Remote Avalanche Warning-, Alarm- and Control Systems, Fundamentals, Applications and Experience

Hansueli Gubler

AlpuG GmbH
CH 7270 Davos Platz, Switzerland
Phone/Fax ++41(0)81 416 10 19, Email alpug@alpug.ch
www.alpug.ch

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Abstract

Today, temporary measures to improve avalanche safety often depend on remote measurements by automatic stations. The snow profile radar allows for direct measurements of snow accumulation, settling, fracture height and water percolation within avalanche release zones. Alarm stations automatically recognize avalanche flow and close traffic lines. Remote avalanche control by Wyssen exploders, profile radar and seismometer reduce the residual risk for avalanche accidents by applying the method of artificial avalanche release. All systems are based on identical technology and can be inferred from control-room computers having the necessary software including access and security codes installed.

Introduction

Temporary measures to improve avalanche safety gain importance. They quite often offer improved benefit/cost ratios at comparable residual risk. Their application is limited to the protection of traffic lines, ski areas and other zones that can be closed and evacuated any time, and where structures are designed to withstand avalanche forces. On the other hand the impact on the countryside is much smaller using temporary methods compared to permanent structures as barricades, dams or galleries.

To configure alarm-, warning- and control-systems, the physics of avalanche formation and avalanche dynamics have to be well understood. Considering this knowledge, it has to be decided what kind of parameters have to be measured. We have designed a new generation of sensors and measuring platforms: a redesigned snow profile radar capable to measure snow accumulation, settling, layering, surface melt and water percolation as well as fracture depth, an infrared thermometer to accurately measure snow surface temperature, sensors to measure directly integrated snow transport by wind and logger software that improves accuracy of snow height measurements, determines quality numbers for the measured parameters and directly indexes the actual state of the snow surface. Therefore the formation of weak layers as one of the necessary conditions for slab avalanche formation is indicated by the system without the necessity of any central computing. Avalanche control systems combine local remote measurements with the control of one or several Wyssen shooting towers. The Wyssen shooting tower is todays most advanced system for remote control of avalanches. The geophones of the Wyssen system also measure and indicate the flow of larger avalanches. A profile radar installed in the release zone below the Wyssen tower measures snow accumulation, layering, settling and fracture depth and therefore help to improve the control work and to reduce residual risk at reduced closure times. Alarm systems that measure avalanche movements use Doppler radar, force-measurements in cables and measurements of the tremble of structures or in the ground to traffic lights. Special attention has been given to reduce the time delay between the recognition of an event and signaling the alarm to less than 3 second. All systems are powered by solar cells and are designed to withstand harsh environmental conditions. Radio links connect the remote systems to the public phone system and to the alarm relays. The systems perform self checks and transmit their status at regular intervals to control centers. All systems use the same visualization and control software running under MS WIN.

