MEASURING AND MONITORING SNOW DEPTH USING THE GLOBAL POSITIONING SYSTEM

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ABSTRACT

Ski resorts need to monitor snow depth over their slopes from the start of the accumulation or snowmaking season until spring closure. There is currently no system available that provides real-time, high-resolution, high-frequency data for mapping snow over space on an operational basis. Air- and space-borne sensors either lack the spatial resolution or temporal frequency necessary for daily ski resort operations. In addition, inclement weather reduces the capabilities of sensors in the visible portion of the spectrum. We evaluated the potential of the Global Positioning System (GPS) to meet the operational needs. We used post processed kinematic GPS equipment for a static survey over a fixed transect to find the capabilities of the system to detect changes in the elevation of the snow surface through time and over space. The GPS equipment was also mounted on over-snow vehicles to determine the effect of vehicle movement on GPS accuracy. Our results suggest that GPS equipment should allow ski resorts to measure snow depth well within the study design constraints of 0.15 m.

INTRODUCTION

Information on snow depth is a valuable for a number of applications including hydrology, transportation, wildlife management and recreation. Measuring snow depth at a point is a relatively simple task, either manually with a probe or remotely with instruments such as acoustic sounders. However, obtaining spatially distributed data of snow depth has remained enigmatic, particularly if frequent temporal observations are sought. Remote sensing of the snowpack in the microwave frequencies offers hope for the future, but no operational tool exists with high spatial and temporal resolution, and high accuracy. Ground penetrating radar has shown potential, but retrieval algorithms for snow depth have proven problematic for the extreme heterogeneity inherent in snowpacks.

Managers in winter recreation pay little attention to water equivalence in accumulated snowpacks, but are critically aware of snow depth. In particular, ski resort managers and personnel are concerned with snow depth for two major reasons. The first reason relates to clients and their experience and safety. Snow depth controls opening and closing dates for ski resorts, and within-season closure of ski runs with marginal depth. Client safety is compromised when rocks and bare patches are exposed and the client's experience is diminished when bare patches are observed, even if the hazard is removed through closure. From an operational perspective bare patches alter local energy balance and increase melt rates of remaining snow around bare patches. Further, thin patches melt faster than thicker snowpacks if they are thin enough to transmit radiation to the substrate, which typically has a much lower albedo than snow. Ski resorts also find greatly increased operational costs due to vehicle damage when groomers and other over-snow machinery encounters dirt, mud and rocks.

The second major reason snow depth information is desirable results from the increased reliance of snow making operations to ski resort viability. Ski resorts in all climatic realms are now installing and using artificial snow. Although most operations know how much water is consumed in snow making to a high degree of accuracy, they have little idea of how much snow they actually produce. Losses to sublimation and drift, and changes in density all affect depth and distribution of snow reaching the ski runs. A method of measuring depth over the ski run before and after snow making would help managers optimize their efforts. Increasing efficiency in snow making operations is motivated by the enormous electrical consumption of compressors, environmental issues such as in-stream and minimum winter flows from water sources, and the high cost of water in some areas.

To put the value of snow making and grooming operations in perspective, it is useful to examine real costs since factors such as visitor perception, environmental impacts and technical inefficiencies are difficult to quantify. Booth Creek Ski holdings spent over 18 million dollars on snow making and grooming operations at their eight ski resorts during the 1999 water year. This figure includes payroll, equipment depreciation and expenses.

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We examined possible solutions to allow us to map snow depth in an operational realm at ski resorts. The solution design criteria we used were: 0.15 m vertical accuracy; 0.15 m horizontal accuracy; 5 to 10 m horizontal spatial frequency; daily temporal frequency; all weather (snow, rain, shine); all time (potentially 24 hours a day, most grooming operations are between 1600 hours and 0900 hours due to client safety); cost effective; and robust equipment (nasty conditions: hot-cold, wet-dry, freezing-thawing, vibration). We examined various methods including the Global Positioning System (GPS), ground penetrating radar (GPR), airborne LIDAR, and other air- and space-borne sensors. All of the possible solutions, except GPS, had some constraint that precluded further investigation.

