Fiber Optic Distributed Temperature Sensing in Avalanche Research

M. Woerndl (1)*, A. Prokop (1), S. W. Tyler (2), C. E. Hatch (2) and J. Dozier (3)

(1) Institute of Mountain Risk Engineering, Department of Civil Engineering and Natural Hazards, BOKU, University, Vienna, Austria.
(2) Dept. of Geological Sciences and Engineering, University of Nevada, Reno, Reno, NV, United States.
(3) Bren School Environmental Science & Management, University of California, Santa Barbara, Santa Barbara, CA, United States.

ABSTRACT: Knowledge about snow pack stability at a certain location and at a certain point in time is important for avalanche practitioners and backcountry travelers. Due to the highly variable character of a snow cover's properties its current stability state is often hard to assess. The character of a snow cover's variability and of its driving forces, including snow temperatures, has been subject of ongoing research. Often findings have been limited due to labor-intensive measurement techniques and too small amounts of data. During the winter of 2008/2009 a Raman Spectra Fiber Optic Distributed Temperature Sensing (DTS) System was installed on Mammoth Mountain, California, USA in order to investigate the system's ability to cover the spatial and temporal variability of snow temperatures. DTS is a laser-light based measurement method measuring temperatures in a multitude of sample spots, simultaneously and continuously in time. Data with high relative accuracies could be achieved. The snow's thermal evolution could be monitored in a large number of sample spots. Spatial patterns of temperature variations at the base and within the snow pack could be detected and their evolution in time could be tracked.

1.INTRODUCTION

The stability of an alpine snow cover can vary in time and in space, on different scales, which can be smaller than a slope and shorter than hours. This poses a problem to avalanche practitioners and backcountry travelers and recreationalists when trying to assess avalanche hazards for a specific location and for a specific point in time. As comprehensive observations of snow stability in space and in time are often not possible, attempts have been made to derive typical correlation lengths of stability characteristics (Hendrikx et al., 2009) or to identify and characterize the behavior of measurable influencing parameters (Deems, 2002, Kozak et al., 2002, Teufelsbauer, 2009) in order to allow improved estimates of the hazards, also from limited observation points. Patterns of the spatial variability of snow stability were identified and it was shown that they could change in time (Hendrikx et al., 2009). The influence of temperatures on the evolution of a snow pack's stability was shown (Kozak et al., 2002).

Corresponding author address: Michaela Woerndl. Institute of Mountain Risk Engineering, Department of Civil Engineering and Natural Hazards, BOKU, University, Vienna, Austria.
Email: michaelawoerndl@hotmail.com

Studies of the variability of snow pack temperatures revealed that they are driven by various influencing factors on different temporal and spatial scales, including radiation, terrain influences and snow depth (Deems, 2002, Teufelsbauer, 2009). In all cases a lack of data limited conclusions, especially about the driving forces and character of quick changes in a snow pack's spatial variability. Limiting was that observations could not be carried out in various sample spots at the same time (Deems, 2002). Due to a lack of data employed 2- and 3-D model simulations could not be verified (Teufelsbauer, 2009). Raman spectra fiber optic distributed temperature sensing (DTS) is a laser-light based measurement technology measuring temperatures. DTS systems are used for pipeline- and fire monitoring, in geothermal wells (Tyler et al., 2009) and in other industrial and engineering applications (Inaudi and Glisic 2006, Yilmaz and Karlik, 2005). Since 2006, they established in environmental applications (Selker et al., 2006). Selker et al. (2006) also used DTS methods at a glacier. 2008 Tyler et al. for the first time installed DTS systems in alpine snow. They can measure temperatures simultaneously in a multitude of sample spots and continuously over several weeks or longer, with temporal resolutions better than 5 min and spatial resolutions of less than 2 m.

