MONITORING SNOW GRAIN SIZE FOR PASSIVE MICROWAVE STUDIES

by

Richard Armstrong[1] and Albert Rango[2]

INTRODUCTION

The application of passive microwave radiometry to the remote sensing of snow properties is based on the ratio of emitted to scattered portions of the upwelling radiation. Increased scattering is indicative of increased snow amount, i.e., the number of snow grains present. However, scattering is also directly proportional to snow grain size for a given snow amount. Current snow cover retrieval algorithms produce inaccurate results when snow grain sizes are unusually large. Therefore, is it necessary to characterize snow grain size on a regional scale (and perhaps local scale in extreme situations) in order to adjust passive microwave algorithms. Preliminary analysis indicates that: (1) algorithms are not as sensitive to the presence of large grain sizes as the initial theory would indicate; (2) average grain size data may serve to characterize the detailed stratigraphy of the total snow cover; (3) variance in grain size diameters throughout the total snow cover may often be quite small (<1.0 mm) allowing some descriptive significance to be attached to "mean grain size" and; (4) conditions in subfreezing snow which produce grain sizes that greatly exceed a mean diameter value of 1 - 2 mm result from snow cover/climate relationships which can be modelled/monitored on a regional scale. A preliminary method is suggested for tuning snow cover algorithms according to prevailing regional-scale grain size.

MICROWAVE EMISSION FROM SNOW

Microwave emission from a layer of snow consists of both emission from the snow volume itself, as well as emission from the underlying ground. Ice particles within the snow cover act as scattering centers for the microwave radiation. This scattering effect, which redistributes the upwelling radiation according to snow thickness (number of grains) and crystal size, provides the physical basis for snow measurements using microwave remote sensing.

At microwave frequencies (1-300 Ghz, or 1 mm to approximately 30 cm wavelength) it is customary to express the signal received by a passive microwave sensor in terms of brightness temperatures (T_b). Brightness temperature is expressed in units of temperature (Kelvin) because for wavelengths in the microwave region the radiation emitted from an object is proportional to its physical temperature (T). However, natural objects emit only some fraction of the radiation which would result from a perfect emitter at a given physical temperature. This fraction defines the emissivity (e) of the object. In the microwave region, $e=T_b/T$, which is a basic equation of passive microwave radiometry (Zwally and Gloersen, 1976).

The usefulness of microwave radiometry as a remote sensing tool results from the fact that the emissivity of an object depends very much on its composition and physical structure. The ability to distinguish between snow-covered and snow-free ground using passive microwave radiometry results from the increased scattering (decreased T_b) described above. When moving from a snow-free to a snow-covered surface, the decrease in T_b is the basis for the detection of snow extent (Foster et al., 1984; Armstrong and Hardman, 1991). For a snow covered surface, T_b decreases further with increasing snow thickness. In addition, T_b decreases with increasing frequency, whereas for bare ground, T_b remains relatively unaffected by change in frequency (assuming constant soil moisture conditions). This general relationship provides the basis for most

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[1] CIRES/NSIDC, University of Colorado, Boulder, CO 80309

[2] USDA Hydrology Laboratory, Agricultural Research Service, Beltsville, MD 20705

passive microwave snow depth or snow water equivalent retrieval algorithms (Figure 1, Chang et al., 1987a).

SNOW GRAIN SIZE DISCUSSION

Grain size is often considered a primary feature in the description of deposited snow, but, due to the highly irregular shapes typically encountered, no generally accepted method to objectively measure grain size has evolved. However, attempts to develop the necessary techniques are underway (Davis and Dozier, 1989). For most field studies this has not been a critical problem as visual estimates, using millimeter grids and hand lenses, have generally been sufficient. For example, the IAHS International Classification for Seasonal Snow on the Ground (Colbeck et al., 1990) suggests that the observer obtain a "more or less homogeneous mass of snow and record the average size of its prevailing or characteristic grains, the size of the grain or particle being its greatest extension (diameter) measured in millimeters".

