Snow (-related) Measurements

Snow (-related) variables and their measurement

(1) Snow properties, (2) energy balance components, (3) mass balance components

- Snow covered area (SCA)
- Snow water equivalent (SWE)*
- Depth
- Density
- Porosity
- Permeability*
- Hardness
- Grain size
- Grain shape
- Specific surface area (SSA)
- Liquid water content (LWC)*
- Temperature
- Cold content*
- Thermal conductivity
- Albedo* (broadband, spectral)

- Solid precipitation (both)
- Snow transport / drift
- Evaporation, sublimation* (both)
- Vapor transport (both)
- Melt, refreeze and percolation (both)
- Conductive heat flux*
- Sensible heat flux*
- Latent heat flux* (both)
- Radiative heat fluxes*
- SW transmission/absorption
- Surface roughness
- Stable water isotopes (O, H)
- Impurities (dust, soot, pollen…)
- Snow strength
- Snowpack stability
- Crack propagation

* derived/computed from other quantities

Measurement of snow variables

Manual vs. automated --- Low tech vs. High tech → Training, experience!

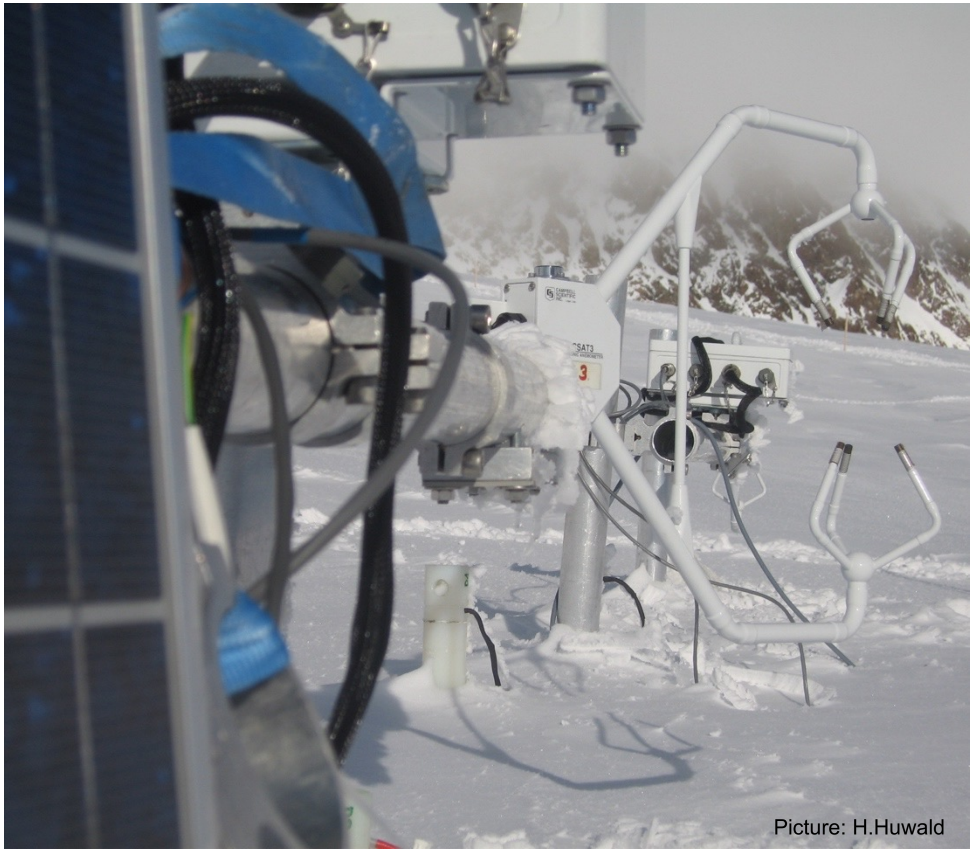
Manual snow sampling

Micro computer tomography

Picture: SLF

Outline:

- Precipitation measurements:
  - Gauges and errors
- SWE measurements
  - Gravimetric approach
  - Snow pillow
  - Airborne gamma radiation
  - SNOTEL sites
  - Snow courses
- Snow pit measurements
  - Depth
  - Density
  - Temperature
  - Hardness
  - Grain size and shape
  - Snowpack stratigraphy
- etc. …



Picture: H.Huwald

- Energy balance components
- Mass balance components

- New techniques and system approaches
- Remote sensing (terrestrial, air, space)

Snow gauges and catch efficiency

Alter (US)

Nipher (CAN)

Hellman (GER)

Tretyakov (Russia)

Seasonal precipitation totals (Nov 91 - Mar 92)

Gauge type	Total Precip.	% of total
Tretyakov in bushes	367	100
DFIR (Tret)	339	92
DFIR (Nipher)	342	93
Nipher shielded	314	86
Tretyakov	258	70
8” Alter shielded	273	75
8” Alter unshielded	208	57

Average catch efficiencies for different gauges, in comparison to the DFIR (Gauge/DFIR) for snow: Catch Ratio (CR) vs. Wind speed (U_a) and Temp. (T)

$$CR_{NIPHER} = 100.0 - 0.44\ U_a^2 - 1.98\ U_a$$

$$CR_{Tretyakov} = 103.11 - 8.67\ U_a + 0.30\ T_{max}$$

$$CR_{NWS\ 8\text{-}Alter\ shielded} = \exp(4.606 - 0.036\ U_a^{1.75})$$

$$CR_{NWS\ 8\text{-}Alter\ unshld} = \exp(4.606 - 0.157\ U_a^{1.28})$$

B. E. Goodison, P. Y. T. Louie, D. Yang, 1998, WMO/TD – No.872.

Precipitation gauges

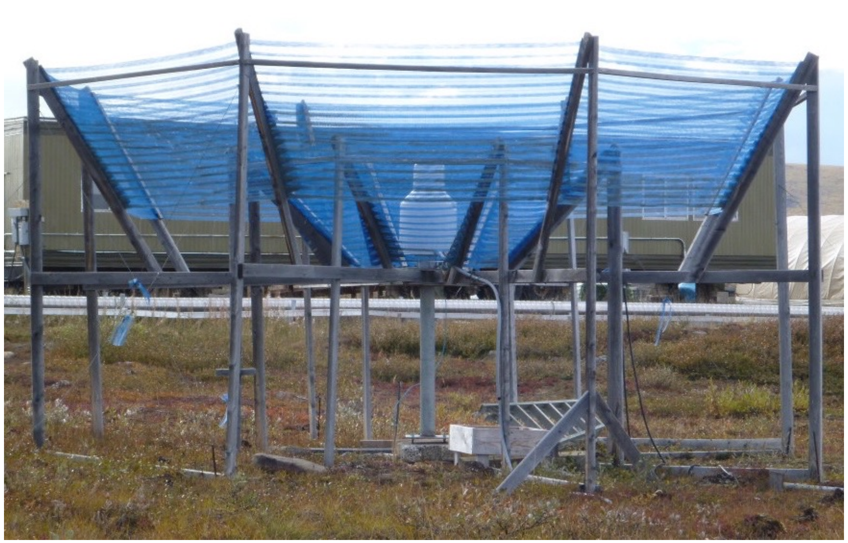
- Precipitation is a fundamental input for snow models, e.g. SNOWPACK
- “ground truth” precipitation (primary standard) is often not available
- a secondary standard often used is the Double Fence Inter-comparison Reference (DFIR)
  - octagonal vertical double fence shield (with manual Tretyakov gauge)

Main problem with solid precipitation measurements: wind → undercatch
Heating of instruments (power supply and artificial convection)

Double Fence Inter-comparison Reference (DFIR)

WMO Solid Precipitation InterComparison Experiment (SPICE)

DFIR Weissfluhjoch, Davos



DFIR Weissfluhjoch, Davos

Hot plate snow gauge

Precipitation rate proportional to changes in latent heat (melting and evaporation)

Hotplate kept at constant temperature → variation in supply current

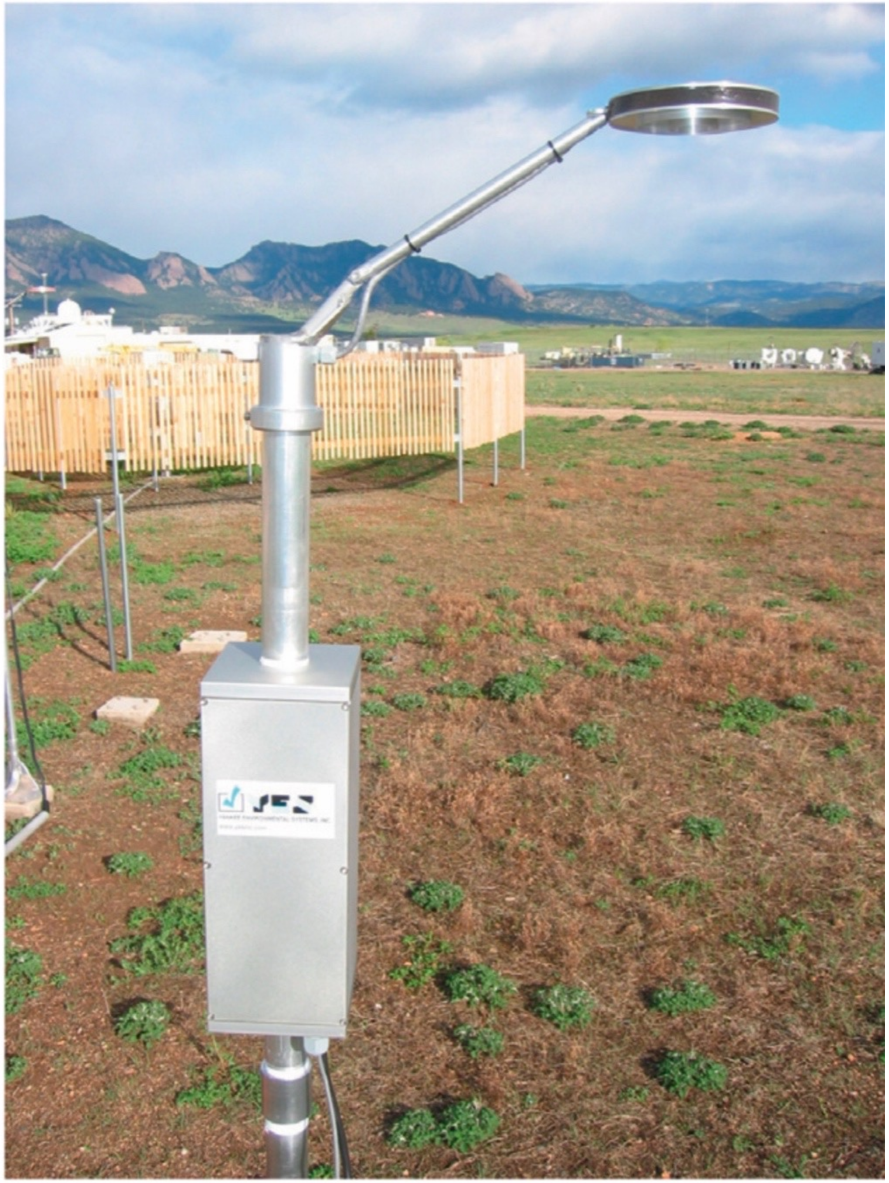
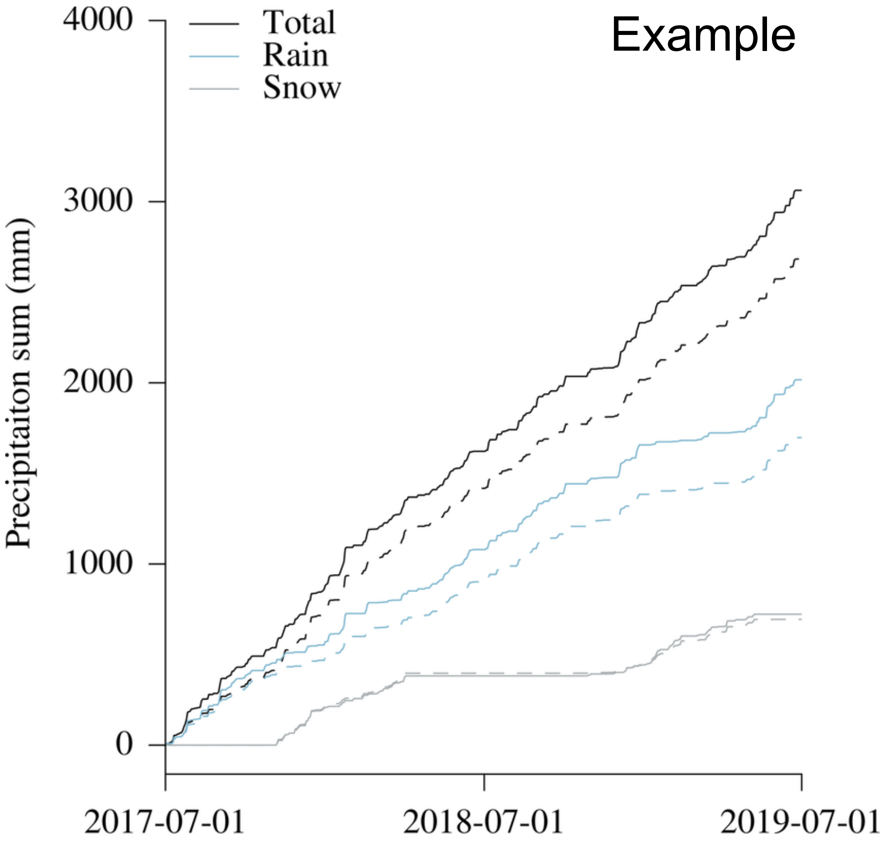


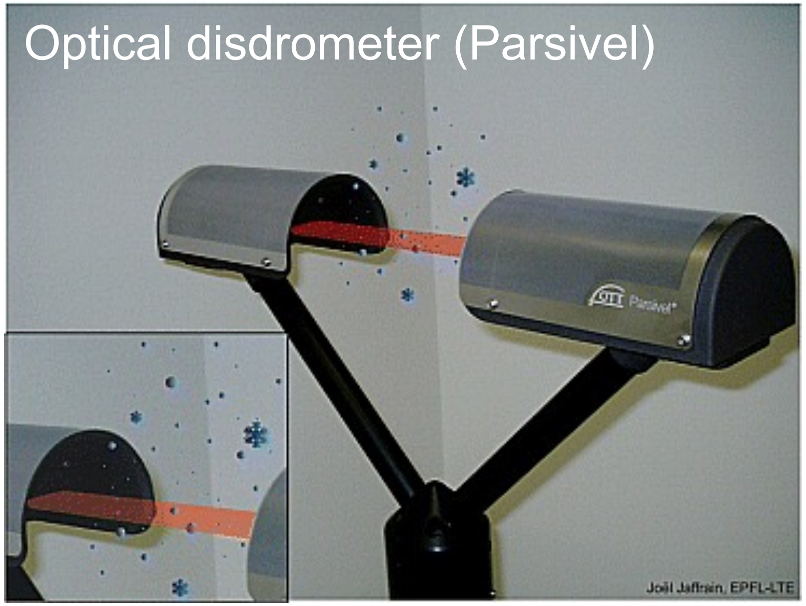
FIG. 2. Commercial version of the hotplate snow gauge from

Cumulative precipitation measurement



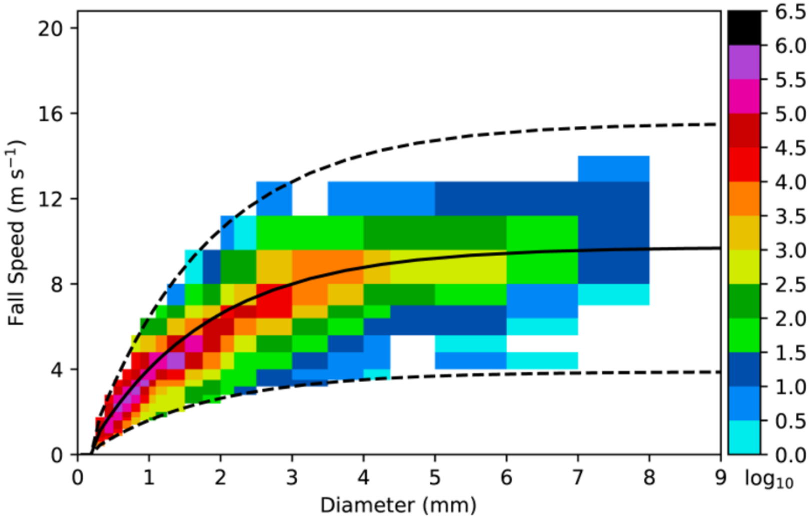
Recording instrument or just period total?
Instrument heated?
Evaporation losses?

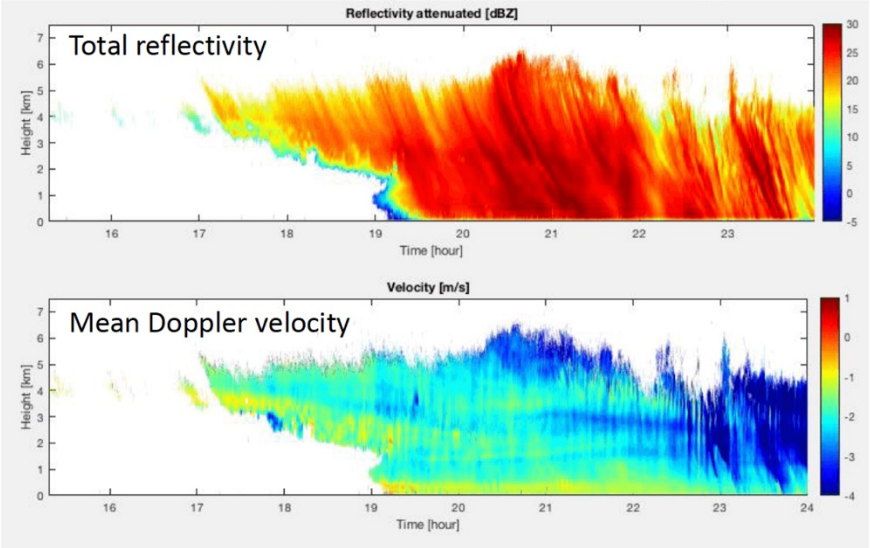
Optical and electromagnetic measurement



Optical disdrometer (Parsivel)

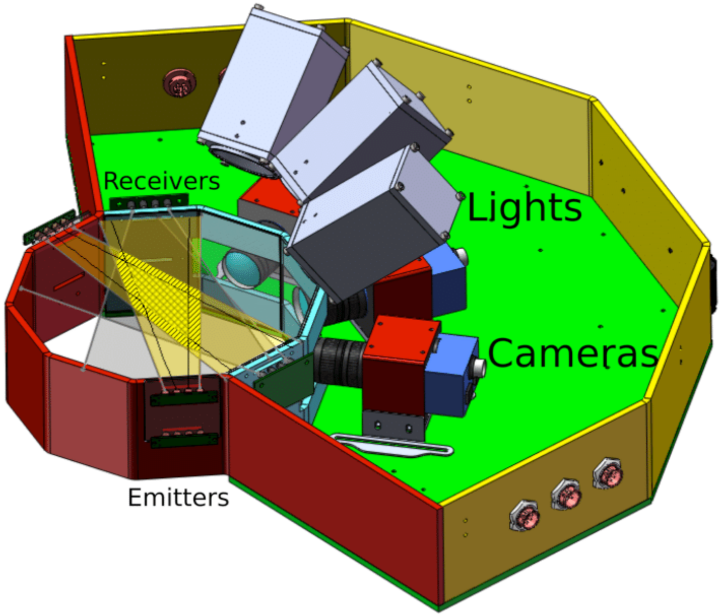
Micro Rain Radar (MRR)

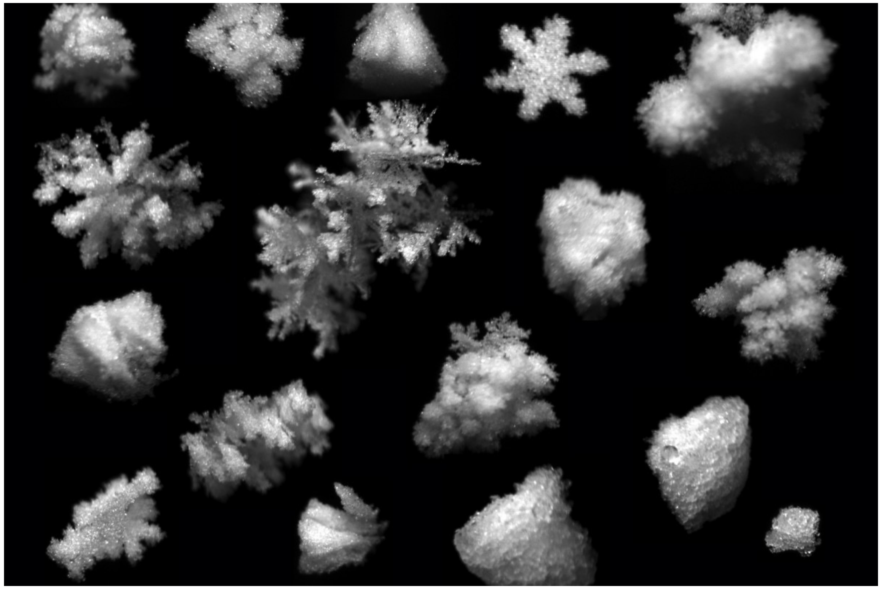




Issues:
very different relations (v vs. d) for solid and liquid precipitation. Designed for liquid precipitation.

MUSC: Multi-angle snowflake camera





Pictures: LTE/EPFL

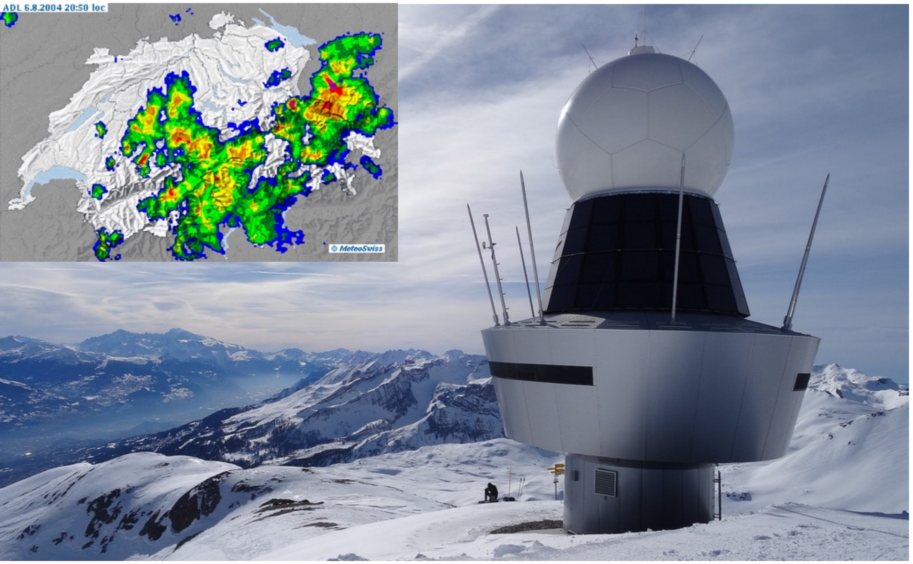
High-speed cameras, flash → number of particles, distribution of diameter → mass flux

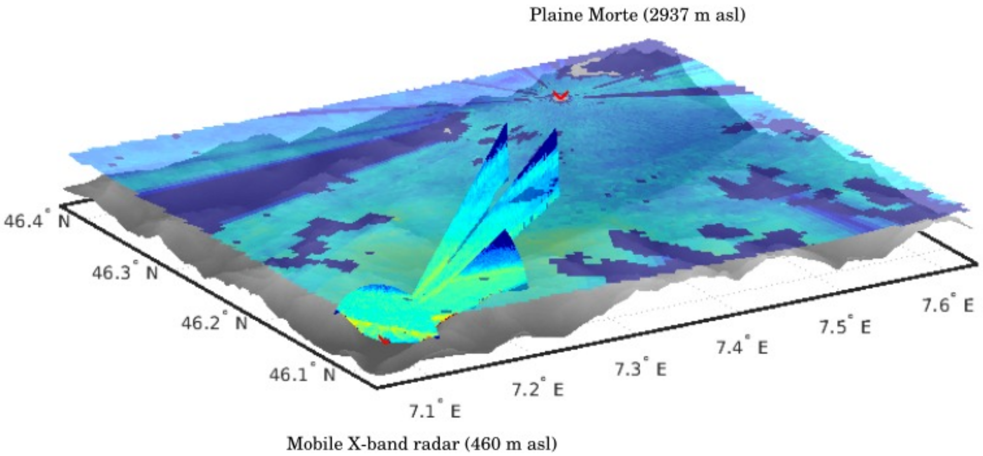
Precipitation radar

Scanning radar → measurements of hemisphere above instrument


© Jan Hellman, Bundesamt für Bauten und Logistik


Picture: LTE/EPFL

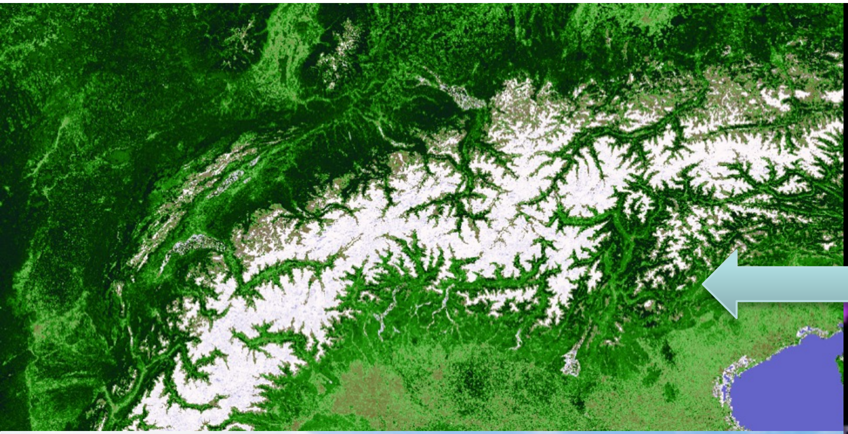


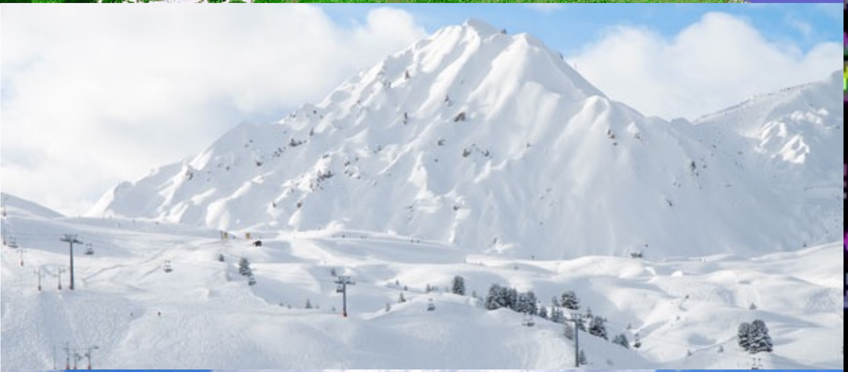


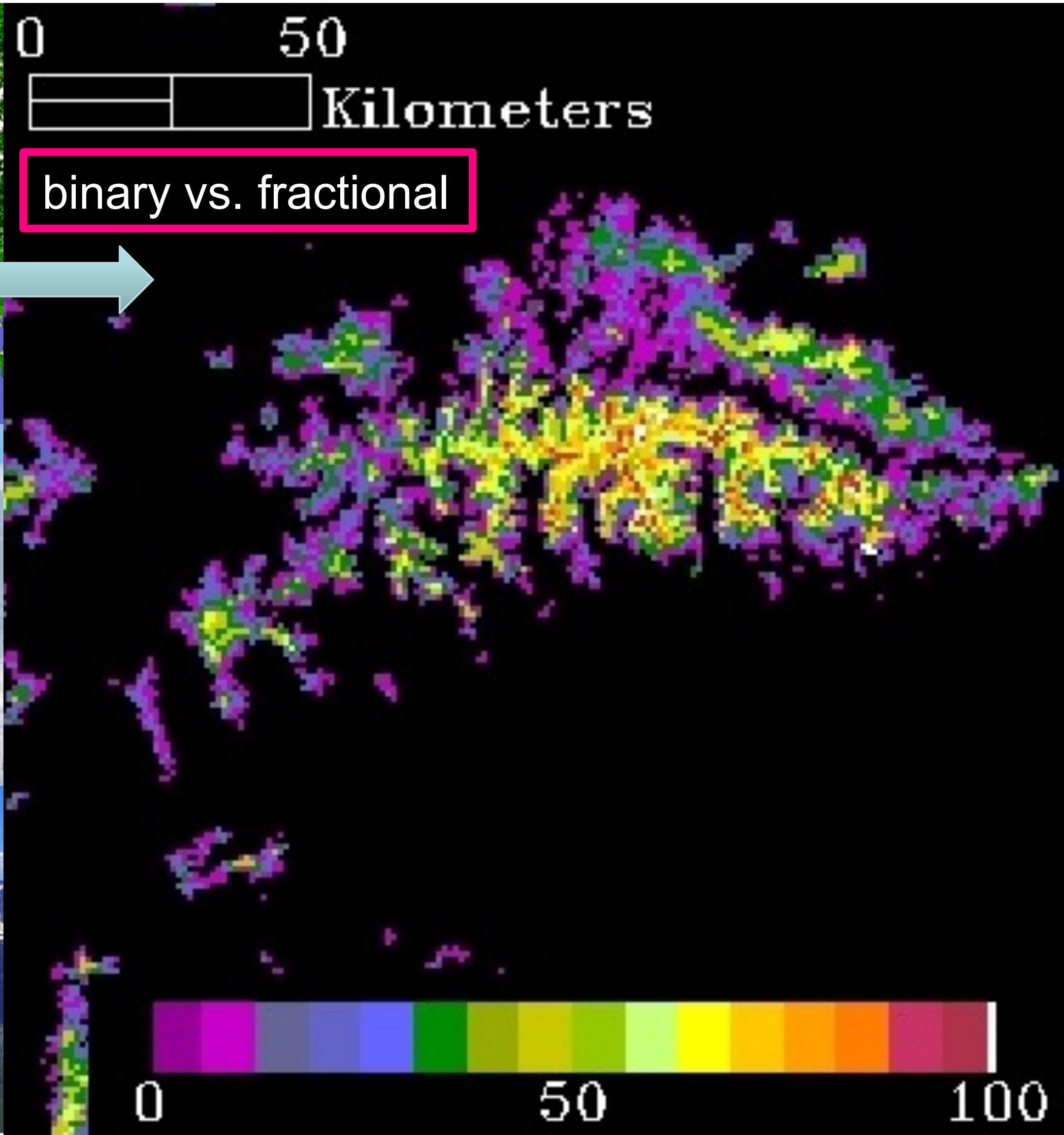
Picture: LTE/EPFL

Snow Covered Area (SCA): remote sensing

- Airborne mapping (drone, aircraft)
- Satellite based mapping → image processing, analysis algorithms







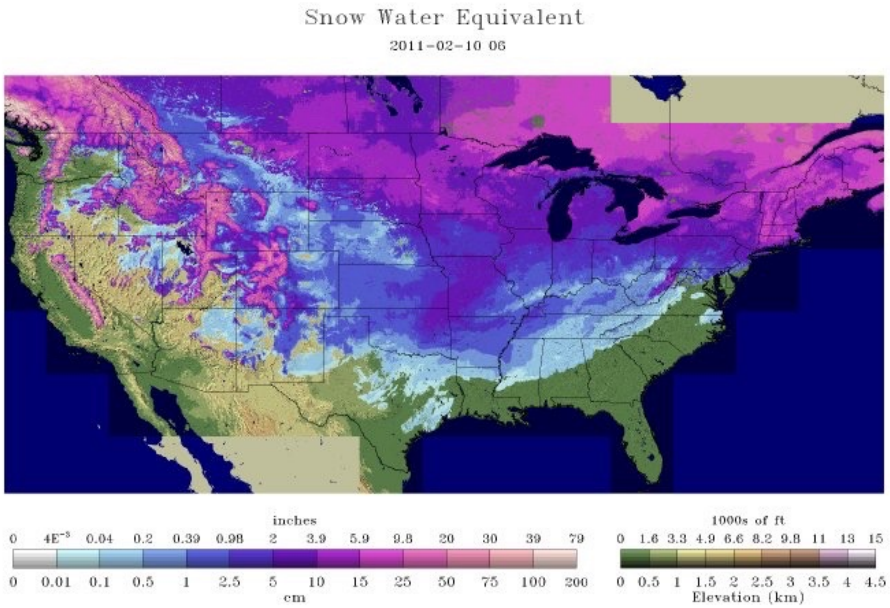
binary vs. fractional

Snow Water Equivalent (1)

SWE = $d_{snow} * \rho_s / \rho_w$; [mm H_2O]

Snow pit method (stratigraphy)

- identify snow layers
- measure thickness of each layer
- measure density of each layer
- compute SWE for each layer and then for the entire snowpack (summation)



Snow Water Equivalent (2)

Gravimetric method

- long tube of known volume is inserted vertically into the snowpack, down to base
- the snow core is removed and then weighed (subtract weight of tube)
- snow depth is measured (graded tube)

weighing the snow-filled tube

X kg per Y m^3 * Z m = kg/m^2 = mm

Y = tube volume, X/Y = mean density

Snow Water Equivalent (3)

Snow pillow
(pressure transducer) method

- weight of snow on a surface

  (kg/m^2 → [mm])

  produces voltage on pressure gauge or movement of fluid in tube
- instrument is calibrated to measure weight of snow

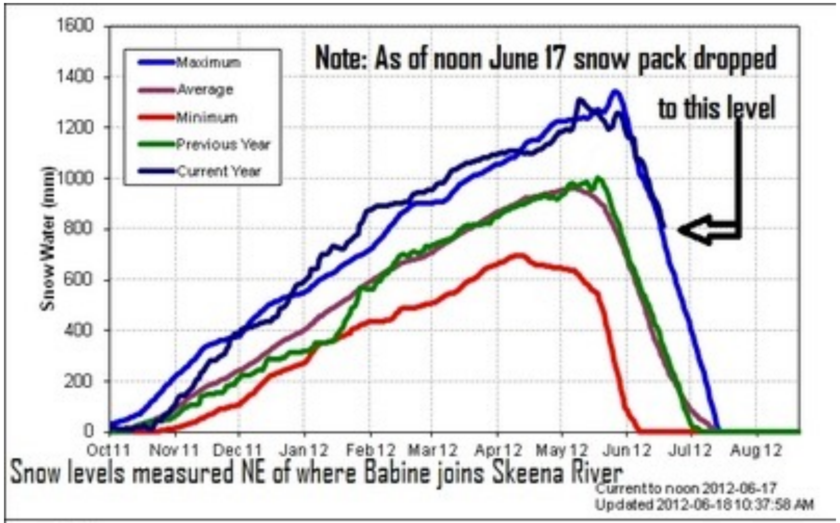
Fluidless Snow Pillow

Snow Pillow

- Hypalon (high-performance elastomer) pillow filled with anti-freeze liquid
- or steel plates arranged in a square

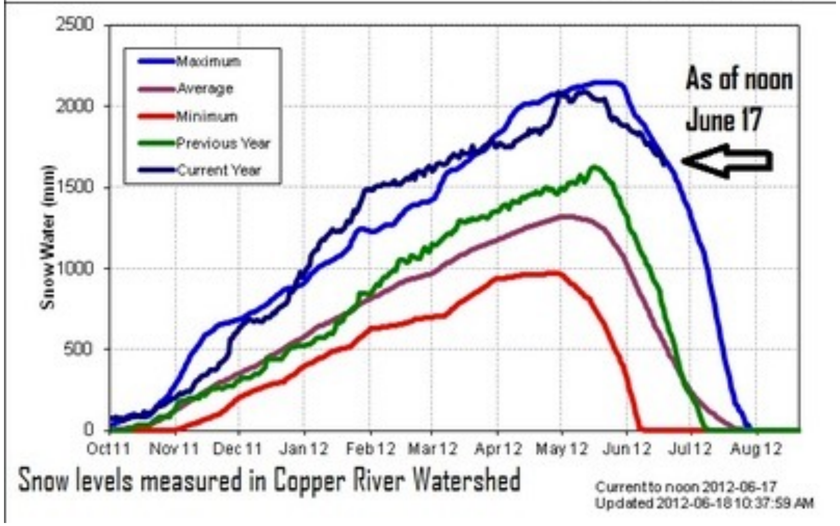
Problems/difficulties:

- Overweigh (snow creep, rain on snow)
- Under-weigh can occur with "bridging"



Snow levels measured NE of where Babine joins Skeena River

Current to noon 2012-06-17
Updated 2012-06-18 10:37:58 AM



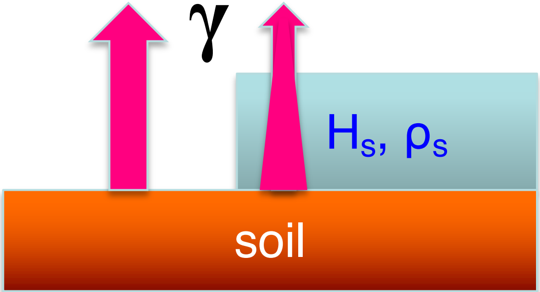
Snow levels measured in Copper River Watershed

Current to noon 2012-06-17
Updated 2012-06-18 10:37:59 AM

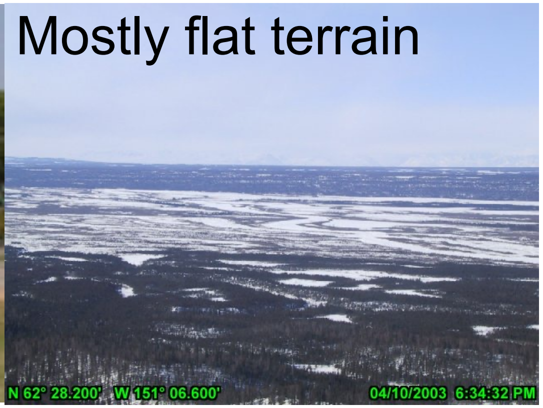
Snow Water Equivalent (4)

Airborne Gamma Radiation Measurements

- Used in operational program by the
  National Operational Hydrologic Remote Sensing Center (NOHRSC)
  to measure SWE over larger regions
- Snow (water) attenuates natural gamma radiation in a predictable manner
- Gamma radiation is measured before snowfall
- Repeat transects are flown when snow is present
- Need to account for soil moisture changes
- RMS error ≈1cm water equivalent




Aircrafts fly 500ft over the ground


Mostly flat terrain

SWE (5): from µ-wave brightness temperatures

Open $SWE = -20.7 - 2.59 [(37V - 19V)/18]$

Conif. Forest $SWE = 16.81 - 1.96 (37V-19V)$

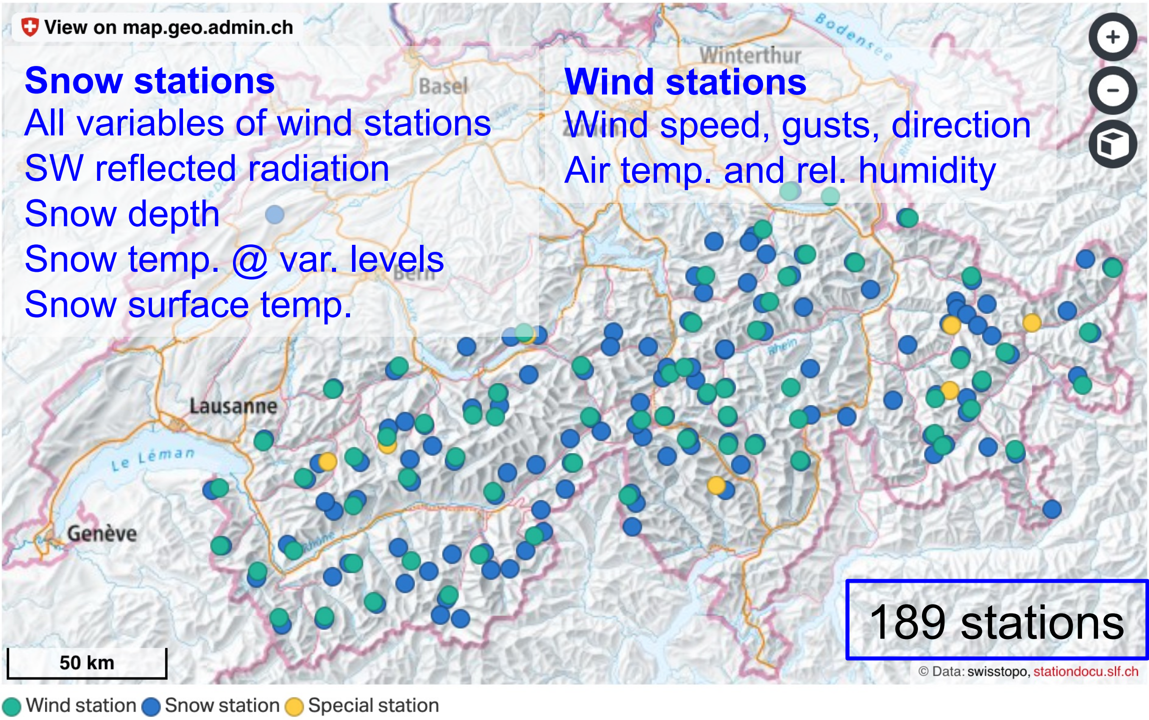
37 and 19 GHz
“V” and “H” are the direction of polarization (vertically , horizontally)

The Special Sensor Microwave/Imager (SSM/I) is a seven-channel, four-frequency, linearly polarized passive microwave radiometric system. The instrument measures surface/atmospheric microwave brightness temperatures (TBs) at 19.35, 22.235, 37.0 and 85.5 GHz. The four frequencies are sampled in both horizontal and vertical polarizations, except the 22 GHz which is sampled in the vertical only.

