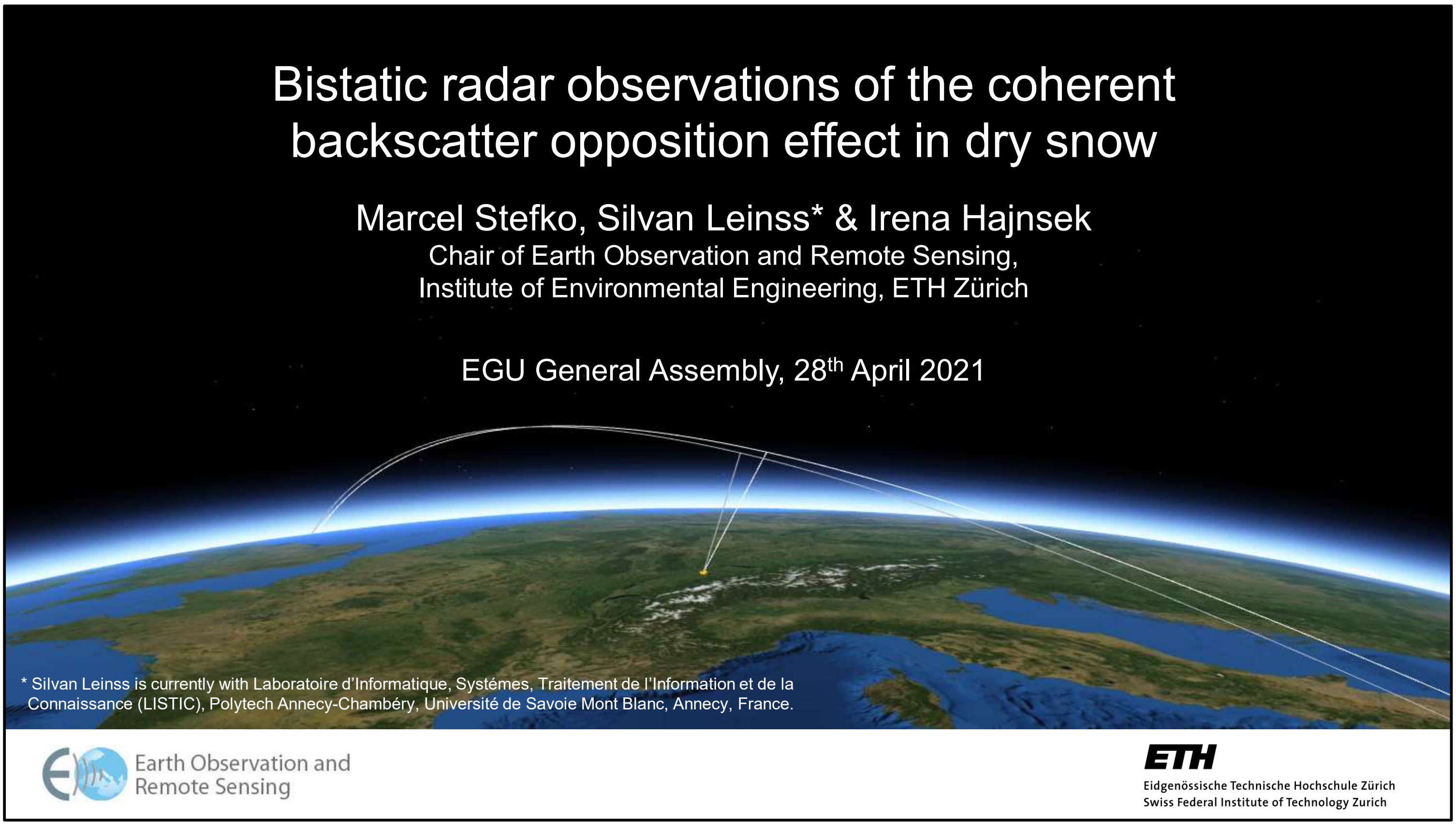