Assessment of avalanche danger by remote measurements

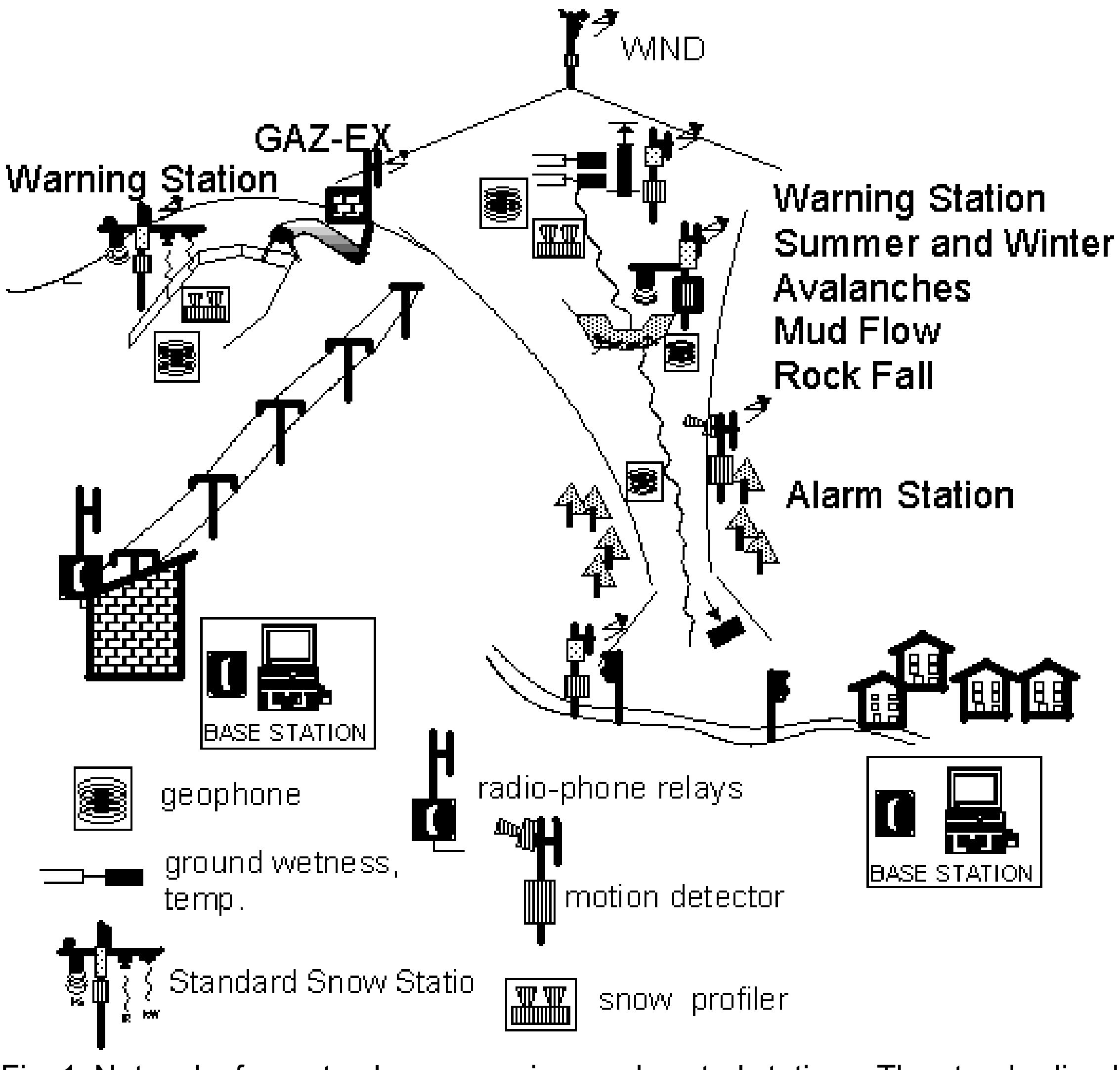

Fig. 1. Network of remote alarm-, warning- and control stations. The standardized remote stations are connected by radio and phone to local and regional base stations.

For local avalanche warning systems, it is necessary to supplement meteorological and manual observations by snow parameters measured automatically in the release zones and at representative locations. The systems have to supply reliable data on the development of dangerous snow cover stratigraphies between and during storms. The parameters measured should be closely related to the processes determining stability of the snow cover in potential release zones (Gubler, 1992). These processes are: formation of weak layers as a necessary condition of slab formation, loading, variation of slab strength and viscosity, and as the most direct stability indicators: initial fracturing and avalanching. With the microwave snow stratigraphy radar placed directly within the release zone (Gubler, 1988, 1991) snow accumulation (loading), settling (increase of strength and viscosity), stratigraphy (crusts, weak layers, water percolation, melting) but also fracture heights and flow heights of avalanches (partial unloading, future avalanche size) can be directly observed. Because the radar are buried in the ground looking upwards through the snow cover, they are not endangered by creep, glide and avalanches. Ultrasonic snow depth gauges, although they have been significantly improved during the last years, measure only total snow depth and cannot be located directly in release zones. Usually they will be installed at representative but safe sites, together with additional instrumentation: snow temperature and IR-surface- temperature measurements, combined with the measurement of reflected short wave radiation, air humidity- and temperature measurements that allow for direct modeling of weak layer formation. For the assessment of snow drift, wind recording can be combined with index measurements of snow drift flux (Fcapt, Mini F*Capt*). Geophones buried in the ground indicate avalanche flows and detonations for artificial release (e.g. Wyssen tower). A typical installation is shown in Fig. 1.

The information is used to assess the actual danger. It may be helpful to store these data together with avalanche observations in a data base to allow comparisons between similar actual and past situations. Expert systems can be adapted to support the assessment. Typical examples are NIVOLOG from Meteorisk and NX2000 from SFISAR. These tools support the method of artificial release of avalanches in given release zones. NIVOLOG combines nearest neighbor methods with rule based symbolic calculation (artificial intelligence techniques, A.I.) to arrive at a probability for an artificially or naturally released avalanche in a given gully.

The Integrated Avalanche Safety System

For experts in charge of avalanche safety, it would be very helpful to have integrated systems at hand that allows them to follow up the development of snow cover stability in given release zones, to remotely initiate explosions and to check if an avalanche has been released. Slabs are released or stability is tested by applying additional stresses to the snow cover. Detonation of explosives, gas mixtures etc. generate the additional stresses. Today there exist several systems that can be remote controlled any time, although firing of projectiles, CATEX and pre-placed dynamite connected to a remote firing control allow for limited remote control of avalanches too. Integrated systems combine remote snow and weather measurements, including snow stratigraphy measurements within the release zone, with an i remote control of Wyssen exploders. Fig. 1 shows the basic setup of the system. If the system is connected to the public phone-system by a radio-phone relays, remote access to the measuring and control systems is possible from any phone line connector using a PC or notebook computer equipped with a phone modem Fig. 2.

