# 94 GHz radar mapping of terrestrial snow cover

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*Collaborators and Funders*

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SAGES
Scottish Alliance for Geoscience, Environment and Society

Scottish Avalanche Information Service
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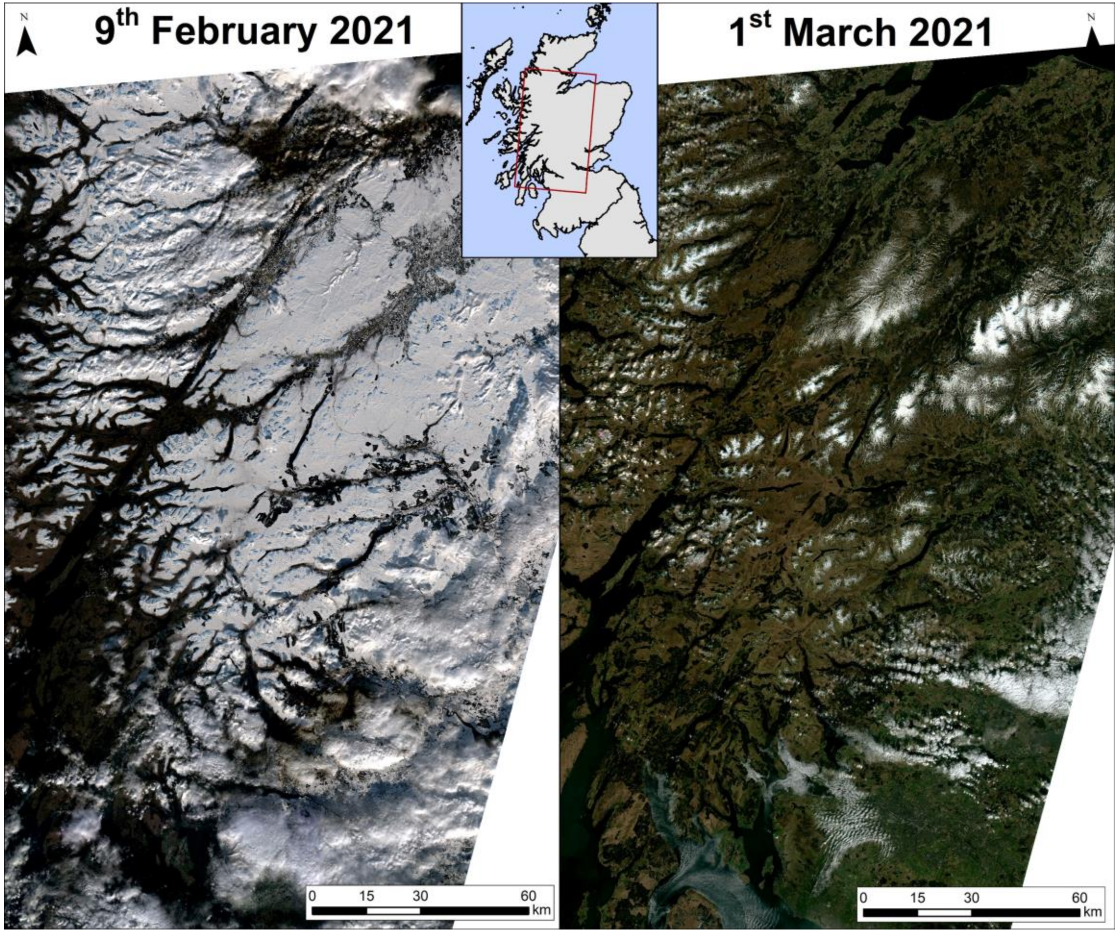
# Snow Cover in Scotland




- In Scotland, snow cover is a perennial feature of the landscape.
- The maritime climate makes weather conditions very changeable.
- This is illustrated in the satellite images on the left – large snow accumulations in mid-February melted away over just 20 days.
- Monitoring these drastic changes in snow cover is a key challenge for the Scottish Avalanche Information Service (SAIS).
- The unpredictable nature of snow cover in Scotland impacts many different areas of the environment and society…

# The Importance of Snow Monitoring

Monitoring terrestrial snow cover is important for several reasons:
**Hazard Warning**

Avalanches

Wind-blasting and wind-slab

*Images taken from SAIS forecast blogs: www.sais.gov.uk*

# The Importance of Snow Monitoring

Monitoring terrestrial snow cover is important for several reasons:

## Local Economy

Tourism attractions including ski centres, funicular railways, restaurants and much more.

# The Importance of Snow Monitoring

Monitoring terrestrial snow cover is important for several reasons:

**Ecology**

Reindeer

Ptarmigan

*Images taken from SAIS forecast blogs: www.sais.gov.uk*

# The Importance of Snow Monitoring

Monitoring terrestrial snow cover is important for several reasons:

**Hydrology**

River discharge changes with snow accumulations and frozen rivers.