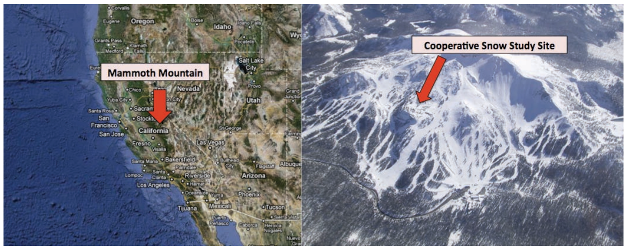

Fig. 1: Mammoth Mountain, California, U.S.A

2. METHODS

During the winter of 2008/2009 a DTS system was installed at the Cooperative Snow Study Site on Mammoth Mountain, CA, U.S.A, (http://neige.bren.ucsb.edu/mmsa/description.html) in order to investigate the method's ability to cover the spatial and temporal variability of snow temperatures and temperature gradients. The site is located on a northeast-facing slope in the Mammoth Mountain Ski Area on the eastern side of California's Sierra Nevada (37 deg. 37 min. N, 119 deg. 2 min. W, 2940m above sea level) (Fig.1).

2.1 *DTS Systems – Theoretical Background*

To measure temperatures with a DTS system, a laser is pulsed through telecommunication fiber-optic cables (Tyler et al., 2009). Temperatures can be measured continuously in time along the cables, which can be permanently installed or can be newly deployed for each use. Spatial and temporal distributions of temperatures in the observed environment can be covered at the same time. Temperatures are derived as average values along segments of the cable, typically of about 1 m to 3 m length (Tyler et al., 2009). An instrument box pulses the laser through the cable(s) and also includes a recording unit to capture backscattered light (Fig. 2). When the laser light collides with the lattice structure in the fiber optic cable it causes them to emit small bursts of light at slightly shifted frequencies, which form the so-called Raman bands (Smolen and van der Spek, 2003) (Fig.3). The two bands, called the Stokes and the Anti-Stokes, differ in wavelengths and in their reaction on temperatures. The measured energy within the temperature sensitive Anti-Stokes signal compared to the fairly stable and temperature insensitive Stokes band renders the temperature of the fiber-optic cable at a given spot. Higher energy within the Anti-Stokes band indicates higher temperatures and vice versa (Smolen and van der Spek, 2003).

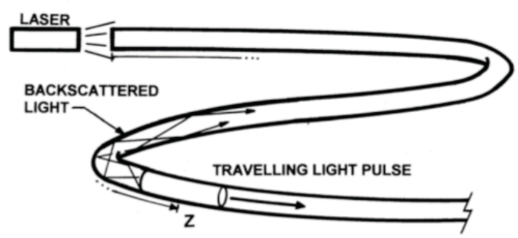

Fig. 2: travelling laser light pulse emitted from instrument box and returning backscattered light (Smolen and van der Spek, 2003)

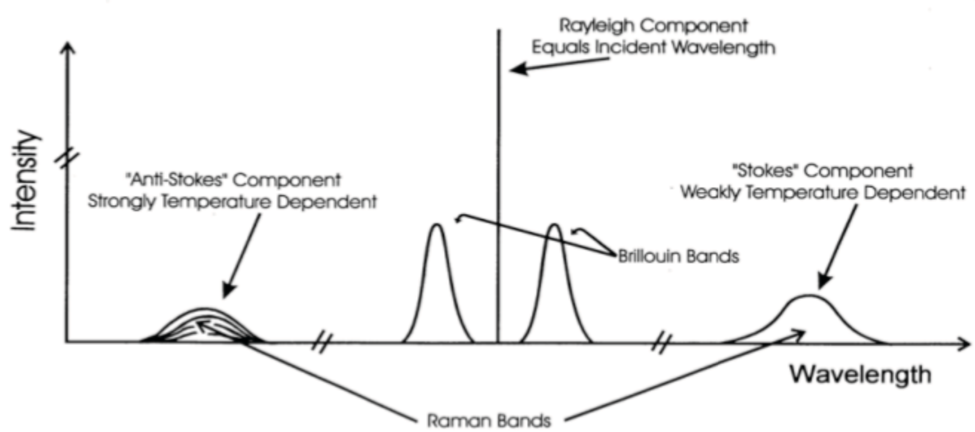

Fig. 3: Backscatter spectrum including Raman bands with Stokes and Anti-Stokes (Smolen and van der Spek, 2003)

