Snow properties retrieval by full polarimetric decomposition in C-band SAR data

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- SOAR #1341 and SOAR-EI #5135 Projects, CSA (Canadian Space Agency) and MDA, 2009-2016

- PNTS 2009 #10 and 2013 #03 Projects, CNES (French Space Agency) and INSU, 2009-2015

Motivation

- What relationship can be set between the temporal evolution of backscattering parameters at C-band and the snow pack metamorphism evolution?

- Which polarimetric parameters offer the best performance for snow physical characteristics retrieval at C-band ?

- How to link properly snow measurements in mountains and SAR data ?

Outline

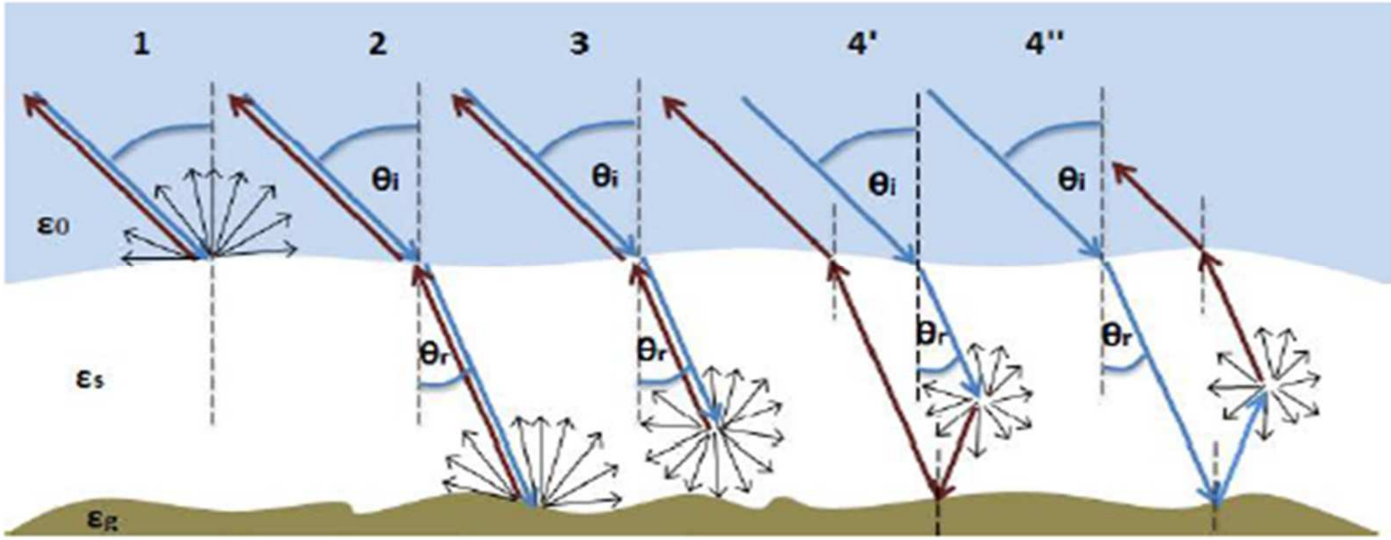
- Snow Backscattering at C-band

- Data and application site

- Retrieval methods for wet snow - Results

- Retrieval methods for dry snow - Results

1. Snow backscattering mechanism



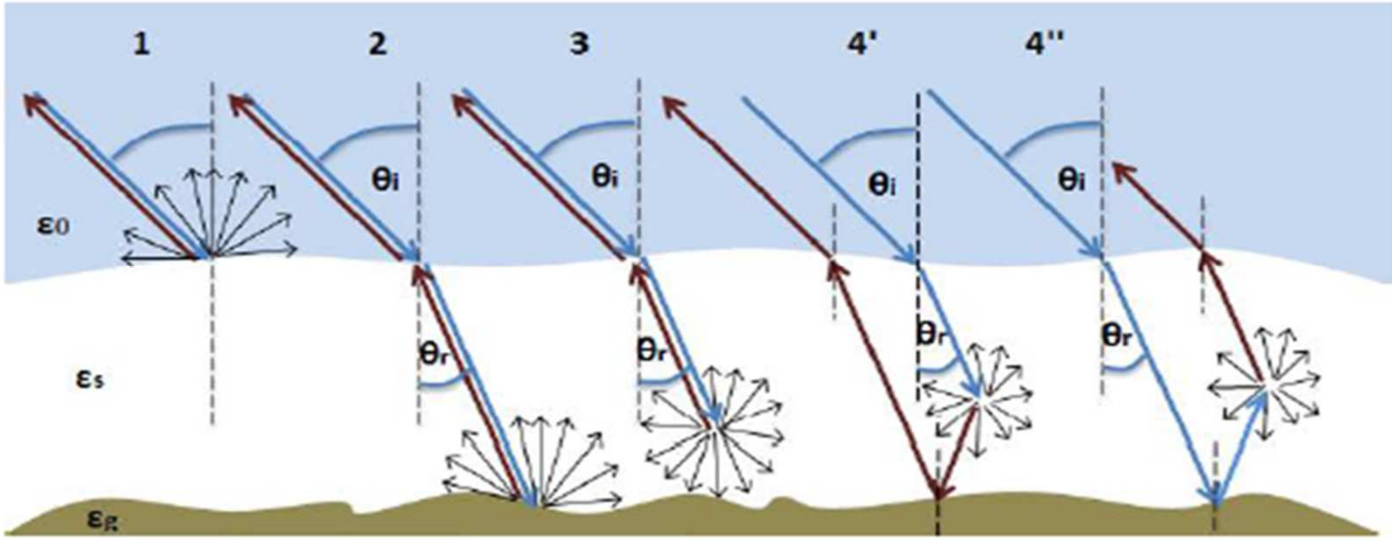
Backscattering Components:

1. Snow surface
2. Underlying ground
3. Volume
4’. Volume+underlying ground interaction
4’’. Underlying ground + volume interaction

(from Besic et al., 2014)

Wet snow (surface) retrieval	Dry snow (depth) retrieval	Snow volume retrieval	Freqency (GHz/cm)	SAR sensors
X	0	0	L (1.2/26)	JERS, ALOS 1&2
X	0 *(**X** polarimetry)*	0	C (5.3/5.6)	ERS 1&2, ASAR, Radarsat 1&2, Sentinel 1.
X	**X**	**X**	X (9.6/3.1)	TerraSAR-X, COSMO-SkyMed
X	**X**	**X**	Ku (17.2/2.5)	Cryosat-2 (Altimeter)

1. Snow backscattering mechanism



Backscattering Components:

1. Snow surface
2. Underlying ground
3. Volume

4’. Volume+underlying ground interaction

4’’. Underlying ground + volume interaction

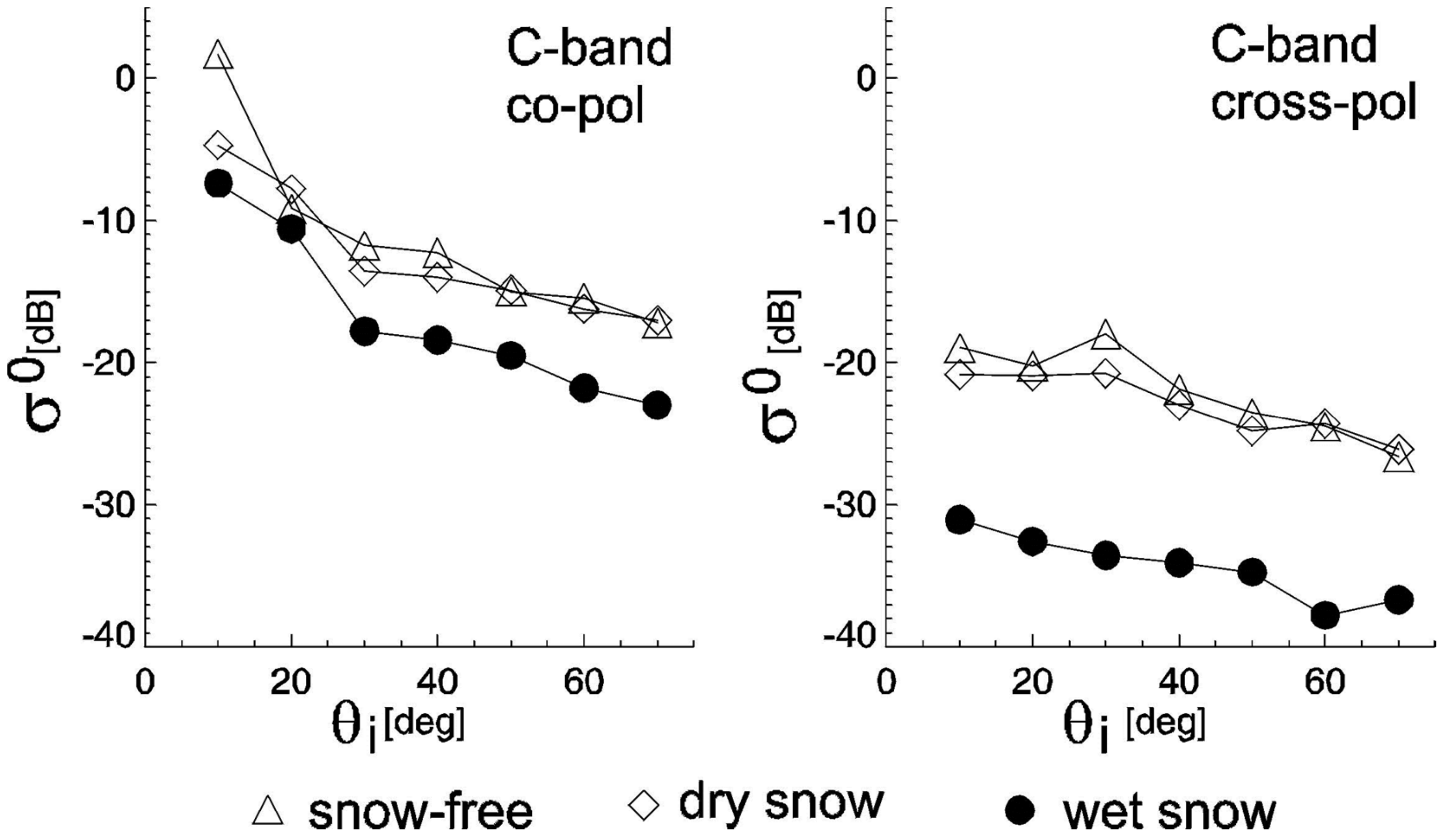
(from Besic et al., 2014)

