Remote sensing of snow and its applications

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Outline

- Some numbers on snow : why is it important to study snow ?
- Satellites and instruments
- Principles of optical and microwave remote sensing for snow applications
- Physics and electromagnetic modeling of snow for RS applications
- Remote sensing snow products and techniques
- Limiting factors
- The NASA Cold Land Processes Experiment (CLPX) and the NASA Cold Land Processes Pathfinder (CLPP)

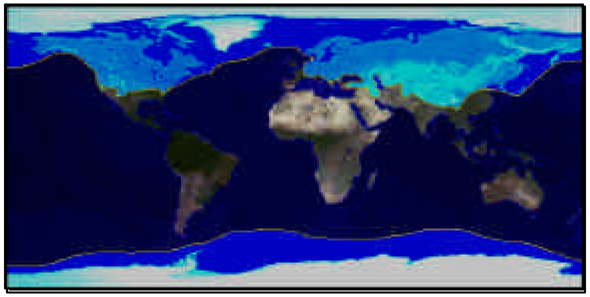
Why are Cold Lands important?

- On average, over 60% of the northern hemisphere and surface has snow cover in midwinter
- Over 30% of Earth's tota   and surface has seasona snow, and about 10% is permanent y covered by snow and ice
- Seasona y and permanent y frozen soi s occur over ~ 35% of the Earth's and surface
- Permanent y frozen soi s (permafrost) under ie ~ 26% of the Earth's and surface These areas are very dynamic; the spatia extents of frozen and thawed areas vary significant y on dai y, seasona and interannua time sca es

•Snow & freezing/thawing soi s dramatica y a ter the partitioning of water & energy at the and surface, a weak point of a   GCM & NWP and packages

•Seasona snowpacks represent an important water resource for hydropower, agricu ture, & industria & domestic consumption

•Long term snow & frozen ground trends are indicators of c imatic change



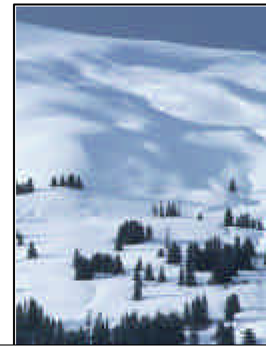
Q: What do we need to observe about cold lands processes?

A (snow): where & when, how much, & how wet

A (frozen ground):   frozen or thawed state

Winter Weather Forecasts

Snow on the ground has important affects on the atmosphere and weather patterns. Air temperature, visibility, cloud development, and precipitation are effected by the extent of snow cover, the amount of water in the snow, and the



Water Supply Forecasts

In the western U.S., most of the annual precipitation occurs as snowfall and as much as 85% of streamflow originates as snowmelt.

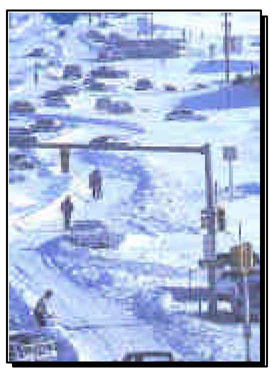
- **8 of the top 20 floods of the 20th century were related to snowmelt *(USGS).* Three caused over $1B each in damages (2002 dollars).**
- **On one day in Feb 2004, NWS model analyses indicated the volume of water stored in snow across the CONUS was 11% of the U.S. total annual renewable fresh water resources (258 km^3; 59% of estimated U.S. total annual freshwater withdrawal).**
- **In the western U.S between 80-90% of total annual streamflow originates as snow .**

“downstream” effects in both space and time. Better snow information will help climate models represent these effects.`

billions of dollars in damages.

Winter Transportation Advisories

Winter storms affect the nation’s transportation system each year, resulting in several billion dollars of snow removal costs annually.

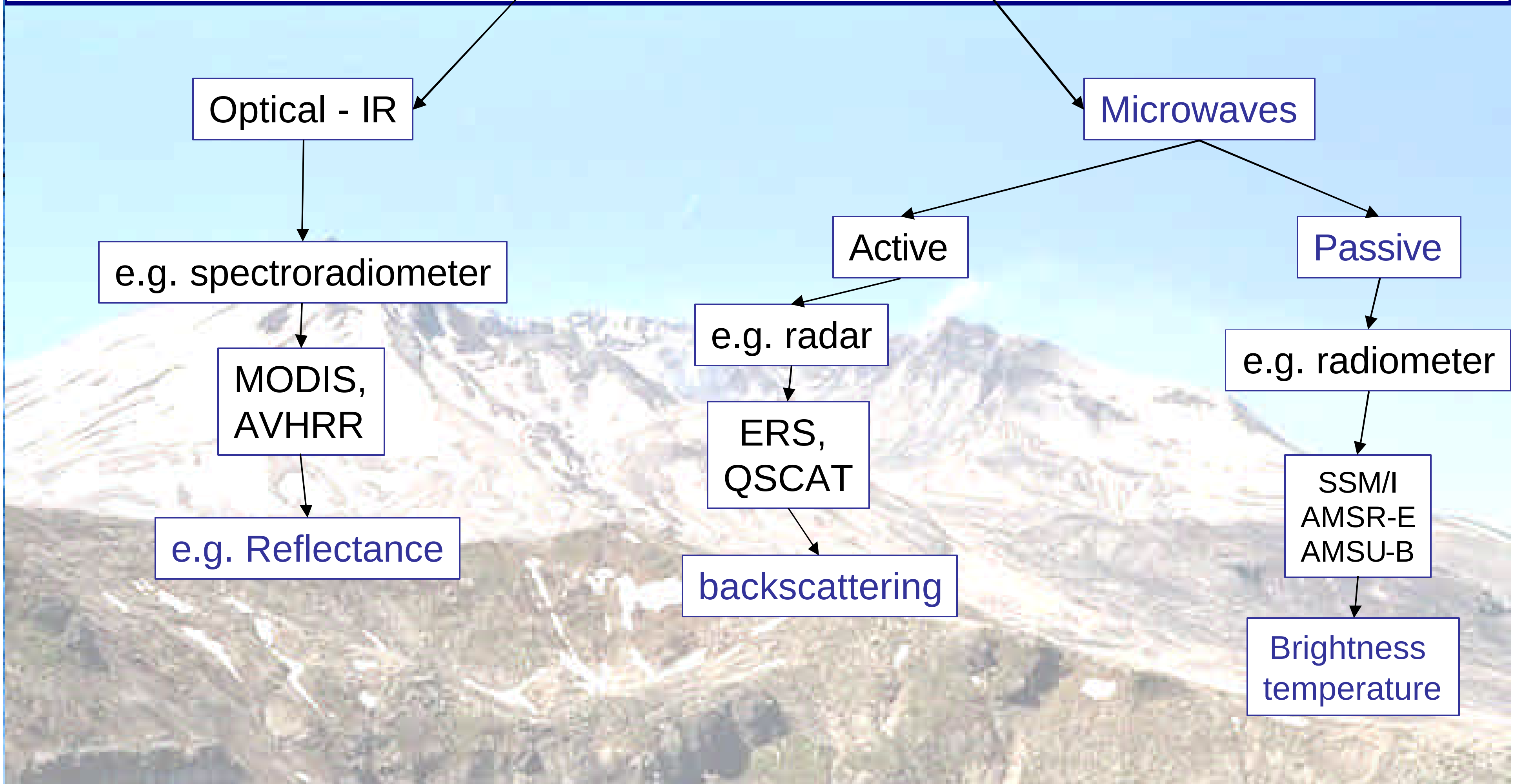


Drought and Wildfire Planning

The first indication of an impending severe drought and fire season is a dry winter. Low snowpacks result in dry soil and fuel moisture conditions going into the spring and summer.

•Instruments and satellites for RS of snow

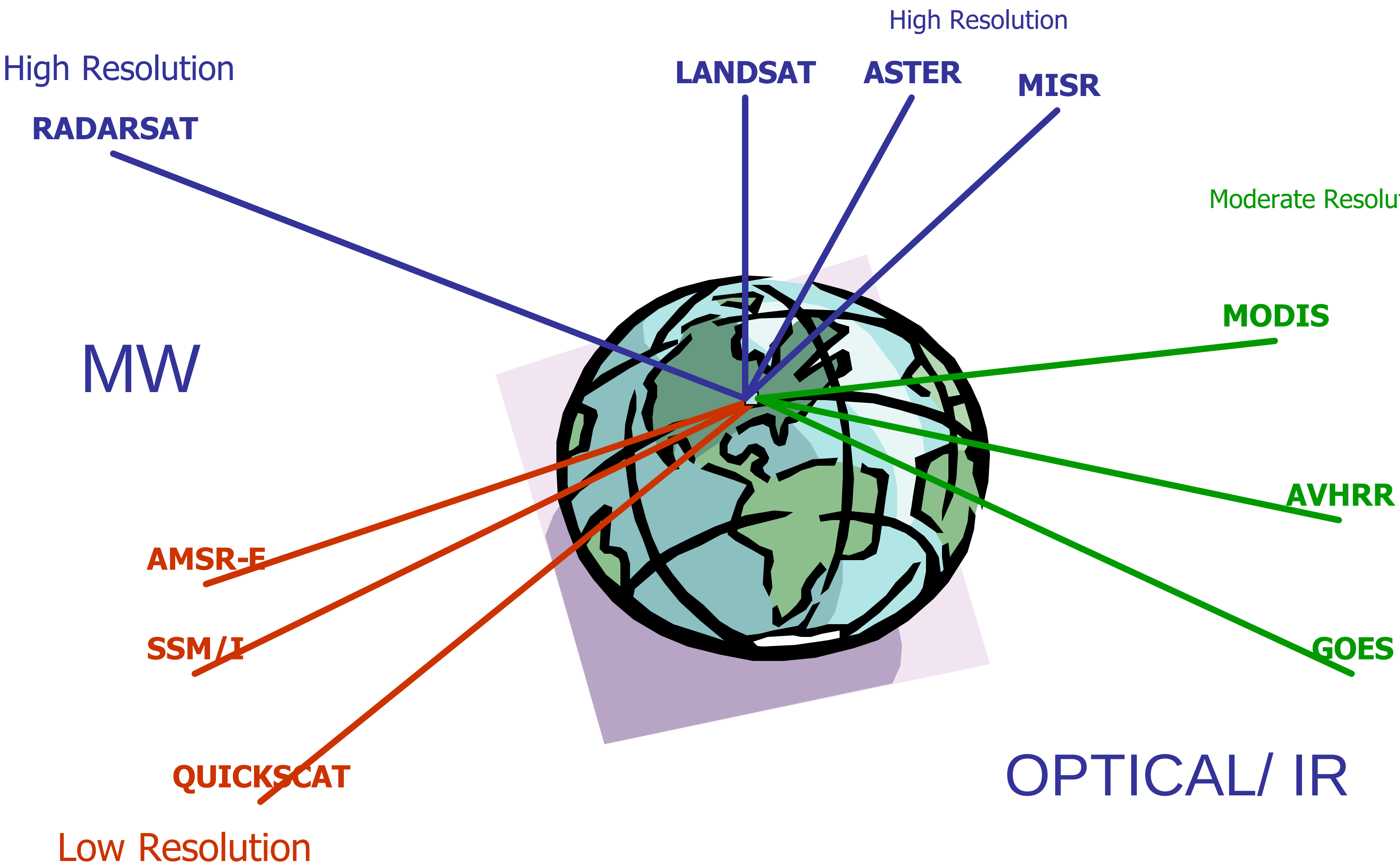
Remote sensing



-Requires solar illumination and Clouds-free areas (potential low temporal resolution)
- High spatial resolution (~250m – 1 Km)
-Low temporal resolution

-Does not require solar illumination and clouds-free areas (high temporal res.)
- Lower spatial resolution (~25 km)
-High temporal resolution

