A Comparison of Temperature Retrieval Algorithms for Snow Covered Surfaces

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Abstract— **Algorithms for retrieval of the temperatures of snow surfaces have been examined for melting snow in mountainous areas in southern Norway. The tested algorithms include dual-band techniques as well as dual-view techniques. The study also included existing calibration data for the algorithms. The study has showed satisfactory results for two dual-band techniques, the Key and Coll algorithms. They were yielding results close to the reference data for ATSR and AVHRR data. The dual view algorithms applied on the ATSR data estimated a slightly colder surface than the reference. Improvements in the dual-view algorithms may be obtained by better calibration data and more precise co-registration between nadir and forward looking images.**

I. INTRODUCTION

Monitoring snow covered areas is an important application of remote sensing. One of the tasks is to predict and monitor the snow melting. At NR we have investigated these problems in several internationally funded research projects, which address applications like climate research, hydropower, and flood warning. When the snow melting already has started, the melting process can be monitored by microwave techniques observing the water content in the snow. However, it is more difficult to detect or forecast the onset of melting. In our projects, we intend to monitor the snow surface temperature in order to predict when the temperature will reach 0°C.

II. RETRIEVAL OF SURFACE TEMPERATURES

Methods for estimating temperatures by means of remote sensing address the problem of estimating the real surface temperature from a set of observed brightness temperatures. The concept of brightness temperature refers to the temperature of a perfect blackbody observed through a non-attenuating atmosphere. Planck's law for blackbodies gives the relationship between the emitted radiance, the wavelength, and the brightness temperature. The brightness temperature can thus be considered as a transformation of the radiance observed in a spectral band. It is closely related to, but somewhat different from, the real temperature of the observed surface.

The thermal characteristics of snow cover are similar to the sea surface in the sense that the emission from a snow surface in the thermal domain corresponds well to a black body. The main problem is to eliminate the effects from atmospheric attenuation. Due to limited knowledge of polar atmospheres, there exist only a few algorithms for estimation of snow surface temperature from satellite data.

In this paper we have tested such algorithms. They can be categorized into multi-channel (split-window) techniques and multi-view techniques. All the algorithms have empirical parameters, and for some of them several parameter sets have been found.

A. Multi-channel (split-window) techniqes

The absorption of the radiation in the atmosphere depends on the wavelength, and the difference between the brightness temperatures in two channels will therefore yield information about the atmospheric attenuation [1, 2]. The split-window technique aims at eliminating the atmospheric effects by utilizing this difference. The surface temperature T is estimated as a weighted sum (or difference) of the brightness temperatures observed. The split-window equation for AVHRR utilizes T_{11} measured in band 4 at 11 µm and T_{12} measured in band 4 at 12 µm:

$$T = b_0 + b_1 T_{11} + b_2 T_{12} \tag{1}$$

The split-window technique is that it is only sensitive to the effect of the atmospheric water vapor, and not to other atmospheric gases or aerosols [1]. The atmospheric influence on the split-window equation depends on the composition of the atmosphere, and the method must therefore be calibrated for different atmospheres. The split-window algorithm has been calibrated for Arctic snow surfaces using simulated data for four different cases and a combined case [1]. The resulting coefficients are listed in Tab. 1.

Coll's modification of the split-window algorithm [2] was proposed in order to avoid the need of several calibration sets. It is a global non-linear equation for global-scale application. Derivation of regionally optimized linear algorithms has been demonstrated for mid-latitude conditions, but not for colder atmospheres. Coll's equations [2] are given by:

$$\begin{gathered} T = T_{11} + A(T_{11} - T_{12}) + B \\ A = b_0 + b_1(T_{11} - T_{12}) \\ b_0 = 1.00 \quad b_1 = 0.58 \quad B = 0.51 \end{gathered} \tag{2}$$

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TABLE I. CALIBRATION OF THE SIMPLE SPLIT-WINDOW ALGORITHM

Split-window coefficients		b_0	b_1	b_2
Case 1	initial case	1.15	3.51	- 2.51
Case 2	volcanic aerosols	6.60	3.12	- 2.12
Case 3	winter aerosols	6.75	3.12	- 2.12
Case 4	winter sub-arctic atm.	6.70	3.12	- 2.12
comb.	combined case	-12.13	0.70	0.36

