Advancing Remote-Sensing Methods for Monitoring Geophysical Parameters

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Advancing Remote-Sensing Methods for Monitoring Geophysical Parameters

Outline

Focus

Refractive Index

Explorative Studies

Applying Remote-Sensing Data

Enhancing Value by Advancing Methods

Advancing Remote-Sensing Methods for Monitoring Geophysical Parameters

Outline

Focus

- Objects: land surface, especially snow
- Methods: active and passive microwave remote sensing

(neglecting up- & downscaling issues)

Land Surface and Atmosphere with Complexity and Variability

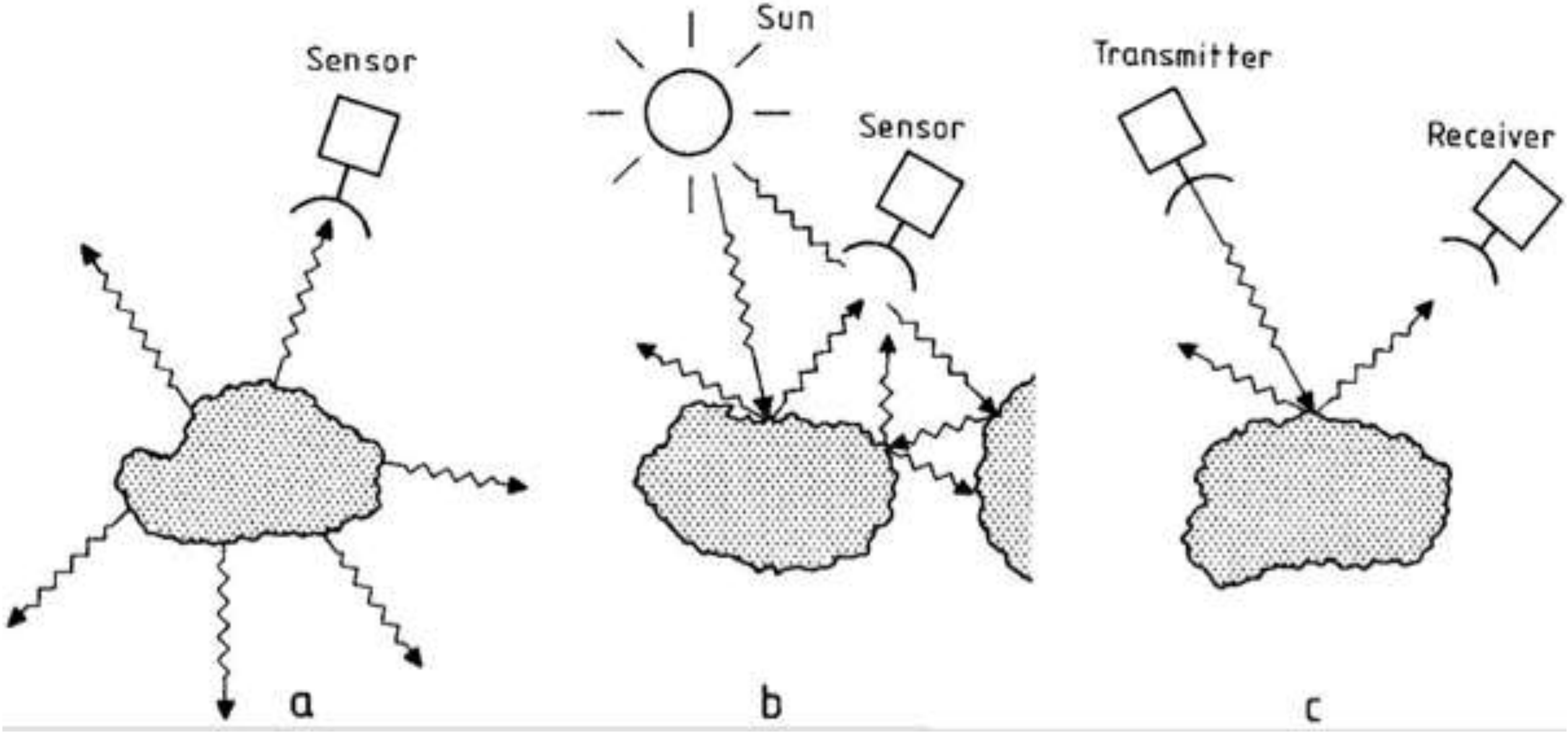
Heterogeneity at the wavelength scale

Forest surface

And much more ...

Layered snow

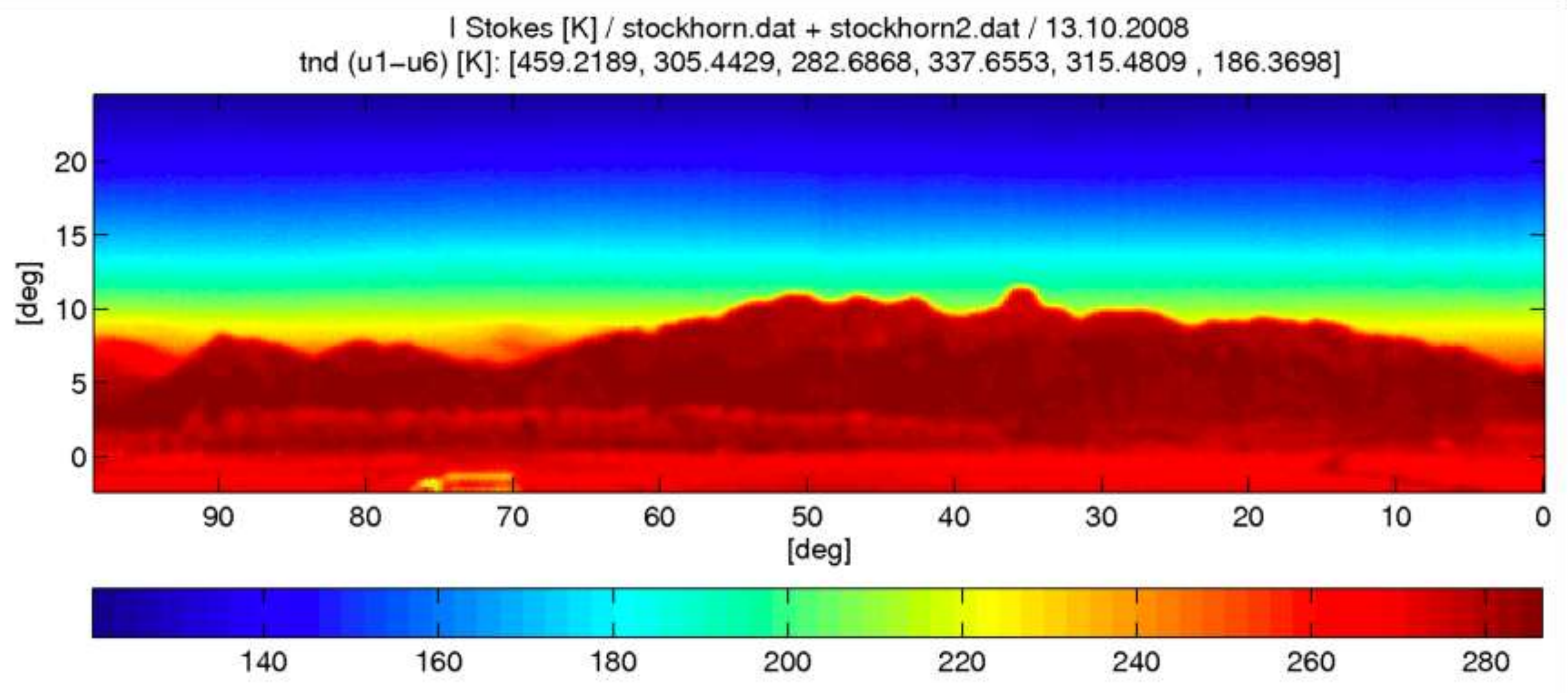
Active and passive microwave remote sensing



Passive methods (*a & b*) make use of existing radiation: Radiometers
Active methods (*c*) create and detect their own signals: RADAR
from Schanda (1986)

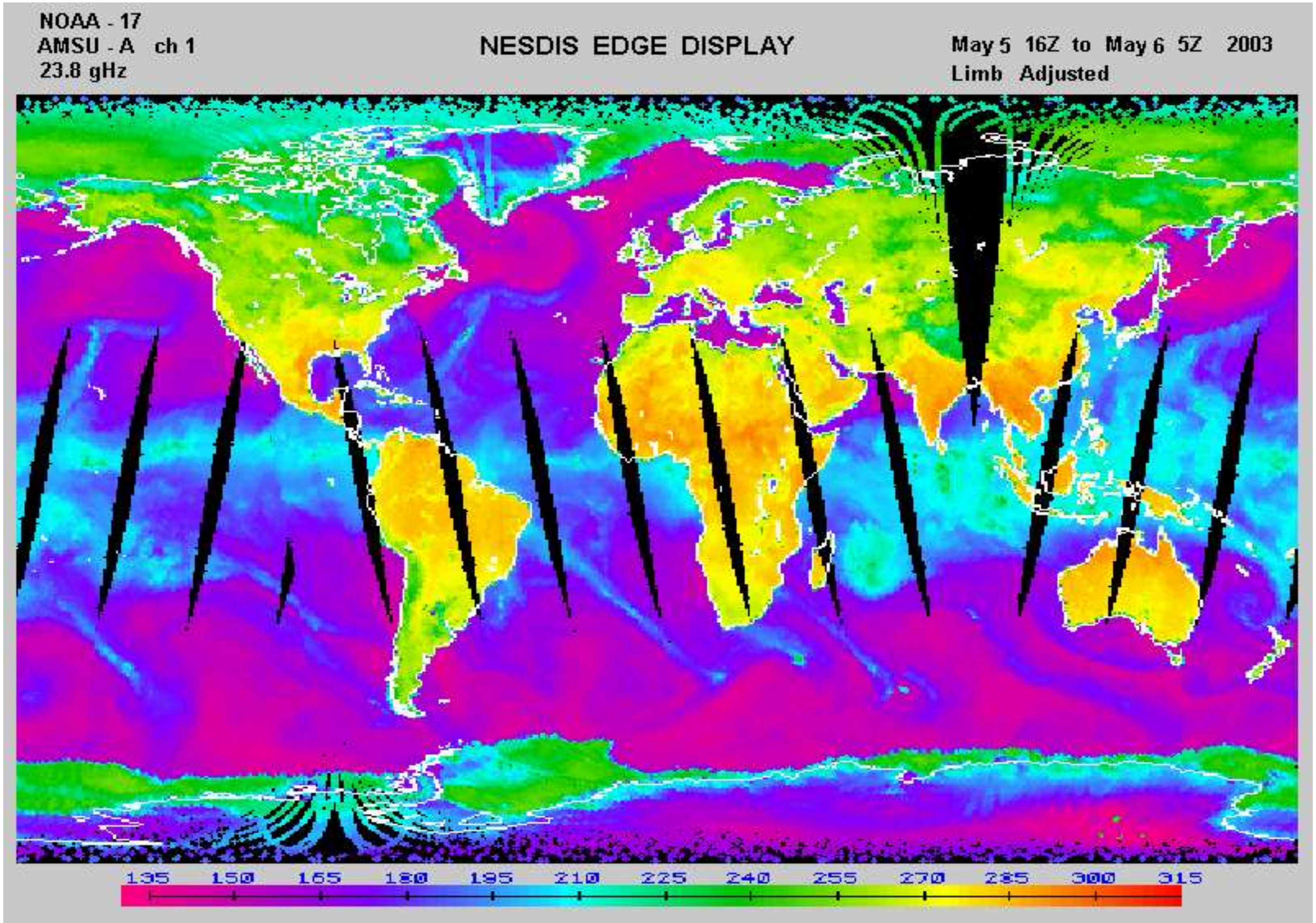
Microwave Radiometry

Key observable: Brightness temperature T_b(K)