Microwave and optical satellites datasets



Advanced Microwave Scanning Radiometer for Earth (AMSR-E)

Aqua Platform Specifics

- Launch date: 4 May 2002
- Orbit inclination: 98.2 degrees
- Orbit Altitude: 705 km
- Local crossing time: 1.30 p.m. (ascending node)
- Mission life target: 6 years

AMSR-E Characteristics

- 1.6 m antenna
- 6.9, 10.7, 18.7, 23.8, 36.5 and 89.0 GHz V/H pol.
- Swath width 1445 km

Heritage/Follow-on

- SMMR
- SSM/I
- AMSR-E (Midori-II AMSR)
- Windsat
- CMIS (NPOESS)

MODIS specifics

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud/Aerosols Boundaries	1	620 - 670	21.8	128
	2	841 - 876	24.7	201
Land/Cloud/Aerosols Properties	3	459 - 479	35.3	243
	4	545 - 565	29.0	228
	5	1230 - 1250	5.4	74
	6	1628 - 1652	7.3	275
	7	2105 - 2155	1.0	110
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405 - 420	44.9	880
	9	438 - 448	41.9	838
	10	483 - 493	32.1	802
	11	526 - 536	27.9	754
	12	546 - 556	21.0	750
	13	662 - 672	9.5	910
	14	673 - 683	8.7	1087
	15	743 - 753	10.2	586
	16	862 - 877	6.2	516
Atmospheric Water Vapor	17	890 - 920	10.0	167
	18	931 - 941	3.6	57
	19	915 - 965	15.0	250

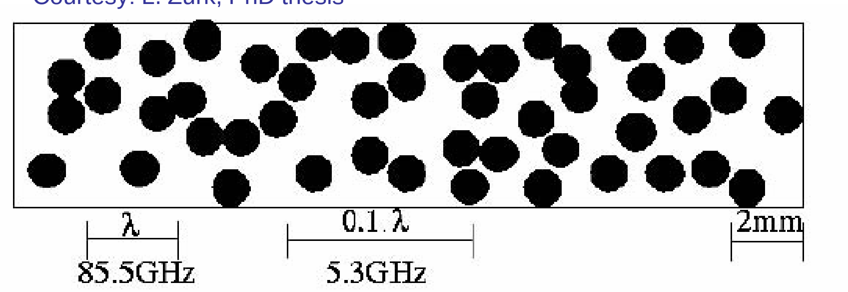
Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required NE[delta]T(K)[4]
Surface/Cloud Temperature	20	3.660 - 3.840	0.45(300K)	0.05
	21	3.929 - 3.989	2.38(335K)	2.00
	22	3.929 - 3.989	0.67(300K)	0.07
	23	4.020 - 4.080	0.79(300K)	0.07
Atmospheric Temperature	24	4.433 - 4.498	0.17(250K)	0.25
	25	4.482 - 4.549	0.59(275K)	0.25
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6.00	150(SNR)
	27	6.535 - 6.895	1.16(240K)	0.25
	28	7.175 - 7.475	2.18(250K)	0.25
Cloud Properties	29	8.400 - 8.700	9.58(300K)	0.05
Ozone	30	9.580 - 9.880	3.69(250K)	0.25
Surface/Cloud Temperature	31	10.780 - 11.280	9.55(300K)	0.05
	32	11.770 - 12.270	8.94(300K)	0.05
Cloud Top Altitude	33	13.185 - 13.485	4.52(260K)	0.25

Orbit:	705 km, 10:30 a.m. descending node (Terra) or 1:30 p.m. ascending node (Aqua), sun-synchronous, near-polar, circular
Spatial Resolution:	250 m (bands 1-2) 500 m (bands 3-7) 1000 m (bands 8-36)
Design Life:	6 years

Physics of snow for RS applications

Snow is a dense medium ….

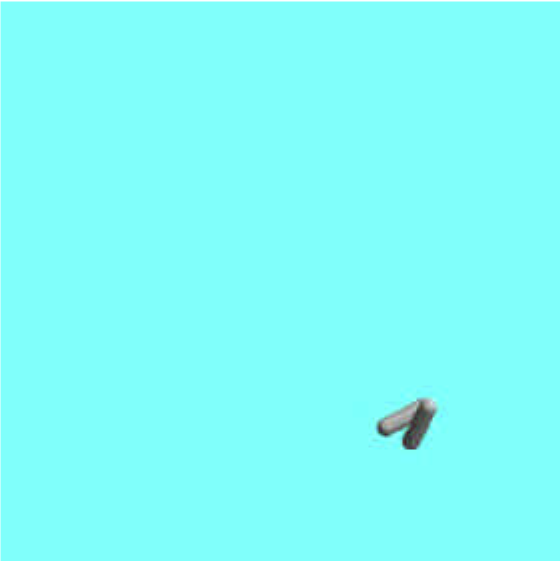
Courtesy: L. Zurk, PhD thesis



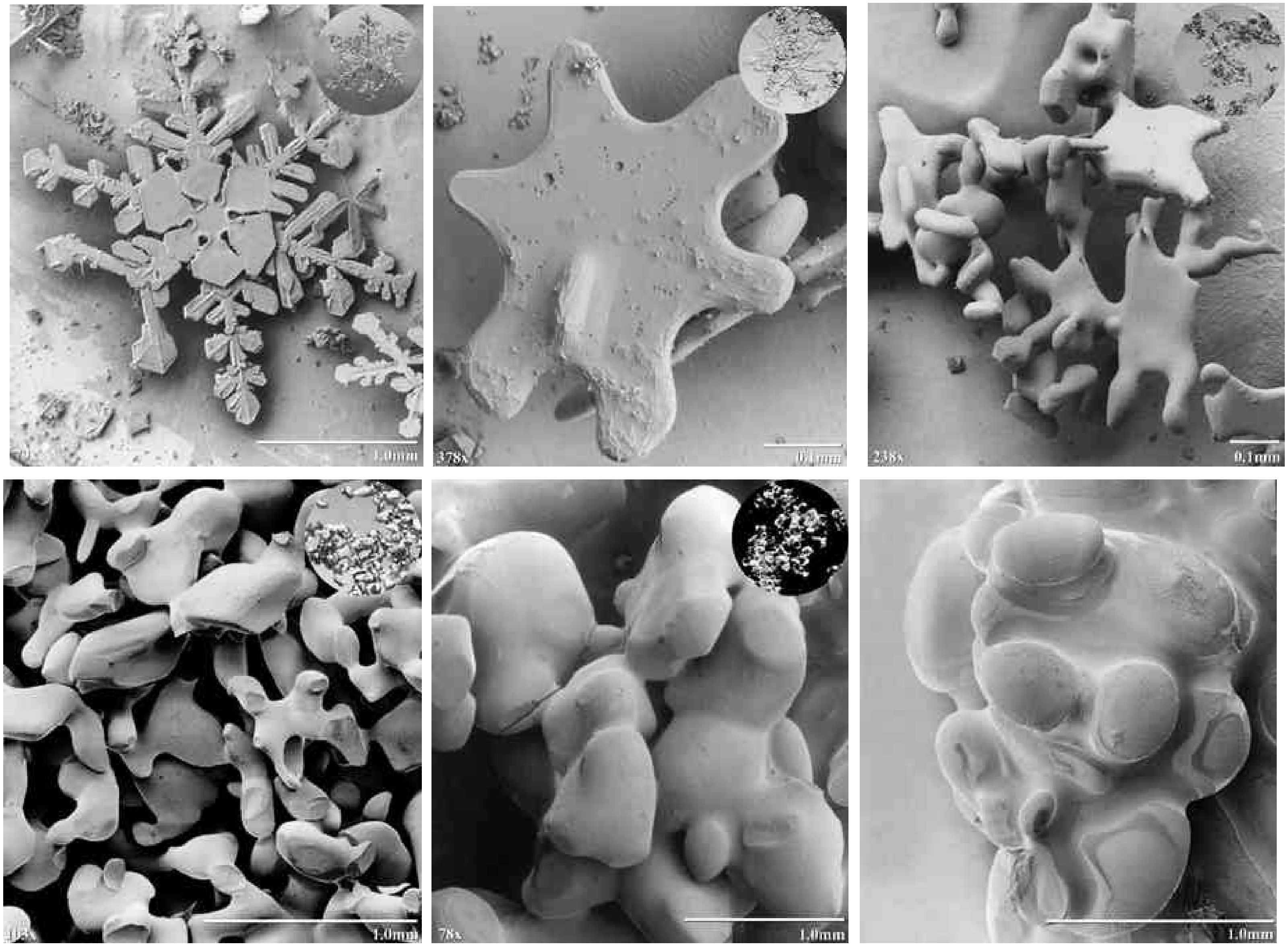
Particle size compared to different wavelengths at microwave frequencies

A ‘**dense**’ medium is a medium where the particles occupy a fractional volume between 10 % and 40 %

Snow particles are very close , in terms of wavelength and the interaction among particles cannot be neglected. Correlated scattering must be considered and the assumption of independent scattering is not valid



Courtesy: CRREL


1.0mm
378x
0.1mm
238x
0.1mm
1.0mm
78x
1.0mm
1.0mm

The Dense Medium Theory (DMRT)

The dense medium theory is used to describe the propagation and scattering in a dense medium.

(Dense medium = the particles occupy an appreciable fractional volume ✍ bigger than 0.1)

DMRT takes the following into account:

1) scattering of correlated scatterers
2) the pair distribution function of scatterers position
3) the effective propagation constant of the medium

Effective propagation constant

$$K^2 \; ? \; K'^2 ? 2iK'K'' ? \; k^2 \; ? \; \frac{f(k_s^2 \; ? \; k^2)}{1 ? \frac{k_s^2 \; ? \; k^2}{3K_0^2}(1 ? \; f)} \; ? ? 1 ? \; i\frac{2}{9}\frac{K_0 a^3 (k_s^2 \; ? \; k^2)}{1 ? \frac{k_s^2 \; ? \; k^2}{3K_0^2}(1 ? \; f)}\frac{(1 ? \; f)^4}{(1 ? \; 2f)^2} \; ?$$

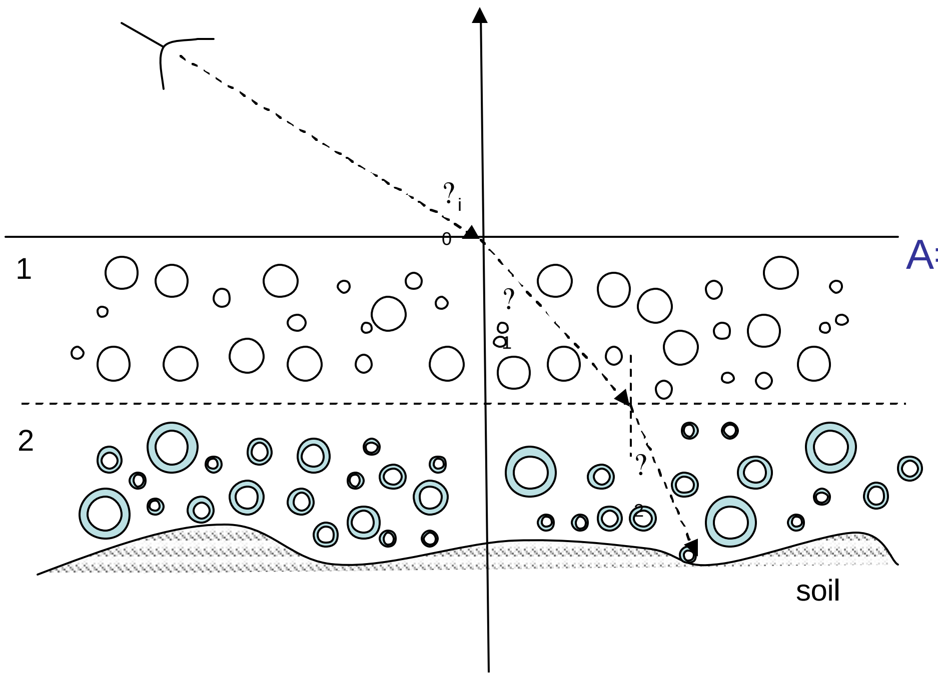
Extinction coefficient

k_e=2Im(K)

