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Brief communication
"Application of mobile laser scanning in snow cover profiling"

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Abstract. We present a snowmobile-based mobile mapping system and its first application to snow cover roughness and change detection measurement. The ROAMER mobile mapping system, constructed at the Finnish Geodetic Institute, consists of the positioning and navigating systems, a terrestrial laser scanner, and the carrying platform (a snowmobile sledge in this application). We demonstrate the applicability of the instrument to snow cover roughness profiling and change detection by presenting preliminary results from a mobile laser scanning (MLS) campaign. The results show the potential of MLS for fast and efficient snow profiling from large areas in a millimetre scale.

1 Introduction

There has been an increasing interest in vehicle-based (mobile) applications of laser scanning in the recent years. The applications to environmental remote sensing have thus far been focused on vegetation studies and hydrology (Barber and Mills, 2007), while a number of applications have been presented for road and traffic monitoring (Kukko et al., 2007 and references therein). In mobile laser scanning, a terrestrial laser scanner (TLS), a global positioning system (GPS) receiver, and an inertial measurement unit (IMU) are implemented in a vehicle-based (mobile) platform (mostly a car, but there have also been applications using boats, snowmobiles, and all-terrain vehicles). Typically, the scanner operates in a two-dimensional profiling mode, and the third dimension is created while the vehicle moves. MLS systems are capable of faster and more efficient 3-D data acquisition than the traditional stationary TLS, especially in cases where ground validation (e.g., small-scale details) is needed for, e.g., airborne experiments or in the areas covered by Earth observing satellites (see Kaasalainen et al., 2008; Connor et al., 2009).

Snow roughness measurements are sparse in spite of their importance for, e.g., radar remote sensing (Rees and Arnold, 2006) and snow reflectance modelling (Warren et al., 1998). The characteristics usually calculated to represent surface roughness are root-mean-square changes and the shape and length of an autocorrelation function. The ability of these parameters to characterize snow features like grain size is still being studied. Multi-scale surface roughness is needed to characterize the surface properties relevant to radar backscattering (Rees and Arnold, 2006). Larger scale topography is important with respect to the local incidence angle in radar measurements, whereas small-scale topographic variation changes the local solar incidence angle and hence affects the surface reflectance measurement. Mobile laser scanning is capable of providing snow roughness in multiple scales. Thus far, snow surface roughness measurements have been mostly based on field techniques (e.g., photography) or airborne laser scanning (Rees, 1998; Rees and Arnold, 2006; Höfle et al., 2007). Terrestrial laser based profiling has also been tested, even on a moving platform, but without the orientation information from the IMU, which lead into correction of mixed signals from the snowmobile movement and actual surface roughness (Lacroix et al., 2008 + see this reference for a review of snow roughness measurements and results).

Laser-based methods have also been used for validation of air and satellite radar measurements of snow cover. As the satellite-based SAR has a global coverage, the higher accuracy provided by laser scanning can be used in validation and ground truth for satellite measurements (e.g., Connor et al., 2009). TLS has been found a potential technology for snow depth measurement in, e.g., avalanche regions