TABLE II. COEFFICIENTS FOR THE KEY ALGORITHM

Key coeff.	b_0	b_1	b_2	b_3
Avhrr-16	-3.676576	1.012527	1.690164	0.347890
Modis	-1.571123	1.005477	1.853279	-0.790518

Key's algorithm for AVHRR data [3] is a modification of the simple split-window technique. An additional correction term addresses the variation of the view angle θ along a scan line and its effect of the atmospheric path length. The algorithm expresses the surface temperature as

$$\mathrm{T_s} = b_0 + b_1 T_{11} + b_2 \left(T_{11} - T_{12}\right) + b_3 \left(T_{11} - T_{12}\right)\left(\sec\theta - 1\right) \quad (3)$$

The calibration coefficients depend on the temperature interval and the satellite sensor [3]. The algorithm is calibrated separately for the Arctic and the Antarctic. Updated calibration data are available on the web [4]. Tab. 2 lists the coefficients for Arctic surfaces warmer than 260K

B. *Dual view techniques*

The dual-view capability of ATSR has made it possible to improve the shortcoming of the split-window technique related to those atmospheric constituents that absorb equally in the two spectral bands. Instead, the differences in the absorption can be attributed to differences in atmospheric path length. By applying a dual-angle technique utilizing the difference between the nadir looking mode and the forward-looking mode of ATSR, these atmospheric effects can be corrected more accurately [1]. The basic idea of the dual-view techniques is similar to the Key algorithm: the brightness temperature T_i will be reduced along the atmospheric path a_i, depending on its length.

The dual-view algorithm for one thermal channel (DV1C) [1] is given by:

$$T = b_0 + b_1 T_1 + b_2 \left(T_n - T_f\right) \frac{a_n}{a_f - a_n} \quad (4)$$

The basic idea is that the reduction in the brightness temperature is proportional to the atmospheric path length a_i. If this assumption is true, then b = [0, 1, 1]. However, empirical or modeled scaling factors will compensate for non-linearity in the model.

The dual-view algorithm for two thermal channels (DV2C) utilizes the nadir and forward observations of the brightness temperatures in the 11 µm and 12 µm wavelength bands [1].

TABLE III. CALIBRATION OF THE DUAL VIEW ALGORITHMS

Dual view coeff.	DV1C			DV2C				
	b_0	b_1	b_2	b_0	b_1	b_2	b_3	b_4
Case 1	-1.67	1.01	1.33	1.73	5.74	-2.64	-3.57	1.73
Case 2	0.50	1.00	1.33	2.02	4.95	-4.38	-1.30	1.72
Case 3	0.46	1.00	1.33	2.98	4.93	-4.30	-1.34	1.79
Case 4	0.45	1.00	1.33	0.67	4.94	-4.36	-1.30	1.71
Comb.	8.21	0.97	1.39	0.50	4.87	-4.86	-0.78	1.76
Key				-0,56	2,23	-0,92	-0,41	0,10

The DV2C surface temperature is modeled by a multiple linear regression of the four brightness temperature observations:

$$\mathrm{T_s} = b_0 + b_1 T_{11n} + b_2 T_{11f} + b_3 T_{12n} + b_4 T_{12f} \quad (5)$$

Calibration data for the DV2C and DV2C algorithms have been calibrated using simulated data for the same cases as the split-window algorithm [1]. The resulting coefficients are given in Tab. 3. Calibration data for the DV2C algorithm have also been retrieved for the same models as for Key's algorithm [4].

III. COMPARISON OF THE METHODS

The five algorithms for retrieval of snow surface temperature described above have been applied on thermal data from three different satellite sensors (AVHRR, ATSR-2 and MODIS). The three split-window techniques were applied on all the sensors, while the two dual techniques were applicable to ATSR only. The test was undertaken on data from one single day, and should therefore be considered as an initial test of the methods demonstrating their potential and limitations.

The algorithms have been calibrated for various conditions, and therefore we also had to select appropriate calibration sets for the test. For the simple split-window and the dual-view algorithms we selected case 4 and the combined case.

The algorithms were implemented in the IDL programming language, and the comparisons were undertaken interactively by means of the ENVI software.

A. *The test data*

The test sites are situated in the mountain areas in Southern Norway, where we have been undertaking fieldwork to collect reference data. The sites are Valdresflya plain and Heimdalshøe mountain in the Jotunheimen mountain range and Imingfjell mountain at the edge of Hardangervidda mountain plain. The satellite data were acquired 06 May 2001, within a one-hour interval close to local noon.

