Satellite based snow monitoring for hydropower production and trade in Norway – results versus operational needs

A. Rognes [a,*], R. Solberg [a], J. Amlien [a], H. Koren [a], L. Eikvil [a], E. Malnes [b], R. Storvold [b], I. Lauknes [b], T. Andersen [c],

[a] Norwegian Computing Center, P.O. Box 114, Blindern, NO-0314 OSLO, Norway, – Anders.Rognes@nr.no
[b] Norut IT, P. O. Box 6434, Forskningsparken, NO-9294 TROMSØ, Norway – Eirik.Malnes@itek.norut.no
[c] Statkraft, P. O. Box 200, Lilleaker, N-0216 OSLO - Tom.Andersen@statkraft.com

Abstract – In Norway more than 99 percent of the electric power produced comes from hydropower plants. The exploitation of waterfalls for the production of electric power in Norway started as early as the beginning of the 20th century. The demand for reliable information on the water catchment properties, precipitation and snow stored during the winter has been increasing ever since. The advent of satellite remote sensing created a new tool for collecting valuable information about snow conditions in remote areas supplying complementary information to the hydropower producer. Labour intensive in situ monitoring campaigns in these areas will probably still be necessary in the future, but satellite imagery is increasingly adding valuable information for the day-to-day modelling of the catchments' status. For many years platforms carrying optical sensors were the only satellite-based source, but because these sensors are limited by clouds and daylight, a combined approach applying both optical and radar sensors is now being developed. The product range has been expanded from traditional snow cover to also include snow temperature, snow wetness and onset of melt, all of them possibly useful for operational snow monitoring. An important goal is to measure the snow water equivalent by remote sensing with sufficient accuracy. This has yet not been achieved, although some recent results are promising. R&D on satellite-based snow monitoring is continuously evolving in Norway, both on the national level as well in cooperation with international partners. In this process, selected users are invited to critically review the results to ensure that user needs form a reliable basis for the development taking place.

Keywords: Hydropower, snow monitoring from satellites, multi-sensor algorithms, user needs.

1. INTRODUCTION

Fresh water is abundant in Norway. The average precipitation amounts to about 1400 mm, of which some 200 mm evaporates. The remaining 1200 mm is discharged into the sea. The annual amount of fresh water delivered to the sea amounts to about 400 km^3. Norway is a mountainous country with peaks up to around 2500 masl and a high mountain plateau at around 1000 masl dominates the terrain in Southern Norway. Hence the precipitation in Norway is not uniformly distributed. In the western part of the country annual precipitation may exceed 5000 mm, whereas some eastern valleys receive less than 300 mm per year. The precipitation also varies with season. On average, about half of the annual precipitation falls as snow. Thus, snow-melt floods are frequent during springtime. The early summer is usually quite dry, whereas rainfall during the autumn may cause flooding (NVE, 2005).

The topography and the rainy climate gave an early start for log floating and water propelled lumber mills that established Norway as a land of lumbering, construction of wooden ships and the shipping trade.

2. THE HISTORY OF SNOW MONITORING

2.1 A century of hydropower plant development

At the end of the 19th century Norway was for the most part a pre-industrial society. The major breakthrough came in the years after 1905. The foundation for the modern industrial society was laid following the dissolution of the union with Sweden and World War I. What was new was primarily the modern process-based industry which came on line with its high consumption of electricity and the new electro-chemical and electro-metallurgic industry. Electricity was the power source that transformed trade and commerce and made industry into the major business area. The availability of cheap electric power attracted foreign capital and new technology to Norway. A boom period from 1905 to the outbreak of World War I generated strong economic growth that changed the structure of industry and settlement patterns once and for all.

During the economic expansion following World War 2, an extensive programme for hydropower development that lasted until the early eighties was carried out .

Today, the Norwegian electric energy supply system is based entirely on hydropower. Environmental flows are gaining increasing attention in Norway and are a strategic element in the management of hydropower development. The new Water Resources Act in Norway of January 2000 emphasizes greater flexibility and the need to take into account ecological, aesthetic and economic considerations, thus increasing the need for site-specific knowledge.