THE GLOBAL POSITIONING SYSTEM

The best potential solution we found to measure snow depth and satisfy the solution criteria was the Global Positioning System. Although it is a relatively new technology, other researchers in snow and ice have quickly realized the utility of the Global Positioning System. GPS has been applied to the field of glaciology to determine mass balance through surface elevations of the ice (Eiken *et al.*, 1997; Jacobsen and Theakstone, 1997). Survey-grade GPS offers vertical accuracy of 0.02 m and horizontal accuracy of 0.01 m, and horizontal spatial resolution at almost any resolution the user desires, although it is dependent on vehicle speed. GPS is an all-weather system. GPS operates 24 hours per day, however, there are optimal times where results are superior and sub-optimal times where results will not meet high-accuracy needs due to satellite availability and geometry. Further details and discussion of these criteria and GPS's ability to meet them are provided below. Theoretical treatments of the Global Positioning System can be found in Hofmann-Wellenhof *et al.* (1994) and Leick (1995).

The concept for an operational snow depth measuring and monitoring program is as follows. A ski resort would invest in a high-resolution digital elevation model (DEM) of the resort's terrain. The DEM could be generated by conventional methods such as aerial photogrammetry or airborne LIDAR, or alternatively could be generated on the ground using the GPS equipment mounted on ATVs or grooming equipment. A horizontal resolution (grid size) of 5 to 10 m would be necessary, with a vertical accuracy of 0.15 m. GPS equipment mounted on groomers used in daily operations would then collect surface elevation data while performing routine tasks. Real time kinematic (RTK) equipment on-board the groomer would then calculate snow depth at the current location based on a comparison of the measured elevation and the corresponding elevation from the DEM. The depth information could be provided in real-time to the equipment operator through a variety of media including an on-dash digital display. Similar systems are used in mining operations at present, e.g. to optimize extraction of a coal seam in an open pit mine.

STUDY SITES

Studies were carried out at Cameron Pass and Telluride, Colorado. The Cameron Pass site is in the Front Range about 2 km south of the pass on State Highway 14 at an elevation of about 3300 m a.s.l. The site was characterized by undulating terrain with a variety of aspects, and a limited range of slope and elevation. This location was used for the fixed transect described below. Figure 1 shows the layout of the fixed transect on Cameron Pass. The tests involving over-snow vehicles were conducted at the Telluride ski resort in the San Juan Mountains, in Southern Colorado. The site consisted of a north-facing ski run typical in aspect, slope and elevation of many North American ski resorts. Figure 2 shows the position of the data collected on a portion of the ski slope at Telluride.

METHODS

Equipment

We used Trimble Navigation, Inc. GPS products for this study. We selected a survey-grade system to meet our accuracy constraints. We chose the PPK equipment, rather than RTK equipment for cost reasons. Application of GPS to operational snow depth measurements would require RTK equipment, but the study was not affected by our choice. We used Trimble's 4600LS system with their TSC1 survey controller. All GPS data were post processed on a lap top computer using Trimble's TSOffice software operating under Windows98. Statistical analyses were carried out using the S-Plus mathematical language in the Unix environment.

Field Studies

We evaluated the GPS equipment for snow depth monitoring in three different realms. First, we monitored changes in snow depth on a fixed stake network where no over-snow vehicles were involved. Fifty sites were chosen in a small alpine basin with a range of slopes, aspects and tree cover. Each location was marked with a 3 m PVC stake and each stake was consecutively numbered. The sites were visited on eight separate occasions through the accumulation and ablation season. At each visit the surface elevation of the snow was measured with the GPS equipment. At the same time the depth of the snowpack was measured to the nearest 0.01 m with depth probes. After two surveys we felt the error in correctly identifying the base of the snowpack was too large due to mud and soil and a lack of a hard interface between the snow and substrate at most sample locations. Beginning on the third survey we measured the distance from the top of the stake to the snow surface to the nearest 0.01 m. Only the final six surveys were used in the subsequent analyses. Change in elevation between survey dates using the GPS was then compared to the change in stake height as measured with the tape. We felt that this test would give us a baseline on the best-case scenario for accuracy of snow depth because the largest potential errors would be our actual measurements of snow depth at the predetermined points. The remaining errors would be attributable to inherent accuracy with the GPS itself. This portion of the study is referred to as the fixed transect hereafter.