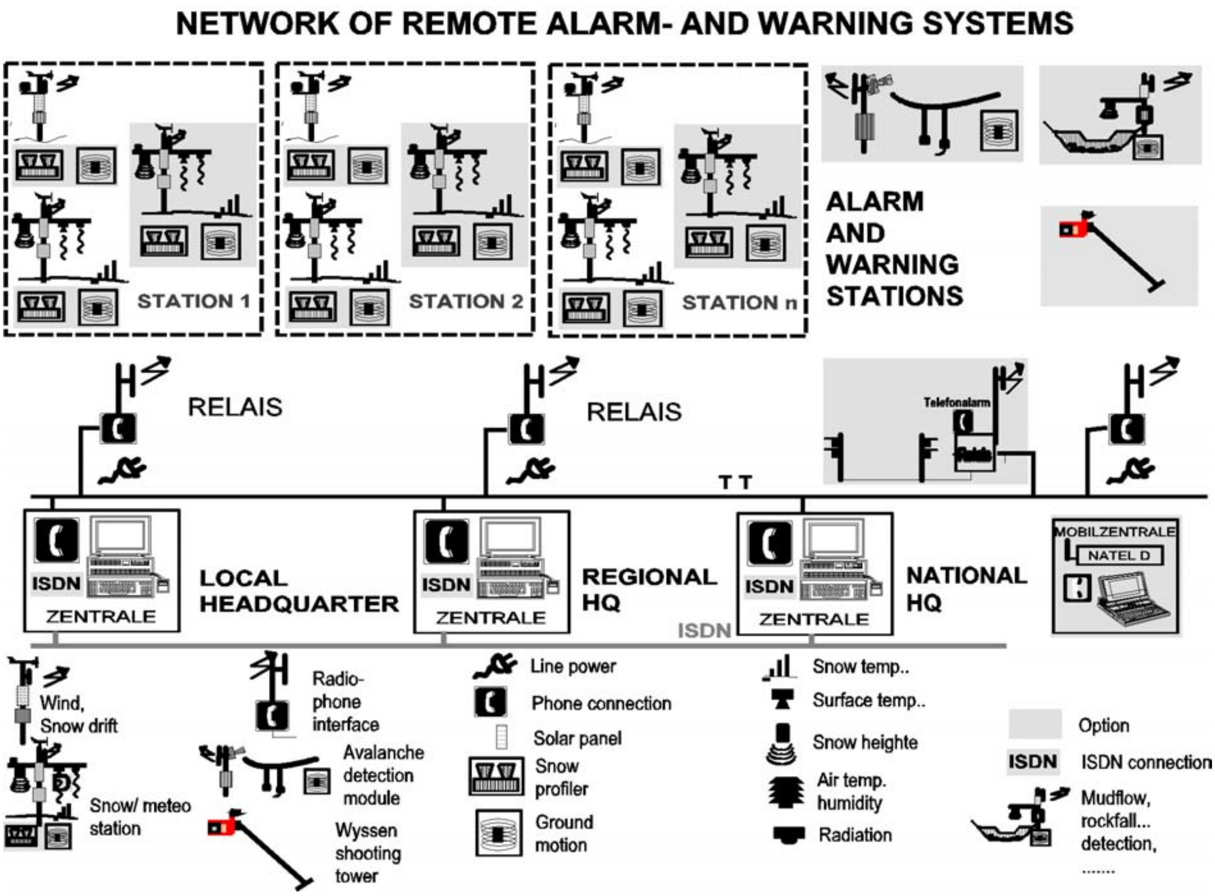

Fig. 2 Typical network for remote warning and alarm systems.

The integrated system has several advantages:

- During storms the development of the snow cover in the release zone can be examined 24 hours a day.
- Recording of natural releases.
- If the area is closed and evacuated, remote control of firing is possible 24 hours a day independent of the weather.
- Within a few minutes after the firing, fracture height of a released avalanche can be estimated.
- Assessment of weak layer formation between storms.
- In spring the necessary conditions for releases of wet surface slabs can be assessed.

All these features help to reduce closure times and to increase avalanche safety, and to reduce the chance for the formation of large avalanches.

Alarm Systems

Avalanche and mud flow alarm systems measure avalanche movements in release zones in the upper part of the respective tracks. The time between recognition of a dangerous movement and the time of impact of the flow on a road or rail tracks is usually very short. In most cases this time interval is less than 60s. This has two consequences: the combined length of the endangered road or track section and the stopping distance of the traffic vehicles has to be short because a vehicle has either to be able to pass before the flow reaches the traffic line or has to be stopped outside the endangered zone. To keep the alarm time as large as possible, recognition of a dangerous flow and transmission of the alarm to set the traffic lights have to occur within a few seconds. Flows are detected by Doppler radar measuring the speed of the flow, and be recording impacts on cables and ground trembling caused by the flow.

Basic system setup

All data collection and control systems have the same basic setup. A CR10X from Campbell Scientific builds the heart of the solar powered system. A radio link connects the remote station to a radio-to-phone base station, to alarm control base stations, and to neighboring remote data stations. Special software for the RF interface in combination with some additional electronics allows to directly set traffic lights in case of alarms but also to drastically increase security in WYSSEN remote control applications. All remote data collection platforms, alarm systems and GAZ-EX control systems are connected to local and regional warn- and control rooms.

Standard sensors and controls connected to remote stations

Wind

To measure alpine wind the Young wind monitor 5103 has been chosen because of its relatively low sensitivity to riming.

Air humidity and temperature

A Rotronic sensor has been chosen because of its low power consumption and wide temperature range. Gill radiation shields protect the sensors. In the past we had problems with humidity sensors loosing their calibration under severe winter conditions. The Rotronic sensors guarantee improved performance.

Short wave radiation

Skye SKS1110 instruments show good performance. These small semiconductor pyranometers are mounted facing down toward the snow. They are less sensitive to riming then conventional glass dome instruments and their diffusor does not cover by snow because he directs down toward the snow surface. Because we are basically interested by the radiation absorbed in the snow, measuring the diffuse reflection of the snow cover seems to be a good choice. Albedo and absorption depend on grain size as well as angle of incidence. The spectrum of reflected radiation is shifted toward shorter wave length , compared to the incident light. These effects can be corrected, knowing the surface state of the snow cover and the spectral sensitivity of the sensor.

Snow temperatures

There has been some discussion about the necessity and feasibility to measure high resolution profiles of snow temperatures: Most sensors used in the past did not really measure snow temperature or were often mechanically damaged by snow pressures. There are ways to measure snow temperatures with floating thin wire sensors, but such systems cannot be used in operational measuring systems. Sensors mounted on branches supported by a pole influence settling of the snow cover. The basic questions must be: What do we learn from a snow temperature profile, where do we have to measure temperatures. Snow metamorphism depends on temperature and temperature gradient and additional parameters. The formation of thin weak layers, grain shape within the slab and slab temperature are important parameters for the formation of slab avalanches. Weak layers form close or at the snow surface where very high temperature gradients may occur caused by infrared emission from the surface and absorption of short wave and near infrared radiation below the surface. Fixed sensors cannot measure temperatures close to the surface. To model typical depth hoar formation during early winter again surface temperature and ground temperatures must be known. Snow gliding depends on ground- and close-to-ground snow temperature. Formation of granular snow in surface layers again depends on surface temperature and some mean temperature some 10cm below the surface. Temperature and therefore snow metamorphism is changing fastest with time close to the surface. During melting conditions in early spring, damming of melt-water in layers causing cohesionless weak layers cannot be predicted with temperature measurements at fixed depth. Final homogenous wetting of the snow cover in spring can be estimated from temperature measurements close to the ground. Therefore we only need to measure surface temperature, ground temperature, snow temperature close the ground and, may be, a sub-ground-surface temperature in permafrost ground. These temperature measurements combined with the common meteorological parameters allow to model those temperatures and temperature gradients within the snow cover that are significant to snow stability. Therefore we decided to measure only a few snow temperatures with sensors fixed on top of isolating poles that penetrate the snow from below, in addition to ground temperature and surface temperature.