Albedo

$$? \quad ? \; \frac{2}{9}\frac{a^3 f}{k_e}\left|\frac{k_s^2 \; ? \; k^2}{1 ? \frac{k_s^2 \; ? \; k^2}{3K_0^2}(1 ? \; f)}\right|^2 \frac{(1 ? \; f)^4}{(1 ? \; 2f)^2}$$

$$? _i \frac{d}{dz} \begin{bmatrix} I_{vi}(z) \\ I_{hi}(z) \end{bmatrix}_? \; ? \; ? k_{ei} \begin{bmatrix} I_{vi}(z) \\ I_{hi}(z) \end{bmatrix} \; ? \; \sum_{j ? ? N}^{N} a_j \begin{bmatrix} ?(v_i, v_j) & (v_i, h_j) \\ ?(h_i, v_j) & (h_i, h_j) \end{bmatrix} \begin{bmatrix} I_{vj}(z) \\ I_{hj}(z) \end{bmatrix} \; ? \; k_a C T_1 \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$



The equation system can be expressed by:

(A-l)I=0

A=matrix coefficients, l=diagonal matrix (eigen-values), I=Stokes vector

The solution of the system is a linear combination of the eigen-vectors E corresponding to the eigen-values so that eigen-vectors are a normalized base of the Ndimensional space of the solutions of I

I=xE

The Helsinki University of Technology model (HUT)

$$T_b(d^?,?) ? T_b(0^?,?)e^{?(k_e ? qk_s)d\cos^{?1}(?)} ? \frac{k_a T_{snow}}{k_e ? qk_s}(1 ? e^{?(k_e ? qk_s)d\cos^{?1}(?)})$$

- q = 0.96 (empirical)

describes the fraction of intensity scattered in the direction ?

- $k_e = 0.0018\ freq^{2.8}\,(D)^{2}$

With D ranging between 0.2 and 1.6 mm

?’= (1+1.58?$_{ds}$????? ?????$_{ds}$?

?’’= PVS model

- $k_s = k_e - k_{abs}$

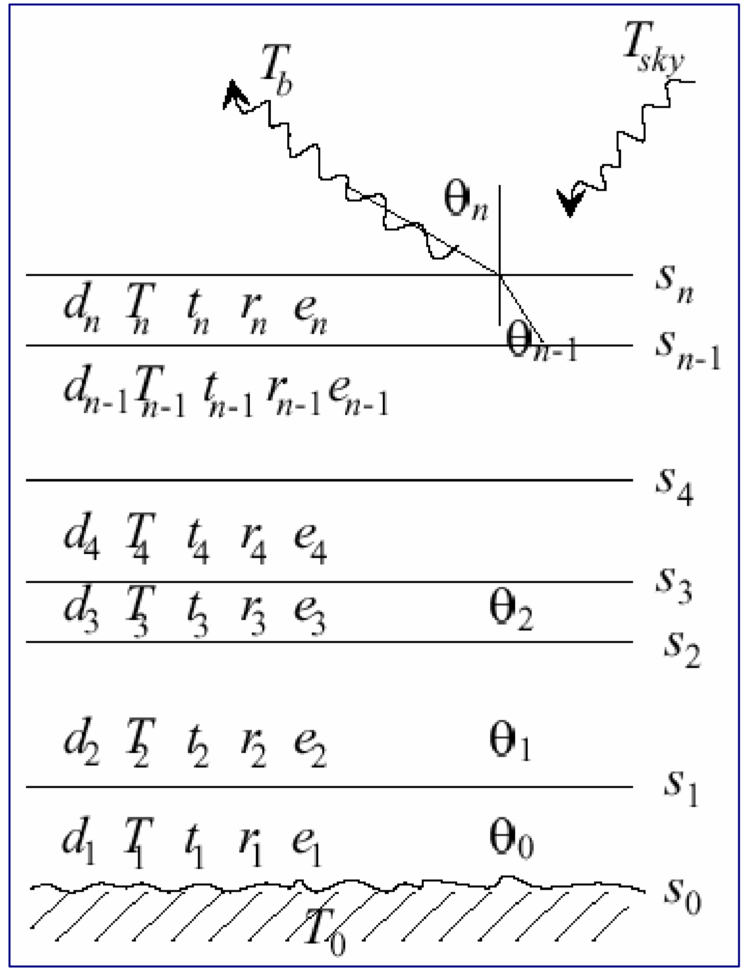
Pulliainen et al. , HUT snow emission model and its applicability to snow water equivalent retrieval, IEEE Trans. On Geosci. Remote Sensing, 37, May 1999, 1378 1390

- A new formula for k_e has been recently proposed by Roy et al. (2004) valid for 1.3 < D < 3.5 mm but the original one is here considered

$$k_e ? ?(f^4 D^6)^?$$

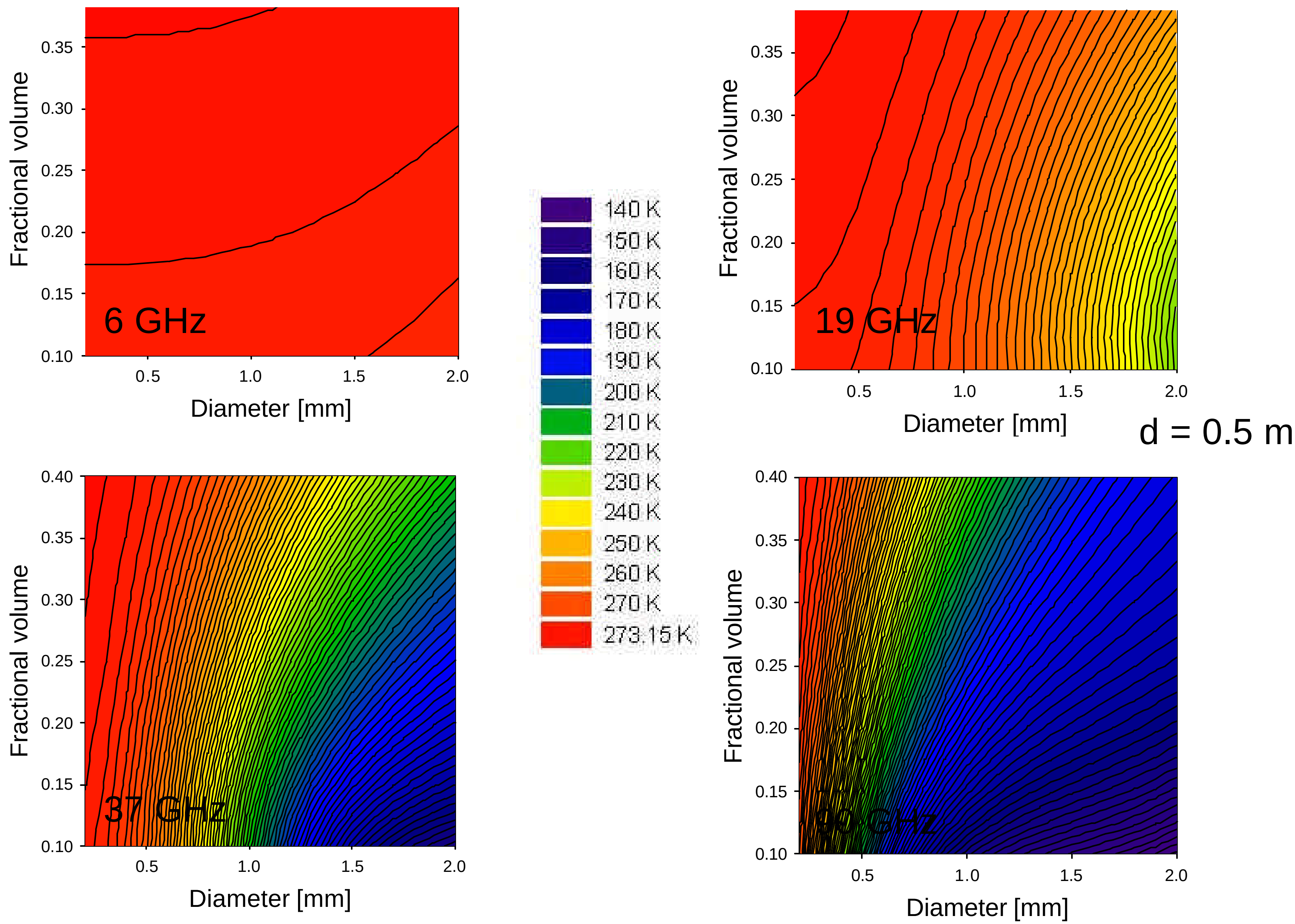
The Microwave Emission Model of Layered Snowpacks

- Frequency range, 5 to 100 GHz.
- It uses six-flux theory (multiple scattering and absorption, including radiation trapping)
- Reflection and a combination of coherent and incoherent superpositions of reflections between layer interfaces.
- The scattering coefficient is determined empirically from measured snow samples
- The number of layers is only limited by computer time and memory.
- Correlation lengths

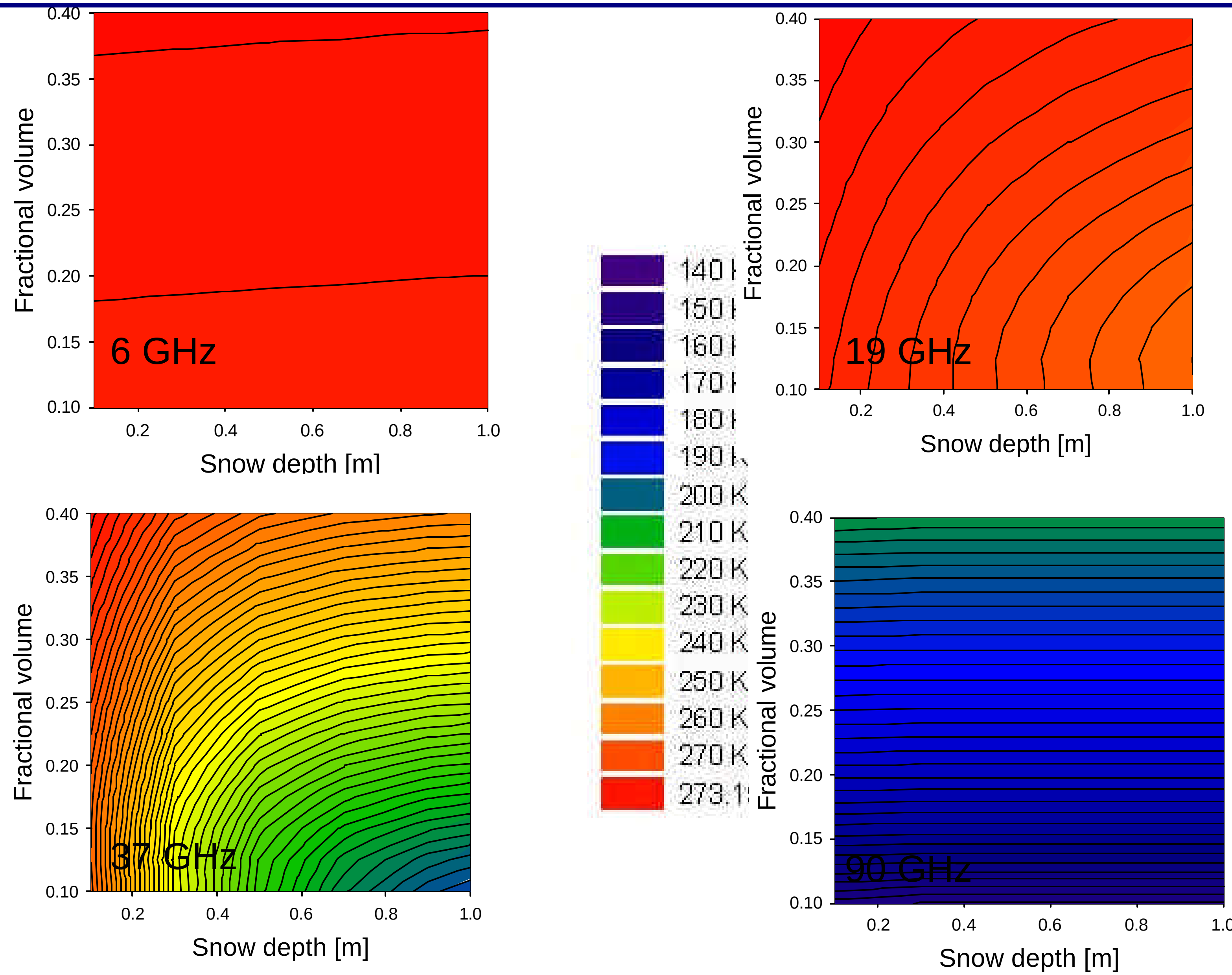


Andreas Wiesmann and Christian Mätzler, Microwave Emission Model of Layered Snowpacks, Remote Sensing of Environment, Volume 70, Issue 3, December 1999, Pages 307-316