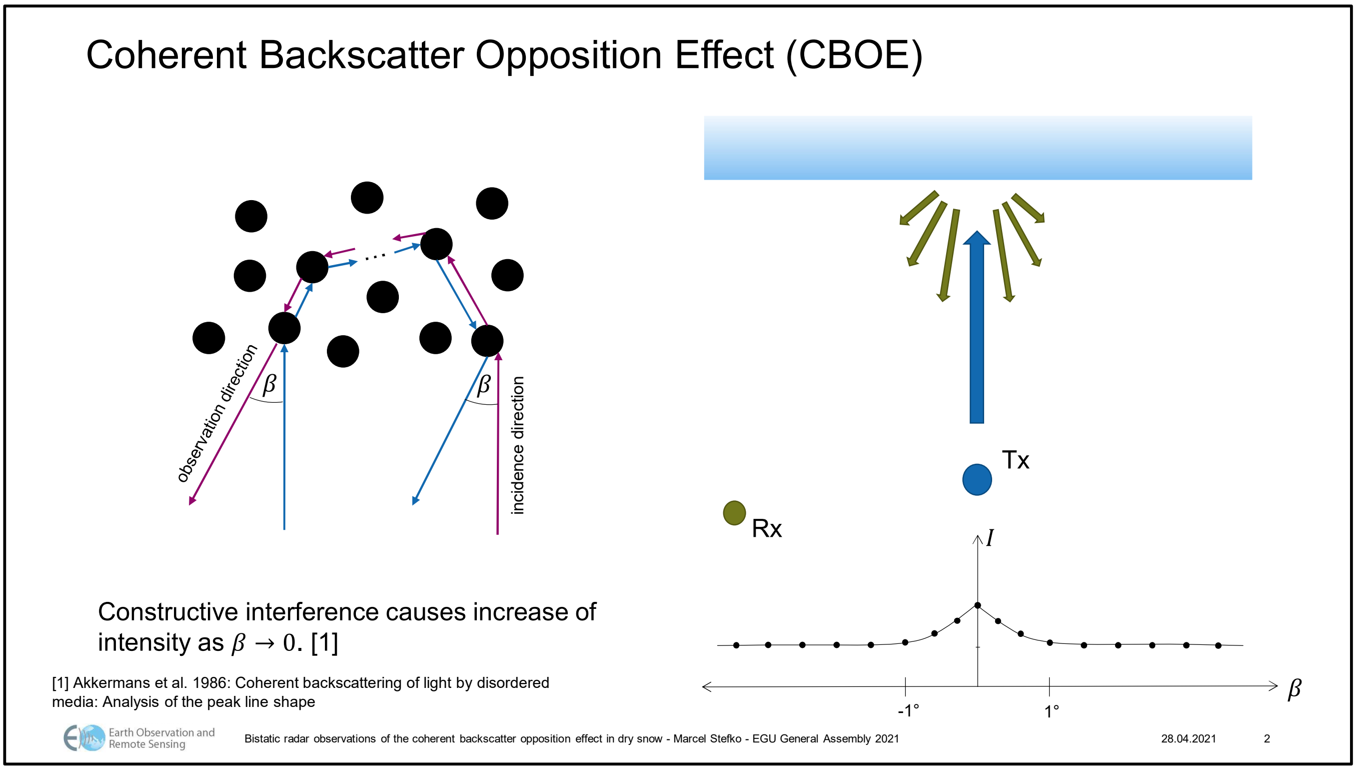