Snow surface temperature

An infrared radiation thermometer, mounted on the instrument tower, measures snow surface temperature. The specially prepared IRT/C infrared thermocouple from Exergen is mounted in a Gill radiation shield and connects directly to the logger. Because the narrowband infrared emissivity of snow is very constant and high, surface temperatures are measured with fair accuracy between 0°C and -30°C. Accuracy is better than 0.5°C at the melting point and about 2°C at -30°C depending on the temperature difference between air/instrument and the snow surface.

Snow Height

For snow height measurements we use the Campbell SR50. In the standard configuration two SR50 can be connected to the SDI bus of the CR10. The standard software also allows to connect 2 SR50 sensors. Snow height is determined from ten measurements made every 30 minutes. The quality of the measurement is stored to a quality parameter. Using multiple snow height measurements on the same site increases redundancy for this very important parameter and gives a possibility to index snow transport if the two sensors are placed accordingly.

Snow Profiler

The Frequency Modulated Continuous Wave profiling Radar (FMCW) shown in Fig.3 measures a spectrum of distances from the ground surface to reflecting layer interfaces and the snow surface. Specular reflection of microwaves depends on the difference of the index of refraction between consecutive layers and layer thickness. Special software at the base station (e.g. at the avalanche forecaster’s office) permits on-line graphic presentation of time-series of electromagnetic profiles of the snow cover. The electromagnetic profile looks very similar to a traditional layer profile. With additional software depth and settling of new snow layers can be determined with fair accuracy (5%). Settling speed relates directly to the rate of increase of strength and viscosity but also to the state of metamorphism (depth hoar inhibits settling). Other important parameters that can be determined are: snow depth, water equivalence of a dry snow cover, significant layer interfaces, avalanche releases, release height, dammed melt water at layer interfaces (in spring occasionally acting as weak layers), and surface wetness. Because wet snow significantly attenuates microwaves at frequencies used for the profiler, installations are limited to high mountain release zones where the snow cover stays essentially dry during the winter season. The main advantage of the system is the possibility to get most important information from within or close to potential release zones of large avalanches. In large bowls several radar may be installed at different representative locations to allow for the monitoring of aspect dependent loading and partial releases. Specifications:

- Frequency modulated continuous C-band radar
- Triangular modulation 4 to 8Ghz at 40Hz
- Approx. conversion rate in air 2kHz/m.
- Approx. conversion rate in dry snow 2.2 to 2.8 kHz/m depending on snow density.
- Maximum range in dry snow for snow densities below 400kg/m^3 is 8m.

The accuracy of the measurements depends on the quality of the microwave reflection at the layer interfaces and of the snow surface, and for the measurements without reference reflector, on the accuracy of the snow density estimates (a change of density by 100kg/m^3 corresponds to a 7% change of optical distance). The absolute error for measurements of the waterequivalence of dry snow amounts to about 5kg/m^2 or 5mm of waterequivalence.

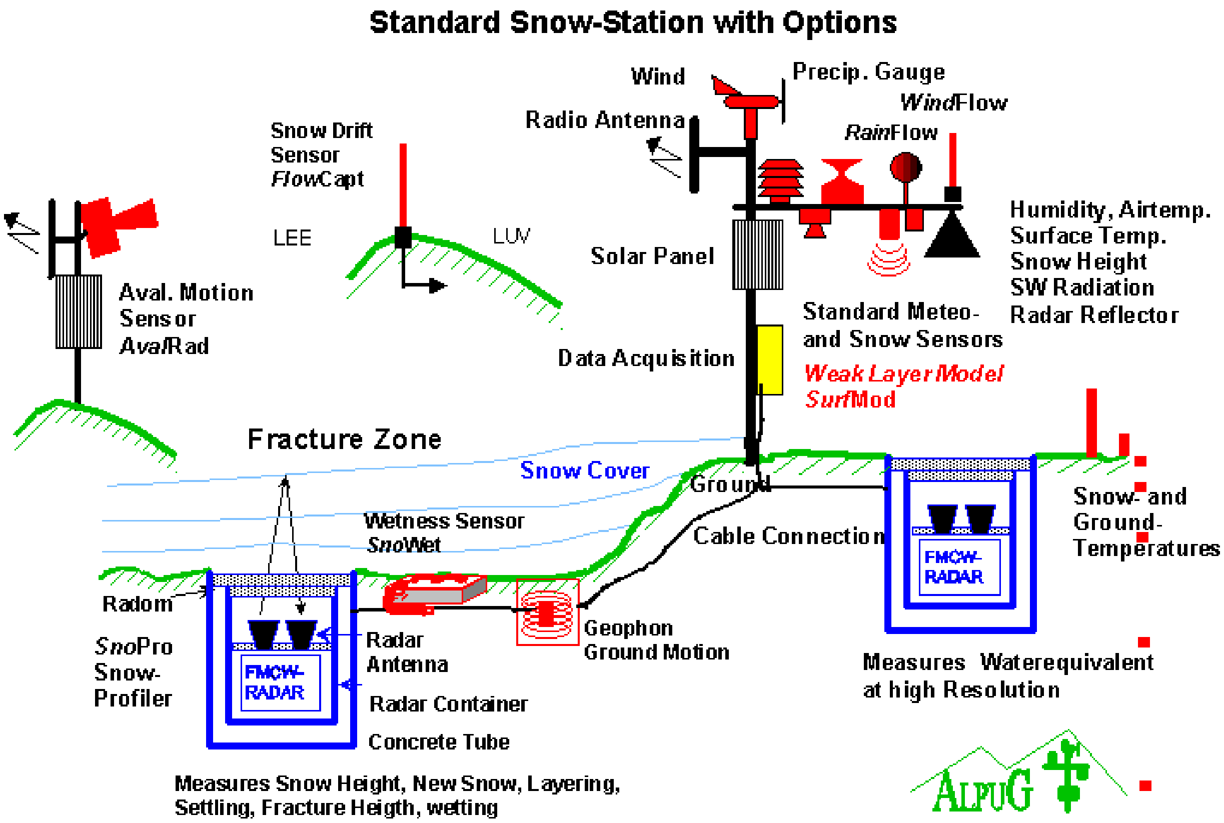

Fig. 3 Basic setup of a remote snow station with options

The system consists of two separate parts: the radar is mounted in a water protected cylindrical container with a max. outer diameter of 68cm and a height of approx. 80cm. In field installations this cylindrical radar-container is installed in a concrete tube that is buried in the ground. The upper end of the tube is closed by a mechanically stable radome that supports the weight of the snow.