Snow backscattering simulation at C frequency band (5.3 GHz) *[Shi, 2000]*	
Wet snow	Dominance of the snow surface component (case 1)
Dry snow	Dominance of the underlying ground component (case 2) and volume – underlying surface interaction (case 4)

* N. Besic et al. *“Dry snow backscattering sensitivity on density change for SWE estimation”, IGARSS 2012*
* N. Besic et al. *“Wet snow backscattering sensitivity on density change for SWE estimation”, IGARSS 2013*
* *JP. Dedieu et al., IGARSS 2014; N, Besic et al., IEEE- GRSL 2015.*

* *Nagler et al., 2008; Stockamp et al., 2014; Leinss et al., 2014 = inversion process for SWE at Ku + X bands (CoreH$_2$O)*

C-band Backscattering of Snow-Covered Ground (non polarimetric)



Test site: Leutasch, Tyrol.   Ground-based scatterometer measurements

Dry snow depth: 0.5 – 1.0 m

(H. Rott, 2005)

Background target : Meadow

➡ *Wet snow mapping at C-band : Nagler (2000), Magagi (2003), Longepe (2009)*

2. Radarsat-2

Full Polarimetry : (*HH, VV, HV, VH*)

- Launched December 14, 2007
- Canadian Space Agency
- C band (5.3 GHz, 5.4 cm)

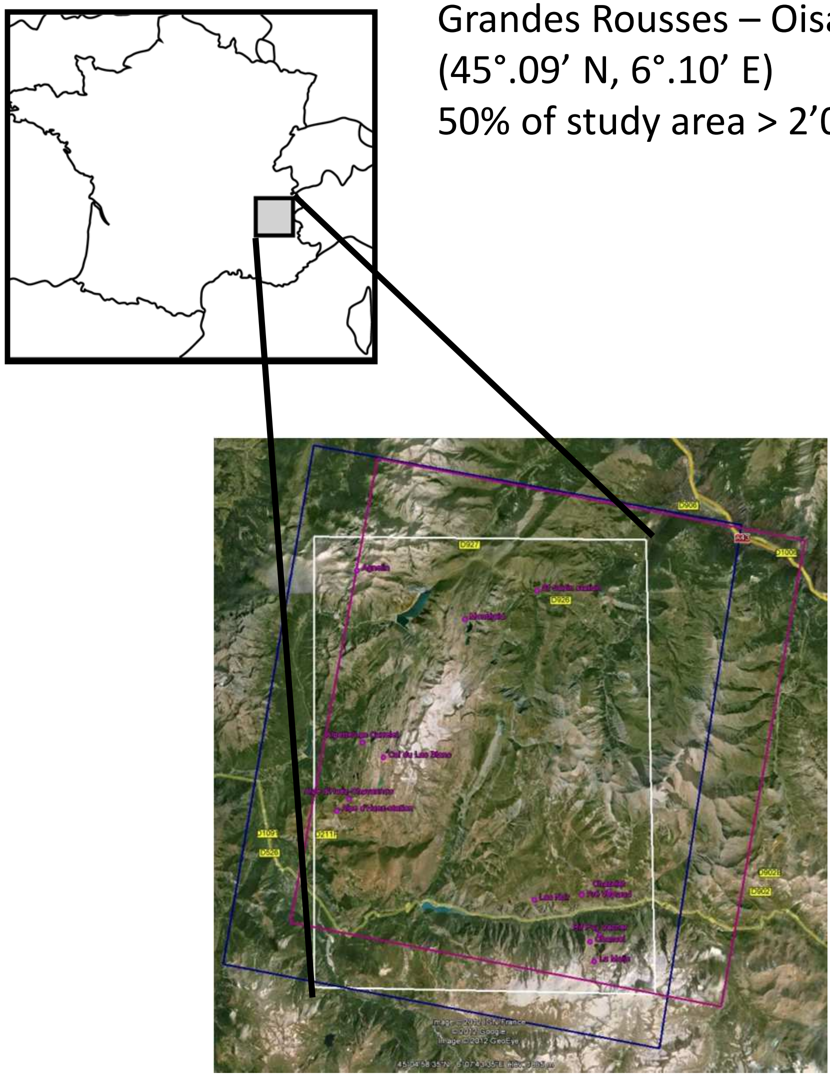
French Alps Mission technical specification

Mode	Swath Width	Repeat Cycle	Look Direction	Spatial Resolution	Incidence Angle center
Fine Quad Pol	25 x 28 km	24 days	Right-looking	7.51 x 4.73 m (1)	39.1 to 39.2

(1) Ground range by azimuth

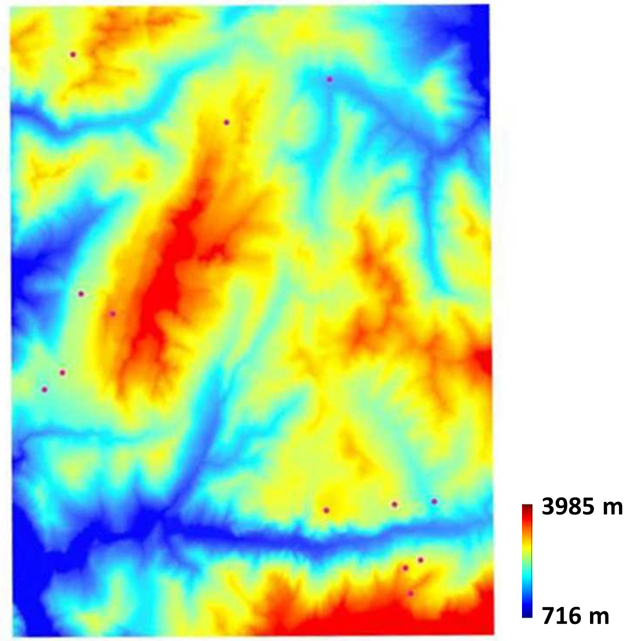
RCM: RADARSAT Constellation Mission = continuity of the RADARSAT Program
A three-satellite configuration, daily access to 90% of the world's surface
Compact polarimetric mode, Launch: 2018.

3. Study site and data: French Alps



Grandes Rousses – Oisans
(45°.09’ N, 6°.10’ E)
50% of study area > 2’000 m asl.