Sensitivity of brightness temperatures to snow parameters



Sensitivity of brightness temperatures to snow parameters



Which parameters do we retrieve ?

Parameters influencing the electromagnetic response

Snow covered area, mean grain size (optical and MW)
- Roughness (optical and wet snow at MW)
-Wetness, Fractional volume, Snow depth, SWE, Temperature , Vertical structure
- **Precipitation, Land type, Footprint size**

Parameters retrieved (existing products)

Snow covered area (optical and MW)
- Albedo (mean grain size, optical),
- Wetness (MW)
- SWE (MW)

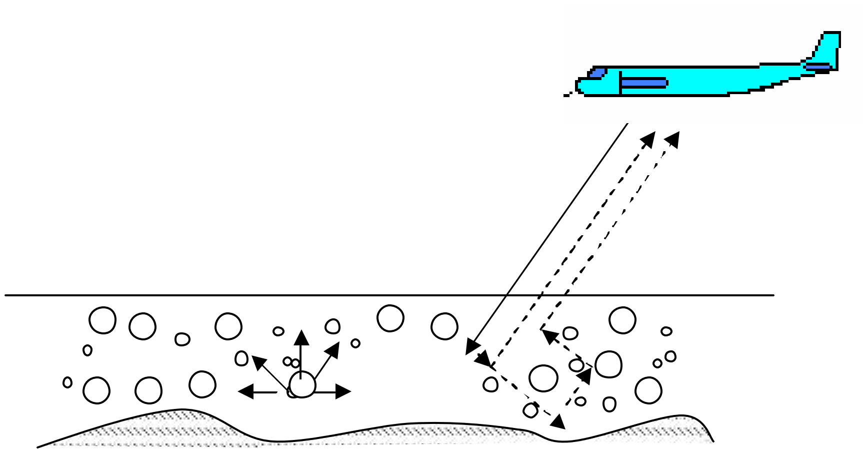
Working on ..

Grain size (optical and MW)
- Snow impurities (optical and IR)

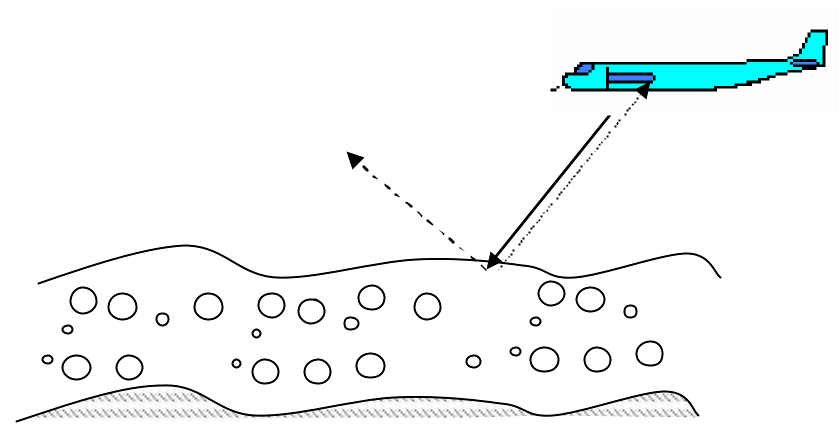

Remote Sensing products
and techniques


USGS 11427000 - North Fork American River at North Fork Dam, California, USA
© QT Luong / terragalleria.com

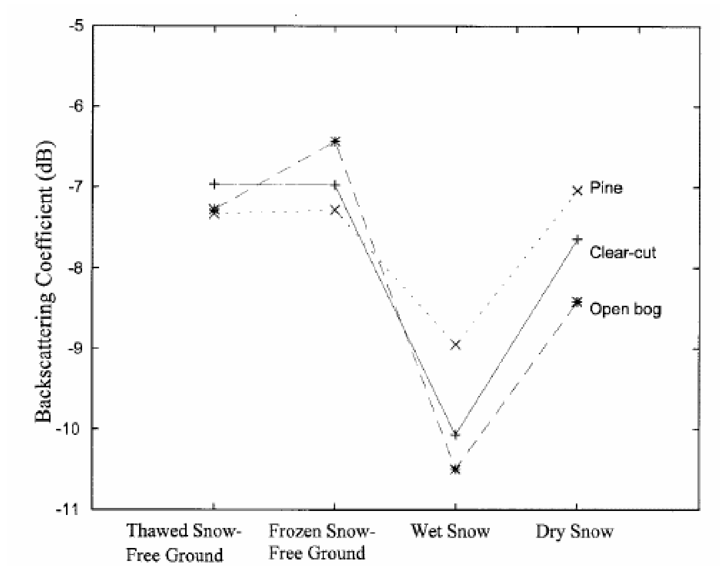
Wet snow detection (active case, MW)



Dry snow

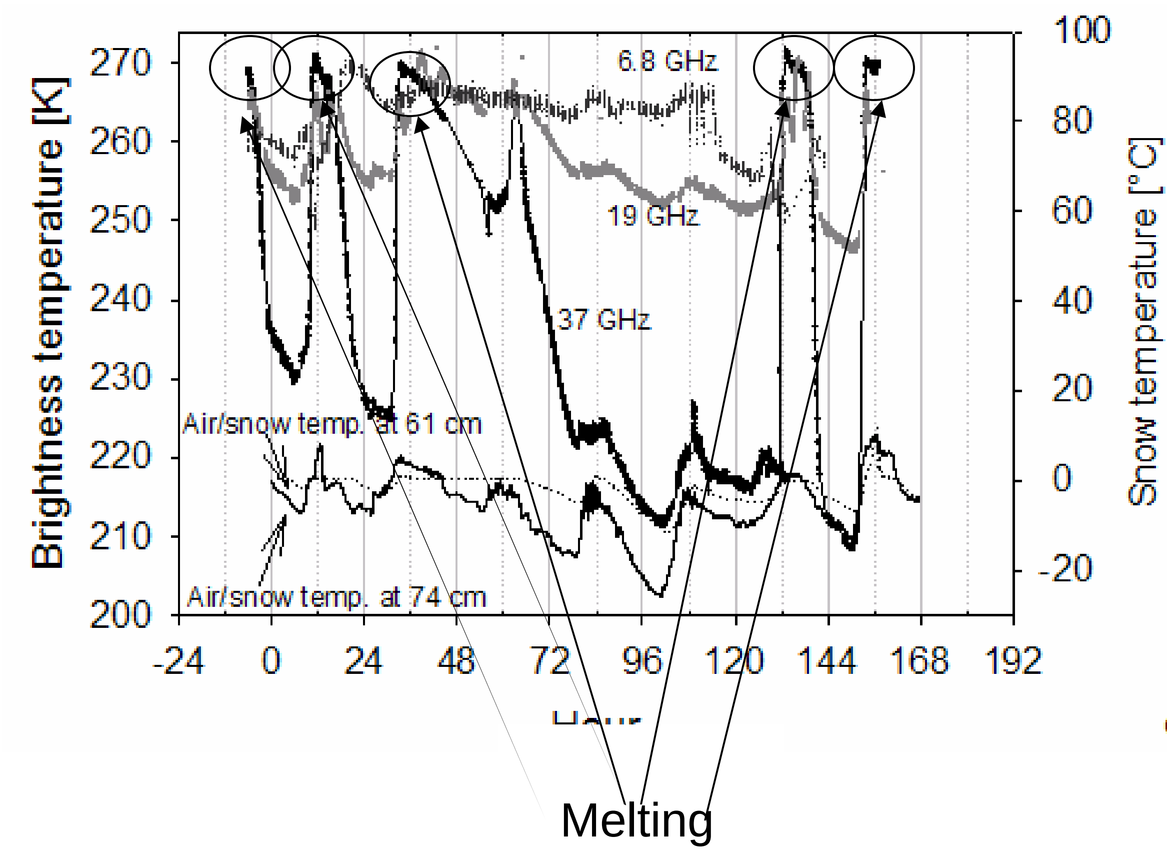


Wet snow



- Reduced penetration depth due to increased wetness and
- Reduced volumetric scattering effects
- Surface roughness becomes fundamental

Wet snow detection (passive case)



Data:
NASA Cold Land Processes Experiment

CLPX

Brightness temperature increases because of the appearance of liquid water which causes a strong increases in the imaginary part of snow permittivity increasing the absorption (emission).


Snow covered area

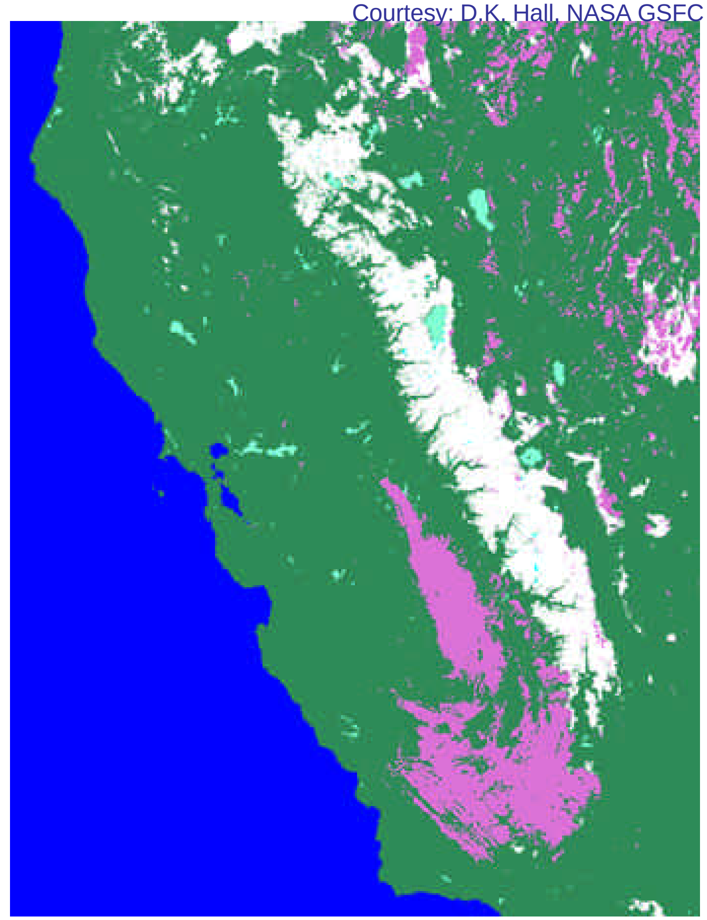
Example of Snow MODIS product

MOD10_L2: 500-m swath product of California and the western U.S., October 31, 2004