*Images taken from SAIS forecast blogs: www.sais.gov.uk*

# The Importance of Snow Monitoring

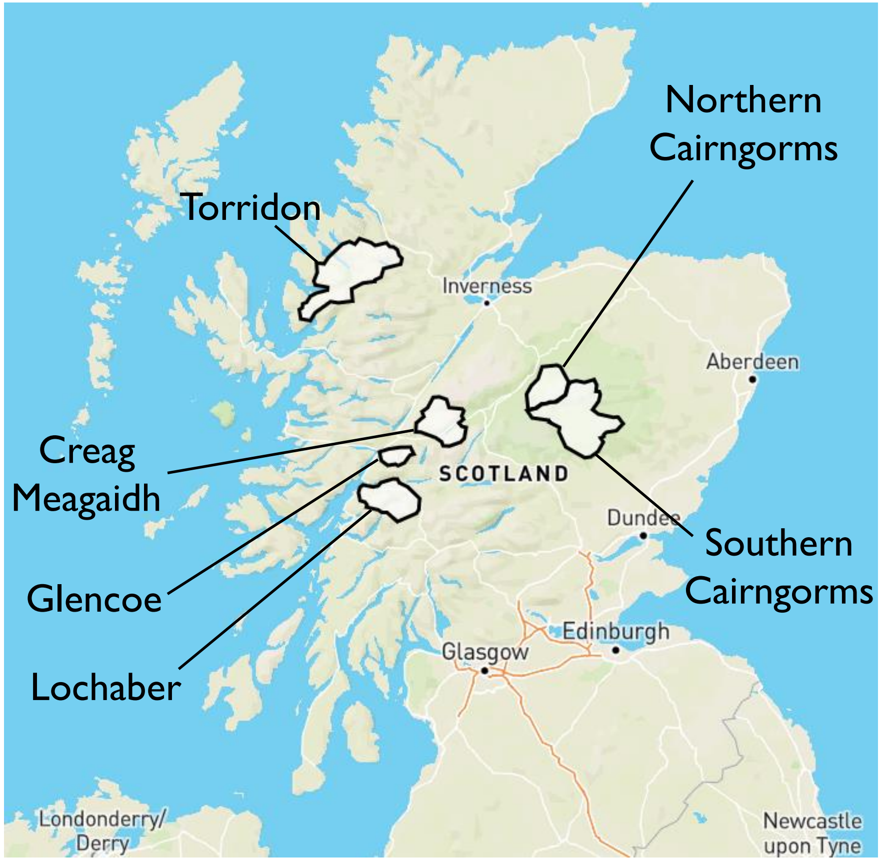
Monitoring terrestrial snow cover is important for several reasons:

## Public Infrastructure

*Images taken from SAIS forecast blogs: www.sais.gov.uk*

# How do we monitor snow in Scotland?

Monitoring in 7 regions across Scotland




Credit: SAIS.

- Snow monitoring in Scotland is led by the SAIS.
- In winter, the SAIS produce daily reports on avalanche risks and post blogs on identified hazards.
- In each region, several assessments are made:
  - Snow temperature profiles are collected in a snow pit (snow texture, temperature).
  - Expert assessment of snow hazards.
  - Snow conditions forecast through the next 24 hours, with weather data as input.
- This hazard monitoring is led by forecasters assessing the snow conditions on the ground.
- New technologies, such as remote sensing, offer new opportunities to improve hazard assessment.
- Here, we assess the capabilities of millimetre-wave radar for mapping and monitoring snow conditions in the Scottish Highlands.