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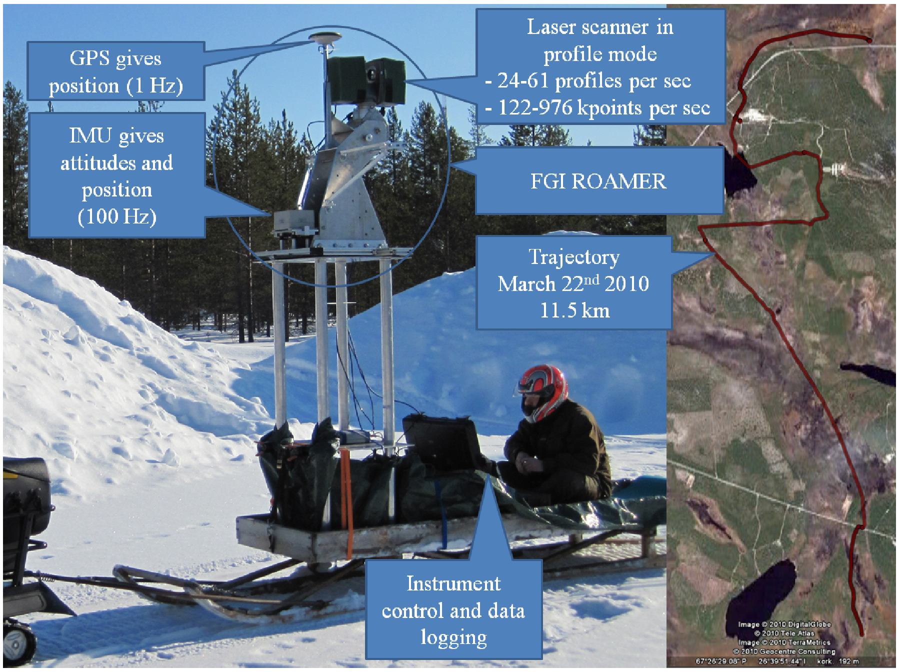

Fig. 1. Left: the ROAMER mobile laser scanning system mounted on the snowmobile sledge. Right: the trajectory of the 22 March measurements.

(Prokop, 2008). Mobile laser scanning could also provide validation for SAR-based snow covered area estimation, especially in forested areas, where the snow forest interaction is increasingly important for hydrological and climate models (e.g., Luojus et al., 2009).

2 Methods and study site

A mobile road environment mapping system called ROAMER (Kukko et al., 2007; Kukko, 2009) was used for the mobile measurements. The FGI in-house developed ROAMER-system consists of a FARO Photon™ 120 terrestrial laser scanner and NovAtel SPAN™ positioning system (NovAtel DL-4 plus GPS-receiver, NovAtel GPS-702 antenna and Honeywell HG1700 AG58 inertial measurement unit). The FARO scanner is a continuous wave, 785 nm terrestrial laser scanner. It uses a phase modulation technique for distance measurement and has an unambiguity range of approximately 153 m. The distance measurement error is 2 mm at 25 m. The beam size is 3.3 mm at exit and the beam divergence is 0.16 mrad. For snow cover mapping, the point measurement frequency was 244 kHz and scanning frequency 49 Hz. For georeferencing of the laser data, continuous GPS observations are logged at 1 Hz and IMU data at 100 Hz intervals to track the carrier vehicle movements. The navigation data are computed in post-processing to solve the scanner trajectory (attitudes and position) at a resolution of 1/100 s. With the computed trajectory and time synchronization information each measured laser point is transformed into a global coordinate system and further to a local map grid system. Prior to detailed surface analysis, filtering methods need to be applied to the georeferenced point data to remove stray and sky points, and noise caused by direct sunlight into the scanner head. Geometric quality control of the mobile data, and the possible adjustment/correction for systematic errors, is an essential phase to get reliable analysis, especially in change detection studies between different data sets. Therefore, Virtual Reference Station (VRS) GPS measurements and additional TLS scans would provide a reasonable way for geometric validation of MLS data.

The MLS on a snowmobile presented in this communication was carried out in March 2010 in Sodankylä, The Finnish Meteorological Institute Arctic Research Centre (67.4° N, 26.6° E). The experiments were a part of the Snow Reflectance Transition Experiment (SNORTEX) campaign supported by the EUMETSAT and meteorological institutes. A more detailed description of the campaign site is provided in Roujean et al. (2009). Some test runs with the snowmobile system were carried out in 2009 with a so-called stop-and-go mode and stationary TLS measurements. Stationary TLS has also been applied for snow cover measurement in our previous research (Kaasalainen et al., 2008). Figure 1 presents the measurement setup on the snowmobile sledge and the measurement trajectory in 22 March. Mobile data were collected on four days, one acquisition run per day. The first three runs were at different locations, but the fourth run (length 11.5 km, see Fig. 1) also covered two of the earlier