2.2 Components of a DTS System

A complete DTS system consists of an instrument box (different manufacturers are available); of one or more connected cable(s); of calibration sections (ice-slush baths, water baths or other constant-temperature sections) equipped with reference temperature devices; and of connectors, which link the cable to the box. Figure 4 shows an example of a DTS system set-up for measurements in a so-called double-ended mode.

2.3 The DTS System on Mammoth Mountain

On Mammoth Mountain a multimode AFL flat drop fiber-optic cable was deployed in November 2008, prior to the first snowfall. 660 m of the cable were deployed on the ground, in seven loops, over variable soil conditions, slightly changing slope aspects and different vegetative covers. Another 100 m were kept in reserve to be laid out later in the season, above one loop of the ground deployment, on about 1 m and about 1.9 m of snow. The remaining cable meters consisted of coils of 40 m to 60 m length, some of which were used in calibration and configuration set-ups. Thermistor strings that were connected to a Campbell CR7 data logger and self-recording pt-100 temperature loggers were placed in several spots along the cable to provide data for control and potentially required corrections.

The cable ends were connected to a Sensornet Halo DTS instrument box. Power supply and shelter for the instrument box were provided in a research container at the site. The Sensornet Halo can measure temperatures along a fiber-optic cable of up to 4 km length, with a manufacturer stated spatial resolution of 2,09 m. Measurements were taken during four distinct measurement sessions: from December 29th 2008 to January 09th 2009; from February 4th to February 16th 2009; from March 7th to March 11th 2009 and from April 21st to May 9th 2009. Figure 4 provides an overview of the fiber-optic cable deployment on Mammoth Mountain.

2.4 Calibration

As temperatures would drop below the freezing point, maintaining a constant temperature ice-slush bath or a well-mixed water bath for calibration was not possible. Alternatively a portion of the snow-pack was chosen as calibration environment. 30 m of coiled cable were put in a river bag and were buried in the snow, together with a reference device. Another 60 m coiled section of the cable was deployed at the soil snow interface, next to another thermistor that was connected to the Campbell CR7 data logger in the research container. This cable section was used for control and corrections during data post processing.

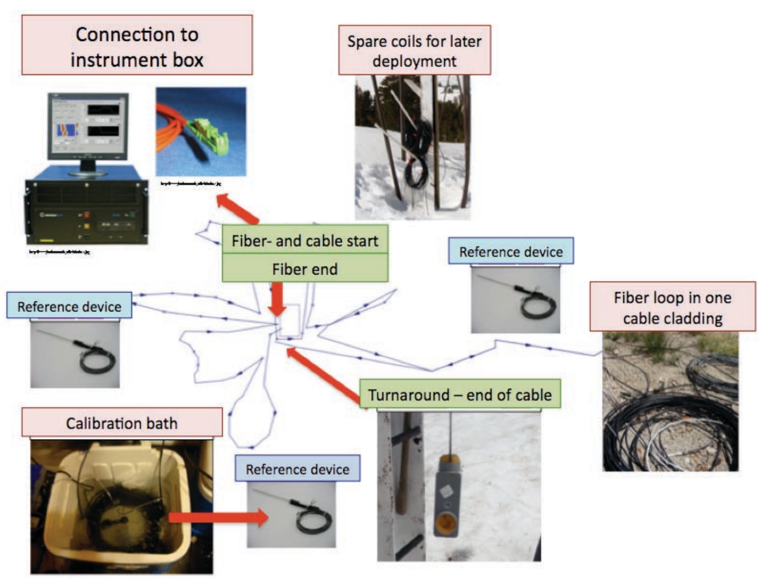

Fig. 4: Sketch of a DTS system for double-ended measurements (Woerndl, 2010)

3. RESULTS AND DISCUSSION

3.1 Accuracy

The Halo instrument box was set to take measurements with a temporal resolution of five min, which, according to the manufacturer, corresponds to a temperature resolution of better than +/- 0.05 °C (www.sensornet.co.uk[1]). The spatial sampling interval was set at 2.09 m.