# Study Aims

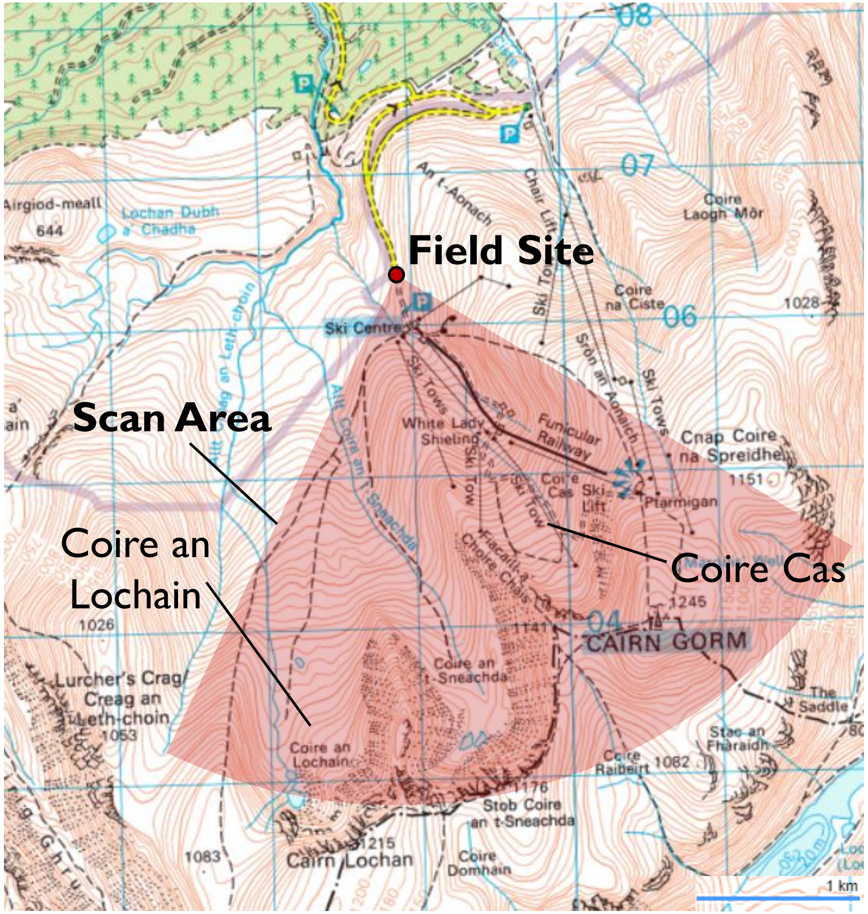
1. Assess the potential of millimetre-wave radar for snow mapping and assessing snow-associated hazards.

2. Generate 3D maps of snow surface topography using millimetre-wave radar and validate using a co-located Terrestrial Laser Scanner (TLS) survey.

3. Understand the effects of snowpack properties on 94 GHz radar backscatter.

# Fieldwork

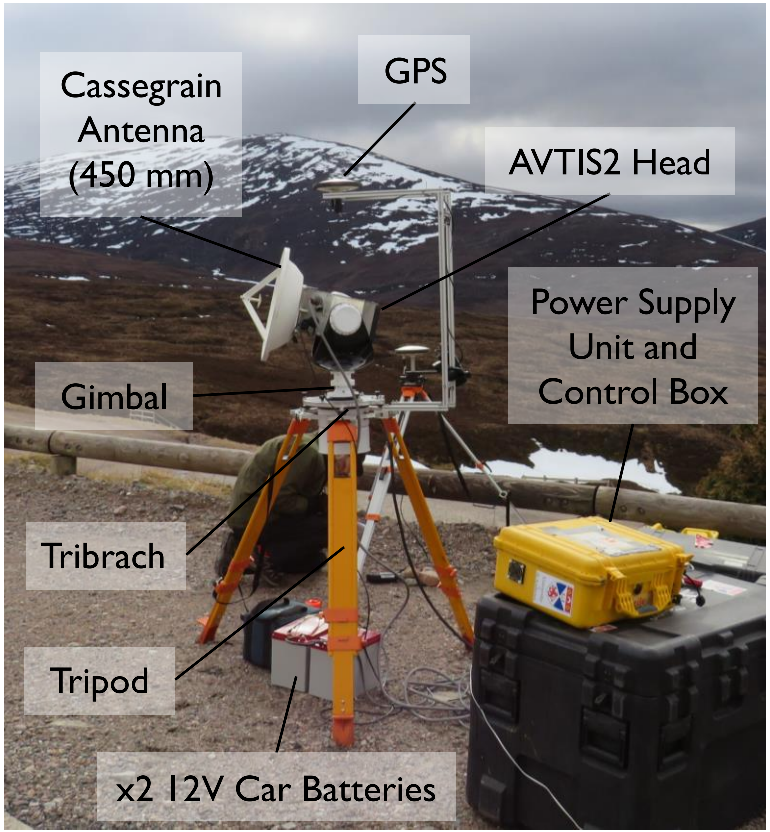
- **Dates**: 22-24 March 2021
- **Field Site**: Cairngorm Mountain Ski Centre, Northern Cairngorms.
- At this location, we deployed a 94 GHz radar and a Terrestrial Laser Scanner (TLS).
- The area scanned by both instruments covered two corries >900 m a.s.l.:
  - Coire Cas (ski centre)
  - Coire an Lochain