Automated snow measurements: IMIS / MCH stations

ENET: Ergänzungsnetz (MeteoCH)

IMIS: Inter-cantonal Measurement and Information System



Snow stations

All variables of wind stations

SW reflected radiation

Snow depth

Snow temp. @ var. levels

Snow surface temp.

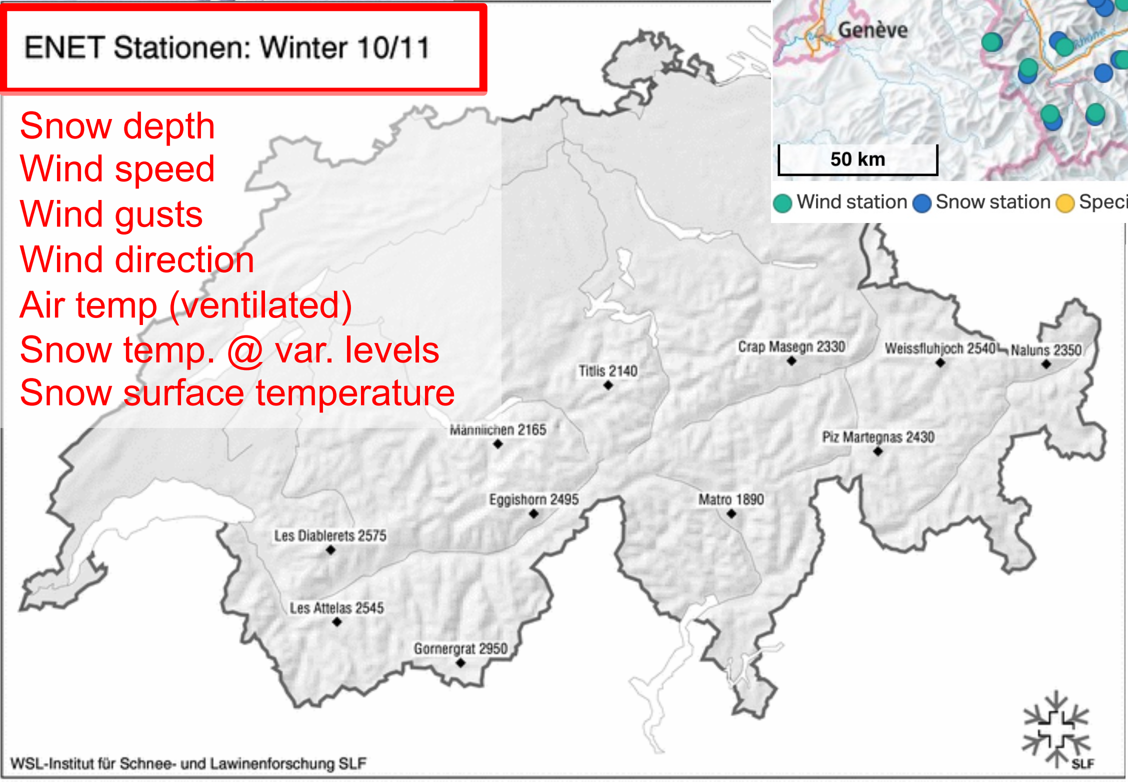
Wind stations

Wind speed, gusts, direction

Air temp. and rel. humidity

189 stations

● Wind station ● Snow station ● Special station



ENET Stationen: Winter 10/11

Snow depth

Wind speed

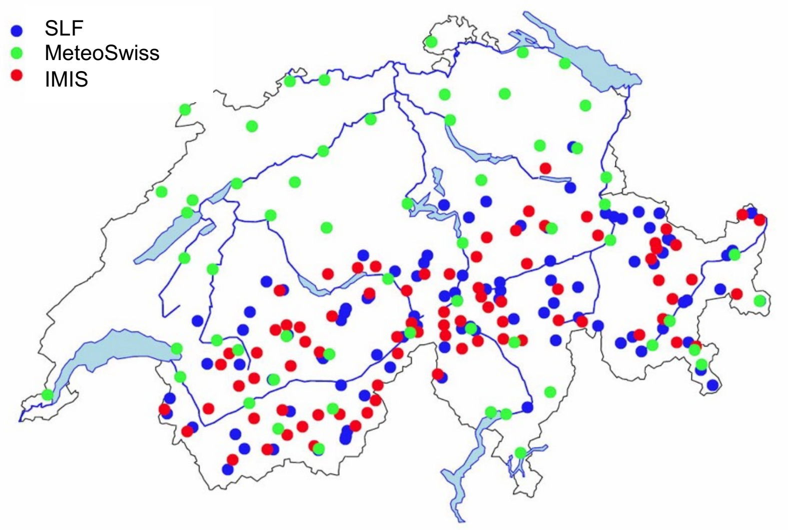
Wind gusts

Wind direction

Air temp (ventilated)

Snow temp. @ var. levels

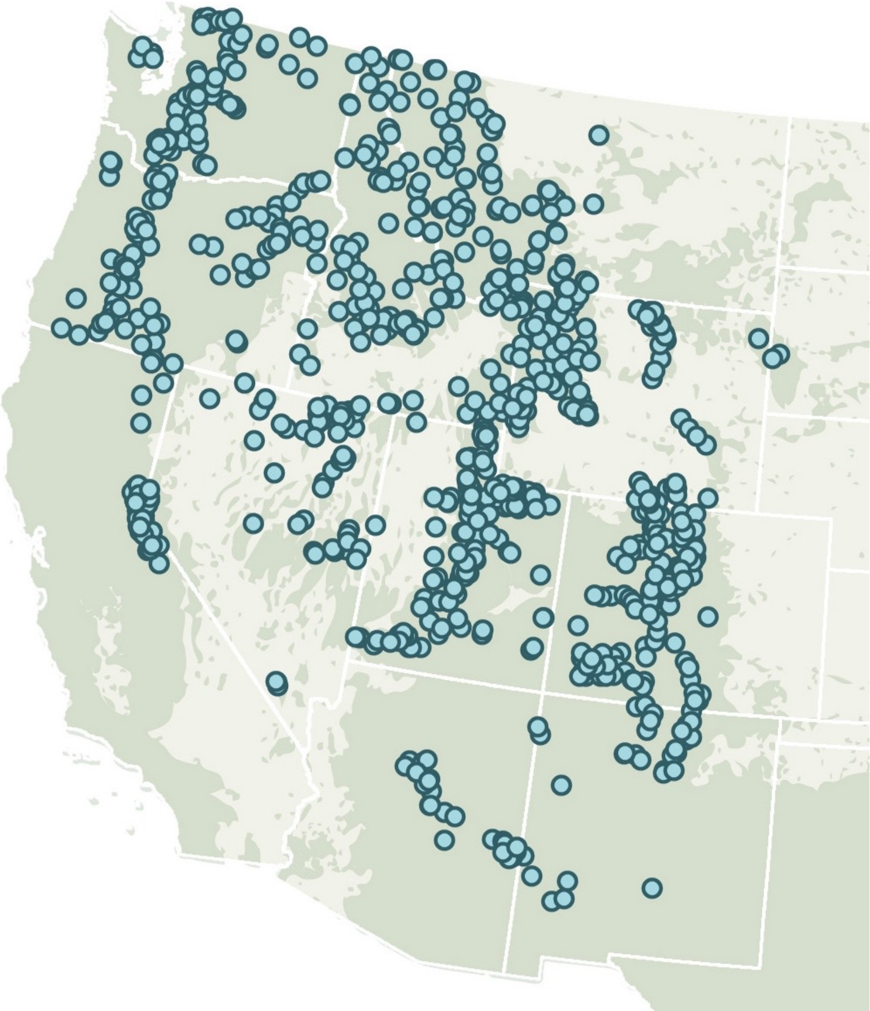
Snow surface temperature

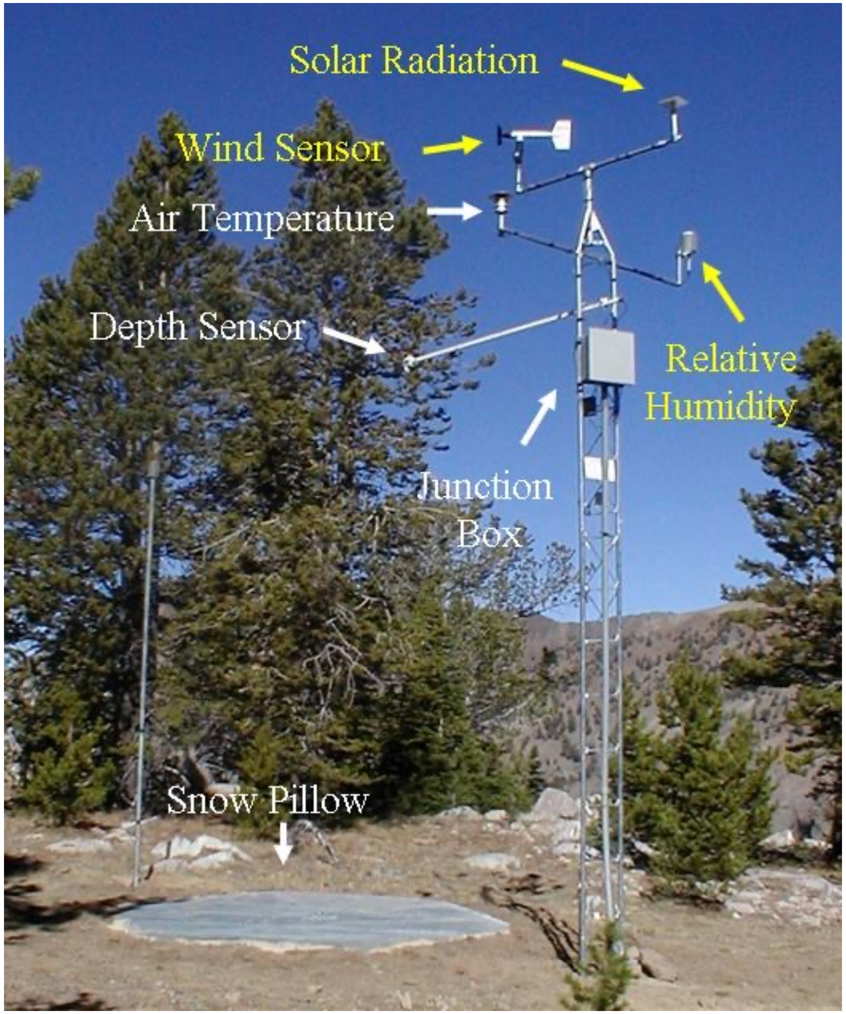


SNOTEL Network, U.S.

Snow pack Telemetry sites: Over 600 sites in the western US

SNOTEL sites consist of snow pillow, precipitation gauge, temperature and wind sensors, power supply and data recording transmission devices

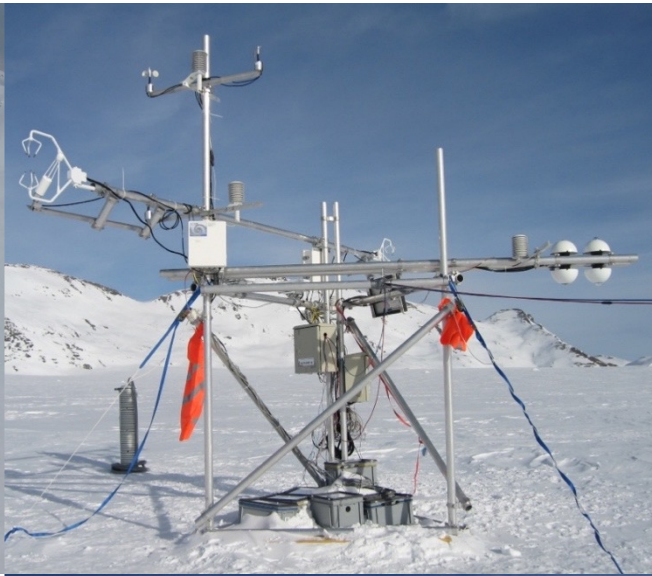


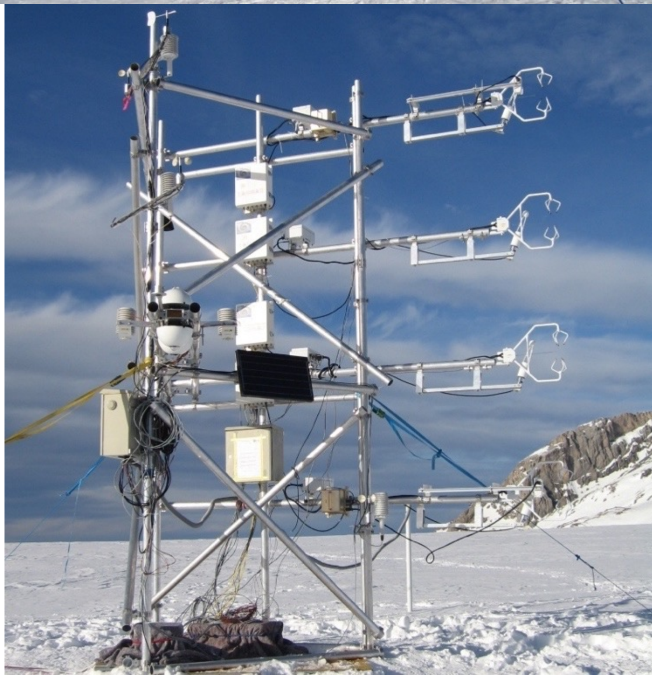


Measurements ABOVE the snow

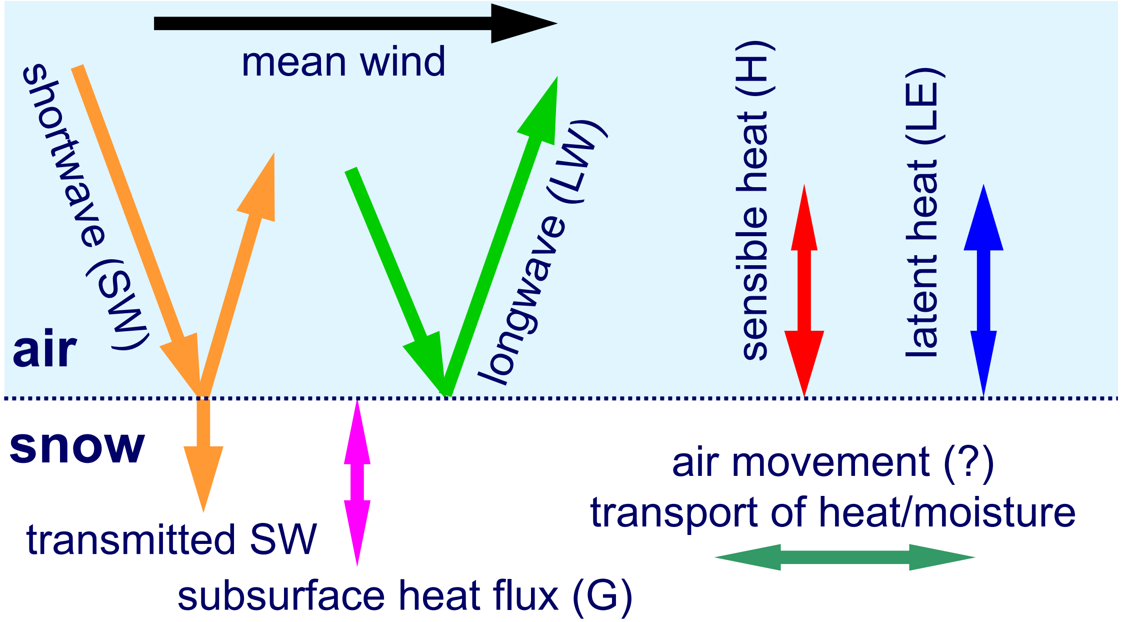
Surface Energy Balance

- Radiation (SW, LW)
- Wind (WS, WD)
- Air Temperature
- Surface Temperature
- Humidity
- Turbulent fluxes
- Snow surface level

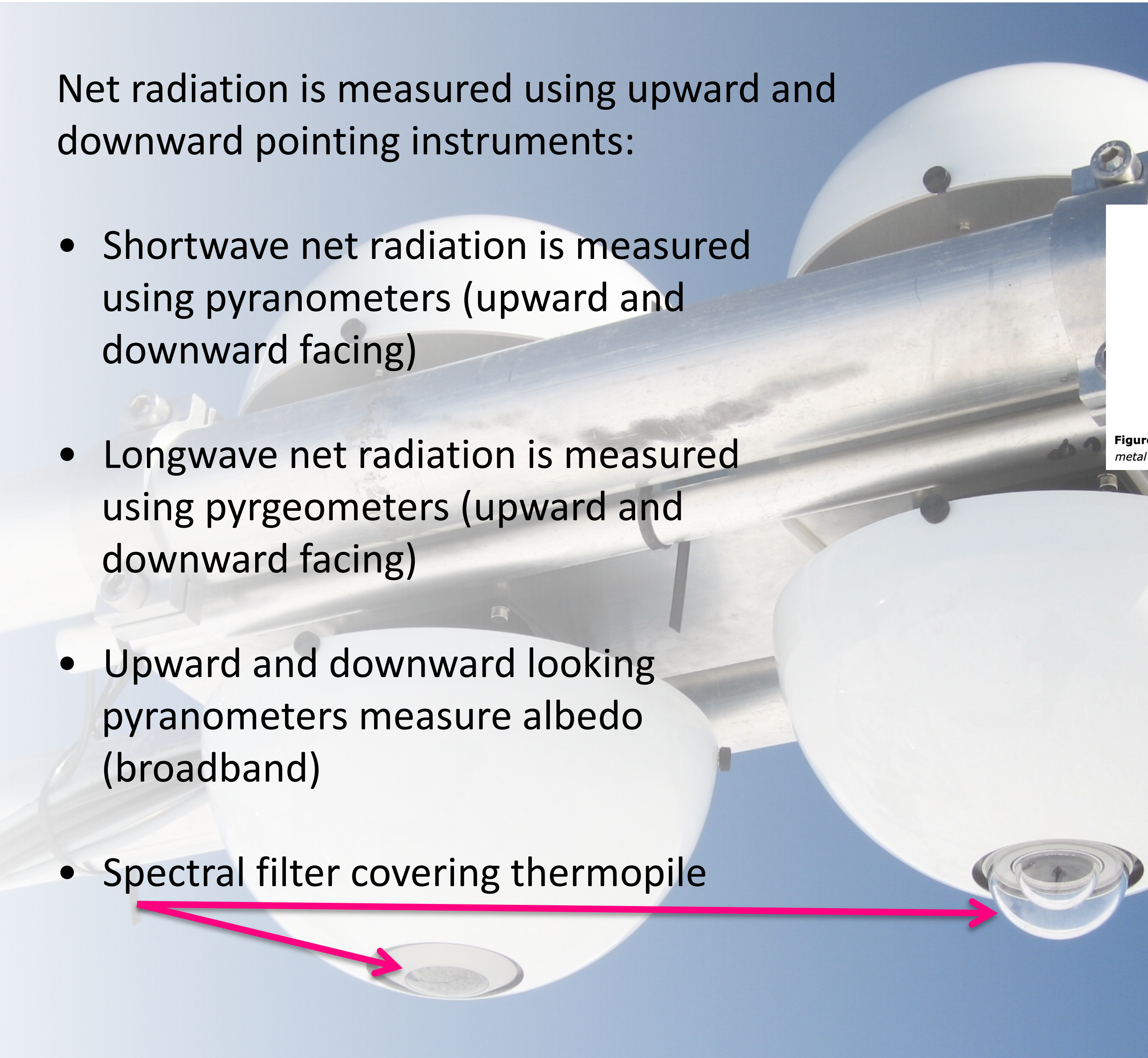




Pictures: H.Huwald



Radiative heat fluxes



Net radiation is measured using upward and downward pointing instruments:

- Shortwave net radiation is measured using pyranometers (upward and downward facing)
- Longwave net radiation is measured using pyrgeometers (upward and downward facing)
- Upward and downward looking pyranometers measure albedo (broadband)
- Spectral filter covering thermopile

Credit: Hukseflux

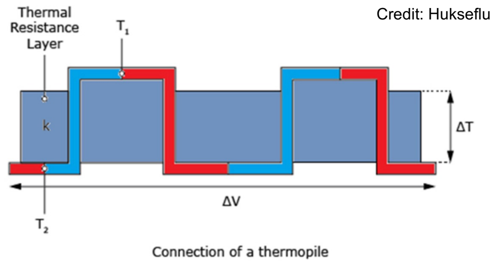


Figure 2 *Schematic overview of a thermopile sensor consisting of two different metal types connected in series, embedded in a "thermal resistance layer".*

Pictures: H.Huwald

Wind: cup anemometer and vane

v = c * #rotations/sec

c = calibration const.

Pulse Counts

Potentiometer

Pictures: H.Huwald

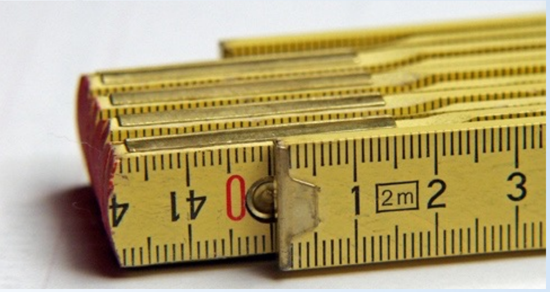
Snow depth

Automated snow depth measurements:
acoustic distance sensor

Measures distance sensor-surface

Requires an air temperature measurement to determine specific correction factor (speed of sound is function of ρ, and ρ is a function of T and RH)

Picture: H.Huwald



Avalanche probe

Snow surface temperature

Infrared radiometer for surface temperature

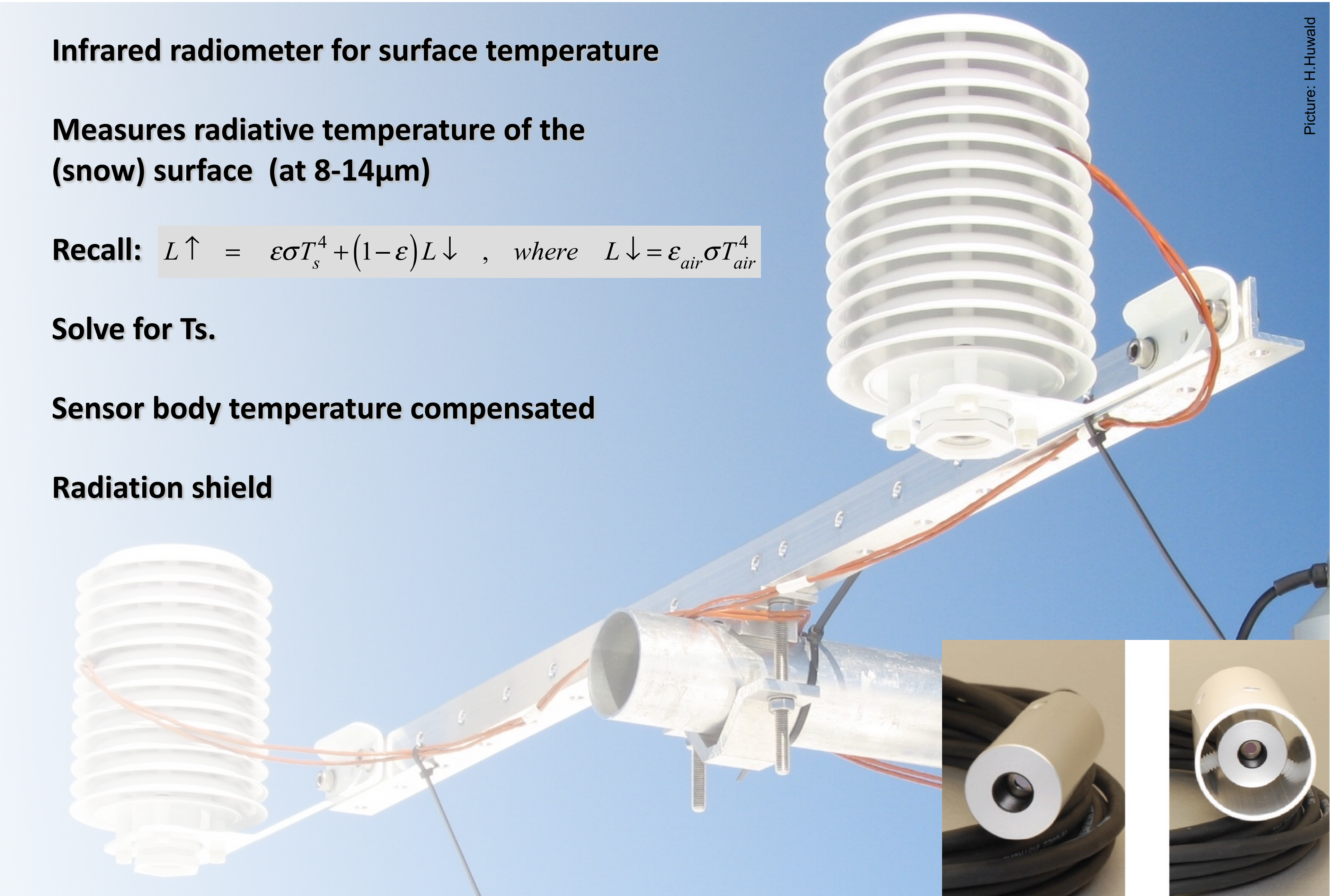
Measures radiative temperature of the (snow) surface (at 8-14µm)

Recall: $L\uparrow \;=\; \varepsilon\sigma T_s^4 + (1-\varepsilon)L\downarrow \quad , \quad where \quad L\downarrow = \varepsilon_{air}\sigma T_{air}^4$

Solve for Ts.

Sensor body temperature compensated

Radiation shield



Picture: H.Huwald

Air temperature and humidity

Air temperature and Relative humidity

Combined T / RH sensor

Radiation shield required

Active ventilation desirable

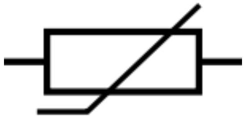
Common T sensors:

Thermistor (e.g. PT100),
Thermocouple (e.g. Type T)
Humidity: capacitor

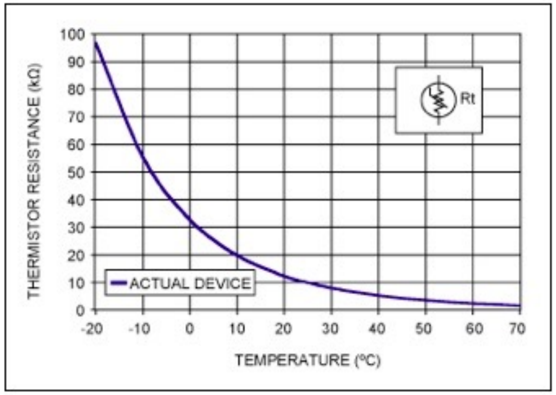
Picture: H.Huwald

Temperature: Thermistor

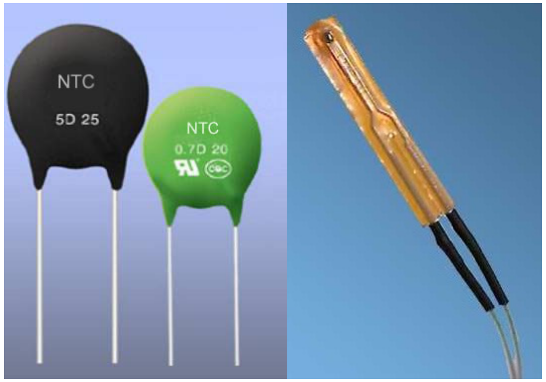
- Thermistor: (thermal + resistor)



- Variable electrical resistor, value varies (reproducibly) with temperature
- Relation of T and R with proportionality factor k:
- $\Delta R = k\Delta T$



- Depending on sign of k we have
- NTC-thermistor with negative coefficient (R↓ for T↑)
- PTC-thermistor with positive coefficient (R↑ for T↑)



- Thermistors: usually ceramic or polymer material
- RTDs (resistance temperature detector)
  typically pure metal
- Widely used sensor: Pt100 (platinum) R_0: 100 Ω at 0°C

Temperature: Thermocouple

- junction between two different metals that produces a voltage if the junction temperature differs from the circuit reference temperature.

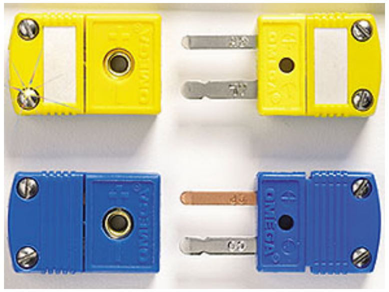
- junctions of specific alloys which have a predictable and repeatable relationship between temperature and voltage

- Different alloys are used for different temperature ranges.

- Voltage–temperature relationship
- For typical metals used in thermocouples, the output voltage increases almost linearly with the temperature difference (ΔT) over a bounded range of temperatures.

- For precise measurements or measurements outside of the linear temperature range, non-linearity must be corrected. The nonlinear relationship between the temperature difference (ΔT) and the output voltage (mV) of a thermocouple can be approximated by a polynomial:

- TC-Types:
- T: copper-constantan
- K: chromel-alumel
- E: chromel-constantan



$$\Delta T = \sum_{n=0}^{N} a_n v^n$$

polynomial coefficients depend on TC type

3-D sonic anemometer

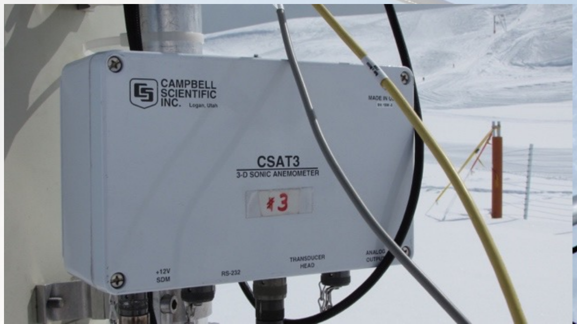

Pictures: H.Huwald

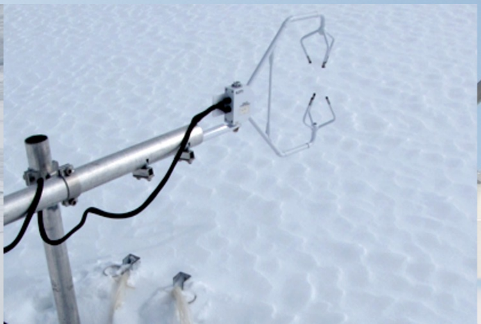
Measures wind components (u,v,w) and (virtual potential) temperature

Typical sampling frequency: 20Hz

Derived quantities:
Wind direction and speed (vector)
Sensible heat flux (eddy covariance)

$Q_H = \rho_a C_{pa} \langle w'T' \rangle$ ← Reynolds decomposition
$u = \langle u \rangle + u'$ (cf. energy balance, slide 35).





Wind and air temperature

Wind:

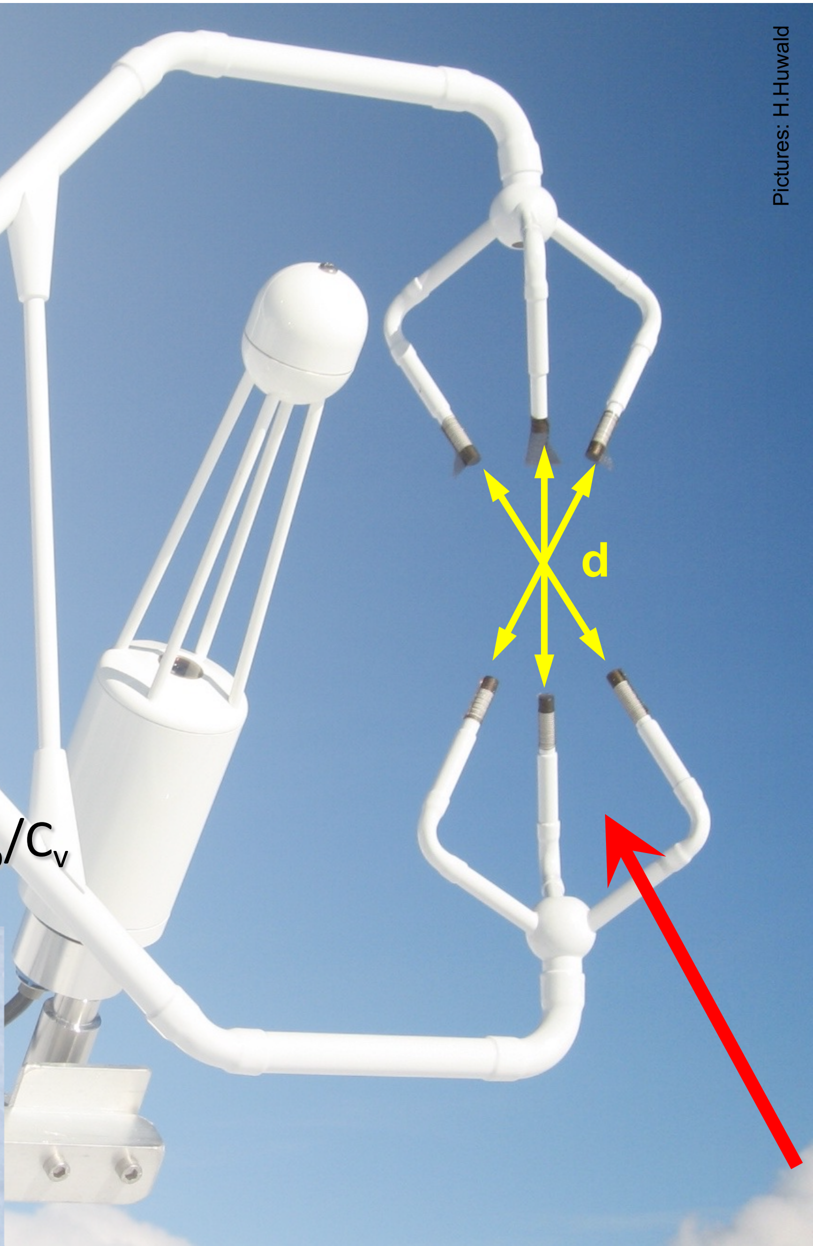
$t_f = d / (c + u_a)$
$t_b = d / (c - u_a)$

$u_a = d/2\ (1/t_f - 1/t_b)$

$[u_x, u_y, u_z] = \mathbf{A}\ [u_a, u_b, u_c]$

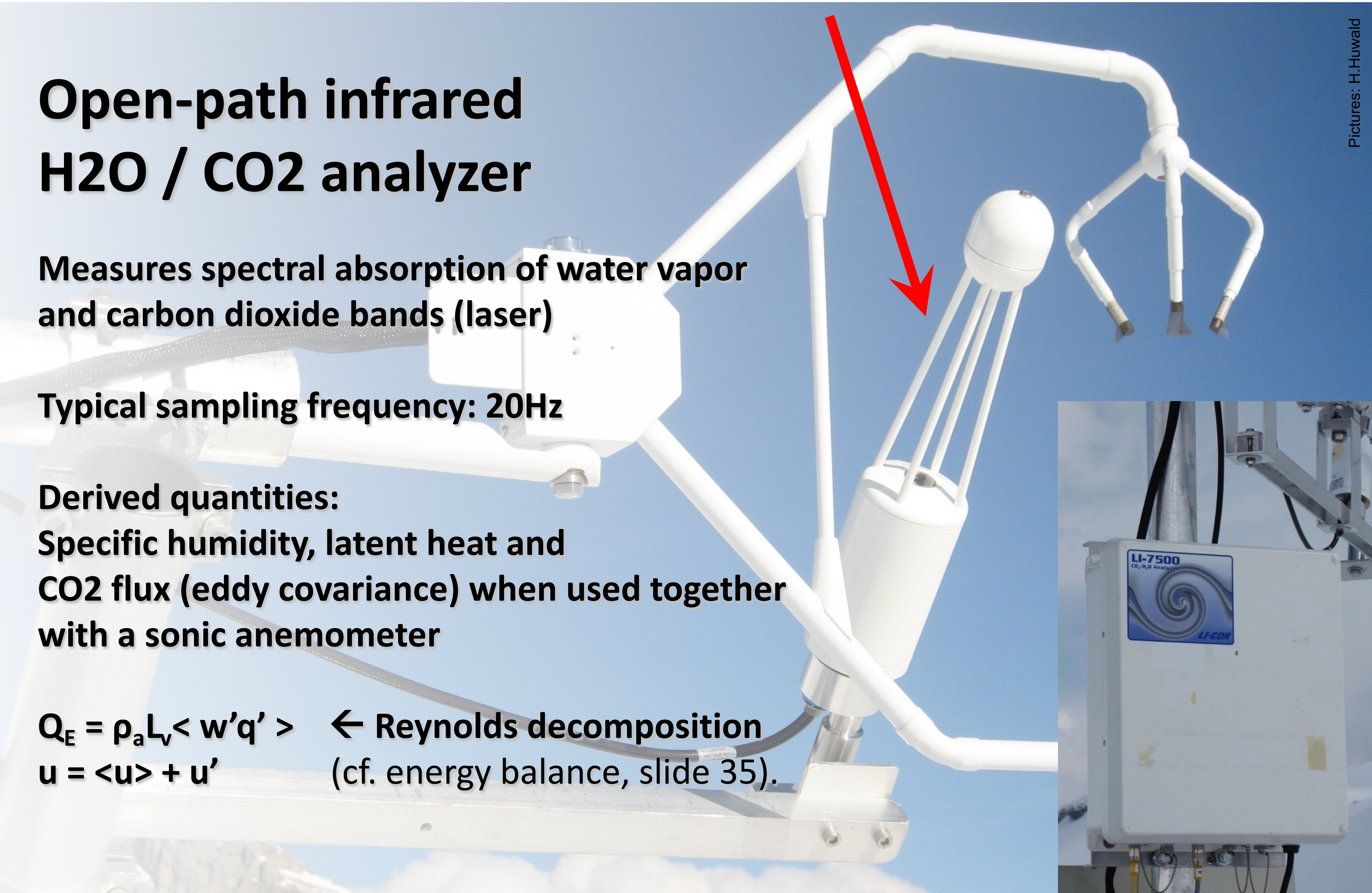
Air temperature:

$c = d/2\ (1/t_f + 1/t_b)$
$c^2 = \gamma P/\rho = \gamma R_d T_v = \gamma R_d T(1 + 0.61q)$ where $\gamma = C_p/C_v$



Pictures: H.Huwald

Fast response humidity



Pictures: H.Huwald

Open-path infrared H2O / CO2 analyzer

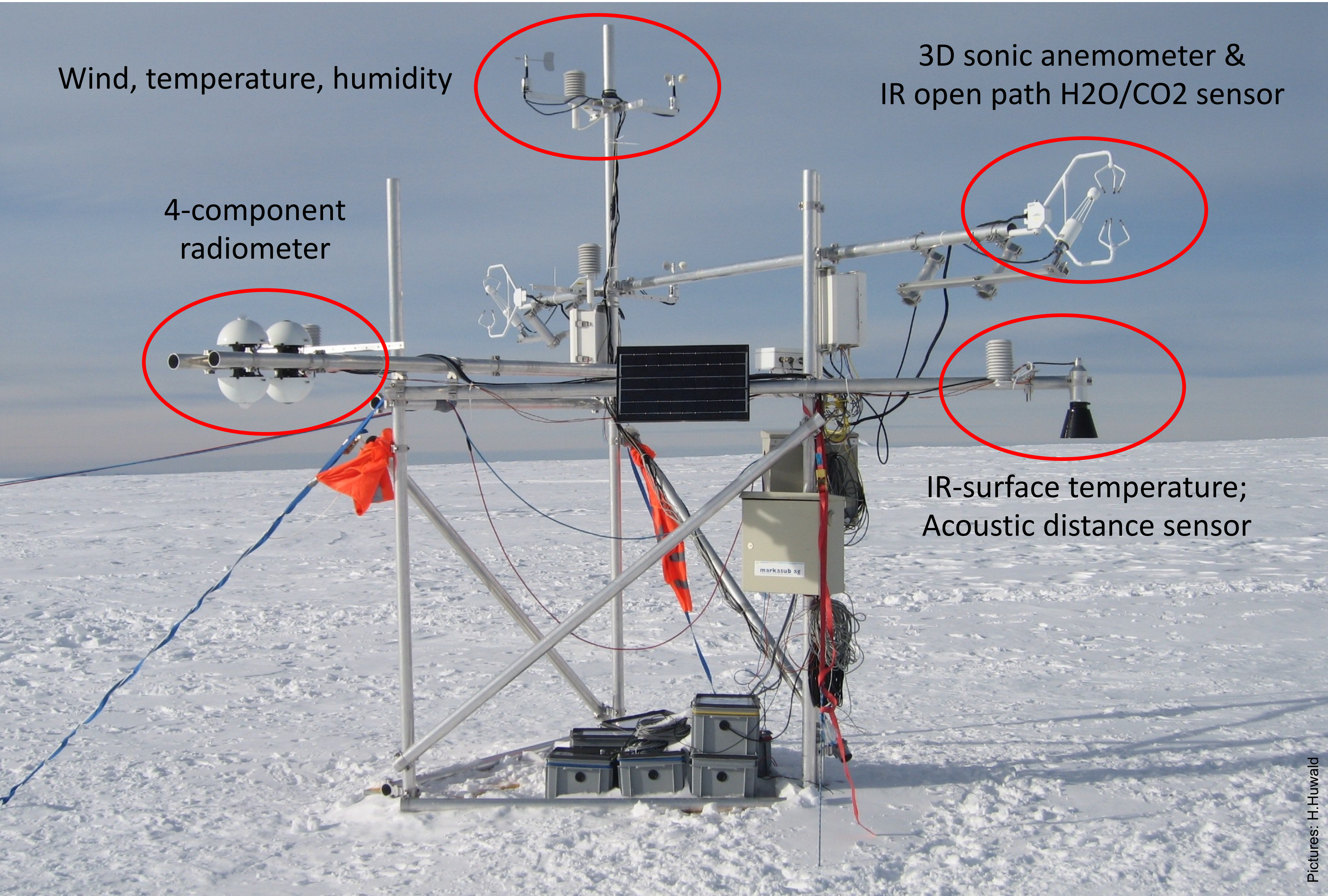
Measures spectral absorption of water vapor and carbon dioxide bands (laser)

Typical sampling frequency: 20Hz

Derived quantities:
Specific humidity, latent heat and CO2 flux (eddy covariance) when used together with a sonic anemometer

$Q_E = \rho_a L_v < w'q' >$ ← **Reynolds decomposition**
$u = <u> + u'$ (cf. energy balance, slide 35).