Due to temperature gradients that established within the calibration section in the snow, the absolute accuracy, usually referenced to any standard measurement method (Tyler et al., 2009), of measured temperatures was limited. While the coiled 40 m cable section in the river bag covered an area of about 0.3- to 0.5- m^2 in width and of 0.1 m to 0.3 m in height, the standard temperature device that was used as a reference measured in only one point. As different areas of the snow were covered, inaccuracies were caused by thermal stratification within the calibration environment.

The 60 m cable coil, which was deployed at the soil snow interface, next to a reference thermistor, was chosen as a reference to calculate the spatial and temporal repeatability. The spatial repeatability determines how reliably a system can detect spatial patterns (Tyler et al., 2009). It is the standard deviation of DTS-measured temperatures along a section of knowingly constant temperatures in space. Table 1 and Table 2 display the average values of all standard deviations and the largest spatial standard deviations that were observed during distinct measurement sessions, for measurements with a temporal resolution of 5 min (minimum temporal resolution) and for data that was transformed to a temporal resolution of 24 hours (Woerndl, 2010). Larger time intervals improve the temporal and spatial repeatability (Smolen and Van der Spek, 2003).

The temporal repeatability is the standard deviation over time of DTS-temperatures that were measured in a temporally isothermal environment (Tyler et al., 2009). It was calculated for measurements with a temporal resolution of 5 min (Table 3) and of 24 hours (Table 4). As small temporal variations in snow temperatures within the reference section could not be fully excluded, especially in December/January when the snow pack was still shallow, also temporal standard deviations over the course of only 24 hours were calculated (Table 3). It can be assumed that real snow temperatures within the reference section remained fairly constant over this shorter time span. Table 4 displays the temporal standard deviations over the full length of each measurement session, of data that was averaged to a temporal resolution of 24 hours (Woerndl, 2010).

Tab. 1: Spatial Repeatability of Measurements with a 5 min Temporal Resolution

Spatial Repeatability	DecJan	Feb	Mar	AprMay
Largest std dev [°C]	0.069	0.057	0.061	0.060
Average of all std dev [°C]	0.046	0.039	0.042	0.034

Tab. 2: Spatial Repeatability of Data Averaged to a 24 h Temporal Resolution

Spatial Repeatability	DecJan	Feb	Mar	AprMay
Largest std dev [°C]	0.03	0.02	0.03	0.01
Average of all std dev [°C]	0.03	0.02	0.03	0.01

Tab. 3: Temporal Repeatability of Measurements with a 5 min Temporal Resolution

Temporal Repeatability	DecJan	Feb	Mar	AprMay
Over entire session [°C]	0.085	0.038	0.039	0.038
Over 24 hours [°C]	0.033	0.038	0.038	0.039

Tab. 4: Temporal Repeatability of Data Averaged to a 24 h Temporal Resolution

Temporal Repeatability	DecJan	Feb	Mar	AprMay
Over entire measurement session [°C]	0.087	0.006	0.006	0.006

3.2 Spatial and Temporal Variability

Georeferenced points along the cable were imported into ArcGis (www.esri.com). An areal photo was used as a reference for adjustments of point locations according to field notes. Temperature data averaged over the course of 24 hours was imported for each point on the map; and interpolations using the Natural Neighbors tool (Spatial Analyst toolbox), were conducted. Figure 5 and 6 show temperature variations in space that were encountered at the base of the snow pack. It should be noted that for this specific field deployment the calculated temperature distribution was influenced by the course of the deployed cable (Woerndl, 2010).