While the above method may be adequate for site-specific field studies, the application of passive microwave remote sensing requires the characterization of average snow grain size over large areas (>100,000 km^2). This is necessary because algorithms used to extract snow cover information are sensitive not only to total snow mass, but also to grain size (Chang et al. 1981). Therefore, in order to develop regional-scale snow cover algorithms, it is necessary to assign an average grain size derived from regional-scale variables.

The passive microwave brightness temperature of snow covered terrain is influenced by numerous factors other than amount and structure of the snow, including soil properties, vegetative cover, and atmospheric conditions, (Foster et al., 1984). However, to successfully apply snow cover algorithms, it is necessary to first evaluate the influence of the most important independent variables on the derived snow cover values. The purpose of this report is to begin to develop a method to characterize snow cover grain size in order to increase the retrieval accuracy of passive microwave algorithms.

The dependence of T_b on grain size results from the fact that an increase in grain size (independent of snow amount) in the snow layer causes increased scattering of the microwave energy. Without regard for grain size, this increased scattering would imply increased snow amounts. Current theory indicates that scattering is highly sensitive to changes in grain size (Figure 2, Chang et al., 1981). An increase in grain diameter of only 0.4 mm (0.6 to 1.0) would produce brightness temperature decreases of more than 50 K. In Figure 2 it can be seen that given a brightness temperature of 175 K, for example, the corresponding snow water equivalent value could vary by a factor of 4 (0.1 - 0.5 m) for a diameter change of only 0.4 mm. Such a range of water equivalent values covers a large portion of the total sensitivity range of typical snow cover algorithms. Thus, theory would imply that without detailed stratigraphic grain size information, perhaps to a precision of approximately 0.1 mm, microwave remote sensing of snow cover would have little or no practical value. In fact, such detailed snow structure information for areas the size of a SSM/I pixel would simply be impossible to obtain. However, algorithms which have been developed (e.g. Kunzi et al., 1982; Hallikainen and Jolma, 1986; Chang et al., 1987a; Goodison, 1989; Aschbacher, 1989; Rott et al., 1991) are typically applied without consideration for the variable grain sizes found in the natural snow cover.

In spite of the strong dependency of grain size, results have been reasonable under a wider range of conditions than might have been expected considering theory alone. The exact reason for this is not currently well understood. The fact that the spherical grains used in the theoretical calculations are more sensitive to grain size variation than the more irregular grain shapes found in the natural snow cover may be a partial explanation for the general success of the algorithms (Chang et al., 1976). Chang (personal communication, 1992) is currently reviewing a new interpretation of the earlier scattering theory to better understand this discrepancy between theory and empirical results. In addition, it should be noted that in terms of satellite remote sensing, the spatial variation in grain size would essentially be averaged over the total pixel (approx. 1000 km^2 in the case of SSM/I) thus reducing the effect of any extreme variations which might exist on a local scale.