*Credit: OS Maps.*

# Measurements

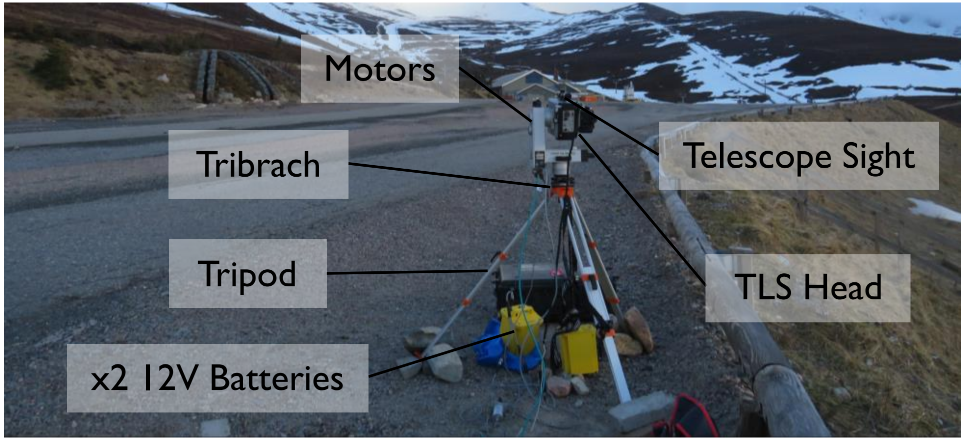
## Millimetre-wave Radar




| | |
|---|---|
| **Sensor Name** | AVTIS2 |
| **Measurement Type** | FMCW |
| **Frequency** | 94 GHz |
| **Wavelength** | 3.19 mm |
| **Two-way Radar Beamwidth** | ~0.35° |
| **Range Resolution** | 0.75 m |
| **Radar Azimuth Resolution (per km)** | 6.1m |
| **Max Range** | ~6 km |
| **Image Acquisition Time (20° x 5°, 0.1° inc.)** | 50 mins |
| **Weight: Radar Head** | 40 kg |

# Measurements

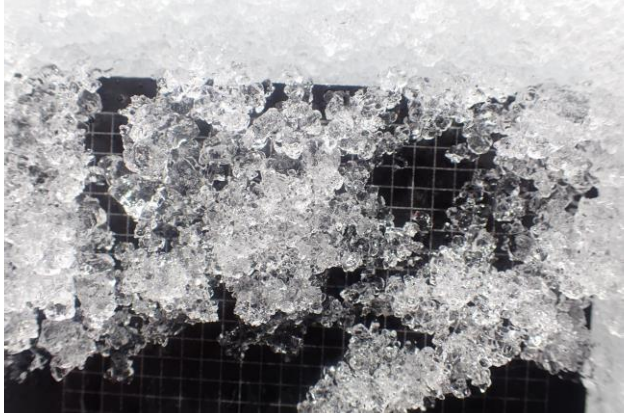
## Terrestrial Laser Scanner (TLS)




| | |
|---|---|
| **Sensor Name** | Riegl LPM-321 |
| **Measurement Type** | Pulsed |
| **Wavelength** | 905 nm |
| **One-way Beam Divergence** | ~0.05° |
| **Measurement Accuracy** | 0.025 m |
| **Max Range** | ~6 km |

## In-Situ Snow Measurements

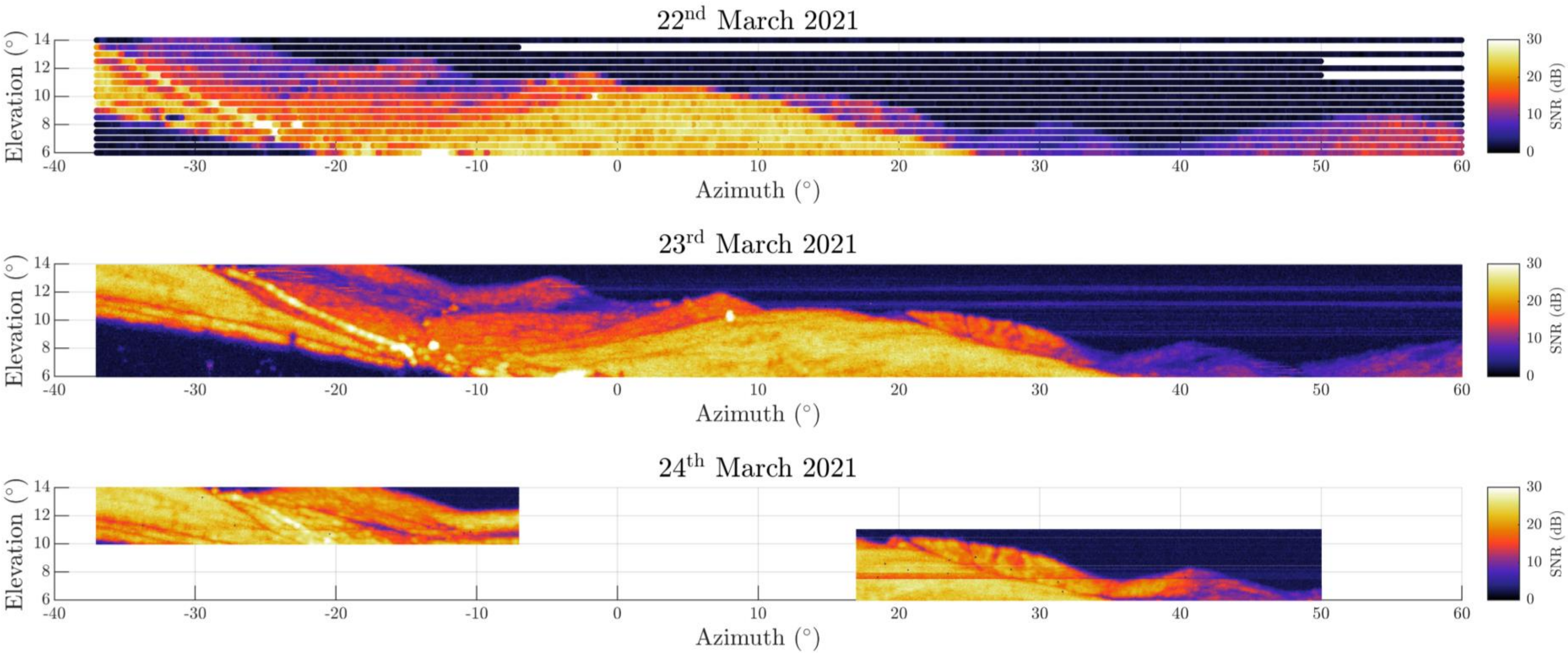
- Snow measurements across two corries:
  - Surface grain size
  - Snow hardness and surface and 5 cm
  - Foot penetration
  - Snow density
  - Snow pit temperature profile
  - Hazard reports