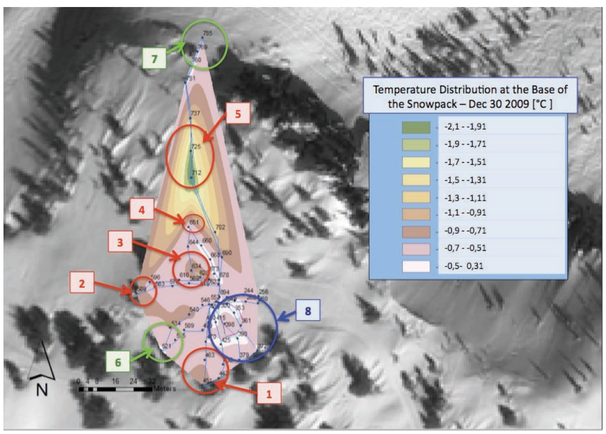

Fig. 5: Distribution of temperatures measured on December 30th at the base of the snow pack (Woerndl, 2010).

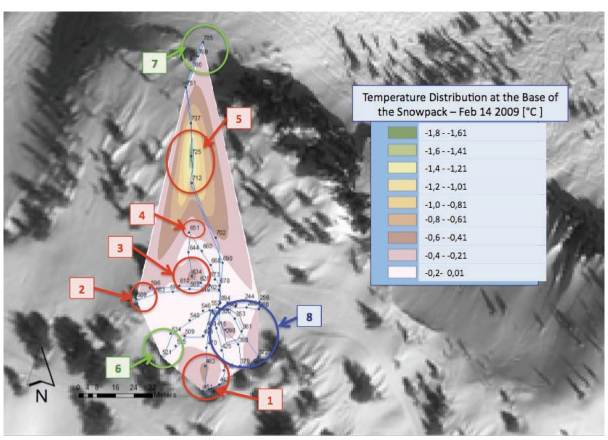

Fig. 6: Distribution of temperatures measured on February 14th at the base of the snow pack (Woerndl, 2010).

In some locations temperatures varied as a reaction to terrain changes (red circles) in others they did not (green circles). The blue circle marks an area where snow temperatures varied even though the terrain did not change (Woerndl, 2010). When comparing Figure 5 and Figure 6 it can be seen that the distribution of basal snow pack temperatures changed from December to February.

Figure 7 and 8 display the evolution of measured temperatures higher in the snow pack, along the cable that was deployed on 1 m of snow. Mind the scale differences between shown temperatures in Fig. 7 and Fig. 8!

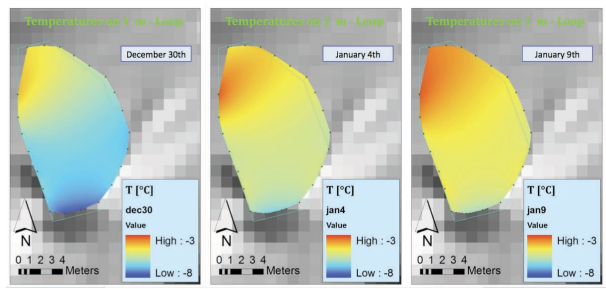

Fig. 7: Interpolated temperatures measured along a cable loop deployed on 1 m of snow, December 30th, January 4th and January 9th, (Woerndl, 2010)

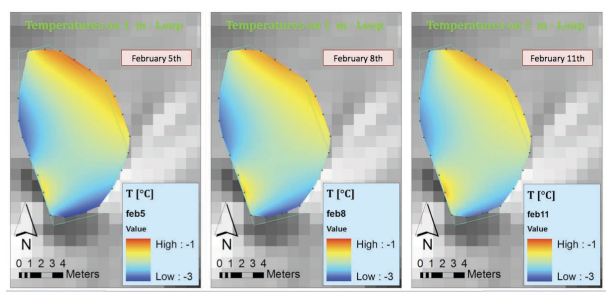

Fig. 8: Interpolated temperatures measured along a cable loop deployed on 1 m of snow, February 14th, February 15th and March 8t, (Woerndl, 2010)

Also on about 1 m of snow the pattern of the temperature's spatial distribution changed from December to February. The extent of spatial temperature variations even changed within distinct measurement sessions.