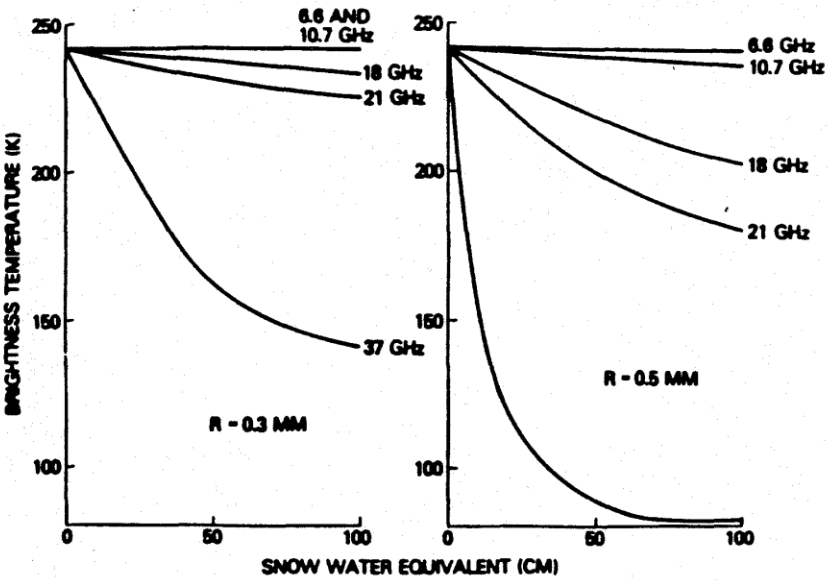

Figure 1. Calculated Brightness Temperature (K) as a Function of Snow Water Equivalent (cm) and Frequency (GHz, Horizontal Polarization) for Two Grain Radii (from Chang et al., 1987a).

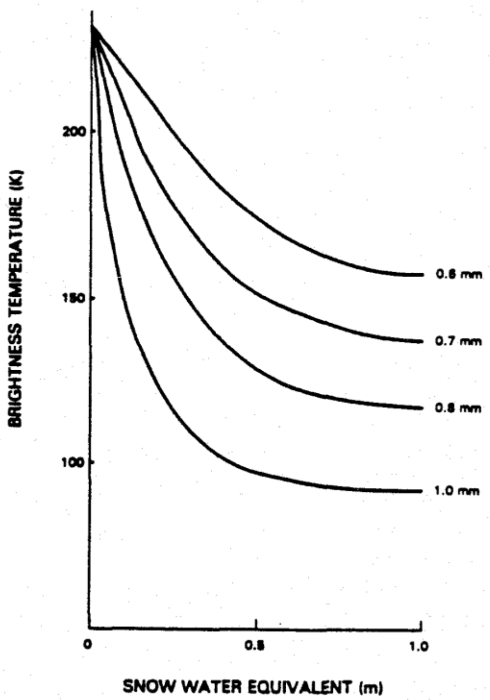

Figure 2. Calculated Relationship Between 37 GHz Brightness Temperature (Vertical Polarization) and Snow Water Equivalent (m) as a Function of Snow Grain Diameter (mm), (from Chang et al., 1981).

It has been shown, however, that conditions clearly exist where the assumption of a single grain size will cause significant retrieval errors. For example Hall et al., (1986), Josberger et al., (1990) and Chang et al., (1987b) found that when the snow cover was composed primarily of large-grained "depth hoar", the standard algorithms tended to greatly overestimate snow amount. Although no quantitative observations regarding grain size were provided in these references, this overestimation of snow amount is most certainly due to the direct relationship between grain size and increased scattering.

Depth hoar is characterized by large faceted grains which grow in the presence of strong temperature gradients. The presence of a temperature gradient within the snow cover is caused by the ground temperatures being higher than the typical air temperatures above the snow surface. The temperature gradient produces an associated vapor pressure gradient which results in the movement of vapor upwards through the snow layer. When water vapor from the warmer layers comes in contact with the adjacent colder grains, the vapor is deposited on the colder surface. If the temperature/vapor pressure gradient, and associated vapor flux, are large enough, the deposition is preferential thus producing the characteristic faceted depth hoar crystal. This more rapid form of snow crystal growth has been referred to as kinetic growth (Colbeck, 1987). Snow grains which metamorphose in the presence of weaker temperature gradients and lower vapor flux rates tend to have a smooth and rounded texture. However, most important for this study, such grains typically do not grow to diameters which exceed about 1.0 mm (Armstrong, 1985).

The rapid formation of depth hoar in a seasonal snow cover typically occurs when the temperature gradients exceed 10°C/m and average temperatures are near 0°C (Figure 3, from Armstrong, 1985). Because a change in either snow depth or average air temperature will affect the temperature gradient in the snow cover, it is important to note that of the two, snow depth typically exhibits greater long-term variability (Armstrong and Armstrong, 1987).