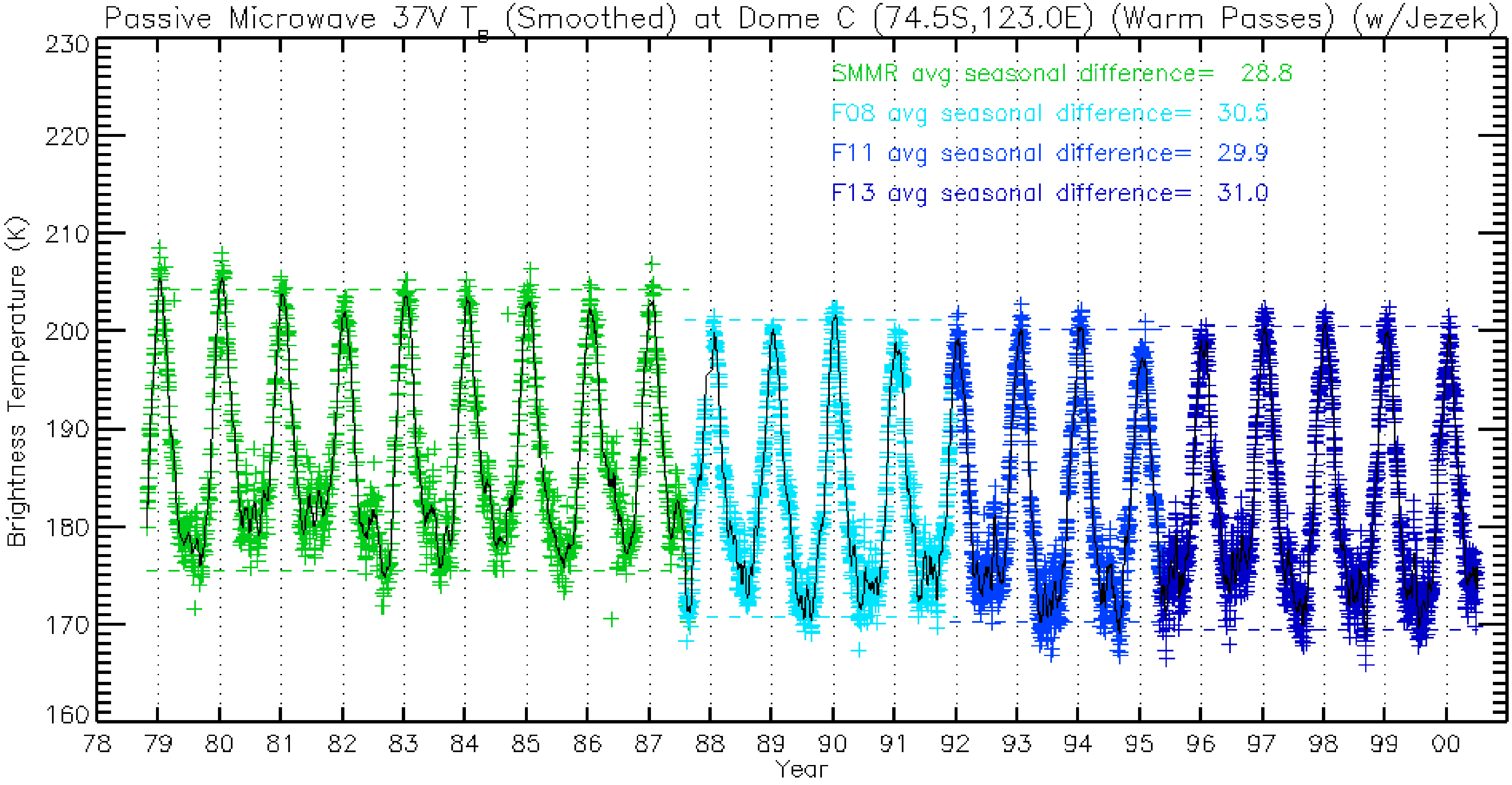


Example: Brightness temperature of Stockhorn mountain range at 91 GHz on 13 Oct 2008, from Stähli (2009)

Microwave Radiometry



Example: Brightness temperature of the earth at 23.8 GHz on May 5-6 2003


Passive Microwave 37V T_B (Smoothed) at Dome C (74.5S,123.0E) (Warm Passes) (w/Jezek)
SMMR avg seasonal difference= 28.8
F08 avg seasonal difference= 30.5
F11 avg seasonal difference= 29.9
F13 avg seasonal difference= 31.0
Brightness Temperature (K)
230
220
210
200
190
180
170
160
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
00
Year

Microwave Radiometry

Basics

1)Rayleigh-Jeans Law: Intensity $\propto$ physical temperature $\Rightarrow$ observable T_b

2)Kirchhoff's Law (1860)* of thermal radiation (in LTE) most general formulation:
Let the observable space be described by N regions at different temperature T_i (i=1,..N)

$T_b = \sum a_i T_i$; $\sum a_i = 1$; where a_i is the absorptivity of Region i (reversed direction)

*Gustav Kirchhoff (1824-1887)

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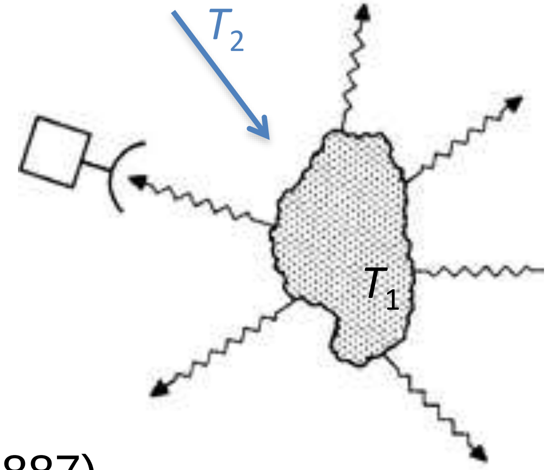
Example: Radiometer pointing at a lonely planet at T_1, cosmic background at T_2 (N=2),
$a_1 = a = e$ planet emissivity, $a_2 = 1 - a = r$ planet reflectivity
$T_b = eT_1 + rT_2$



Thus reflection and emission are linked through
$r = 1 - e$

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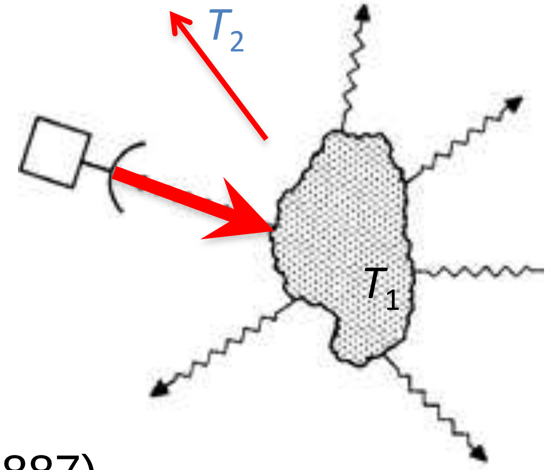

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$r=1-e$

*Gustav Kirchhoff (1824-1887)

RADAR

Key observable: backscattering coefficient γ_{ij}
Furthermore: backscatter phase between transmit and receive signal

$$\gamma_{ij} = \sigma^0_{ij}/\cos\theta,$$

transmit pol j, receive pol i, nadir angle θ,
normalised backscatter cross section σ^0_{ij}

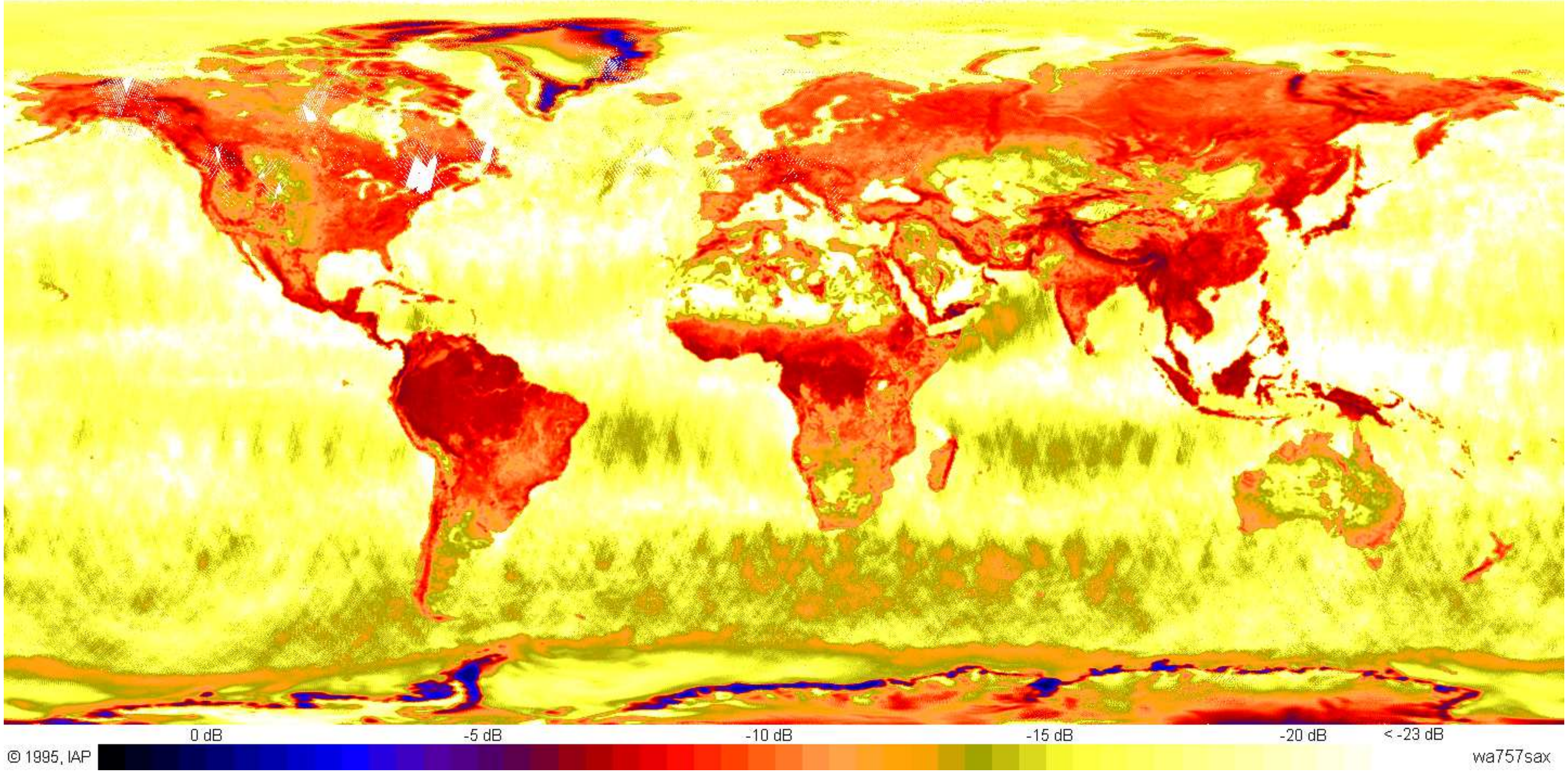
Lambertian (rough) surface:

$$\gamma_{hj}+\gamma_{vj} = 4r_j\cos\theta \quad (r_j \text{ indep. of pol and } \theta)$$