Figure 9 compares the evolution of the variances of DTS measured snow temperatures along cable transects in different snow depths. The variances were calculated along cable segments, for snow temperatures that were averaged over the course of 24 hours. They are shown for the two cable loops that were deployed on about 1 m and on 1.9 m of snow, for a ground loop that was located below them and for temperatures measured along the entire 660 m ground loop of fiber-optic cable.

The spatial variability of snow temperatures was found to evolve differently in different layers of the snow pack. While at about 1 m above the ground the variance of temperatures decreased between February and March (Fig. 9, green arrow), it increased on about 1.9 m above the ground during the same time period (Fig. 9, blue arrow). Between March and April the spatial variability at 1.9 m above the ground decreased at a higher rate than along the cable transect deployed on 1 m (Woerndl, 2010).

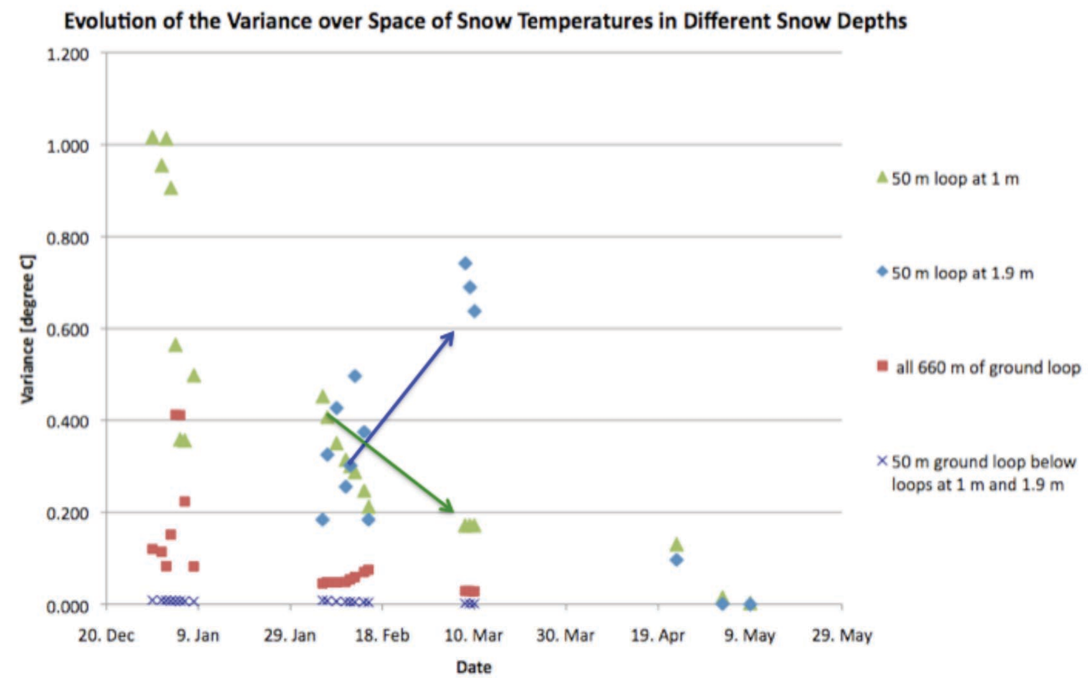

Fig. 9: Variance of DTS measured snow temperatures along cable transects in different snow depths (Woerndl, 2010)