The radar connects with a coaxial RG/U 58 cable (up to 700m) to the field data controller that controls the radar, recharges batteries, initiates measurements and performs the necessary computing (Fast Fourier Transform). The radar interface controller connects to the CR10X by the SDM-bus.The radar controller (CR10X) transmits frequency spectra (256 points per measurements) to the base station. The base station software allows individual analyses of the spectra and conversion to a bitmap presentation as shown in Fig. 4/5.

Ground tremble, seismic signals

Geophones fixed to the ground measure seismic signals produced by snow avalanches, mud flows or rock fall as well as GAZ-EX explosions. Sensitivity is selected by hardware jumpers or from the base station for alarm stations, depending on the hardware used. The frequency range is 2 to 25Hz. If dislocation speed reaches a certain selectable threshold, A/D conversion of the signal turns on for about 20s. Seismograms are automatically analyzed and characterized by a set of parameters which in turn may automatically initiate an alarm if additional conditions are fulfilled. Seismograms and its parametrizations allow to check performance of the remote

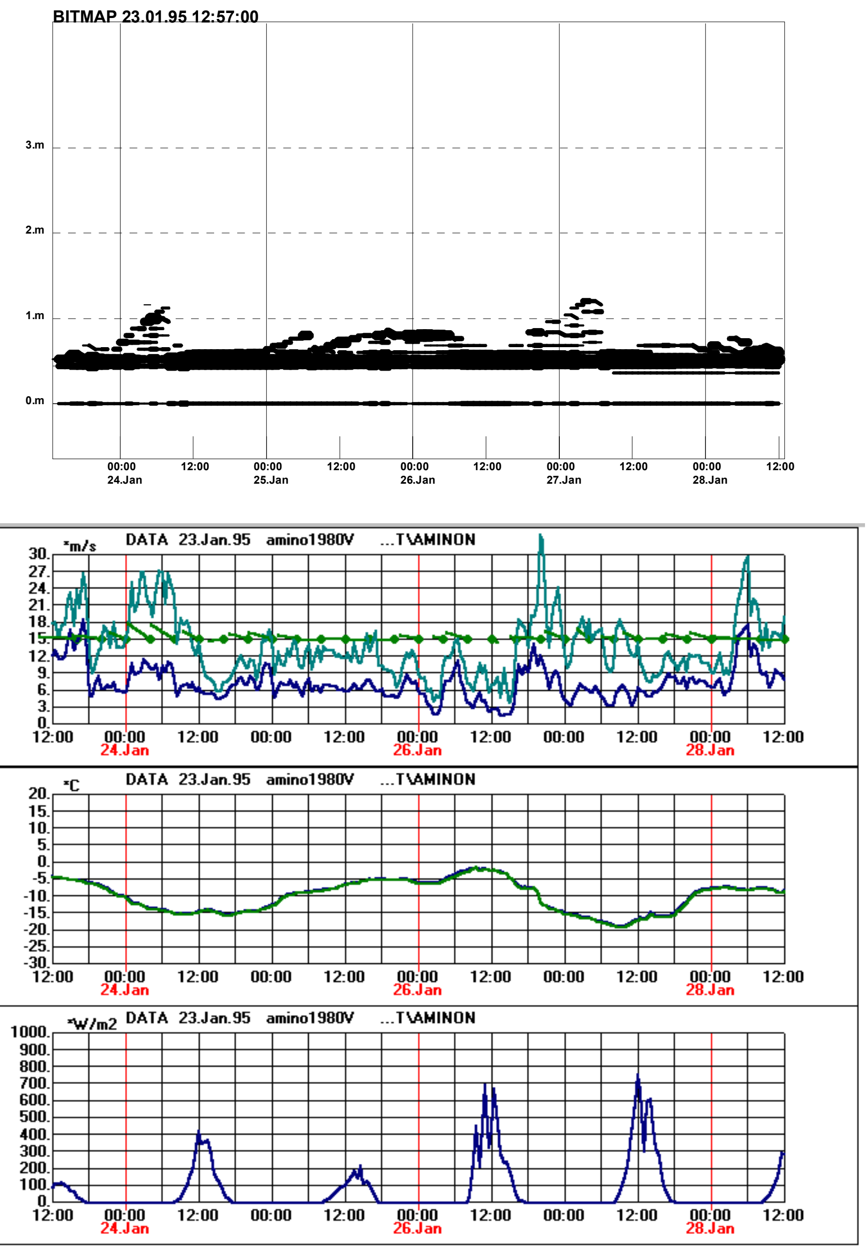

Fig. 4. The development of meteorological parameters and layering measured at a remote site during a storm. Several avalanches have been released by the remote controlled exploder system. The base layers have been wet before the storm. Shown are wind, air and snow surface temperatures (which are the same during the storm), reflected short wave radiation and a bitmap presentation of snow layering measured by the profiler at a location below the exploder.

exploders, and to assess size and type of mud flows and avalanches. Maximum sensitivity of the instrument is about 10^{-5}m/s.

Geophones are also used to measure oscillations in cables produced by avalanches interfering with the cables.