➔ Emission and backscattering are related through Kirchhoff's Law

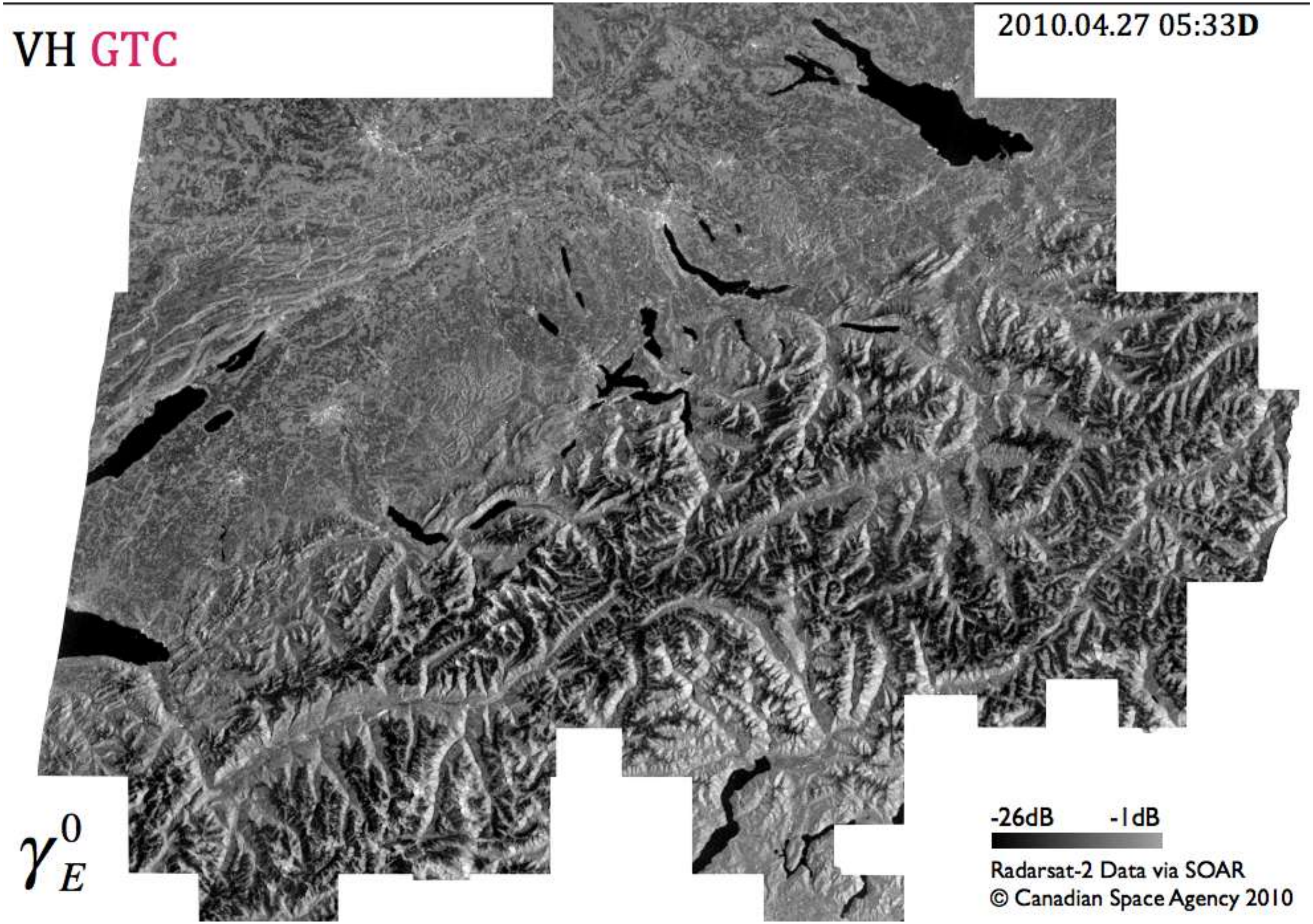
RADAR

Key observable: backscattering coefficient



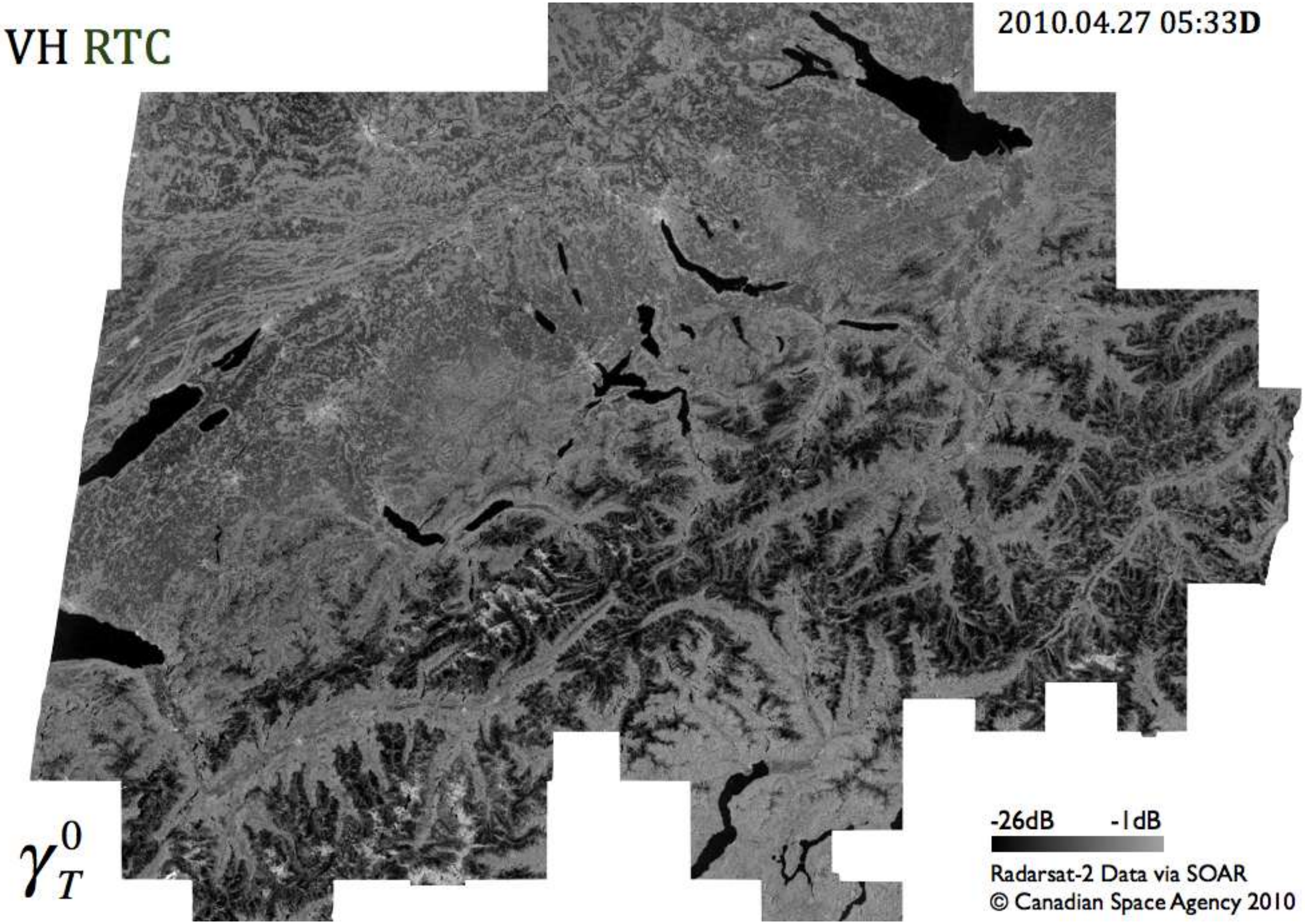
Example: Global backscattering coefficient at 5 GHz, 40 incidence angle (ERS-1 Scatterometer)
Wiesmann & Mätzler (1993).

RADAR: Radarsat 2



Cross-pol backscat coeff at 5 GHz (ellipsoid adapted) during snowmelt in the Alps, Small (2011)

RADAR: Radarsat 2



Radarsat-2 Data via SOAR
© Canadian Space Agency 2010

Cross-pol backscat coeff at 5 GHz (terrain adapted) during snowmelt in the Alps, Small (2011)

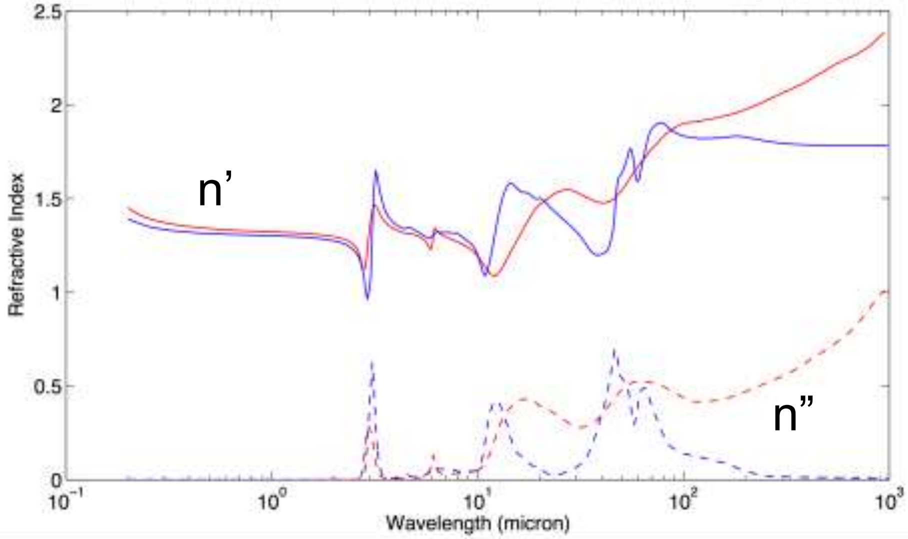
Advancing Remote-Sensing Methods for Monitoring Geophysical Parameters

Outline

Refractive Index
Key parameter for interaction between wave and medium

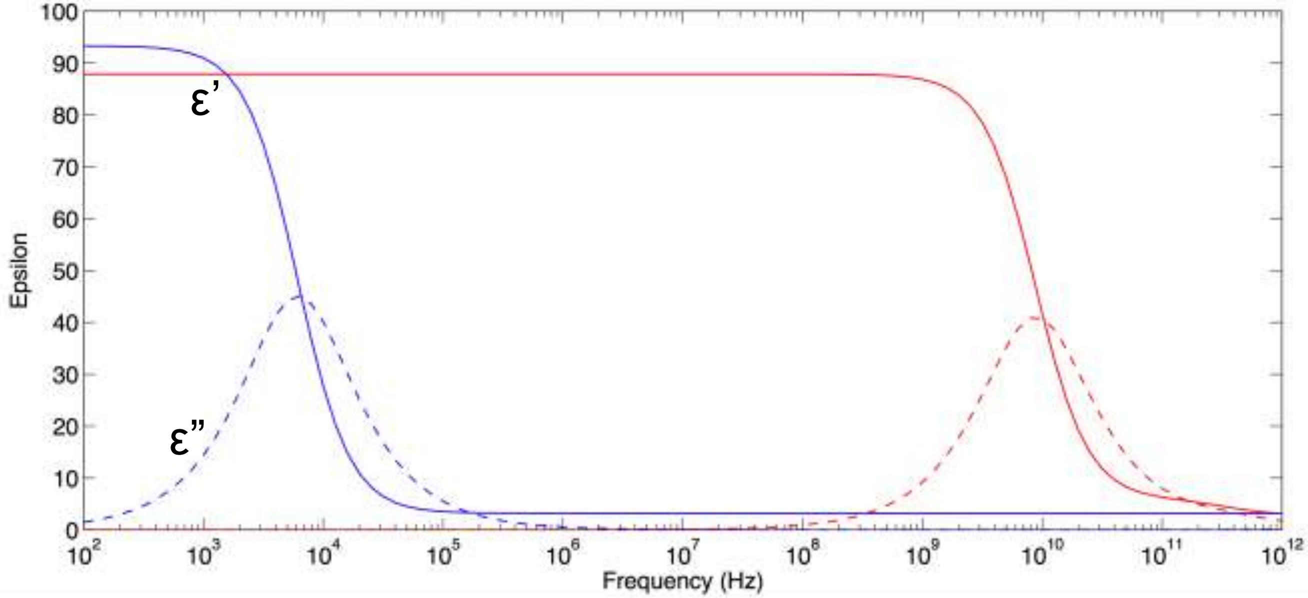
Dielectric & refractive measurements of natural media
are delicate, needing ‘generic’ sensors

Importance of water



Refractive index $n=n'+in''$
Dielectric constant $\varepsilon=\varepsilon'+i\varepsilon''=n^2$