Surface Energy Balance station



Wind, temperature, humidity

3D sonic anemometer &
IR open path H2O/CO2 sensor

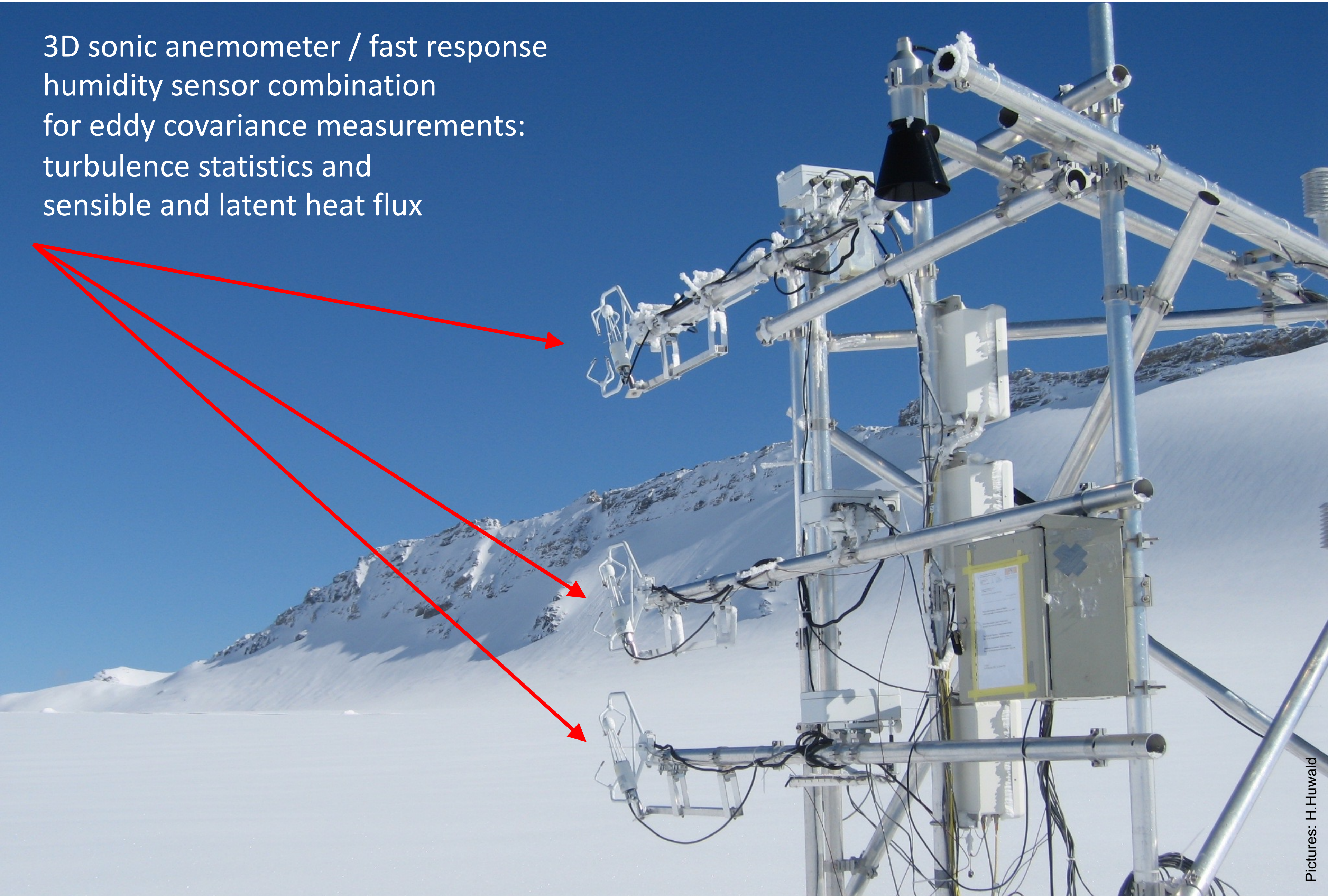
4-component
radiometer

IR-surface temperature;
Acoustic distance sensor

Pictures: H.Huwald

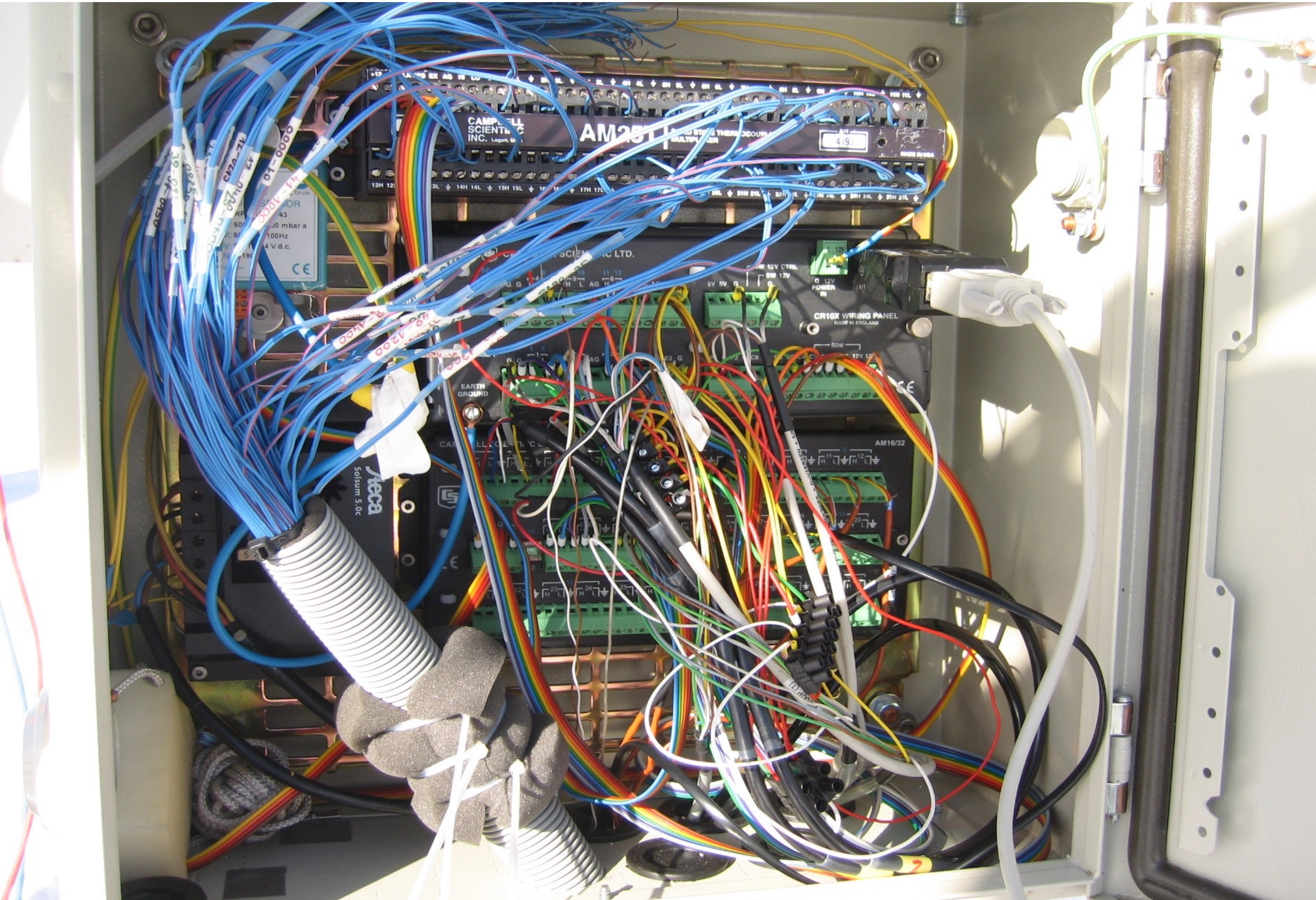
Turbulent heat flux measurements

3D sonic anemometer / fast response humidity sensor combination
for eddy covariance measurements:
turbulence statistics and
sensible and latent heat flux



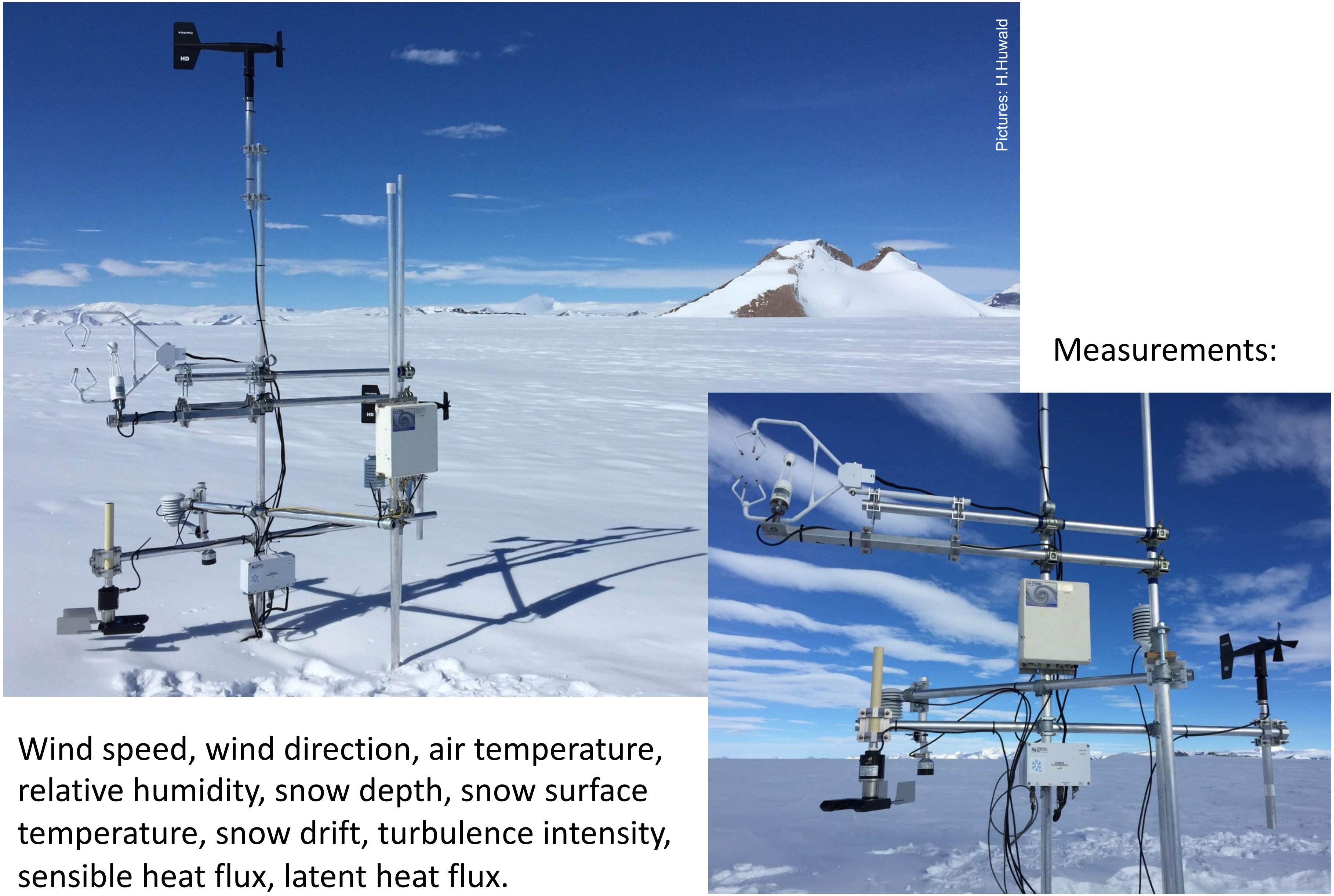
Pictures: H.Huwald

Energy balance station wiring and logging system



Pictures: H.Huwald

Energy and Mass Balance stations, Antarctica



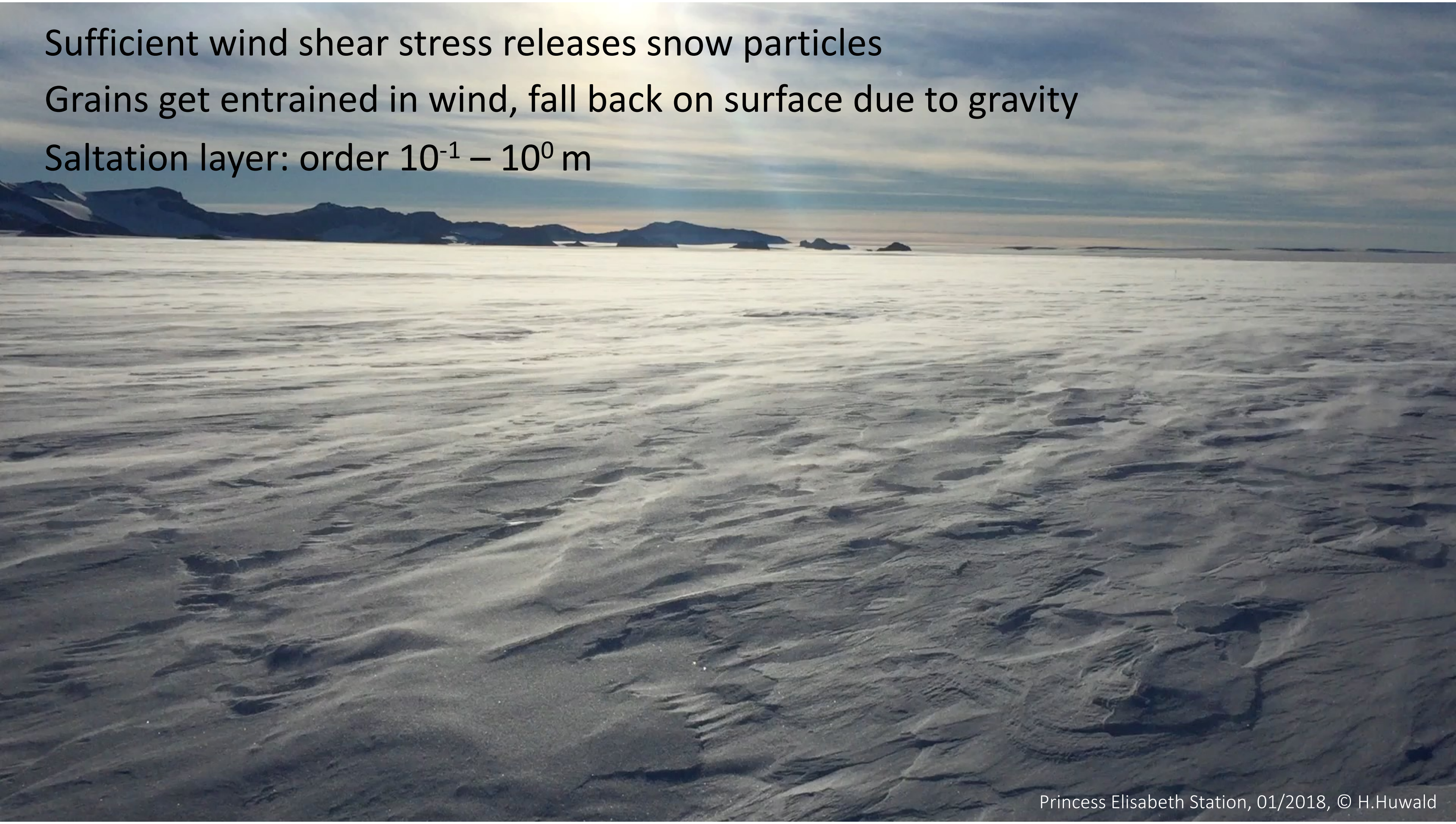
Pictures: H.Huwald

Measurements:

Wind speed, wind direction, air temperature, relative humidity, snow depth, snow surface temperature, snow drift, turbulence intensity, sensible heat flux, latent heat flux.

Saltation (snow drift)

What is the resulting vertically integrated mass flux?



Sufficient wind shear stress releases snow particles

Grains get entrained in wind, fall back on surface due to gravity

Saltation layer: order $10^{-1} – 10^{0}$ m

Princess Elisabeth Station, 01/2018, © H.Huwald

Suspension (blowing snow)

What is the resulting vertically integrated mass flux?

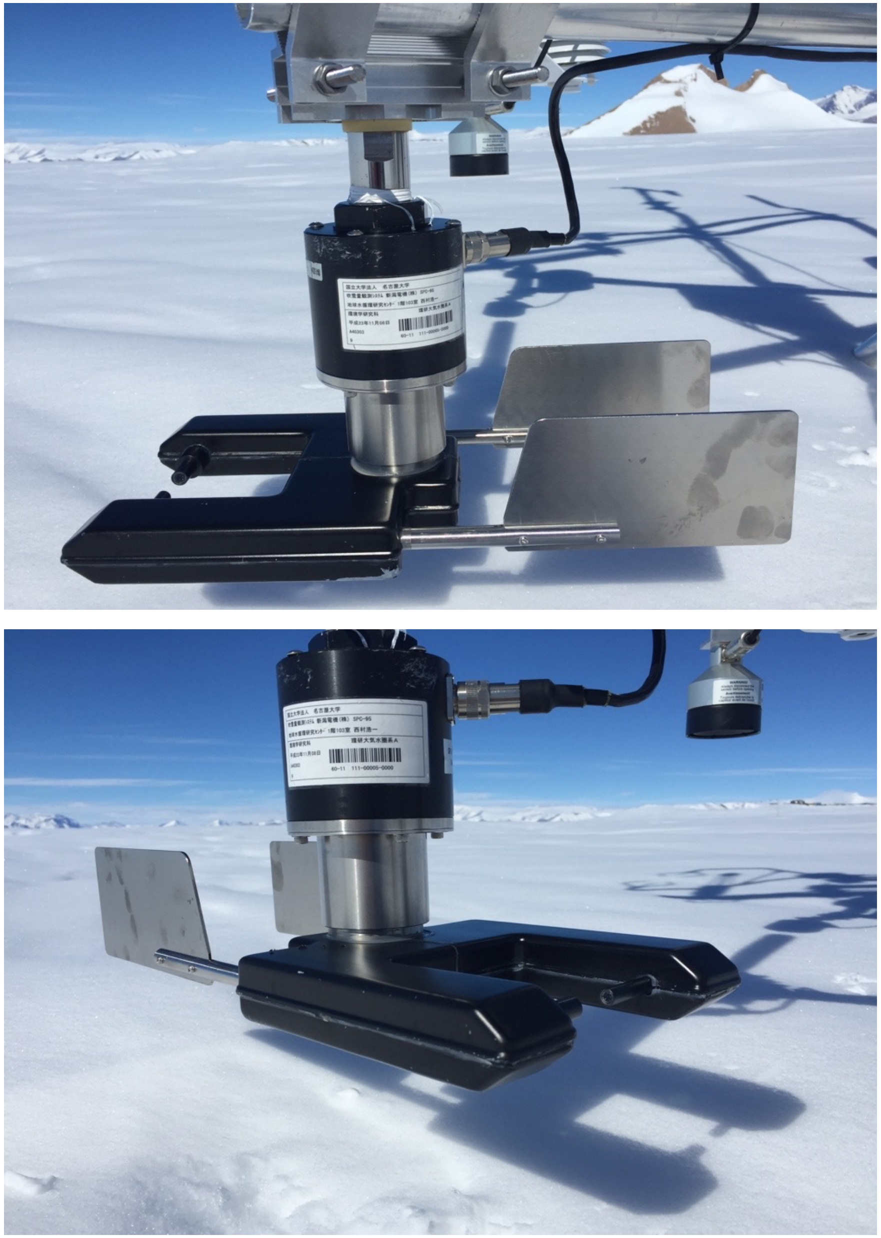
Blowing snow at Princess Elizabeth Station, Wind speed: > 20 m/s

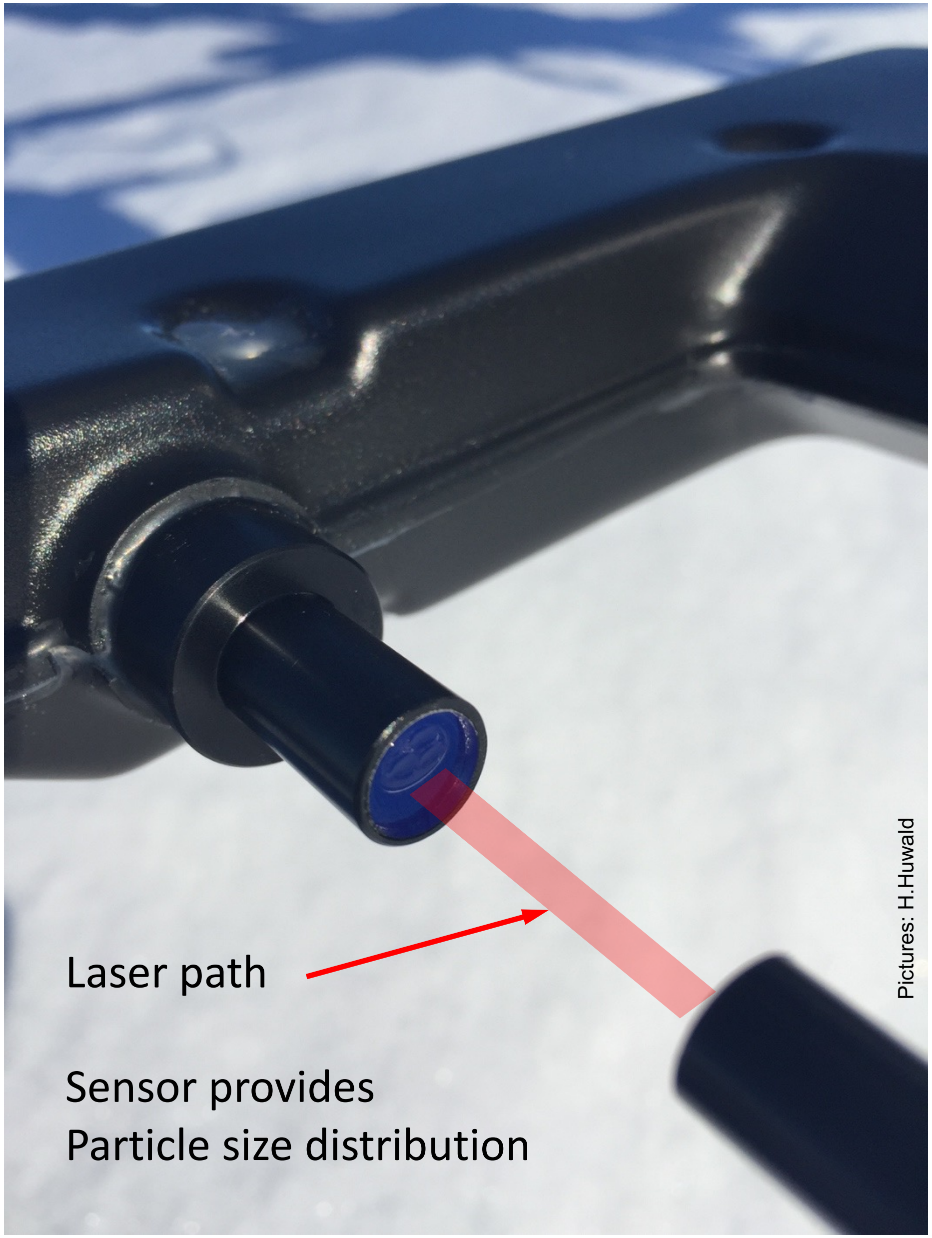
High wind speed and turbulent eddies carry particles in the atmosphere.

Suspension layer: order $10^0 – 10^2$ m

Princess Elisabeth Station, 01/2018, © H.Huwald

Snow particle counting (SPC)

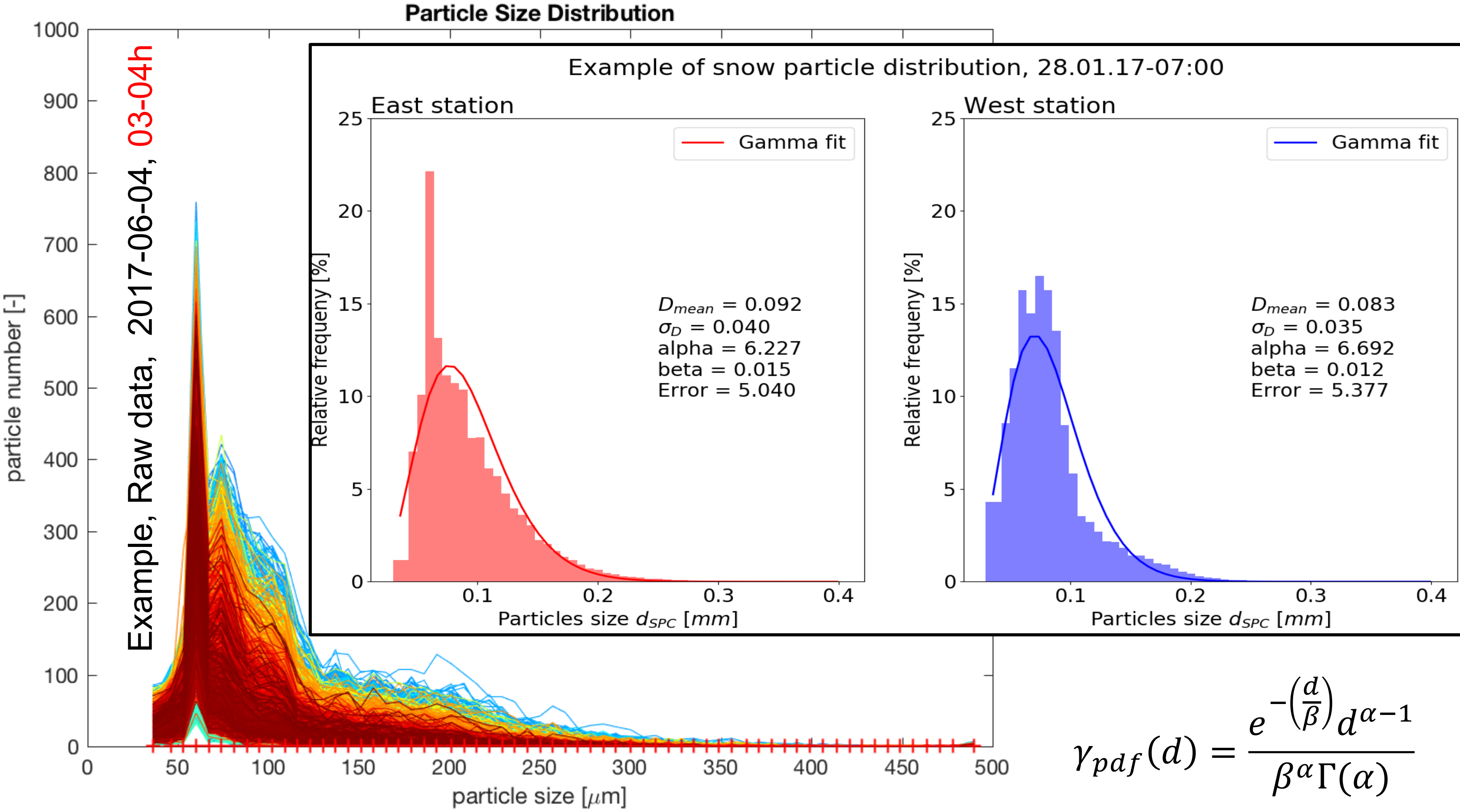




Sensor provides
Particle size distribution

Pictures: H.Huwald

Snow particle size distribution



Example, Raw data, 2017-06-04, 03-04h

$$\gamma_{pdf}(d) = \frac{e^{-\left(\frac{d}{\beta}\right)} d^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)}$$

- SPC: # particles/sec classified in 64 diameter bins $(50 - 500\ \mu m)$
- Assuming fully rounded particles and density of ice → mass flux; MF = f(z)
- Particle size distribution described with gamma pdf*:

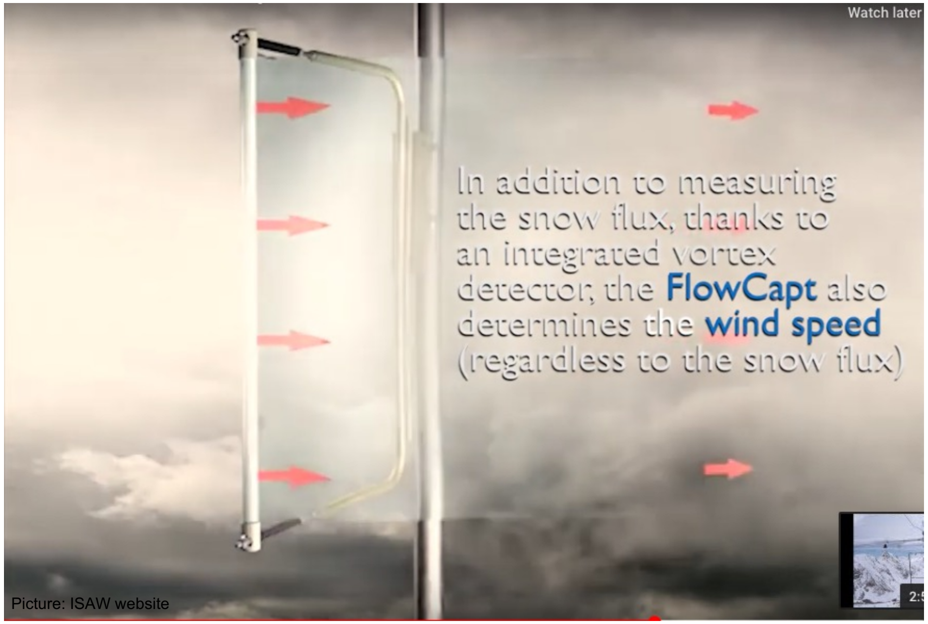
Acoustic sensors for particle flux

ISAW FlowCapt FC4 sensor

Snow drift
Blowing snow

No moving parts
Acoustic signal from particle impact

→ Snow mass flux (flux of drifting and blowing ice particles



In addition to measuring the snow flux, thanks to an integrated vortex detector, the **FlowCapt** also determines the **wind speed** (regardless to the snow flux)

Picture: ISAW website

Picture: ISAW website

FlowCapt FC4 - Snowdrift and Wind Monitoring Sensor

Picture: ISAW website

Measurements WITHIN the Snow

- **Density**
- **Temperature /-gradient**
- **Grain size & shape**
- **Layer hardness**
- **Stratigraphy:**

  Crusts, weak layers, etc.

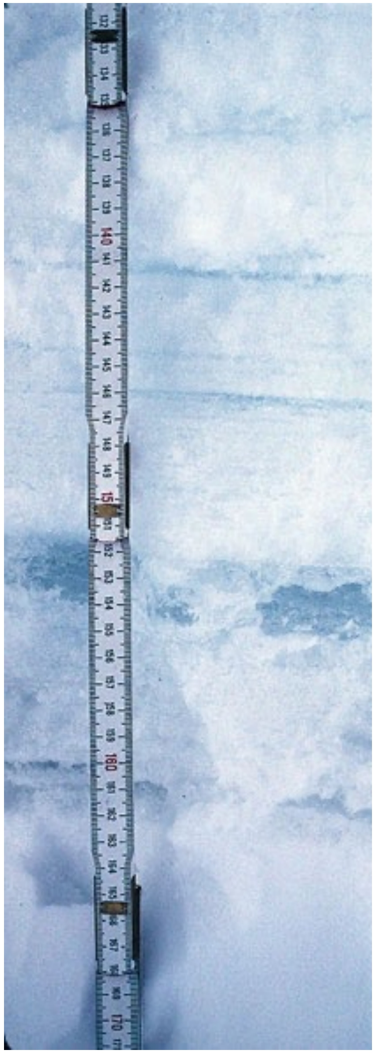
Snow Pits

Snow stratigraphy

- Identify and measure layers: number and thickness

  (use brushes, sweep sideways)
- Measure density profile
- Measure temperature profile
- Determine snow hardness
- Determine grain size
- Determine grain shape & type

- Measure liquid water content
- Measure specific surface area
- Measure mechanical resistance



Snow pits

- Select representative location and dig the snow pit
- Pit wall should be perpendicular to direction to the sun, facing away from the sun (shade!)
- Pile snow away from pit wall, dig steps, make it large enough to work in

Snow pit equipment:

- shovels: flat blade, large scoop
- measuring stick or long meter tape
- layer markers (toothpicks, cable ties)
- needle thermometer (with steel rod)
- density kit (tube and spring scale or cutter and electronic scale)
- brush and knife
- 10x lens and gridded plate
- waterproof notebook and pen

Snow density

Weigh a known volume of snow

Calibrate and tare the scale

- Insert tube into snow (vertically) and remove by cutting off at the bottom, dump snow into bag, weigh bag + snow using spring scale

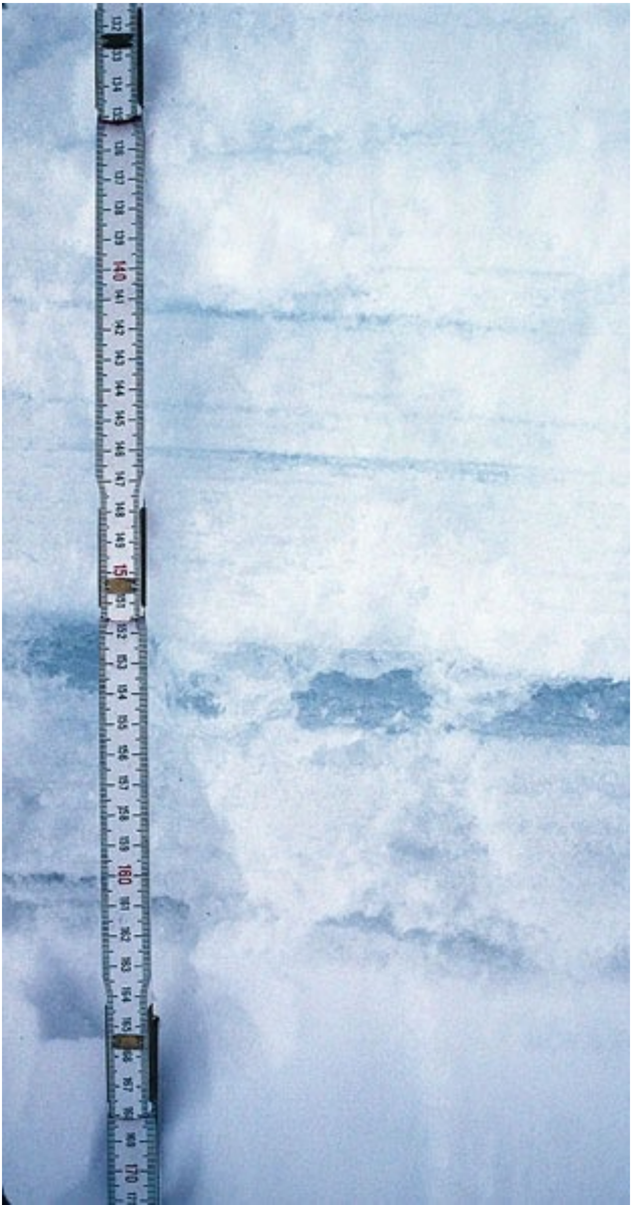
or

- Insert wedge cutter into snow pit wall (horizontally) slide cutter plate over wedge, remove plate and wedge cutter, weigh on electronic scale

Snow hardness

Hand test: Make hardness measurements in the center of each layer (horizontal)

Fist	10 g/m^2
4 Fingers	25 g/m^2
1 Finger	100 g/m^2
Pencil	500 g/m^2
Knife	900 g/m^2

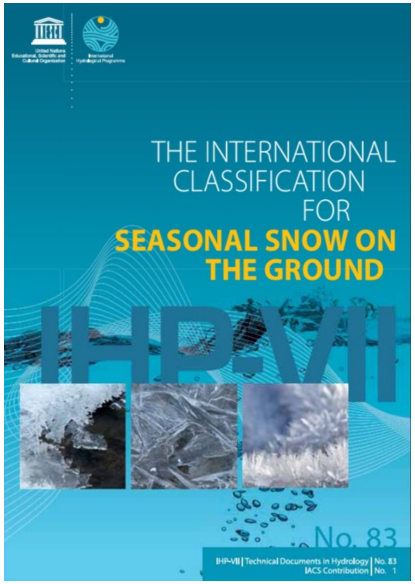


Snow temperature and T-gradient

- Calibrate thermometers in ice-water bath
- Insert thermometer in regular (10 cm) intervals (or into individual layers)
- Insert thermistor array into shaded pit wall
- Use data logger to record temperatures
- Calculate temperature gradient as $\Delta T/\Delta z$


Snow grain size and type

- Visual observation using lens and gridded card (or lens w/grids included)
- Classification according to international standards

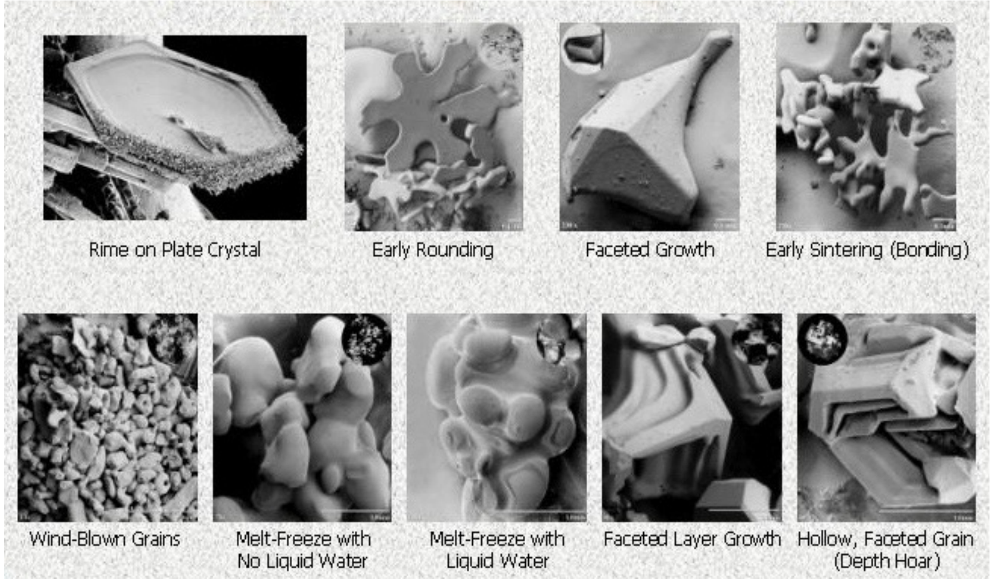


THE INTERNATIONAL CLASSIFICATION FOR
SEASONAL SNOW ON THE GROUND

IHP-VII

No. 83

IHP-VII | Technical Documents in Hydrology | No. 83
IACS Contribution | No. 1



Rime on Plate Crystal

Early Rounding

Faceted Growth

Early Sintering (Bonding)

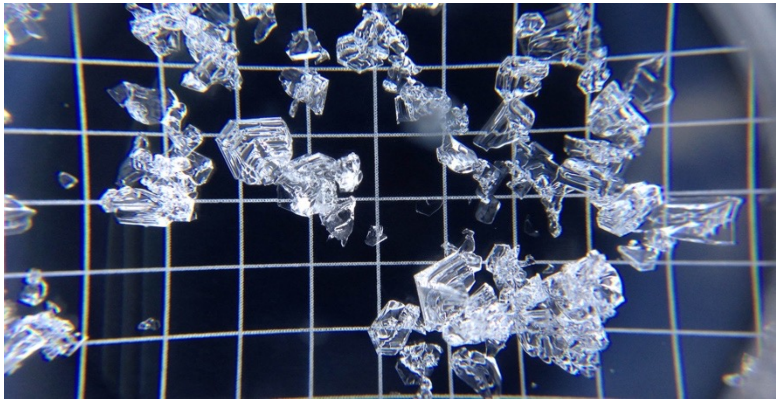
Wind-Blown Grains

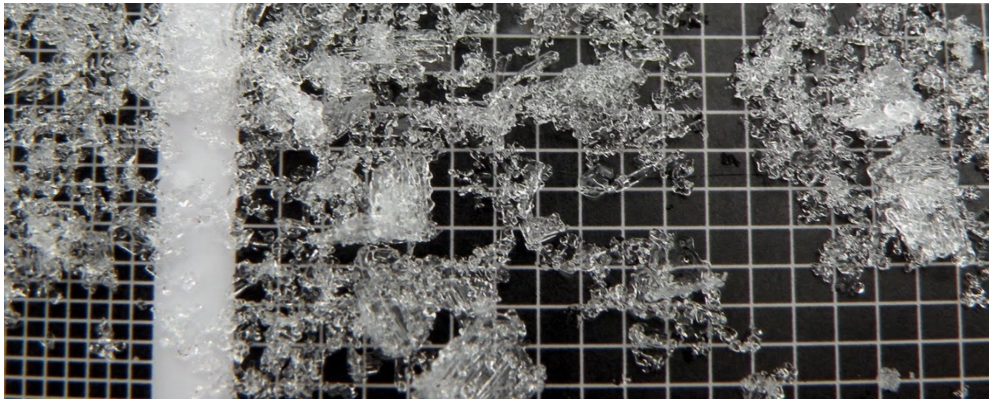
Melt-Freeze with No Liquid Water

Melt-Freeze with Liquid Water

Faceted Layer Growth

Hollow, Faceted Grain (Depth Hoar)





Liquid Water Content (LWC)

Dielectric constant of ice is about 3, for liquid water it is about 86 → related to LWC

Fig. 1. Denoth (left) and Snow Fork (right) measurement devices.