Courtesy: D.K. Hall, NASA GSFC

MODIS true-color image

(bands 1, 4, 3)



Snow map

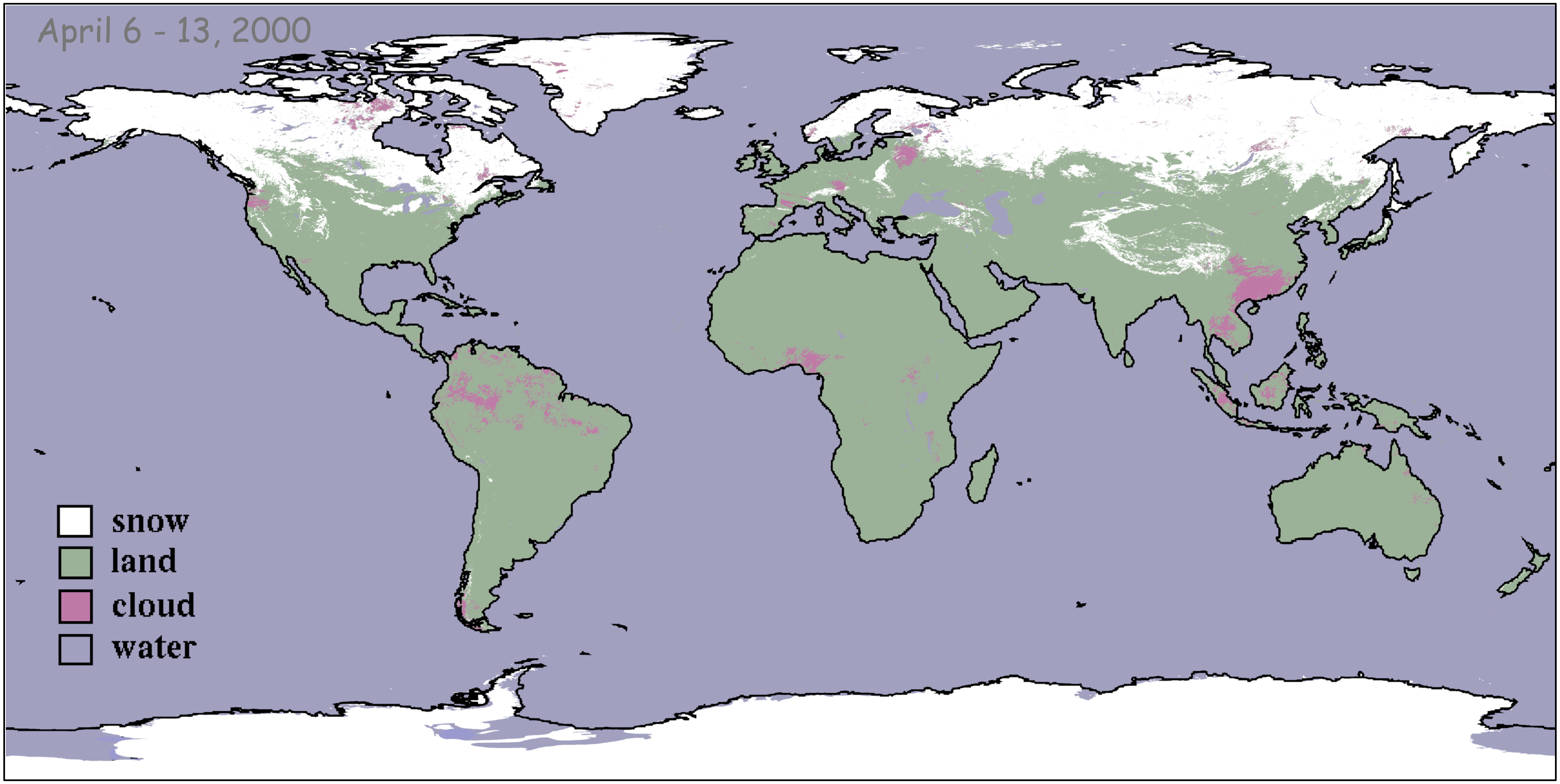
NDSI=B4-B6/(B4+B6)

MODIS product for climatological applications

8-Day Composite CMG snow map (5 km res.)

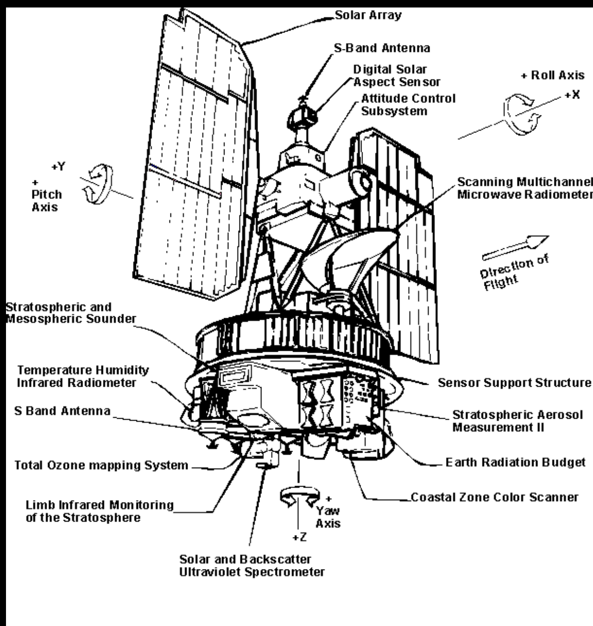
fractional snow cover from 1 - 100% not shown

Courtesy: D.K. Hall, NASA GSFC

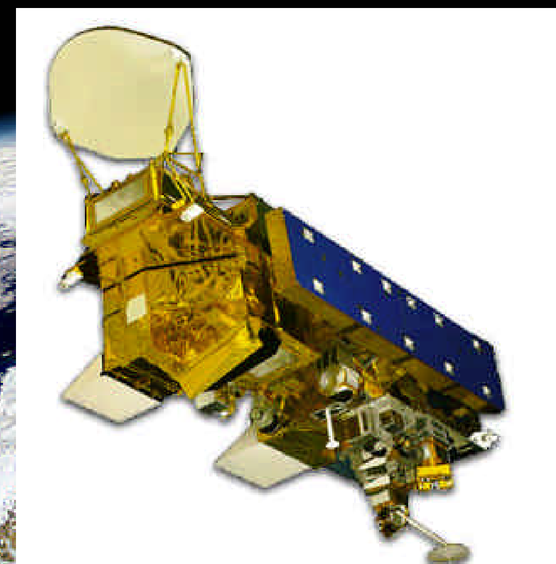


The 8-day composite CMG maps maximize snow cover and minimize cloud cover for the compositing period