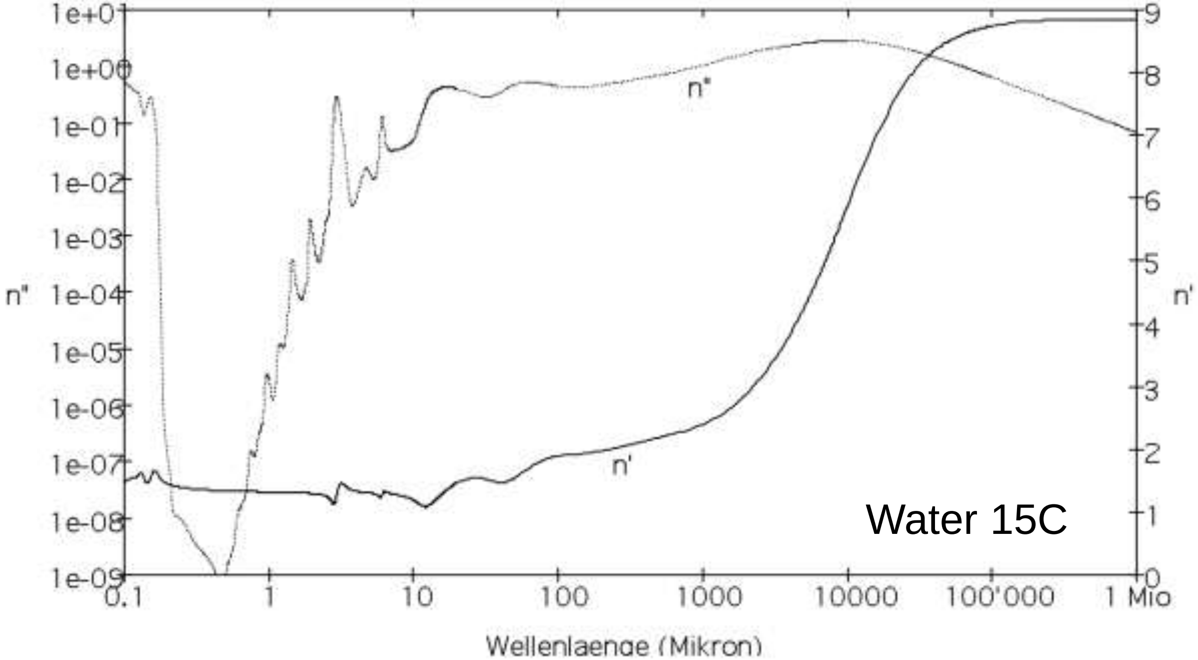
Liquid water
Ice



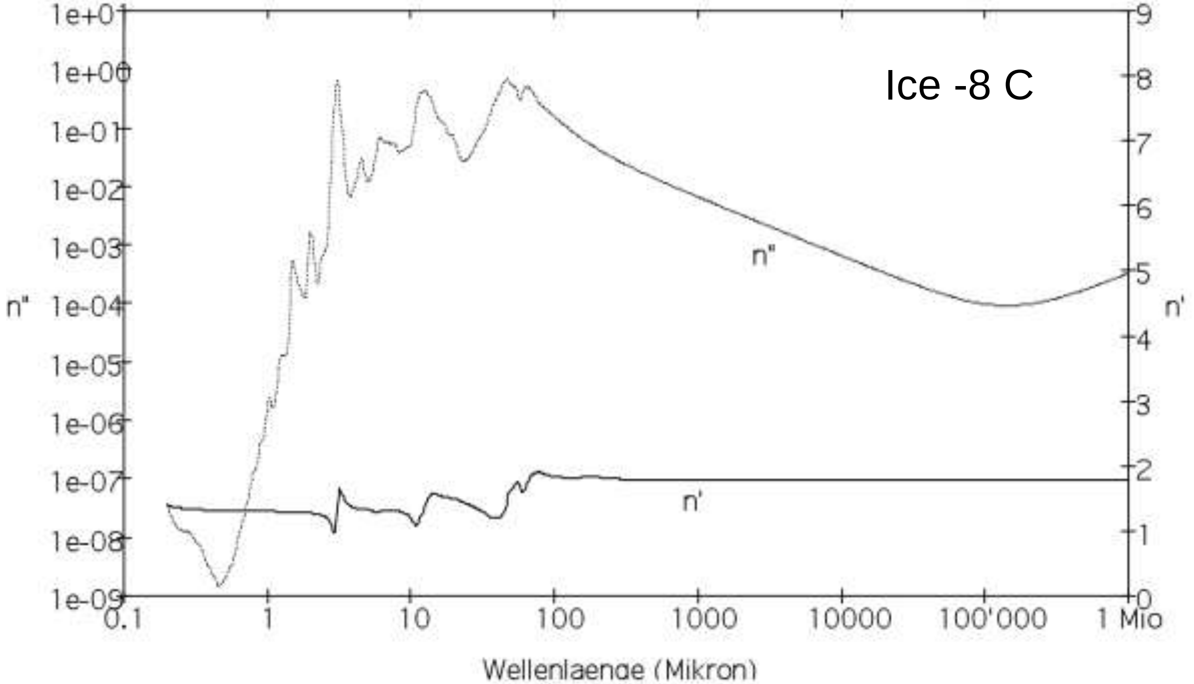
Water

Complex refractive index

$n=n'+in''$



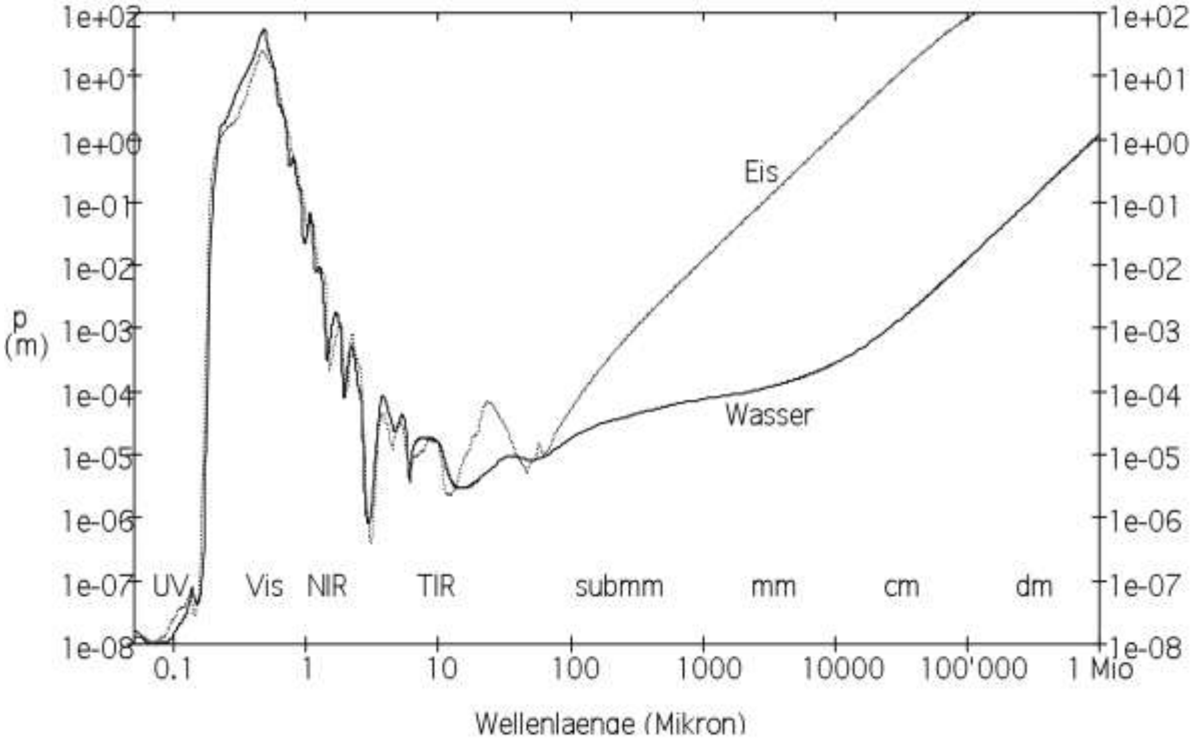
Water 15C



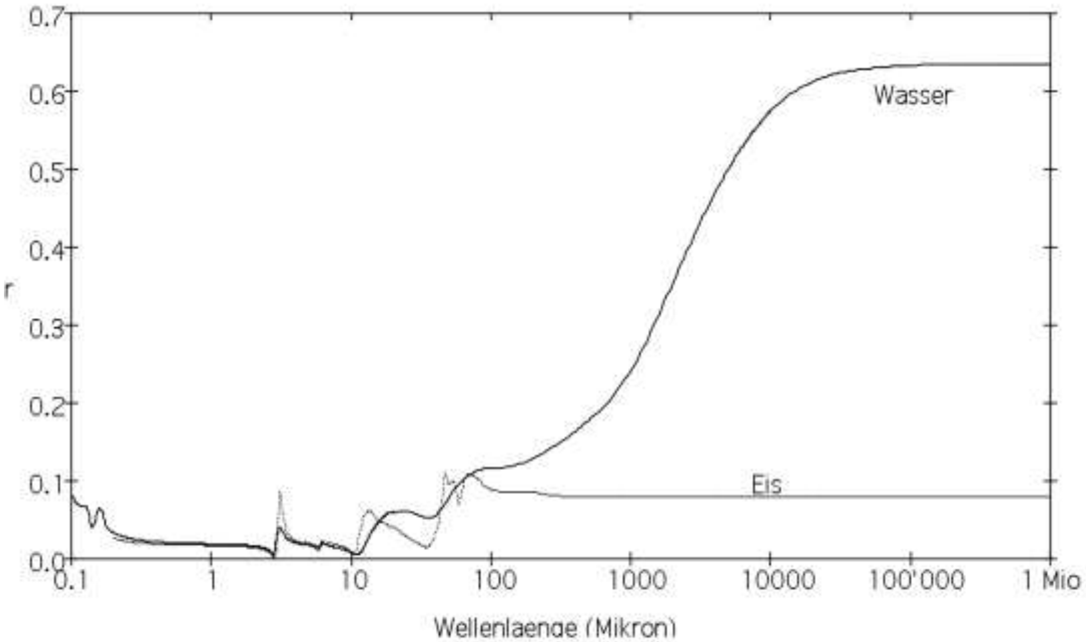
Ice -8 C

Water

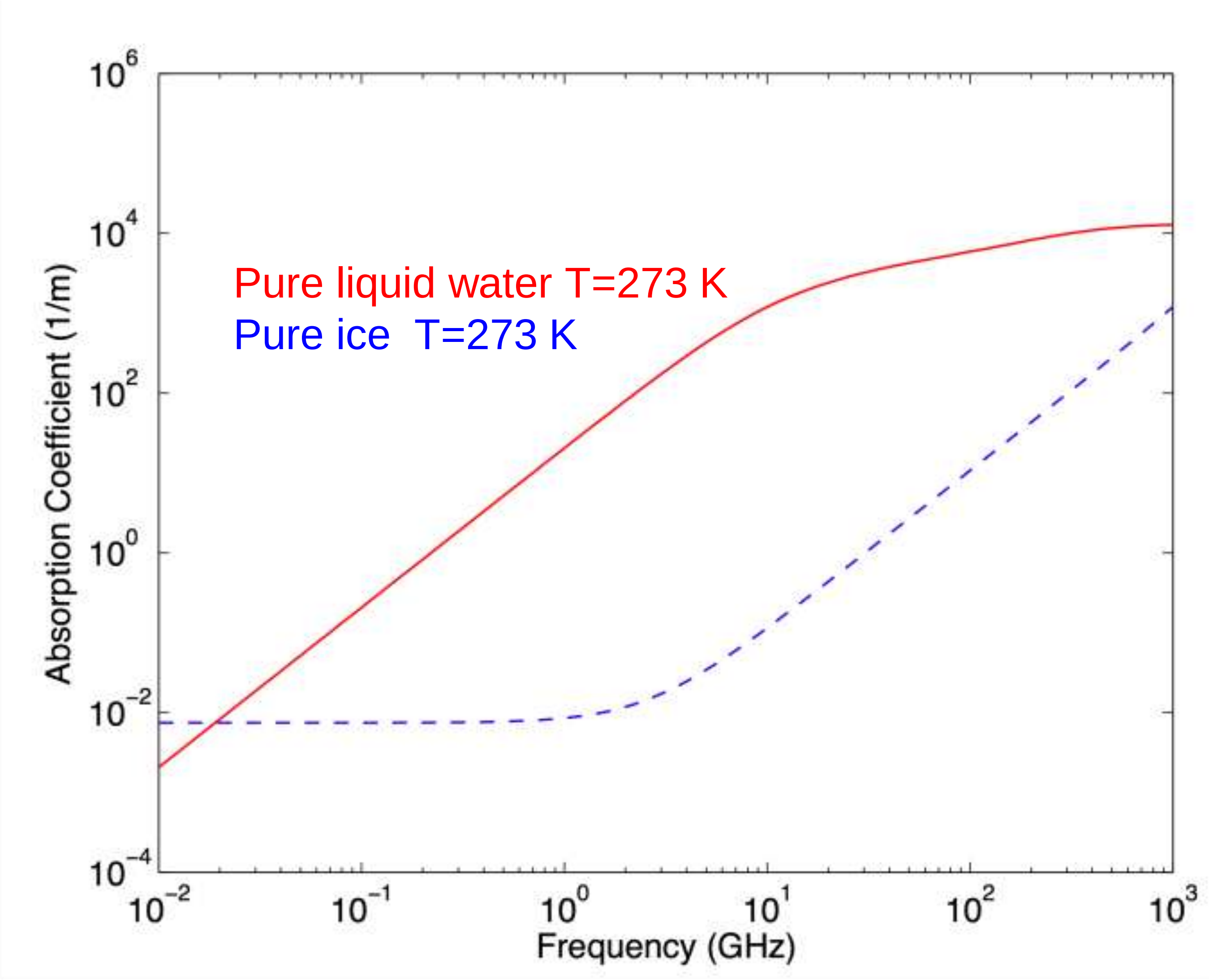
Penetration depth p



Fresnel reflectivity r
vertical incidence



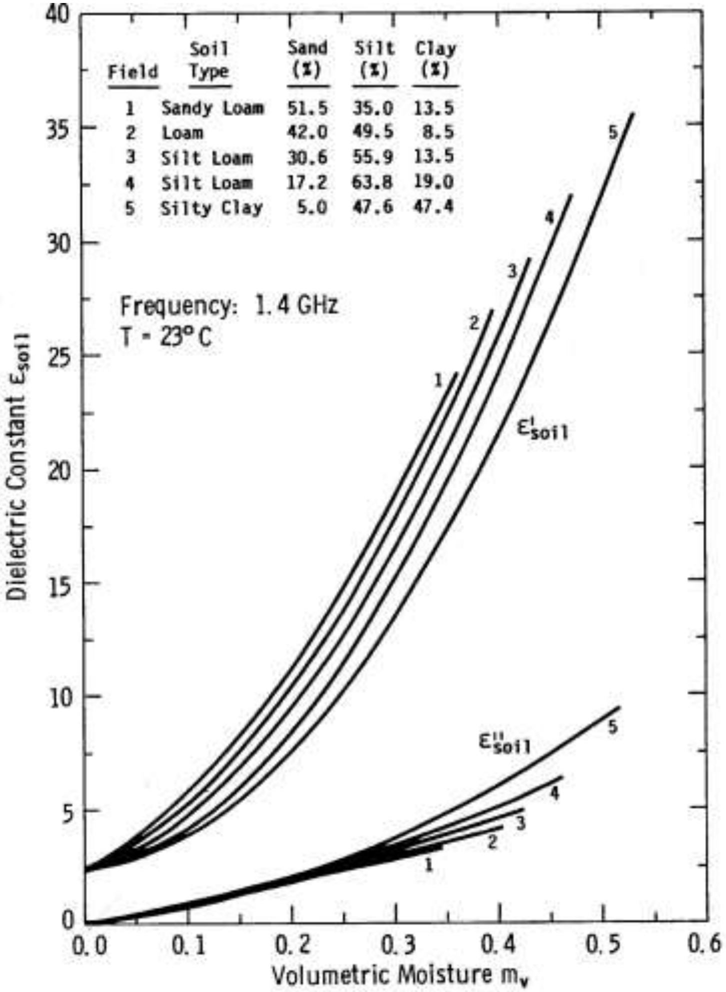
Water: Absorption coefficient =1/p



But note:
Sensitivity to
- temperature
- impurities

Soil

Dielectric constant dominated by water content.   Clays are different !



Field	Soil Type	Sand (%)	Silt (%)	Clay (%)
1	Sandy Loam	51.5	35.0	13.5
2	Loam	42.0	49.5	8.5
3	Silt Loam	30.6	55.9	13.5
4	Silt Loam	17.2	63.8	19.0
5	Silty Clay	5.0	47.6	47.4

Fig. E.47 Measured dielectric constant for five soils at 1.4 GHz.