Figures: Techel and Pielmeier (2011)

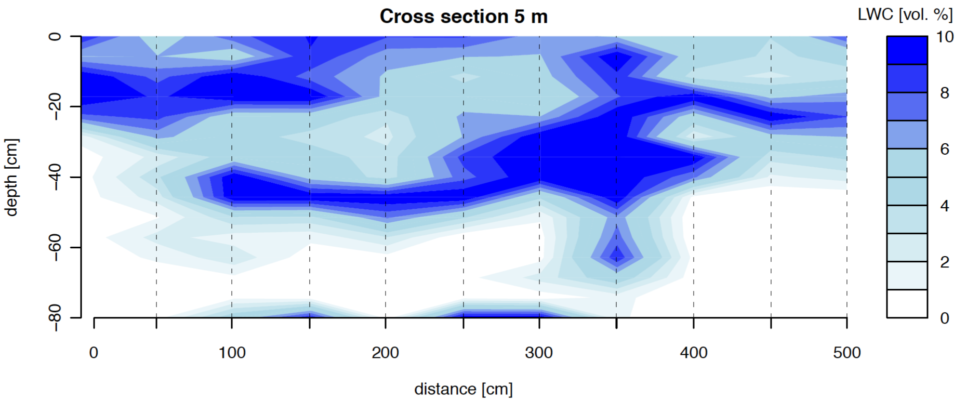
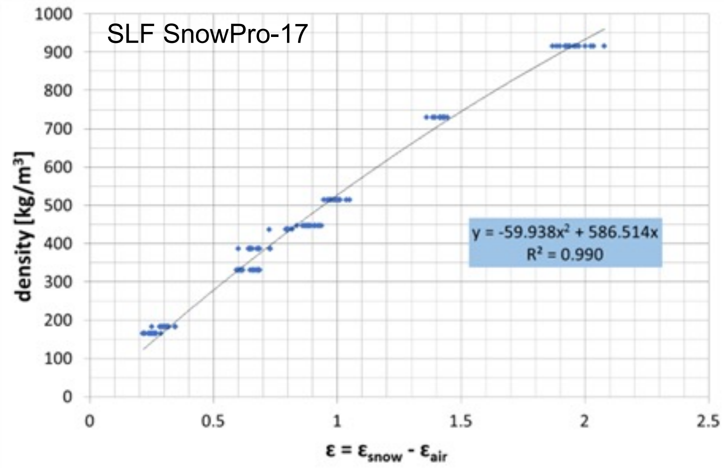
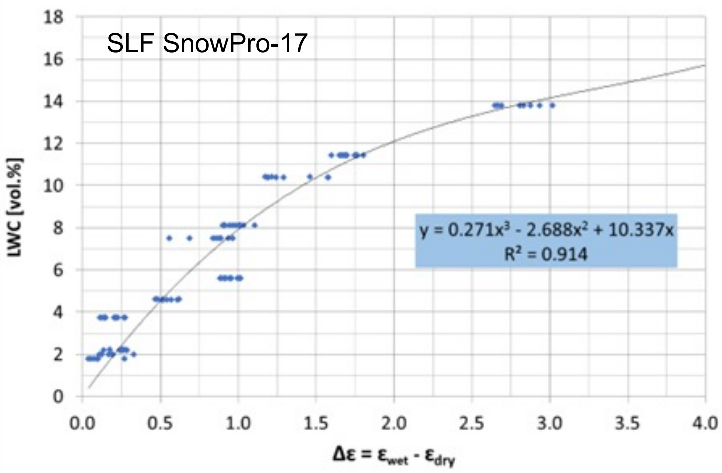


Fig. 5. Contour plot showing cross-section of snow wetness (θ) to a depth of 80 cm over 5 m wide areas across the slope. Measurements were conducted at horizontal intervals of 50 cm (lines) with a vertical spacing of 5 cm. 4 April 2009, S aspect, 2660 m, 30°. θ, measured with the Snow Fork, is corrected by −0.8 vol. % (this corresponds to the median offset in dry snow).



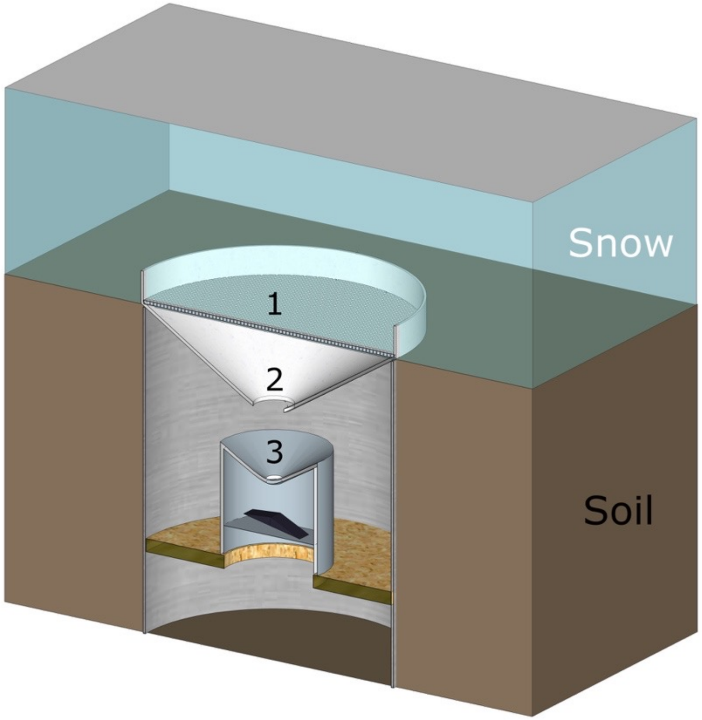


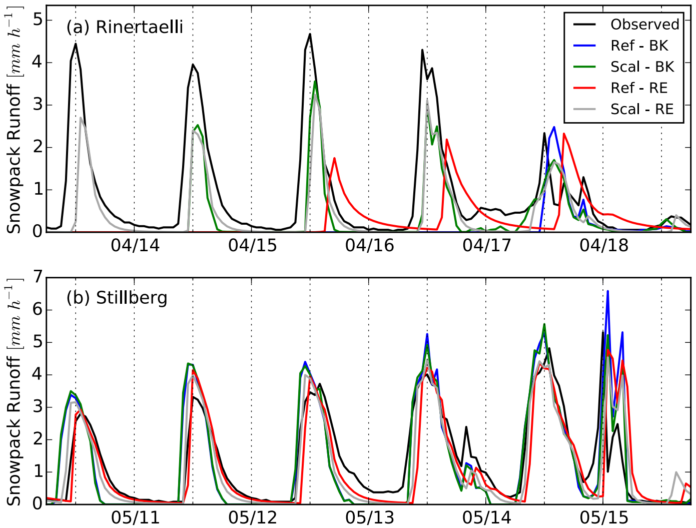
Melt water percolation

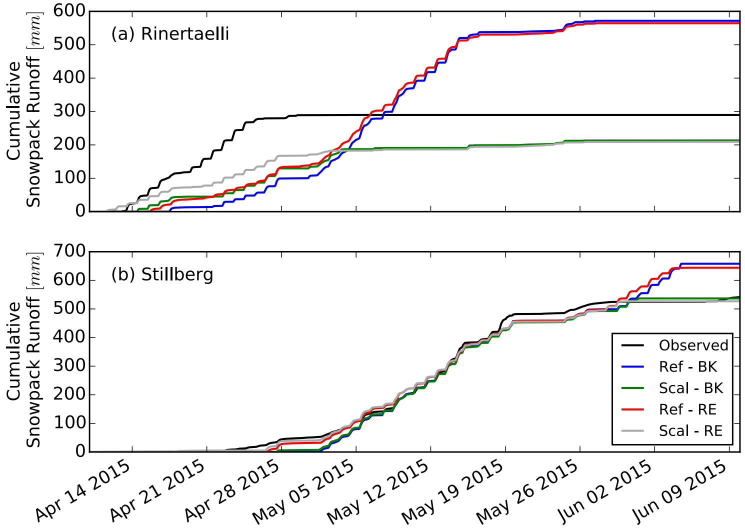
Recall:
SNOWPACK dual domain
Richard’s equation approach

Pictures: H.Huwald

Snow melt, liquid water output: Snow Lysimeter

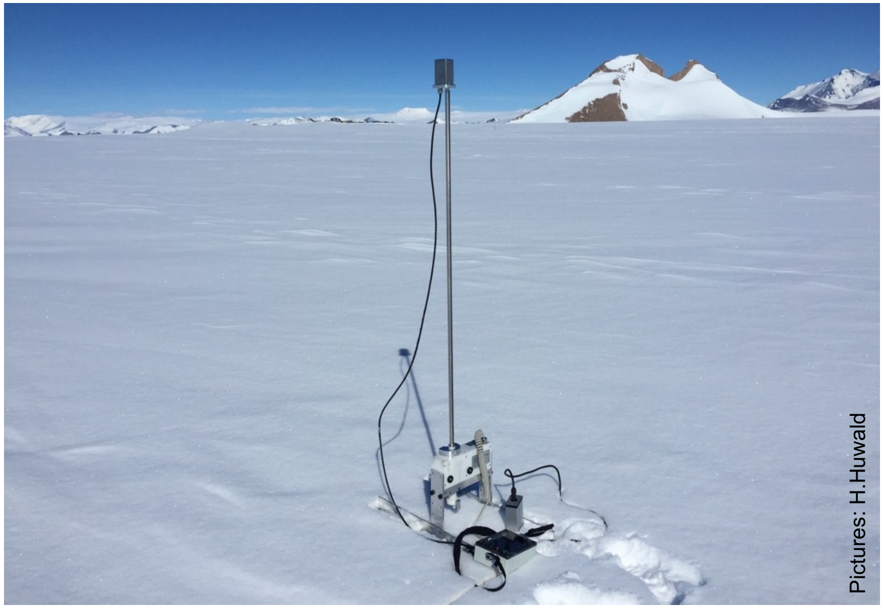




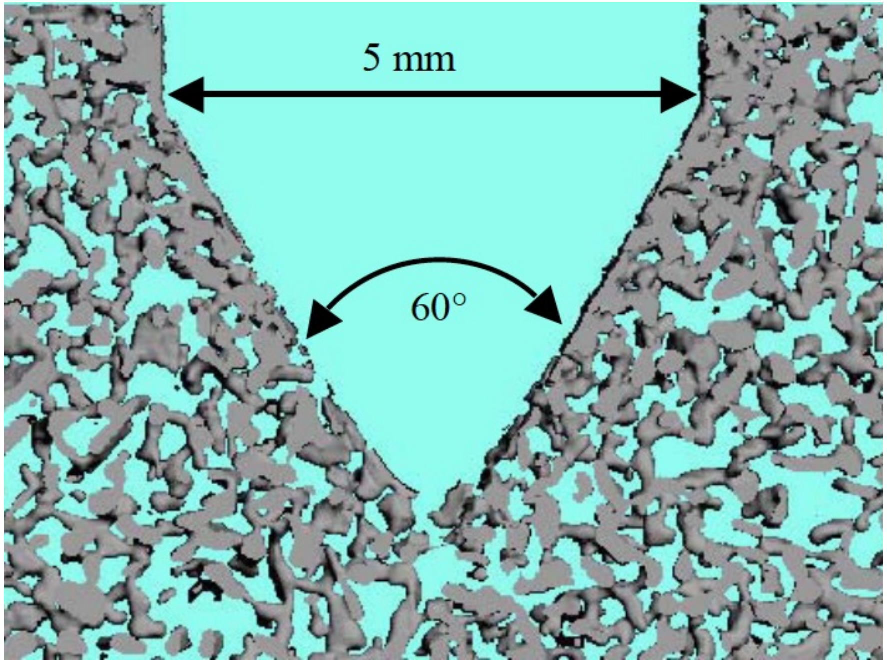


Brauchli et al. 2016

Snow Micro-Penetrometer (SMP)



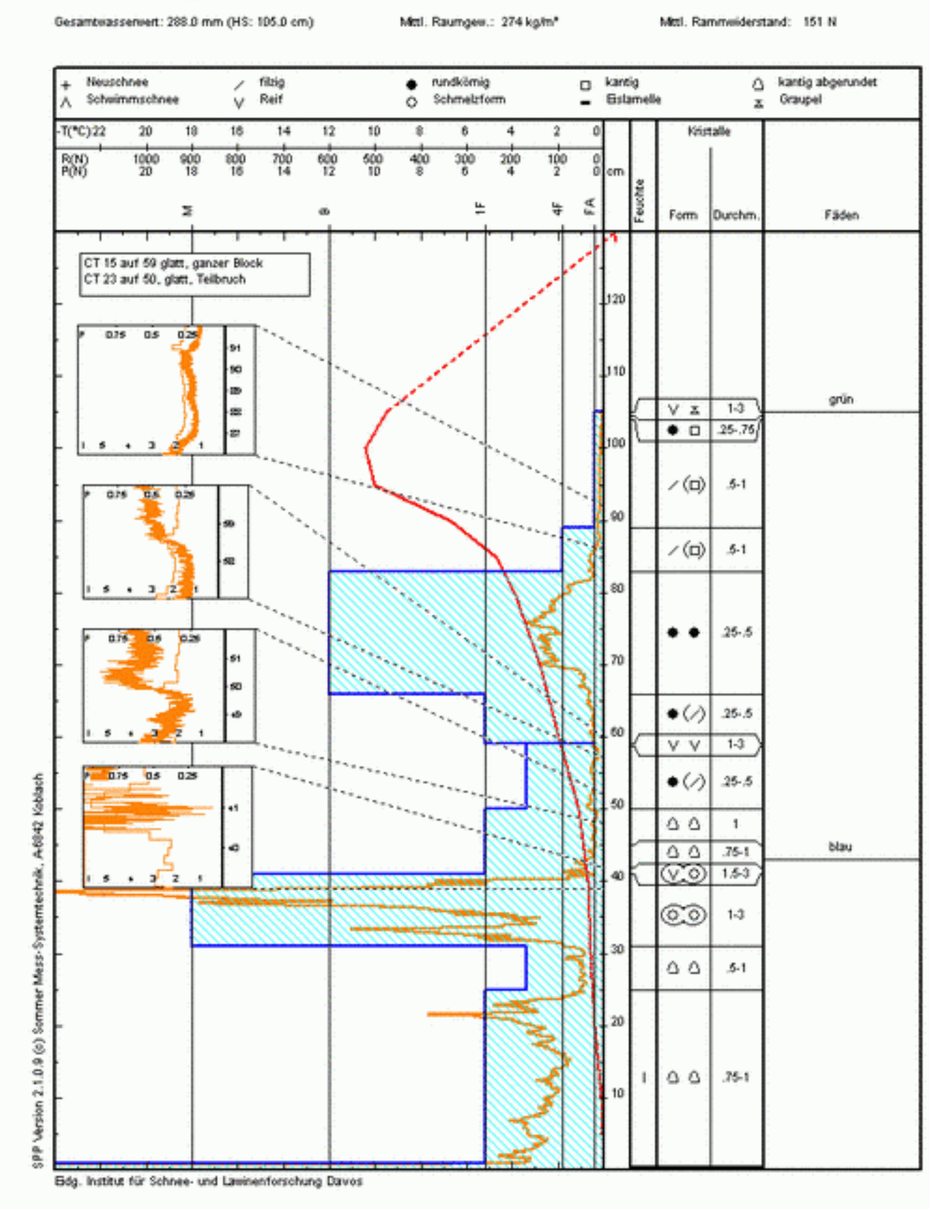
Pictures: H.Huwald



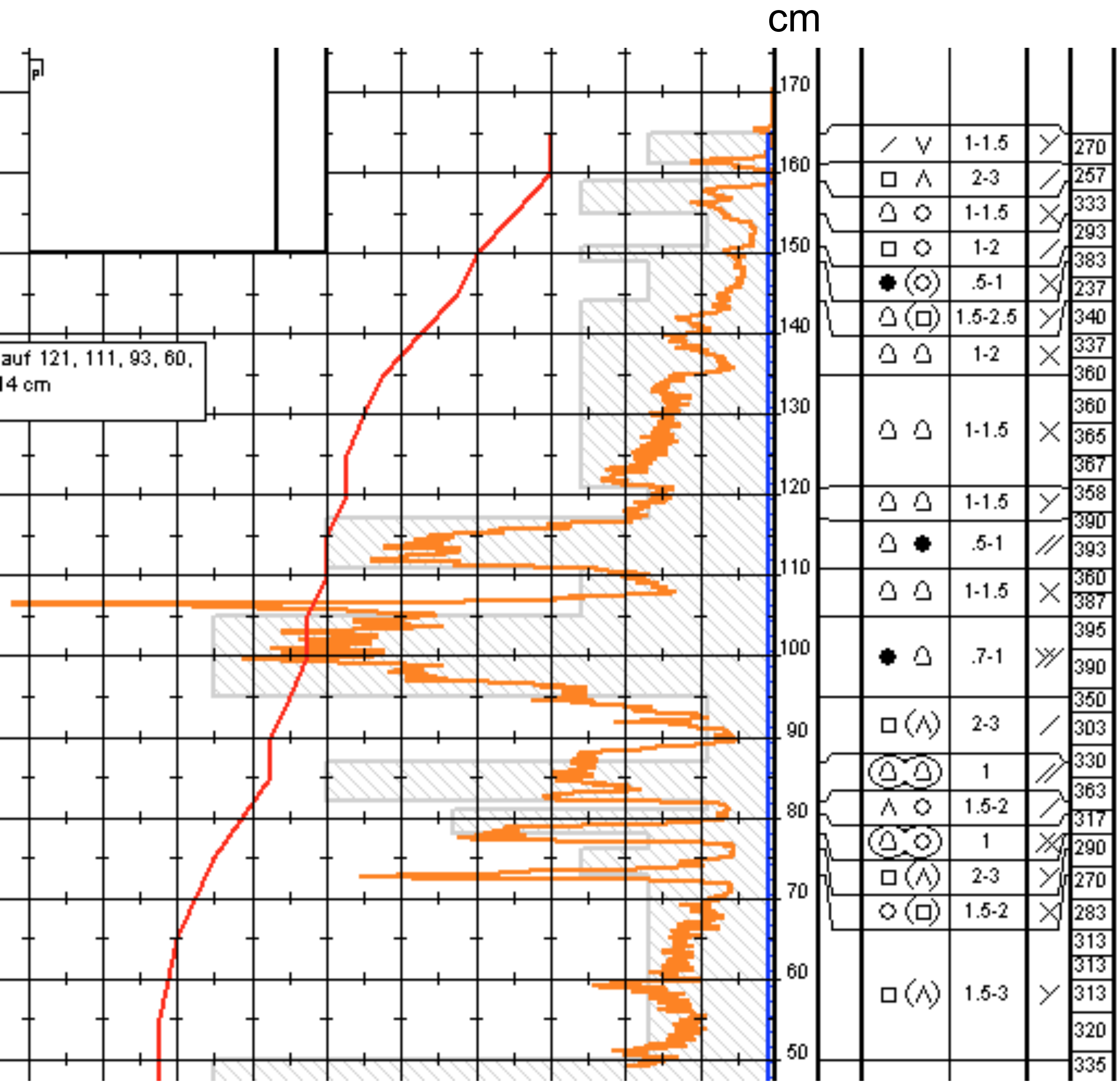
Snow Micro-Penetrometer (SMP)

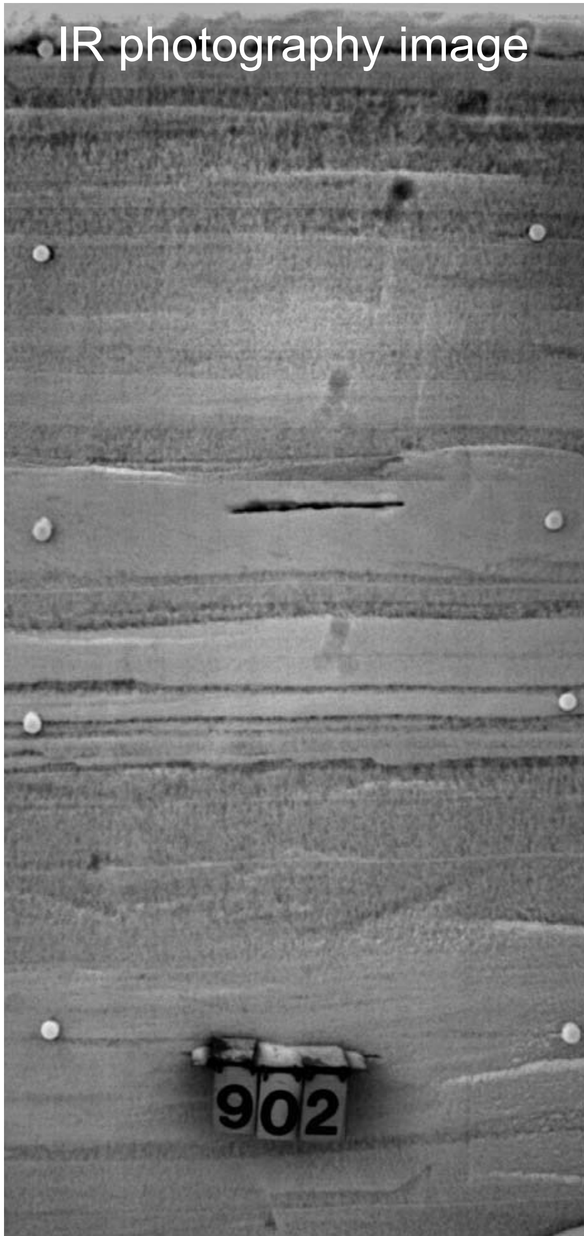
SMP – **S**now **M**icro **P**en:

- Measures penetration resistance (range 0-42 N ± 0.02 N)
- Fast speed penetrometer (20 mm s^{-1})
- High spatial resolution (4 µm, sampling rate 5 kHz
- Fine resolution force profile
- Detection of microstructural properties of snow
- Penetration force can be related to snow density and specific surface area

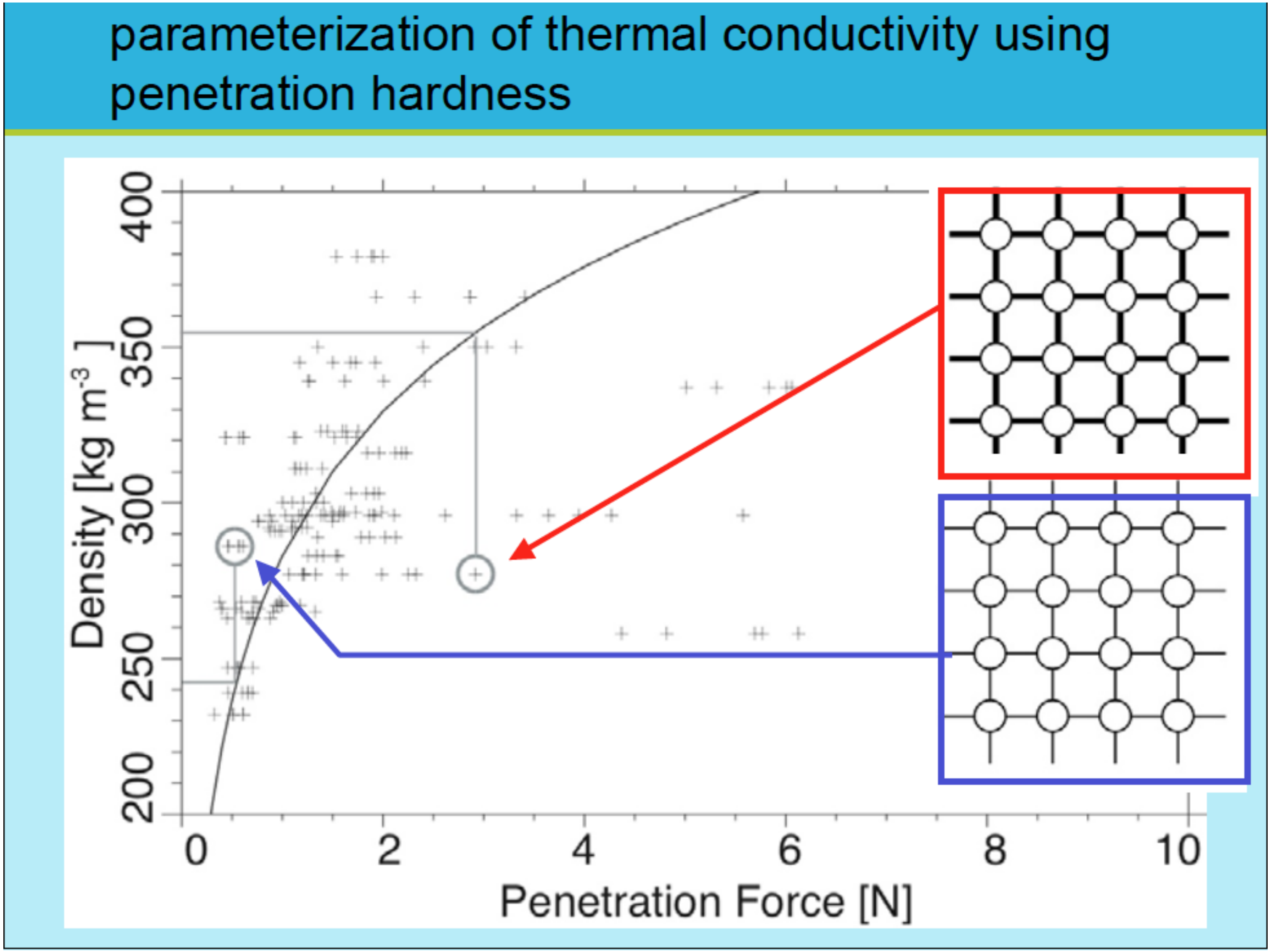


SMP @ Summit, Greenland





Thermal conductivity from penetration force ???



parameterization of thermal conductivity using penetration hardness

strong bonds

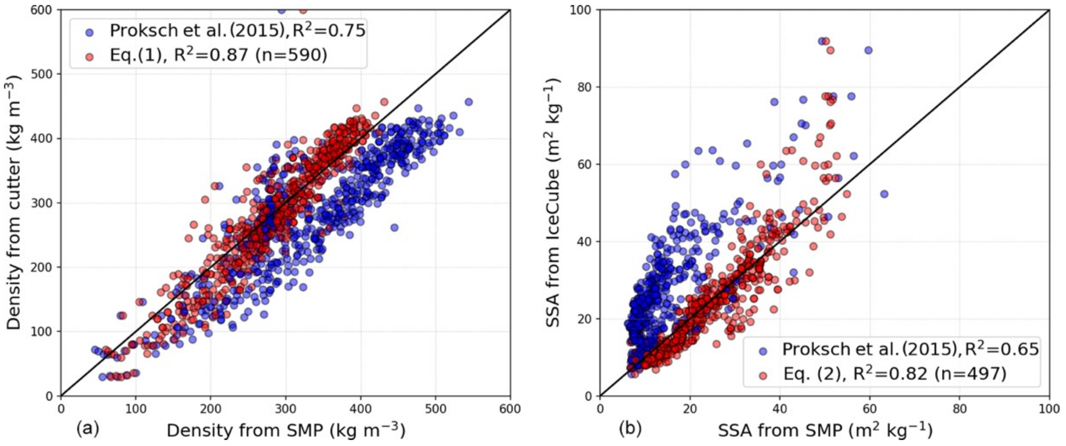
week bonds

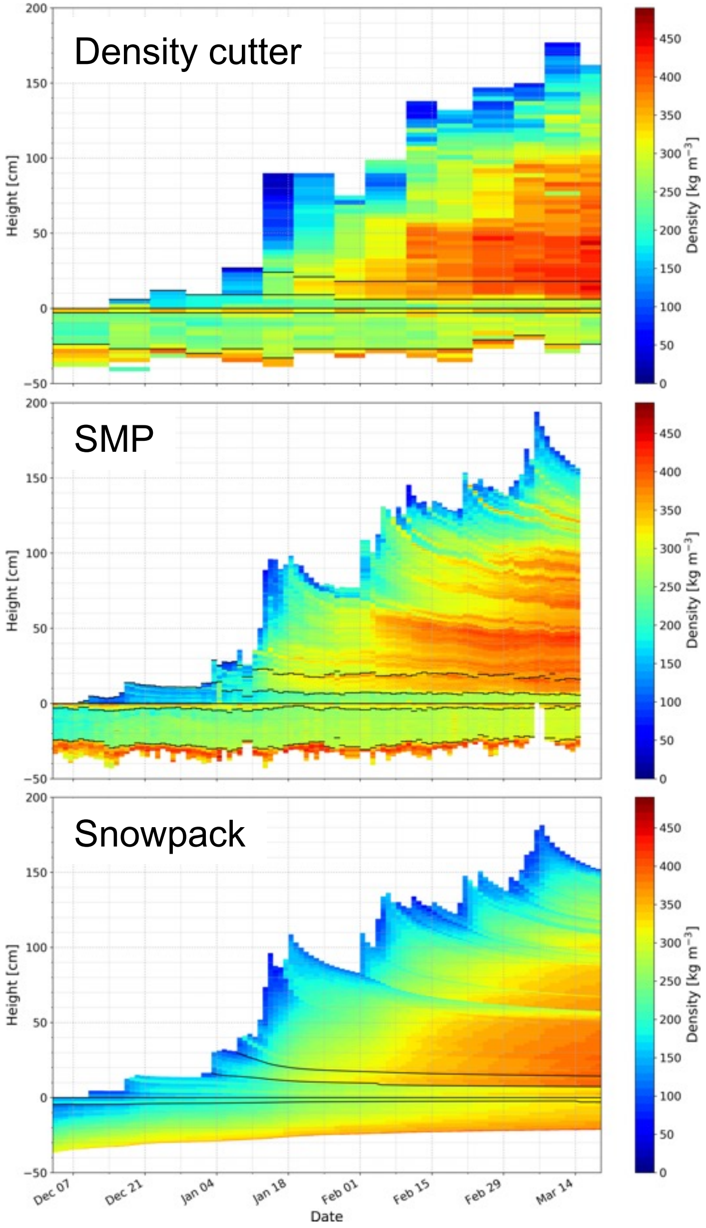
SMP derived quantities: ρ and SSA

$$\rho_{smp} = a_1 + a_2 \ln(F) + a_3 \ln(F)\, L + a_4 L$$

$$SSA_{smp} = b_1 + b_2 \ln(L) + b_3 \ln(F)$$

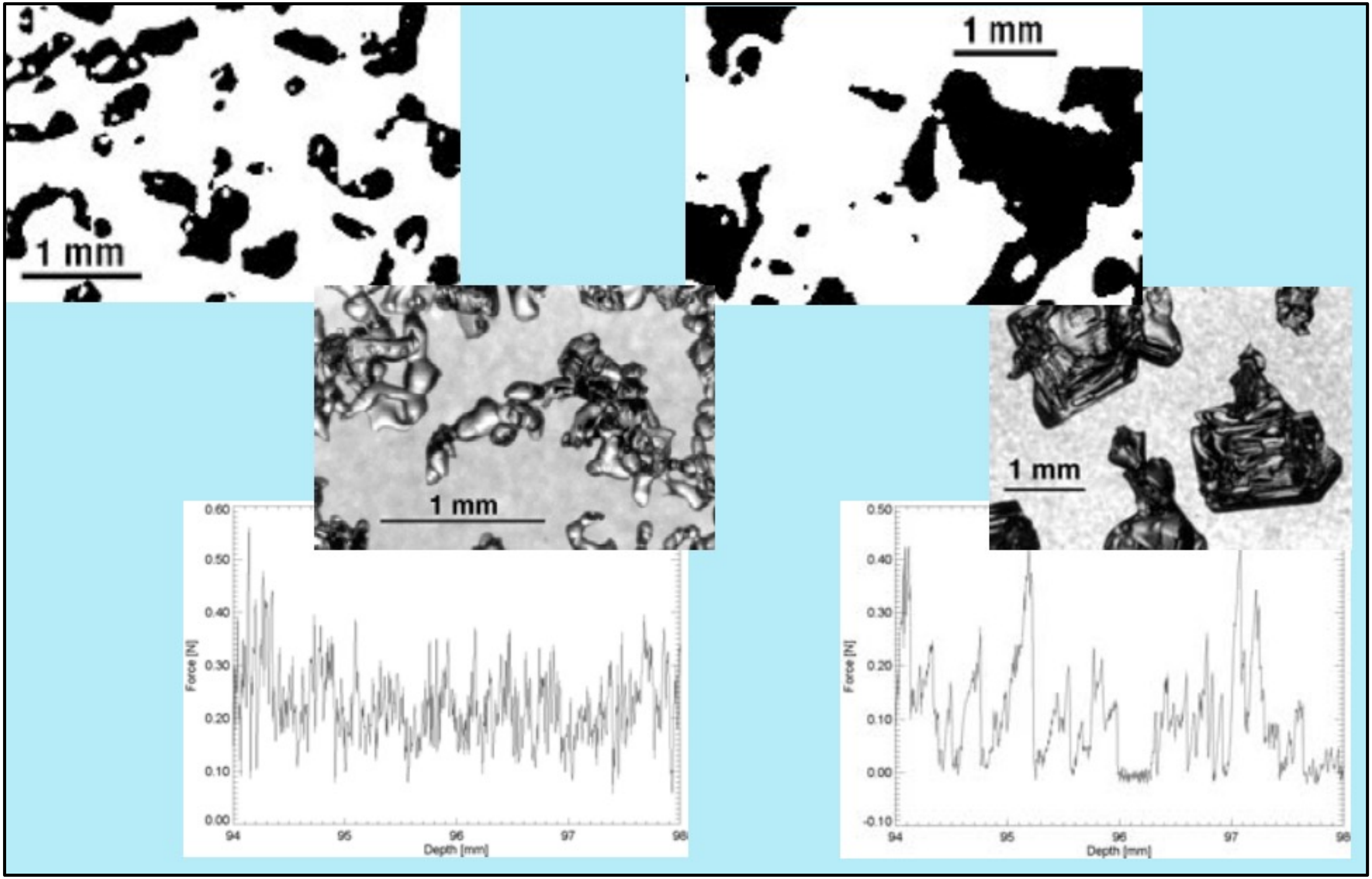
where F is penetration force [N]
and L is characteristic length [mm]





Calonne et al. TC, 2020

SMP Force signal for two snow types



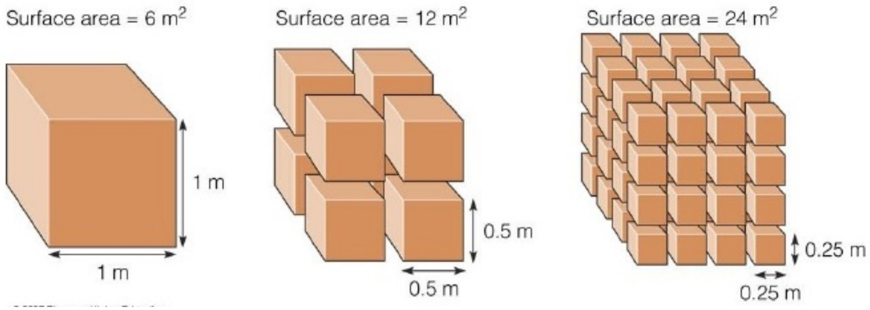
Summary / conclusion SMP

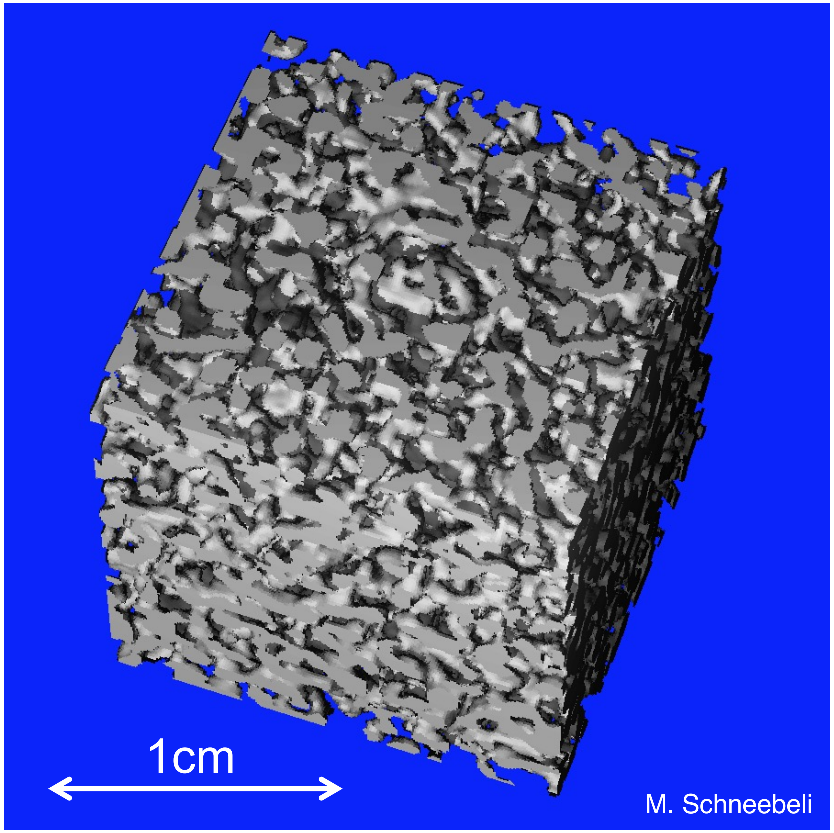
- The SnowMicroPen is a unique tool to detect highly resolved, spatially distributed microstructural properties
- Quantitative measurement of mechanical properties at the sub-millimeter scale
- Mechanical snow strength and SMP strength are well correlated
- Snow stability can be calculated from a penetration profile
- Shows subtle features within layers: gradients, cyclic features, micro-layers
- SMP is used in diverse, alpine, and polar environments: Alps, Rocky Mountains, Alaska, Andes, Himalaya, Greenland, Antarctica
- SMP is a precision instrument

Specific surface area (SSA)