In this submission we present results of investigations of the coherent backscatter opposition effect (CBOE) in dry snow using both spaceborne and terrestrial bistatic radar sensors, and possible implications for future enhancement of snow parameter retrieval from radar data. The main points covered by this presentation are:

1. Description of CBOE and short history of its investigation across different fields.
2. Investigation of CBOE presence in dry snow in the accumulation area of the Aletsch glacier, using the spaceborne TanDEM-X radar system.
3. Sampling of the CBOE enhancement peak using a ground-based radar system KAPRI.
4. CBOE-model based inversion of the measurement data to obtain the mean free path of the scattered radiation within the snow layer.
5. Discussion of possibilities for physical parameter estimation.



The coherent backscatter opposition effect CBOE occurs when coherent radiation scatters in a medium of randomly distributed scatterers.

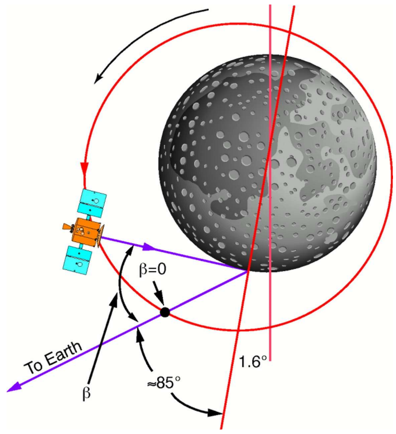
For each trajectory, we have two directions that incident rays could take through the medium. In the general case of beta not equal to zero, both of these directions are unlikely to be viable for the scattered radiation to follow at the same time. However, as the beta angle approaches zero, both of these paths become equally likely owing to time reversal symmetry, and also are guaranteed to interfere constructively since their path lengths are equal. This results in an increase of the intensity of scattered radiation as the beta angle approaches zero. A narrow intensity peak can be detected by a portable receiver. The theoretical maximal magnitude of the effect is a doubling of intensity, and usually the peak is quite narrow with a sub-degree half-width at half-maximum (HWHM).

This type of measurement where the transmitter is spatially separated from the receiver is called a “bistatic” measurement, and the angle beta is referred to as the “bistatic angle”, and the distance between the Tx and Rx is the “bistatic baseline”.

Occurrences of CBOE

- Visible light:
  - Particulate suspensions [2]
  - Cells of plants [3]
  - Lunar regolith (soil) [4]

- Radio waves:
  - Lunar ice deposits [5]
  - Mars' poles [6]
  - Jupiter's moons [7]
  - Earth observations [8]



Nozette et al. 1996: The Clementine bistatic radar experiment

[2] Kuga et al. 1984: Retroreflectance from a dense distribution of spherical particles
[3] Hapke et al. 1996: The cause of the hot spot in vegetation canopies and soils: Shadow-hiding versus coherent backscatter
[4] Hapke et al. 1998: The opposition effect of the Moon: Coherent backscatter and shadow hiding
[5] Nozette et al. 2001: Integration of lunar polar remote-sensing data sets: Evidence for ice at the lunar south pole
[6] Muhleman et al. 1991: Radar images of Mars
[7] Mishchenko 1992: The angular width of the coherent back-scatter opposition effect: An application to icy outer planet satellites
[8] Rignot 1995: Backscatter model for the unusual radar properties of the Greenland ice sheet

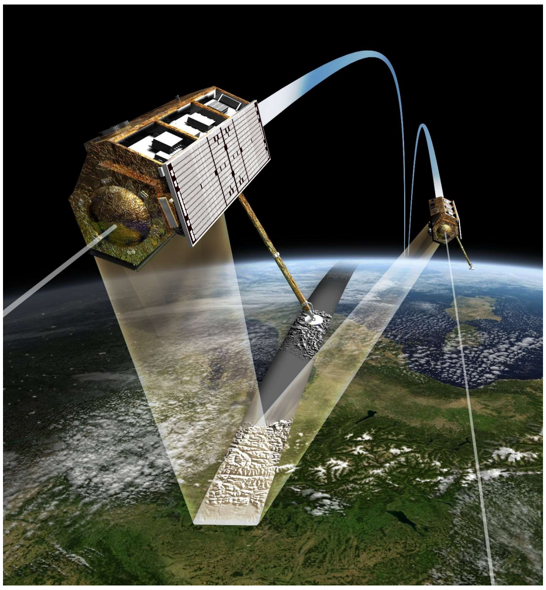
CBOE occurs across the EM spectrum and has been investigated in multiple fields:

- Optical frequencies both in laboratories and real world
- For radio waves, it plays an important role in remote probing of surfaces of various Solar System bodies, especially those covered with water ice. The reason for the extensive investigation in planetary science is that in interplanetary explorations, the geometry ideal for measurement of the CBOE intensity peak naturally arises, and the complexity of this bistatic measurement is small relative to the complexity of the entire mission.
- Earth-focused radar observations usually focus on purely monostatic observations, and thus the whole shape of the enhancement peak remains hidden, since for the measurement you need a bistatic system. However, in recent years the attention has also shifted towards bistatic measurements, and the first bistatic systems are operational.