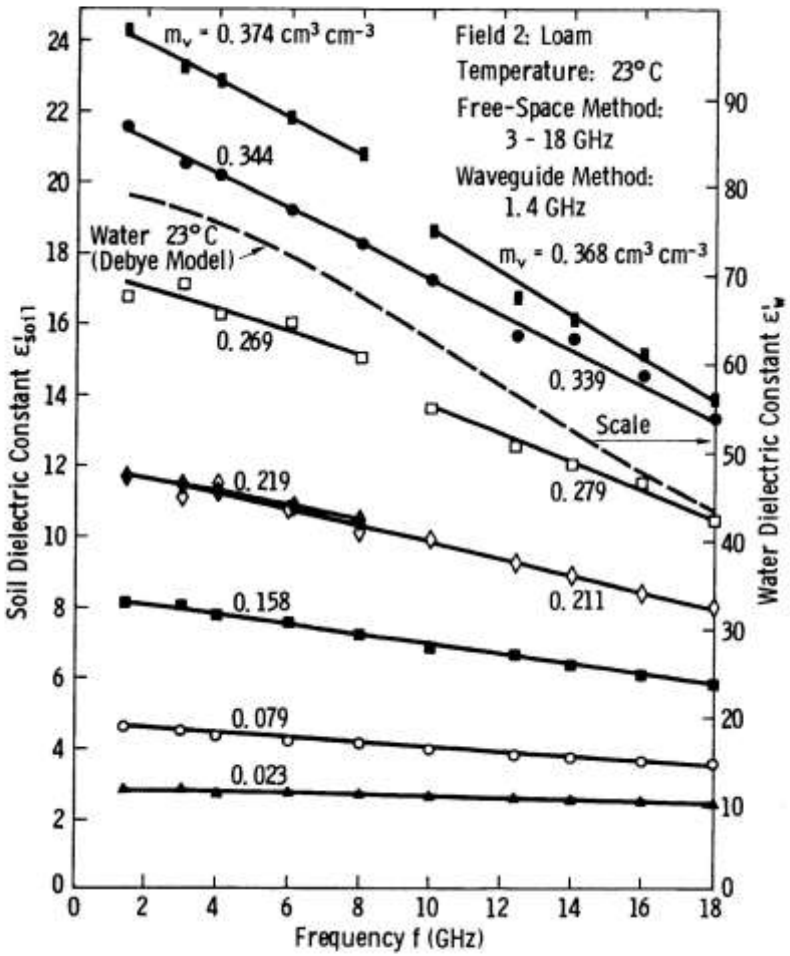
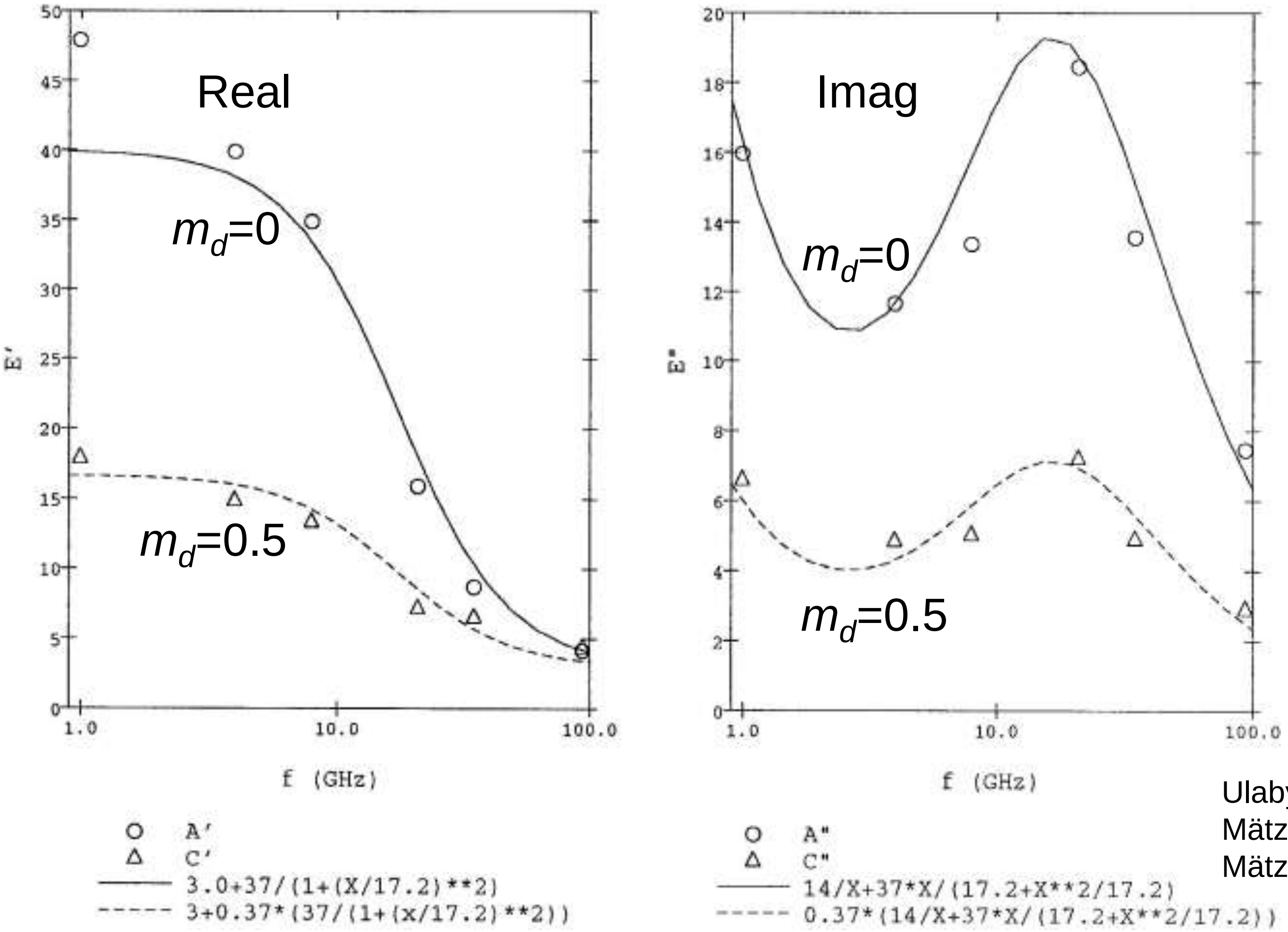


Fig. E.53 Measured dielectric permittivity of loamy soil as a function of frequency with volumetric moisture content as a parameter. The scale on the right is for water (from Hallikainen *et al.*, 1985).

Green vegetation

Dielectric constant dominated by water (ε_{sw}), m_d dry-matter fraction

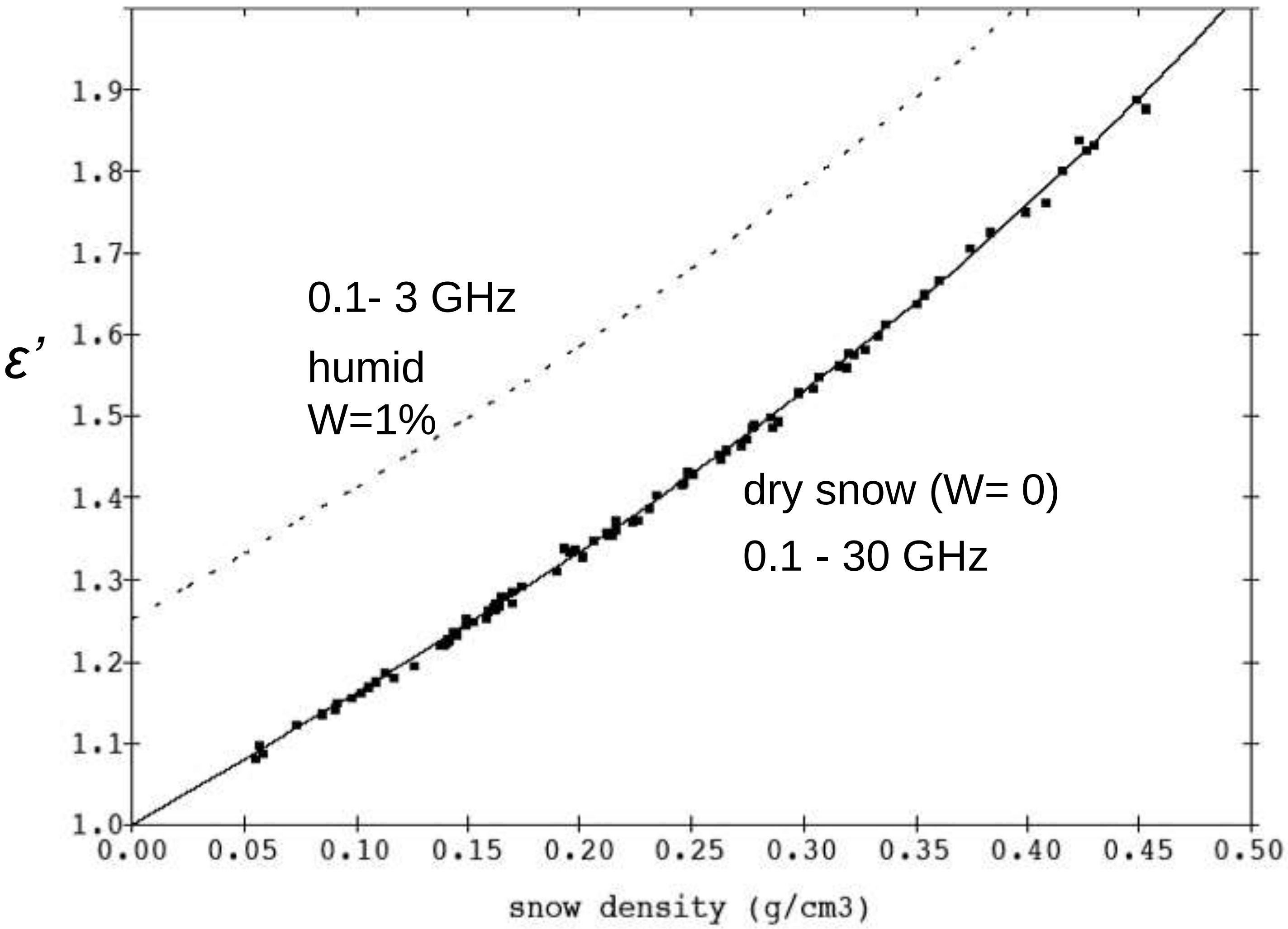
$$\varepsilon = 0.51 + 3.84 m_d + 0.522(1 - 1.32 m_d)\varepsilon_{sw}$$



Ulaby & El Rayes (1987)
Mätzler & Sume (1989)
Mätzler (1994b)

Snow

Dielectric constant dominated by density and vol. liquid-water content W



0.1- 3 GHz

humid
W=1%

dry snow (W= 0)

0.1 - 30 GHz

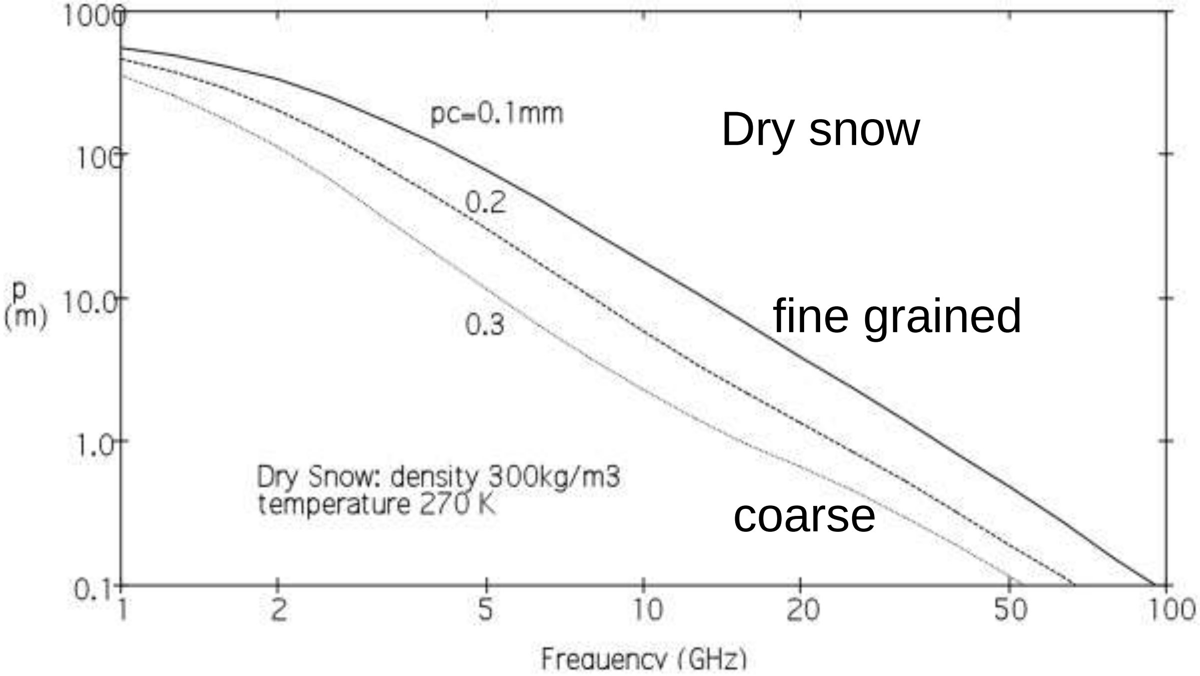
Mätzler (1996)

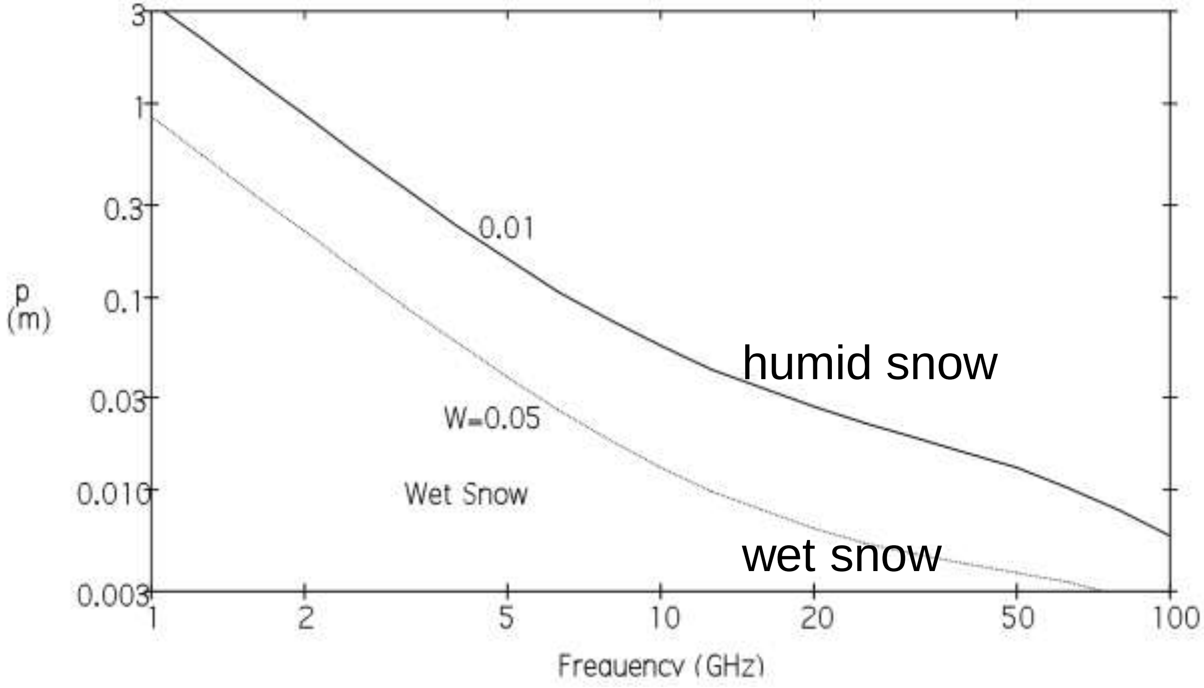
Snow

Penetration depth versus frequency

Model simulations – close agreement with observations

p_c correlation length (inversely related to the specific surface)





