REMOTE INSTRUMENTATION FOR AVALANCHE WARNING SYSTEMS AND SNOW COVER MONITORING

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Abstract.--Different types of instruments have been developed and tested during the last decade to help local forecasters. Meteorological instruments adapted for their remote use in an alpine environment , special instruments to measure snow depth, snow water equivalence, snow cover stratigraphy and avalanche occurrences are described. Some basic problems of avalanche forecasting based on localized initial state measurements are discussed.

INTRODUCTION

Ski area operators, road and railway managers in avalanche endangered areas often ask for methods to predict the time and size of local avalanche occurrences. Based on theoretical as well as on practical reasons only probabilities for occurrences of certain events can be determined. It is a basic principle that infinite observational precision is not possible. In most of the dynamical systems, errors propagate exponentially and make the future unpredictable in the sense of a determinate prediction. To improve the accuracy of the prediction significantly, we have to improve the initial state observations at times as close as possible to the time of the occurrence. However the analytical rate equations describing the future development of the snow cover also have to be further investigated. Basically three types of initial state measurements are possible. They are listed below in decreasing order of complexity of the avalanche prediction process:

- Meteorological and snow stratigraphical measurements (precipitation or snow accumulation rate, drifting and blowing snow, wind, air temperature, solar radiation, snow temperature profile, snow surface temperature, air humidity, snow cover stratgraphy in release zones).
- Measurements related to the natural mechanical stability of the snow cover in a potential avalanche release zone (acoustic emission, strain-rates, observations of natural releases in an ensemble of similar avalanches).
- Avalanche control using explosives (direct test of stability, determination of the time of occurrence of an avalanche).

The aim of this paper is to describe different types of remote instrumentations to measure the parameters mentioned above.

METEOROLOGICAL AND STRATIGRAPHICAL MEASUREMENTS

Meteorological measurements combined with periodical mapping of the snow stratigraphy are the common types of initial state observations in avalanche forecasting. But unfortunately this is the most indirect type of initial state observations to predict stability development. The prediction of avalanche occurrence from meteorological data including snow stratigraphy involves three different stages: Metamorphism of snow, constitutive equations for snow related to snow morphology, and initial fracture mechanism including fracture propagation. The answers can only be in terms of probabilites.

Nevertheless, experience and the rule of thumb, qualitative and semi-quantitative knowledge of the basic processes involved possibly combined with computer based memory aids (Buser, 1983) permit an estimate of the release probabilites, at least for ensembles of similar slopes: A good description of this type of forecasting is given by LaChapelle (1980). Special instruments and types of measurements have been developed to help the local forecasters.

The following methods have been tested and are operational: Ultrasonic snow depth gauge, determination of total snow water equivalent by snow pressure pillows, measurements of snow transport over a ridge crest, snow temperature profile recordings, windspeed and direction measurements by non-icing anemometers, snow surface temperature index measurements, microwave radar-based stratigraphy profiling, air temperature, air humidity and global radiation measurements.

Remote snow depth gauge

Total snow depth is determined by measuring the time of flight of an ultrasonic wave packet emitted by a sonic transmitter above the snow surface and reflected from the snow surface back to the receiver transmitter system. (Gubler, 1981). The light-weight transducer system is battery powered and may be fixed to any post above the snow surface (fig. 1). Data and commands are transmitted by a two-wire cable to the data acquisition device. The power consumption of the system is very low, one battery pack (9V, 0.5Ah) allows for more than 15'000 measurements during a 1 year period. The buffered data are available either in BCD code or as an analog signal. The long time accuracy is better than 0.03 m in the temperature range 0 to -20^{o}C. Data losses may occur as the result of intense snow drifting below the sensor or extremely soft snow surface conditions. The system automatically performs additional measurements in cases of very weak return signals.

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Figure 1.--Ultrasonic snow depth gauge. The transmitter (left) is balanced by the radiation shielded controller.