26 Years of passive microwave measurements



Nimbus 7 Observatory

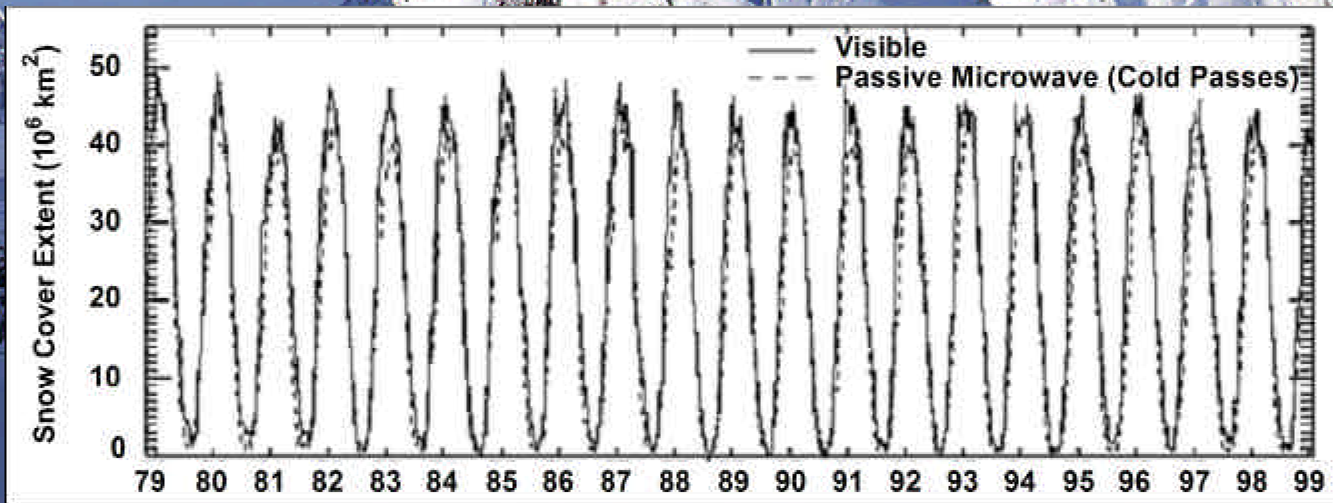


SMMR
1979-1987

SSM/I
1987-present

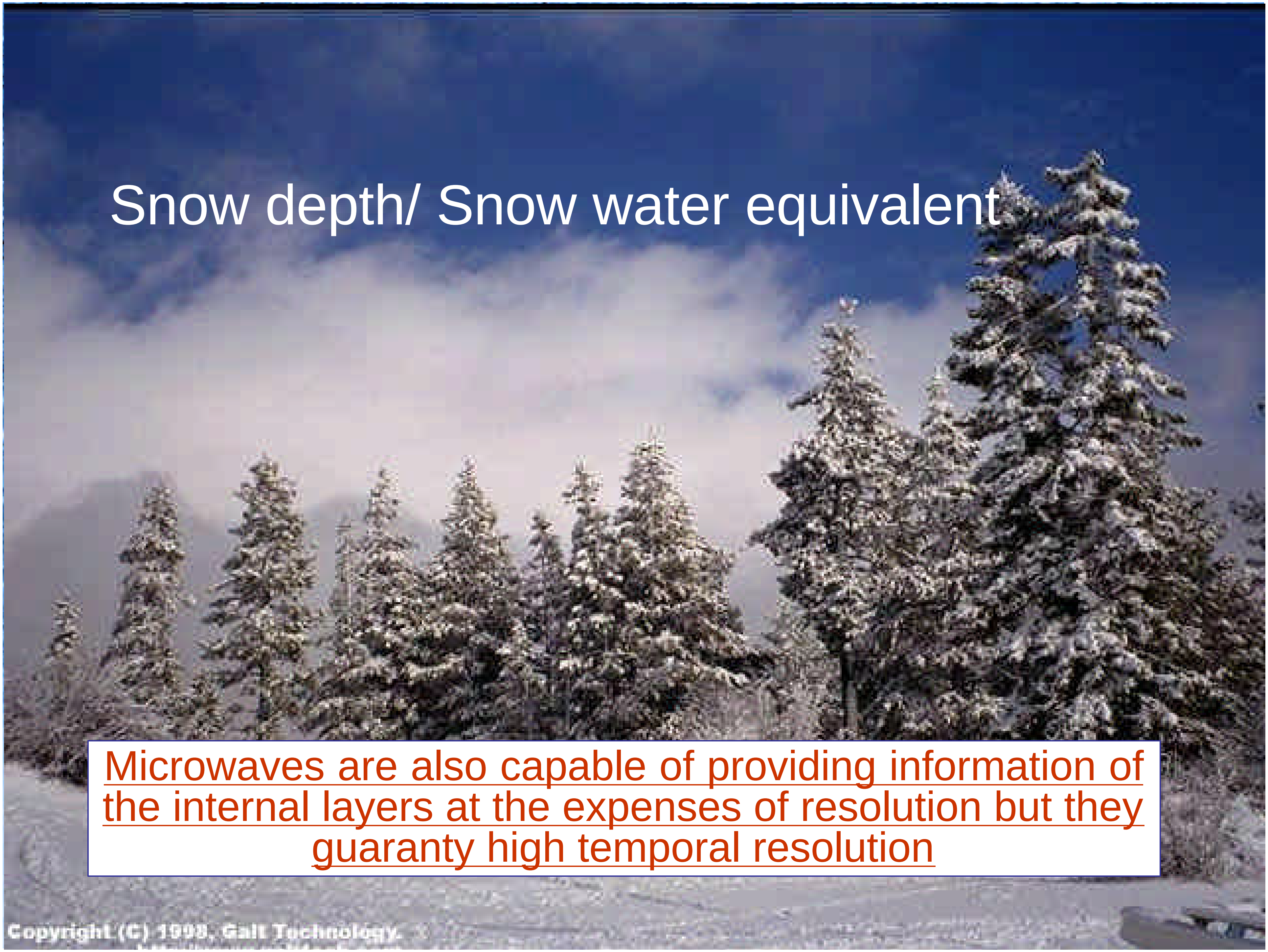
AMSR-E
2002-present

Comparison between optical and microwave data



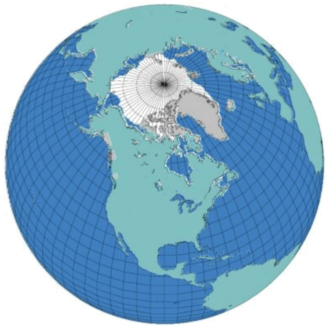
Remote sensing record doesn't indicate significant changes in northern hemisphere snow cover extent over past 25 years. Extended record (100 years) indicates long-term reduction in Eurasia, no change in North America.

Snow depth/ Snow water equivalent



Microwaves are also capable of providing information of the internal layers at the expenses of resolution but they guaranty high temporal resolution

Baseline algorithm for AMSR-E daily product



Brightness temperature at 18 and 36 GHz H-Polarization

$$SWE = \frac{4.8\,(Tb18H - Tb36H)}{2\,(1 - 0.2\,ff)} \quad [\text{ mm }]$$

Time & space static coefficient (based on grain size 0.3 mm radius and density 0.3 g cm^{-3})

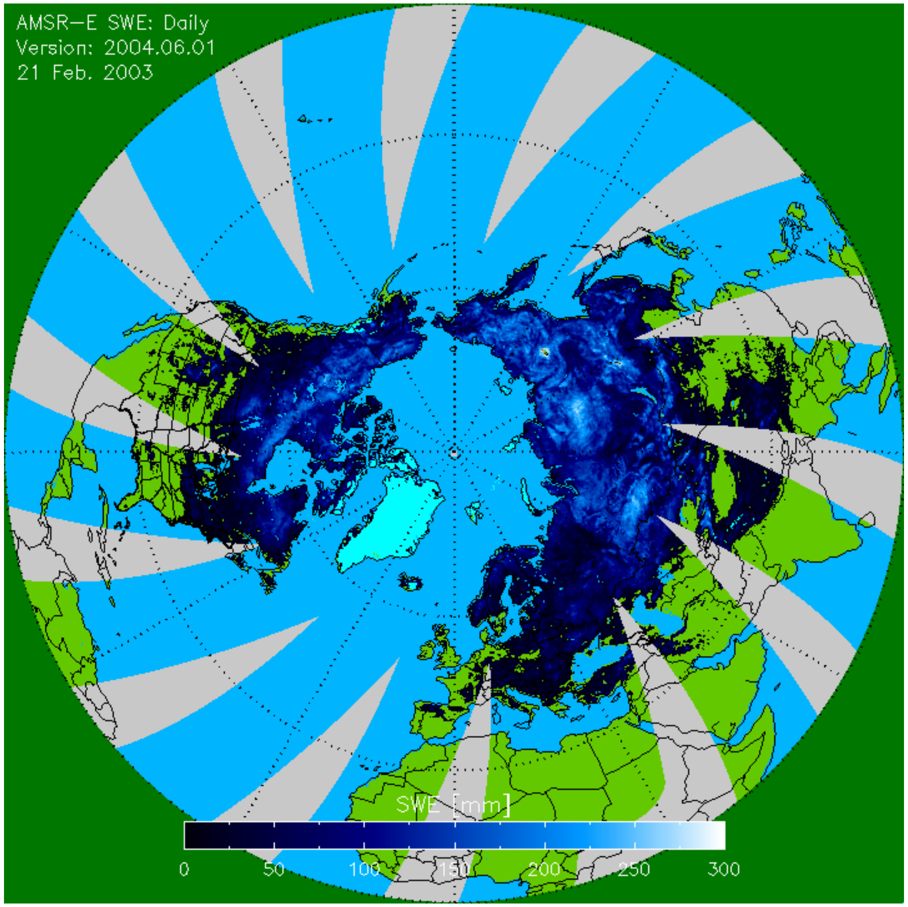
Scaling factor to enable SWE range of 1-480 mm

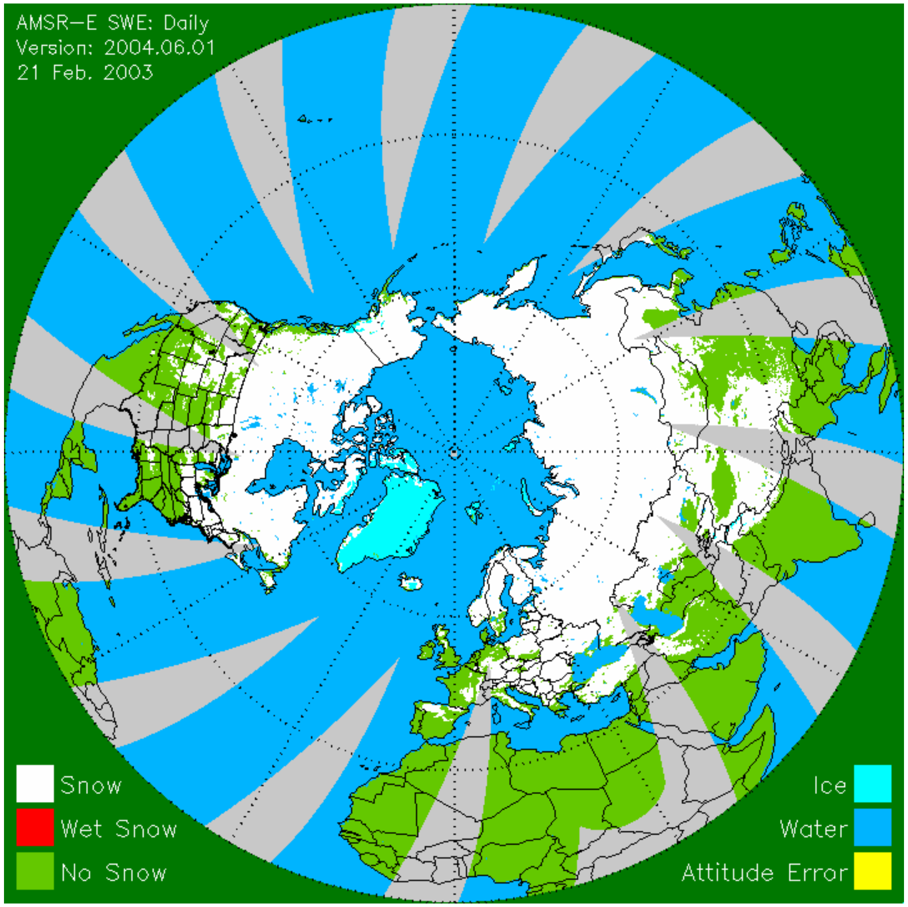
Forest fraction (derived from Robinson & Kukla, 1986)

Practical implementation:

- negligible liquid water content (choose early morning passes)
- Baseline retrievals of SWE parameterize grain size and volumetric fraction as constant.
- snow is greater than ~5-10 cm deep (early season snow often not observed)
- IFOV is 'reasonably' covered with snow
- Correction for forest fraction is required

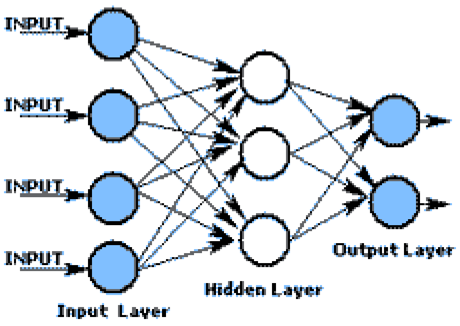
AMSR-E product: example

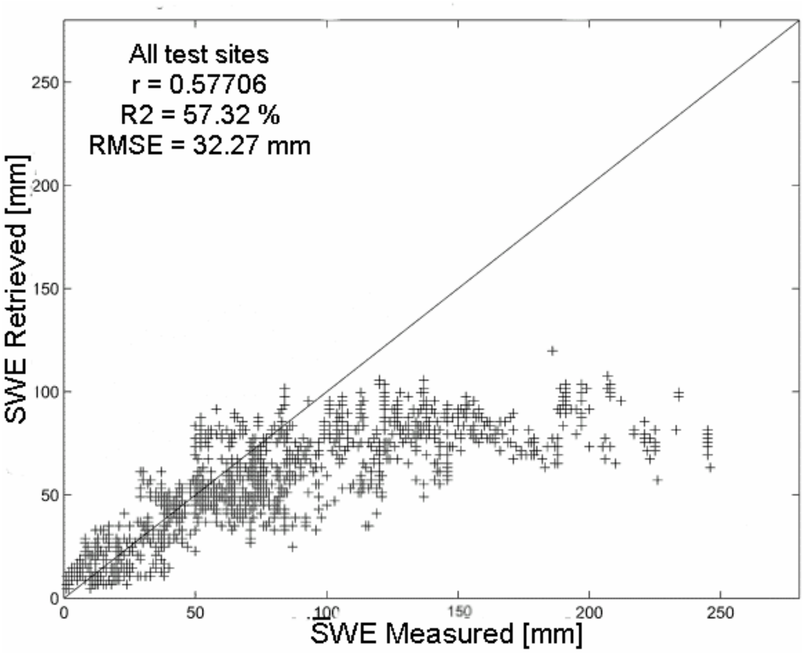




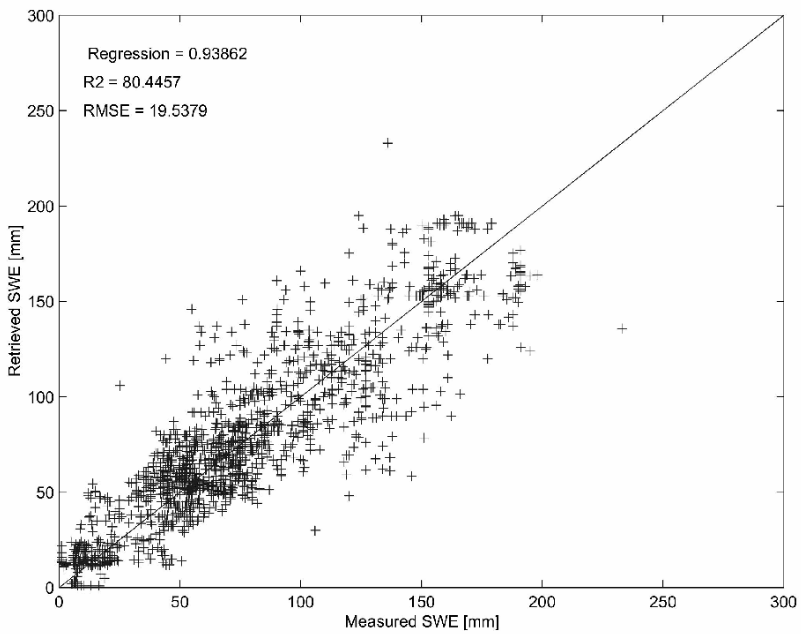
- Last product version ('baseline') delivered 1 June 2004 and will be implemented after the '89 GHz B-scan problem' has been fixed. Expect to back-process Nov/Oct/Sept 2004.
- Data availability: from June 2002 to present.
- Current product is 'conservative' in detection and adjustments (e.g. forest fraction).