Outline

Explorative Studies

(assuming given research questions)

Information - Carrying Observables (*Signatures*)

Field campaigns (e.g. at TERENO sites) using calibrated sensors

- Semi-empirical methods
- Theoretical: physical concepts
- Combination of both

Resulting in

- Signature catalogues
- Empirical relationships
- Forward models and advanced process models

Information - Carrying Observables (*Signatures*)

Interaction processes between objects and sensing waves:
Reflection & scattering
Absorption & emission

Controlled by object properties
Electromagnetic (refractive index)
Geometric (path length, direction, object size, shape, orientation, roughness, specific surface)

Implicitly dependent on geophysical state and its history
Composition
Thermodynamic state variables

Field campaigns using calibrated sensors

Calibrated sensors enable

- Reproducible results
- Intercomparisons with other instruments
- Application of physical concepts

Semi empirical: Often nature is too complex to allow a full quantitative understanding of the observed phenomenon.

Exact models for simplified conditions, such as the Fresnel formula for reflection at a flat surface, are useful as reference.

Approximations or empirical relations that take into account model distortions.

Aim is a sufficiently accurate and general radiative model that converges to agreement with observations. Note range of validity!

Object description must be confirmed or improved, and all **errors** must be under control.

Results

Signature catalogues: Radiative properties and object descriptions, including error statistics

Empirical relationships between object parameters and observables, including range of validity

Forward models (physical and empirical): Generalised rules to project object properties into observable space.

Object properties projected through forward model in observable space advance the **process models** (such as snow metamorphism, freeze-thaw, heat and water transport)

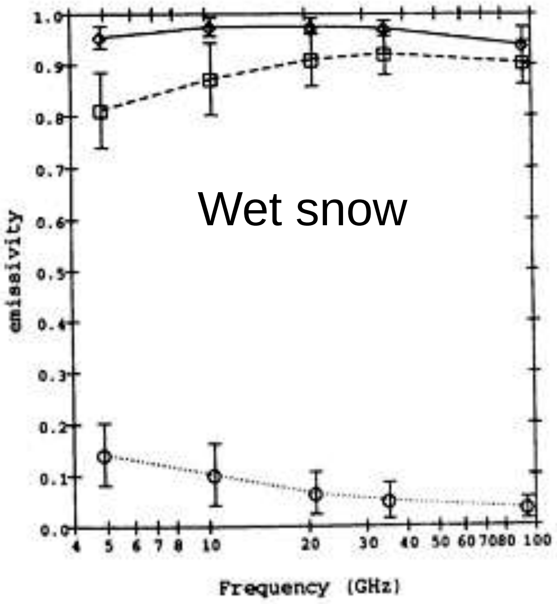
Example: Snow

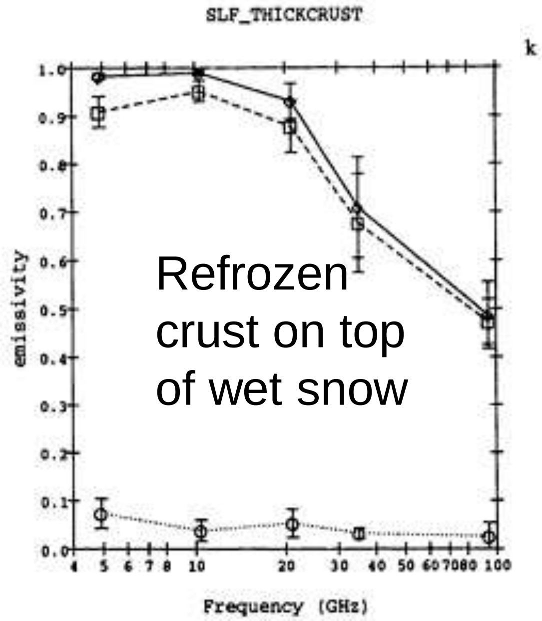
Signature study for several years to cover the natural variability.

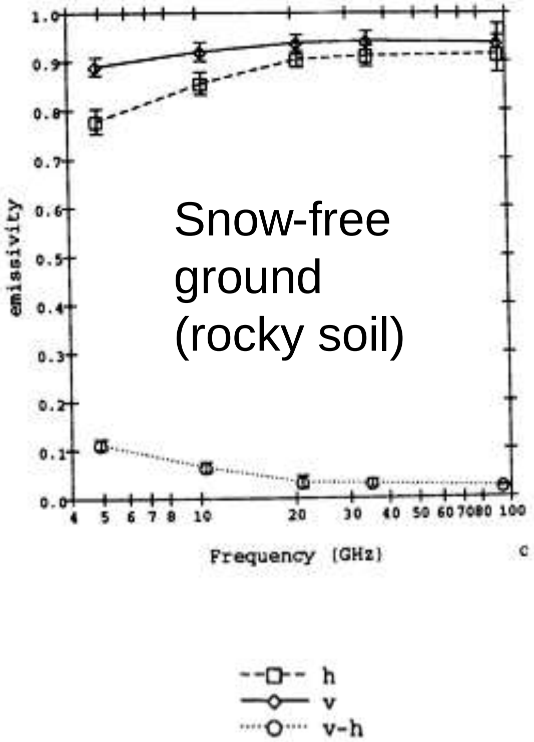
Here the Passive and Active Microwave and Infrared Radiometer (PAMIR) at Weissfluhjoch, Davos 1977 – 1986

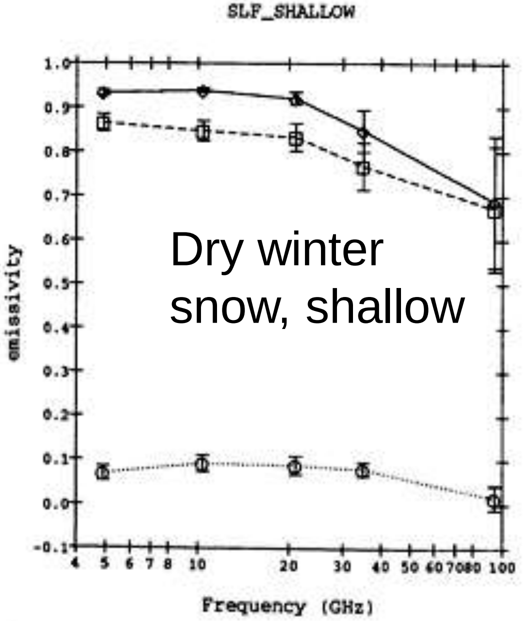
Empirical snow signatures: Emissivity spectra

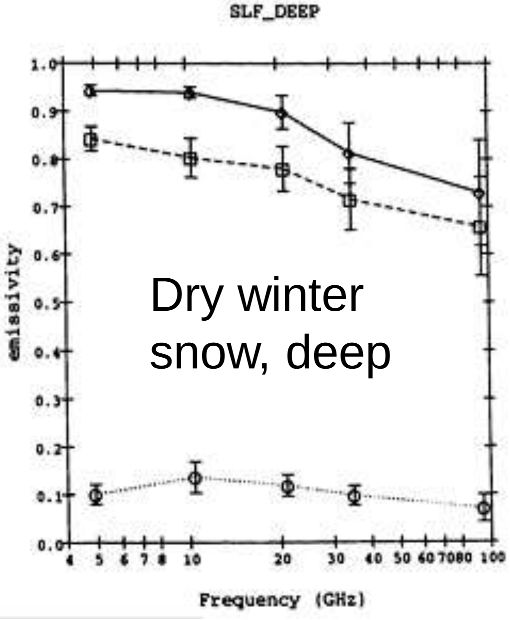
(v- & h-pol, nadir angle 50 deg)


Wet snow


Refrozen crust on top of wet snow

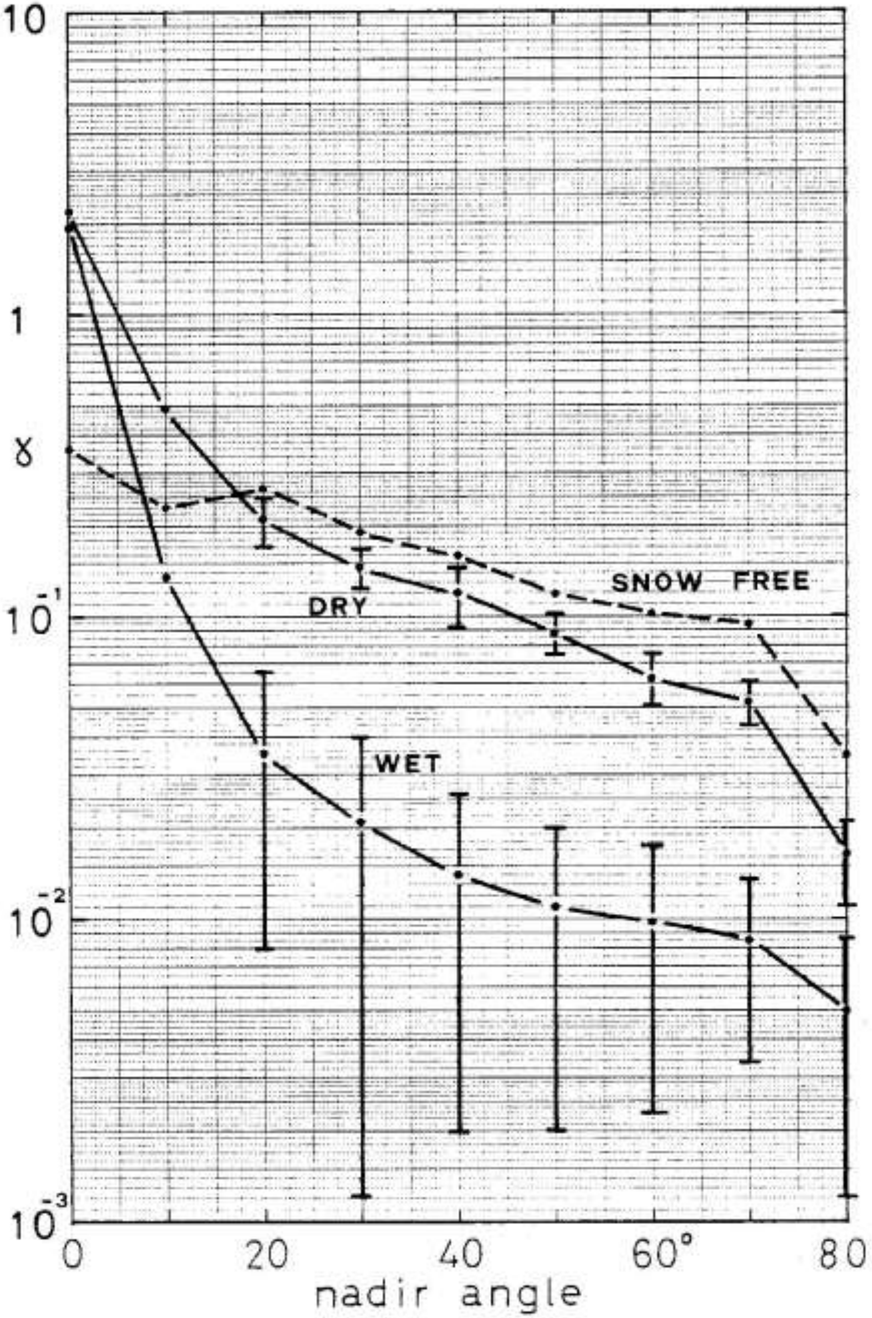

Snow-free ground (rocky soil)


Dry winter snow, shallow


Dry winter snow, deep

Mätzler (1994)

Empirical snow signatures:
Backscattering coefficient
10 GHz, like polarised



Conclusion:

Low backscatter enables detection of **wet snow**

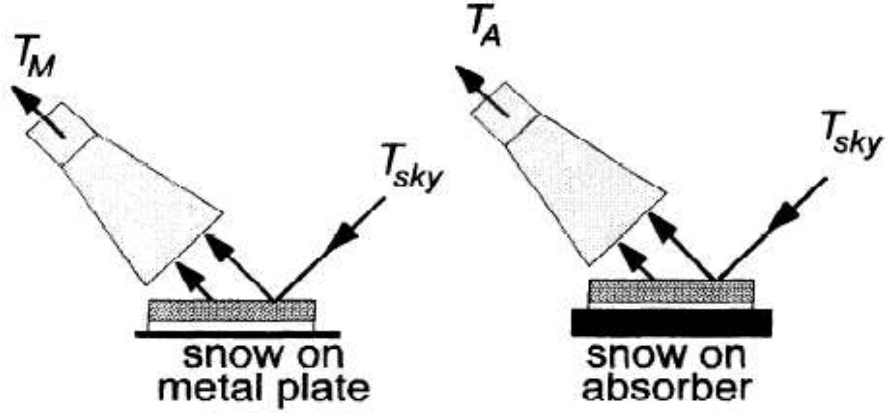
Low emissivity at high frequency enables detection of **dry snow**