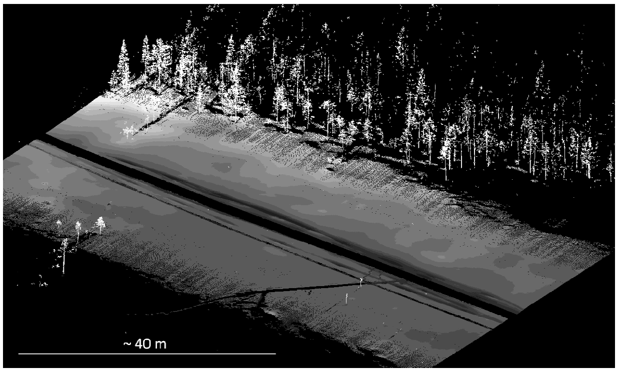

Fig. 2. Example of an MLS data block from the test site. Grey tones denote the surface elevation. Snowmobile track and the shadow of the laser sensor split the data in the middle. Continuous profiling along the track is possible over the entire 11.5 km study area.

runs. At snowmobile velocity of $3\,m\,s^{-1}$ the scanning of the 11.5 km leg took approximately 65 min, and the time required for GPS/IMU initialization was about 1 h.

A snowfall occurred before the fourth run; the increase in thickness was 6cm according to FMI's automatic snow depth monitor. The average velocity of the snowmobile was about $3\,m\,s^{-1}$, resulting in 16 profiles per 1 m. VRS-GPS (Leica SR530 + AT502) was used to measure control points along the snowmobile track: route sign pole tops, corners of signs, bridge railing and asphalt points. These points were used for controlling the MLS data quality between different scanning runs.

3 Results

Examples of surface profiles from the ROAMER measurements in 18 March and 22 March are presented in Figs. 2 and 3. Although the absolute repeatability (precision) of the measurements can be several centimetres (caused by the positioning error of the GPS/IMU solution, see Kukko et al. (2007) for more details), the relative accuracy is good enough in representing the vertical mm-scale changes in the surface shape. This is visible in the data in Fig. 3. Figure 2 also illustrates the efficiency of the method: continuous surface profiling along the track is available in the entire 11.5 km trajectory. To assess the accuracy and repeatability of the distance measurement of the laser scanner, we analyzed a measurement of 212 profiles taken in the same spot, i.e., while the snowmobile was not moving. The standard deviation of the average of the 212 corresponding points from each profile increased linearly as a function of distance from about 0.7 mm at 3 m to about 2 mm in 11 m, which indicates that the system is capable distinguishing the surface roughness features in the (sub)millimetre scale. The repeatability of the moving system was assessed by measuring the systematic elevation error by means of comparing MLS data with VRS-GPS checkpoints on a bare asphalt surface. The data from 18 March were in good agreement with the 44 overlapping checkpoints, as the average difference was −3 mm with 16 mm root mean square error (RMSE) and 16 mm standard deviation (STD). On 22 March the same road patch was measured twice resulting in a 31 mm average difference to 67 check points, with 36 mm RMSE and 18 mm STD in the first run. The corresponding values for the second run for 59 checkpoints were 27 mm mean difference, with RMSE 30 mm and STD 13 mm. This indicates the system absolute repeatability to be better than 5 cm. It is also notable that the mean elevation difference between the two runs in 22 March was only 4 mm. Together with the results from the stationary test of the 212 profiles, this indicates a relative accuracy of less than 10 mm for the system. The major part of the systematic error is most likely caused by the GPS-IMU initialization. The increase in snow depth is visible in Fig. 3, where laser profiles from 18 March and 22 March measurements have been combined. The systematic elevation error between the two data sets was eliminated by comparison of the reference point elevations (described above). Along the snow profile transect the snow surface change was found to be 3–6 cm, the best reliability at points closer to the scanner trajectory. The result also points out the feasibility of the instrument in snow cover change detection and measuring relative differences in the snow surface.