Snow grain size measurement. Photo Credit: Blair Fyffe

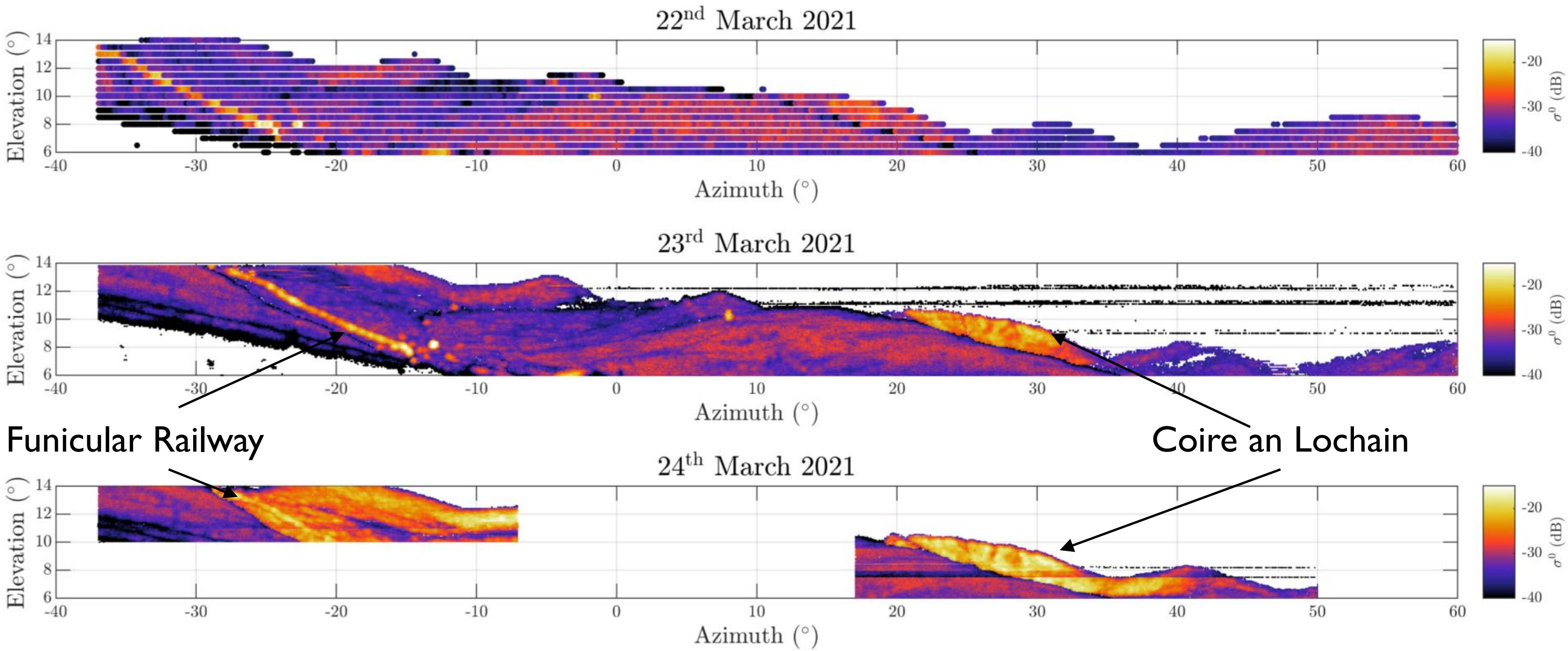
# Radar Received Power

- We measured radar backscatter across 3 days, which we convert to Signal-to-Noise Ratio (SNR) by correcting for the radar noise floor. We used slightly different scanning configurations each day, which altered the resolution.