TanDEM-X

- First bistatic synthetic aperture radar (SAR) system for Earth observation

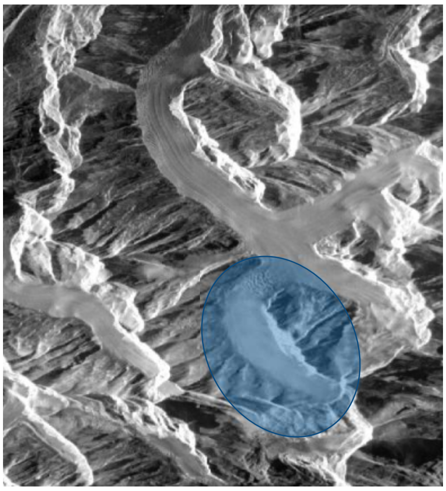
Platform	Spaceborne
Type	Synthetic aperture
Wavelength	3.1 cm
Frequency band	X-band
Launch year	2010
Orbital height	515 km
Bistatic baseline	50-500 m (up to 2000 m)
Polarization	Dual (half)



The first bistatic synthetic aperture radar system for Earth observation is TanDEM-X. In its nominal configuration, there is a small but non-zero bistatic angle between the main Tx-Rx satellite and the secondary Rx-only satellite. This provides an opportunity to investigate the presence of intensity differences between the two satellites as the bistatic angle varies.

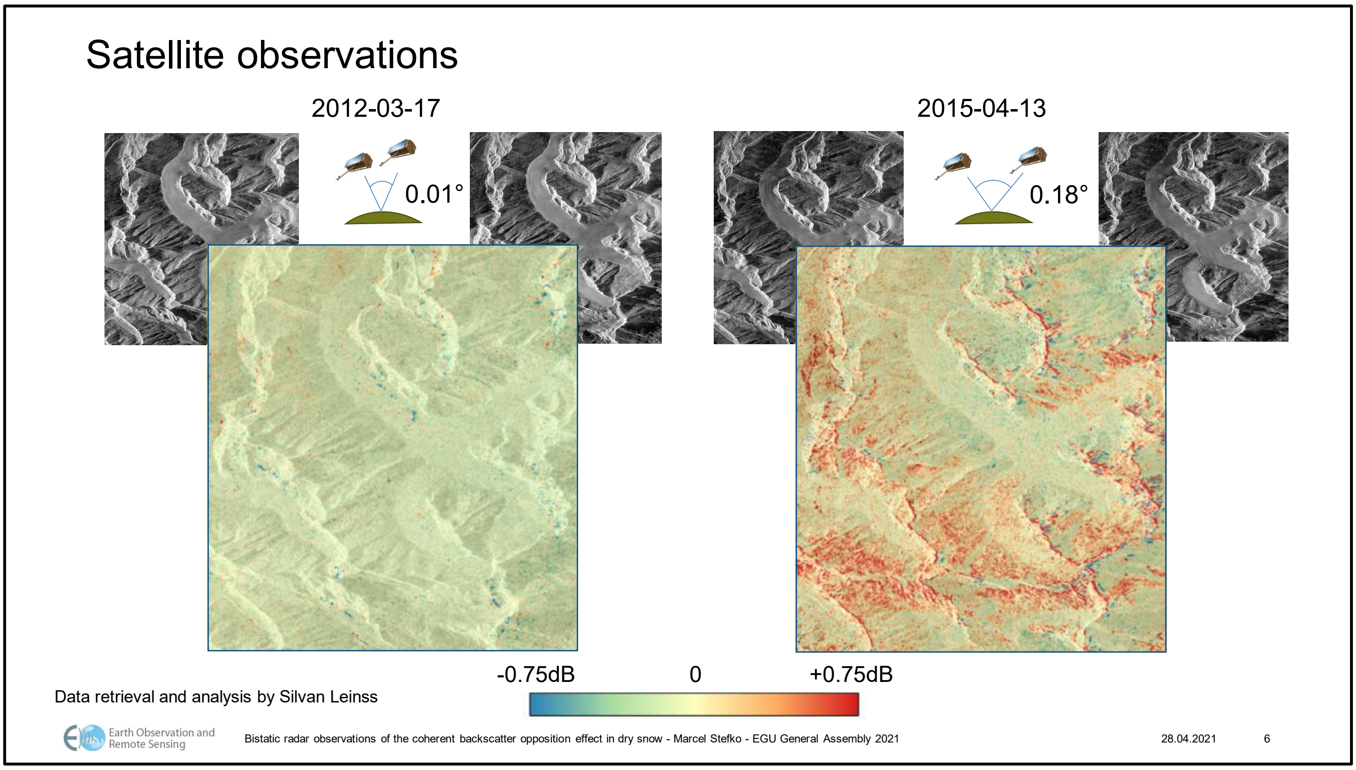
Observation site #1 - Ewigschneefeld

	Pass 1	Pass 2
Date	2012-03-17	2015-04-13
Baseline	54 m	2018 m
Bistatic angle	~0.01°	~0.18°



