CoReH2O – A Ku- and X-Band SAR Mission for Snow and Ice Monitoring

Helmut Rott, Institute for Meteorology and Geophysics, University of Innsbruck, Austria
Don Cline, NOAA-NOHRSC, Chanhassen, MN, USA
Claude Duguay, University of Waterloo, Canada
Richard Essery, University of Edinburgh, UK
Christian Haas, Alfred-Wegener-Institut, Bremerhaven, Germany, and University of Alberta, Canada
Giovanni Macelloni, IFAC-CNR, Firenze, Italy
Eirik Malnes, NORUT, Tromsö, Norway
Jouni Pulliainen, FMI, Helsinki, Finland
Helge Rebhan, ESA-ESTEC, Noordwijk, Netherlands
Simon Yueh, JPL-CalTech, Pasadena, CA, USA

Abstract

The COld REgions Hydrology High-resolution Observatory (CoReH2O) satellite mission has been selected by the ESA for scientific and technical studies within the Earth Explorer Programme. The mission addresses major gaps in present snow and ice observations. Improved, spatially detailed measurements of snow and ice properties are needed to advance the understanding of the role of the cryosphere in the climate system and to improve the knowledge and prediction of water cycle variability and changes. Basic measurements of CoReH2O will include extent, water equivalent and melting state of the seasonal snow cover, snow accumulation and diagenetic facies of glaciers, permafrost features, and sea ice types. The proposed sensor is a dual frequency SAR, operating at 17 GHz and 9.6 GHz, VV and VH polarizations. The dual frequency, dual polarization approach enables the decomposition of the scattering signal for retrieving physical properties of snow and ice. Scientific preparation activities include experimental campaigns with in situ and airborne scatterometers, improvement of radar backscatter models, the analysis of satellite data from Ku-band scatterometers and X-band SAR, and the development of retrieval algorithms for snow and ice parameters.

1 Introduction

Snow and ice are key elements of the climate system, responding very sensitively to changes in temperature and precipitation, and interacting with other climate variables through complex feedback mechanisms. Snow and ice play also an important role in biogeochemical cycles. Snow and glacier melt is a basic resource of water for many densely populated areas of the world, the abundance of which is seriously threatened by climate change. Therefore accurate inventories of the snow and ice masses and their temporal dynamics, as well as improved parameterizations and modelling of water and energy exchange processes are important for advancing the understanding of climate change and its impact on the environment.

There is a lack of spatially distributed information on snow accumulation on land surfaces, glaciers and sea ice. In its Cryosphere Theme Report [1] the Integrated Global Observing Strategy (IGOS) Partnership recommends the development and implementation of satellite systems for spatially distributed measurements of snow water equivalent (SWE) and other snow properties. In order to close gaps in cryosphere observations, the satellite mission COld REgions Hydrology High-resolution Observatory, CoRe-H_2O, has been proposed to ESA in response to the 2005 Call for Earth Explorer Core Missions and selected for pre-feasibility studies.

2 Scientific Requirements

The objectives of the CoRe-H_2O mission are spatially detailed observations of snow, ice, and water cycle characteristics in cold environments. The satellite measurements will address the following applications:

- Improved modeling and prediction of water balance and stream flow in snow covered and glacierized basins
- Assessing effects of climate change on water supply from snow and glaciers
- Improving parameterization of snow and ice processes in numerical weather prediction and climate models
- Studying and modeling mass balance of glaciers and ice caps
- Supporting process studies for lake and river ice
- Monitoring surface water extent in high latitudes and its relation to climate variability
- Studies of small-scale sea ice kinematics and thin ice properties and processes in polynyas and leads
- Improving estimates of sea ice surface heat fluxes and mass balance by monitoring snow cover on the ice.

Based on the mission objectives, the observational requirements for seasonal snow cover, glaciers and ice sheets, fresh-water ice, sea ice, and surface water were defined. For snow cover the main parameters are snow extent, water equivalent, and depth; for glaciers the diagenetic facies and winter snow accumulation; for sea ice the snow depth, ice type, and motion (with emphasis on thin ice).