# Normalised Cross Section ($\sigma^0$)

- We convert SNR to $\sigma^0$ by correcting for range fall-off, beam spreading and atmospheric attenuation. Values of $\sigma^0$ appear larger across the corries on 24th March, which may be due to changes in the snow surface properties.



# Snowpack Properties: Influence on Radar Backscatter

## Snowpack Measurements

| Site | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Altitude | 650 | 820 | 900 | 1030 | 1070 |
| Surface Grain Size | 2-3 mm | 2-3 mm | 2-3 mm | 3 mm | 2 mm |
| Surface Hardness | 1F | 1F | 1F | P | 1F |
| Hardness at 5 cm | P | P | P | P | P |
| Foot Penetration | 1 cm | 1 cm | 1 cm | 1 cm | 1 cm |
| Average Density | 492 kg/m$^3$ | 508 kg/m$^3$ | 513 kg/m$^3$ | 460 kg/m$^3$ | 400 kg/m$^3$ |

Hardness (i.e. what can be pressed with a force of 10N):
- P: Pencil
- 1F: One Finger

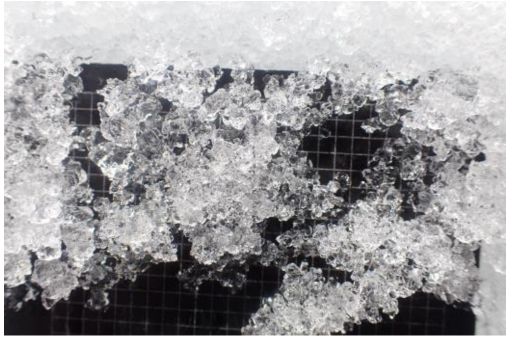
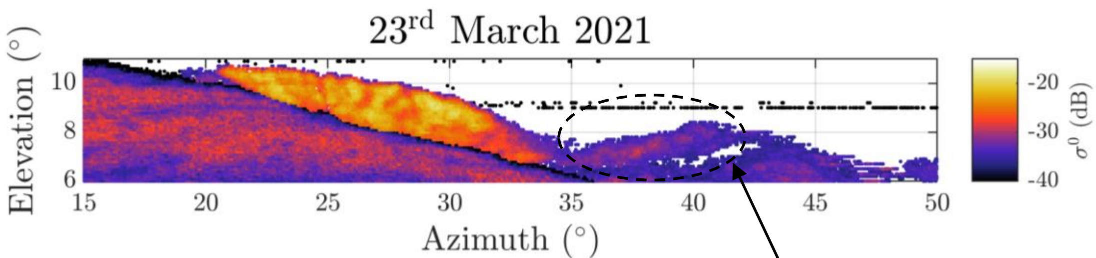


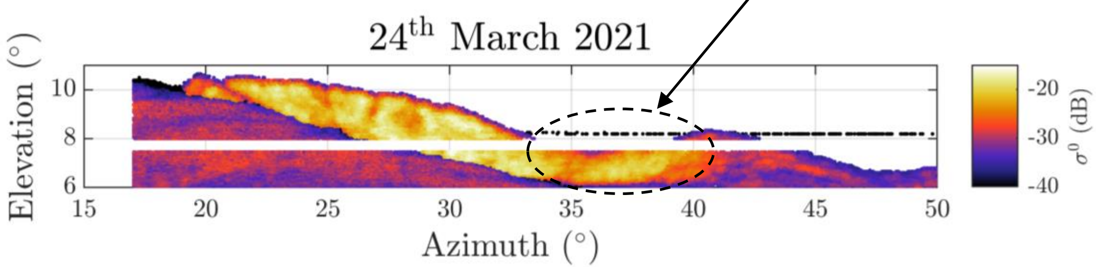
Photo Credit: Blair Fyffe

- Snowpack conditions were measured along a transect through the Corrie Cas ski centre – given its homogeneity, we expect these values to also be representative of Coire an Lochain.
- The snow grains have gone through multiple melt and freeze cycles, hence they are quite large grains at 2-3 mm.
- The snowpack in general had a medium hardness, likely softer 5 cm below the surface.
- The high snow density will reduce signal penetration into the snowpack.