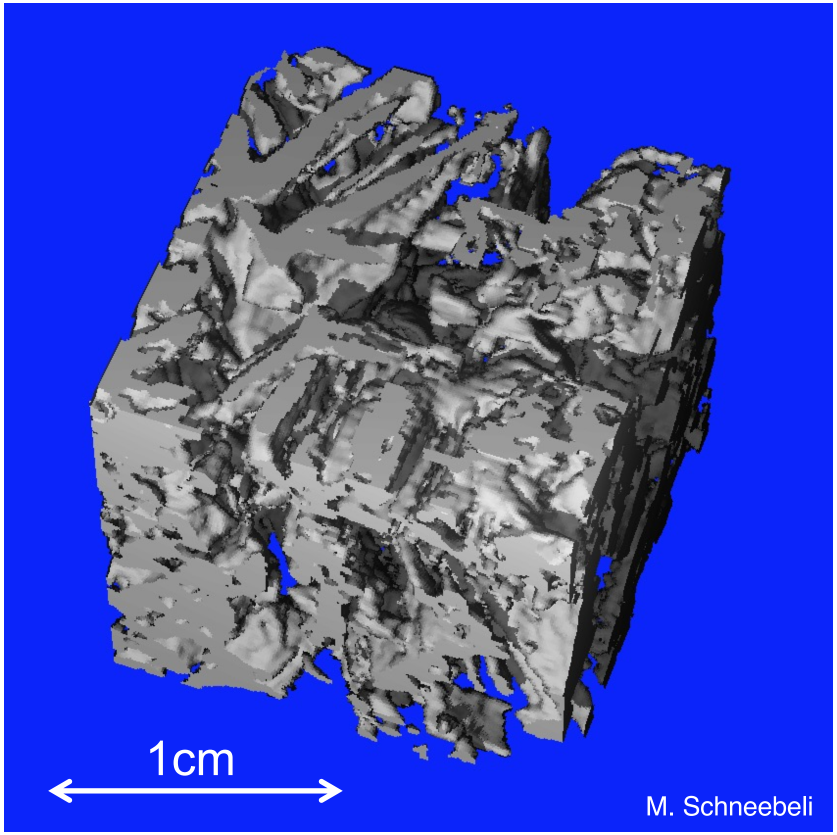
Surface area of ice / volume of ice:

$$SSA = A_{ice} / V_{ice}$$



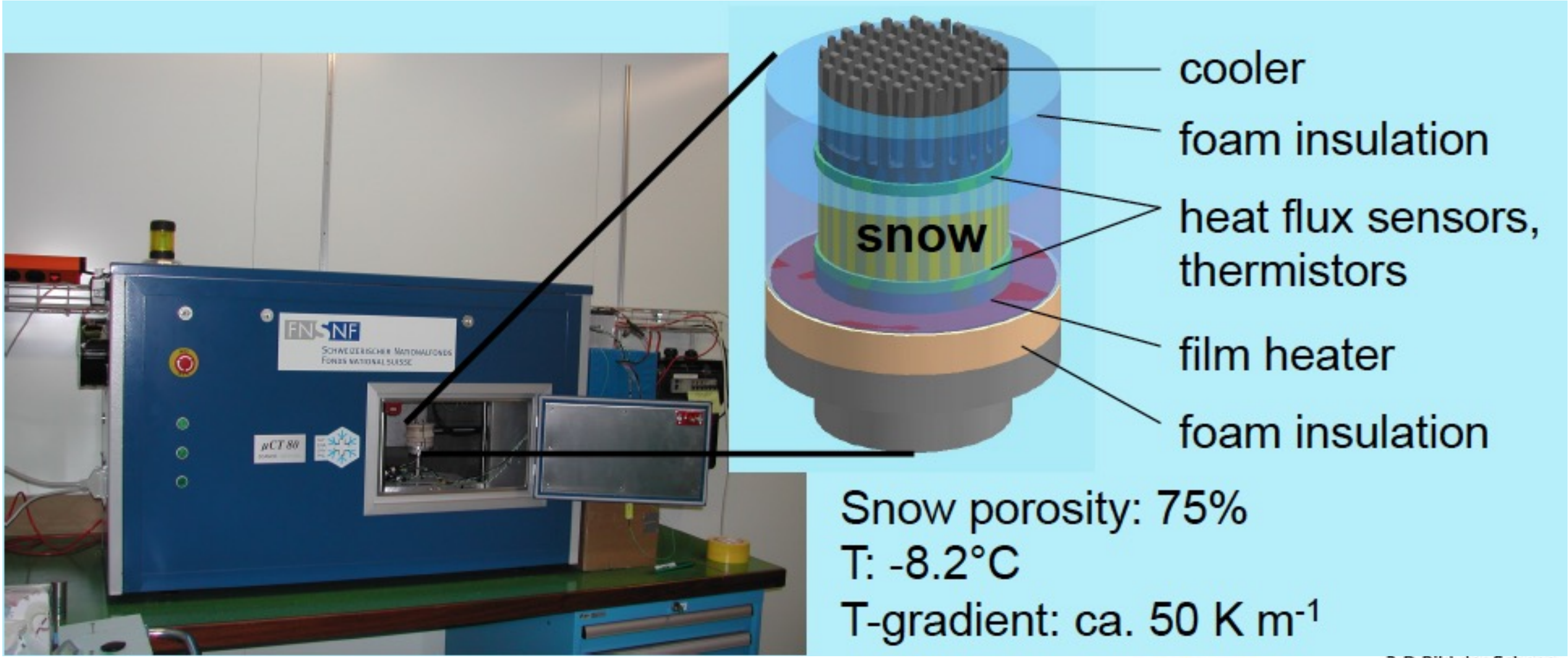


M. Schneebeli



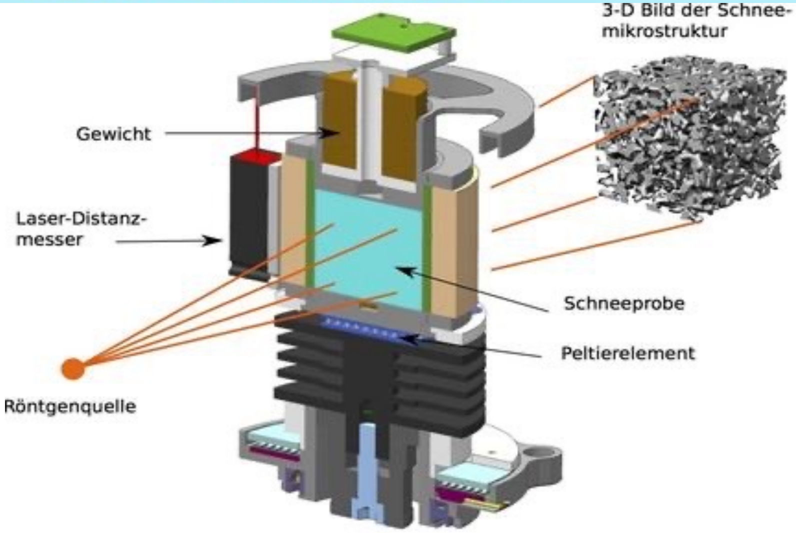
M. Schneebeli

μ-CT: in-situ observation of snow



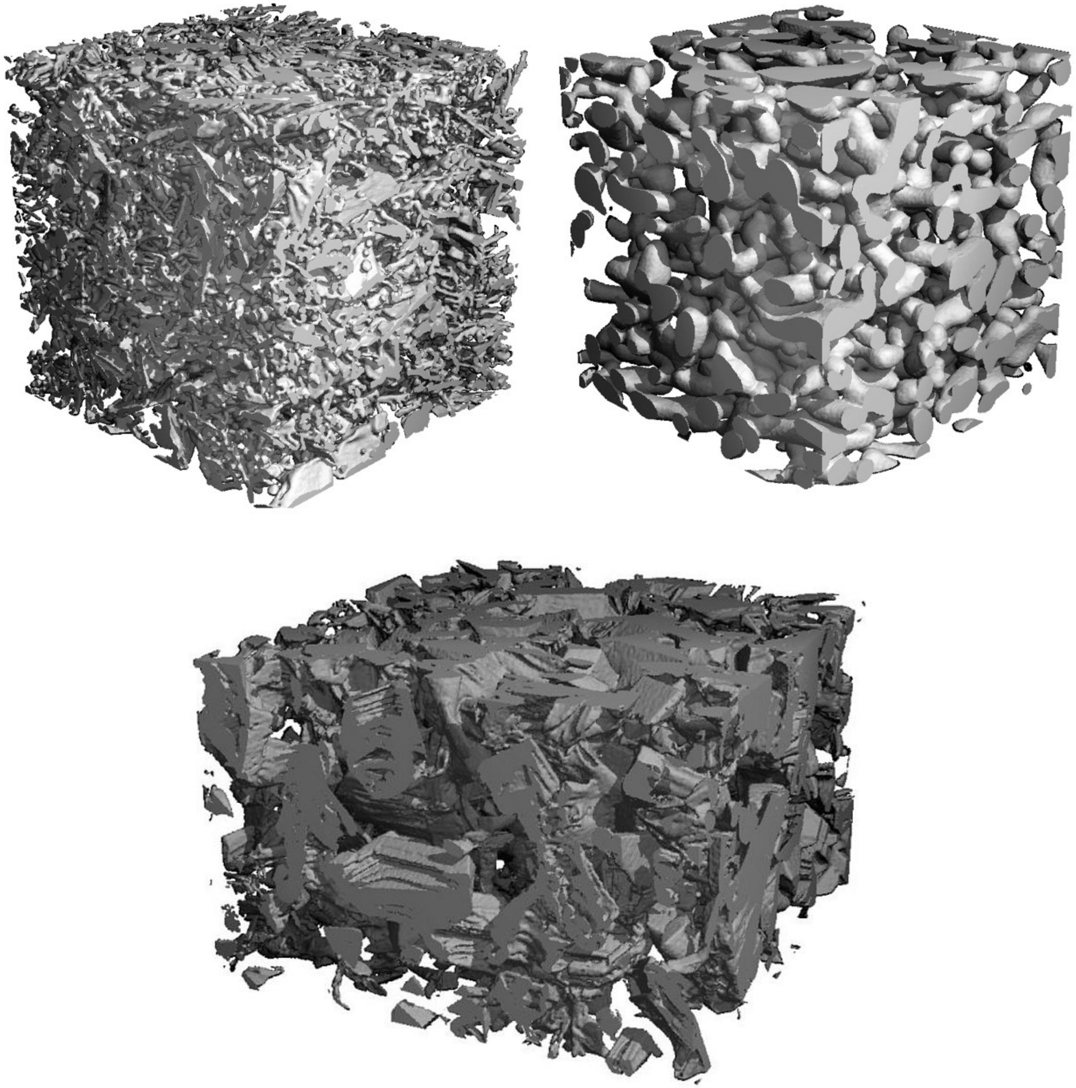
Snow porosity: 75%
T: -8.2°C
T-gradient: ca. 50 K m^{-1}

- Micro-CT in cold-room (-17°C)
- Controlled T & gradT in sample
- Undisturbed snow structure observation
- Simultaneous heat flux measurements

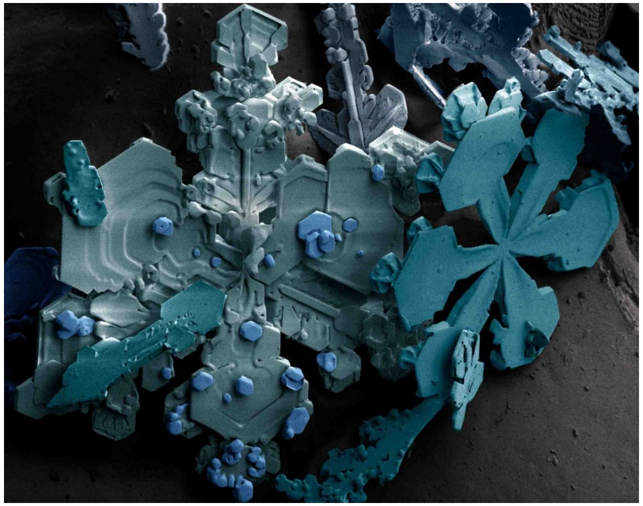


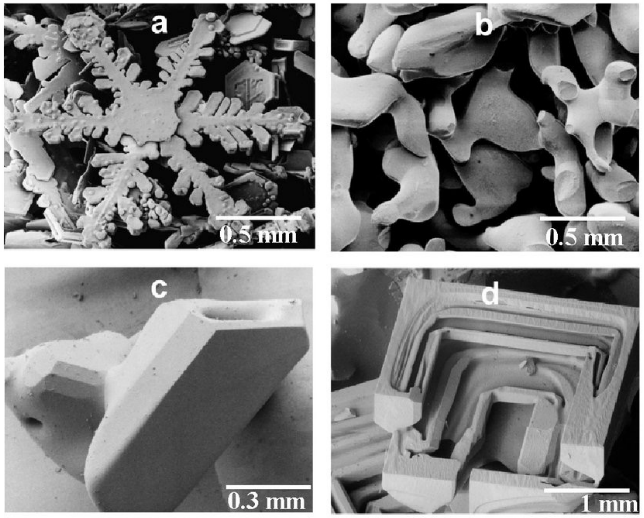
Crystal and snow matrix imaging

X-Ray Computed Tomography



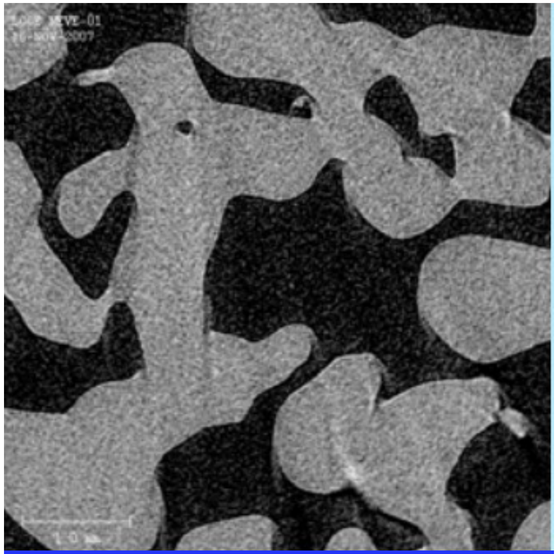
Scanning Electron Microscope

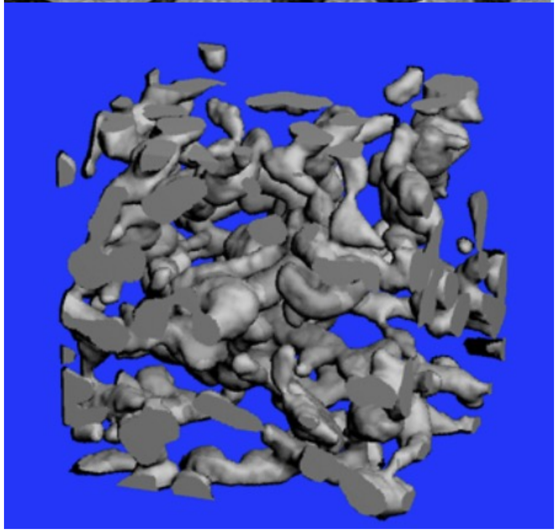


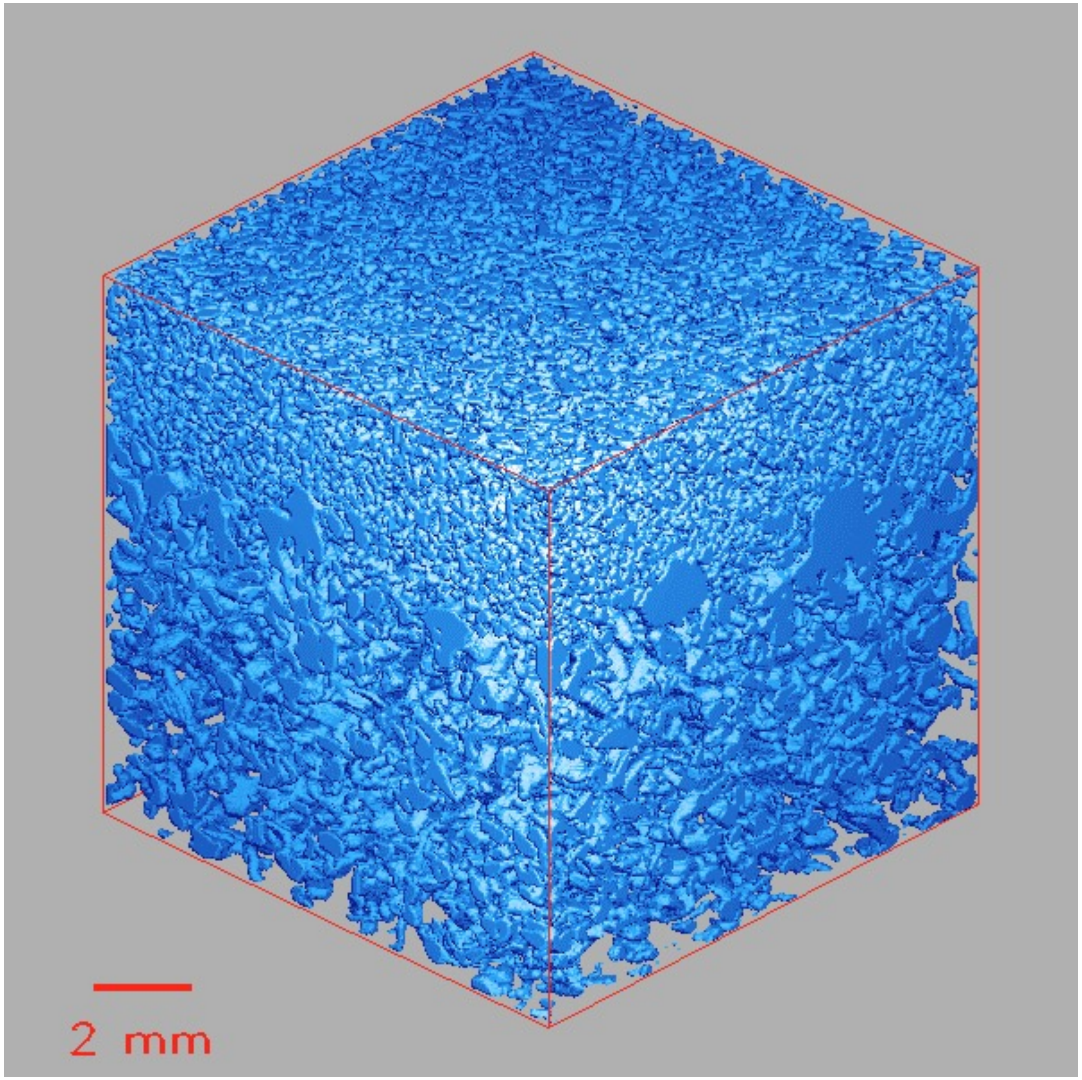


Snow microstructure measurement

2D section and 3D image





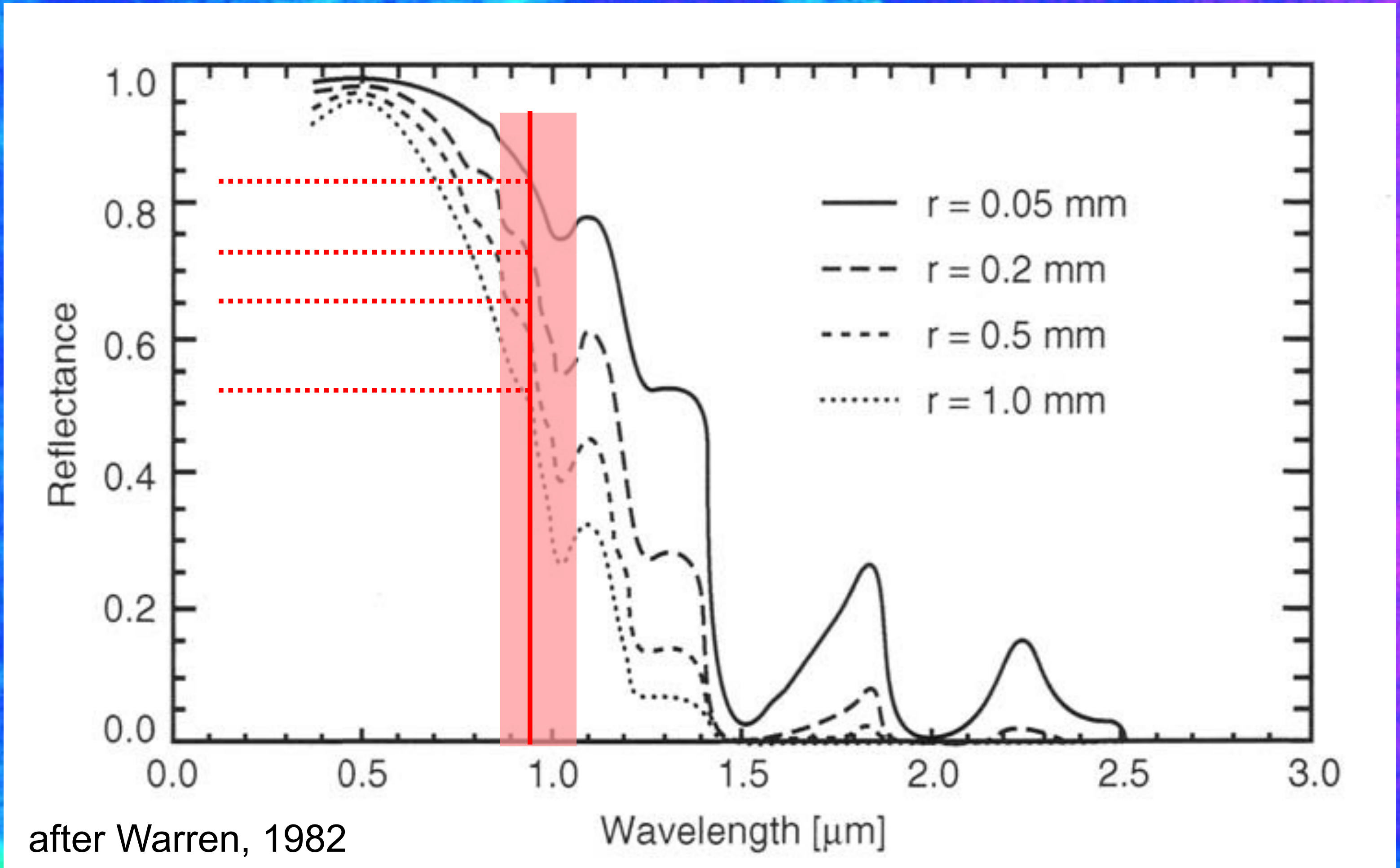


Snow types in the micro-CT

new snow **rounded snow** **depth hoar**

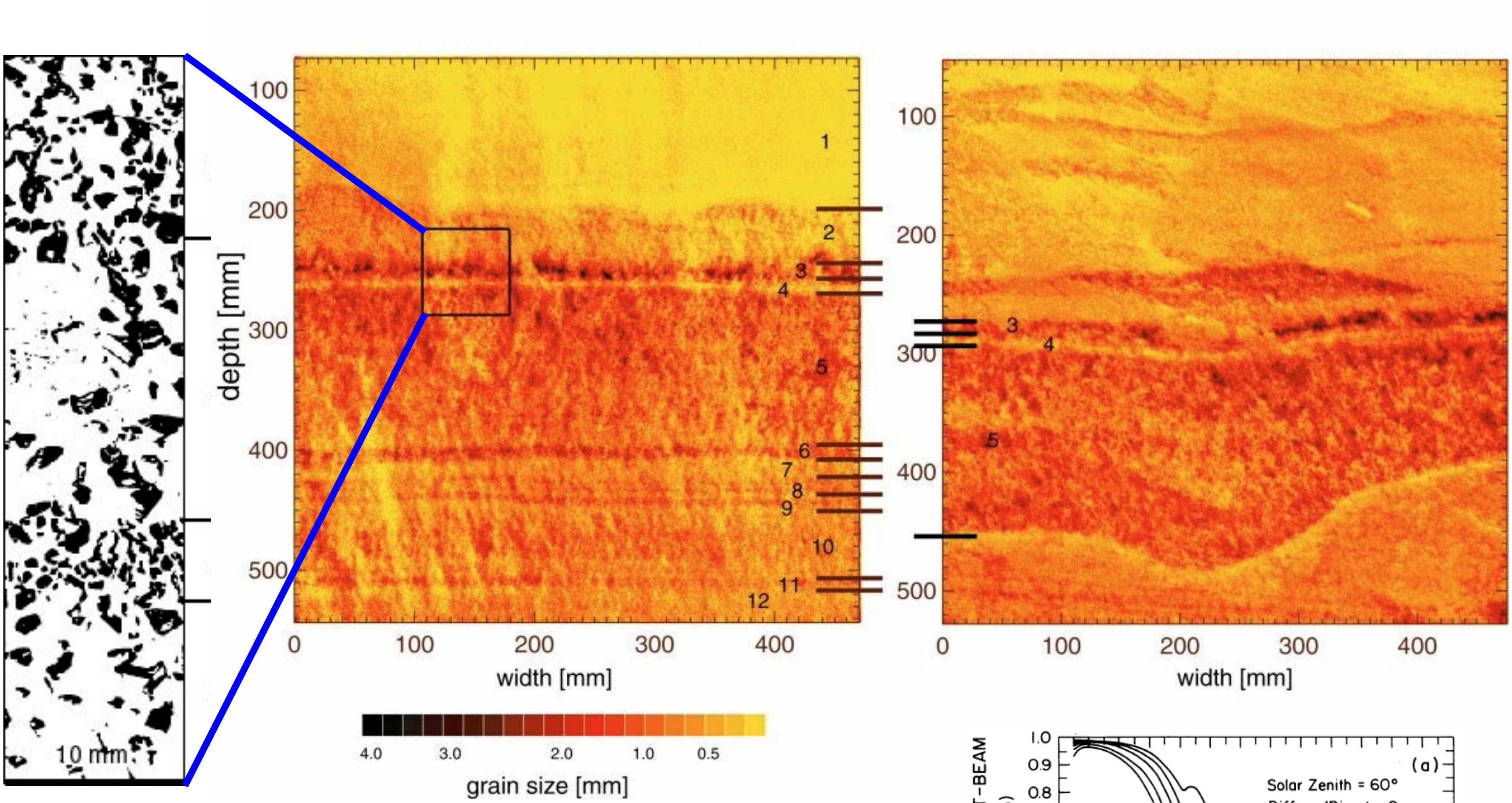
Near-infrared (NIR) photography (multi-spectral)

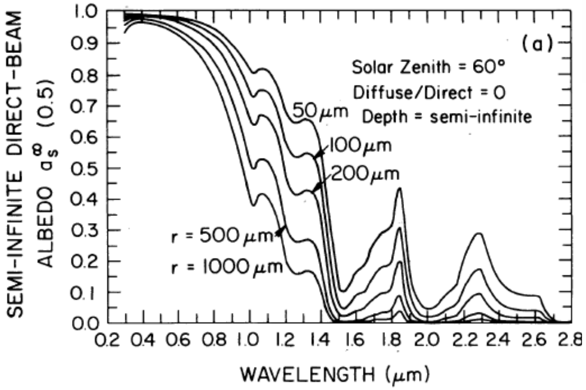
- Imaging of snow grain size; reflectance = f(r)
- Detection of microstructure and stratigraphy



after Warren, 1982

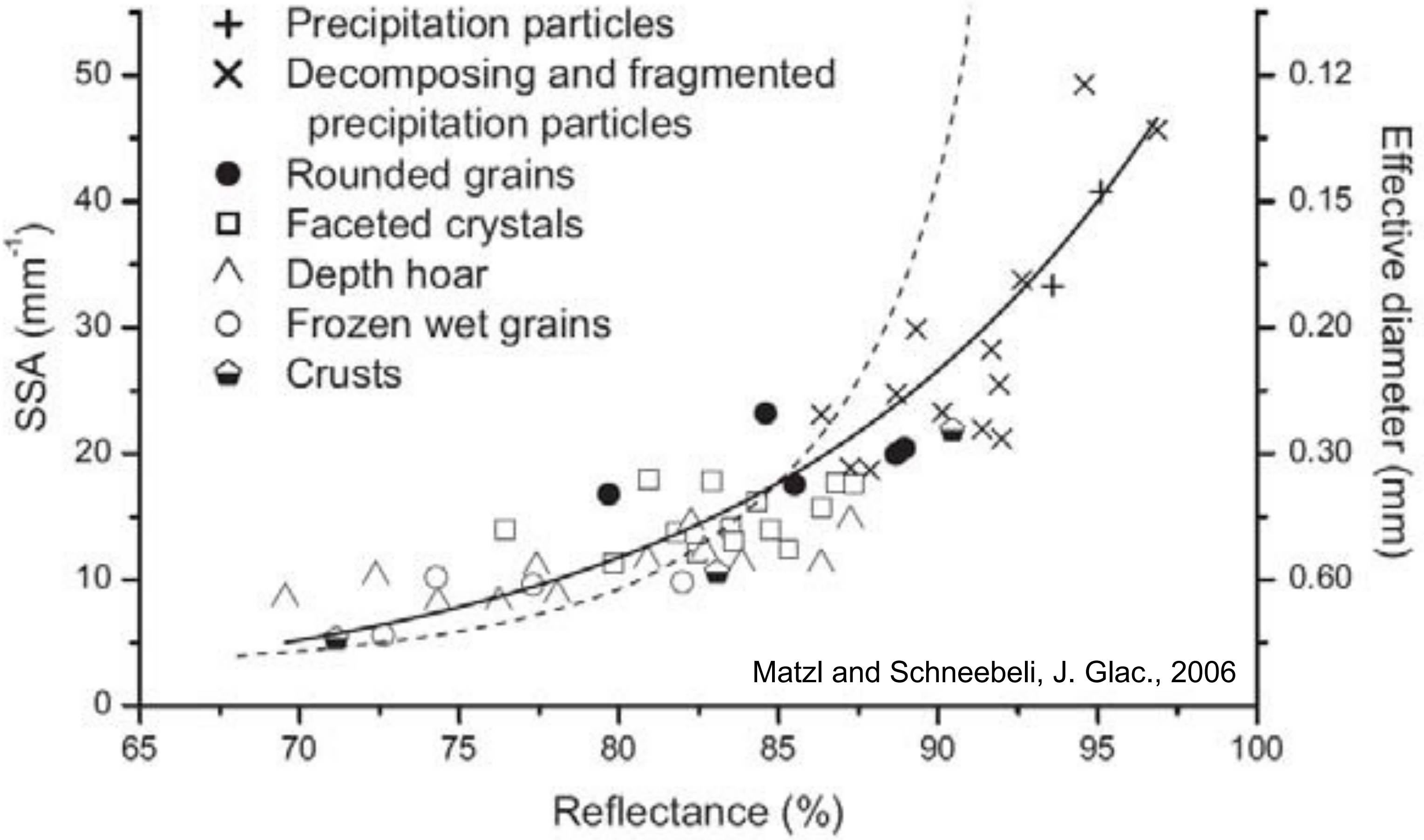
NIR photography examples





Recall:
(energy balance, spectral reflectance)

SSA optical diameter vs. NIR reflectivity



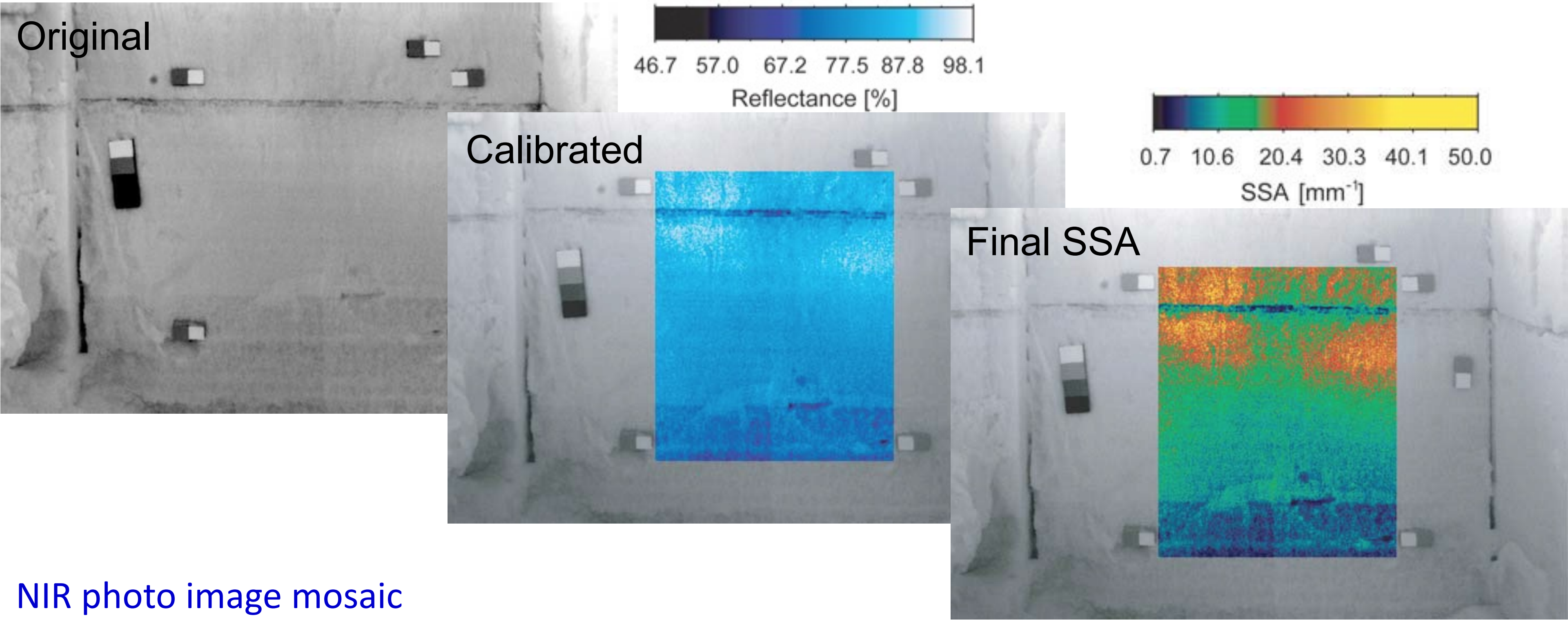
Matzl and Schneebeli, J. Glac., 2006

SSA = A e^(r / t), where

$A = 0.02 \pm 0.01 mm^{-1}$ and

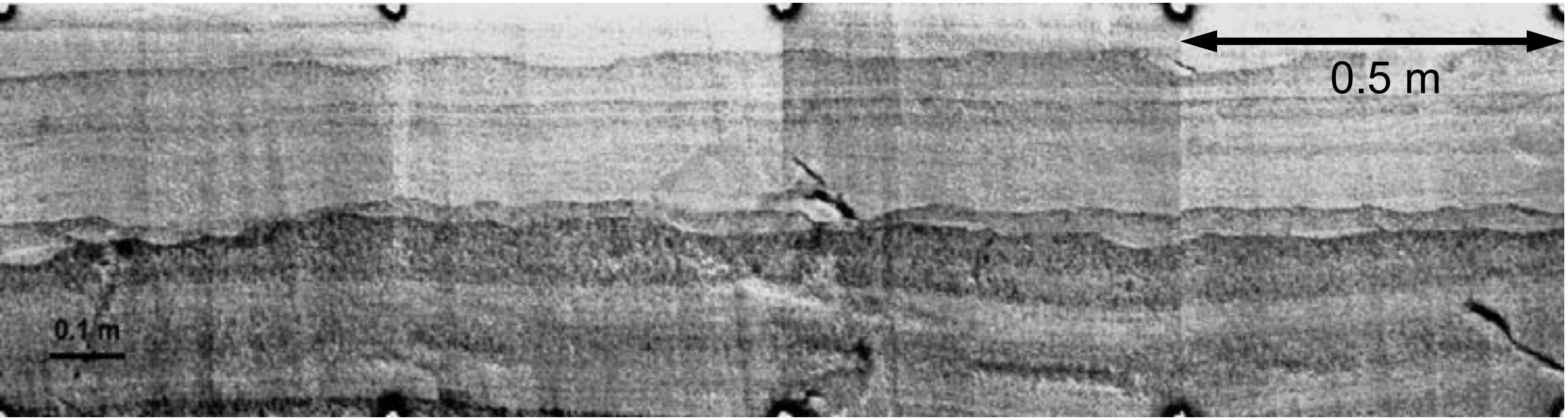
$t = 12.22 \pm 0.84$. $R^2 = 0.908$.

From NIR-photo to SSA



NIR photo image mosaic

Snow stratigraphy, from NIR photography (2m horizontal)

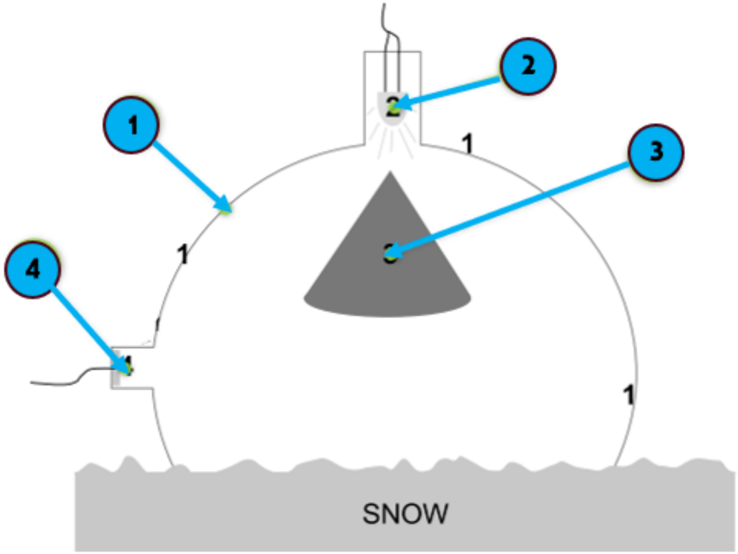


SSA optical measurement

SLF InfraSnow SSA sensor

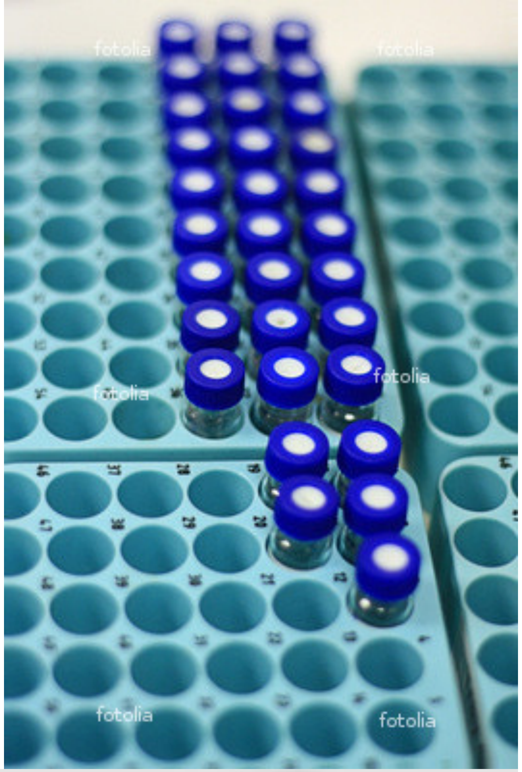
Measures SSA of snow with an optical sensor. The method consists of diffuse near-infrared reflectance measurements using a compact integrating sphere setup to derive SSA. Diffuse reflectance is measured at a NIR wavelength, where impurities have only a weak influence on the reflectance of snow.

InfraSnow Measurement Principle [Gergely et. al, 2014]



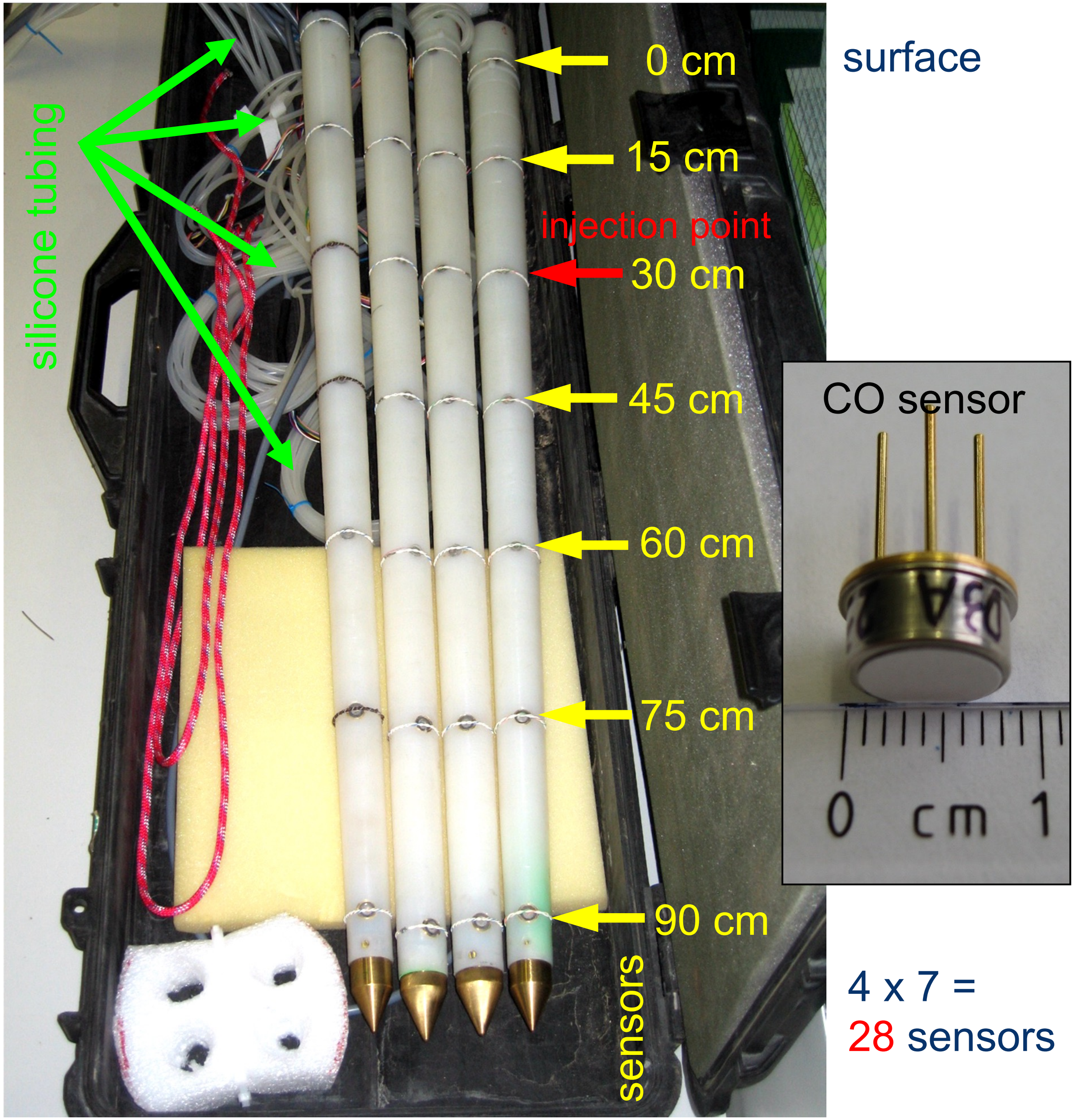
(1) Integrating Sphere, (2) NIR Light Source, (3) Diffusor, (4) Photodiode Detector

Stable isotopes of water



Evaluating sublimation processes using stable isotopes of water

Gas dispersion in snow



surface

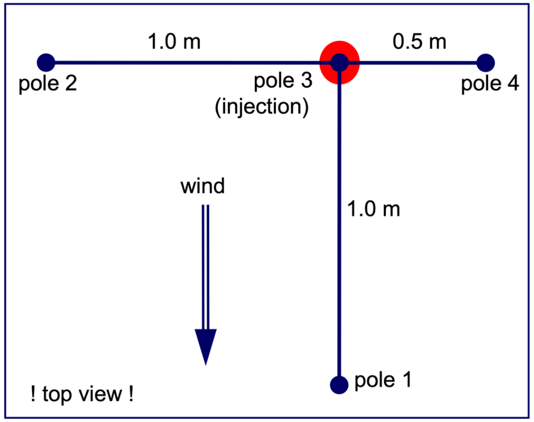
4 x 7 =
28 sensors

Field site and experimental setup:

Glacier de la Plaine Morte, Crans-Montana, Switzerland,

2775m altitude, January 2007.

