SATELLITE SNOW-COVER MAPPING: A BRIEF REVIEW

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INTRODUCTION

Satellite snow mapping has been accomplished since 1966, initially using data from the reflective part of the electromagnetic spectrum, and now also employing data from the microwave part of the spectrum. Visible and near-infrared sensors can provide excellent spatial resolution from space enabling detailed snow mapping. When digital elevation models are also used, snow mapping can provide realistic measurements of snow extent even in mountainous areas. Passive-microwave satellite data permit global snow cover to be mapped on a near-daily basis and estimates of snow depth to be made, but with relatively poor spatial resolution (approximately 25 km). Dense forest cover limits both techniques and optical remote sensing is limited further by cloudcover conditions. Satellite remote sensing of snow cover with imaging radars is still in the early stages of research, but shows promise at least for mapping wet or melting snow using C-band (5.3 GHz) synthetic aperture radar (SAR) data.

Algorithms are being developed to map global snow and ice cover using Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) data beginning with the launch of the first EOS platform in 1998 (Hall et al., in press). Digital maps will be produced that will provide daily, and maximum weekly global snow, sea ice and lake ice cover at 1-km spatial resolution. Statistics will be generated on the extent and persistence of snow or ice cover in each pixel for each weekly map, cloudcover permitting. It will also be possible to generate snow- and ice-cover maps using MODIS data at 250- and 500-m resolution, and to study and map snow and ice characteristics such as albedo.

Algorithms to map global snow cover using passive-microwave data have also been under development. Passive-microwave data offer the potential for determining not only snow cover, but snow water equivalent, depth and wetness under all sky conditions. A number of algorithms have been developed to utilize passive-microwave brightness temperatures to provide information on snow cover and water equivalent (Kunzi et al., 1982; Chang et al., 1987; Goodison and Walker, 1994). The variability of vegetative

cover and of snow grain size, globally, limits the utility of a single algorithm to map global snow cover.

THE USE OF OPTICAL REMOTE SENSING TECHNIQUES FOR MAPPING SNOW COVER

The National Oceanographic and Atmospheric Administration (NOAA) maps snow cover for North America using satellite data (Matson, 1991). Snow charts are digitized weekly using the National Meteorological Center's standard-analysis grid, an 89 X 89 cell Northern Hemisphere grid with polar-stereographic projection. Cell resolution ranges from 16,000 - 42,000 km^2. Only cells with at least 50 percent snow cover are mapped as snow (Robinson et al., 1993). Regional snow products are produced by NOAA's National Hydrologic Remote Sensing Center for more than 4000 drainage basins in the western United States and Canada on a weekly basis during the snow season using Advanced High Resolution Radiometer (AVHRR) and ancillary data (Carroll et al., 1989; Carroll, 1990; Rango, 1993; also see paper by T. Carroll in this volume). Landsat data, both from the multispectral scanner (MSS) and the thematic mapper (TM), are suitable for measuring snow cover at resolutions of 80 m and 30 m, respectively, and the TM bands are suitable for separating snow and clouds, but TM data are only acquired on a 16-day repeat cycle (cloud-cover permitting) and are therefore not very useful for operational studies. This is especially true because during the melt season, when the snowpack is changing rapidly, a maximum of one image every 16 days is not adequate for operational use.

Planned MODIS algorithm for mapping snow

MODIS is an imaging radiometer that uses a cross-track scan mirror and collecting optics, and a set of individual detector elements to acquire imagery of the Earth's surface and clouds in 36 discrete spectral bands. MODIS will acquire data of the land, atmosphere and oceans on a daily or near-daily basis. Spatial resolution of MODIS varies with spectral band and is 250, 500 or 1000 m. The spectral bands cover parts of the electromagnetic spectrum from about 0.4 - 14.0 μm, thus spanning the visible and thermal-infrared parts of the spectrum. The wide swath (± 55°) of the MODIS instrument will be suitable for large-area coverage. Further information on the MODIS can be found in Salomonson and Barker (1992).