Two different temporal observation phases are proposed. A 3-day repeat cycle with limited coverage is aimed at a time scale compatible with meteorological forcing, particularly addressing cryosphere-atmosphere exchange and the parameterization of snow and ice processes, and providing input to numerical weather forecasting models and hydrological models. The second phase shall provide near complete observations of the global cryosphere at about 15 day repeat cycle.

3 Scientific Preparations

The proposed mission concept, aimed at spatially detailed measurements of snow and ice parameters, is based on co- and cross-polarized backscatter measurements at X-band (9.6 GHz) and Ku-band (17.2 GHz). In order to achieve the required spatial coverage and resolution, a SAR with swath width ~ 100 km and pixel size ~ 50m (5 looks) is proposed.

The scientific activities for mission preparation include theoretical and experimental work on interaction of Ku- and X-band radar waves with snow and ice, studies on the impact of atmospheric effects and vegetation on backscatter signatures, and the development and testing of algorithms for retrieval of snow and ice physical properties.

3.1 Effects of Atmospheric Propagation

The main objectives of the mission are observations of land surfaces, oceans and ice sheets in cold environment. In order to estimate the impact of atmospheric propagation effects for retrieving snow and ice parameters, calculations of atmospheric transmittance were carried out for a range of atmospheric conditions. Figure 1 shows results of calculations of atmospheric transmittance using the climatology of winter time atmospheric profiles from the ECMWF ERA40 atmosphere data of northern Finland. The study suggests that corrections for atmospheric propagation effects over cold environment can be based on climatological values of atmospheric water vapour content and cloud conditions. Another option would be the use of numerical meteorological data from atmospheric circulation models.

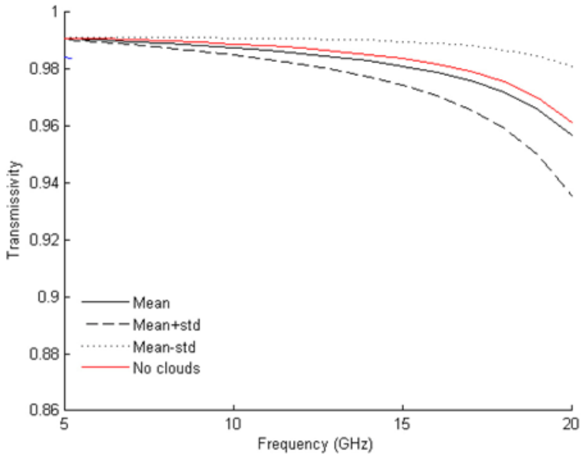

Figure 1 Atmospheric transmissivity for winter atmosphere conditions, incidence angle 30° off nadir.

3.2 Backscatter Sensitivity to Snow Physical Properties

Theoretical and experimental studies were performed to investigate the relations between backscatter signatures and physical properties of snow and ice.

A main parameter to be measured by CoRe-H_2O is the mass of snow on ground, the snow water equivalent, SWE. Radiative transfer modelling with the dense medium approach (DMRT) was performed to study the sensitivity of the backscatter coefficient to SWE and to investigate effects of snow grain size and grain shape, and of the background target.

For measuring SWE by means of SAR the snow has to be dry so that the signal is able to penetrate into the snow pack. At Ku-band one-way penetration depth for dry snow is about 3 to 4 m, whereas at X-band it is about 10 m [2]. In the DMRT model the total backscatter signal of dry snow over ground at polarization pq takes into account the following contributions:

$$\sigma_{pq}^{T} = \sigma_{pq}^{as} + \sigma_{pq}^{v} + \sigma_{pq}^{gv} + \sigma_{pq}^{g}$$

The first term on the right hand side accounts for scattering at the air/snow interface, the second term for snow volume scattering, the third term for ground surface/volume interaction, and the last term represents backscatter at the ground surface after transmission through the snowpack.