Injection of 500 ml 1% CO in pole no.3 at 30 cm depth.



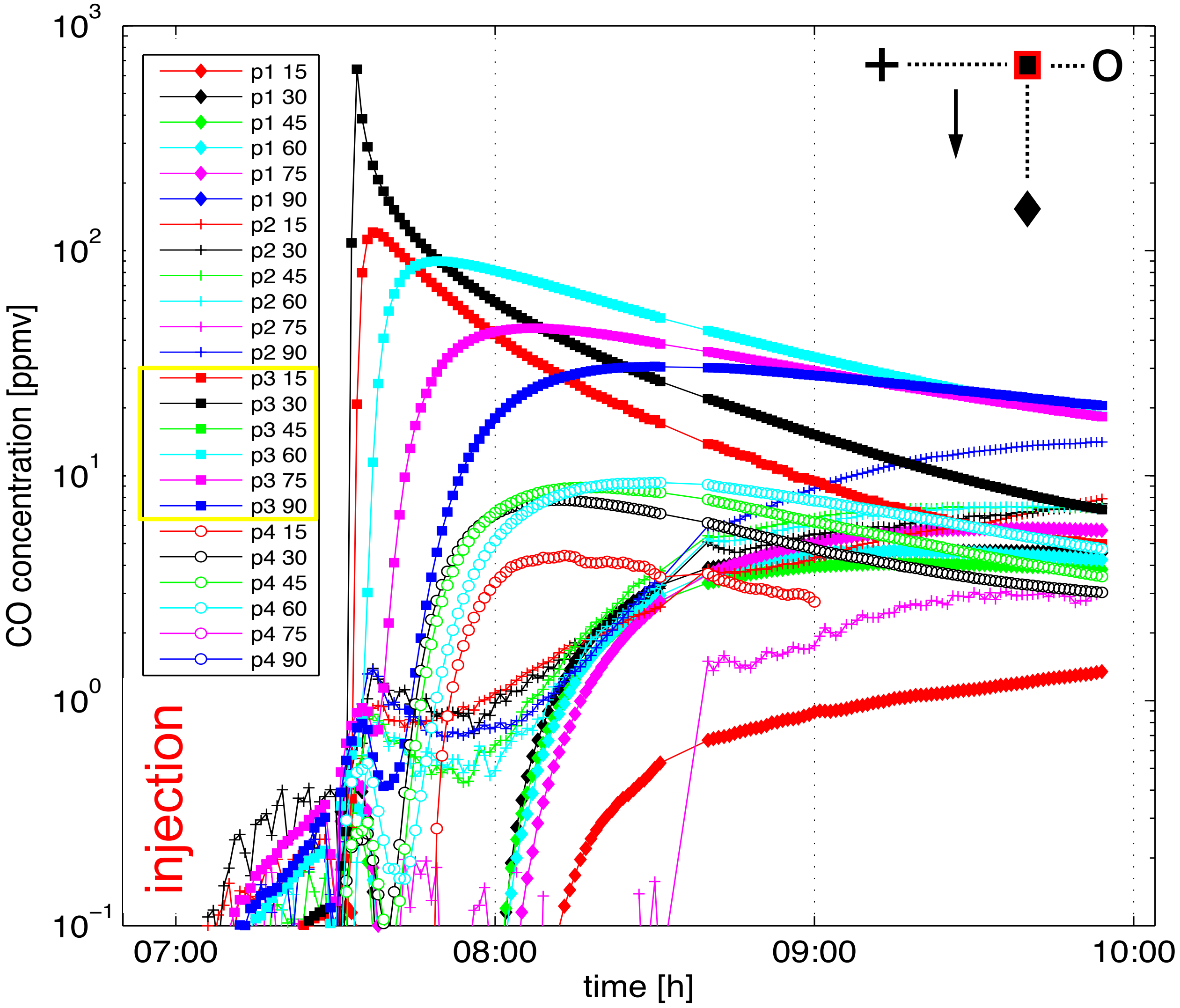
Calibrated data: log-linear

Advection – diffusion equation:

$$\theta\frac{\partial C}{\partial t}+\nabla\cdot\mathbf{u}C-\nabla\cdot\left(\mathbf{D}\cdot\nabla C\right)=0$$

$$D=\varepsilon\,\theta D_{CO}$$

D: diffusion coeff.
θ: porosity
ε: tortuosity



Solution for an instantaneous point injection:

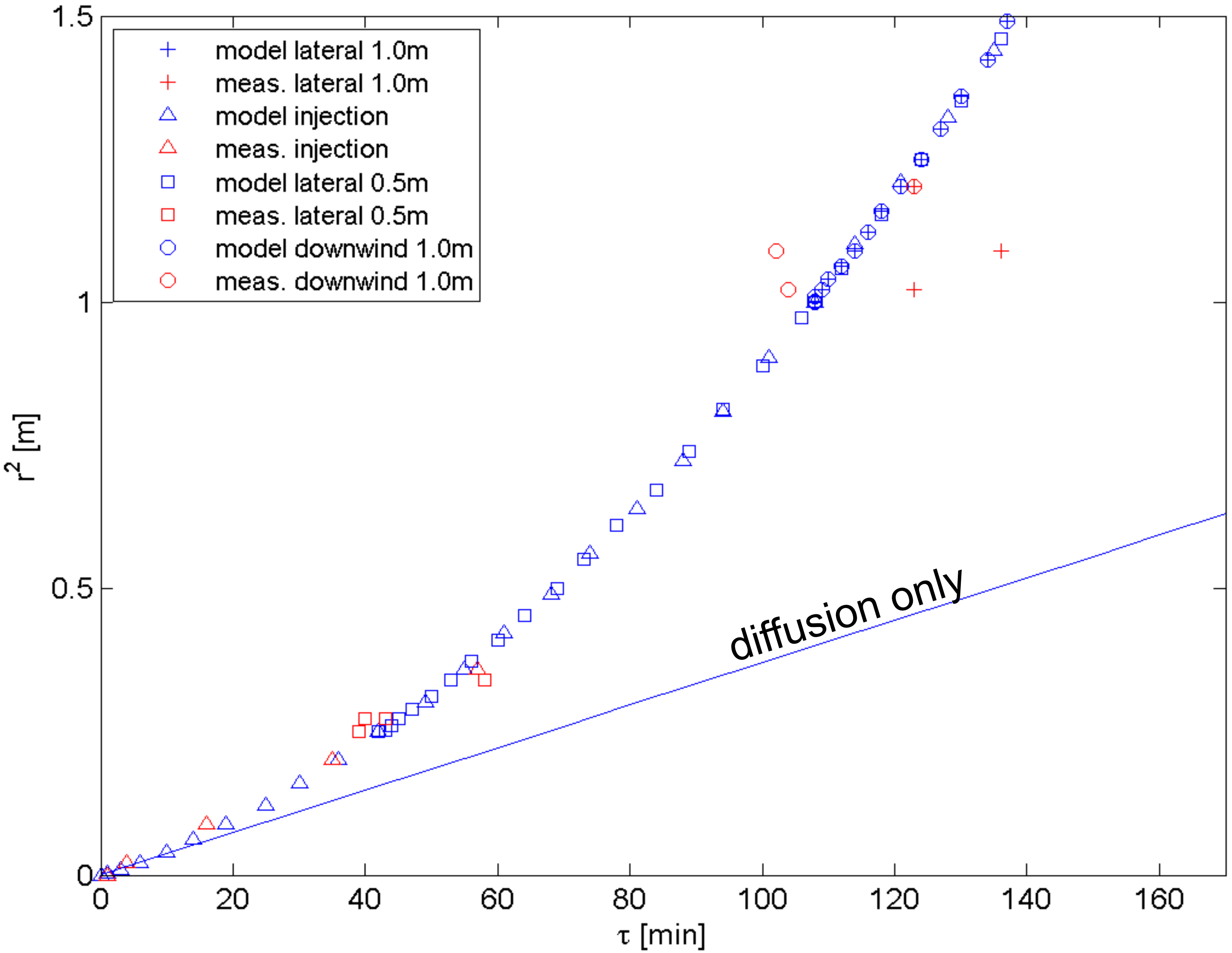
$$C(x,y,z,t)=\frac{M}{\theta(4\pi t)^{3/2}(D_xD_yD_z)^{1/2}}*\Bigg[\exp\left(-\frac{(x-ut)^2}{4D_xt}-\frac{(y-vt)^2}{4D_yt}-\frac{(z-d-wt)^2}{4D_zt}\right)\boxed{+\exp\left(-\frac{(x-ut)^2}{4D_xt}-\frac{(y-vt)^2}{4D_yt}-\frac{(z+d-wt)^2}{4D_zt}\right)}\boxed{-\exp\left(-\frac{(x-ut)^2}{4D_xt}-\frac{(y-vt)^2}{4D_yt}-\frac{(z-(h+d)-wt)^2}{4D_zt}\right)}\Bigg].$$

Base: no-flux BC

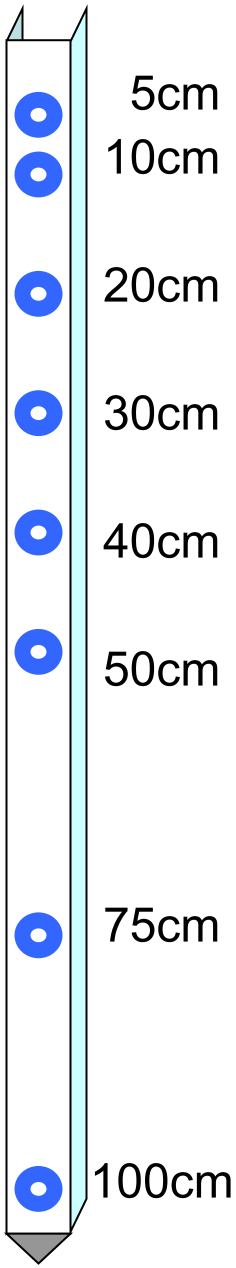
Surface: zero-concentration BC

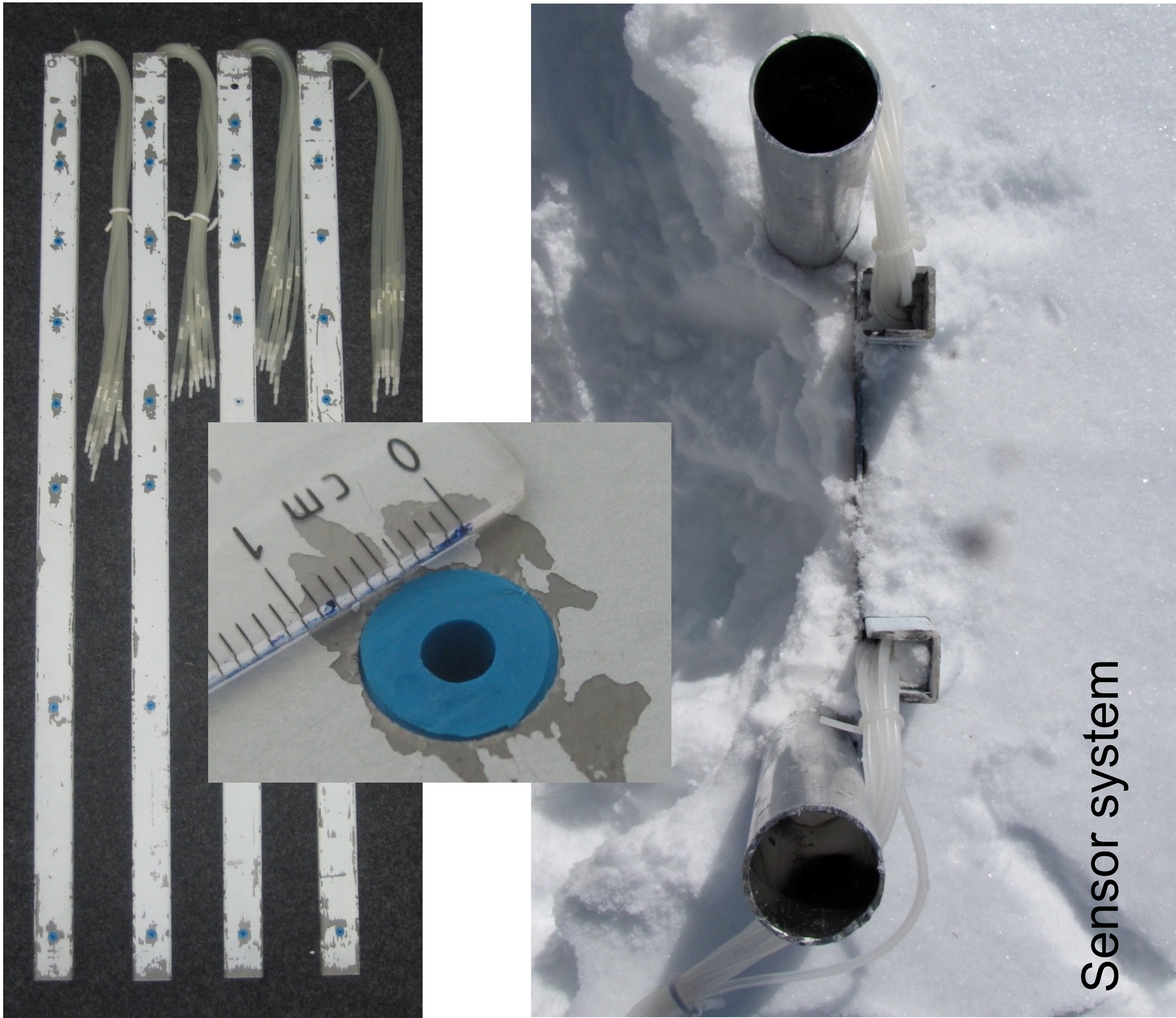
Impact of advection velocity

Radial distance from the injection point versus the breakthrough time



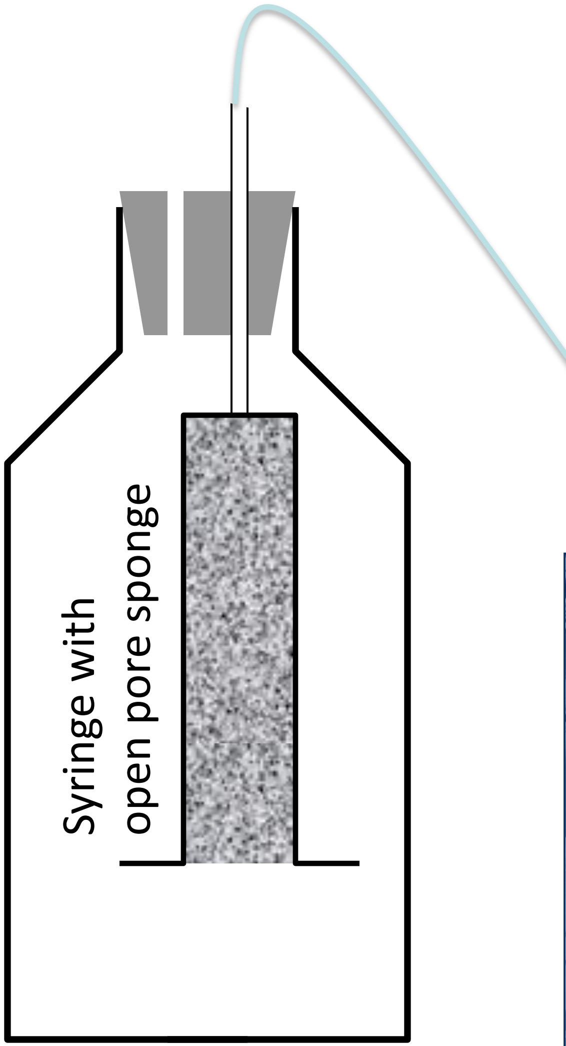
Air pressure fluctuations in the snow

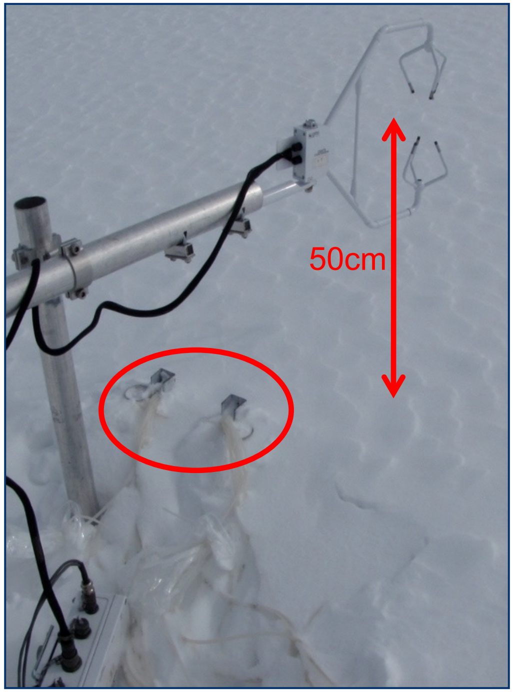


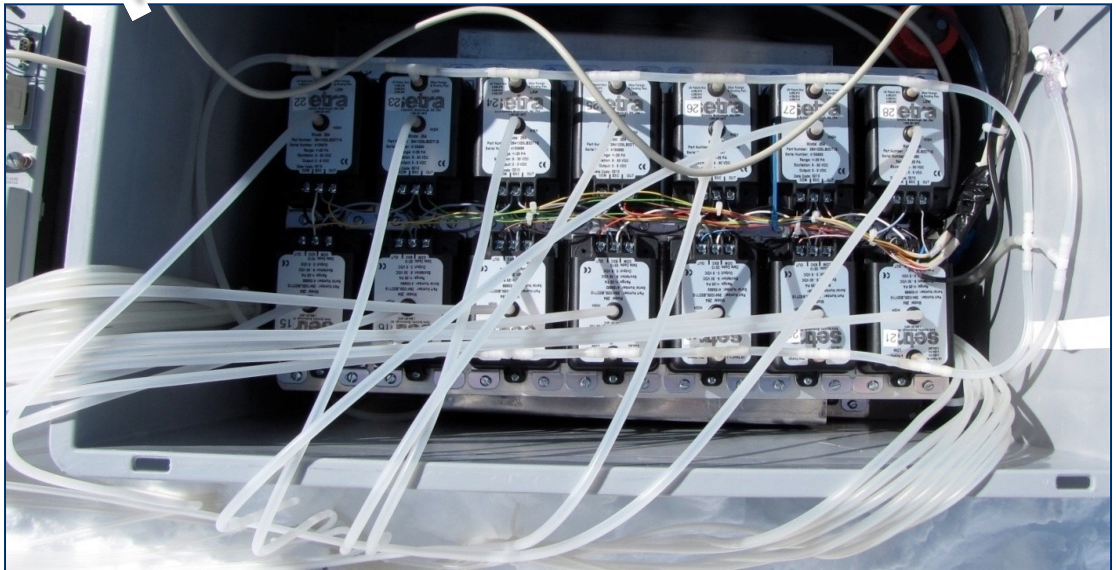


Pressure sensor system

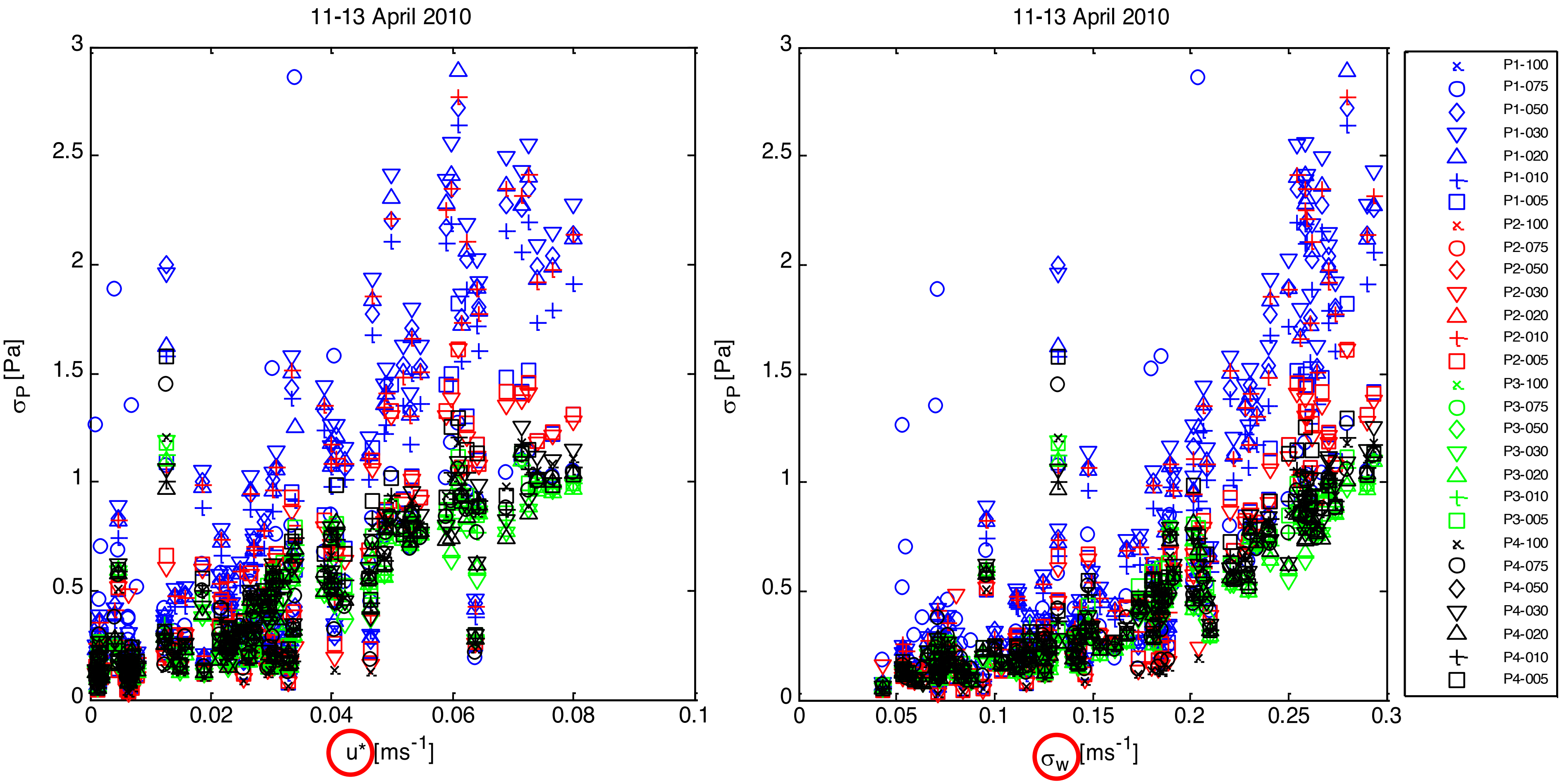
Slow response pressure reference chamber





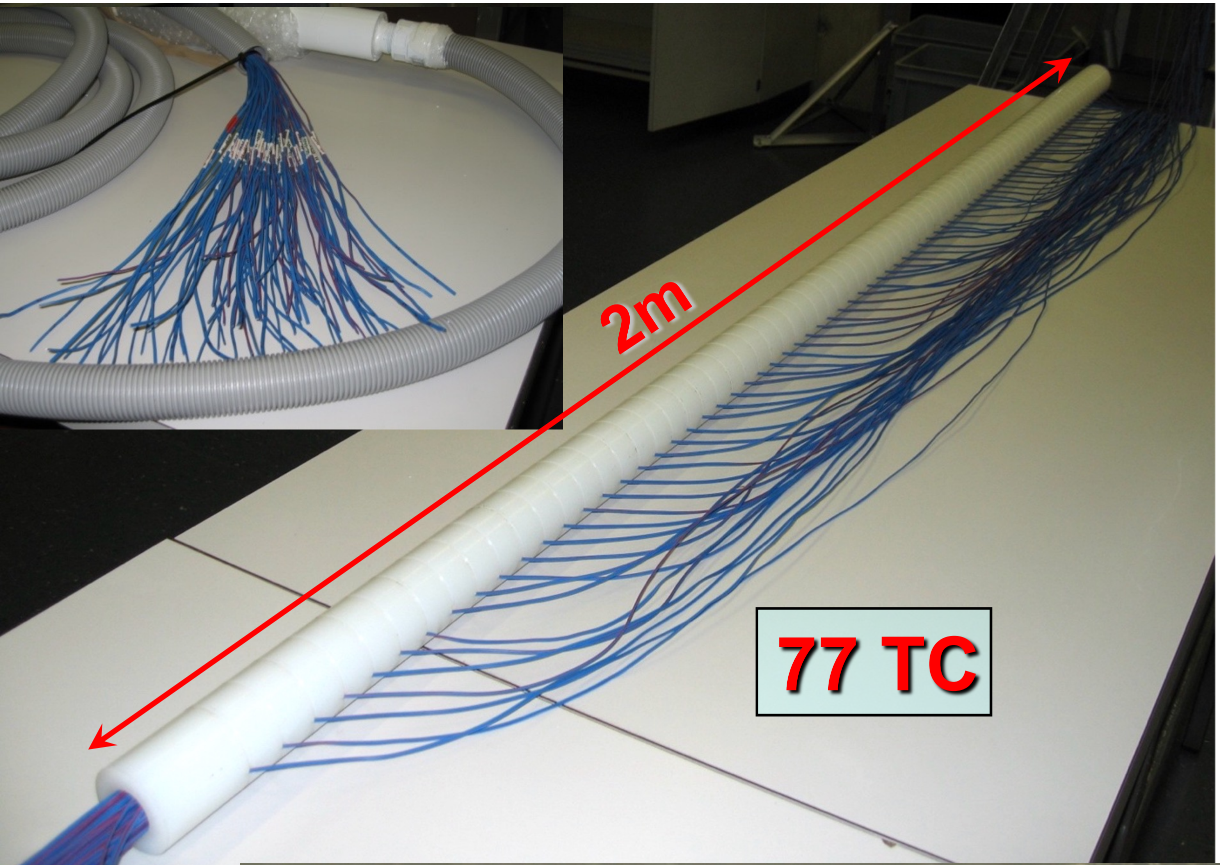


Preliminary results

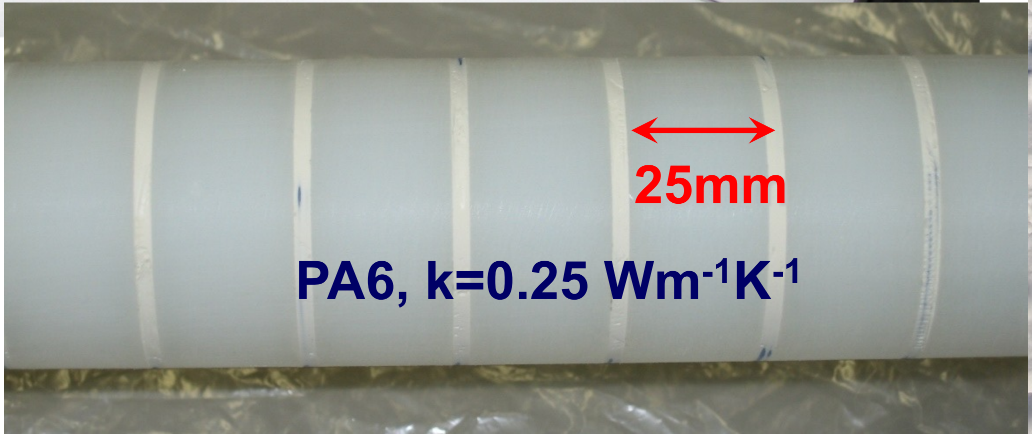


What does this mean for heat and moisture transfer?

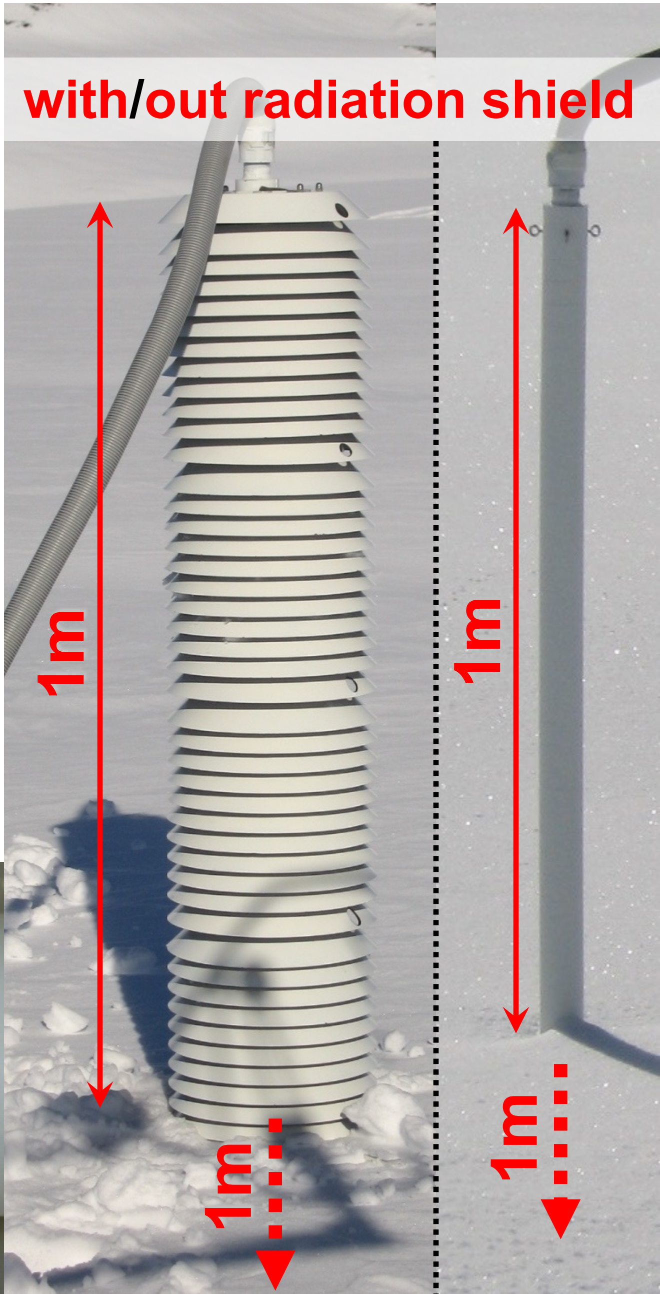
Thermocouple snow temperature



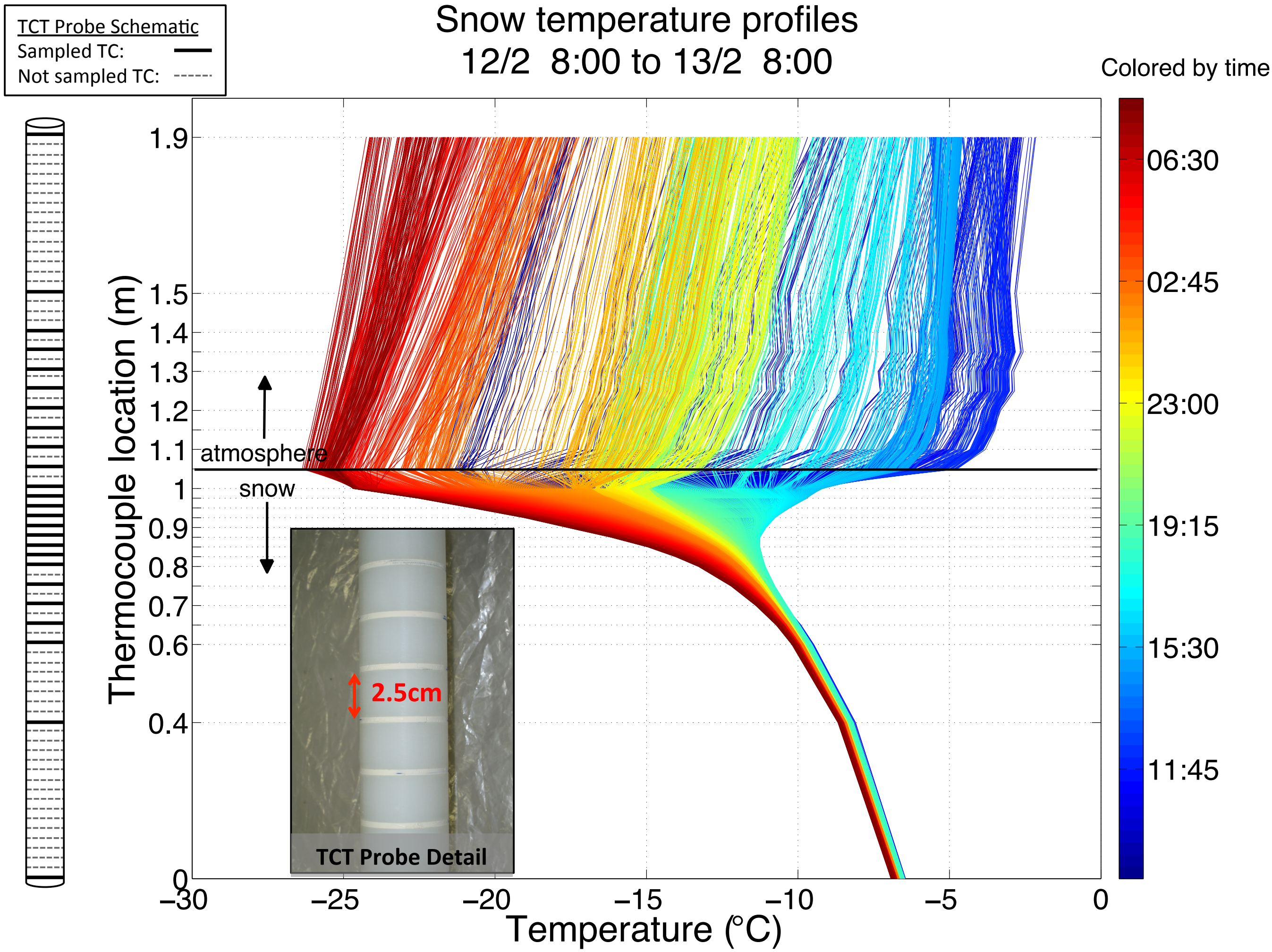
77 TC

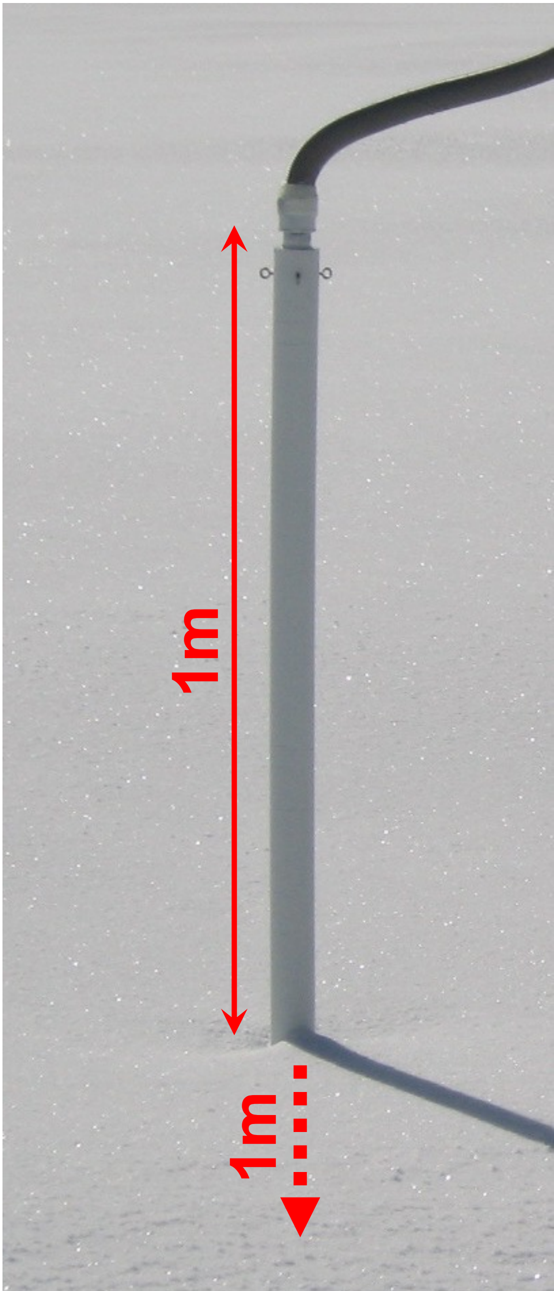


PA6, $k=0.25\ \mathrm{Wm^{-1}K^{-1}}$


with/out radiation shield

High-res. T profiles in snow



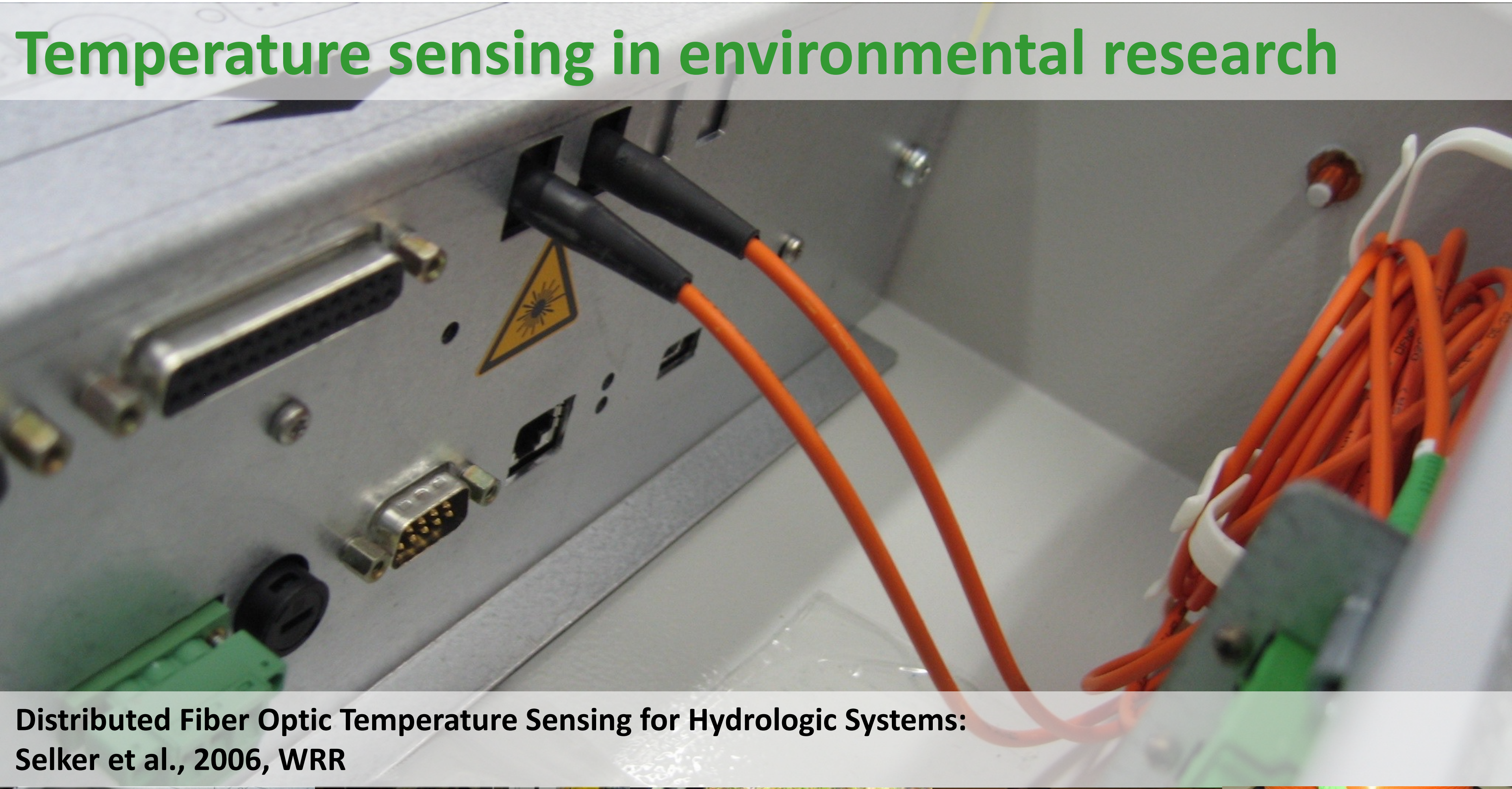


Inversion Methods:

Measure temperature and invert the 1D heat equation for thermal diffusivity:

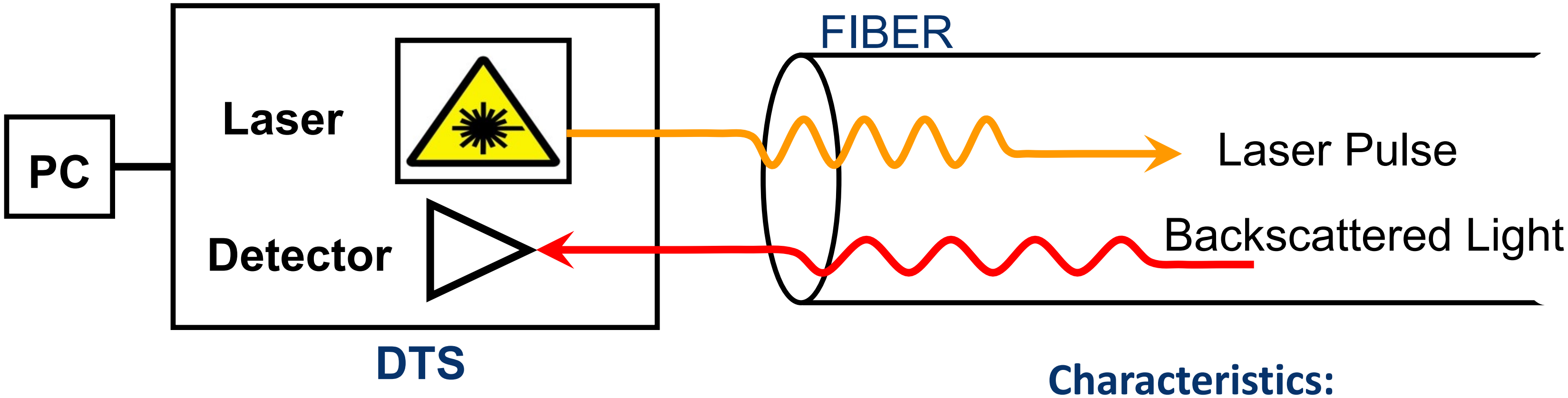
$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$$

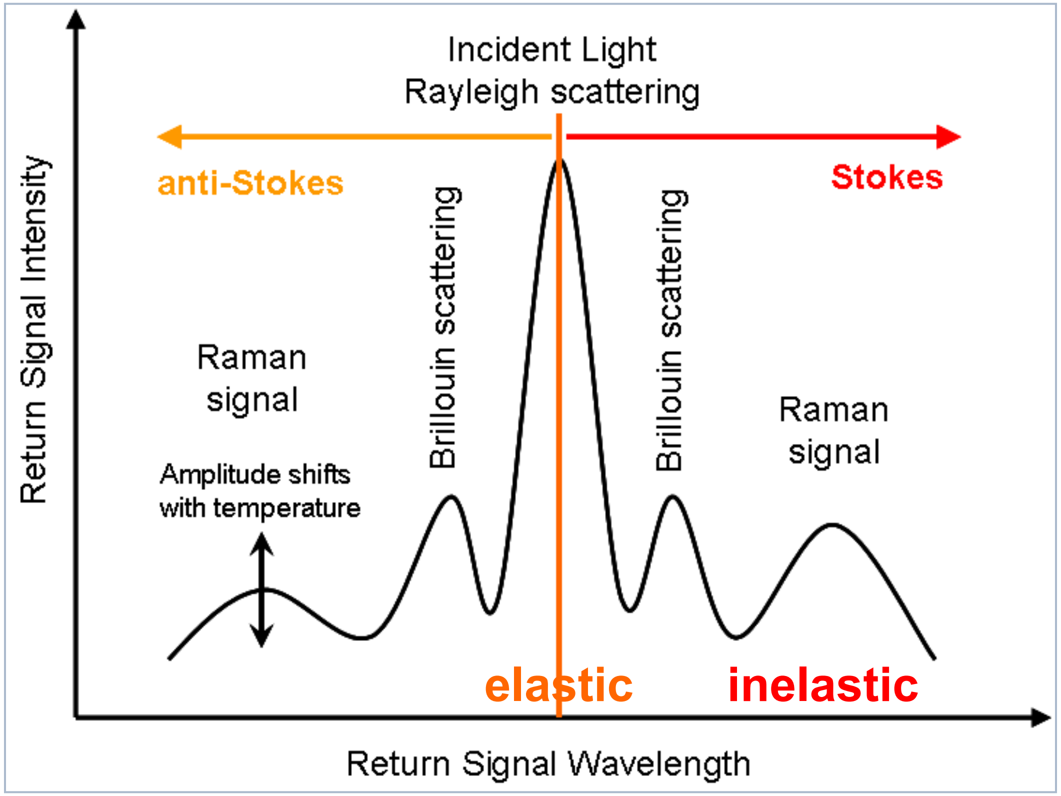
Temperature sensing in environmental research



**Distributed Fiber Optic Temperature Sensing for Hydrologic Systems:
Selker et al., 2006, WRR**

FO-Distributed Temperature Sensing





Characteristics:

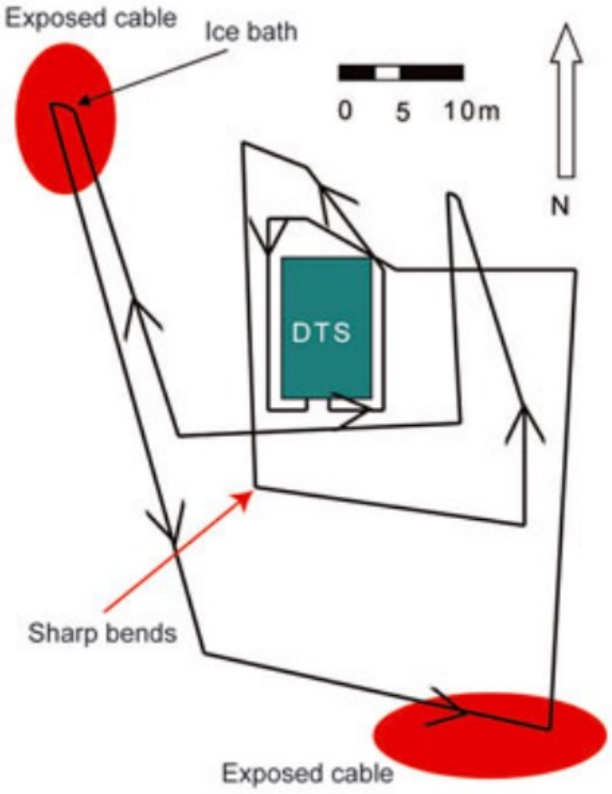
- up to 10km range
- up to 25cm spatial resolution
- up to 1s temporal resolution
- up to 0.05C T-resolution

T-resolution depends on:

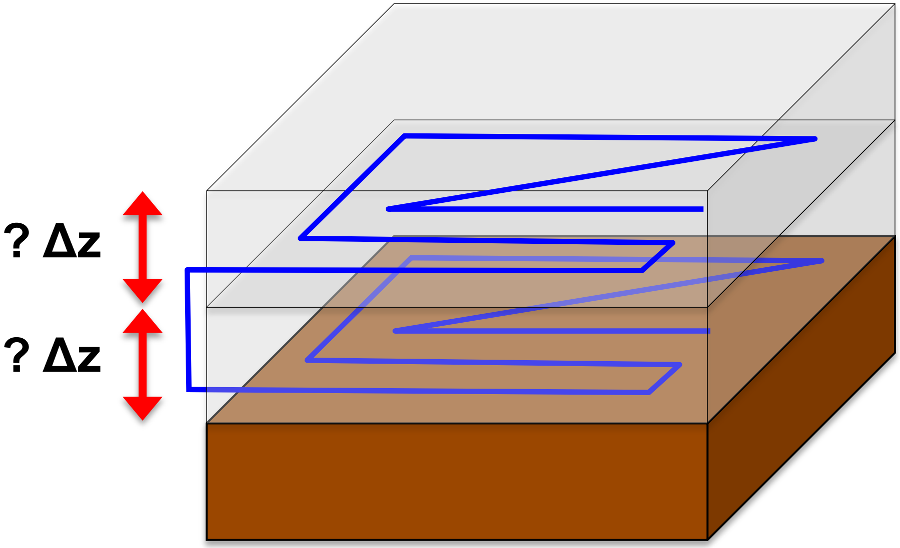
- **Measurement time**
- **Spatial resolution**
- **Length of fiber**
- **Loss in fiber, splices, connectors**

Soil – snow interface temperature

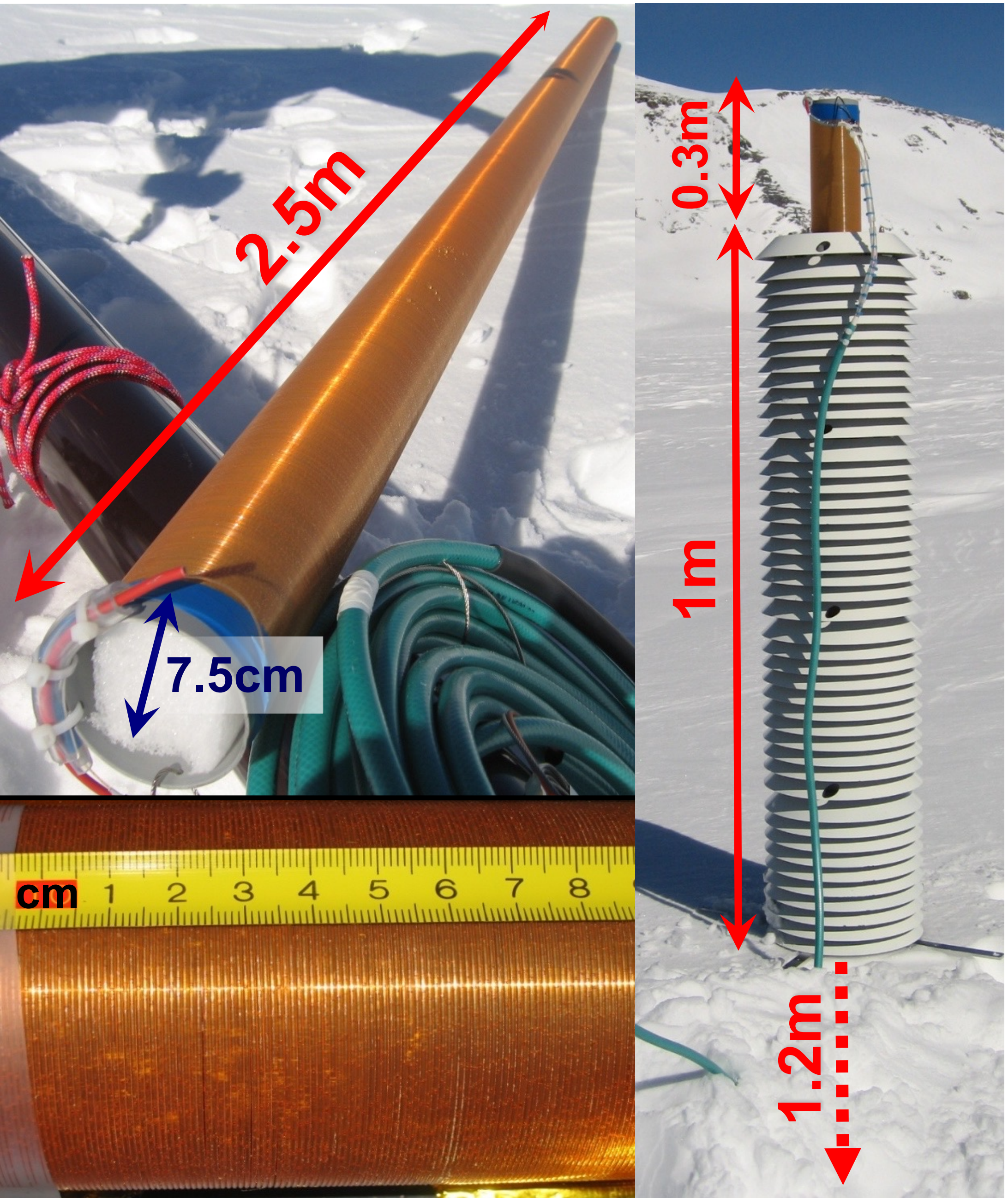
- Quantify influence of topography, exposition, slope, vegetation etc.
- Information on snow melt onset and evolution



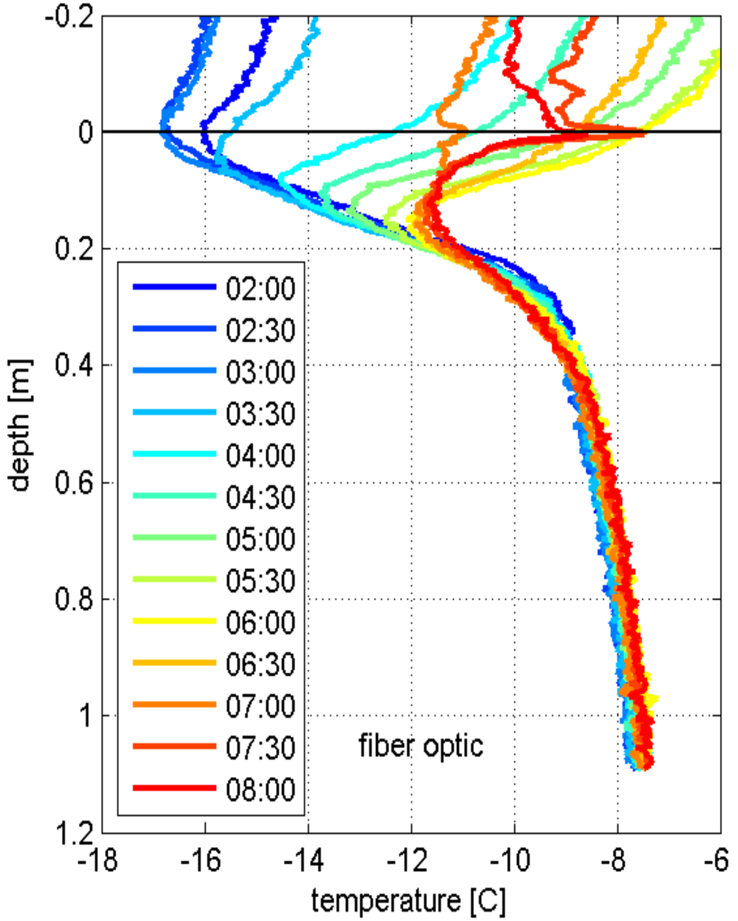
From Tyler et al., 2008, J.Glac.



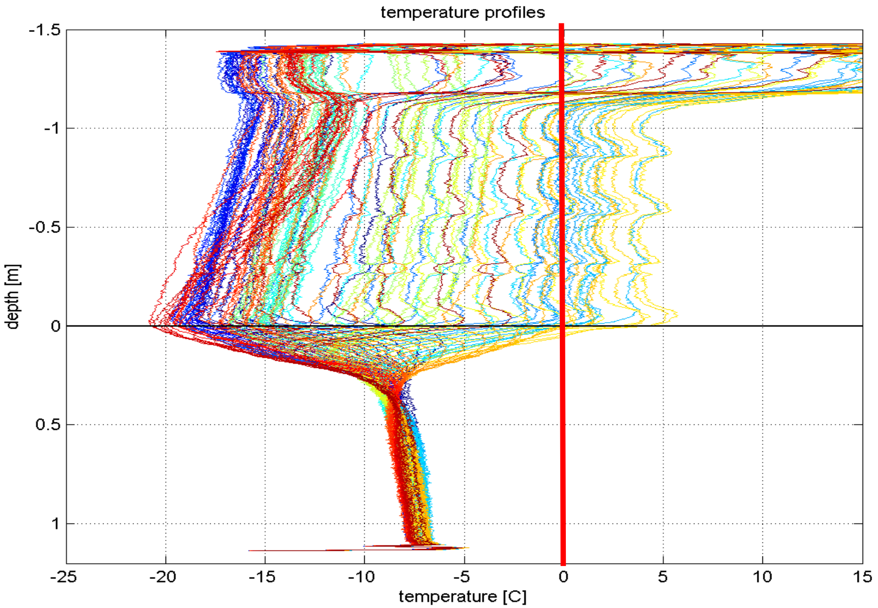
High resolution snow DTS

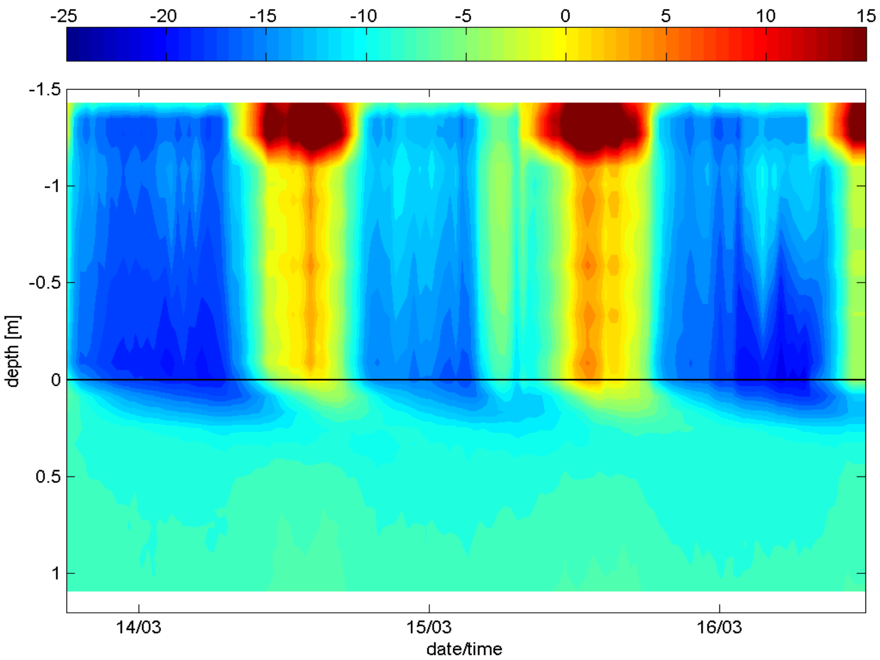


600m of 900µm o.d. fiber,
on 2m 7.5cm o.d. PVC pipe,
1m fiber ≈ 4mm tube length
dx: 1m, dz: 4mm, dt: 30min.
precision: < 0.2ºC



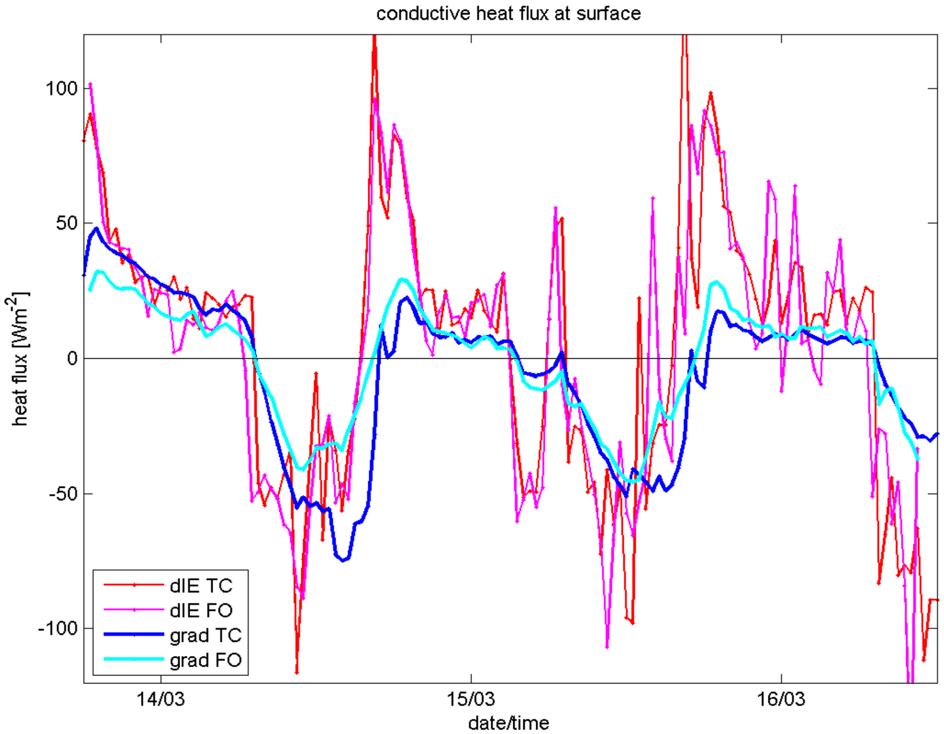
Temperature & subsurface heat flux



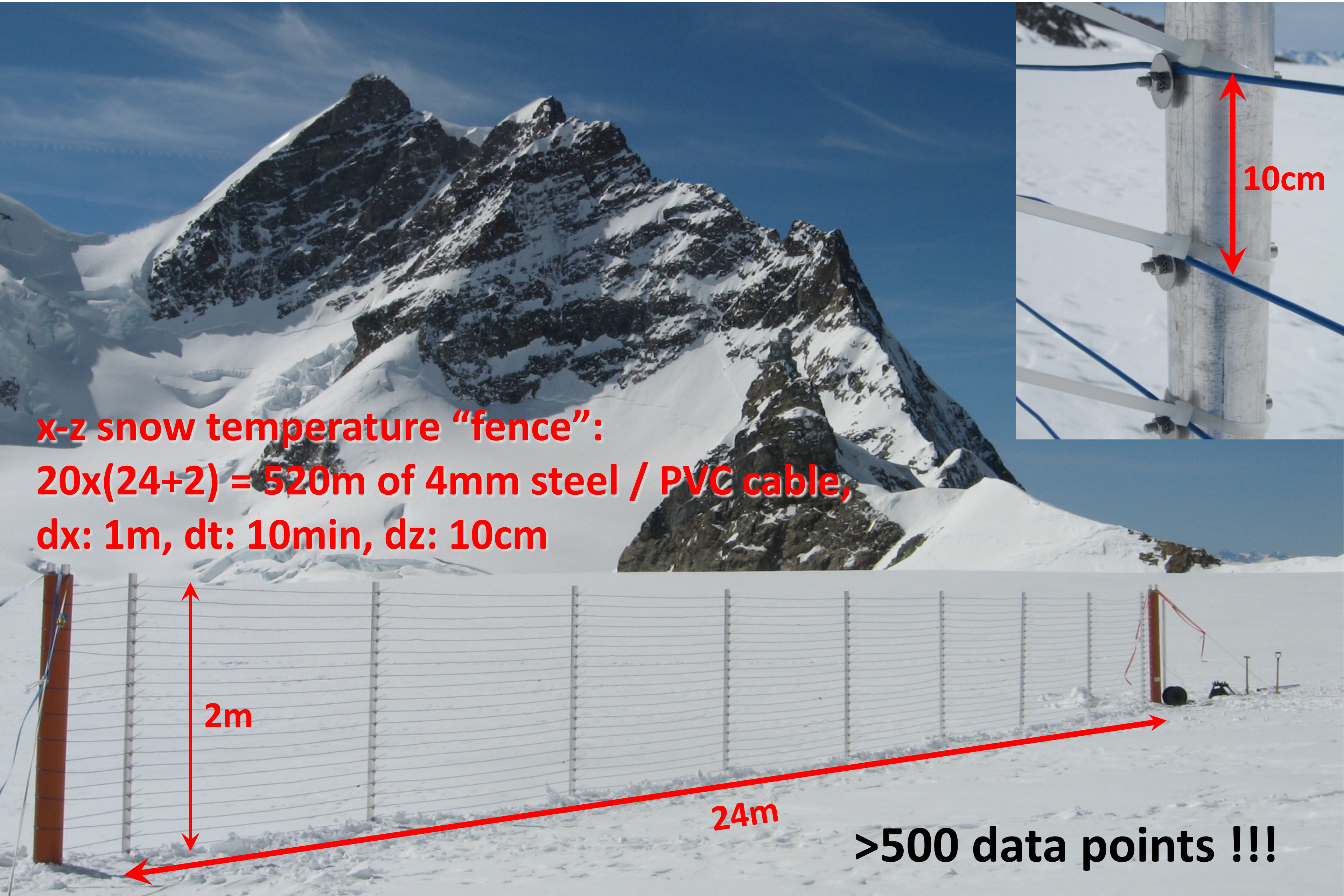


$$G = \int_z \rho_s(z)\, c_p \frac{\partial T}{\partial t}\, dz$$

$$G = -k_{eff} \frac{\partial T}{\partial z}$$



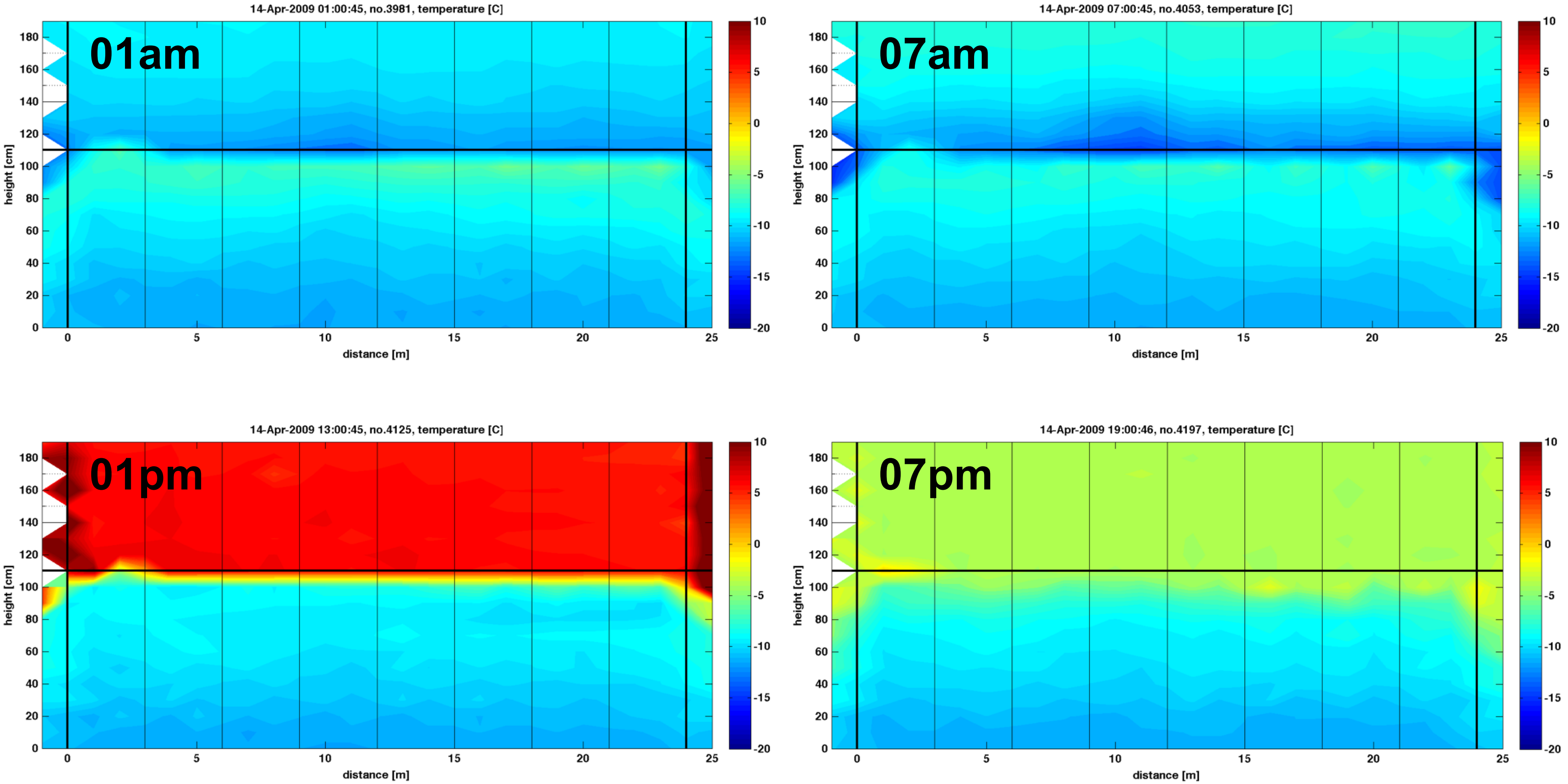
STF Jungfraujoch (2009)



x-z snow temperature “fence”:
20x(24+2) = 520m of 4mm steel / PVC cable,
dx: 1m, dt: 10min, dz: 10cm

>500 data points !!!

Typical diurnal cycle of transect



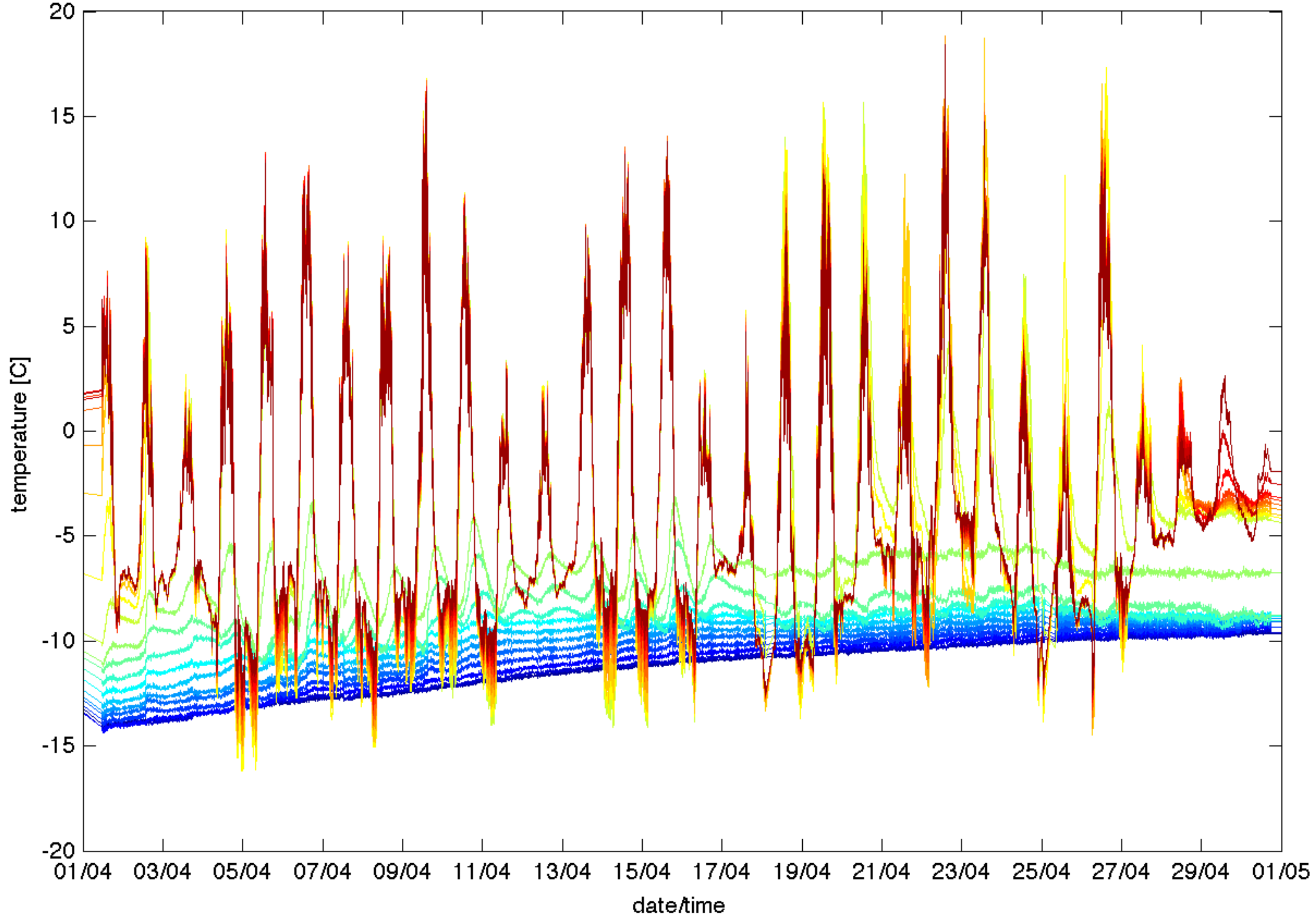
14-Apr-2009 01:00:45, no.3981, temperature [C]

14-Apr-2009 07:00:45, no.4053, temperature [C]

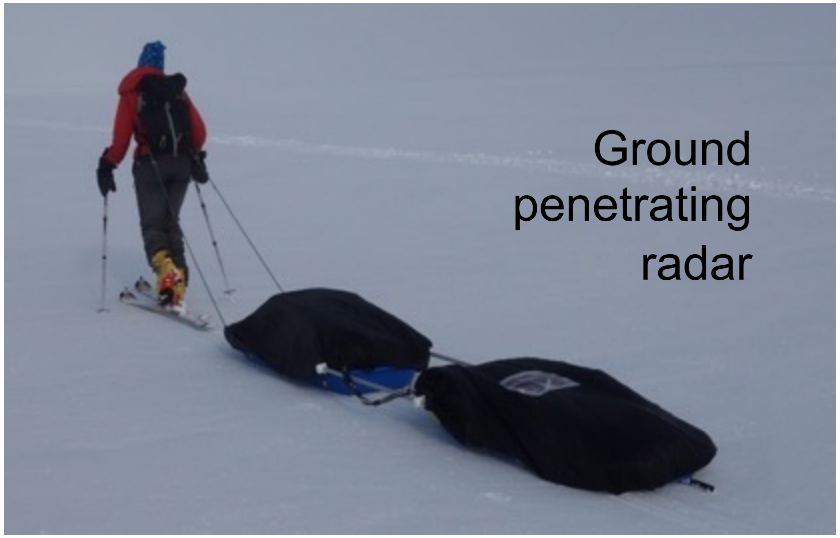
14-Apr-2009 13:00:45, no.4125, temperature [C]

14-Apr-2009 19:00:46, no.4197, temperature [C]

Horizontally averaged temperatures



Remote sensing of snow

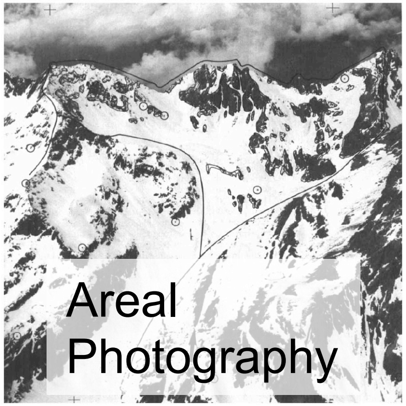


Ground penetrating radar

Drones

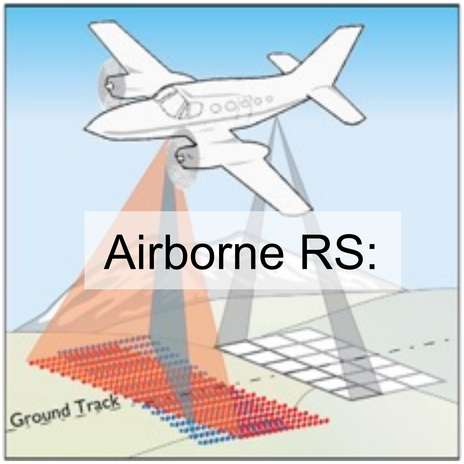
Ground based

Airborne

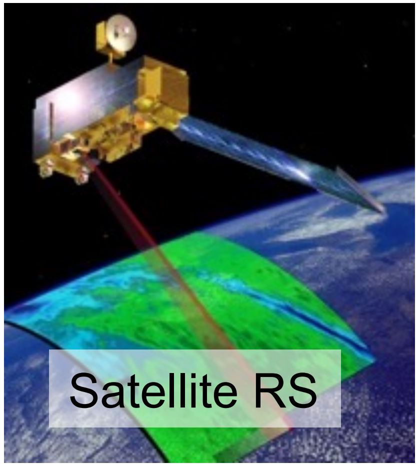


Areal Photography

Terrestrial LiDAR



Airborne RS:



Satellite RS

Remote Sensing – GPR: snow density / SWE

Ground Penetrating Radar (GPR):

- Hybrid: Line measurements
- Depth and density → SWE

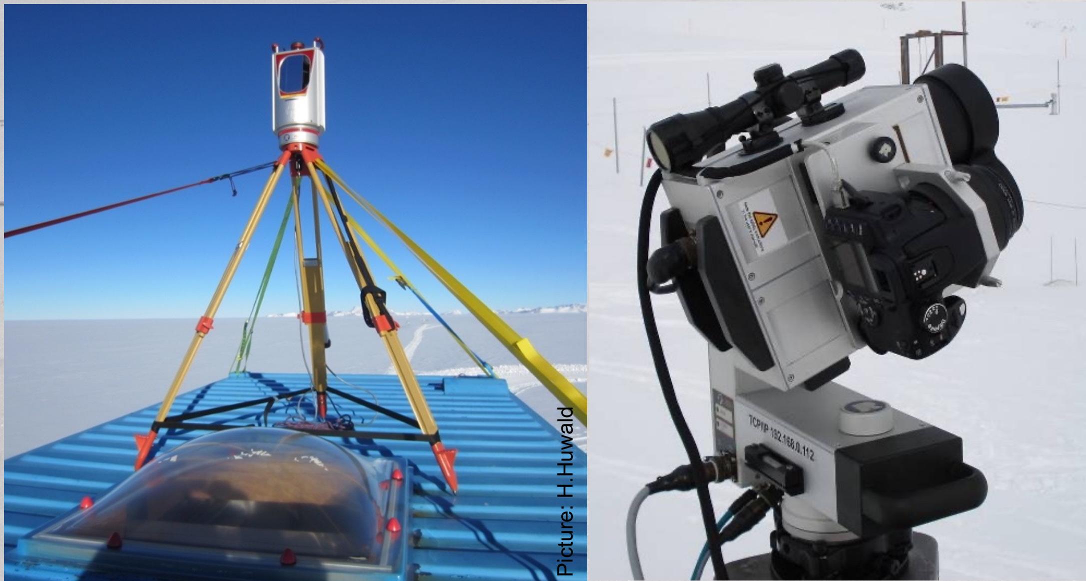
- Pulses of EM radiation in the microwave range
- Travel speed depends on dielectric permittivity
- Interface between different materials generate reflected signal (travel time → snow depth)
- Back scattering gives information about material properties (density, microstructure)
- Low penetration depth in moist snow (why?)