Total water equivalent measured by snow pressure pillows

An array of stainless steel pressure pillows has been in position for several years at a field measurement site near Davos (Rychetnik, 1981). Carefully installed pillows allow accurate measurements of total water equivalence at least for high winter conditions. Wet spring type snow occasionally causes erroneous measurements. If snow depth is measured right on top of the pillow using the ultrasonic gauge, mean snow density can be evaluated.

Snow drifting measurements

The measurement of the snow transport over an alpine ridge crest enables forecasters to estimate the additional loading of a potential avalanche release zone by wind dislocated snow. Combined with a wind speed sensor this type of measurement gives additional information on the erodibility or hardness of the snow surface. Different types of photoelectric instruments have been developed (Schmidt, Meister and Gubler, 1984) for remote drift flux measurements. The systems determine on line drift flux, threshold windspeed and at least mean particle size. The information on the particle size distribution enables the operator to estimate the portion of precipitation induced flux in the total flux (Schmidt, 1984). Fig. 2 shows an installation on a ridge crest near Davos (Gubler, 1980). The flux sensor is mounted below a wind roof. This concept was selected for its ability to

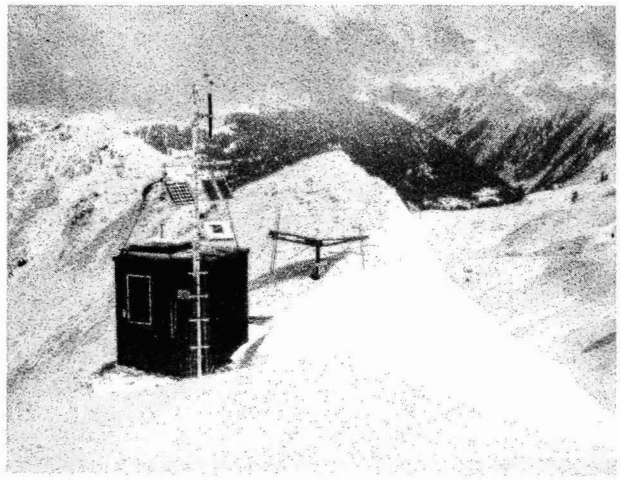

Figure 2.--Solar powered remote instrumentation on a ridge crest near Davos. Snow drift flux over the ridge is measured by an electro-optical device mounted below a wind roof behind the cabin. In addition, the installation records wind, air temperature, air humidity, global radiation, an index of snow surface temperature (mirror on white insulation above the roof of the cabin), snow temperature profiles and snow depths on both sides of the ridge, and acoustic emission in nearby release zones. Data are transmitted by radio to the Institute on Weissfluhjoch.

perform measurements of the horizontal mass flux over a crest at constant height above the surface, independent of the actual snow depth and cornice formation.

Meteorolological instrumentation, snow temperature profile

Icing and snow accreation are the main sources of malfunction of meteorological sensors. Instrumentations at remote locations often have to be powered for the whole season from batteries or solarpannels. Therefore de-icing of the sensors by electrical heating is inpractical. We found that the periodic spraying of alcohol from a pressurized tank keeps a small cup anemometer free of ice and snow. The electric valve is controlled by air temperature and air humidity. Applications of about ten milliliters every half hour kept the instrument practically ice free even under severe icing conditions. Newly developed paintings (Murase, 1984) which reduce ice adhesion significantly compared to Teflon will hopefully reduce the problem in the near future. The data from sensors for air temperature, humidity and solarradiation have to be carefully interpreted during and after icing events.

Arrangements of temperature sensors to measure temperature profiles in the snow cover have to be carefully designed to withstand the settlement, creep and glide of the snow. The shape of the sensors has to guarantee good contact with the snow at all times. If settlement is the predominant deformation of the snow cover an arrangement of knife-blade shaped sensors cutting the snow cover vertically, proved to be reliable. If the sensors have to be mounted in a steep slope cone shaped sensors orientated slope upwards showed good results.