- ERS-2 ATSR 06 May 11:09 UTC
- NOAA-16 AVHRR 06 May 11:22 UTC
- TERRA MODIS 06 May 11:55 UTC

The field reference data showed that the snow surface temperatures in the test areas were at the melting point (273.15K). The MODIS Land Surface Temperature (LST) product verified the field data for all three areas. In the shadowed north facing hills at Heimdalshøe also colder surface temperatures were retrieved from MODIS LST.

TABLE IV. ESTIMATED SURFACE TEMPERATURES FROM THE TEST DATA

	Hardangervidda						**Jotunheimen**									
	Imingfjell						**Valdresflya**					**Heimdalshøe**				
	ATSR				***AVHRR***	***MODIS***	***ATSR***			***AVHRR***	***MODIS***	***ATSR***			***AVHRR***	***MODIS***
Key	273,13	272,93	272,92	272,67	273,27	272,90	272,00	271,48	272,16	273,24	273,09	270,97	272,61	269,98	268,67	269,82	265,87
Coll	273,96	273,67	273,59	273,37	273,83	273,44	272,68	272,09	272,85	273,83	273,77	271,54	273,28	270,71	269,30	270,38	266,66
Splitw case 4	280,64	280,38	280,32	280,09	280,56	280,15	279,41	278,80	279,58	280,56	280,46	278,26	280,01	277,43	275,94	277,10	273,30
Splitw comb.	274,99	275,06	275,32	274,98	275,35	274,75	274,36	274,29	274,49	275,35	274,85	272,74	275,02	272,14	271,78	272,30	266,88
DV1C case4	271,80	271,85	272,11	271,74			271,10	270,95	271,26				271,80	268,92	268,45		
DV1C comb.	271,43	271,47	271,73	271,37			270,74	270,59	270,90				271,43	268,62	268,17		
DV2C case4	269,93	270,30	271,86	270,19			271,24	269,49	275,09				278,70	259,56	262,11		
DV2C comb.	269,28	269,81	271,65	269,72			271,04	269,26	275,49				279,60	257,78	261,20		
DV2C Key	272,06	272,20	272,74	272,01			271,90	271,35	273,10				274,47	266,95	267,39		

B. *Results*

For the ATSR images we selected four localities in Imingfjell, three at Valdresflya, and three at Heimdalshøe along a temperature gradient. For AVHRR and MODIS fewer observations were made. The results are shown in Tab. 5.

A general result for the single view algorithms was that the variation between the points was as expected. The variation between the examined points at Imingfjell and Valdresflya, was small, and at Heimdalshøe they corresponded to the expected gradient. For Jotunheimen the Modis data returned colder temperatures than the reference data and other two sensors. The surface temperatures from the single view split-window algorithms were obviously too high. The best results for the single view algorithms were obtained from the Key and Coll algorithms, which yielded results close to the melting point.

The dual view algorithms yielded a colder surface than the reference at Imingfjell. The best results were obtained by using Key's calibration data. In Jotunheimen, and in particular at Heimdalshøe, the dual view algorithms yielded very large variations and differences in the results.

IV. DISCUSSION

The results are of varying quality. The dual-view results from Jotunheimen, where the spatial variation in temperature was larger than at Imingfjell suggest that geometrical mismatch between the two views may have caused the variations in the results. In addition, improved geometric correction will also make it easier to identify the correct position of the test locations.

The promising results from Key's algorithm indicate that the atmospheric path length is an important parameter and that dual-view techniques therefore have a larger potential than obtained in this experiment.

Coll's non-linear algorithm yielded satisfactory results. Its parameters are already established and we may therefore consider it as a robust global algorithm. This indicates that improvements in more empirically based algorithms may be obtained by improving their coefficients. Key's coefficients for DV2C yielded the best results for that algorithm, and is therefore considered as better than the other two coefficient set.

The algorithms and calibration sets are going to be further tested and compared with field measurements during the melting season 2003. The satellite data include MODIS data from TERRA and AQUA, and AATSR data from ENVISAT. The melting season had not yet started when this paper was written, and therefore the results are not yet presented.

The dual-view algorithms did not outperform the more conventional methods. We think that precise geometric co-registration and better atmospheric models will make it possible to improve the algorithms by means of dual-view techniques.

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