In geographic regions where the seasonal snow cover depths commonly exceed 0.5-1.0 m, the extent to which large depth hoar grains are present is controlled primarily by the magnitude of the temperature gradients during early winter. However, by the time the lower portion of the snowcover has developed depth hoar grains which may exceed 2.0 mm in diameter, the upper portions of deepening snow cover are often metamorphosing in the absence of a strong gradient. This occurs because the temperature difference is now averaged over a greater thickness and thus the average gradient is reduced. Therefore, although the average grain size of the individual depth hoar layers lower in the snow cover might be large, the average grain size for the total snow cover remains below the approximate threshold value of 2.0 mm. This condition may provide at least partial explanation as to why algorithms which apply a single grain size seem to perform well under a wide range of conditions. Exceptions to this would be the shallow cold snow of the Arctic and sub-Arctic (Benson and Trabant, 1972) and those periods at mid-latitudes when snow depths remain well below normal well into the winter season. Such conditions would cause the depth hoar crystal form to dominate in the snow cover resulting in average grain sizes exceeding 2.0 mm diameter.

In summary, conditions which produce large average grain sizes may result from two general snow-climate patterns. In one case, the typical winter snow cover may be shallow (less than approximately 0.5-1.0 m) combined with mean monthly temperatures consistently less than -10.0°C, causing the development of depth hoar grains throughout the snow cover. The second general case occurs in a snow climate where mean monthly air temperatures are approximately -10.0 °C, but snow depths typically exceed 0.5-1.0 m by early to mid-winter, thus preventing the temperature gradients necessary to produce depth hoar grains throughout the total snow cover. However, when drought years occur in these locations, snow depths often may not exceed the 0.5-1.0 m range, and the resulting strong temperature gradients are sufficient to convert the entire snow thickness to depth hoar. An example of this condition is provided in the following section.

What is implied here is that, for a given snow climate or region, there is some rough correlation between depth and average grain size. If a relationship between regional scale snow-climates and the associated potential to produce a snow cover primarily composed of depth hoar grains can be established, it would be possible to develop a method to adjust the microwave algorithms for grain size.

ANALYSIS OF FIELD DATA

Preliminary investigation of the relationship between snow depth and average grain size has been undertaken using data obtained from field measurements made by the U.S. Geological Survey and cooperating agencies, Upper Colorado River Basin (Josberger and Beauvillain, 1989; Josberger et al., 1990), the University of Colorado, Red Mountain Pass, Colorado (Armstrong, 1987), the Canadian Atmospheric Environment Service, Manitoba and Saskatchewan (Goodison, 1989), and the Swiss Federal Institute for Snow and Avalanche Research (W. Good and P. Foehn, personal communication, 1991).

The average grain size was computed for each snow pit in the data sample. This was calculated as a weighted mean by multiplying the observed grain size (diameter, mm) within an individual layer by the percent of total snow cover thickness represented by that layer and then summing the layer values. For example, the mean grain size for the entire USGS sample obtained during the period 1984-1988 in the Upper Colorado River Basin was 1.4 mm (diameter) with a standard deviation of 0.5 mm. The Red Mountain Pass data for the years 1972-1977 provided a mean diameter of 1.0 mm and a standard deviation of 0.3 mm. (This relatively small standard deviation would indicate that it is appropriate to characterize the stratigraphic grain diameters of the total snow cover with one mean value, i.e. 90% of the samples will not be expected to differ from the mean by more than about 1.0 mm.)

Figure 4 shows the relationship between mean grain size (diameter, mm) and depth for all data obtained from the Upper Colorado River Basin, and there is no obvious correlation or pattern ($r^2 = 0.18$). Figures 5 through 7 contain these data by month. In Figure 5 the data for January do not show a statistical correlation ($r^2 = 0.09$) but a general pattern does emerge which allows some physical interpretation. In most cases the grain sizes are less than 2.0 mm, although the depths range from less than 0.5 m to nearly 2.0 m. If our initial assumption is correct, we would expect smaller grain sizes to be associated with depths greater than about 1.0 to 1.5 m. However, in January the mean grain size is also small where depths are less than 1.0 m. This is likely due to the fact that even in those locations where temperature gradient conditions may favor the growth of larger grains, there has not been sufficient time for this growth to take place and while some grains larger than 2.0 mm may exist at the base of the snow cover, the average size of the total snow cover remains small.