Indexing surface hoar development

A direct measurement of surface hoar development is very difficult. But surface hoar and prowder snow layers may determine the stability of the following new snow layers. Emission of long wave radiation from the snow surface into space during clear weather periods causes the cooling of the snow surface below the ambient air temperature. Resulting high temperature gradients in a soft surface layer allow for the development of powder snow by high gradient metamorphism (Pulverschnee). If water vapor pressure in the air at the surface reaches or exceeds the equilibrium vapor pressure of ice at the actual surface temperature, crystal growth at the surface is greatly enhanced. Field experiments have shown that the long wave emissivity of a simple bathroom mirror during night time compares well with the corresponding emissivity of the snow surface. The mirror should be well insulated on the back. If the mirror is tilted toward the south, snow and rime slide off the mirror heated by the sun during the day. Fig. 2 shows the test mirror. Fig. 3 indicates the range of conditions indexed by the mirror assembly favorable for surface hoar development.

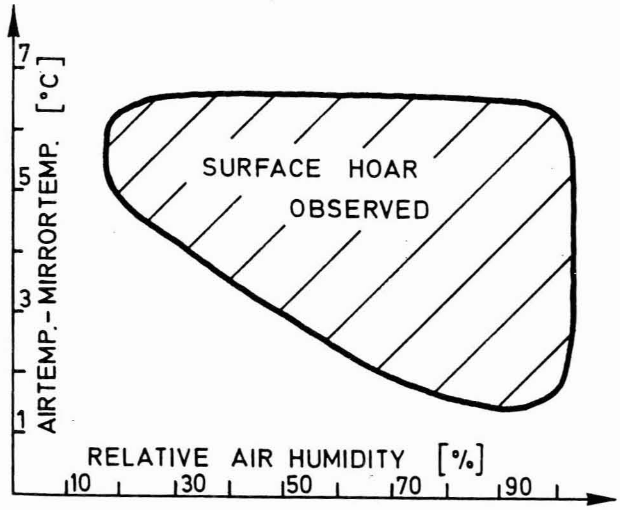

Figure 3.--Range of conditions favorable for surface hoar development indexed by the mirror assembly.

FMCW - Microwave radar

The FMCW radar (Frequency Modulated, Continous Wave radar) is used to measure electromagnetic distances in snow (Gubler, 1984). Discontinuities of snow density and snow wetness at layer interfaces act as natural microwave targets in the snow cover. The geometrical distance equals the electromagnetic distance divided by the index of refraction. Fairly well known relationships between the index of refraction, snow density and snow wetness are available. For most applications the instrumentations consist of the radar including the control electronics and batteries hermetically sealed in a plastic container (fig. 4) which can be buried in the ground anywhere in a flat field, an avalanche release zone or an avalanche track, a control unit which is connected to the radar by a coaxial cable (up to 1km) and a FFT analyser (Fast Fourier Transform analyser).

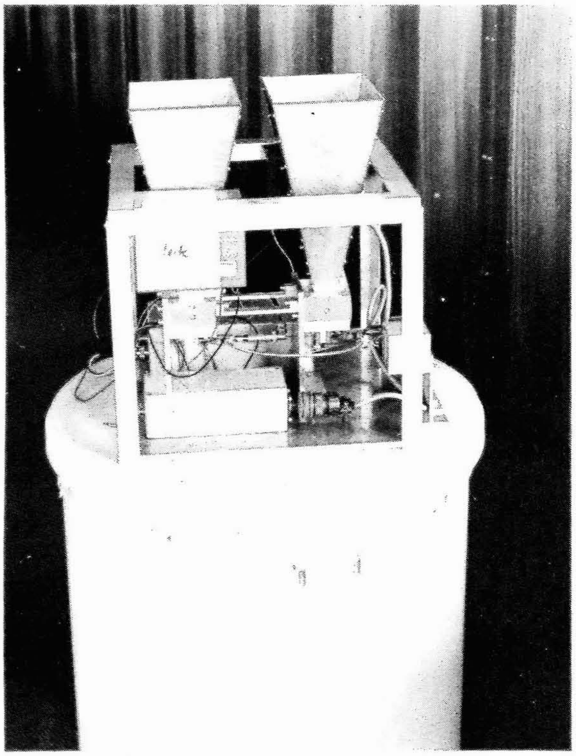

Figure 4.--FMCW radar standing on its plastic container. The container diameter is 0.7 m.