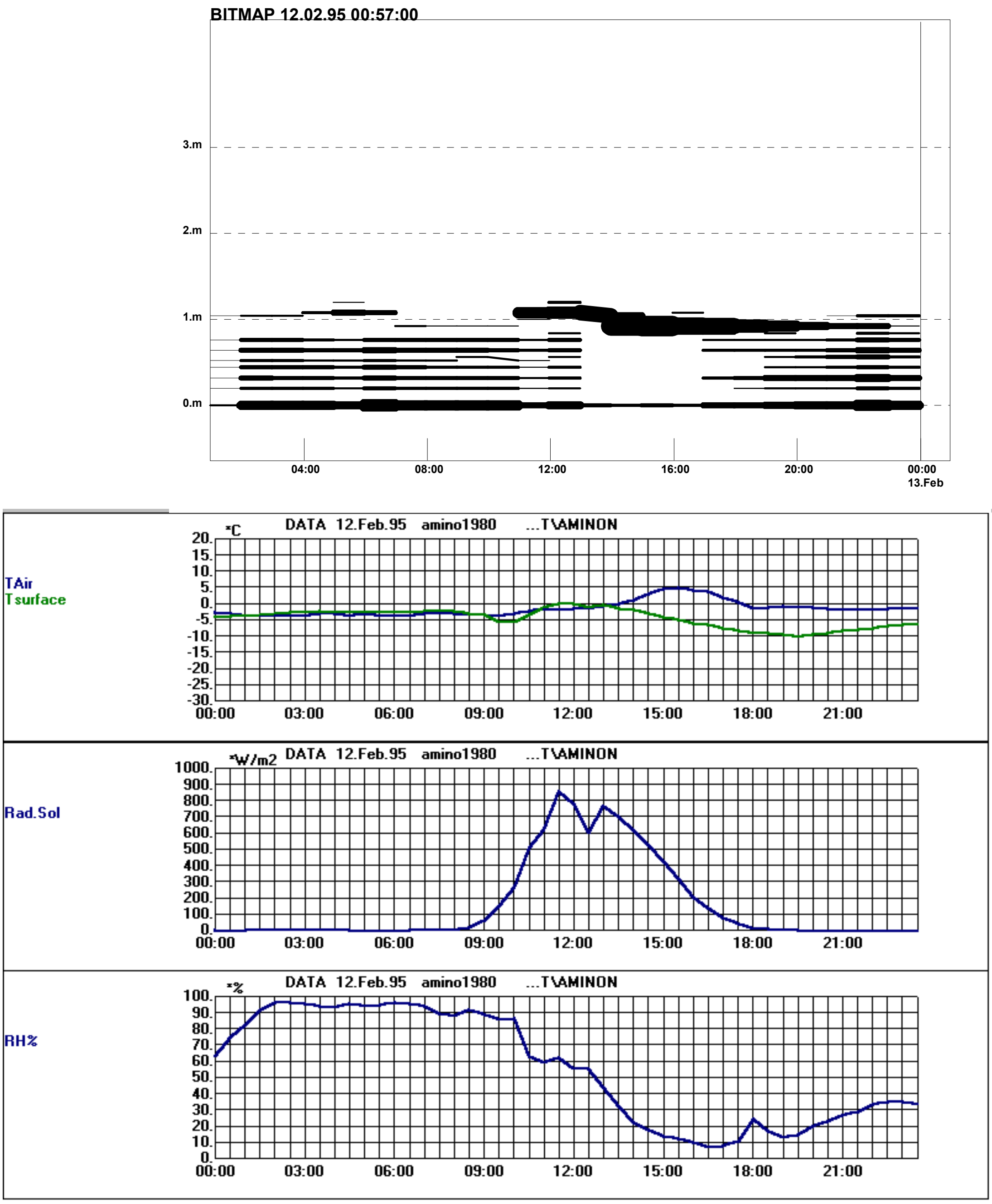

Fig. 5. Melting in the surface layer and refreezing after a sudden decrease of cloudiness and nebulosity. The thick bars in the snow profile show the wetting front. The sudden drop of surface temperature because of increased net outward IR-radiation of the snow surface causes the fast refreezing

Flow speed

X-Band Doppler radar measures flow speeds. The radar with a range of several hundred meters, depending on the reflectivity of the target, operates intermittent to save energy. Hardware and software initiate an alarm if speed, reflectivity and duration of the flow reach critical threshold values. The radar is mounted on an instrument tower at the border of the avalanche channel, looking upward into the track. Up to 10s of prealarm-time can be gained in this way.

Force measurements

If avalanches at the detection point run in channels, a horizontal cable may be installed well above the flow height of the dense part of the avalanche. A few detection cables hanging from this horizontal cable into the flow transmit impact forces of the flow on this detection cables to the main cable. The force in the horizontal cable is measured with strain gauges. Cable oszillation is measured with vibration sensors. Signals of the sensors are analyzed by local hard- and software. An alarm transmission is initiated if a typical signature for a dangerous flow is found.

Snow Drift

*The Flow*capt is a sensor to measure flux of windblown snow and wind developed by IAV and AlpuG. Blowing snow can significantly increase actual avalanche danger but also stop road traffic. *Flow*Capt measures blowing snow flux and the wind causing snow transport. The sensor improves information on additional snow accumulation in potential release zones by wind, the erodibility of the snow surface, the type of snow accumulating in the release zones, but also on visibility on roads, accumulation of windblown snow on roads, icing of roads, snow redistributions around avalanche and blowing snow defense structures etc. The sensor consists of special tubes, with a diameter of about 3cm and a segment length of about 1m that contain an acoustical measuring system. The tubes are mounted vertically. The measurements are either done for each of the up to six segments separately or integrating over the whole length of the sensor tube. Basically the system measures the momentum of the impinging snow particles and the turbidity of wind flow around the tube.