IGN-DEM of the site 28 x 25 km^2

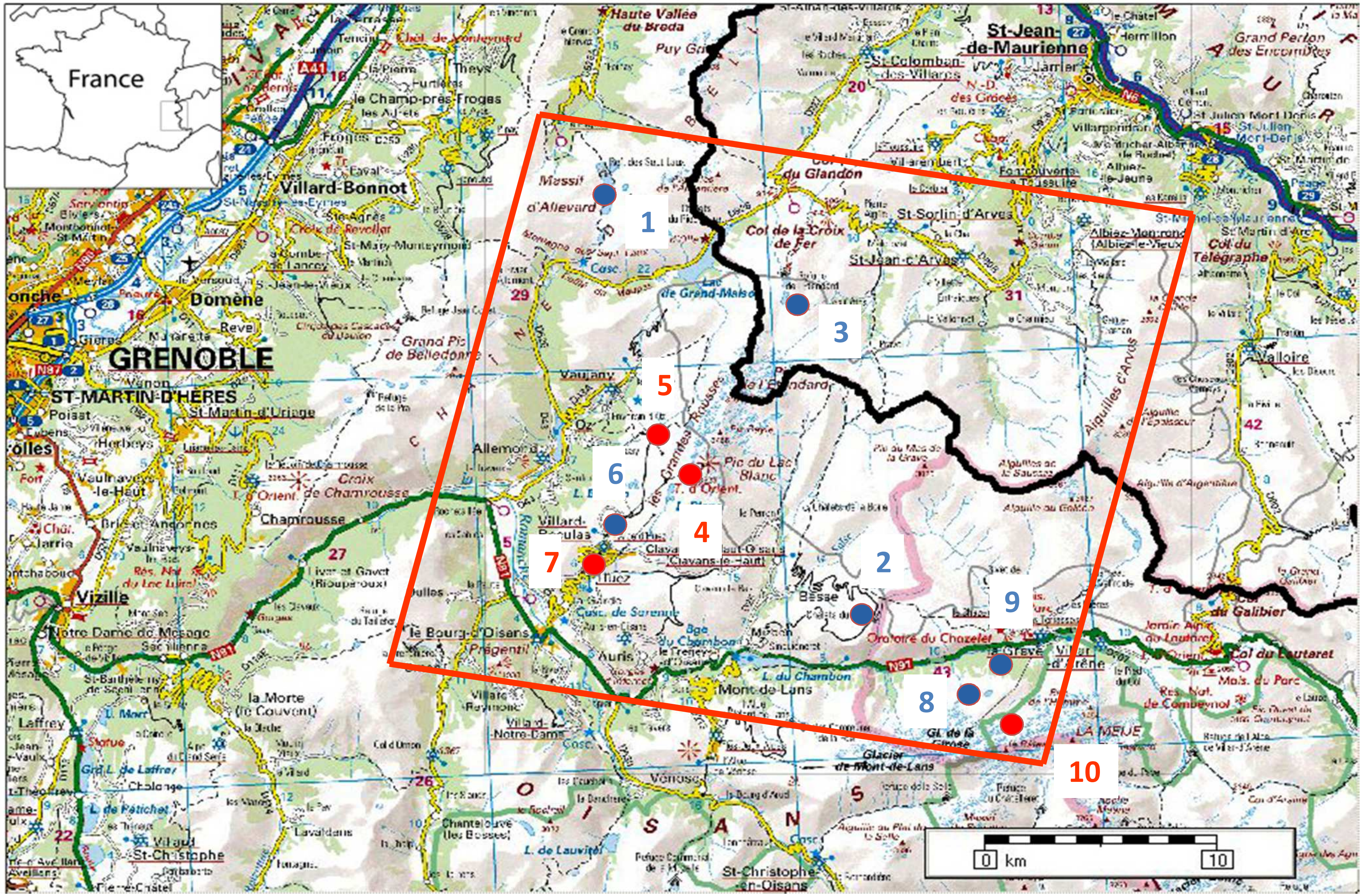


- ⇨ Rugged Terrain
  - Complex to analyse
  - snow cover heterogeneity
- ⇨ Landcover
  - Presence of Glaciers
  - Grasslands and rocks

Date	Orbit	Pass (5:42 UTC)	Near and far Incidence Angles	Snow conditions
2009-01-12	FQ19	Descending	38.3-39.8	Dry
2009-03-01	FQ19	Descending	38.3-39.8	Dry
2009-03-25	FQ19	Descending	38.3-39.8	Multi layer
2009-05-12	FQ19	Descending	38.3-39.8	Wet
2009-08-16	FQ19	Descending	38.3-39.8	Snow free
2010-01-07	FQ19	Descending	38.3-39.8	Dry
2011-01-02	FQ19	Descending	38.3-39.8	Dry
2011-02-19	FQ19	Descending	38.3-39.8	Multi layer
2011-03-08	FQ14	Descending	36.4-38.1	Multi layer
2011-04-01	FQ14	Descending	36.4-38.1	Wet
2011-04-25	FQ14	Descending	36.4-38.1	Wet
2013-09-05	FQ14	Descending	36.4-38.1	Snow free
2014-01-03	FQ14	Descending	36.4-38.1	Dry
2014-01-27	FQ14	Descending	36.4-38.1	Dry
2014-02-20	FQ14	Descending	36.4-38.1	Multi layer
2014-03-16	FQ14	Descending	36.4-38.1	Multi layer
2014-04-09	FQ14	Descending	36.4-38.1	Wet
2014-05-03	FQ14	Descending	36.4-38.1	Wet
2014-05-27	FQ14	Descending	36.4-38.1	Wet

Radarsat -2 acquisition dates: 4 winter season (17) + 2 snow-free

3.1 Fieldwork: snow measurements sites (10)



● Météo-France ● Electricité de France

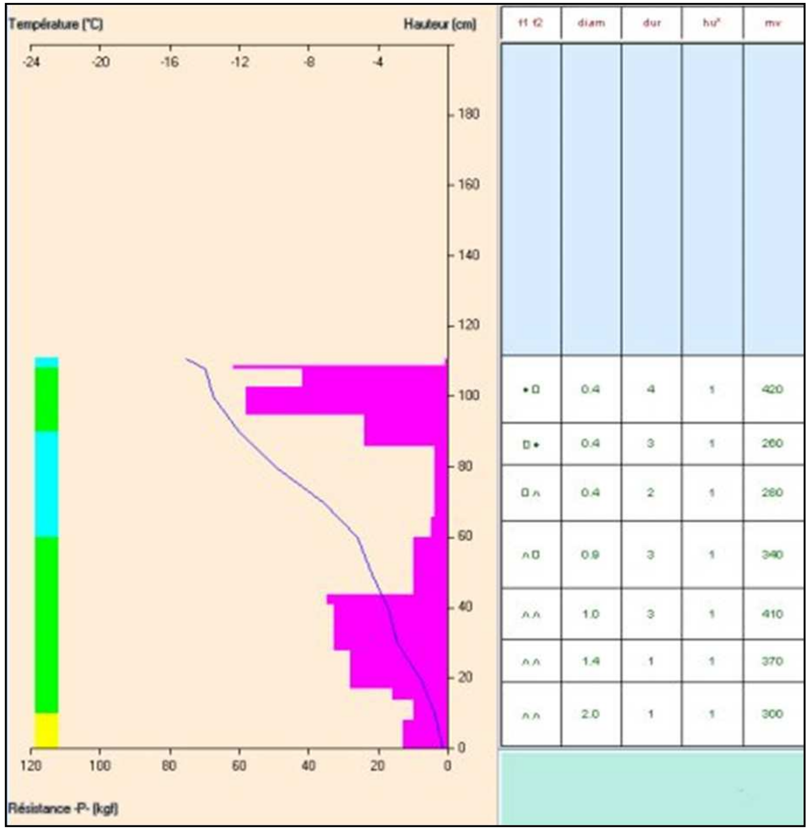
Characteristics of measurement sites

SITE	COORDINATES (Lat/long)	ELEVATION (m asl.)	AZIMUTH* (°)	SURFACE TYPE
AGNELIN (1)	N 45° 13’ 55’’ E 06° 05’ 15’’	2230	270	Alpine grassland
LAC NOIR (2)	N 45° 03’ 01’’ E 06° 13’ 34’’	2435	160	Bare rocks
MONTFROID (3)	N 45° 12’ 17’’ E 06° 10’ 20’’	2270	25	Alpine grassland
LAC BLANC (4)	N 45° 07’ 43’’ E 06° 06’ 32’’	2720	260	Bare rocks
CARRELET (5)	N 45° 08’ 12’’ E 06° 05’ 29’’	2010	280	Alpine grassland
HUEZ 1800 (6)	N 45° 05’ 55’’ E 06° 04’ 15’’	1860	220	Alpine grassland
HUEZ Chavanus (7)	N 45° 06’ 19’’ E 06° 04’ 51’’	2065	240	Alpine grassland
CHANCEL (8)	N 45° 01’ 37’’ E 06° 16’ 10’’	2510	35	Bare rocks
RIF Puy Vacher (9)	N 45° 01’ 48’’ E 06° 16’ 40’’	2190	30	Grassland open forest
MEIJE Nivose (10)	N 45° 00’ 20’’ E 06° 09’ 43’’	3100	45	Bare rocks

(*) Main orientation of the mountain general slope where the flat sites are located (0° to 10°)

3.2 *In situ* snow measurements (Météo-France, EDF)

Cosmic-ray Snow Gauge (EDF)



Snow stratigraphy profiles and physical parameters (T°, ϕ, ε, σ, h, LWC, ..)

Field measurements parameters (6) selected for dry snow polarimetric analysis:

h : depth (cm) = total and above the 1st rough ice layer (refrozen solid crust, slightly wet)

σ : density (kg/m^3)

SWE: snow water equivalent (mm) = given by H x *σ*

ϕ and **T°:** grain type, size and temperature (fresh to fine grains and T°<0° in case of dry snow)

LWC : liquide water content (zero in case of dry snow)
*given by = ε - (A*σ -B*σ^2) /C with A = 1.202, B = 0.983, C = 21.3 (LEAS capacitance probe)*
ε : dielectric constant (c/Vm)

3.3 Ancillary Data

- **DEM** IGN 25m (SD in elevation ± 5m)

- **CROCUS** snow metamorphism model (Brun et al., 1989; 1992; Lafaysse, 2012)

- **PolSARPro** and **SNAP** , free ESA toolboxes : pre-processing steps

• ESA-IETR « The Polarimetric SAR Data Processing and Educational Tool » (Pottier/Ferro-Famil) for polarimetric parameters retrieval
http://eath.esa.int/polsarpro/

• SNAP (ESA-STEP) : SENTINEL-1 Toolbox for slant-to-ground images geocoding
http://step.esa.int/main/toolboxes/snap/

4. WET SNOW Application

4.1 Non polarimetric analysis

Wet snow mapping : threshold-based method using polarized SAR data (Nagler et al., 2000)

– Wet snow detected using change detection against dry snow reference.