A new Energy Act came into effect in 1991. From 1 January 1991 competition and commercial principles were introduced into the production and trading of electrical power. The objectives of the new Energy Act were to exploit energy supply resources more efficiently, ensure electricity supplies and equalise power prices from one geographic area to another. The overall annual generation of hydropower in Norway now sums up to 118 TWh.

2.2 Operational user needs

The major Norwegian power producer, Statkraft, has more than 60 power stations with related regulation facilities across the entire country. Many of the more than 120 reservoirs are located at high elevations and the catchment areas cover extensive mountain areas. In order to monitor the hydrological conditions in the catchment areas, it is necessary to have a nation-wide overview.

* Corresponding author.

For production planning and market operations it is important to have the best knowledge of how much snow there is in the mountains. In fact, knowledge of the snow reserves in the catchment areas gives, as of today, the best way of forecasting inflow during the summer with an accuracy that is far better than using average values. The inflow during the summer period will determine whether the hydropower water reservoirs will be filled up again before next winter or whether there will be overflow and spill of water. This in turn is important for the power price development throughout the year and this is extremely important from a market point of view (Statkraft, 2005).

There are a number of activities that contribute to Statkraft's overview of the snow situation. The data collected by the Norwegian Meteorological Institute and the Norwegian Water Resources and Energy Directorate are obtained via internet and the amount of snow in all mountain basins is calculated throughout the winter with the use of hydrological models. Nevertheless, possibly the most important information source are the manual measurements that are carried out in the catchment areas during the winter season according to fixed measurement plans. During melting periods the snowmelt process in the mountain areas is monitored with the help of satellite data and an in-house computer system. This gives Statkraft maps and snow data for the entire country at short notice when conditions make it possible to download satellite data (Solberg and Andersen, 1994).

With the help of mathematical and statistical models, the trend in inflow conditions in the catchment areas is forecasted and simulations are made to predict the future level of the water reservoirs. This in turn gives a basis for production planning, and for buying and selling power in the power markets. Modern computer tools help in passing on information on the hydrological and meteorological situation in the field so that Statkraft is able to plan for power production that ensures its power delivery obligations are met with the best possible financial result.

3. THE LONG HISTORY OF WORK ON SATELLITE REMOTE SENSING

The interest for satellite remote sensing data as a source for snow cover started to develop rapidly in the 1970’s with the first Landsat satellites (see e.g. Meier, 1973, and Ødegaard and Østrem, 1977). Hydroelectric companies soon realised the economic benefits that remote sensing could provide as a data source for snow cover in precipitation areas draining to their production plants. In countries with large alpine and high-mountain areas, a substantial proportion of the drainage basins are located in areas where more than 50% of the precipitation falls as snow. The amount and distribution of the snow is crucial for planning the power production (Solberg and Andersen, 1994).

3.1 Two decades of snow monitoring with optical sensors

The optical snow covered area (SCA) algorithm is based on an empirical reflectance-to-snow-cover model originally proposed for NOAA AVHRR in Andersen (1982) and later refined in Solberg and Andersen (1994). The algorithm has recently been tailored to MODIS data by Norwegian Computing Center. It retrieves the snow-cover fraction for each pixel. The model is calibrated by providing two points of a linear function relating observed reflectance (or radiance) to fractional snow-cover area (see Figure 1). The calibration is usually done automatically by means of calibration areas. Statistics from the calibration areas are then used to compute calibration points for the linear relationship (see Figure 1).

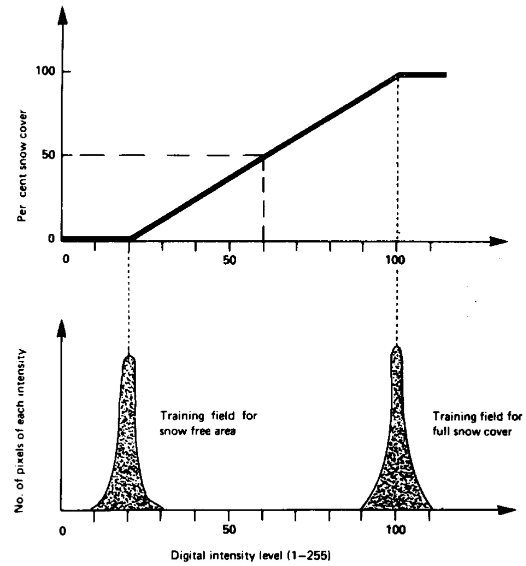

Figure 1: The linear reflectance-to-snow-cover algorithm illustrated. A pixel value is linearly transformed to a snow cover percentage for that pixel. The algorithms are based on the assumption that the bare-ground reflectance is constant (Andersen 1982).