The February data (Figure 6) show a stronger correlation ($r^2 = 0.50$) and again the overall pattern can be interpreted in terms of our knowledge of snow metamorphism. Where snow depths are greater than 1.0 m, the mean grain sizes have remained less than 2.0 mm, but in the shallower snow, most of the mean grain sizes exceed 2.0 mm. At this point in the winter enough time has elapsed for the process of temperature gradient (kinetic) metamorphism to create layers with grain sizes exceeding 2.0 mm.

The March (Figure 7) data set shows a lower r^2 value of 0.17 and the pattern which existed for the February data is less well defined. In this geographic region, the March data do not offer a good opportunity for analysis because of the frequent occurrence of melt conditions, especially at lower elevation sites. The continued process of melting and refreezing of the snow would result in large grains due to melt-freeze metamorphism which, as described above, is completely independent of the kinetic grain growth process in subfreezing dry snow. The data set presented in the preceding figures represents the USGS measurements for the period 1984 to 1988 (irregular times from late January to early April) from approximately 55 sites in the Upper Colorado River Basin. These winters represented typical or near-average snow cover conditions in that no single winter resulted in significant drought or exceptionally deep snow conditions. In order to test the theory of a general relationship between depth and grain size, it is instructive to introduce additional data into Figures 5-7 which approach these two snow-climate extremes. This information is provided from the University of Colorado, Red Mountain Pass data set (Armstrong, 1987) for the winters of 1977 (drought, 47% of the 15 year mean) and 1975 (well above normal

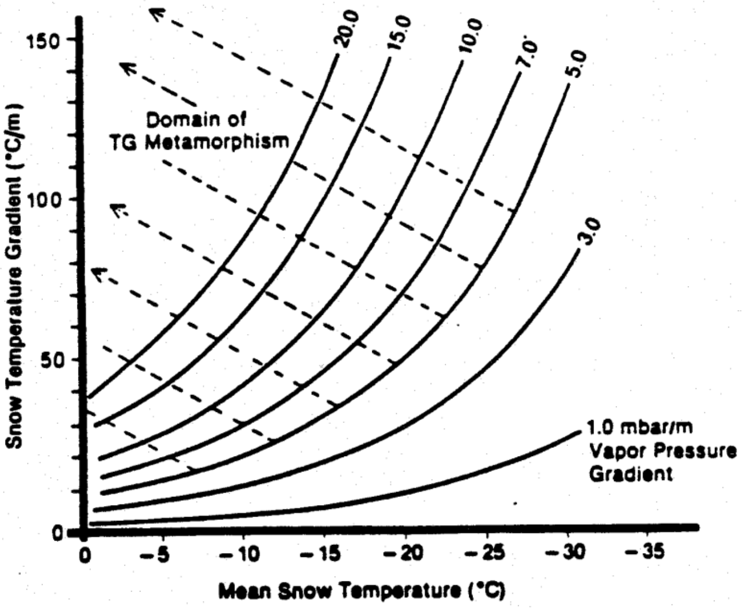

Figure 3. Relationship between Saturation Vapor Pressure Gradient, Temperature Gradient, and Mean Temperature within the Pore Space of a Snow Cover. The Value of 5.0 mbar/m is Considered here to be the Lower Limit for Temperature-Gradient (Kinetic) Metamorphism.