Wireless control and data transmission are possible by combining the specially developed low power FFT analyser with the radar unit. If the radar is buried in the ground below the snow cover, the following point measurements can be performed: snow cover stratigraphy, estimate of new snow, slab thickness and avalanche occurrence in a release zone, avalanche flow height in an avalanche track, total water equivalent of the snow cover if combined with a geometrical snow depth measurement (ultrasonic snow depth gauge) or with microwave reflectors, position of the wetness front in a mixed cold/isothermal snow cover. If

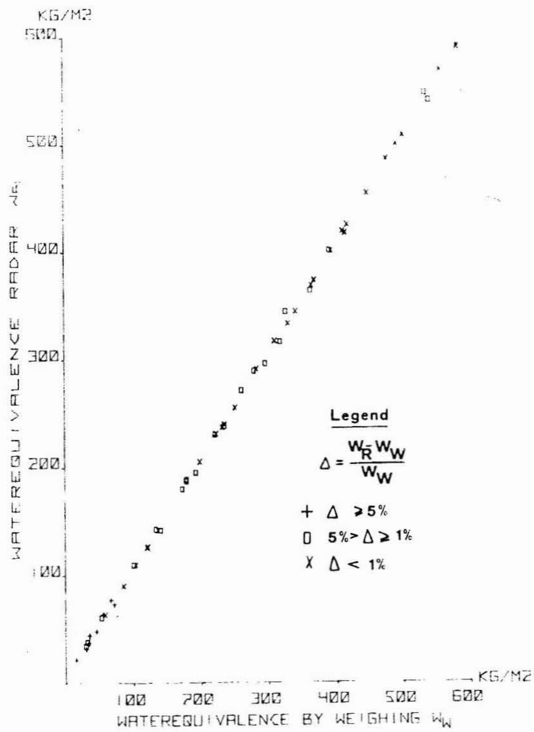

Figure 5.--Accuracy of the determination of the water equivalence using the FMCW radar combined with a geometrical snow depth measurement.