A threshold-based algorithm, designed to map global snow cover, has been developed based on heritage algorithms devised by Kyle et al. (1978), Bunting and d'Entremont (1982) and Dozier (1984). This algorithm is called SNOMAP. The intent in selecting the thresholding approach to mapping snow is to utilize proven methods to map global snow and ice for the EOS at-launch global snow-cover product. More advanced snow-and ice-mapping techniques are also being investigated (e.g. Rosenthal, 1993) for use in developing post-launch products. Such advanced methods are currently useful on local and regional scales for snow and ice mapping.

SNOMAP is an algorithm designed to identify snow, if present, in each MODIS pixel each day. If snow is present in any pixel on any day during a 7-day period, that pixel will be considered to be snow covered; results will be composited for 7 days. There will

be a daily and a weekly snow-cover product. The weekly snow-cover product will represent maximum snow cover for the previous 7-day period (Riggs et al., 1994; Hall et al., in press).

SNOMAP has been tested on approximately 25 Landsat TM scenes. Study of these SNOMAP-derived maps has helped us to identify various sources of error. Additionally, field studies conducted in Montana, Saskatchewan and Alaska have allowed us to validate the algorithm when used on TM scenes acquired nearly simultaneously with the field measurements. Errors are associated with mapping snow in deep shadows of clouds and mountains. There are also errors associated with mapping snow under low-solar-elevation angles using SNOMAP, and with mapping snow in mountainous terrain unless a digital elevation model (DEM) is available (Hall et al., 1995). And, under certain conditions, cumulus clouds can be mistaken for snow, using SNOMAP, and mapped as snow cover whether or not snow is underneath the clouds.

Unique aspects of the MODIS-derived global snow maps include: fully-automated production, anticipated improved spectral discrimination between snow and other features, relative to what is available today for global snow mapping, and statistics describing snow-cover persistence in each pixel of the weekly product. A cloud mask, being developed by other MODIS investigators, will be used as will a water mask.

Having its heritage with the Normalized Difference Vegetation Index (NDVI) (Tucker, 1979), and band-ratioing techniques (Kyle et al., 1978; Bunting and d'Entremont, 1982 and Dozier, 1984), the Normalized Difference Snow Index (NDSI) is the primary component of SNOMAP that is used to identify snow. The utility of the NDSI is based on the fact that snow reflects visible radiation more strongly than it reflects radiation in the middle-infrared part of the spectrum. Since the reflectance of clouds remains high in the middle-infrared region of the spectrum, and the reflectance of snow drops to near-zero values, the NDSI also functions as a snow/cloud discriminator. For the Landsat TM, TM band 5 (1.55 - 1.75 μm) acts as a snow/cloud discriminator band.

THE USE OF PASSIVE-MICROWAVE DATA FOR MAPPING GLOBAL SNOW COVER

Passive-microwave algorithms are very useful for measuring snow-covered area and snow depth in parts of the world where the vegetative cover is not dense. However, where dense forest cover exists, passive-microwave data are less accurate for mapping snow and for estimating snow-water equivalent (Hall et al., 1982; Foster et al. 1994 and Foster, 1995).

The intensity of the microwave radiation that is emitted from a snowpack depends on the physical temperature, grain size, density and the underlying surface conditions of the snowpack. By knowing these parameters, the radiation that emerges from a snowpack can be derived by solving the radiative transfer equation (Chang et al., 1976; Foster et al., 1987). The snow grains scatter the electromagnetic radiation incoherently and are assumed to be spherical and randomly spaced within the snowpack. Although snow particles are generally not spherical in shape, their optical properties can be simulated as

spheres by utilizing Mie theory (Chang et al., 1976). The scattering effect is more pronounced at the shorter wavelengths and for larger particle sizes and drier snow.