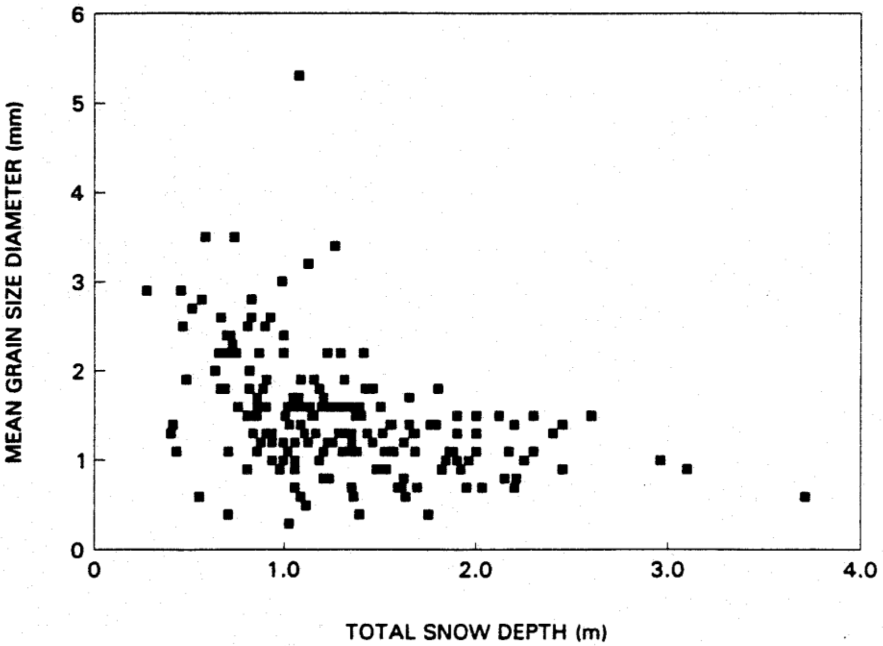

Figure 4. Relationship Between Mean Snow Grain Diameter and Snow Depth for the Full Upper Colorado River Basin Data Set (1984-1988).

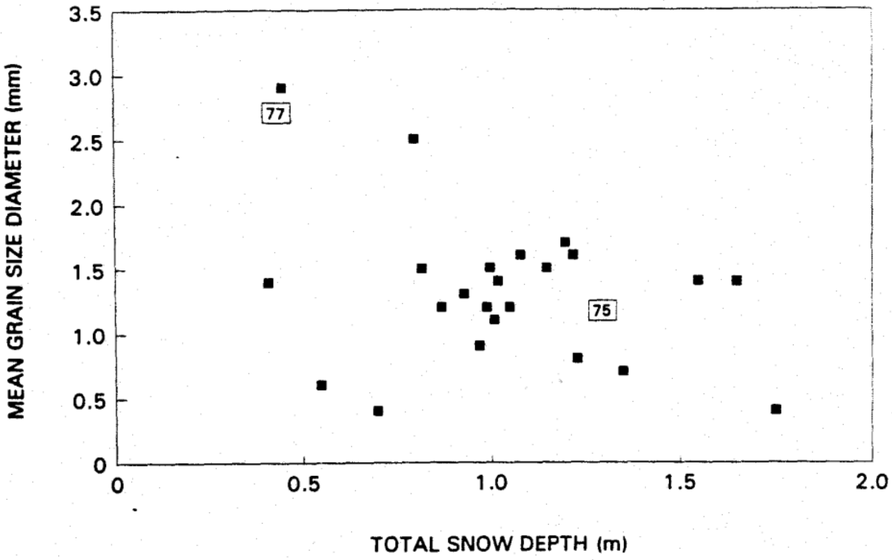

Figure 5. Relationship Between Mean Snow Grain Diameter and Snow Depth for the January Data Contained in Figure 4.