3.2 The need for new innovative solutions

Optical remote sensing sensors are able to map snow cover quite accurately, but are limited by clouds. Radar sensors penetrate the clouds, but current satellite-borne sensors are only able to map wet snow accurately. The research institutes NR and Norut IT have together developed algorithms for snow variable mapping applying a multi-sensor and multi-temporal approach (Solberg et al, 2004b). The overall idea is to combine the use of optical and SAR sensors and utilise the best features of each sensor when possible in order to map snow variables more frequently and with better spatial coverage than would otherwise be possible.

4. RECENT WORK IN NORWAY

4.1 Evolving methods applying optical sensors

In addition to the optical snow covered area (SCA) algorithm based on the empirical reflectance-to-snow-cover model recently tailored to the American MODIS data by NR, other algorithms using data from this sensor have been developed. In the pipeline are various products being developed for advanced snow monitoring for hydropower trade, flood monitoring and climate monitoring in addition to hydropower production.

A few fractional snow cover algorithms have been developed by various research groups. However, there is still a gap between the accuracy needed and what is obtained in practice. A method has been developed where the actual, current spectral and BRDF characteristics of the snow and bare ground is modelled locally, per pixel (Solberg, 2004c).

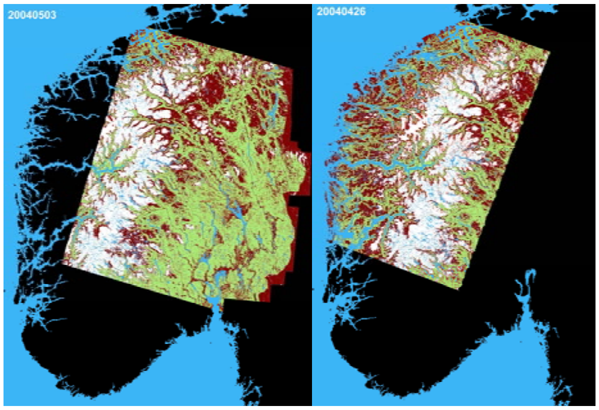

Figure 3: Snow covered area map for part of Southern Norway, April 26 (left) and May 3 (right), 2004 using Envisat ASAR for snow detection.

The main principle of remote sensing of temperature is that Earth's surface emits long-wave radiation according to the surface temperature and surface characteristics (emissivity). The atmosphere will absorb some of the radiation before it reaches the satellite. The snow surface will therefore appear as colder than it really is. Key's algorithm, a modification of the simple split-window technique (using two nearby bands in the thermal region of the spectrum), was finally selected for our applications (see Solberg et al 2004b).

For snow wetness and snowmelt onset, a new approach NR has developed is to infer wet snow from a combination of measurements of snow temperature of surface and snow grain size in a time series of observations. The temperature observations give a good indication of where wet snow potentially may be present, but are in themselves not accurate enough to provide very strong evidence of wet snow. However, a strong indication of a wet snow surface is a rapid increase of the effective grain size observed simultaneously with a snow surface temperature of approximately 0^{o}C.

4.2 Synthetic aperture radar – solving the cloud problem?

Radar remote sensing of snow parameters such as snow cover area, snow wetness and snow water equivalent is attractive since it solves the problems due to clouds and darkness. During winter time the northern part of Norway is dark for two months, and cannot be studied by optical methods. Furthermore, in the important melting season, clouds are a prominent feature making continuous monitoring of snow impossible with optical sensors. Mapping of snow has been demonstrated with Synthetic Aperture Radars (SAR) such as ERS, Envisat ASAR and Radarsat. Recently, Storvold and Malnes (2004) demonstrated how the wide-swath modes of Envisat ASAR can be used to map larger areas, such as southern Norway, frequently with SAR. The method used is based on change detection between a dry snow reference scene and a wet snow image. The resulting image is a mask of wet snow. To make the snow product comparable to optical imagery, pixels above the wet snow line are postulated as dry snow. Figure 2 shows two examples of classified snow for southern Norway using Envisat ASAR data.