The second test we performed was to mount the GPS equipment on a snowmobile and measure the snow surface elevation, then repeat the measurements and quantify the differences. The snowmobile allowed us to collect a large data sample during business hours because snowmobiles are semi-compatible with skiers during operational hours, whereas grooming equipment can only be used when the ski resort is closed to the public. The snowmobile tests were, however, constrained by time and cost. We did not have a high-resolution DEM of the Telluride ski terrain and we did not have the luxury of repeated visits to the study site. There are, however, two ways to evaluate the accuracy of the equipment. One method would be to measure real changes in snow depth with manual equipment (probes) and the GPS and compare results. The second alternative is to measure the same surface twice, with no change in depth, and compare the results. Any difference in depth between the repeated measurements indicates an error in measurement attributable to the GPS. This method has the advantage of little investment in time or infrastructure, while producing a quantification of errors. The latter method was used in this study. These data allowed us to quantify the effects of vehicle speed and cover a large portion of a ski resort where the system may eventually be used. This portion of the study is referred to as over-snow vehicle hereafter.

The third test involved mounting the GPS equipment on a groomer, as it would be for operational purposes. We then mapped the existing snow surface elevations over a transect with the groomer. The groomer then repeated the same transect while cutting and filling sections of the transect with the blade. The difference in the treatment (cut/fill) from the previous surface would then be compared to snow depths measured manually with depth probes before and after the treatment. A shallow snowpack at the Telluride ski resort made significant treatments undesirable for ski management and difficulty in relocating the exact probe sites with post processed kinematic (PPK) GPS equipment made this portion of our test inconclusive. The following discussion will be limited to the fixed transect and the snowmobile results.

RESULTS

Fixed Transect

Table 1 shows the transect results from the Cameron Pass study site. Values are based on the difference between the elevations measured with the GPS equipment on two separate dates and the change in height of the stakes measured above the snow on the same dates as described above. Thus, these values represent errors rather than actual surface elevations or changes in elevations. If both measurement techniques were perfect, then these differences would all be zero. The data are separated into ranges of differences, which effectively removes outliers by constraining the differences. The 0 to 5.00 m range includes all of the data. The large errors between 1.00 and 5.00 m have a profound effect on the statistics such as the mean and standard deviation. These values represent 28 measurements, or about 5% of the data. Constraining the data further improves the mean and standard deviation of the differences considerably. By removing about 10% of the data we reduce the standard deviation of the differences to only 0.05 m. Note that removal of one data point from the 0 to 0.75 m range reduces the maximum difference to 0.15 m. Note also that the median value of the differences is very stable throughout at 0.05 to 0.06 m and the standard error of the mean is small in all cases. Figure 3 shows the histogram of frequency versus the errors for the full set of comparisons (row 1, Table 1, less the 4.57 m value, n = 552).

Figure 4 is a scatter plot of the differences in surface elevations from the different surveys with the values measured by tape plotted against the corresponding values measured by the GPS. The two data clusters on the line of 1:1 correspondence simply an artifact of the sampling schedule and precipitation regime and represent the fact that our surveys represented two separate conditions. The first showed little real change in snowpack depth between surveys and the second showed substantial change.

Table 1. Statistics for errors between GPS and tape measurements on the fixed transect located near Cameron Pass, CO. The rows represent different thresholds of errors, effectively removing potential outliers.

Range of Differences	Minimum (m)	Maximum (m)	Median (m)	Mean (m)	Std. Dev. (m)	Std. Error of the Mean (m)	n
0 – 5.00 m	0.00	4.57	0.06	0.22	0.58	0.025	553
0 – 1.00 m	0.00	0.98	0.06	0.06	0.17	0.007	525
0 – 0.75 m	0.00	0.72	0.05	0.06	0.05	0.002	502
0 – 0.15 m	0.00	0.15	0.05	0.06	0.04	0.002	501