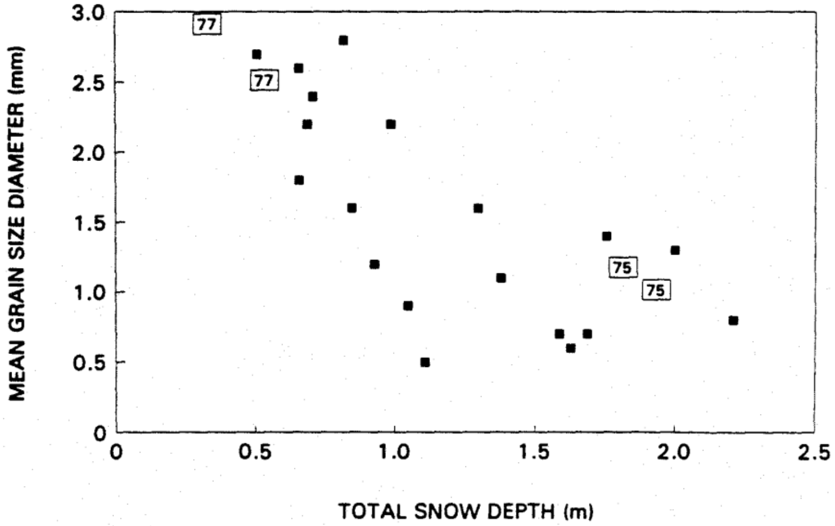

Figure 6. Relationship Between Mean Snow Grain Diameter and Snow Depth for the February Data Contained in Figure 4.

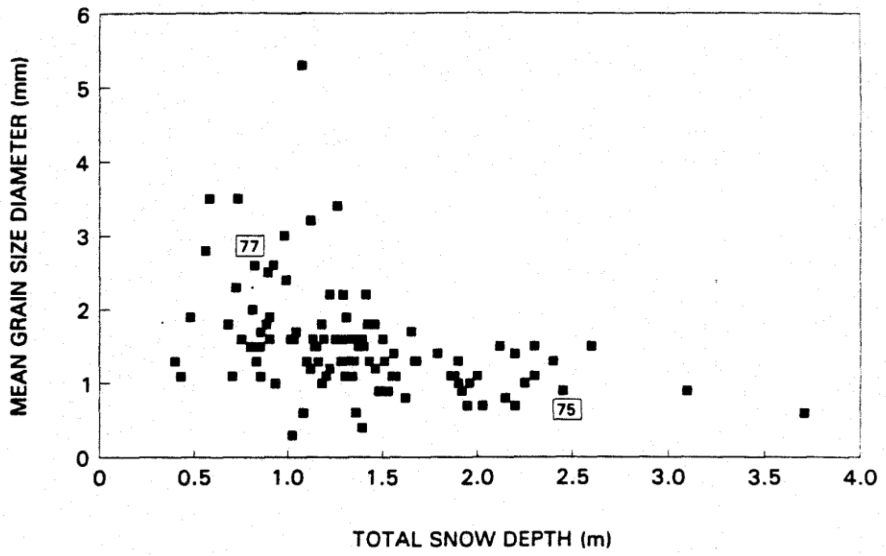

Figure 7. Relationship Between Mean Snow Grain Diameter and Snow Depth for the March Data Contained in Figure 4.

depths, 129% of the 15 year mean) as indicated by the "77" and "75" data points in Figure 5-7. These data points define the approximate "end members" for the depth/grain size relationship. The mean grain size for the 1977 Red Mountain Pass sample was 2.9 mm with a standard deviation of 0.4 mm while for 1975 these values were 1.1 mm and 0.3 mm respectively.

CONCLUSIONS

There is no doubt that there is some minimal requirement to characterize snow grain size on a regional basis if the level of accuracy of passive microwave snow cover algorithms is to be enhanced. The first level of characterization necessary is to determine, on a regional scale, the extent to which the average snow grain sizes exceed a threshold value of approximately 2.0 mm in diameter. The preliminary analysis described above indicates that even a crude relationship between snow depth (subfreezing snow) and grain size can make a significant contribution to improved algorithm accuracy.

Two grain size data sets have been examined thus far. For the upper Colorado River Basin, the best empirical regression relationship between snow depth and grain size occurs in February. February may be the ideal month to establish a relationship because 1) conditions favorable for temperature-gradient metamorphism will have had sufficient time to work, and 2) significant melt metamorphism is unlikely prior to March 1. More detailed data from Red Mountain Pass, Colorado for two extreme winters seem to fall near the ends of the February Upper Colorado River Basin snow depth/grain size relationship.

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