4. CONCLUSIONS

The DTS system installed on Mammoth Mountain in 2008/2009 could provide spatially and temporally distributed temperature data in snow, with a spatial resolution of 2 m and a temporal resolution of 5 min. Due to an error that was introduced through temperature stratification in the calibration section, absolute snow temperatures remained unknown. However, for measurements with a temporal measurement interval of 5 min, a spatial repeatability (spatial standard deviation over a constant temperature section) of about 0.06 °C and a temporal repeatability (temporal standard deviation over a constant temperature section) of about 0.04 °C could be achieved. For measurements averaged over the course of 24 hours the spatial repeatability was 0.03 °C or better and the temporal repeatability was about

0.006 °C, allowing conclusions about relative temperature changes in space and in time, and about the evolution of spatial patterns of the snow's temperatures. The manufacturer stated temperature resolution of the system was 0.05 °C. Temperatures in a multitude of sample spots were observed and continuously monitored over time spans of up to 18 days. Spatial patterns of the temperature's distribution could be identified; it could be shown that they change over time and that they can evolve differently in different parts of the snow pack.

5. REFERENCES

Deems, J.S., 2002: Topographic effects on the spatial and temporal patterns of snow temperature gradients in a mountain snow pack, Master Thesis, Montana State University, Bozeman, Montana.

Hendrikx, J., Birkeland, K., Clark, M., 2009: Asessing changes in the spatial variability of the snow pack fracture propagation propensity over time, Cold Regions Science and Technology, 56, 152-160.

Inaudi, D., Glisic, B. 2006: Distributed Fiber optic Strain and Temperature Sensing for Structural Health Monitoring, IABMAS'06 The Third Int'l Conference on Bridge Maintenance, Safety and Management, Proto, Portugal.

Kozak, M.C., Elder, K., Birkeland, K., Chapman, P., 2003: Variability of snow layer hardness by aspect and prediction using meteorological factors, Cold Regions Science and Technology, 37, 357-371.

Selker, J.S., Thevenaz, L., Huwald, H., Mallet, A., Luxembourg, W., van de Giesen, N., Stejskal, M., Zeman, J., Westhoff, M., Parlange, M.B., 2006: Distributed fiber optic temperature sensing for hydrologic systems, Water Resources Research, 42.

Smolen, J.J., van der Spek, A., 2003: Distributed Temperature Sensing, A DTS Primer for Oil & Gas Production, Smolen Associates, Texas, and Shell International Exploration and Production B.V., The Netherlands.

Teufelsbauer, H., 2009: Linking laser scanning and snow pack modeling: data processing and visualization, Computers and Geosciences, 35, (7), 1481-1490.

Tyler, S.W., Selker, J.S., Hausner, M.B., Hatch, C.E., Torgersen, T., Thodal, C.E., Schladow, S.G., 2009: Environmental temperature sensing using Raman spectra DTS fiber-optic methods, Water Resources Research, 45.

Tyler, S.W., Burak, S.A., McNamara, J.P., Lamontagne, A., Selker, J.S., Dozier, J., 2008: Spatially distributed temperatures at the base of two mountain snow packs measured with fiber-optic sensors, Journal of Glaciology, Vol. 54, No. 187.

Woerndl, M., 2010: Raman Spectra Fiber Optic Distributed Temperature Sensing in Avalanche Research, Master Thesis, Institute of Mountain Risk Engineering, Department of Structural Engineering and Natural Hazards, University of Natural Resources and Applied Life Sciences - BOKU, Vienna, Austria.

Yilmaz, G., Karlik, S.E., 2005: A distributed optical fiber sensor for temperature detection in power cables, Sensors and Actuators, A 125 (2006) 148-155.

www.sensornet.co.uk:

1. http://www.sensornet.co.uk/technology/distributed-temperature-sensing/halo-dts/