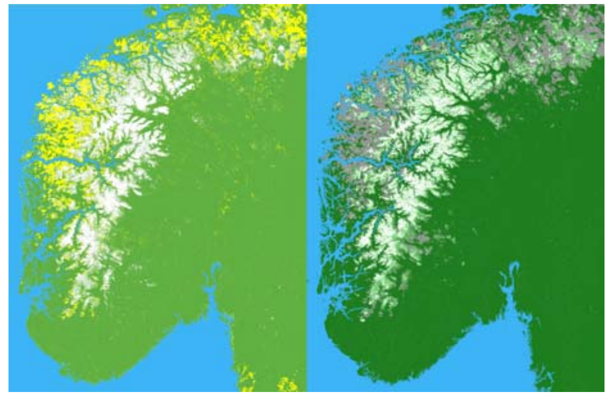

Figure 2: Multisensor products for May 25, 2004 from Norut IT (left) and NR (right). The colour coding, in particular for clouds, is different in the two images. There are also other differences in the snow classification of snow covered area due to different weighting of SAR and optical products in the respective multi-sensor algorithms.

The SAR-mapping method for snow works well when the snow is wet, but has problems when large areas are covered with dry snow. C-band SARs, such as ASAR and Radarsat, have too little sensitivity to discriminate dry snow from bare soil based on the amplitude of the returned radar signal. In an innovative approach, using repeat-pass SAR interferometry, the team at Norut IT, demonstrated that the interferometric phase change between a summer reference image and a dry snow image is a direct measure of the snow water equivalence (SWE), see Engen et al, 2004. Although these results do not yet satisfy users with respect to resolution, one of the ultimate goals for remote sensing of snow is to be able to measure SWE using earth observation. Future satellites with improved capabilities may prove successful in achieving this.

4.3 The multi-sensor techniques

The teams at Norut IT and NR have collaborated to develop a multitemporal and multisensor technique for mapping snow cover area in Scandinavia based on a common framework. The technique hinges on single sensor snow maps from the Envisat ASAR and the Terra MODIS sensors. Each single-sensor product is resampled to a common grid covering southern Norway and Sweden. In addition to the snow cover map, we also produce a confidence map that quantifies the probability of correct classification of each pixel. The confidence is model based, and is a function of viewing angle and proximity to clouds for optical products and probability for wet snow, presence of dry snow and viewing angle for SAR products.

NR and Norut IT have developed separate implementations of the multisensor algorithms, (see Solberg et al, 2004b). The method developed by Norut IT is tuned for near real-time operations and generates a new multisensor product each time a new single sensor scene enters the system. NR's algorithm is based on combining all single sensor products from each day into a day product. The day products may later be combined into monthly, seasonal and annual snow climate change related products. The difference between the day product from NR and the latest multisensor product for a day from Norut IT is only a function of the small differences in algorithm tuning between the two methods, e.g. lapse rate for confidence degradation, weighting between SAR and optical confidence. In Figure 3 we show examples of multisensor products for the same day from NR and Norut IT.

5. THE MATCH BETWEEN USER NEEDS AND AVAILABLE SERVICES

The focus for the development of satellite based snow monitoring services should always be user needs. Norwegian hydropower plants have almost one hundred years of operational service and have thus adapted to a regime of mainly in situ data collection and corresponding data utilisation. In other words, this means that new technology has to compete with this legacy of methods and tools. The keywords for the new technology are coverage and repetitiveness. Satellite-based snow monitoring gives a frequent view over large areas that cannot be challenged by in situ campaigns and ground-based monitoring networks. However, a challenge is that remotely sensed data will necessarily introduce uncertainties compared to ground measurements due to the mere distance of acquisition.

It is important to make sure that satellite data is calibrated to available ground data according to a well-considered plan and that the data are presented with the uncertainties they have.