Data retrieval and analysis by Silvan Leinss

We have identified two passes over the accumulation area of the Aletschgletscher with different values of bistatic angle. In Pass 1, the two satellites were flying in a very tight formation with negligible bistatic angle, and thus they are expected to detect equal backscatter intensity values. However in Pass 2, the bistatic angle is increased, and if a narrow backscatter enhancement peak is present, there should be a difference in measured intensity between the two satellites.



The two large images show the difference of detected intensity between the main Tx-Rx satellite, and the secondary Rx-only satellite of the TanDEM-X constellation for the two passes over the Aletsch glacier region.

The left dataset shows that when the secondary Rx satellite is very close to the main Tx-Rx, both satellites detect the same backscatter intensity.
The right dataset shows that if the satellites move further apart (which increases the bistatic angle to a still small but non-zero value of 0.18°), there is a noticeable difference in detected intensity between the two satellites, which indicates a presence of a backscatter enhancement peak around the monostatic direction in the red-colored regions of the observed area. These regions are at a high altitude and are covered with snow, which is a very strong indicator that CBOE is occurring in the dry snow layers.

Satellite observations are highly performing for global mapping, but suffer from high revisit times. Furthermore, TanDEM-X does not focus on covering areas with a variety of bistatic angles, so the availability of suitable data is limited. For a more detailed investigation, more flexible measurements with ground-based sensors are a suitable tool.

Ground-based observations – KAPRI

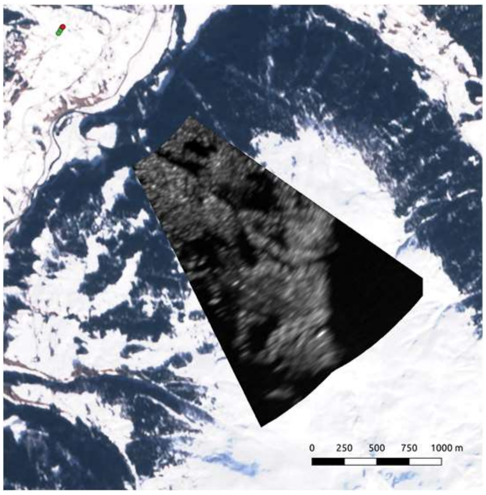
- Ku-Band Advanced Polarimetric Radar Interferometer
- Developed by GAMMA Remote Sensing & ETH Zurich

Platform	Ground-based
Type	Real aperture
Wavelength	1.8 cm
Frequency band	Ku-band
Max. range	10 km
Bistatic baseline	Up to 100m / 5km
Polarization	Quad (full)

Mounting the secondary receiver on a portable platform (Hornschlitten) allows variation of the bistatic angle β.

KAPRI is an experimental radar instrument developed in cooperation between our chair and the company Gamma Remote Sensing. It is one of the first systems of its kind capable of bistatic acquisitions with necessary coverage and is well suited for measurements in mountainous areas owing to its portability. This allows us to control and vary the bistatic angle of a measurement with very high degree of precision and acquire a complete profile of the intensity curve.

Observation site #2 – Davos / Rinerhorn



Modified Copernicus Sentinel data 2020/Sentinel Hub

During this winter, we performed an acquisition campaign observing the peak Rinerhorn under dry snow conditions, using a variety of bistatic baselines. The covered area consists of a forested part where the terrain is obstructed by trees, and an exposed, bare slope with clear visibility of the snow cover. In order to verify the influence of the snow layer, we also performed the same measurement in summer to get a control dataset without snow cover.