* Characteristics

- Not requiring polarimetric data, only co- or cross-polarized mode (HH, VV or HV, VH)
- Binary Segmentation (snow/no-snow) as a mask
- Either a summer (no-snow) or a dry snow scene can be used as reference

* Principle: Wet snow on the ground → Backscattered signal decreases: $\frac{\sigma^0_{winter}}{\sigma^0_{ref}} \leq -3\ dB$

Flexible threshold (Longépé et al., 2009)

* Characteristics

– Take into account the snow heterogeneity using a steepness factor for the -3 dB threshold as a sygmoidal function:

$$F_a = \left[1 + \exp\left(s.\left(\frac{\sigma^0_{wet}}{\sigma^0_{ref}} + 3\right)\right)\right]^{-1}$$

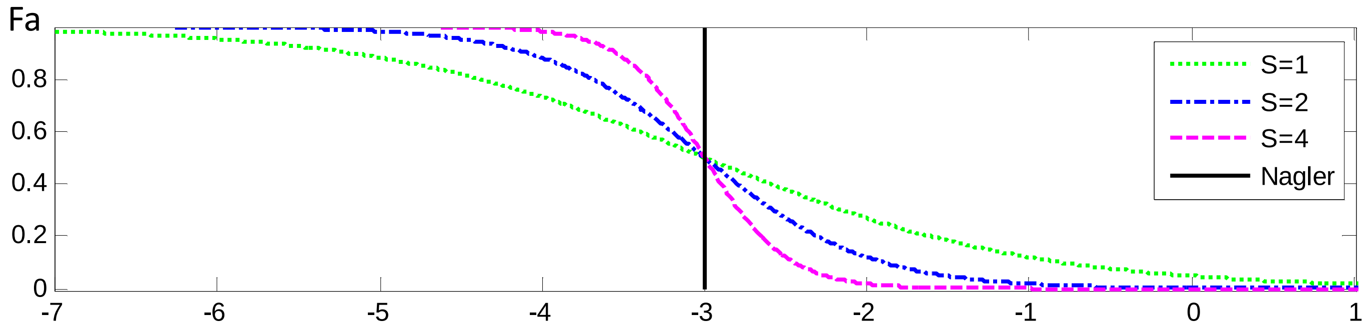
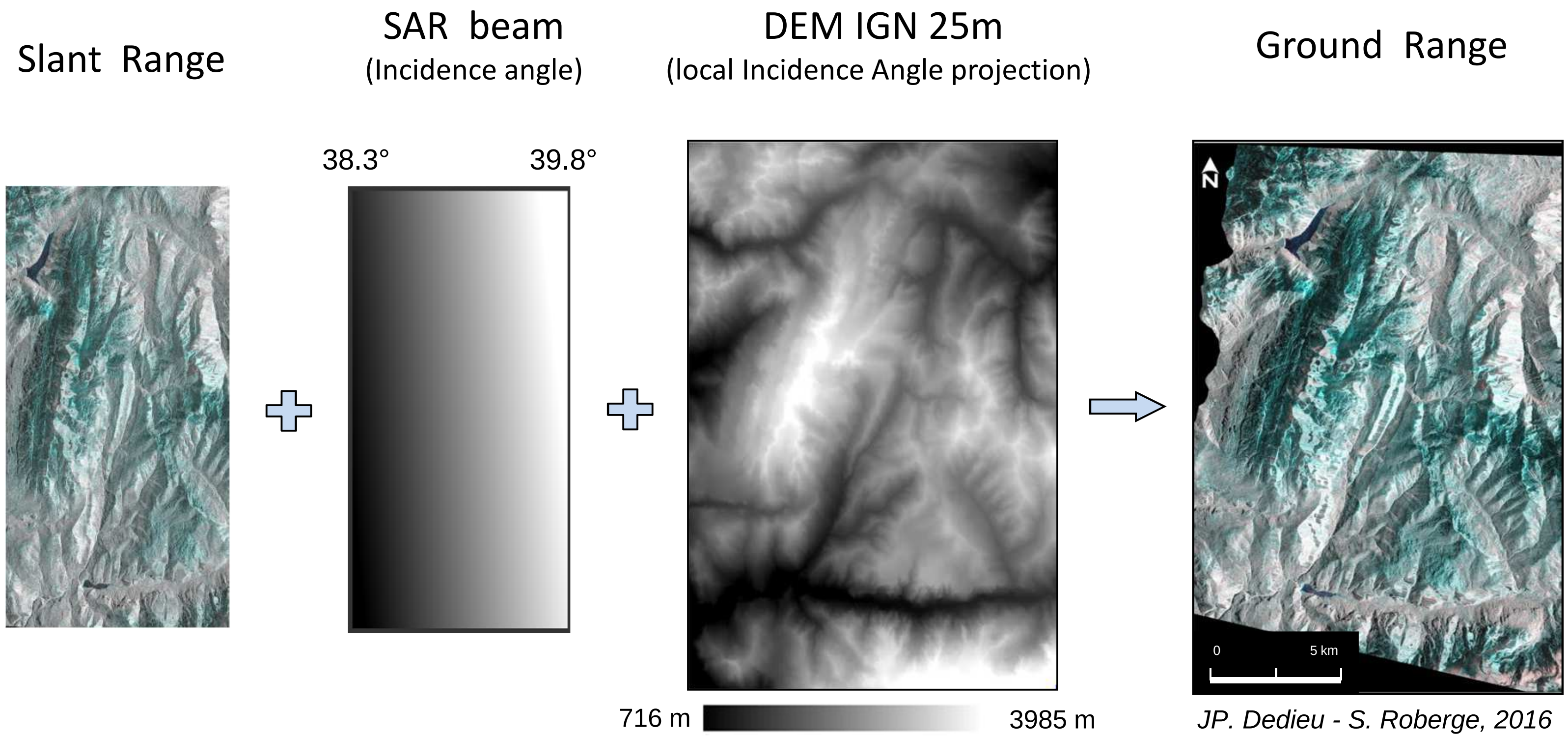


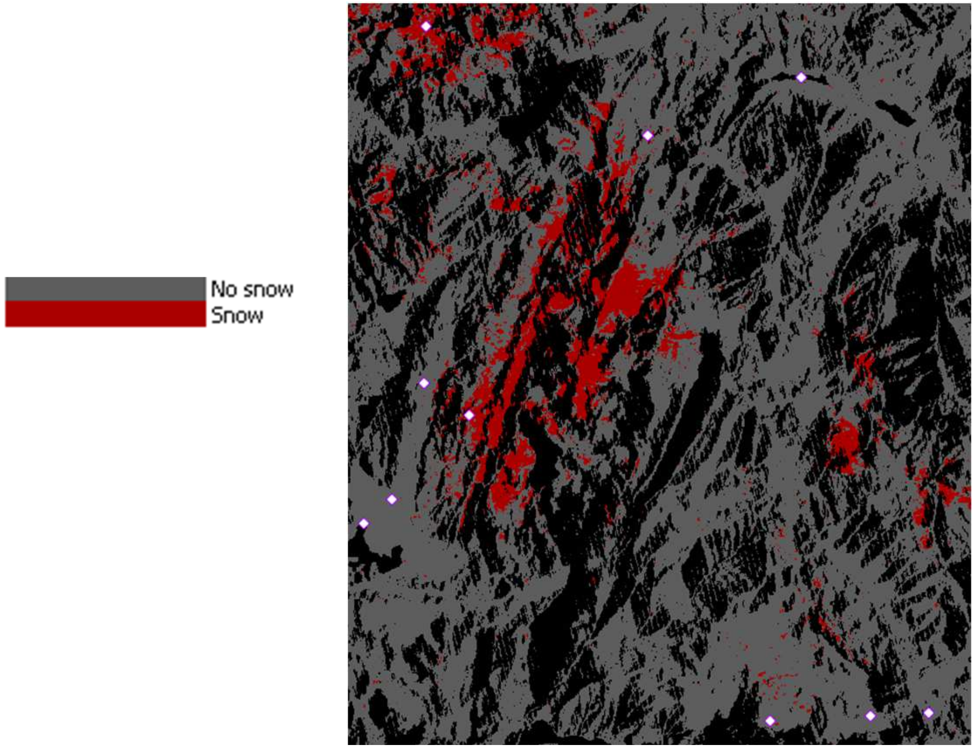
Image processing (SNAP/ESA Toolbox)



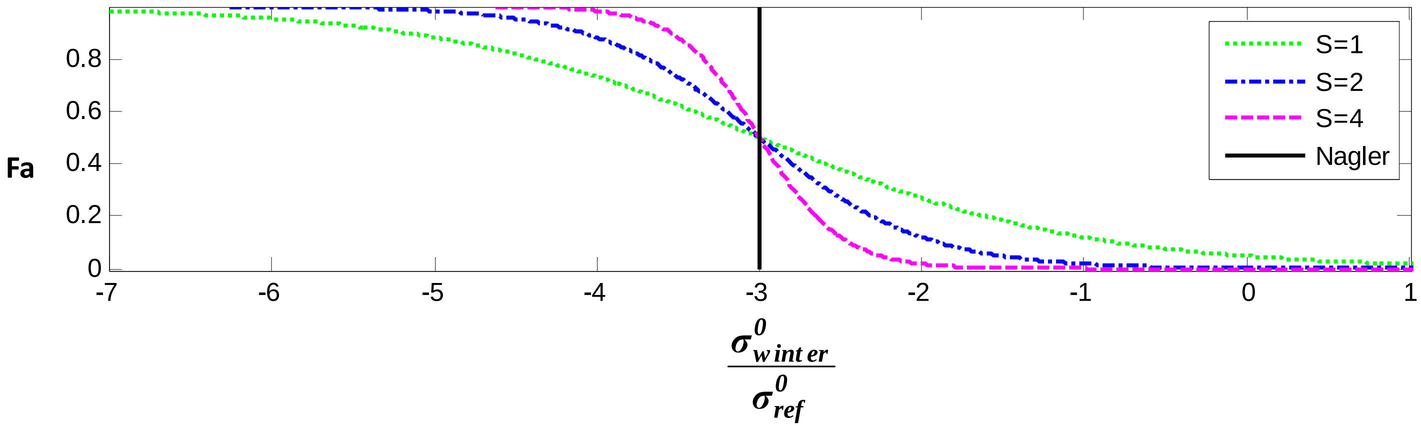
Wet snow conditions: Radarsat2 image. HH-2HV-VV color composition 27/05/2014 © MDA-CSA / SOAR-EI.