The Nimbus series of spacecraft provided passive microwave snow-cover observations beginning in the early 1970s. The Scanning Multichannel Microwave Radiometer (SMMR) data set extends from 1978 to 1987. These passive-microwave observations have been used to map snow-covered area on a hemispheric scale at a scale of 1/2° latitude by 1/2° longitude. Several investigators have attempted to produce reliable global snow-cover algorithms using theoretical calculations (Kunzi et al., 1982; Hallikainen, 1984 and Chang et al., 1987). For example, Chang et al. (1987) developed an algorithm that assumes a snow density of 0.30 and a snow grain size of 0.35 mm for the entire snowpack. The difference between the SMMR 37-GHz and 18-GHz channels is used to derive a snow depth/brightness temperature relationship for a uniform snow field that is expressed as follows:

$$SD = 1.59 * (T_{B18H} - T_{B37H})$$

where SD is snow depth in cm, H is horizontal polarization, and 1.59 is a constant derived by using the linear portion of the 37-GHz frequencies. If the 18-GHz brightness temperature is less than the 37 GHz-brightness temperature, the snow depth is zero and no snow cover is mapped (Foster et al., 1987). This algorithm was used to produce maps of Northern Hemisphere snow-covered area and depth. These maps compare favorably with the NOAA maps except that the SMMR maps may underestimate the snow-covered area relative to the NOAA maps.

Analysis of global passive microwave snow data has revealed that the algorithms tend to underestimate snow mass due, primarily, to the effects of vegetation, especially dense conifers (Hallikainen et al., 1984; Foster et al., 1994). Forests not only absorb some of the radiation scattered by snow crystals, but they emit microwave radiation. Foster et al. (1994) have used a vegetation index derived from satellite data to account for forest cover in a given pixel, and to thus improve estimates of snow depth, especially in North America, using algorithms designed to estimate snow depth globally.

Combining visible/near-infrared and passive-microwave data for snow mapping in the EOS era

Both optical and passive-microwave data should be used in synergy to provide optimum results in snow-cover mapping. In the future, when data sets are gridded to a common grid, this will enable comparison and accurate registration of the data sets. The passive-microwave data are invaluable under conditions of darkness and persistent cloud cover, while the optical data provide a high-resolution view of snow cover. The high-resolution optical data are particularly important near the snowline when thin, dry, or wet snow may not be mapped using passive-microwave techniques, or when snow and frozen ground have similar microwave signatures (see, for example, Salomonson et al., 1995).

The Advanced Microwave Sounding Radiometer (AMSR) is a passive-microwave sensor that will be launched early in the next century and will provide improved spatial resolution relative to the currently-operating Special Sensor Microwave Imager (SSMI). AMSR is a Japanese instrument that senses from 40 GHz to 6.0 GHz with a spatial

resolution ranging from 5 to 20 km^2 and an incidence angle of 45°. It is anticipated that algorithms will be developed to utilize both MODIS and AMSR data to provide optimum snow maps.

THE USE OF IMAGING RADAR DATA FOR MAPPING SNOW COVER

The dielectric properties of snow at a given microwave frequency are generally dependent on the relative proportion of liquid and solid water in the snow by volume. Even a thin layer of liquid water will cause the radar signal to be absorbed. Snow that contains a large amount of liquid water has a high dielectric constant (>35 below 20 GHz) relative to that of dry snow. The dielectric properties of the snow mixture are not only influenced strongly by snow wetness, but by the inhomogeneity in the snow volume introduced by the highly-conductive water particles.

The amount of backscatter received by a radar antenna is the sum of surface scattering at the air/snow interface, volume scattering within the snowpack, scattering at the snow/soil interface and volumetric scattering from the underlying surface (if applicable). In a dry snowpack, the microwave scattering is governed by snow depth and density. Volume scattering in dry snow results from scattering at dielectric discontinuities created by the differences in electrical properties of ice crystals and air (Leconte et al., 1990).