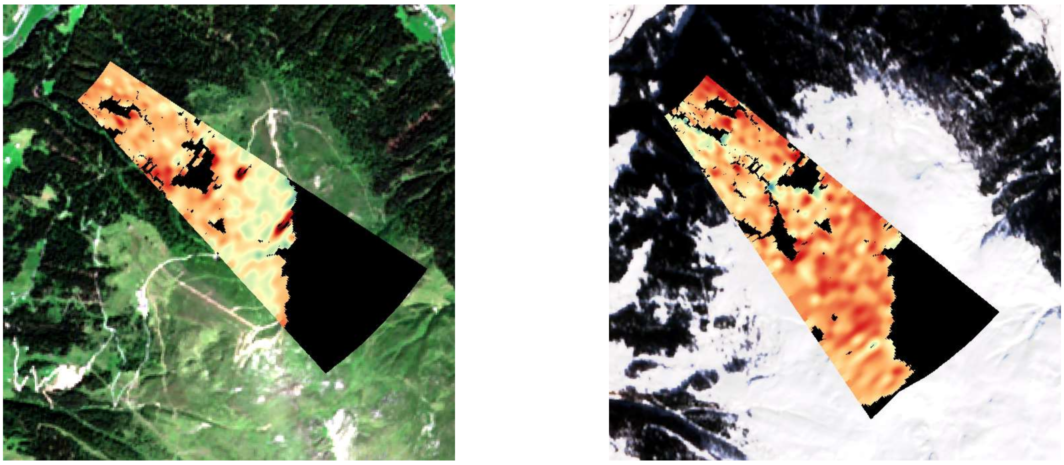
Ground-based observations

2020-08-03

$I(2\mathrm{m}) - I(50\mathrm{m}) \rightarrow \beta = 0.78°$

2020-03-04

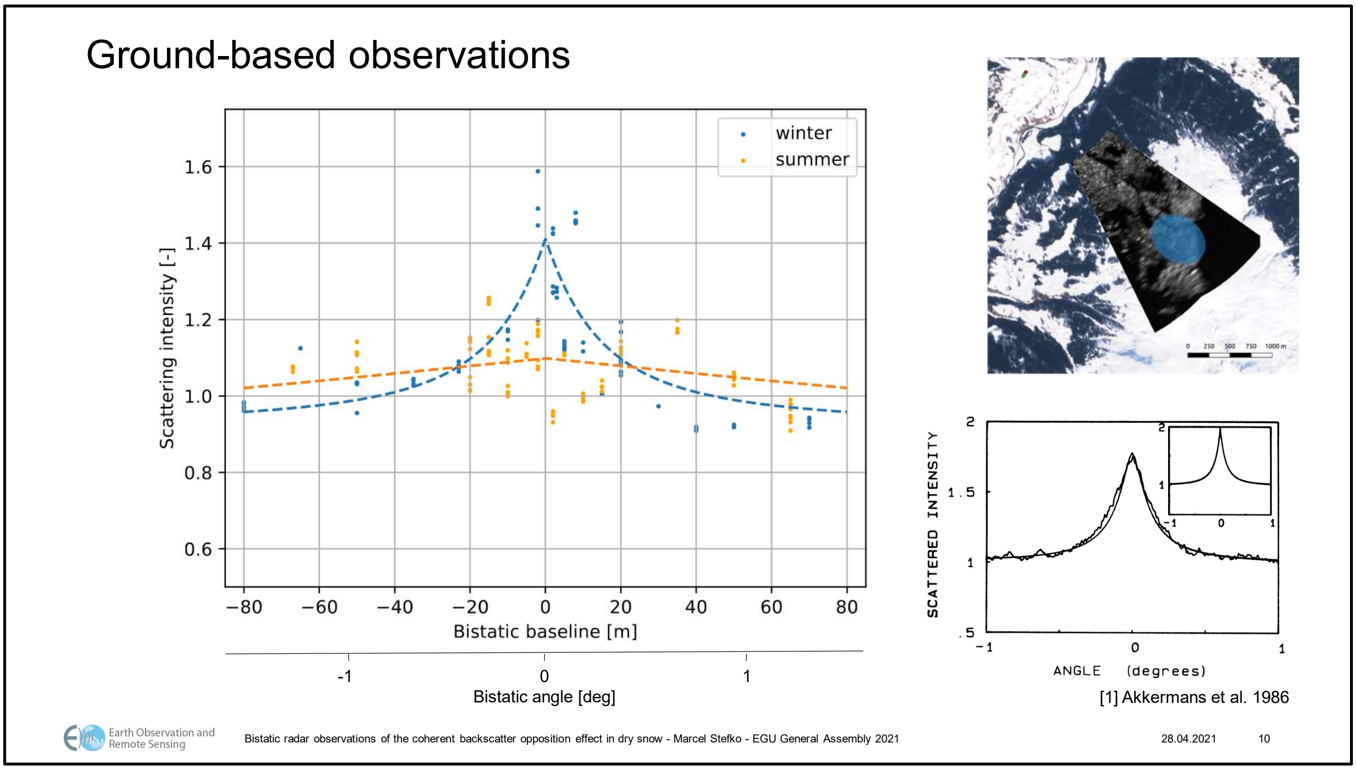
$I(2\mathrm{m}) - I(55\mathrm{m}) \rightarrow \beta = 0.85°$