Improvement of the method

12 may 2009

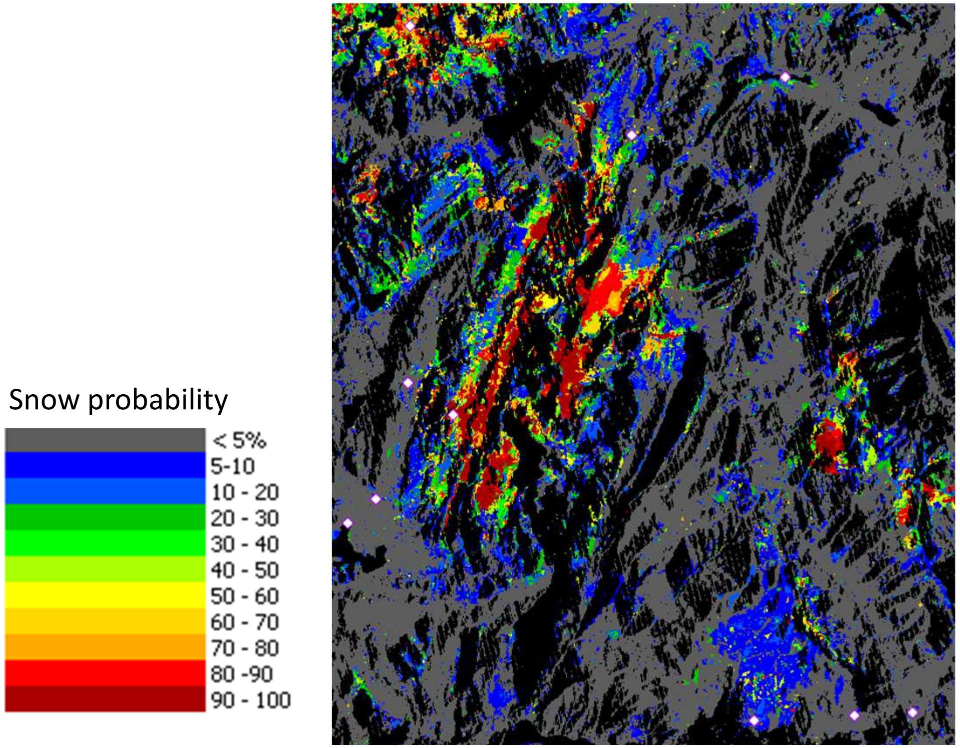


- Nagler's initial model
- Threshold: -3 dB



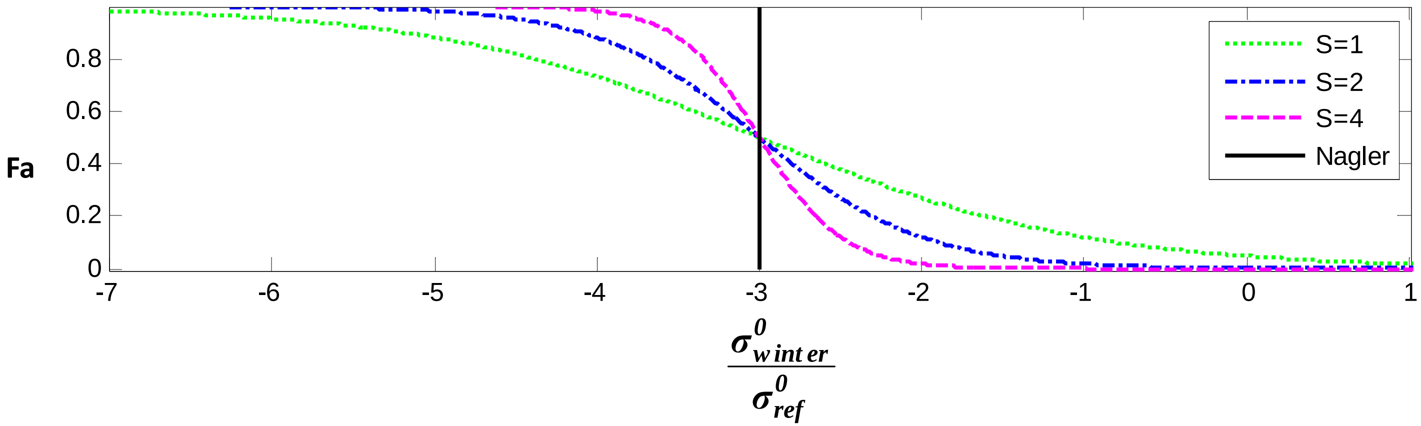
Improvement of the method

12 may 2009



- Modified Nagler
- S = 1
- Validation: Crocus model

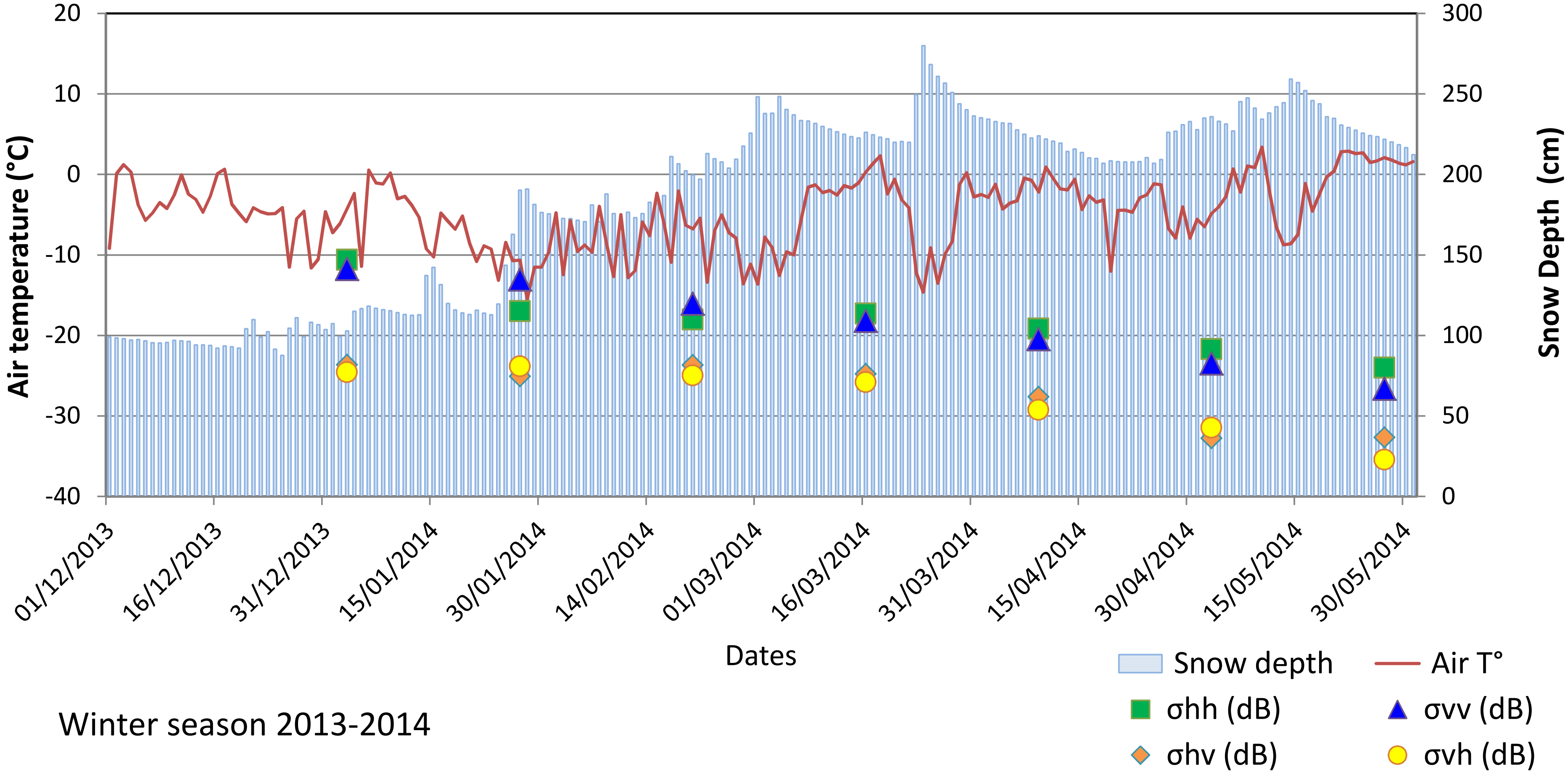
Longépé et al., IEEE 2009
Leissard-Fontaine et al., Igarss 2012



4.2 Sensiblity analysis of σ0 temporal correlation with snow metamorphism

Meteorological data and multipolarisation time-series of backscatter signal

Col du Lac Blanc (Météo-France) weather station (2780 m)