Over-Snow Vehicle

The results from the GPS measurements taken on the snowmobile are shown in Table 2. Measurements of location and elevation were recorded at a regular time step (1 second) rather than at fixed points. Therefore, the probability is small that any two measurements were perfectly coincident in space was small. In order to evaluate the repeatability of the GPS system for point elevations we used various thresholds of horizontal distances between points to select the relevant data. Thresholds between 0.10 m and 10.0 meters were used where the distance was simply the horizontal vector between the locations without consideration of changes in elevation. Table 2 shows that for points separated horizontally by no more than 0.10 m the elevations were consistent with a maximum elevation difference of 0.03 m, a median difference of 0.003 m, and a mean difference of 0.004 m. For points separated by 10.0 m or less the maximum difference in elevation was 0.31 m, with a median value of 0.032 m and a mean value of 0.049 m. Even at separation distances less than or equal to 10.0 m the maximum difference was 1.58 m and the median and mean were 0.136 and 0.230 m, respectively. The median and mean values indicate a right skewed distribution where the mean values are heavily affected by a few large differences. Standard error of the mean is small in all cases. Figure 5 shows the histogram of frequency versus measured differences for all of the data in the 10.0 m comparison (n = 2260).

Table 2. Results from the over-snow vehicle tests. Statistics on elevation differences are a function of horizontal separation distance between two measurements.

Separation Distance (m)	Minimum Difference (m)	Maximum Difference (m)	Median Difference (m)	Mean Difference (m)	Std. Dev. Difference (m)	Std. Error of the Mean (m)	n
0.10	0.00	0.03	0.003	0.004	0.004	0.0003	131
0.25	0.00	0.05	0.004	0.008	0.009	0.0007	180
0.50	0.00	0.09	0.008	0.015	0.018	0.001	264
1.00	0.00	0.31	0.032	0.049	0.051	0.002	648
5.00	0.00	0.70	0.078	0.116	0.119	0.003	1428
10.00	0.00	1.58	0.136	0.230	0.253	0.005	2260

DISCUSSION

Fixed Transect

The data in Table 1 indicate that the errors are right skewed and the distribution is affected by the few large errors. The low and consistent median values indicate this skew for the entire data set when compared to the mean values as shown in Figure 3. The reason for the large errors is not readily evident. Our observations in the field while surveying the points suggested that the large errors would be associated with high position dilution of precision (PDOP) or low numbers of satellites. PDOP is an index of the geometric quality of the satellite configuration in the sky at the time of measurement. High PDOP values are generally correlated with large errors and result when the satellites are clustered or lined up rather than spread out across the available sky hemisphere. Analyses of errors and associated PDOP and satellite numbers did not support our conjecture. We did notice that two portions of the transect consistently produced the largest errors. We believe the effect on the GPS measurements is attributable to terrain and proximity of trees.

A portion of the errors in Table 2 were due to GPS related variability. Measurement of the change in snow height relative to the stake is an additional source of error. Measurements with the tape is probably plus or minus 0.01 to 0.02 m due to slope effects and variability in repeating the measurements at exactly the same point. An attempt was made to place all of the stakes in the snow with the base at or below the ground surface. The stakes may have moved slightly in soft soil or mud as the ablation season progressed. Such a change would not be detected by the GPS measurements but would affect the tape measurements.

Over-Snow Vehicle

The values shown in Table 2 do not suggest error in measurement alone. We must also account for the geometry of slope and distance. The mean slope of the study area was about 10°. For a 10° slope the vertical difference over a horizontal distance of 10 m is about 1.7 m. Therefore, we would expect to measure differences with a mean value on the order of 1.7 m or less in the 10 m category. It may be in fact that we are getting compensating errors, however, we would expect the errors to be random and there should be some values in excess of those attributable to slope alone. Slopes on the field site varied between 5° and 15°. Figure 5 shows the elevation differences plotted against the distance between points. The two envelopes for the 5° and 15° slopes are plotted for reference. It is clear that in general the magnitude of the differences is proportional to the horizontal distance between the points. This result suggests that the true error in the measurement technique is probably best described by the 0.10 m separation range shown in Table 2. The errors are small and are probably more representative of attainable accuracy than the fixed transect results discussed above. Note also that the errors are normally distributed around zero (the histograms in Figures 3 and 5 and statistics in Tables 1 and 2 are for the absolute values of the differences). The fixed transect data had a larger mean and median difference which is partially due to errors in the tape measurements, rather than the GPS measurements.

