 and with horizontal and vertical accuracies partially better than 0.5 m.

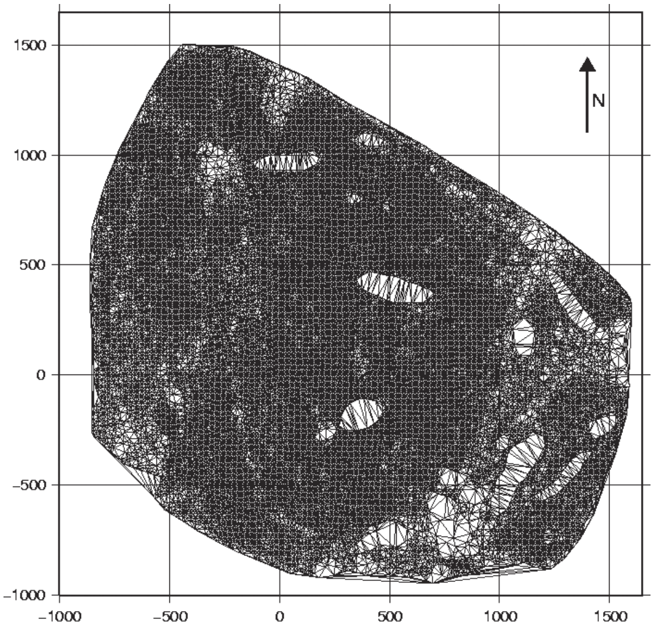

Figure 6. Triangulated irregular DEM with an approximated step size of 10 m of Samoylov Island: x- and y-coordinates are in a local coordinate-system (scale in m).

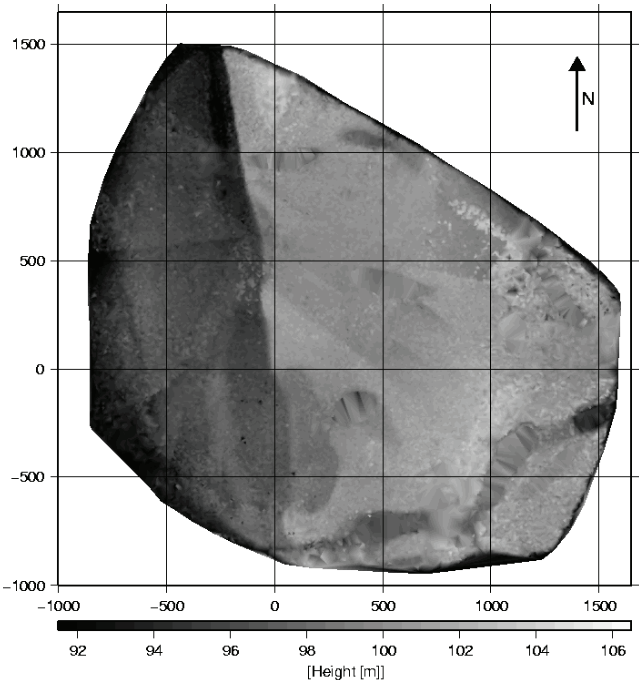

Figure 7. Surface of Samoylov Island: x- and y-coordinates are in a local coordinate system (scale in m). The heights of the points of the DEM are relative heights with respect to the origin of the local coordinate system (0.0) with a height of 100 m.

In Figure 7 the triangulated network from Figure 6 is shown as a surface for the whole island. The flood plain is easy to distinguish, as well as the ridge between the flood plain and the plateau and the cliff line with height differences up to 8 m.

Discussion

The goal of this project was to generate a DEM of the whole of Samoylov Island. The short observation period and the cost of and permission for the equipment formed the boundary conditions for the field work, under which a trade-off between the resolution, accuracy, and practicable amount of work for the acquisition and evaluation of photos had to be found. We finally decided to use a tethered, helium-filled balloon and a camera with a high precision lens (Nikon D200 with 14 mm lens). On the ground, 20 fabric-made targets with a diameter of 2.5 m and 6 targets with a diameter of 1.0 m spanned a network of GCPs.

Taking aerial photographs with a balloon is a low-cost and efficient method to acquire high-resolution aerial images. However, to take images with a balloon-borne camera, a calm day with good illumination conditions is required. Especially the wind speeds limit the observation time – during the 3 weeks of the field work on Samoylov Island we had only 2 days with good weather conditions. Taking images from a helicopter is independent from wind conditions and more stable in maintaining the height and the flight path. But this application is very expensive, and it is also dependent on good illumination conditions.

A sensitive step within the data analysis is the matching algorithm, because different illumination conditions like cloud shadows and different scaling factors of the images are a disadvantage. Also the search patch has to be big enough to get sufficient correlations between different images with high correlation factors. To avoid correlations between neighboring points of the DEM (this would degrade the accuracy of coordinates) the step size has to be at least twice the size of the search patch. Depending on the survey height of 800 m and a search patch of 24 x 24 pixel, the resolution on the ground of the DEM was set to 10 m. Therefore, all points of the generated DEM should be independent from each other.

Under these terms each point of the DEM has a horizontal and vertical accuracy better than 1 m. Naturally there are improvement possibilities to retrieve the micro relief of the polygonal wet tundra, such as the use of more and smaller targets for GCPs concomitant with a lower flight height and thus a higher resolution and accuracy. Furthermore the standard deviation of the coordinates of the DEM improve, if the points can be found in more than 2 images. Therefore, a better and regular image-coverage of the whole island from the same survey heights and good stereoscopic bases (relation between survey height and image-spacing) are a requirement for high resolution DEMs.

Conclusions

The method described in this paper is, depending on the measurement time, cost, and equipment, very useful to measure typical permafrost landscapes with the desired resolution and accuracy. Depending on the survey height and conditions described above, the horizontal and vertical accuracy of each point in the generated DEM of Samoylov Island shown in Figures 6 and 7 is better than 1.0 m for nearly 70% of all triangulated points. The obtained resolution of the DEM amounts to 10 m. Additionally, the combination of images from balloon and helicopter was successful if the flight height was approximately equal.

The meso-scale DEM discussed in this paper is now utilized (at the Alfred Wegener Institute for Polar and Marine Research in Potsdam) to determine the channel routing in a spatially distributed hydrologic model for Samoylov Island. Additionally, it is also possible to generate a orthomosaic (Bitelli & Girelli 2004) with the known parameters of the outer orientation of the images. This methodology provides a good basis for quantification of fluctuating coastlines in permafrost landscapes.

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