3D terrestrial laser scanner (TLS)

- Laser measures the distance to objects (travel time from emitting to receiving the signal)

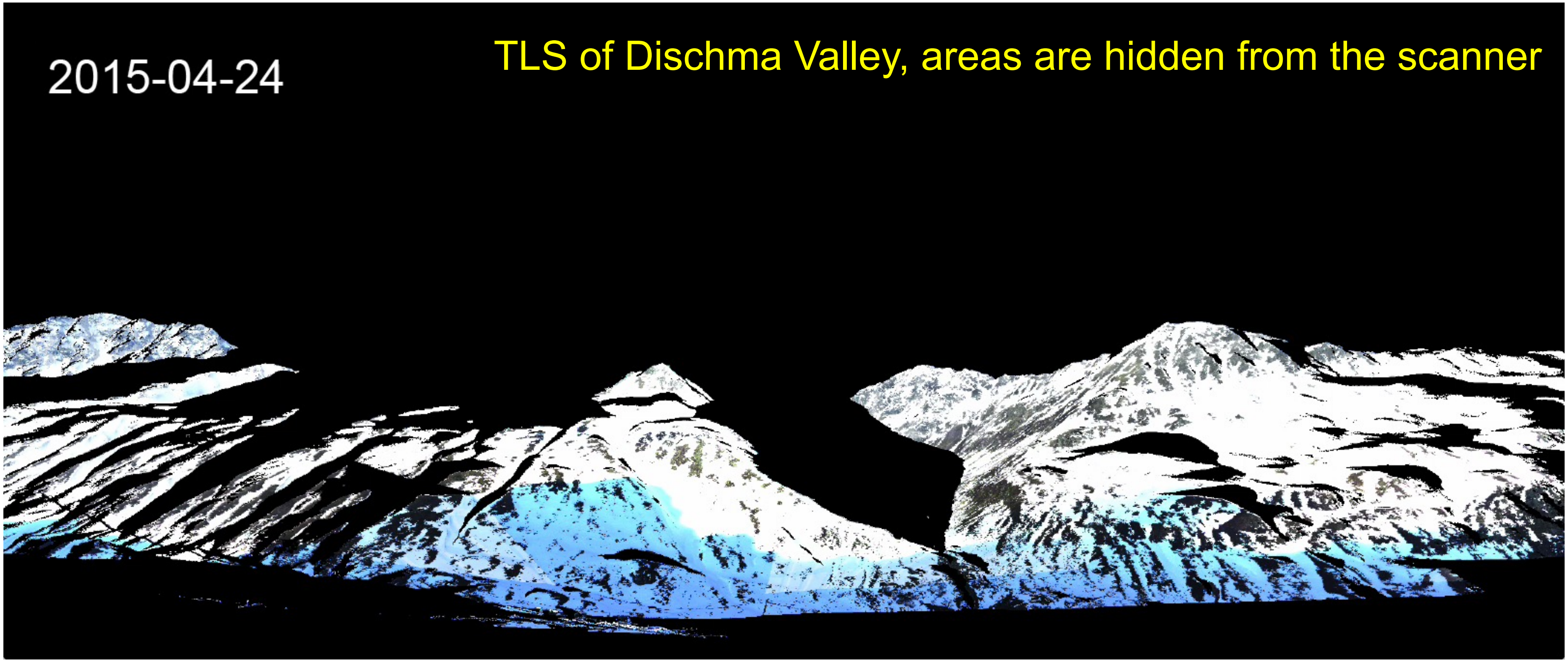
- Light Detection and Ranging (LiDAR)
- Digital Surface Models (DSM)
- Subtracting winter and summer DSM delivers snow depth maps

- Obtain 2D surfaces, Large data sets
- Spatial coverage: r < 2km
- Accuracy: cm range
- Snow depth: from Δt
- Data: only field of view
- Diff. GPS antenna



Picture: H.Huwald

Spatio-temporal distribution of snow



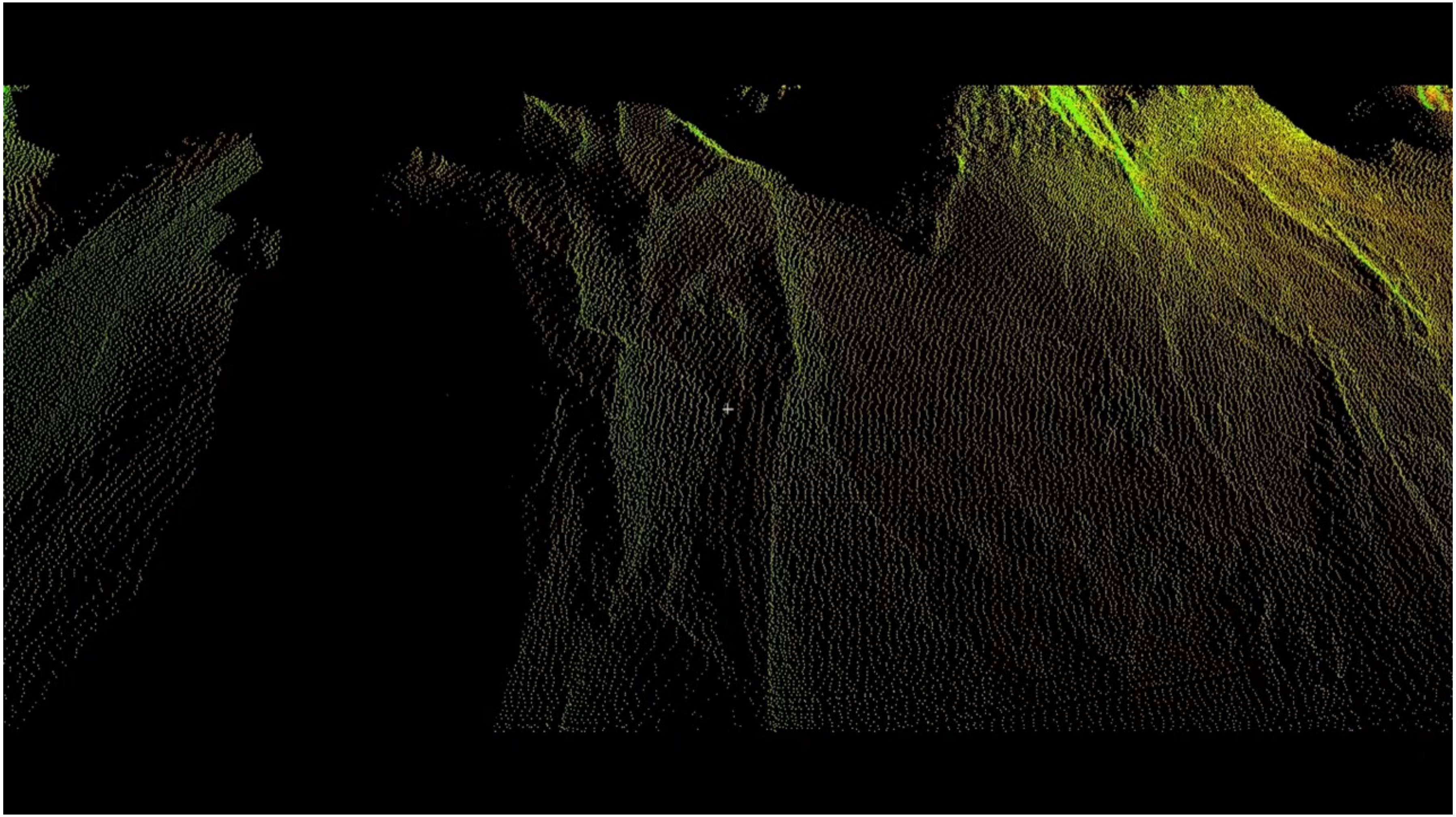
2015-04-24

TLS of Dischma Valley, areas are hidden from the scanner

Multiple scans represent development throughout the season

Snow cover on sea ice near Antarctica

Laser scans during the SIPEX II Expedition to Antarctica (2012)



Remote Sensing – Drones: Photogrammetry

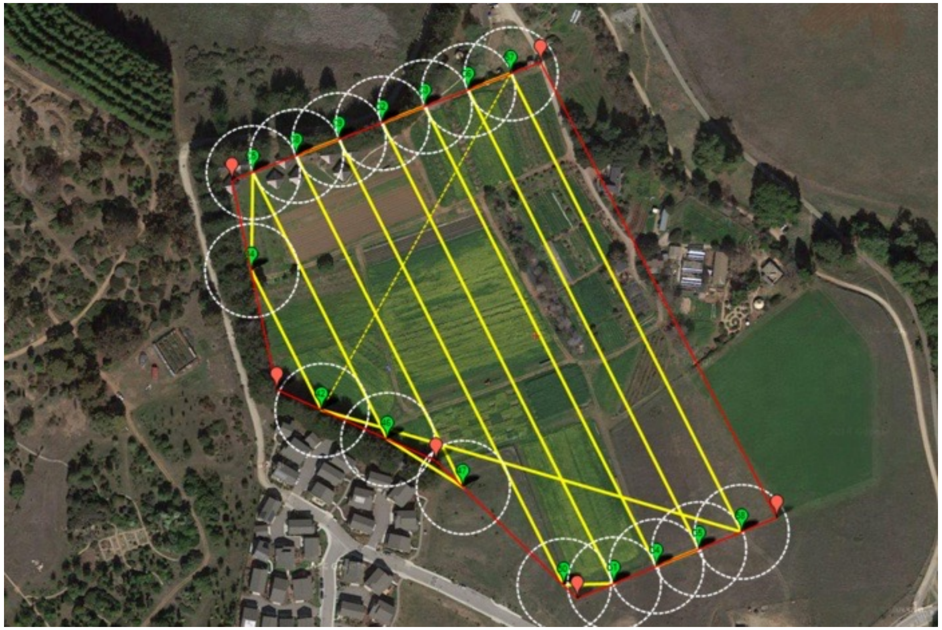
- DSM retrieval by photogrammetry from drones
- Triangulation of pictures of same scene taken under many angles
- Limited extent, but relatively cheap and flexible
- Difference in DSM → snow depth

Photogrammetry and 3D reconstruction

Aerial surveys, requiring:

- Robust drone system
- Good digital camera
- Differential GPS for geo-referencing

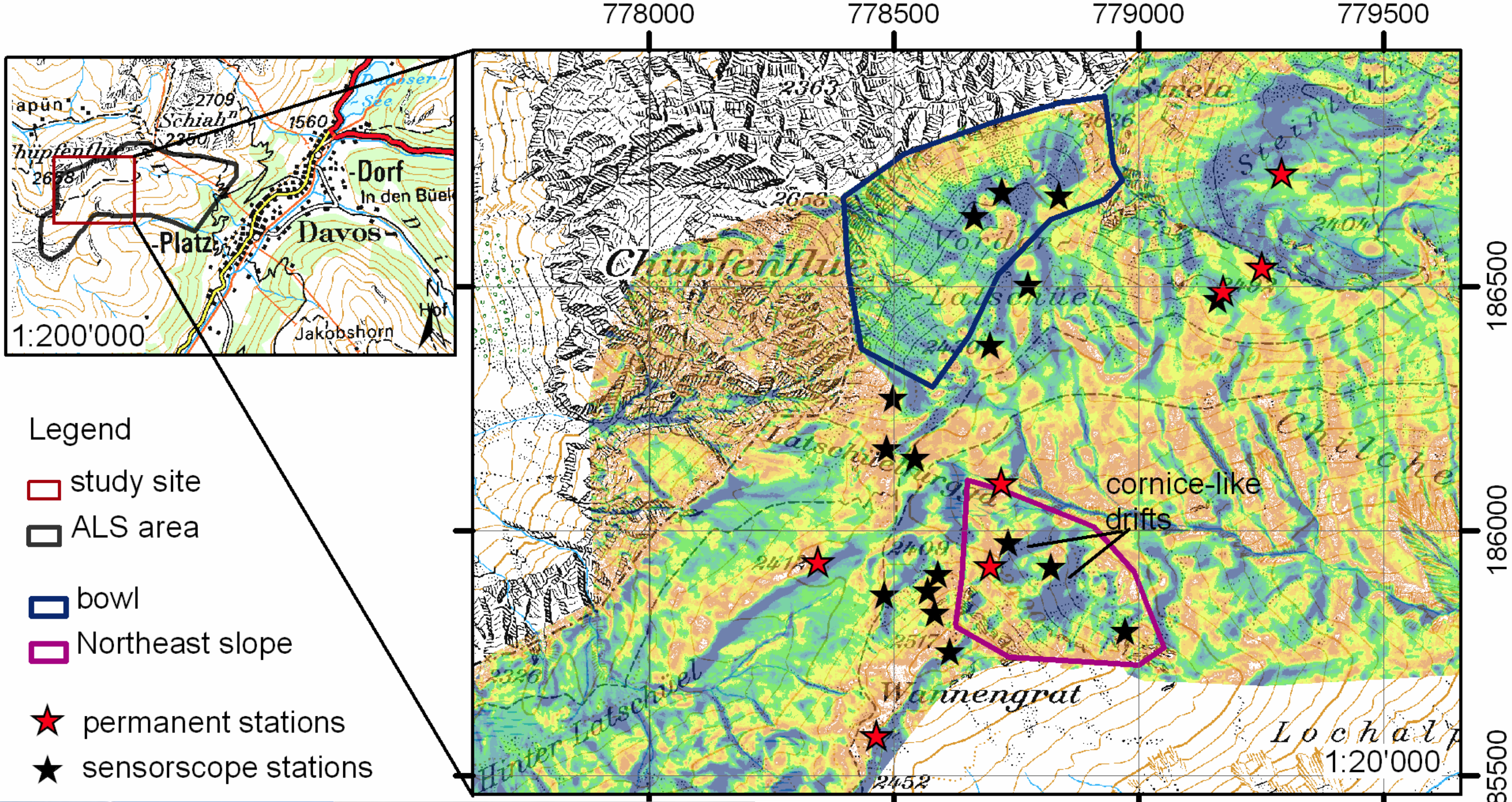
Currently, a 42MP full frame sensor flown at a height above ground of about 120m gives a ground sampling distance (GSD) of less than 1cm/px



PIX4D

Pix4Dmapper

Terrestrial & airborne laser scanning

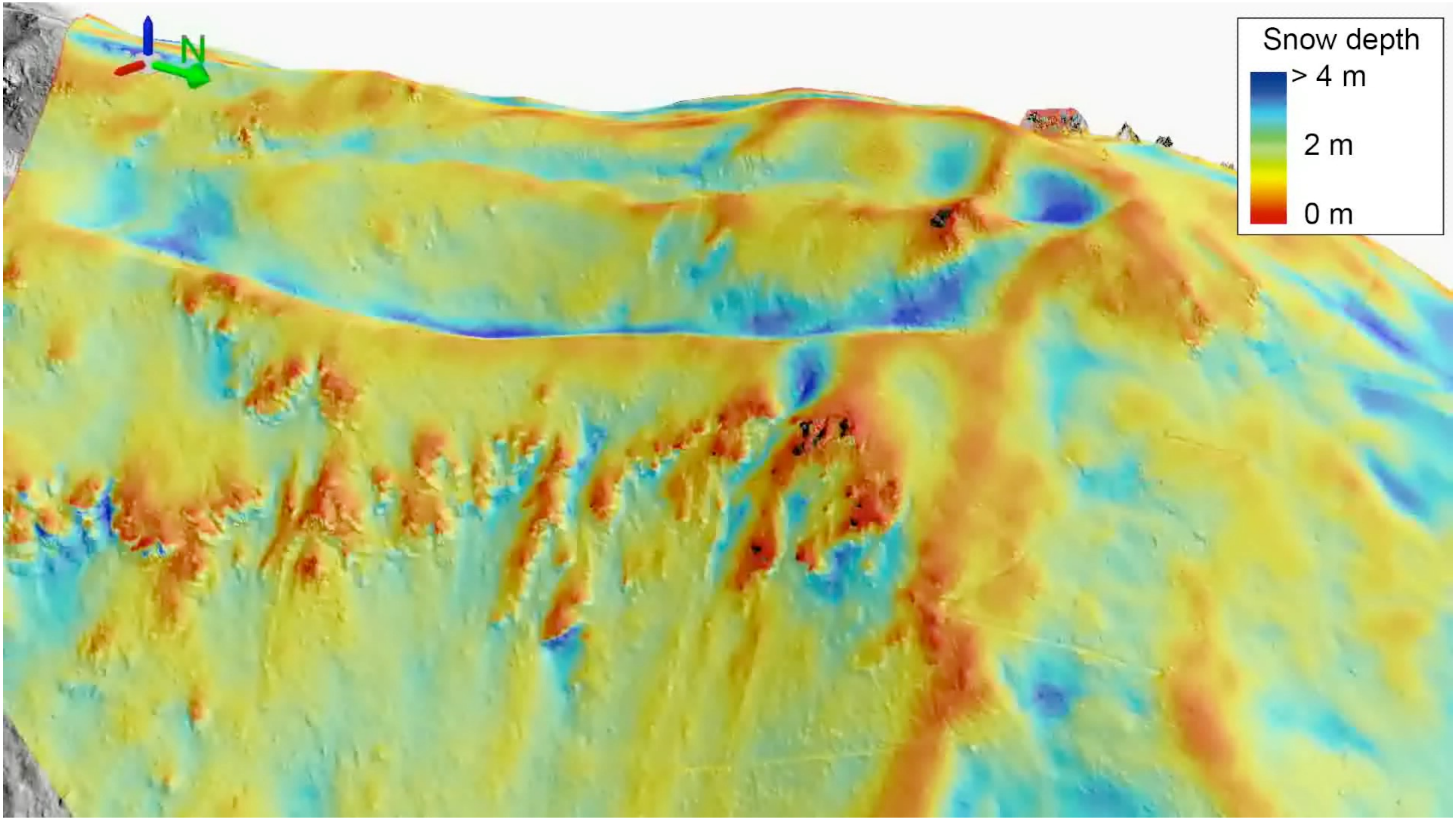


snow depth [m]

0	0.5 - 1	1.51 - 2	2.51 - 3
0 - 0.5	1.1 - 1.5	2.1 - 2.5	> 3.1

Schneebeli/Lehning, SLF

Spatio-temporal distribution of snow



Remote sensing - Airborne Lidar

Advantages:

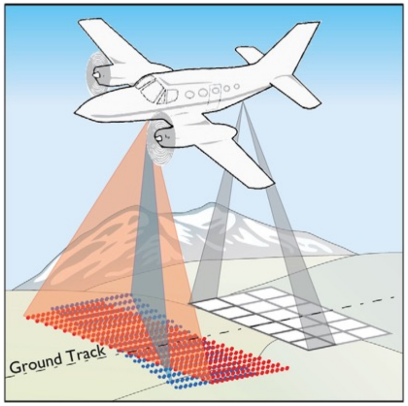
- Larger surface areas
- Better view angle

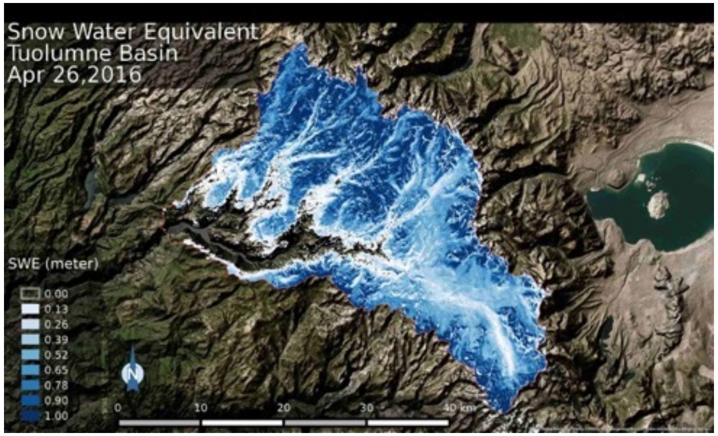
Disadvantage:

- Expensive
- Complex logistics

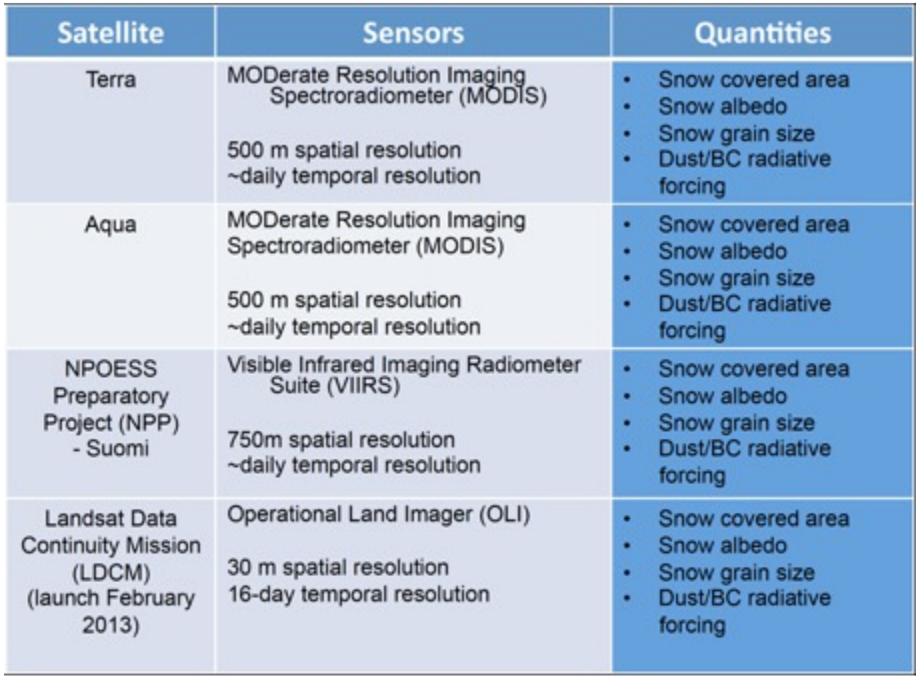
- NASA/JPL: Launch 2013
- Sierra Nevada and Colorado
- Imagine spectrometer:
  - – 72 spectral bands (vis – NIR)
  - – Spatial resolution: 2m
  - → spectral and broadband albedo
- Scanning LiDAR:
  - – Vertical accuracy < 10cm
  - → snow depth (+ snow density → SWE)

- Complete snowpack and albedo of 2 entire mountain basins
  - → prediction for water management
  - → accurate forcings for hydrological models
- Spatially complete snowfall measurements
  - → understanding of mountain precipitation





Satellite Remote Sensing of snow



Satellite	Sensors	Quantities
Terra	MODerate Resolution Imaging Spectroradiometer (MODIS) 500 m spatial resolution ~daily temporal resolution	• Snow covered area • Snow albedo • Snow grain size • Dust/BC radiative forcing
Aqua	MODerate Resolution Imaging Spectroradiometer (MODIS) 500 m spatial resolution ~daily temporal resolution	• Snow covered area • Snow albedo • Snow grain size • Dust/BC radiative forcing
NPOESS Preparatory Project (NPP) - Suomi	Visible Infrared Imaging Radiometer Suite (VIIRS) 750m spatial resolution ~daily temporal resolution	• Snow covered area • Snow albedo • Snow grain size • Dust/BC radiative forcing
Landsat Data Continuity Mission (LDCM) (launch February 2013)	Operational Land Imager (OLI) 30 m spatial resolution 16-day temporal resolution	• Snow covered area • Snow albedo • Snow grain size • Dust/BC radiative forcing

Need for large scale information about snow cover

Remote sensing provides best tool

Spectral regimes: Physics and Applications

Different physical behavior in different parts of the spectrum

Microwave

- Extinction per unit volume
- Polarized signal
- Large penetration in dry snow (meters), small in wet snow
  - Effects of microstructure & stratigraphy
- Large dielectric contrast between ice and water

Visible and infrared

- Independent scattering
- Weak polarization
- Small penetration near surface
  - ~ 0.3 m in blue,
  - few mm in NIR and IR
- Small dielectric contrast between ice and water

Different applications in different parts of the spectrum

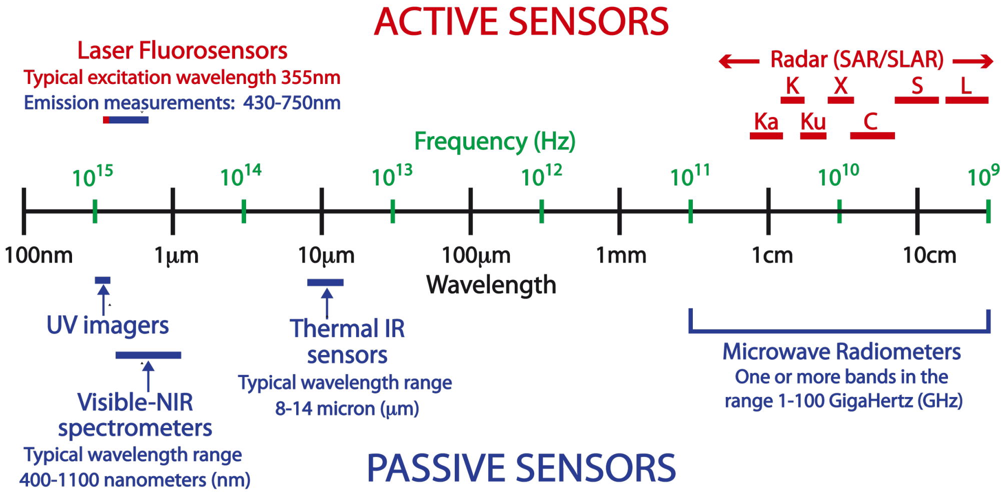
- direct measurement of SWE
- can see through clouds and at night
- low spatial resolution

→ disqualified in complex terrain

- higher spatial resolution
- only detects surface reflectance

→ spatial extent (SCA and fSCA), but not volume (SWE)

Active microwave measurements



ACTIVE SENSORS

Laser Fluorosensors
Typical excitation wavelength 355nm
Emission measurements: 430-750nm

Radar (SAR/SLAR)
K X S L
Ka Ku C

Frequency (Hz)

10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9}

100nm 1μm 10μm 100μm 1mm 1cm 10cm

Wavelength

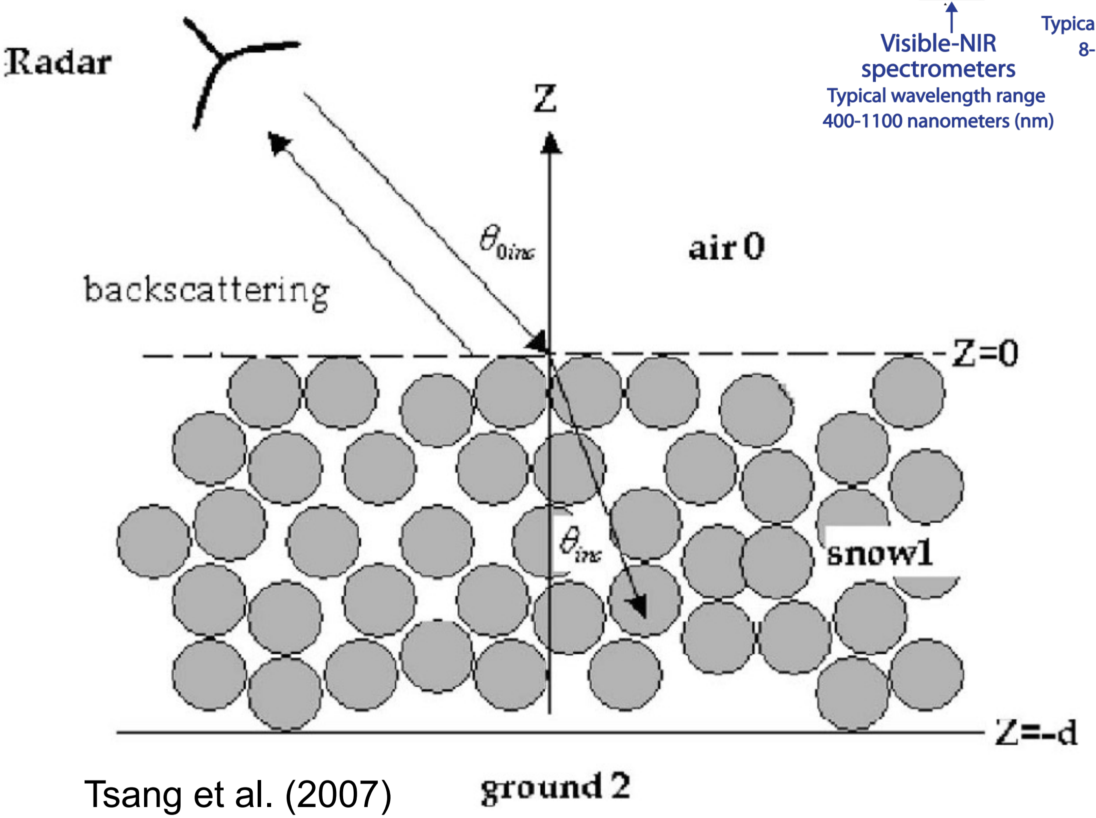
UV imagers

Visible-NIR spectrometers
Typical wavelength range
400-1100 nanometers (nm)

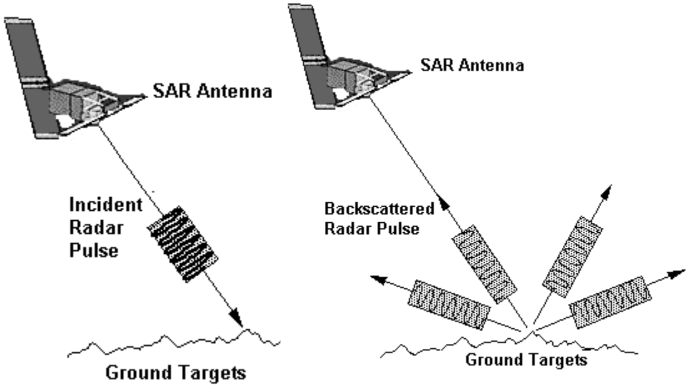
Thermal IR sensors
Typical wavelength range
8-14 micron (μm)

Microwave Radiometers
One or more bands in the
range 1-100 GigaHertz (GHz)

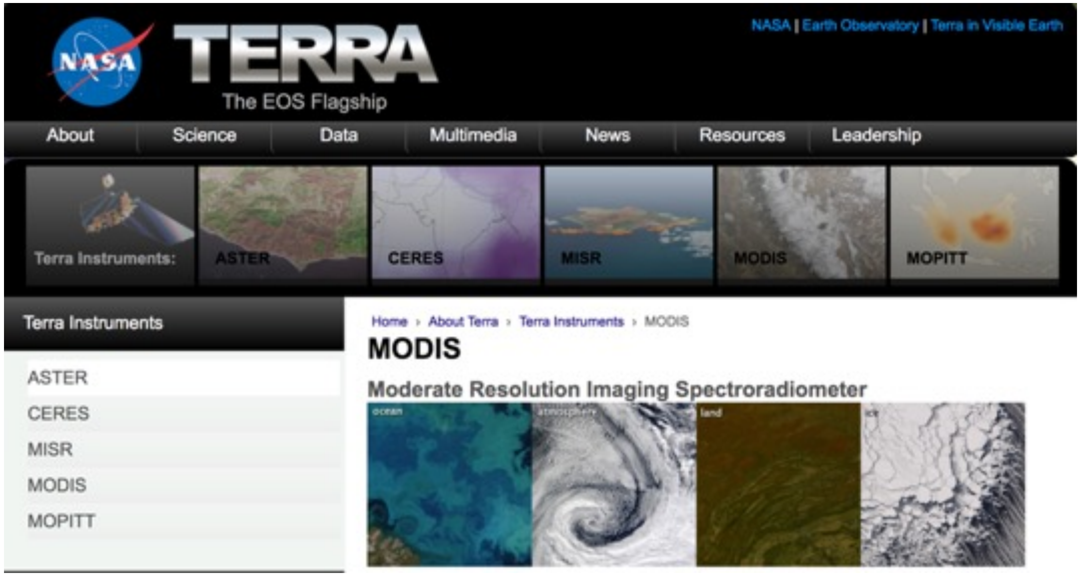
PASSIVE SENSORS



Tsang et al. (2007)



Satellite vs. Sensor



Satellite: Terra

Sensors: ASTER
CERES
MISR
MODIS
MOPITT

Satellite: Aqua

Sensors: AIRS
AMSU
CERES
MODIS

Satellite/Sensor Classifications

1. **Orbit**
   - Polar vs Geostationary
2. **Energy source**
   - Passive vs Active
3. **Solar Spectrum**
   - Visible, UV, IR, Microwave
4. **Measurement Technique**
   - Scanning, non-scanning, imager, sounders
5. **Resolution** (spatial, temporal, spectral, radiometric)
   - Low vs high
6. **Application**
   - Weather, Ocean colors, Land mapping, Atmospheric Physics, Atmospheric Chemistry, Air quality, Radiation budget, Hydrology, Cryosphere, …

Satellite orbits: Geostationary Earth Orbit (GEO)

Characteristics:

- Geosynchronous, equatorial orbit
- Follows earth's rotation
  (appears motionless from the earth)
- 35 000km above surface
  (→ v= 3km/s, T=1day)

Advantages:

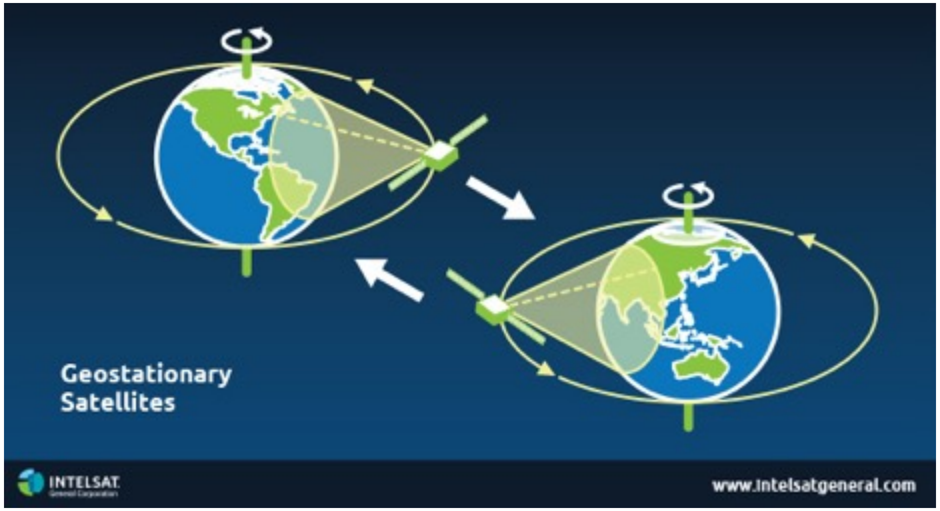
- High acquisition frequency (~minutes)
- Large ground cover
- Receiving antenna does not need to move (communication satellites)

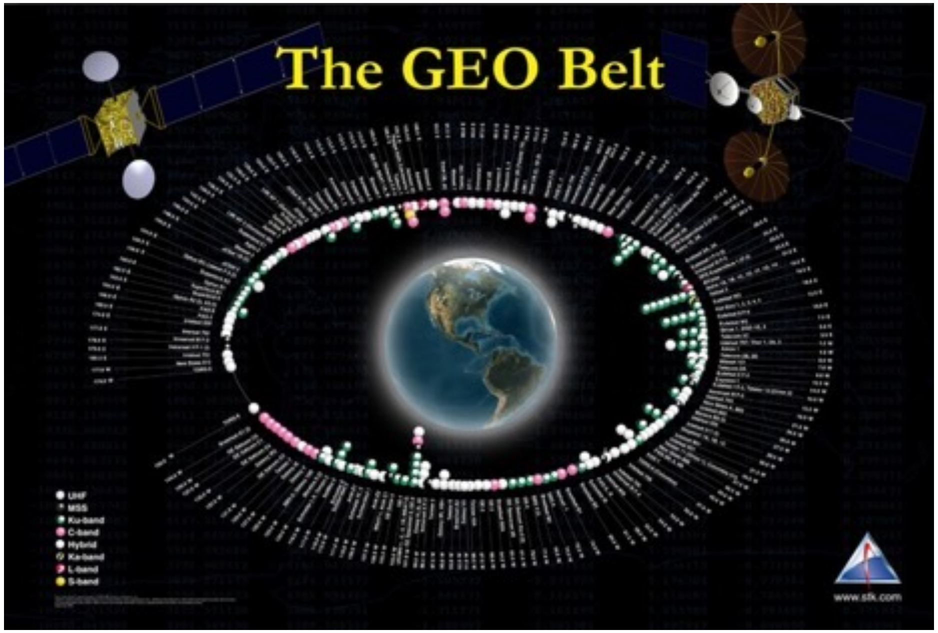
Disadvantages:

- 0.5s roundtrip travel time
- No polar view (low view angle, too much atmospheric disturbance)

Examples:

- most communication and meteorological satellites,
- Meteosat first and second generation
  (MFG: 7 satellites, MSG: 5 satellites)





Satellite orbits: Low Earth Orbit (LEO)

Characteristics:

- 160 – 2000km above surface, 7.8km/s (28 000km/h), T ~ 90min,
- Sun/helio synchronous orbit (near-polar): same local solar time

Advantages:

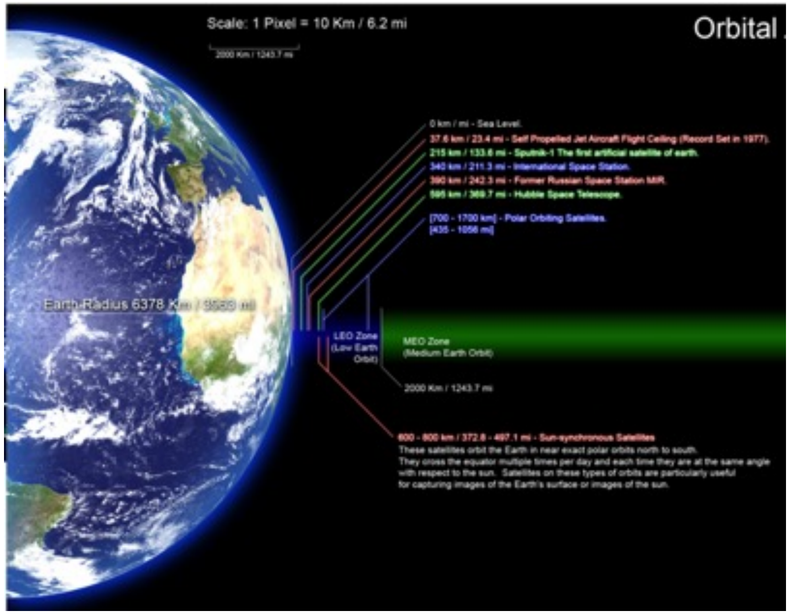
- Easier communication (low latency, less powerful amplifiers for transmission)
- Less energy required for placement in orbit
- Easier access for crewing (ISS) and servicing
- High spatial resolution,
- Global coverage

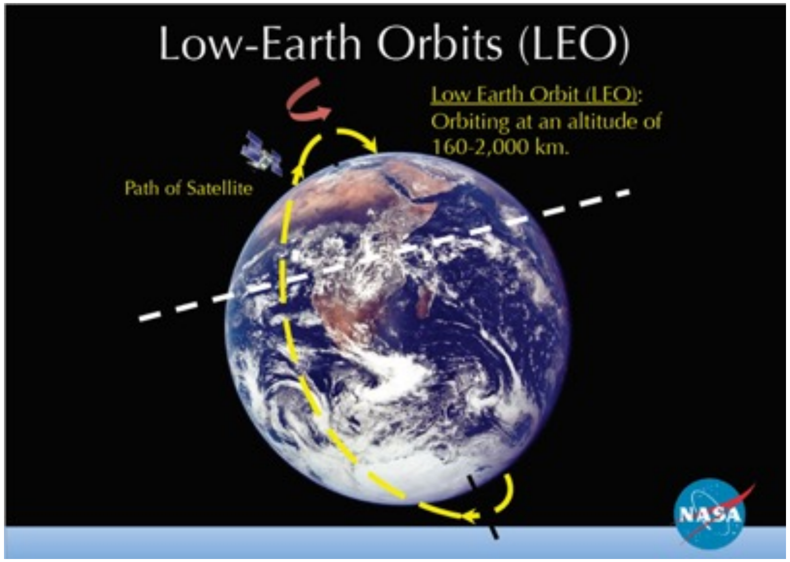
Disadvantages:

- Small Ground Instantaneous Field of View (GIFOV)
- Fast orbital decay (periodic reboosting required),
- Increasing congestion

Example:

most earth observing satellites, ISS, Hubble, spy satellites



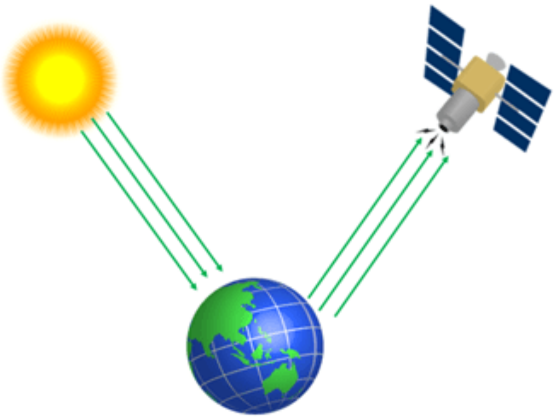


Energy Source

Passive:

Source of energy is either the sun or earth/atmosphere

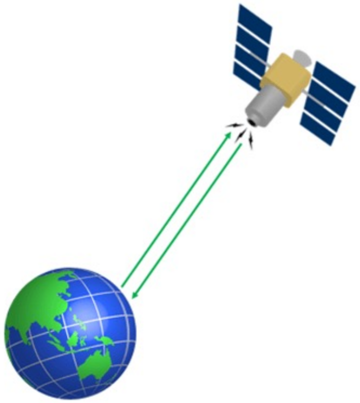
- Sun:
  - Wavelengths from 0.3 to 5 μm
- Earth or its atmosphere:
  - Wavelengths from 3 μm to 30 cm



Active:

Source of energy is part of the system

- Radar (radio detecting and ranging)
  - Wavelengths from mm to m
- Lidar (light detecting and ranging)
  - Typically around 0.5 -1.5 μm



Resolutions

- Spatial resolution (pixel size) and coverage (field-of-view)
  - Limiting factor: Satellite orbit, sensor optics, viewing geometry
  - Examples: MODIS: 500 m, Landsat: 30 m, MSG: 1.6 km x 2.3 km

- Spectral resolution (Δλ) and coverage (λ_{min} to λ_{max})
  - Limiting factor: # of bands; narrow bands need bigger aperture, more detectors, longer integration time
  - Example: MODIS: 36 bands, 30nm – 300nm bandwidth, λmin = 420nm, λmax 14 385nm)

- Radiometric resolution (signal-to-noise) and coverage (dynamic range)
  - Limiting factor: aperture size, detector size, number of detectors, integration time
  - Examples:

    8 bit sensor (Landsat TM), 28 = 256 levels,

    10 bit sensor (AVHRR), 210 = 1024 levels

    12 bit sensor (MODIS), 212 = 4096 levels

- Temporal resolution (revisit) and coverage (repeat)
  - Limiting factor: type and height of orbit, size of measurement swath
  - LEO: 1-16 days (more around poles); GEO: ~minutes

Next:

Snow mechanics & avalanches