It should be noted that the test for separation distance automatically culls the extreme outliers from the data set. There are a small number of data points that clearly represent errors as seen in Figure 2 where points fall outside the linear paths followed by the snowmobile. These represent real errors and potential problems in the measurement system. However, simple error checking algorithms incorporated in the data reduction or mapping programs could eliminate such outliers. These anomalous data points lead to peaks and holes when the data are mapped that are obviously erroneous. These points with large errors occur when the satellite geometry is poor or there are too few satellites above the local horizon. These circumstances occur due to the constantly changing orbit of the satellites and local horizon effects caused by terrain or vegetation. Mission planning will help reduce these errors by choosing measurement times when optimal satellite numbers and geometry occur. Using vendor software, these optimal periods are easily identified before they occur.

The results also suggest that the GPS measurement technique is viable for over-snow vehicles in motion. The speeds used in the data collection were 15 to 30 kph with a mean speed of about 20 kph. This range of speeds is typical of grooming operations. The upper bounds are probably too high for the larger over-snow vehicles, particularly if the vehicle is tilling or climbing. We would expect measurement accuracy to decline with increased velocity, which suggests that our results are conservative rather than optimistic.

The tests were performed on a north-facing slope which provides the poorest satellite geometry for GPS derived locations in mid-latitudes. Results on north-facing, mid-latitude slopes in the Northern Hemisphere are compromised due to decreased satellite coverage as a function of latitude and horizon effects. Better results could be expected on slopes with southerly exposures. However, most ski resorts in North America are located with northerly aspects because of the favorable energy balance that prolongs the snow accumulation and ablation seasons.

CONCLUSIONS

It appears that the GPS is capable of operating in the ski resort environment at an accuracy close to the GPS manufacture's specifications, i.e. 0.01 m in the horizontal and 0.02 m in the vertical. Terrain, weather, vegetation, vehicle movement, satellite geometry and other variables will all potentially diminish the accuracy. Our results suggest that actual accuracy will be within the constraints desired by ski resorts for measuring snow depth: 0.15 m. Final accuracy of mapped snow depth and utility of the method will ultimately depend on the software developed for the application.

FUTURE WORK

The method needs to be tested operationally using GPS equipment with RTK capabilities. Ideally the method should be tested over an entire season at a ski resort with a wide range of terrain represented. The operational tests need to be combined with data reduction and mapping exercises that will allow error checking and mapping of snow depth on a real-time basis. Testing the method would require dedicating several hours per day of a computer operator's time for data processing and mapping. One grooming machine would need to be outfitted with the RTK GPS equipment.

ACKNOWLEDGEMENTS

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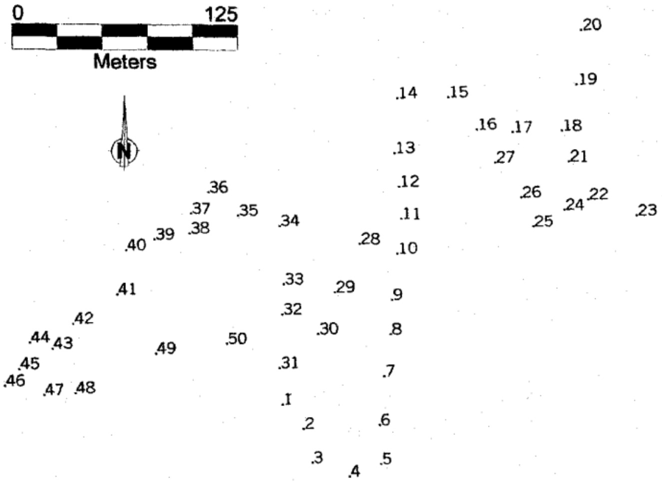

Figure 1. Point locations on the fixed transect near Cameron Pass, Colorado. A PVC stake was placed at each numbered point for reference.