Professional customers will in any case have strict requirements for the reliability, availability, maintainability and safety (RAMS) whereof reliability covers the service provision in technical terms comprising product quality and delivery on agreed conditions. The parameters shown in the maps will have to be accurate when it comes to area, temperature, position etc. and delivered on time. Availability in the broader meaning is that the service can be purchased for the water catchments and in the time period of interest for the customers. Maintainability means the service is furnished with a guarantee that necessary fixes and updates are available when needed. In addition, it will be desirable to carry out continuous activities in research and development to ensure that the service always remains in the forefront and complies with new enabling technology. This would be the case for new sensors, better coverage with increasing number of satellites, data fusion or other innovations. Service safety is probably the most critical issue as the space segment relies on the satellites remaining in operation as foreseen. The ground segment can to a larger degree be safeguarded by redundant systems. However, an ever increasing number of satellites in orbit may also allow for redundancy in data acquisition.

Statkraft is simulating the status of their reservoirs and catchments daily based on figures for precipitation and temperature. However, direct measurements are always necessary for calibration of the models applied. Satellite imagery gives valuable input for a set of important parameters and new methods are showing promising results to extend this list with snow temperature and onset of snowmelt. The ultimate goal for R&D will be directly to derive the total water content of the snowpack. Promising work following different paths is taking place, but the resulting products will probably not become operational for some time yet.

6. FURTHER WORK PLANNED

For the near future, continued research and development should involve an increasing operational use of satellite-based snow monitoring products. Operational use of a few, but well-proven products will stimulate efforts to bring forward a new generation of products.

In Norway, a lot of focus has recently been on this work through several national and international projects. Currently, new projects are being consolidated with partners in Norway and abroad. The aim will be to reveal new innovative solutions that the customer will benefit from either in terms of better products or a better tailored service.

6. REFERENCES

6.1 References from Journals

Andersen, T. (1982): "Operational Snow mapping by Satellites", Hydrological Aspects of Alpine and High-Mountain Areas, Proceedings from Exeter Symposium, July 1982. IAHS Publication no. 138.

Engen, G., Guneriussen, T., and Overrein, Ø. (2004): Delta-K interferometric SAR technique for snow water equivalent (SWE) retrieval. IEEE Geoscience and Remote Sensing Letters, 1(2):57–61, 2004

Meier, M. F. (1973): "Evaluation of ERTS Imagery for Mapping of Changes of Snow Cover on Land and on Glaciers". Symposium on Significant Results Obtained from the Earth Resources Technology Satellite-1, New Carrolton, Maryland, NASA, Vol 1.

Solberg R, and T. Andersen (1994): "An Automatic System for Operational Snow-Cover Monitoring in the Norwegian Mountain Regions". Proceeding of IEEE International Geoscience and Remote Sensing Symposium, 8-12 August 1994, Pasadena, California, pp 2084-2086.

Solberg, R., J. Amlien, H. Koren, L. Eikvil, E. Malnes and R. Storvold (2004a) "Multi-sensor/Multi-temporal Analysis of Envisat Data for Snow Monitoring". 2004 Envisat & ERS Symposium, Salzburg, Austria. In press.

Solberg R., J. Amlien, H. Koren, E. Malnes, R. Storvold (2004b) "Multi-sensor and time-series approaches for monitoring of snow parameters". Proceedings IGARSS 04, Anchorage, USA, September 2004

Solberg, R. (2004c): "A high-precision dynamic and adaptive BRDF and fractional snow-cover monitoring algorithm." IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2004), Anchorage, Alaska, USA, 20-24 September 2004

Storvold R. and E. Malnes (2004): "Snow Covered Area Retrieval Using ENVISAT ASAR Wideswath in Mountainous Areas", Proceedings to IGARSS-04, Ancorage, USA, 2004

Ødegaard, H. A. and G. Østrem (1977): Application of Landsat Imagery for Snow Mapping in Norway". Norwegian Water Resources and Electricity Board, Final Report, Landsat-2 Contract 29020.

6.2 References from Websites

NVE: The Hydrology of Norway. http://www.nve.no/ 2005

Statkraft: Press package. http://www.statkraft.com/ 2005