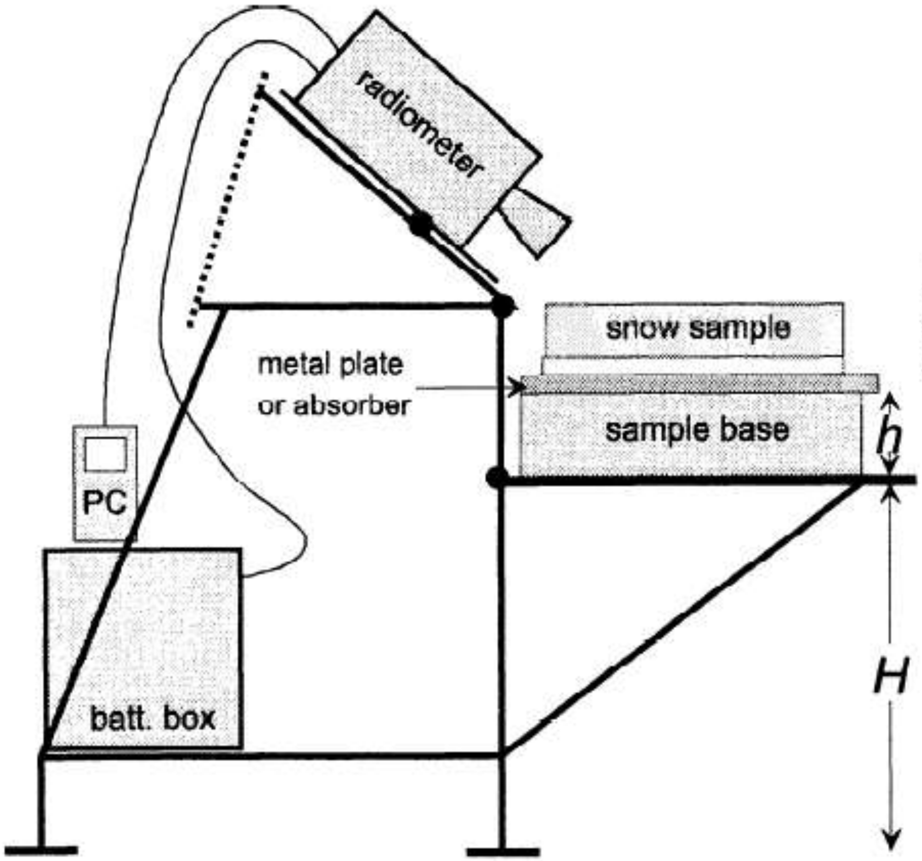
Mätzler and Schanda (1984), Mätzler (1987)

Snow: Quantitative study

Bicontinuous structure (ice – air) induces scattering.

Quantification: snow samples (d=10 cm) with radiometer and snow-section investigations





Wiesmann et al. (1998)

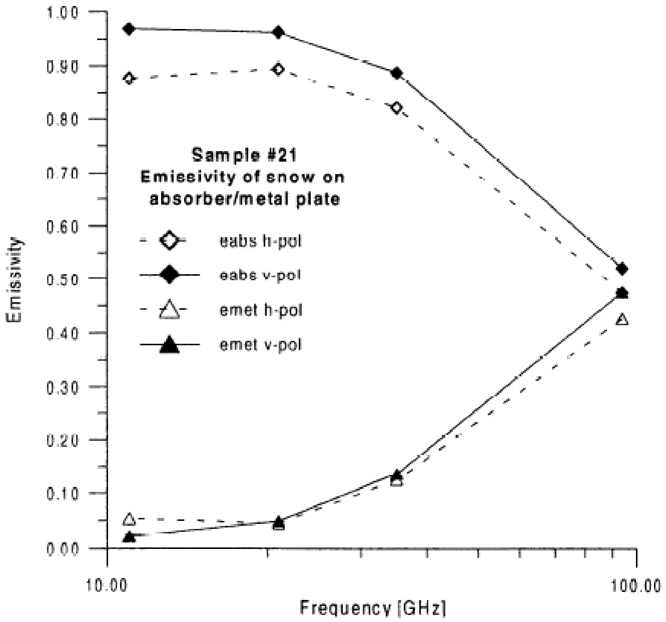
Snow

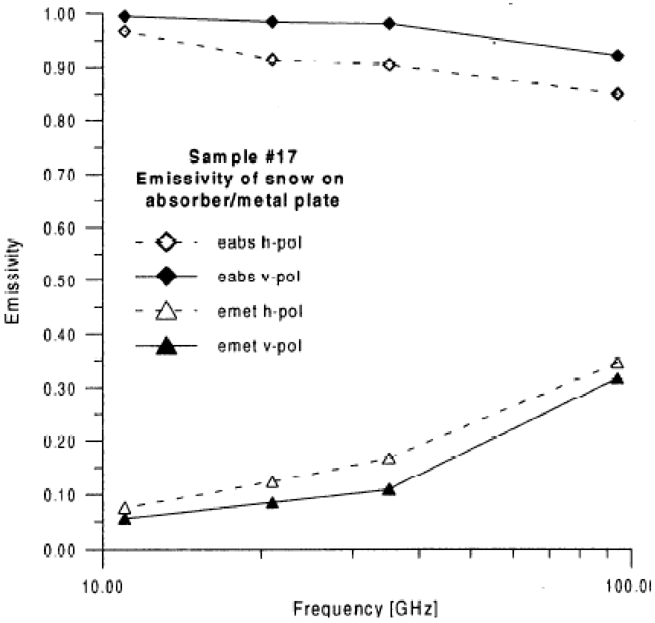
2 Examples:
Emissivities
of samples on
absorber (upper)

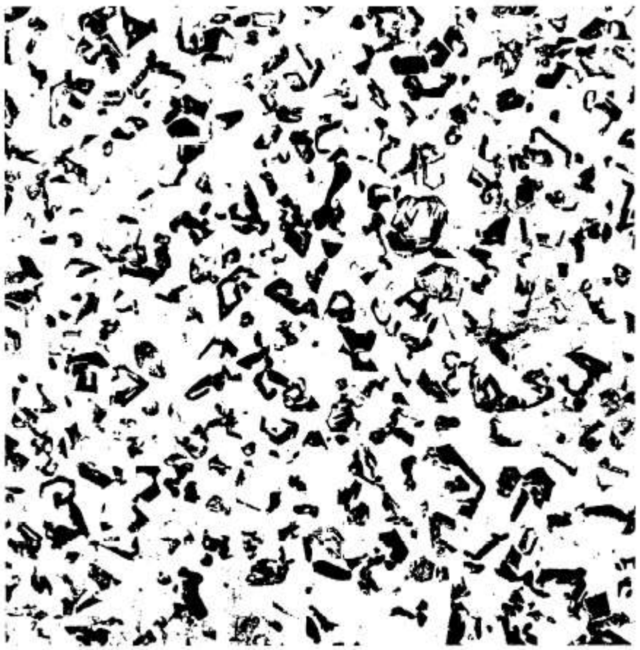
on metal plate
(lower curves)

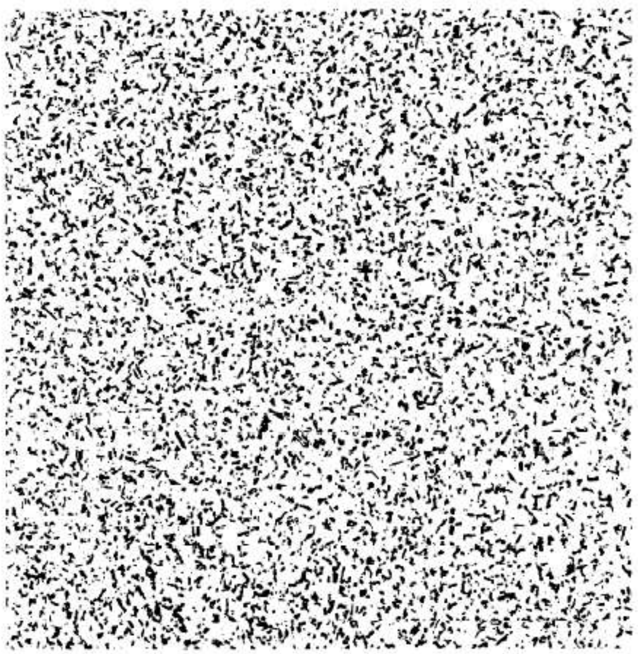
for
coarse-grained
snow (left)

fine-grained
snow (right)



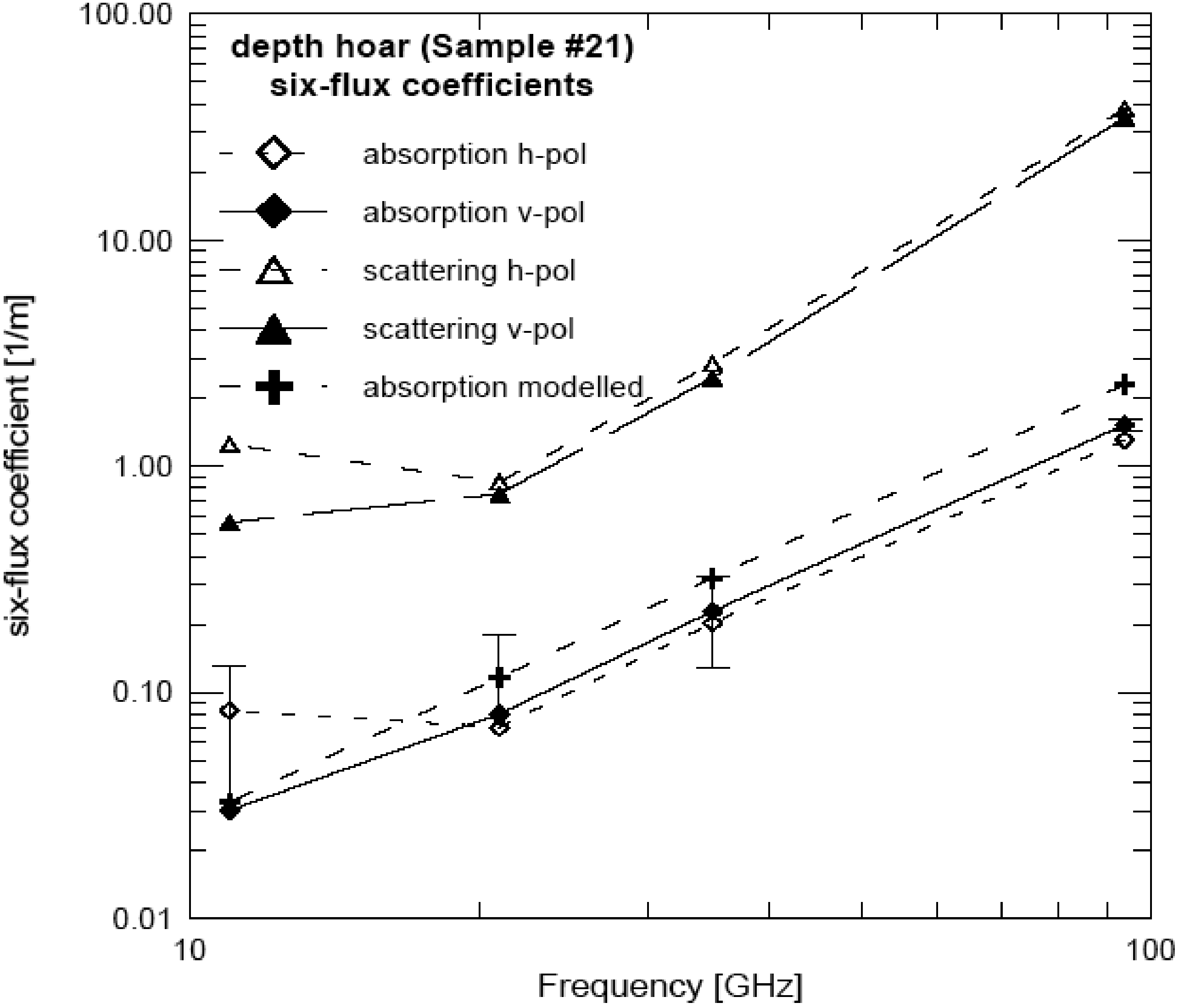






Snow sections
3 cm x 3 cm

Resulting spectra of scattering and absorption coefficients, for coarse-grained sample, using a 6-flux radiative transfer model