Modified Copernicus Sentinel data 2020/Sentinel Hub

Using the same procedure as for the satellite data, the summer dataset shows two interesting features. The forested area does exhibit backscatter enhancement, signified by the red values. However, the higher situated exposed slope does not exhibit any enhancement peak when the area is not covered by snow.

Looking at the winter measurement, we can see a different story. The forested area exhibits similar enhancement as in summer, but the exposed slope area now also exhibits a considerable increase in backscatter intensity when the bistatic angle approaches zero.

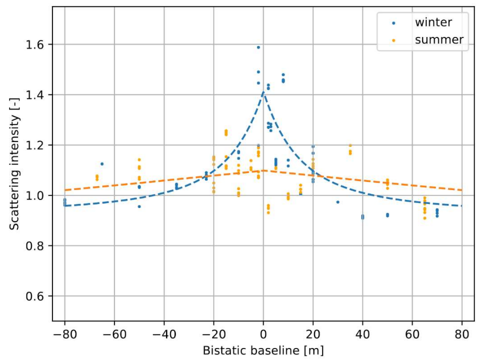


Comparing the backscatter intensity dependence of the exposed slope region between the two seasons, we can observe a significant peak around the monostatic direction in winter when the slope is covered by snow. The summer dataset does not exhibit this intensity peak. Comparing the shape and width of the intensity peak to a measurement by Akkermans et al. [1], we can see that the shape of the enhancement peak matches the CBOE theoretical prediction.

Parameter inversion

$$L = \frac{0.36\lambda}{2\pi \mathrm{HWHM}}$$

- The half-width at half-maximum (HWHM) of the peak can be correlated to mean free path of the signal within the medium. [9]
- KAPRI observations:
  - ➢ HWHM ~ 0.25°-0.4°
  - – Wavelength = 1.8 cm
  - ➢ Mean free path ~ **15-25 cm**
- Mean free path of signal within the medium is dependent on the medium's scattering efficiency.



[9] Van Albata et al. 1988: Polarisation effects in weak localization of light

On the data, we can apply the EM scattering model of CBOE. According to one such model, when we extract the width at half-maximum of such peak, it can be correlated to the mean free path of the signal within the medium.

And this mean free path is of course then closely tied to the scattering efficiency of the snow layer, which is a very important parameter if the goal is to extract other physical parameters such as snow water equivalent (SWE).

The narrower the peak, the longer the mean free path, i.e. it could be correlated to the scattering efficiency of the medium.

Conclusions

- Backscatter enhancement matching CBOE observed in dry snow layers at radio wavelengths at very small bistatic angles.
- Models of CBOE relate the properties of the peak (width, height, polarimetric behaviour) to physical properties of the scattering medium (layer thickness, grain size, scattering efficiency).
- Further study of CBOE in the context of Earth-focused observations of snow and ice opens new opportunities for development of quantitative models aiming to derive snow properties from radar observations.

Thank you for your attention!

Any questions?

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Thank you for your attention.

REFERENCES:
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[2] Kuga et al. 1984: Retroreflectance from a dense distribution of spherical particles
[3] Hapke et al. 1996: The cause of the hot spot in vegetation canopies and soils: Shadow-hiding versus coherent backscatter
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