# Detection of Snow Surface Activity




Differences in $\sigma^0$





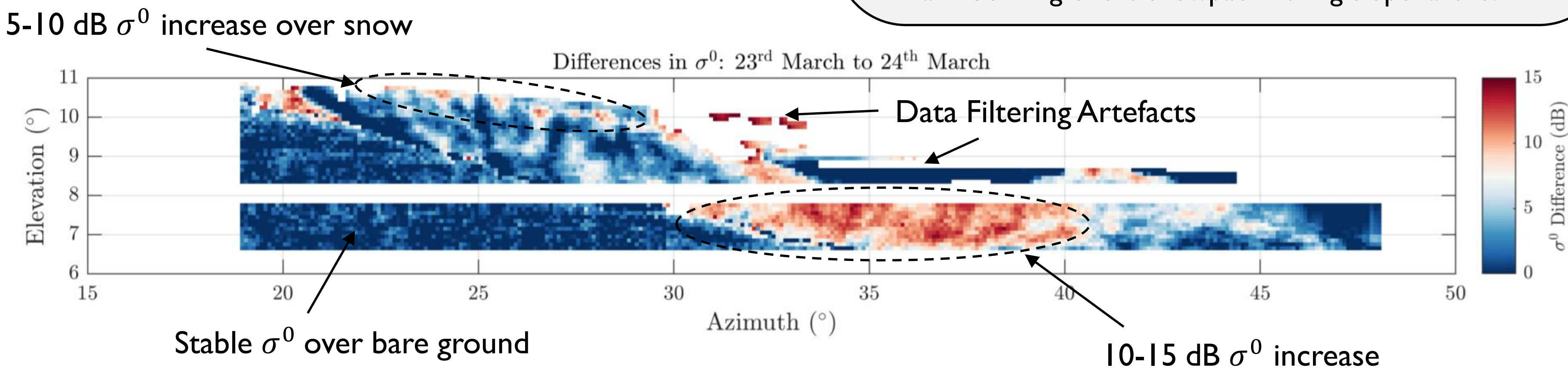

- Heavy winds overnight forced snow to accumulate along the corrie ridges and eventually led to small avalanche streams along the steepest slopes of Coire an Lochain.
- This led to an increase in $\sigma^0$ values on 24th March – possibly due to increased surface roughness, or exposure of dry snow beneath the snowpack.

# Causes of Change: Implications for Snow Monitoring

Temperature Differences

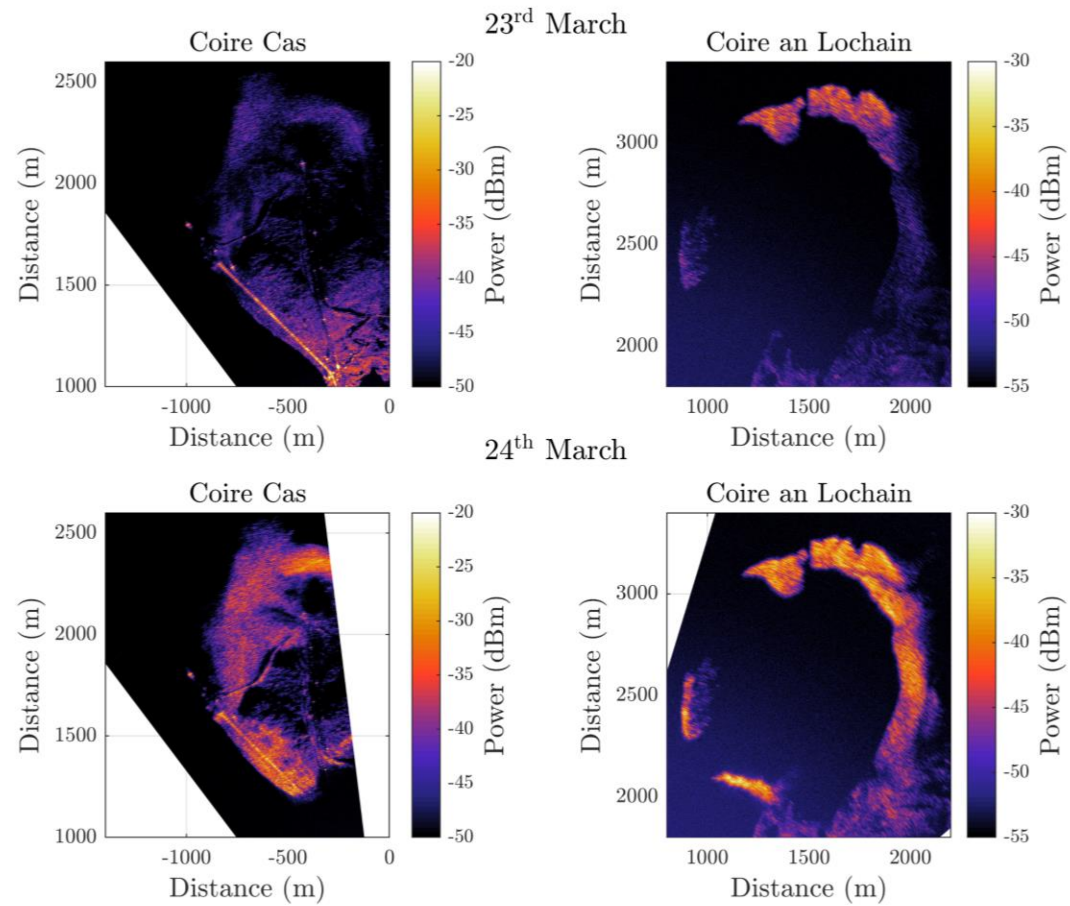
| Parameter | 22nd March | 23rd March | 24th March |
|---|---|---|---|
| Air Temperature (Snow Pit) | 4.1° | 3.5° | 0.6° |
| Air Temperature (Summit) | 0.0° | 0.0° | -3.0° |