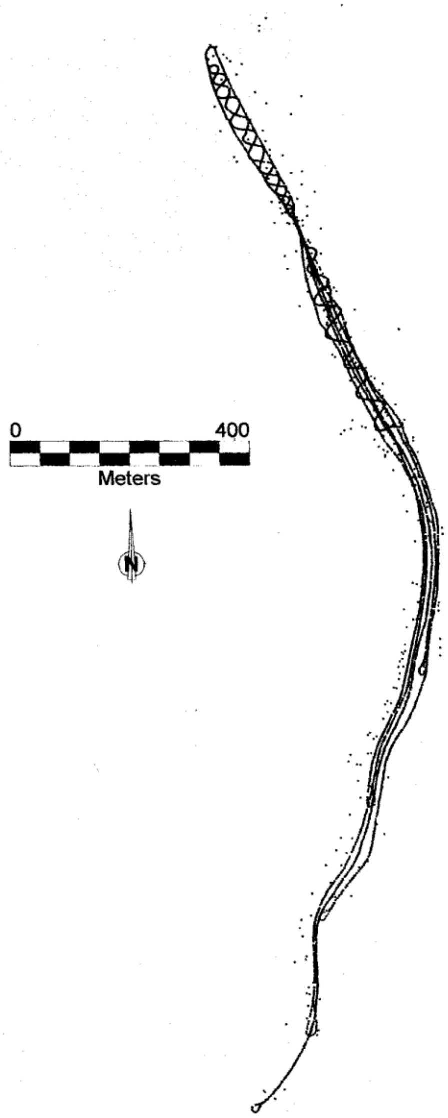

Figure 2. Measurement points from over-snow vehicle survey at Telluride, Colorado. Each point represents an acquired location measurement with an associated latitude, longitude and elevation. The linear features represent two passes over the same track.

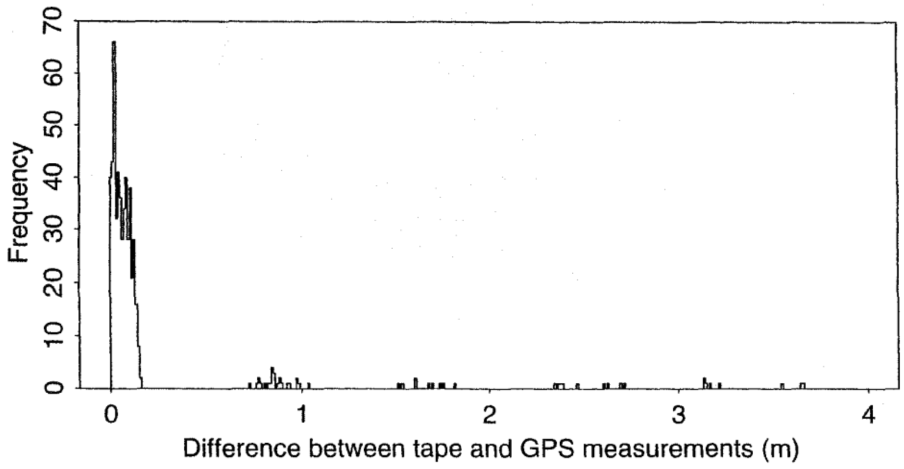

Figure 3. Histogram of frequency versus error for the full data set of comparisons from the fixed transect near Cameron Pass, Colorado. The data represent differences between all survey dates. A single maximum value of 4.57 m is not plotted in the graph to increase readability.

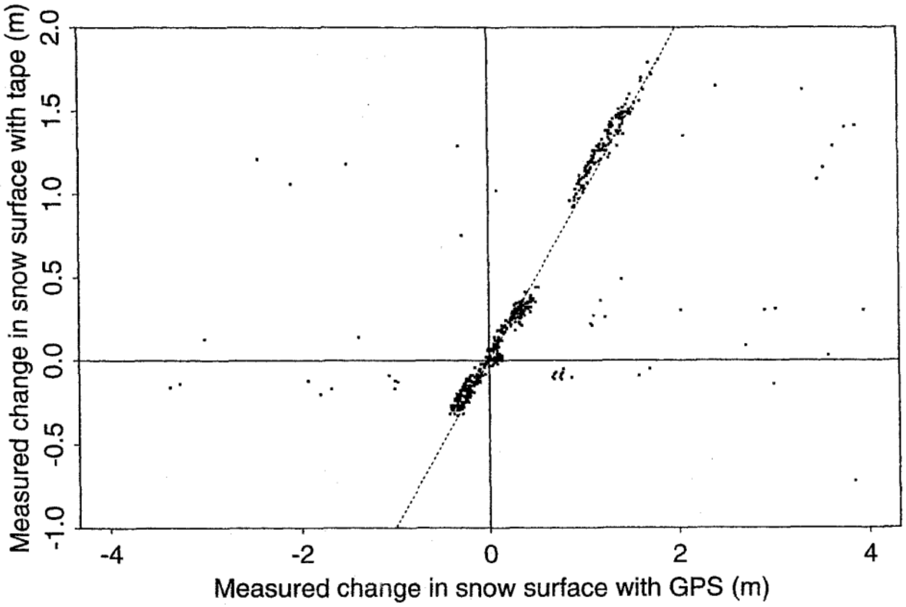

Figure 4. Scatter plot of the difference in snow surface elevation measured with the tape versus the elevation difference measured with the GPS. The dotted line represents the line of 1:1 correspondence.