The scanning range of the FARO Photon™ 120 scanner is about 120 m, and there are scanners with even greater range for the distance measurement. However, the measurement geometry (i.e., the scanner mounted in about 2.5 m height from the ground, see Fig. 1) causes the received signal to decrease significantly at distances greater than 20–30 m, because the beam incidence angle to the snow surface is quite large (about 60°–70°) at these distances. Therefore the maximum cross-track distance is limited to 20–30 m for flat surfaces. Also the laser footprint increases and the spatial distribution of the points becomes unfavourable as the range extends. With the scanning parameters in this experiment (244 kHz point measurement and 49 Hz scanning frequency), the cross-track point spacing in the profile on the snow surface is less than a centimetre at ranges below 5 m, and equals to the approximate (along track) profile spacing of 4–6 cm at 10–15 m.

4 Conclusions

In this communication, we introduce a mobile laser scanning application that it is capable of efficiently retrieving snow roughness (parameters) over large areas from centimetre to millimetre scale, as well as snow surface change detection. This is to our knowledge the first application of vehicle-based (mobile) laser scanning in the context of cryospheric studies (especially as the environmental applications of mobile laser scanning in general have thus far been limited). The mobile

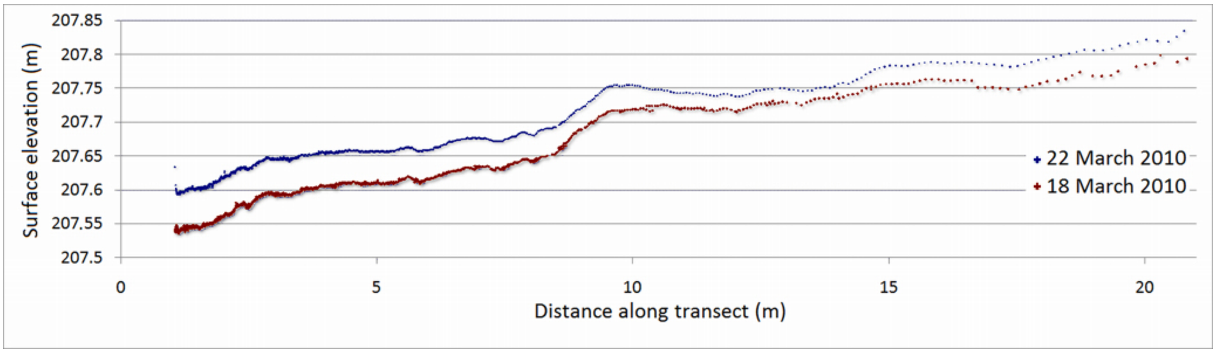

Fig. 3. Snow surface roughness from 18 March and 22 March MLS profiles. The roughness graphs are plotted along the scanned profile (i.e., perpendicular to the trajectory), the first point is at the distance of 1.05 m from the scanner.

approach is capable of providing multi-scale data from 1mm to several meters in the vertical scale, and from cm-scale to several meters (and even kilometers) in the horizontal scale. Small-scale surface roughness is important in the study of surface reflectance. Mobile laser scanning provides better possibilities for statistical analysis of snow surface roughness and its impact on surface albedo, than the traditional (field) methods, which are labour intensive and spatially limited. The horizontal profiling measurement frequency will increase in the near future, along with new scanners with increased profiling frequency. Comparing MLS data with that obtained from other methods will be important for accuracy validation in the future studies. The future work will focus on improving the efficiency of the measurement and data processing, and improved synergy between other data sources (such as airborne and field techniques), to provide reference data and ground truth for airborne and satellite applications.

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