At present, the European ERS-1 and -2, and the Japanese JERS-1 satellites are operating, and Canada's RADARSAT is planned for launch later this year. Because the satellite-borne C-band (5.3 GHz) and L-band (1.275 GHz) wavelengths (5.7 and 23.5 cm, respectively) are much larger than the average snow crystal or grain, it is unclear whether or not C- and L-band synthetic aperture radar (SAR) data are potentially useful for monitoring and measuring dry snow. However, studies have shown that there can be a high contrast between snow-free ground and ground covered with wet snow (Matzler and Schanda, 1984) thus making it possible to distinguish wet and dry snow, and to measure snow-covered area when the snow is wet using ERS-1 data. For example, Way et al. (1990) noted a possible increase in backscatter due to snow becoming moist under thawing conditions in central Alaska. This effect was also observed in northern Alaska using ERS-1 data by Hall (in press).

CONCLUSION

The outlook for improving snow mapping in the near future is excellent. Refinements of passive-microwave algorithms for mapping snow cover and snow depth are leading to improved estimates of these parameters globally. Additionally, EOS will allow an enhanced ability to map global snow cover using future MODIS and AMSR data due to improved spatial and spectral resolution. Algorithms will be developed that use data from both sensors to optimize results. These data will be available as input to general circulation models and hydrologic models.

Long-term studies of global snow cover will also be possible with the EOS data, and will extend the satellite record of North America snow cover that dates back to 1966. Satellite-borne SAR data are still being studied for their utility in snow mapping and in

determining snow water equivalent. If, in the future, higher-frequency SAR sensors are flown on satellites, such data may be more useful for the study of seasonal snow cover than are the currently-available C-band SAR satellite data.

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REFERENCES

Bunting, J.T. and d'Entremont, R.P., 1982: Improved cloud detection utilizing defense meteorological satellite program near infrared measurements, Air Force Geophysics Laboratory, Hanscom AFB, MA, AFGL-TR-82-0027, Environmental Research Papers, No. 765, 91 pp.

Carroll, T.R., Baglio, J.V., Jr., Verdin, J.P. and Holroyd, E.W.,III, 1989: Operational mapping of snow cover in the United States and Canada using airborne and satellite data, *Proceedings of the 12th Canadian Symposium on Remote Sensing*, V.3, IGARSS'89, 10-14 July 1989, Vancouver, Canada.

Carroll, T.R., 1990: Operational airborne and satellite snow cover products of the National Operational Hydrologic Remote Sensing Center, *Proceedings of the forty-seventh Annual Eastern Snow Conference*, 7-8 June 1990, Bangor, Maine, CRREL Special Report 90-44.

Chang, A.T.C., Gloersen, P., Schmugge, T., Wilheit, T. and Zwally, H.J., 1976: Microwave emission from snow and glacier ice, *Journal of Glaciology*, 16:23-39.

Chang, A.T.C., Foster, J.L. and Hall, D.K.,1987: Nimbus-7 derived global snow cover parameters, *Annals of Glaciology*, 9:39-44.

Foster, J.L., Hall, D.K. and Chang, A.T.C, 1987: Remote sensing of snow, *EOS Transactions of the American Geophysical Union*, 68:681-684.

Foster, J.L., Chang, A.T.C. and Hall, D.K., 1994: Snow mass in boreal forests derived from a modified passive microwave algorithm, *Proceedings of the European Symposium on Satellite Remote Sensing*, 26-30 September 1994, Rome, Italy.

Foster, J.L., 1995: Improving and evaluating remotely-sensed snow/microwave algorithms and snow output from general circulation models, Ph.D. dissertation, Department of Geography, University of Reading, Reading, England.

Goodison, B.E. and Walker, A.E., 1994: Canadian development and use of snow cover information from passive microwave satellite data, *Proceedings of the ESA/NASA International Workshop*, B.J. Choudhury, Y.H. Kerr, E.G. Njoku and P. Pampaloni (eds.), pp.245-262.

Hall, D.K., Foster, J.L., Chien, J.Y.L. and Riggs, G.A., 1995: Determination of actual snow-covered area using Landsat TM and digital elevation model data in Glacier National Park, Montana, *Polar Record*, 31(177):191-198.