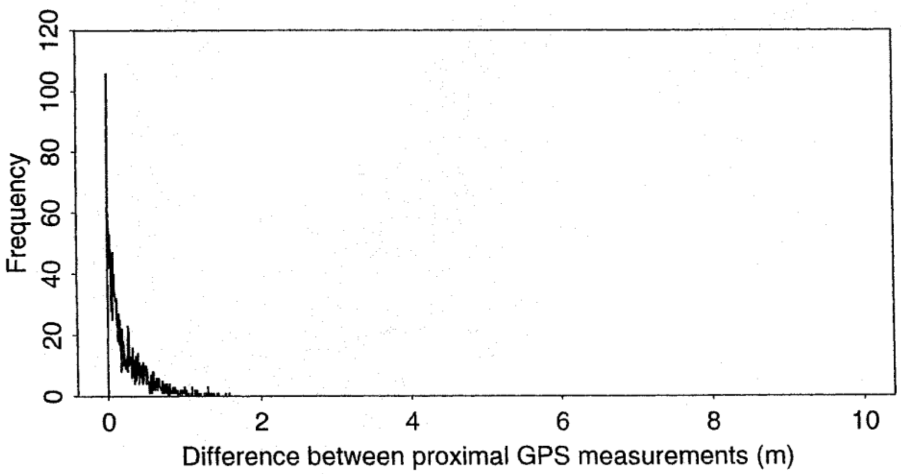

Figure 5. Histogram of frequency versus error for the full data set of comparisons from the ski area data acquired at Telluride, Colorado. The data represent errors or elevation differences between all data points with a separation distance of 10.0 m or less (last row of Table 2).

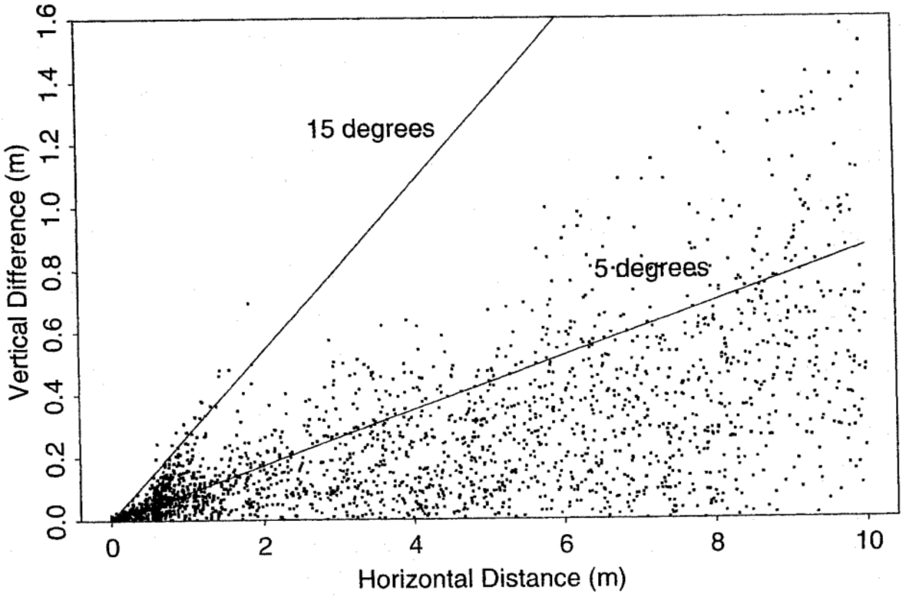

Figure 6. Absolute value of the elevation differences versus the horizontal separation distance between the measurements. The 5° slope line represents the lower end of the range of observed slopes at the study area and the 15° slope represents the upper value.