Artificial Neural Networks





SPD algorithm



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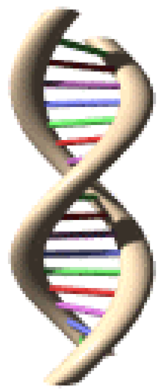
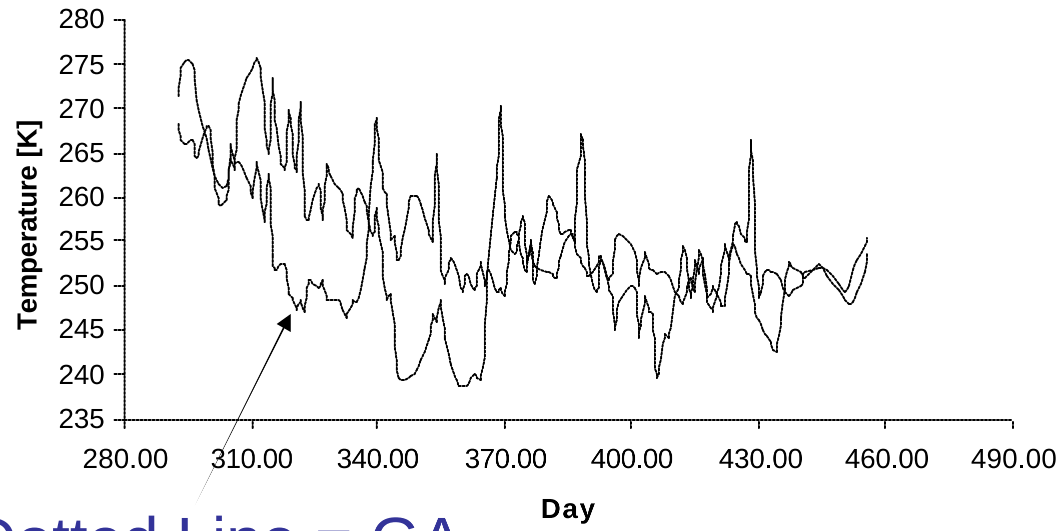
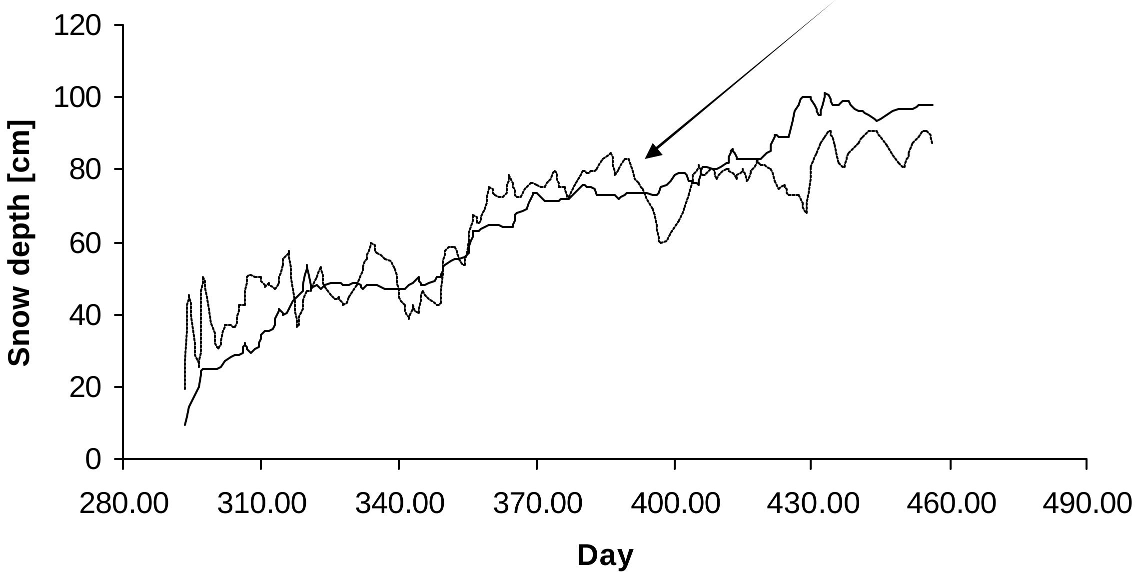
Genetic algorithms



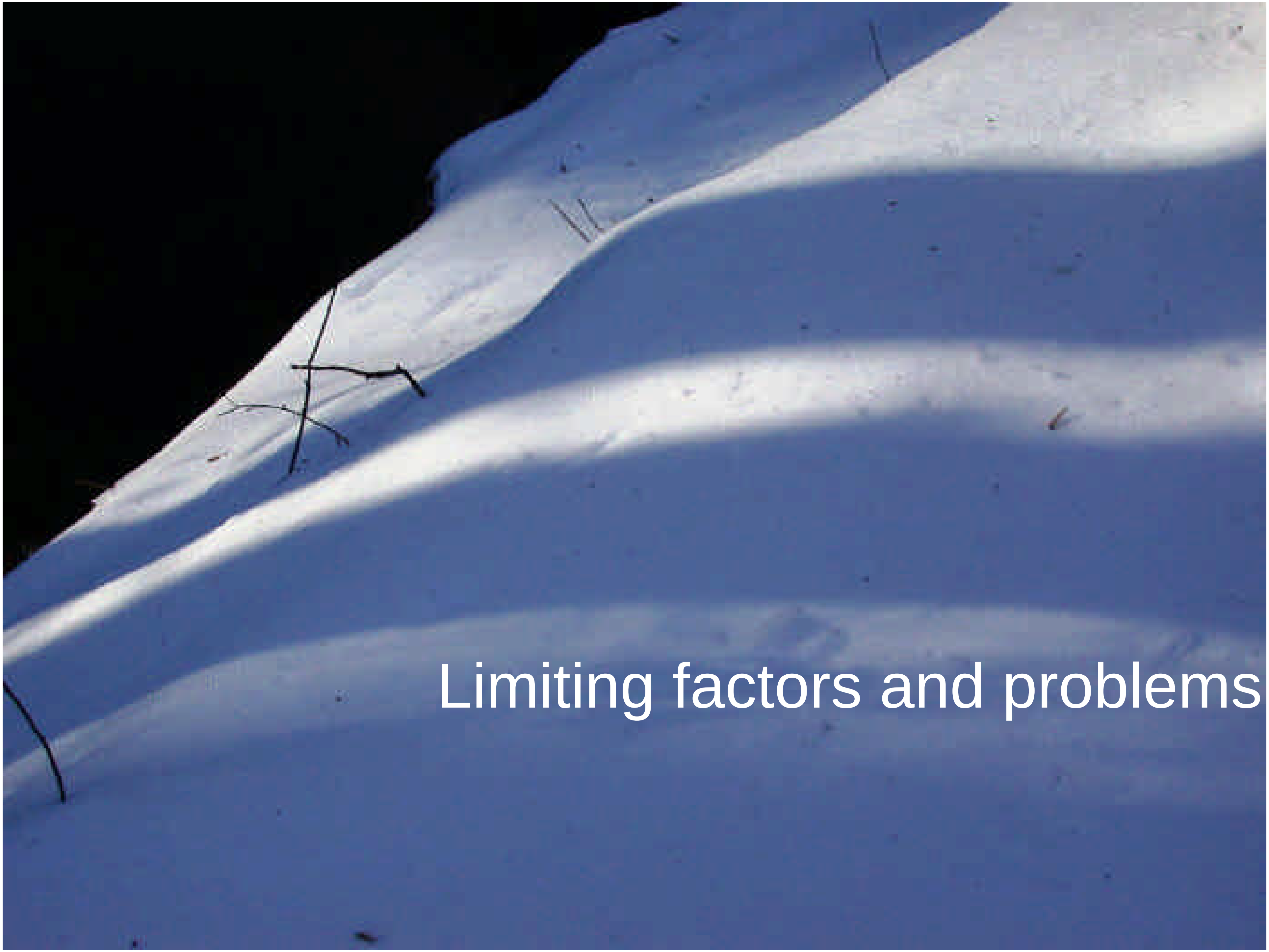


Dotted Line = GA



5 days average
2002 – 2003

Bajkit, Siberia


Limiting factors and problems

Factor affecting the estimation of snow properties

-Rapid temporal changes within few hours and complex spatial variability (both vertical and horizontal)

- Atmospheric effects are negligible at microwave frequencies up to 37 GHz but must be considered at higher frequencies

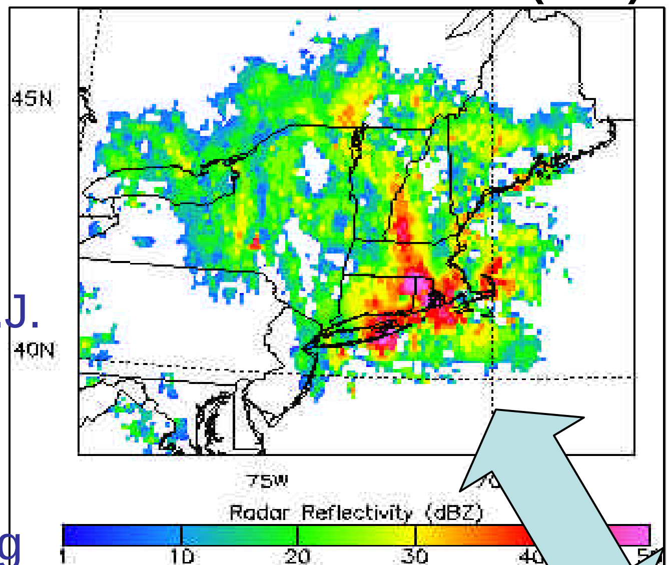
- Precipitation
- Forest coverage
- Footprint scale

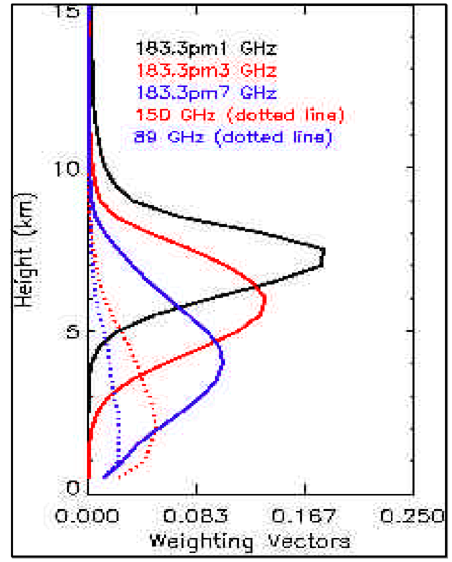
Precipitation

An improved algorithm for the retrieval of snowfall precipitation is under development at NASA (M.J. Kim)

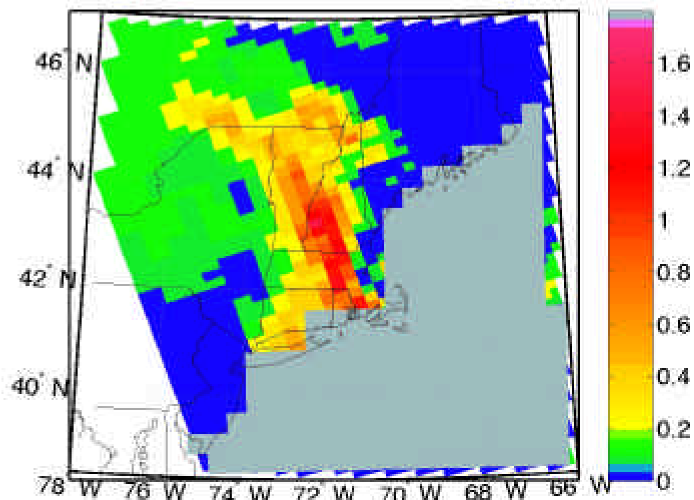
An approach combining techniques for precipitating snow and snow on ground is under study.