- 24th March was ~3° colder than the first 2 days.
- The warmer temperatures on the 22nd and 23rd March would have led to some minor surface melting on the snowpack.
- This would have enhanced absorption of the 94 GHz signal – we suggest this is the result of the regionally lower $\sigma^0$ between 22nd-23rd March.
- A localised region of 10-15 dB $\sigma^0$ increases is likely due to local snowpack failures identified previously – we suggest this is mostly due to enhanced surface roughness and bonding of the snowpack during slope failure.

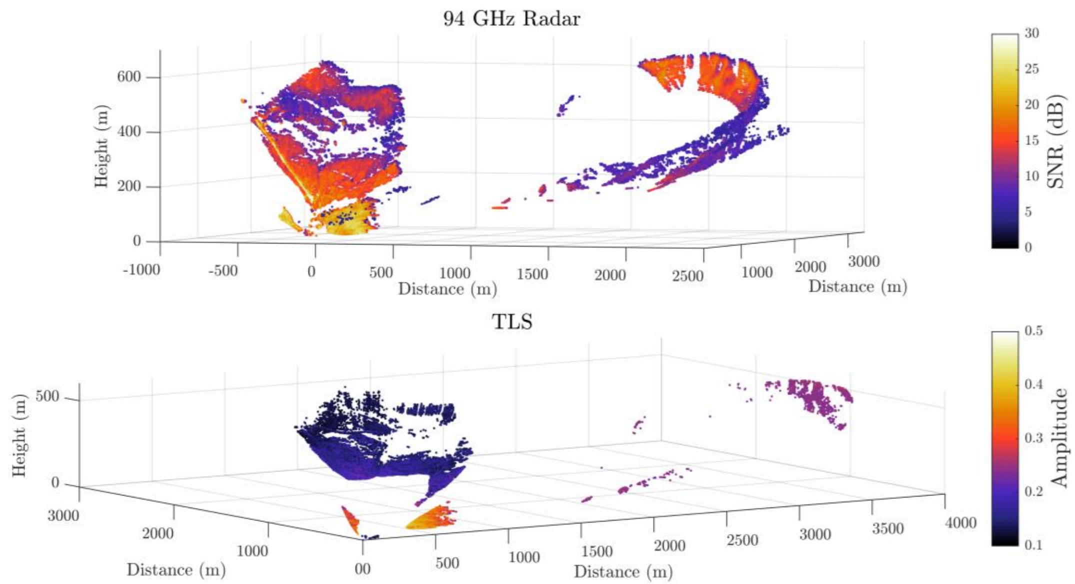


# Radar Backscatter Maps

- The images on the right show a planar view over the two corries.
- They were created by calculating the maximum power at each range bin across the scene – they are analogous to SAR images but acquired through the mechanical scanning process of AVTIS2.
- The increase in received power between the two acquisition dates illustrate the sensitivity of snow surface conditions to 94 GHz radar backscatter.
- These overview images also illustrate the high-resolution capabilities of millimetre-wave radar.
- These images could be used to assess snow hazards: low backscatter would suggest melting snow, large backscatter could indicate unstable slopes.



# Point Clouds




Point Cloud Differences

| | |
|---|---|
| **94 GHz Radar** | 109,483 Points |
| **TLS** | 30,332 Points |

- Above, we showcase points clouds derived from 94 GHz radar and TLS, alongside a picture of a typical scene of the corries.
- Cloud cover moved across the corries swiftly, interrupting TLS scans. This led to reduced TLS coverage of both corries.
- The point clouds will next need to be aligned for a quantitative analysis.

# Summary

1. 94 GHz radar allows for high-resolution mapping of snow surface conditions.

2. We have been able to detect small snow surface failures using changes in radar backscatter, demonstrating the radars' ability to be used as a hazard mapping tool.

3. Regional changes in radar backscatter from a spring snowpack were mostly related to changes in air temperature and its influence on snow surface melt.

4. We are planning further field tests to assess the capabilities of the radar to map a variety of snow surface conditions.



**Session CR2.4: *Geophysical and in-situ methods for snow and ice studies***
Paper Number: [*EGU21-2747*]()
Live: *15:52-15:54 CEST*
Breakout Chats: *16:20-1700 CEST*

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With special thanks to the SAIS and Cairngorm Mountain Ski Centre for all their help, particularly in these very difficult times!

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Please contact me if you are interested to hear more!

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