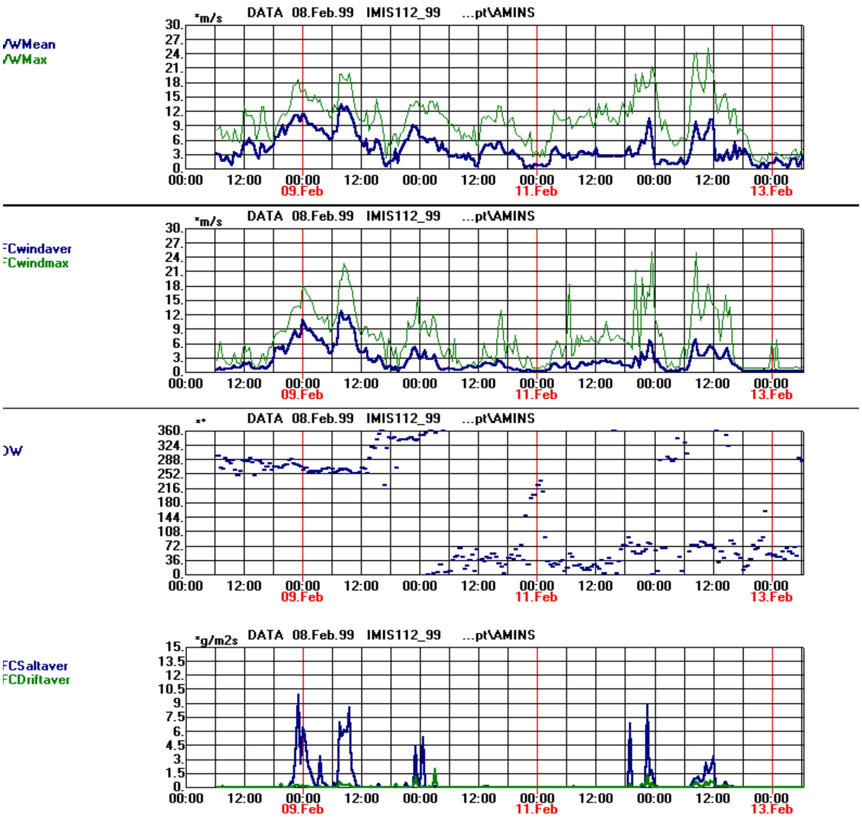

Fig. 6 Measurement of snow transport by a standard Swiss snow monitoring station in Aminona, VS. Up to down: mean and max. wind speed measured with a Youg propeller anemometer at 6m above ground , 2^d corresponding measurement with *Flow*Capt at 1m above ground, 3^d winddirection, lowest: Flux measurements, high values 0 to 1m, low values 1 to 1.2m abve ground.

The system allows to measure snow flux profiles or more important for practical applications, integrated blowing snow flux independent of actual snow height. The location of measurement should be selected between the zones of erosion and deposition, if possible on a slight crest with little snow deposition. On a crest the sensor can be placed under a jet roof to locally avoid the build up of a cornice. In a standard setup 3 to 5 1m segments are mounted sideward to a pylon. A data example is given in Fig. 6.

Assessment of the quality of the actual snow surface

Fast recrystallization at or just below the actual snow surface causes the formation of weak layers. The long-wave balance and the exchange of latent and sensible heat between the snow surface and the atmosphere, the absorption of solar radiation as well as snow accumulation and erosion drive the corresponding flows of mass and energy. Based on the measurements mentioned above, a model coded into the CR10X calculates periodically values for dendricity (decomposing metamorphism in new snow), spharicity (importance of equilibrium- compared to kinetic growth form metamorphism) , formation of surface rime, surface melting, melt-crust formation and to some extend even cloudiness. These index parameters are transmitted to the base stations in the same way as the directly measured values.

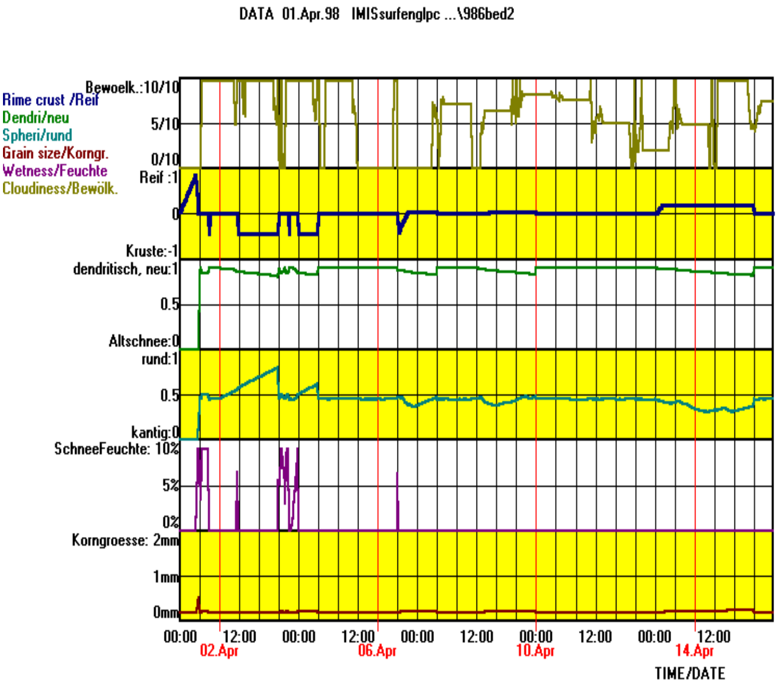

Fig. 7 Typical example for modeled snow surface parameters.