NOAA NWS NEXRAD (dBZ)





Retrieved snow water content (g/m^3) at 0.02 km

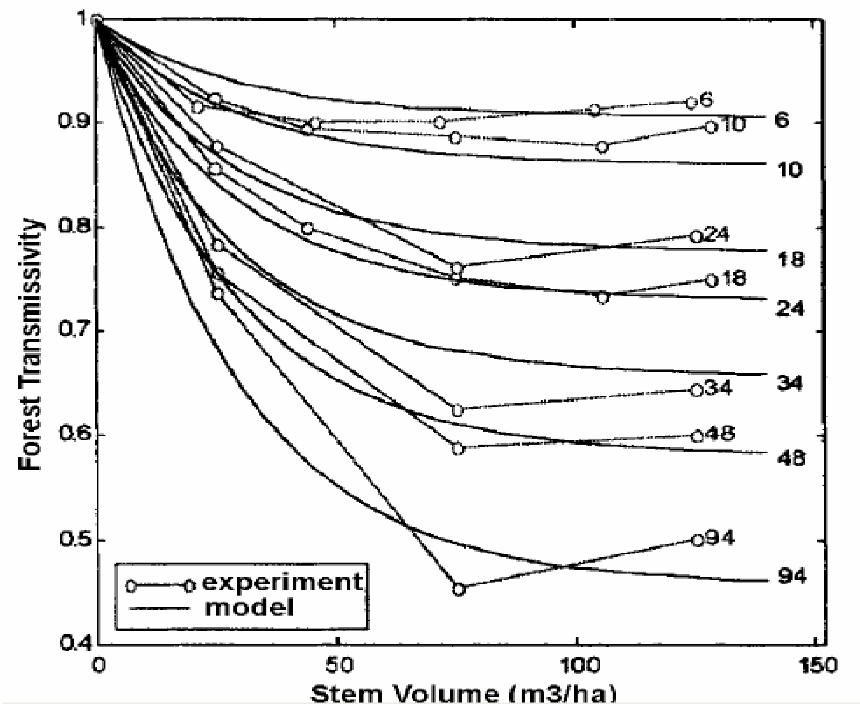


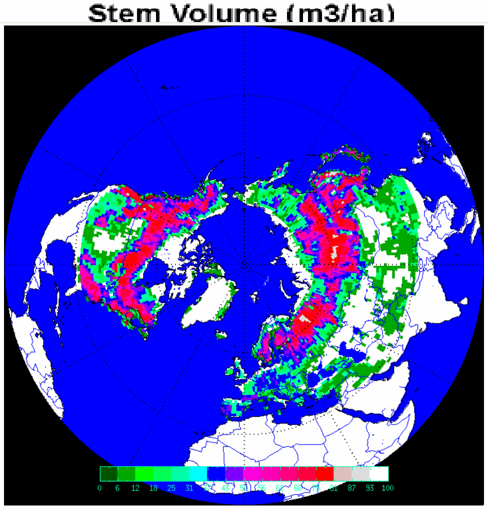
March 5-6, 2001 New England Blizzard

-Rain and wet snow strongly compromises the retrieval at both optical and microwave frequencies

- Dry snow precipitation weakly affects microwave techniques using 19 and 37 GHz, and affects those using the 89 GHz channel

Forest coverage





Dense forests mask the radiation coming from the underlying snowpack or the sun light with the effect of reducing the sensitivity to the retrieval of snow properties.

At 19 GHz the effect is smaller, however it is stronger at 37 GHz and, therefore, the retrieval becomes difficult.

Mixed pixels also can increase the underestimation of snow depth or snow water equivalent

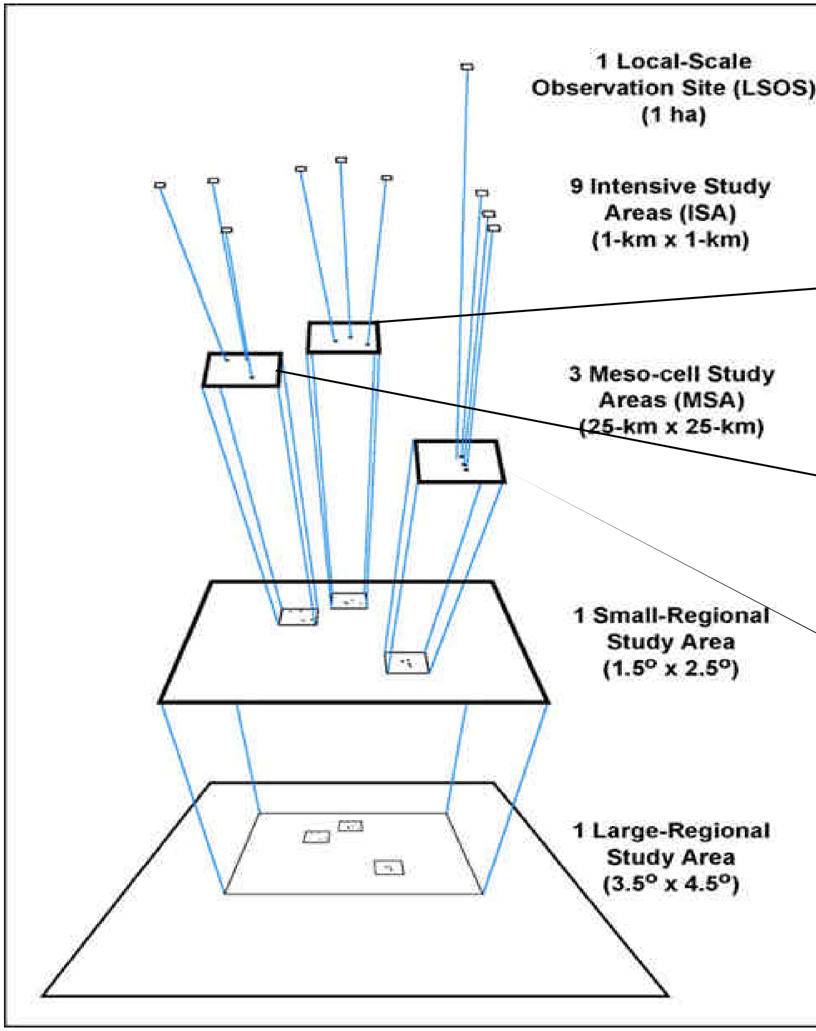
Scaling issues

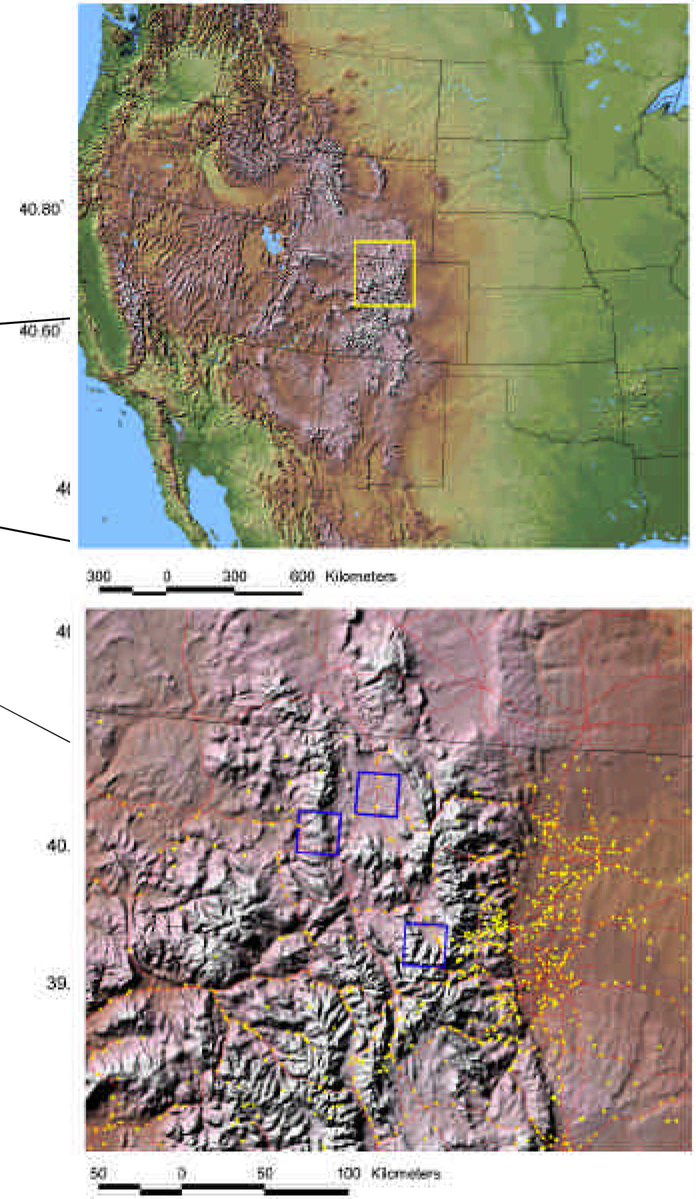
1. What do sensors actually see at different spatial scales for areas with different topography, vegetation cover, and snow types? i.e., how much variability can a sensor detect at different spatial scales?

2. What are the true snow properties over an area? i.e.,What is the true variability on the ground at different scales?

3. What happens when we try to retrieve SWE at different spatial scales?

Answering #1 and #2 requires a field experiment…





Multi-scale, multi-sensor approach to build comprehensive data set needed to meet NASA Earth Science Enterprise science objectives.

CLPX Cold Land Processes Field Experiment

NASA Land Surface Hydrology Program - Cold Land Processes Working Group

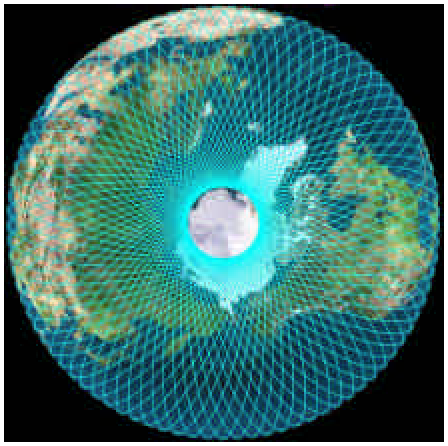








Baseline CLPP Summary



- Orbit/Launch/Spacecraft:
  - Sun-synchronous, 613 km, 5-6pm ascending
  - 6-day repeat
  - Ball 2000 or SA200HP
  - Peacekeeper L/V
- Antenna:
  - 1.95-m pushbroom reflector with 4 Ku-band feeds, 2 C-band feeds, 7 K-band feeds, and 13 Ka-band feeds
- Ku-/C-band SAR:
  - 100 m resolution (50/100 looks)
  - Swath: 35km (Ku-band), 40 km (C-band)
  - 100 W transmit power (peak)
  - Incidence angle: ~20 degrees
  - Polarization: VV, VH
- K/Ka-band radiometer:
  - 7/4 km resolution
  - Swath: 45km (K-band), 40 km (Ka-band)
  - Polarization: V, H