Winter season 2013-2014

Time period 2009-2014 statistics (10 sites x 19 dates)

- Dual-pol difference hh/vv or hv/vh: 0.3 to 0.6 dB
- Co-pol vs cross-pol difference: 7.9 to 9.5 dB

4.3 Polarimetric analysis: Liquid Water Content (LWC) estimation

*** Field measurements** (10 sites, 15 images)

LWC : liquide water content % is given by = Epsilon - $(A*\sigma - B*\sigma^2)$ /C
with A = 1.202, B = 0.983, C = 21.3 (LEAS capacitance probe) **ε** : dielectric constant (c/V m)

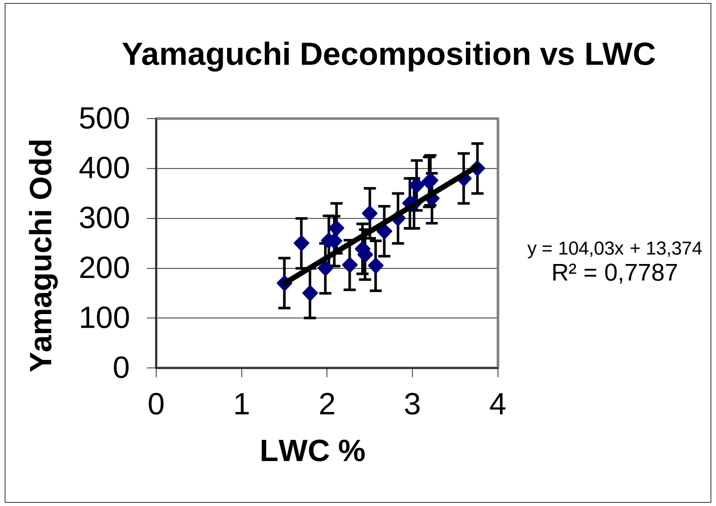
Conductivity function : relationship between ε and volumetric water content θ

*** Polarimetric decomposition modeling**

Yamaguchi (2005), Arii (2011).
Sites window size = 25x25 m

LWC characterization : relationship between ε and SAR phase signal $\vec{E}$

Validation: Crocus snow model



Radarsat-2, 2009-2014 dataset

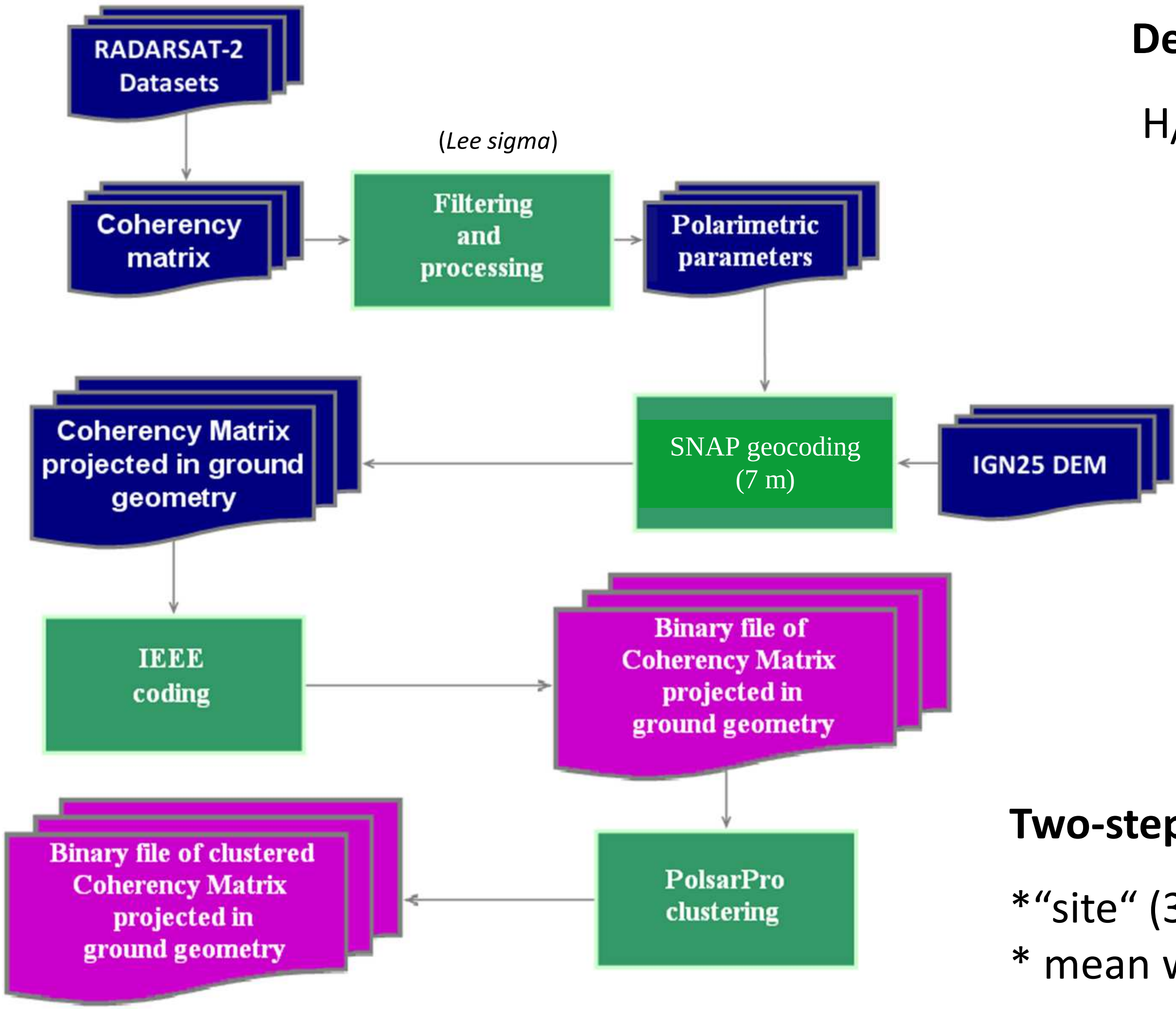
(Dedieu, Besic et al., under preparation for IEEE-GRSL)

Date	Orbit	Pass (17:31 UTC)	Near and far Incidence Angles	Snow conditions
2015-03-17	FQ20	Ascending	39.2-40.7	Multi layer
2015-04-03	FQ25	Ascending	43.6-44.9	Wet
2015-04-10	FQ20	Ascending	39.2-40.7	Wet
2015-04-27	FQ25	Ascending	43.6-44.9	Wet
2015-05-04	FQ20	Ascending	39.2-40.7	Wet
2015-05-21	FQ25	Ascending	43.6-44.9	Wet
2015-05-28	FQ20	Ascending	39.2-40.7	Wet

Radarsat -2 acquisition dates (7) spring 2015 for LWC estimation

4. DRY SNOW Application

4.1 Polarimetric parameters retrieval



Decomposition theorem:

H/α (Cloude-Pottier; 1996, 1997)

Two-step scale outputs:

*"site" (3 x 3 pixels) = 25x25 m
* mean window (20 x 20) = 150x150 m

- *Dedieu et al. Canadian Journal of Remote Sensing, 2012.*
- *Dedieu et al. IEEE-IGARSS, 2014.*

4.2 H/α decomposition: (based on the backscattering matrix)

- Algebraic decomposition

Target vector coherency matrix →

$$[T] = \lambda_1 \vec{v}_1 \vec{v}_1^{*T} + \lambda_2 \vec{v}_2 \vec{v}_2^{*T} + \lambda_3 \vec{v}_3 \vec{v}_3^{*T} =$$