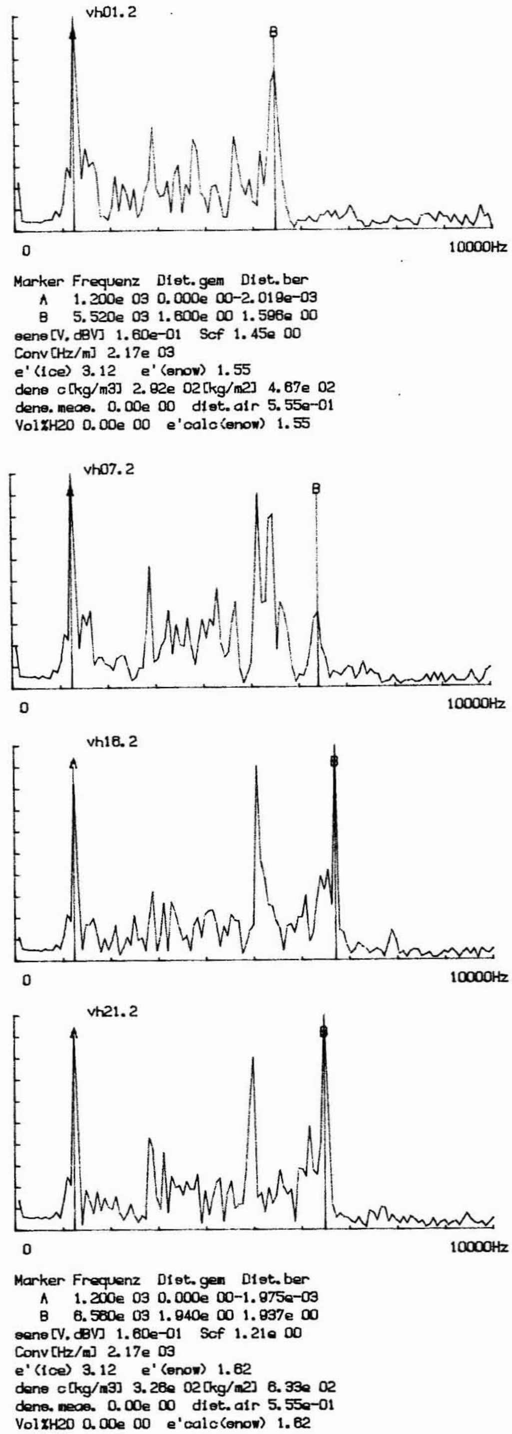

Figure 6.--Examples of FMCW spectra recorded before and after the February 1984 snowstorm in the Swiss Alps. Relative target size is plotted as a function of electromagnetic distance. The leftmost peaks (marker A) in the spectra correspond to the ground-snow interface, the rightmost peaks (marker B) correspond to the snow surface. Marker frequencies (Frequenz) and corresponding geometrical distances (Dist.gem), mean density dens (kg/m^3) water equivalence (kg/m^2) and the mean dielectric constant e'calc (snow) are plotted below the spectra.

the radar is mounted on a sled, snow distributions along profile lines, snow distributions in release zones, or for example snow distributions behind snow fences (Schmidt, 1984) can be investigated. Fig. 5 shows the result of a calibration test comparing water equivalence measured by weighing the snow with the water equivalence calculated from the ratio of electrical to geometrical snow depth. The series of spectra in fig. 6 was measured during the beginning state and at the end of a very heavy snow storm increasing the total water equivalence on the ground by about 160 kg/m^2 in 4 days. The snow cover was fairly homogeneous, nevertheless the settlement of a few layer interfaces and of the snow surface between vh16.2 and vh21.2 (16th to 21st of February 1984) can be recognized. Fig. 7 shows a FMCW spectra taken from above the snow cover. Some of the major peaks in the spectra are correlated with the corresponding ramindex profile. Our experience is that the radar profile is a very sensitive tool to investigate the snow stratigraphy. Metamorphism of snow during the day-night cycle in the surface near layers, which is hardly recognized during ordinary snow pitwork, is clearly indicated in the radar profile.

The second peak in the spectra of fig. 7 is a typical day-time peak which almost completely disappears at the end of a clear night characterized by high temperature gradient metamorphism in the surface layer. Although much more research is necessary to improve our knowledge of the microwave interaction with snow, the FMCW radar looks very promising for operational use in avalanche

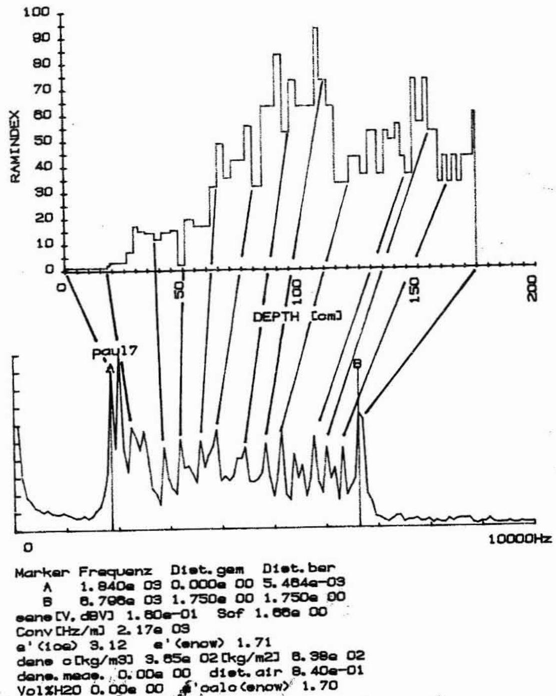

Figure 7.--FMCW spectra measured from above the snow cover (leftmost peak corresponds to the snow surface). Major peaks of the spectra are correlated with corresponding layer interfaces in the ram index profile.

warning systems, for snow hydrological networks, for ground truth evaluation in connection with space craft-based active and passive microwave sensors, but also for research programmes to investigate natural snow metamorphism, water percolation through the snow cover and avalanche flow mechanics.