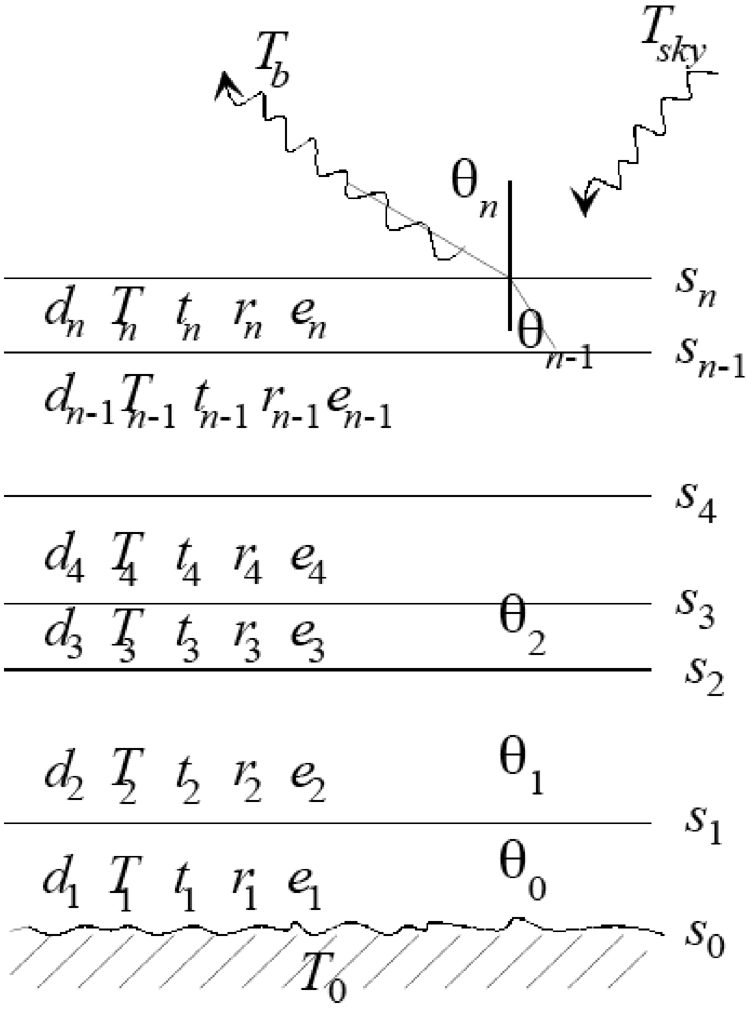


Result: Microwave Emission Model of Layered Snowpacks (MEMLS)

Wiesmann & Mätzler (1999)

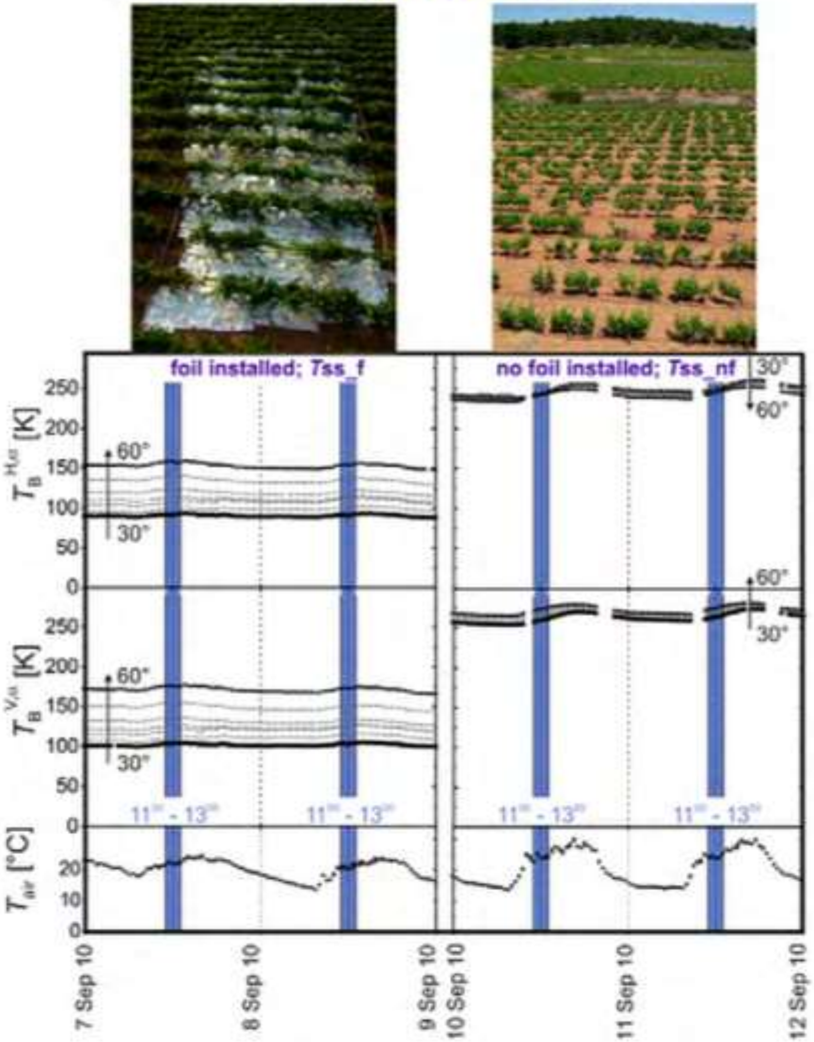
Input parameters:
Number of layers n
For each layer:
thickness,
temperature
density,
correlation length,
liquid water content,
salinity (Version 3).

Tested frequency range:
10 – 100 GHz
Extended range
down to 1 GHz

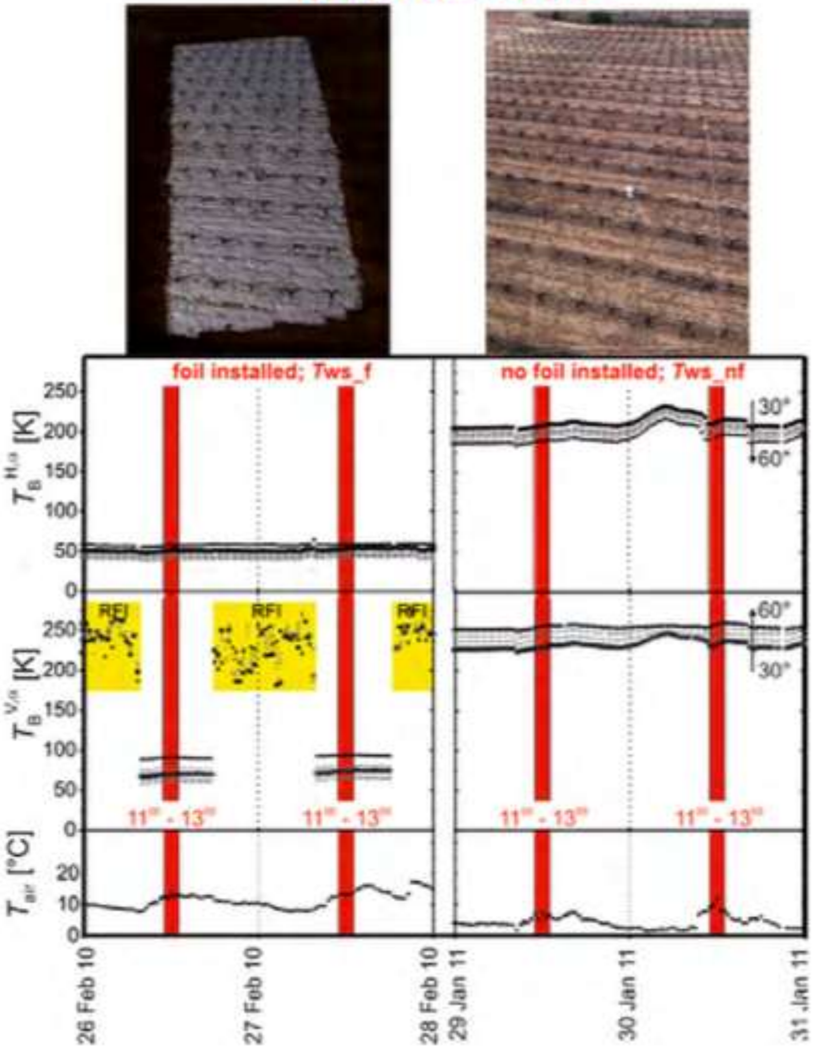


Analogy to Vine vegetation, Schwank et al (2011) at 1.4 GHz

summer state

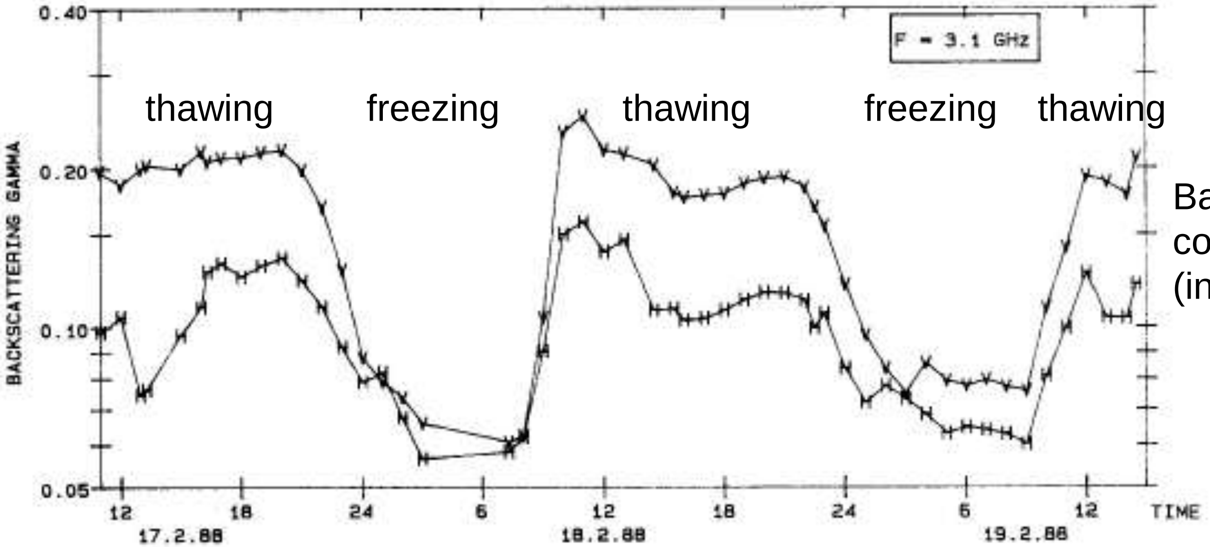


winter state



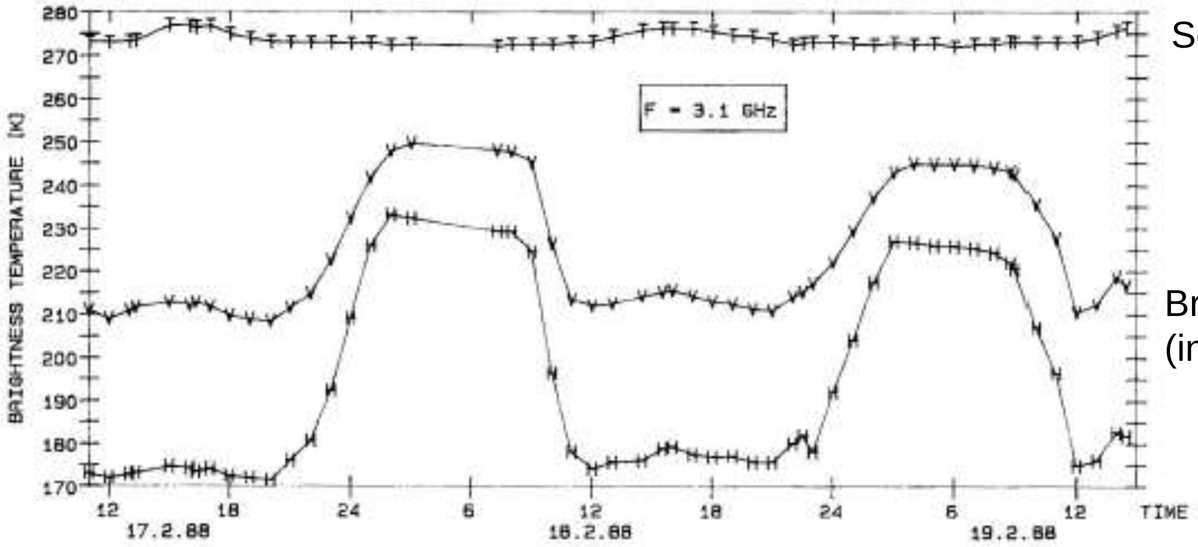
Another example: Active and passive signatures of a bare-soil field

Freeze-Thaw cycles



thawing freezing thawing freezing thawing

Backscattering coefficients
(inc angle 50 deg)



Soil temperature (0-5 cm)

Brightness temperatures
(inc angle 50 deg)

Wegmüller et al. (1989)

Outline

Applying Remote-Sensing Data

Direct inversion (signatures / forward models) to selected geophysical parameters

Data assimilation into a process model allowing all state variables being monitored

Applying Remote-Sensing Data

Direct inversion (signatures / forward models) to selected geophysical parameters:

- Snow mapping
- Forest mapping
- Open-water (flooding) mapping
- Frozen ground mapping
- Retrieval of surface temperature
- Retrieval of soil moisture
- Retrieval of vegetation-water content
- Retrieval of thermal inertia
- etc.

Main problem:
Retrievals are ill-posed if solutions are ambiguous.
Improvement by optimal estimation using a-priori information.

Applying Remote-Sensing Data

Data assimilation into a process model allowing
all state variables to be monitored:

This method is most useful because it combines spatial and temporal information with a physical process model in combination with a forward model.

Comparison is in observable space. Inversion not required.

Standard method in meteorology.

Problem: Unobservable processes may be missed.

But advantage of microwave radiation due to the penetrability of clouds and independence of daylight.

Enhancing Value by Advancing Methods

Potential generally increases with increasing number of observables (method, polarisation, resolution in wavelength, space & time)

Potential also increases with improved understanding of the involved process due to the improvement of the process models, decrease of the a-priori error – an evolutionary process

I think this is the most important motivation for TERENO activities.

Advancing Remote-Sensing Methods for Monitoring Geophysical Parameters

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