Forward calculations of snow backscatter in dependence of target properties were carried out by a second order version of DMRT, developed by J. Du and J. Shi [3], [4]. The model includes multiple scattering effects and allows for selecting various grain shapes (spheres, ellipsoids, cylinders). Figure 2 shows an example for studies of backscatter sensitivity to SWE at X-band (9.6 GHz) and Ku-band (17.2 GHz). For this case a snow density of ρ = 250 kg/m^3 has been assumed, and ellipsoidal grains with axial ratio (b/a) of 0.25 and grain equivalent diameter of 1 mm (typical for aged seasonal snow). As background medium frozen soil with medium scale roughness is assumed.

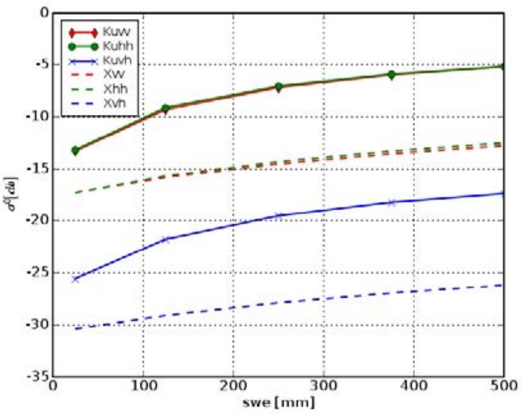

Figure 2 Backscatter coefficients in dependence of snow water equivalent (SWE) at Ku-band and X-band (right), 40° incidence angle, calculated by means of DMRT model.

This example shows clearly that Ku-band is more sensitive to SWE than X-band because the snow grains are more efficient scatterers at the shorter wavelength. The sensitivities at co- and cross polarizations are similar. There is very little difference between hh- and vv-polarized σ° of snow-covered ground, as also known from experimental data. At Ku-band the sensitivity declines towards high SWE values whereas at X-band the sensitivity changes only slightly because of the larger penetration depth. The comparison of the model calculations with field measurements at an alpine test site, carried out with a ground-based SAR, shows good agreement for co-polarizations, and some underestimation for the cross-polarized signal [5].

3.3 Effects of Vegetation

For retrieval of snow properties in vegetated areas it is important to take into account the attenuation and interaction of the radar signals with the canopy. Whereas low vegetation in the dormant winter stage has little effect, the attenuation in forests is important. Impacts of attenuation in forest for retrieval of snow parameters were studied using a radiative transfer model for vegetation [6] and the second order DMRT for calculating the backscatter contribution of snow. In the vegetation model the incoming wave is supposed to undergo three fundamental effects by vegetation elements, i.e. backscattering, specular scattering (i.e. downward scattering toward the ground floor in the specular direction with respect to the incident one) and attenuation. The scattering and attenuation functions of the vegetation layer are obtained by adding incoherently the scattering and attenuation functions of the scattering objects embedded in the canopy, and by averaging their dimensions and orientation.

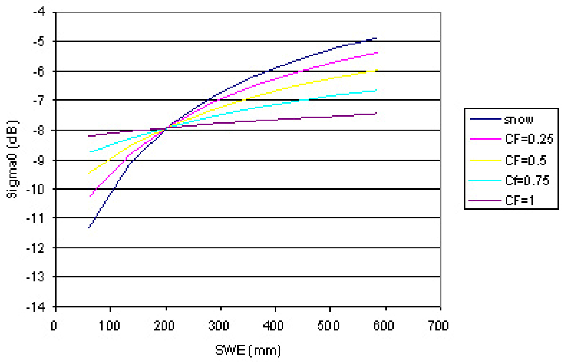

Figure 3 Simulated backscattering coefficient of forest canopy and snow covered ground as a function of SWE at 17.2 GHz, VV polarizations, incidence angle 30°, for Forest Cover Fraction (CF) from 0 % (non vegetated surface) to 100% (closed canopy). Woody volume = 110 m^3/ha.