Hall, D.K. in press: Remote sensing of snow and ice using imaging radar, in *Manual of Remote Sensing*, 3rd. edition.

Hall, D.K., Foster, J.L. and Chang, A.T.C., 1982: Measurement and modeling of microwave emission from forested snowfields in Michigan, *Nordic Hydrology*, 13:129-138.

Hall, D.K., Riggs, G.A. and Salomonson, V.V., in press: Development of methods for mapping global snow cover using Moderate Resolution Imaging Spectroradiometer (MODIS) data, *Remote Sensing of Environment*.

Hallikainen, M., 1984: Retrieval of snow water equivalent from Nimbus-7 SMMR data: effect of land-cover categories and weather conditions, *IEEE Journal of Oceanic Engineering*. OE9:372.

Kunzi, K.F., Patil, S. and Rott, H.,1982: Snow-cover parameters retrieved from Nimbus-7 SMMR data, *IEEE Transactions on Geoscience and Remote Sensing*, GE20:452-467.

Kyle, H.L.,. Curran, R.J., Barnes, W.L. and Escoe, D., 1978: A cloud physics radiometer, *Third Conference on Atmospheric Radiation*, Davis, CA, pp.107-109.

Leconte, R., Carroll, T. and Tang, P., 1990: Preliminary investigations on monitoring the snow water equivalent using synthetic aperture radar, *Proceedings of the Eastern Snow Conference*, 7-8 June 1990, Bangor, Maine, pp.73-86.

Matson, M., 1991: NOAA satellite snow cover data, *Paleogeography and Paleoecology*, 90:213-218.

Matzler, C. and E. Schanda, 1984: Snow mapping with active microwave sensors, *International Journal of Remote Sensing*, 5(2):409-422.

Rango, A., 1993: Snow hydrology processes and remote sensing, *Hydrological Processes*, 7:121-138.

Riggs, G.A., Hall, D.K. and Salomonson, V.V., 1994: A snow index for the Landsat Thematic Mapper and Moderate Resolution Imaging Spectroradiometer, *Proceedings of the International Geoscience and Remote Sensing Symposium*, IGARSS '94, 8-12 August, 1994, Pasadena, CA, pp.1942-1944.

Robinson, D.A., Dewey, K.F. and Heim, R.R., Jr., 1993: Global snow cover monitoring: an update. *Bulletin of the American Meteorological Society*, 74:1689-1696.

Rosenthal, C.W., 1993: Mapping montane snow cover at subpixel resolution from the Landsat thematic mapper, M.A. thesis, Department of Geography, University of California at Santa Barbara, 70 p.

Salomonson, V.V. and Barker, J.L., 1992: EOS Moderate Resolution Imaging Spectroradiometer: phase C/D status and comments on calibration and georeferencing approaches, *Proceedings of the 15th Annual Guidance and Control Conference,* 8-12 February 1992, Keystone, Colorado, pp.1-14.

Salomonson, V.V., Hall, D.K. and Chien, J.Y.L., 1995: Use of passive microwave and optical data for large-scale snow-cover mapping, *Proceedings of the Second Topical Symposium on Combined Optical-Microwave Earth and Atmosphere Sensing,* 3-6 April, 1995, Atlanta, GA, pp.35-37.

Tucker, C.J., 1979: Red and photographic infrared linear combinations for mapping vegetation, *Remote Sensing of Environment,* 8:127-150.

Way, J., Paris, J., Kasischke, E., Slaughter, C., Viereck, L., Christensen, N., Dobson, M., Ulaby, F., Richards, J., Milne, A., Seiber, A., Ahern, F., Simonett, D., Hoffer, R., Imhoff, M. and Weber, J., 1990: The effect of changing environmental conditions on microwave signatures of forest ecosystems: preliminary results of the March 1988 Alaskan aircraft SAR experiment, *International Journal of Remote Sensing,* 11(7):1119-1144.