MEASUREMENTS RELATED TO NATURAL MECHANICAL SLOPE STABILITY

The next most direct method of predicting avalanches involves stability related measurements. One possible tool is the recording of different types of acoustic emission activity in a stressed snow cover of a potential avalanche release zone (Sommerfeld and Gubler, 1983). Analyses of several years of acoustic data show that infrasonic emission activity is increased in low stability packs prior to avalanching.

Increased acoustic emission activity indicates the development of limited fracture surfaces in the stressed snow cover. Local strain rate and stress concentrations initiate limited fractures (acoustic emission) or unlimited fracture propagation (avalanche release). Because acoustic emissions from snow are of very low amplitudes (displacement 10^{-7} to 10^{-5} m, velocities 10^{-6} to 10^{-5} ms^{-1}, accelerations 10^{-4} to 10^{-3} ms^{-2}) special sensors and signal enhancement systems had to be developed. Typical signals and system components are described in Sommerfeld and Gubler (1984).

A similar instrumentation is able to predict avalanche releases from snow gliding.

Stability information may also be deduced from direct observations of avalanche occurrences in a local ensemble of similar avalanche slopes. Avalanche releases can be recorded by seismic technics (Lafeuille, 1984), by mechanical sensors or different types of microwave radars. The uses of the FMCW radar have already been mentioned. Doppler radar systems could be used to surveille several adjacent release zones (Salm and Gubler, 1985). Oversnow vehicle based doppler radars used to investigate the flow mechanics of avalanches are shown in fig. 8. Avalanche front velocities of a large avalanche measured by doppler radar are plotted in fig. 9.

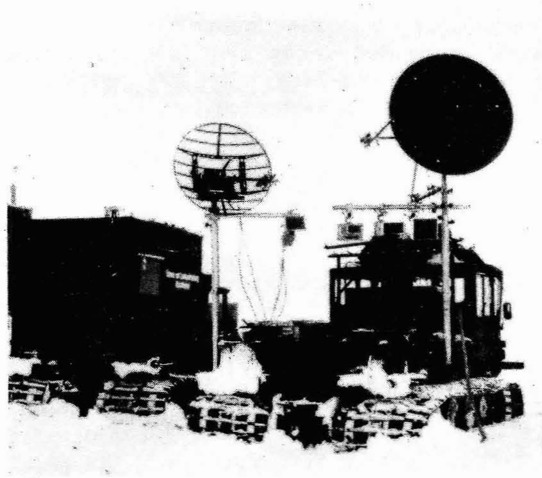

Figure 8.--Microwave doppler radar systems for avalanche speed measurements mounted on oversnow vehicles.

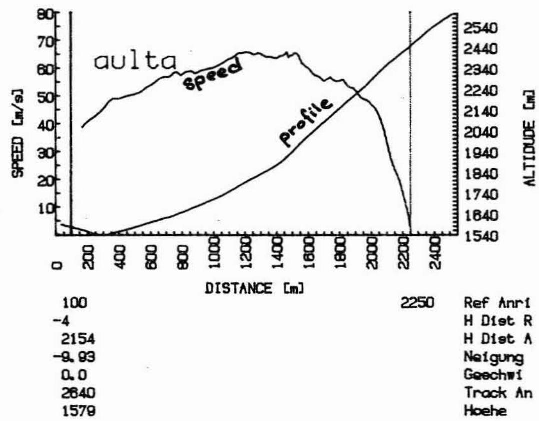

Figure 9.--Speed of a large avalanche (estimated discharge 8000 m^3/s) measured by doppler radar.

Correlation studies for local ensembles have been done by Judson (1983) and Bonnet (1980). They indicate that the ensemble has to be quite large to get a sensitive prediction for natural stability. This again proves the contingent character of the avalanche release mechanism.

CONCLUSIONS

Several types of instruments and methods have been developed during the last decade. However, most of these instruments perform only point measurements. This very localized information has to be interpreted by the forecaster to predict areal slope stability by taking care of the contingent character of the avalanche release mechanism. Improved instrumentation will decrease the ambiguity of the measurements but more research is needed to improve the physical rate equations and to understand the contingent character of snow fracture mechanics.

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