As an example, Figure 3 shows the relation between the Ku-band VV polarized backscattering coefficient and SWE for different percentages of forest cover fraction. For this case a medium dense forest (woody volume 110m^3/ha) has been assumed. The model calculations show an appreciable sensitivity of σ° to SWE up to forest cover fraction CF = 0.5. For producing SWE maps from the SAR backscatter measurements it is planned to use land cover maps for supporting the retrievals and to exclude dense forests.

3.4 Snow Retrieval Methods

Various options for retrieval of snow properties from the dual frequency, dual polarized SAR data have been studied. Empirical models, based on relations between snow parameters and experimental backscatter data, work well for the snow conditions for which they have been calibrated. These methods are usually fast and reliable, but require extensive experimental data sets to cover a wide range of target conditions which is a drawback for global applications.

The inversion of theoretical backscatter models can account for a wide range of physical properties of the target. A prototype algorithm for retrieval of SWE from dual frequency (9.6 and 17 GHz), dual polarized (VV and VH) backscatter measurements has been developed by J. Shi, based on a second order radiative transfer model [4]. The selected combination of frequencies and polarizations enables the separation of volume and surface scattering contributions and the determination of grain size effects. The volume scattering contribution can be determined from the depolarisation factor at both frequencies. For SWE retrieval grain size effects need to be corrected, which is based on the scattering albedo estimated from the optical thickness ratio of the two frequencies. The residual optical thickness is applied to retrieve SWE. Although this method is attractive due to its broad applicability in terms of target properties, it suffers from the problem of accurately representing the complex structure of natural snow cover in the theoretical model. In addition, with this approach it is necessary to solve for several target properties (σ° of background, scattering albedo, volume absorption coefficient) before retrieving SWE. Each processing step introduces some uncertainty.

In order to reduce the number of unknowns, we developed an iterative algorithm for SWE retrieval based on the radiative transfer concept. The basic equation for retrieval of SWE from the backscatter measurements σ^T in the 4 CoRe-H_2O radar channels, k, is:

$$SWE = \frac{(1-\omega_k)\cos\theta'}{k'_{a,k}} \ln\left[\frac{\sigma_k^T(\theta) - \frac{\omega_k}{2}\cos\theta'}{\sigma_k^G(\theta') - \frac{\omega_k}{2}\cos\theta'}\right]$$

The backscatter contribution of the ground, σ^G, can be estimated from the backscatter time series before the snow season starts. For calculating the density normalized absorption coefficient, k'_a, snow temperature needs to be known which can be obtained from numerical meteorological data or from climatological data. This leaves the scattering albedo, ω, as unknown. The retrieval starts with a first guess for ω in one channel and uses relations for frequency and polarization dependence of volume scattering to estimate ω in the other channels. Iteratively the ω values are improved to match the SWE value of the 4 channels.

3.5 Experimental Activities

Experimental data are important for validating backscatter models and retrieval algorithms. Field experiments were carried out in Europe and North America to acquire backscatter data for various snow cover regimes. In the Austrian Alps backscatter data were measured with a ground-based Ku- and X-band SAR in winter 2006/07 [5] and with a five-frequency polarimetric airborne scatterometer in winter 2007/08. Extensive field campaigns with various instruments, including the airborne polarimetric Ku-band scatterometer (PolScat) of NASA-JPL, were conducted in winter 2006/07 in Colorado and 2007/08 in Alaska.

4 Conclusion

Significant advancements in the observation of snow and ice for applications in climate research, meteorology, hydrology, and glaciology are expected from the CoRe-H_2O mission. The dual frequency Ku- and X-band SAR sensor will open up the possibility to observe snow and ice physical properties that cannot be detected at lower radar frequencies. The proposed mission concept will enable accurate repeat observations of snow characteristics over lowlands and mountain areas, provide snow cover products for distributed hydrological models, enable advanced studies of surface/atmosphere interaction processes on snow and ice covered surfaces, and support studies on formation and thermodynamic processes of sea ice.

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