Remote measuring, alarm and control systems

The systems are built for reliability, redundancy and fast maintenance. The electronics, battery and terminals are mounted in a ventilated double-wall box made of aluminium. The box is temporarily slightly heated by surplus solar energy to avoid condensation. The electronic box, sensors, solar panel and antenna are integrated into a carrier system that my be moved along the towers and can easily be lifted from and to the towers by a helicopter (Fig. 8/9). The towers may be fixed on micro piles, on concrete foundations or at rock walls. This system has several advantages: Low sensibility to lightning, all system components are completely pre-installed, the systems are completely tested and operational before they are flown to the towers. The systems can be replaced within very short time. Adjusting sensors on cantilevers is easily possible by lowering the carrier to the actual snow or ground surface. All electronic units within the box are replacable

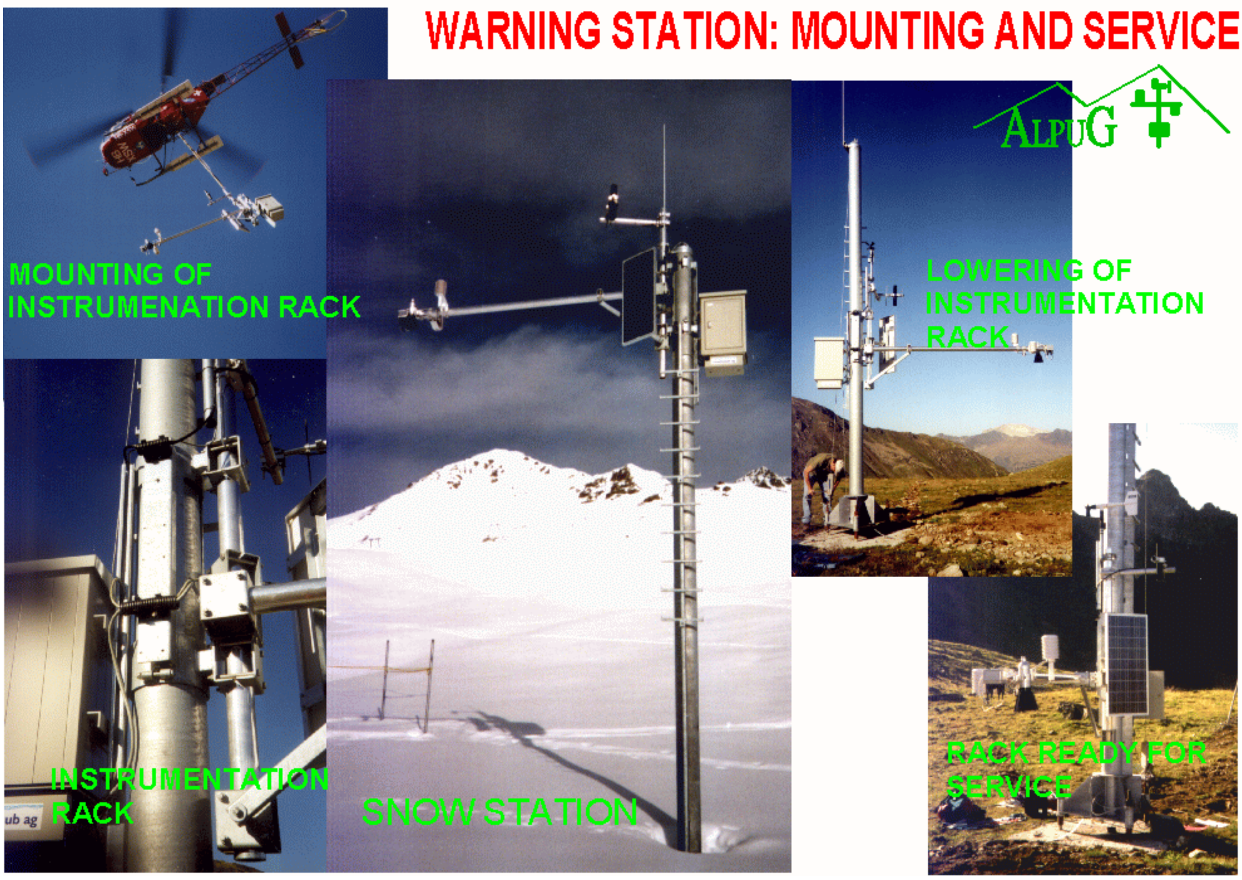

Fig.8 Mounting and service of a remote installation

without the use of any tools. The standard software (8Kb) for CR10X includes modules for all sensors described above. The sensors can be turned on and off by a status word. All measurements undergo plausibility tests. The results of these tests are registered in a quality number. The battery management is done by the logger software allowing for remote uncharge of the battery to measure battery capacitance. In case of low battery, the synthesizer radios (Motorola HT 1100), that unfortunately have a high standby current, are only switched on during the transmission intervals.

Special software routines have been developed for alarm systems. The alarm conditions can be optimized from the base station computer. The logger software allows also for the clearing of alarms in case of small events that may not endanger the zone to be protected. Each event triggers a cycle of intensified measurements and analyses.

Presentation of data and experience

Special windows software has been developed to present the data and to control and configure alarm and WYSSEN installations.

So far 70 warning stations, 15 alarm systems and several Wyssen avalanche shooting towers have been installed. Each warning station consists of two remote data acquisition systems, one for wind and additional meteorological parameters located on a ridge crest, the second for snow measurements at a location that represents the snow cover development of the region. The alarm systems are protect roads and railway lines from mud flows, rockfalls and avalanches. Three profile radar are operational. Experience with the traditional sensors was good, some minor problems have already been mentioned. Fig. 4 shows a typical plot of data. The snow profilers turned out to be especially helpful to assess snow accumulation and fracture heights below installations (Fig .4) for remote avalanche control and to predict spring type surface slides (Fig 5).

Conclusions

Remote measurements close to and within release zones significantly improve local avalanche warning and protection. Remote stations located in places that represent the development of the snow cover within a region help to improve regional avalanche forecast. Alarm systems allow to reduce the risk of avalanche accidents on traffic lines. Remote WYSSEN avalanche control systems combined with measurements of snow accumulation, fracture height etc. within the release zone improve the availability and reliability of the method of artificial avalanche release. Standardized electronics, instrument towers and software again increase system reliability and decrease maintenance costs.

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