eigenvalues

eigenvectors

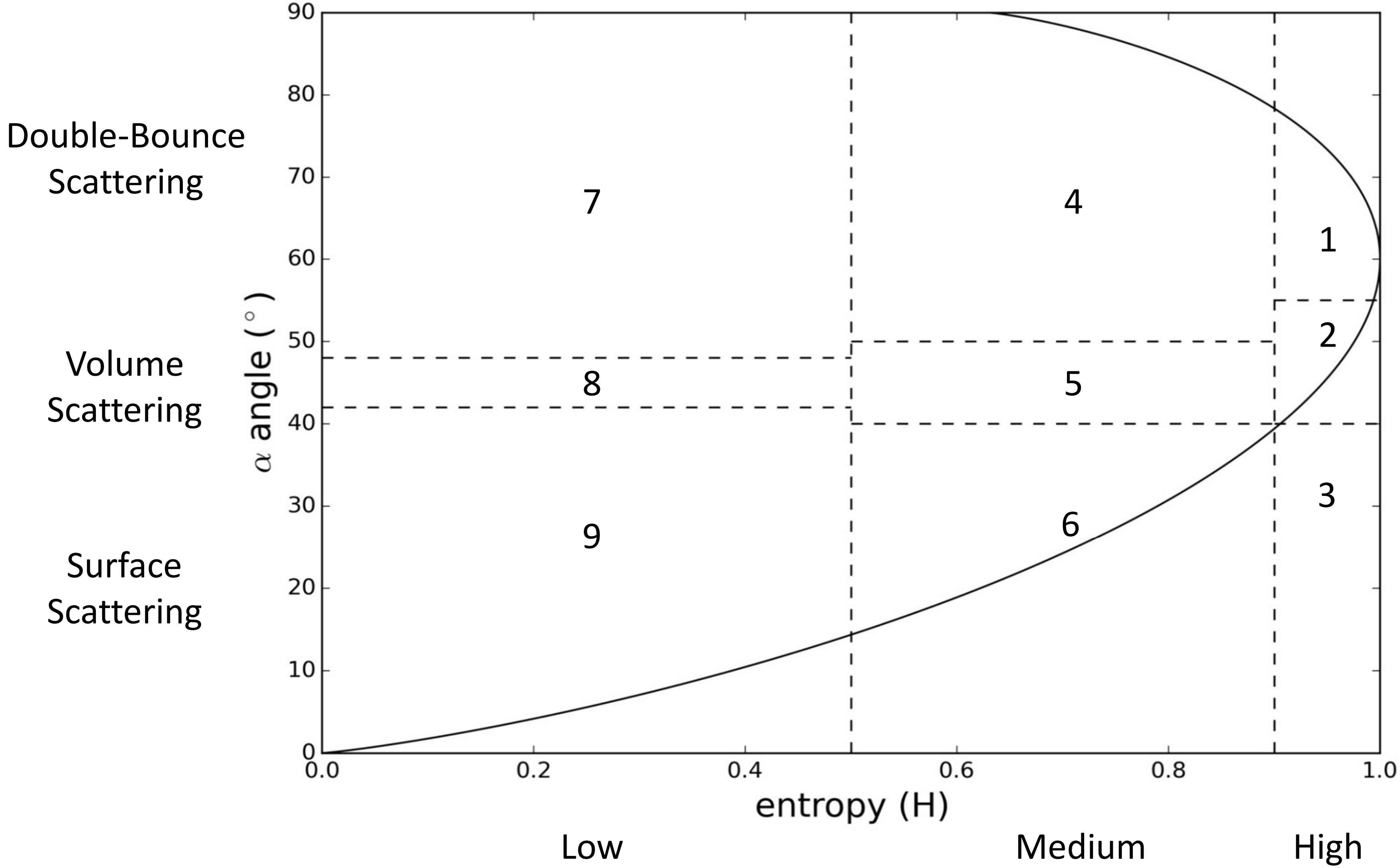
$$= \lambda_1 [T_1] + \lambda_2 [T_2] + \lambda_3 [T_3]$$

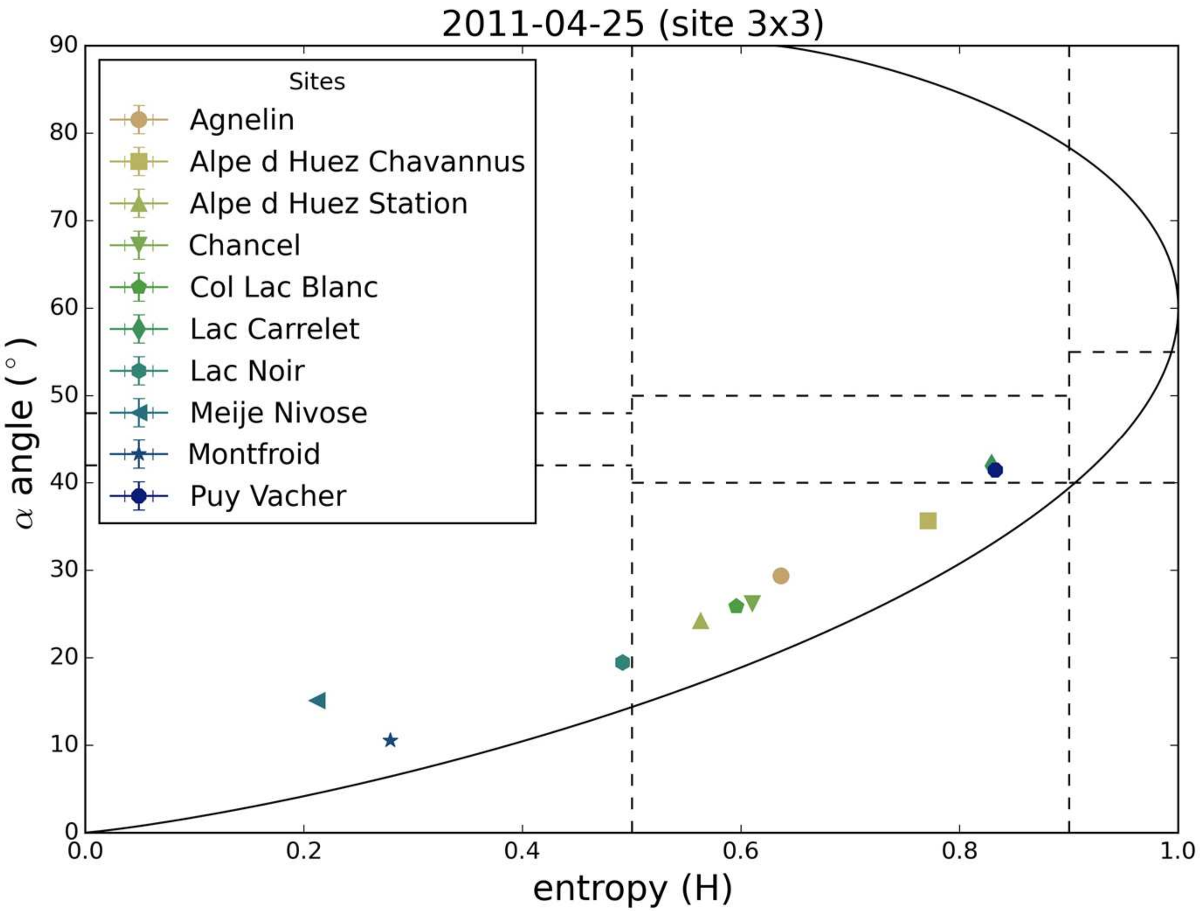
uncorrelated backscattering mechanisms

ENTROPY : 0 to 1	Alpha (α) : 0 to 90°
$H = -\sum_{i=1}^{3} P_i \log_3 P_i, P_i = \frac{\lambda_i}{\sum_{j=1}^{3} \lambda_j}$	$\vec{v}_i = \begin{bmatrix} \cos\alpha_i \\ \sin\alpha_i \cos\beta_i e^{j\delta_i} \\ \sin\alpha_i \sin\beta_i e^{j\gamma_i} \end{bmatrix}$ $\alpha = P_1\alpha_1 + P_2\alpha_2 + P_3\alpha_3$

S. R. Cloude, E. Pottier, "A Review of Target Decomposition Theorems in Radar Polarimetry", IEEE Transactions on Geoscience and Remote Sensing, vol. 34, no. 2, 1996.

H – α segmentation plane





Example of mean entropy (H) and Alpha angle for 10 measurements sites, Radarsat-2 images of 25 April 2011.
The values are set in the nine H/α plane segmentation. We observe a change in scattering behaviour from left bottom (low entropy) for dry and cold snow, to the right side (higher entropy) with increasing humidity and multiple scattering interaction.
Results are in accordance with Hanjnsek et al,, 2003; Martini et al, 2006; Stockamp et al., 2014).

(Dedieu & Roberge, in Télédétection des Surfaces Continentales, Vol 4, ISTE Eds 2016, in Press)

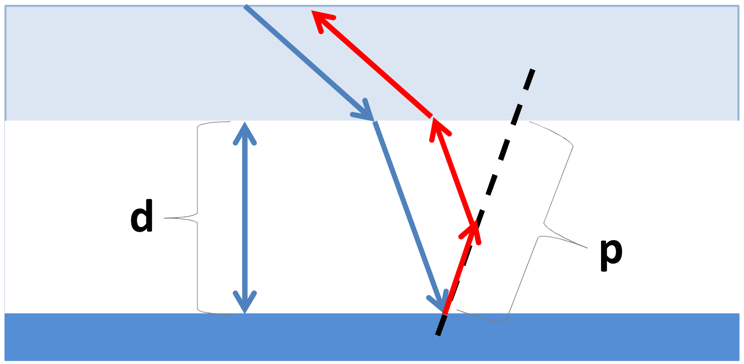
4.3 Physical justification – hypothesis:

First rough ice layer considered as the underlying « ground » surface

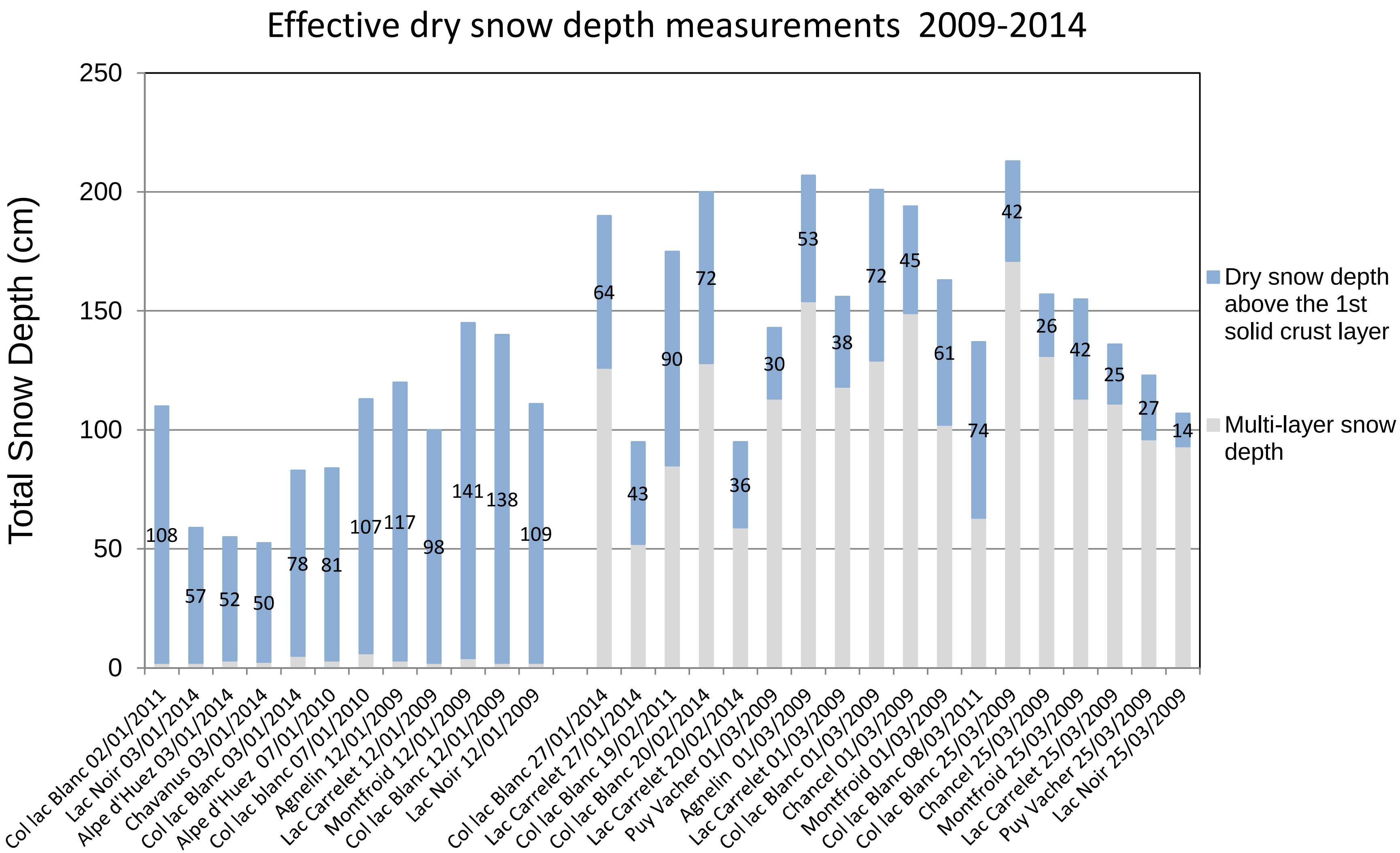
Reflection dominates over scattering at C band (5.4 cm)

« Volume-underlying ground interaction component » (case **4**)
= the most dominant backscattering component

The bigger depth of the dry snow layer (d) means the bigger distance (p)



The bigger probability of interaction with snow particles the bigger probability of recovering the most dominant mechanism, leading to the smaller entropy.


Effective dry snow depth measurements 2009-2014
Total Snow Depth (cm)
250
200
150
100
50
0
108
57
52
50
78
81
107
117
98
141
138
109
64
43
90
72
36
30
53
38
72
45
61
74
42
26
42
25
27
14
Dry snow depth above the 1st solid crust layer
Multi-layer snow depth
Col lac Blanc 02/01/2011
Lac Noir 03/01/2014
Alpe d'Huez 03/01/2014
Chavanus 03/01/2014
Col lac Blanc 03/01/2014
Alpe d'Huez 07/01/2010
Col lac blanc 07/01/2010
Agnelin 12/01/2009
Lac Carrelet 12/01/2009
Montfroid 12/01/2009
Col lac Blanc 12/01/2009
Lac Noir 12/01/2009
Col lac Blanc 27/01/2014
Lac Carrelet 27/01/2014
Col lac Blanc 19/02/2011
Col lac Blanc 20/02/2014
Lac Carrelet 20/02/2014
Puy Vacher 01/03/2009
Agnelin 01/03/2009
Lac Carrelet 01/03/2009
Col lac Blanc 01/03/2009
Chancel 01/03/2009
Montfroid 01/03/2009
Col lac Blanc 08/03/2011
Col lac Blanc 25/03/2009
Chancel 25/03/2009
Montfroid 25/03/2009
Lac Carrelet 25/03/2009
Puy Vacher 25/03/2009
Lac Noir 25/03/2009

4.4 Statistical experiment design

➡ Status: No relationship directly observed between H and α polarimetric parameters versus snow characteristics measurements (depth, SWE).

➡ Decision: to process a multivariate statistical analysis on the data, taking in account that each parameter is interactively combined with other factors, as for snow measurements as for polarimetric descriptors.

➡ Method: to create a contengency table (x,y): each row is a snow observation, each column is a polarimetric attribute/feature.

➡ Statistical tool : the canonical correlation analysis (CCA) [Seber, 1984].

- CCA compares these two quantitative variables groups (snow, polar) applied both on the same individuals (sites + dates), to see if they describe the same phenomenon
- The purpose of CCA is to compare these two groups of variables to see if they describe the same phenomenon (correlation).
- CCA is a way of making sense of cross-covariance matrices.

- Question 1: how many polarimetric descriptors to select (total 27) ?

The main representative drivers are (E. Pottier):

- **Entropy** = indicates the random profile for global scattering of the target.

If zero, only one dominant mecanism (pure target)

If 1, the three mechanisms are equal (distributed target)

- **Alpha angle** = describes the scattering type (parametrization angle)

If 0°, surface scattering

If 45°, volume scattering

If 90°, double bounce

Nature and importance of the different backscattering mechanisms:

- **SERD** = single eingenvalue relative difference (expresses the relative part of the simple diffusion in the signal phase)
- **DERD** = double eingenvalue relative difference (expresses the relative part of the multiple diffusion in the signal phase)

- Question 2: wich snow parameter to choose as input data ?

The most reliable *in situ* snow measurements are: depth, density, SWE.

4.5 Results : comparison with field measurements

" Cloude-Pottier"
polarimetric
decomposition
(4 parameters)

vs

Snow
measurements
(3 parameters)

for
30 sites (10 dates)

→

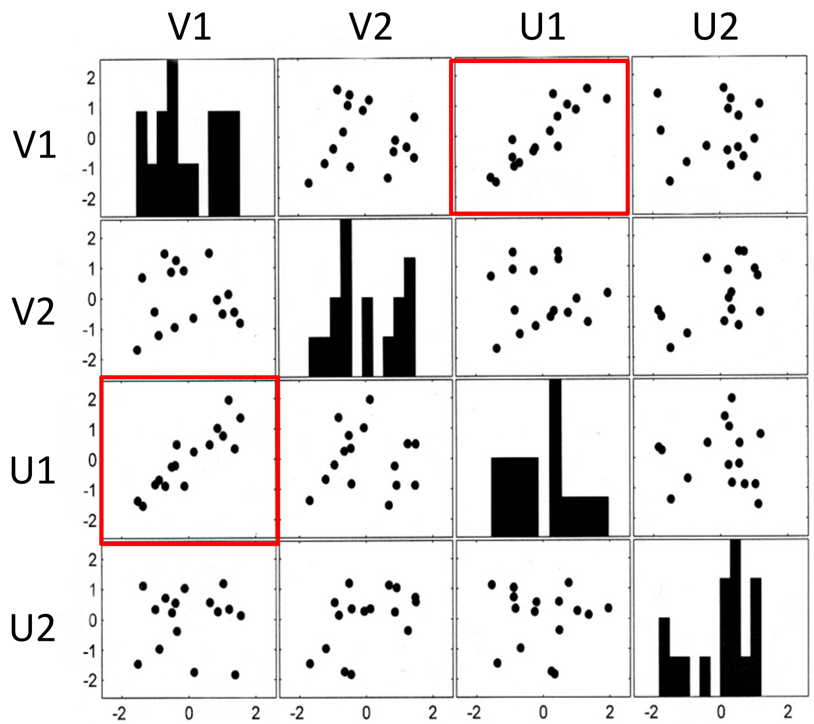
Canonical
Correlation
Analysis

(linear regression)

→

Correlation Table
with snow field data
(Matlab)

↓



After CCA runs, strong relationship
between V1 and U1: **R = 0.89** **R^2 = 0,81**

(Dedieu, Besic et al., under preparation for IEEE-GRSL)

5. Conclusion and Perspectives

Conclusion

1. Wet snow multi-temporal mapping using Radarsat-2 non polarimetric mode:
simple threshold method to implement for time series (Sentinel-1),

Limitation: layover and SAR shadow mask => optimal incidence angle ± 40°

2. Dry snow depth retrieval using Radarsat-2 polarimetric mode:
interaction between Cloude-Pottier H/α polarimetric decomposition and *in situ* snow height measurement, using CCA statistical processing.
Validated for 2009-2011 time series, confirmed with 2014 second mission.

Limitation: concern only the dry snow upper ground or last solid crust layer in snow pack, concern only flat areas (slopes > 12° are here excluded).

Perspectives

1. Wet snow: complemetary data acquisition during winter 2015 =
snow LWC retrieval for sites and at massif scale (Crocus model) <u>work in progress</u>

2. Dry snow: (i) radiometric slope correction to be done (Small, 2004; 2011) and Crocus snow model for validation at the massif scale.
(ii) Improve the CCA process at X-band (TerraSAR-X) with polarimetric phase difference.

Picture Mth. Laval   12/01/2009

Thanks to Météo-France/CEN and EDF/DTG technical staff   !