# The WBSCAT Polarimetric Synthetic Aperture Scatterometer for Retrieval of In-Situ Time-Series of Snow Structure

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### Abstract

WBSCAT is a new terrestrial microwave scatterometer supporting polarimetric observations over 1 to 40 GHz. This instrument is being developed for the European Space Agency (ESA) to conduct microwave studies of a wide range of ground covers including snow and ice. This instrument is built upon the heritage of SnowScat , operating over the range of 9.2 to 17.8 GHz, that has been used for generating tomographic time-series of snow pack and is part of the ongoing ESA SnowLab project [2]. WBSCAT, like its predecessor, acquires coherent data and can measure polarimetric scattering matrices, interferometric phase, and coherence. Both instruments will be operated in Winter 2018/2019 in Davos Laret, Switzerland mounted on a 10- meter tower and performing multiple daily observations of the snow pack. Either instrument can be attached to a 2.2-meter linear scanner inclined at 45-degrees permitting tomographic snow profiling [1]. The WBSCAT instrument uses radial-scan aperture synthesis to acquire independent observations of the scattering volume and also to restrict the field of view to the undisturbed test site, despite wide antenna beamwidths at low frequencies. The 6 horn antennas, with overlapping frequency ranges of 1 to 6, 2 to 18, and 10 to 40 GHz, are mounted approximately 60 cm radially from the rotation axis of the pan/tilt scanner. The antennas can be scanned between +35 and -45 degrees in elevation and +/- 90 degrees in azimuth, creating a synthetic aperture. The aperture dimensions are mostly determined by the antenna pattern, but at low frequencies, the antenna beamwidth exceeds 90 degrees. Aperture synthesis substantially increases the number of looks for improved radiometric resolution and is a novel approach for ground-based microwave scatterometry. Combining ranging information along with WBSCAT aperture synthesis perpendicular to the line of sight, has the potential for direct 3D imaging of the snow pack.

# The WBSCAT Polarimetric Synthetic Aperture Microwave Scatterometer for Retrieval of In-Situ Snow Structure Time-Series


GAMMA REMOTE SENSING

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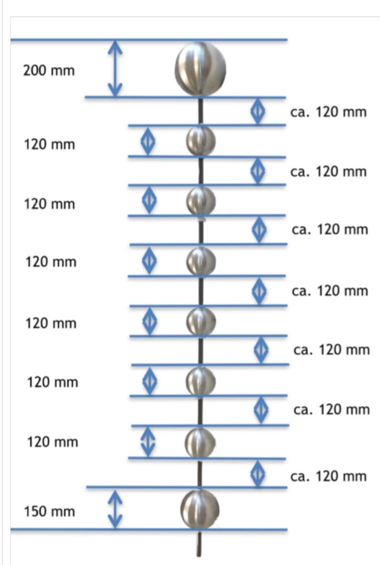
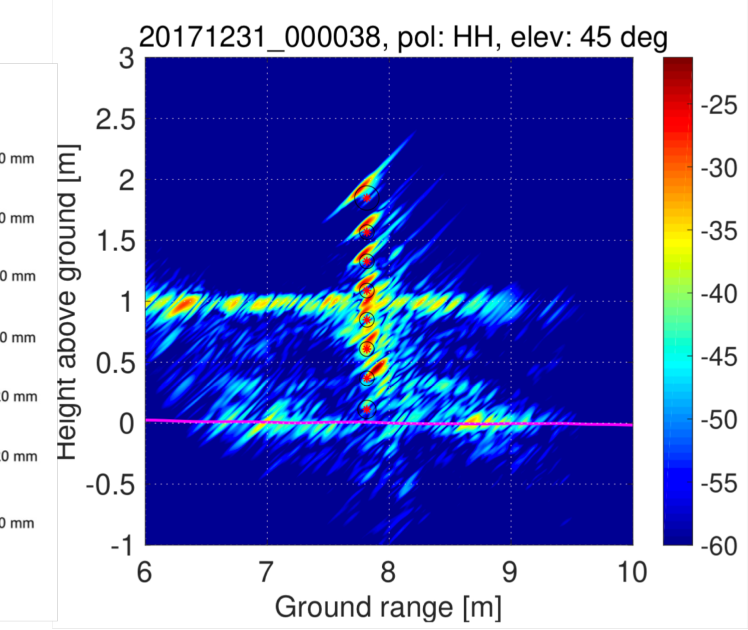
## Motivation

WBSCAT is a new terrestrial microwave scatterometer supporting polarimetric observations over 1–40 GHz. This instrument is being developed for the European Space Agency (ESA) by Gamma Remote Sensing AG to conduct microwave studies of a wide range of ground covers including snow and ice. It is built upon the heritage of the SnowScat scatterometer [1], that operates over 9.2 to 17.8 GHz. SnowScat is part of the ongoing SNOWLAB collaboration [2] generating tomographic image time-series of the snow pack in Davos, Switzerland. WBSCAT, like its predecessor, acquires fully polarimetric coherent backscatter data. Both instruments will be operated in Winter 2018/2019 mounted on a 10-meter high tower to perform multiple daily observations. Either instrument can be attached to a 2.5-meter linear scanner, inclined at 45-degrees, that permits linear aperture synthesis for 2D tomographic snow profiling [1].

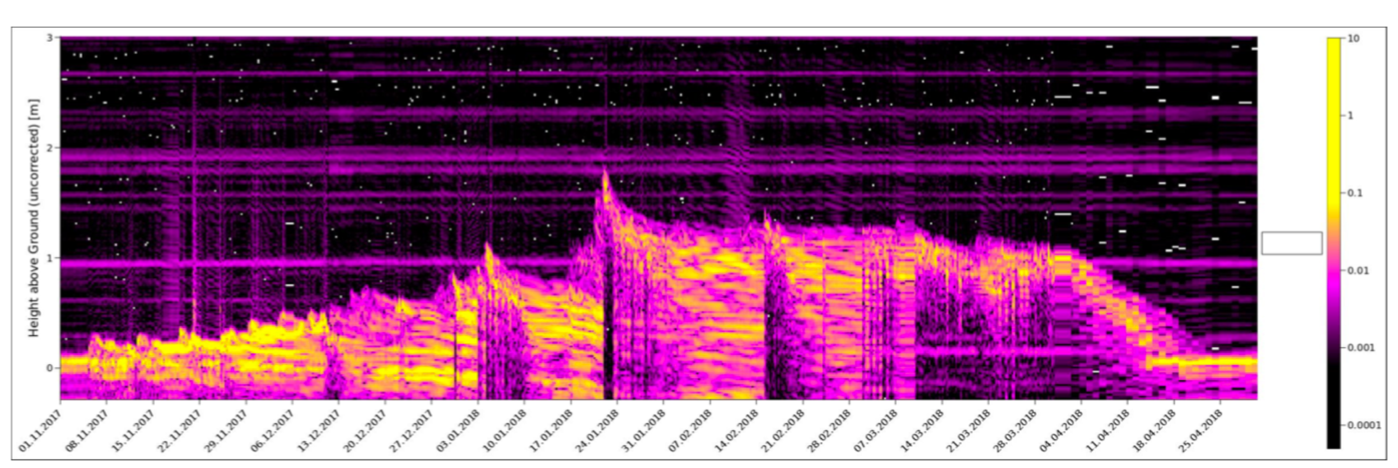

Snowscat deployed on the TomoRail




Tomo-target



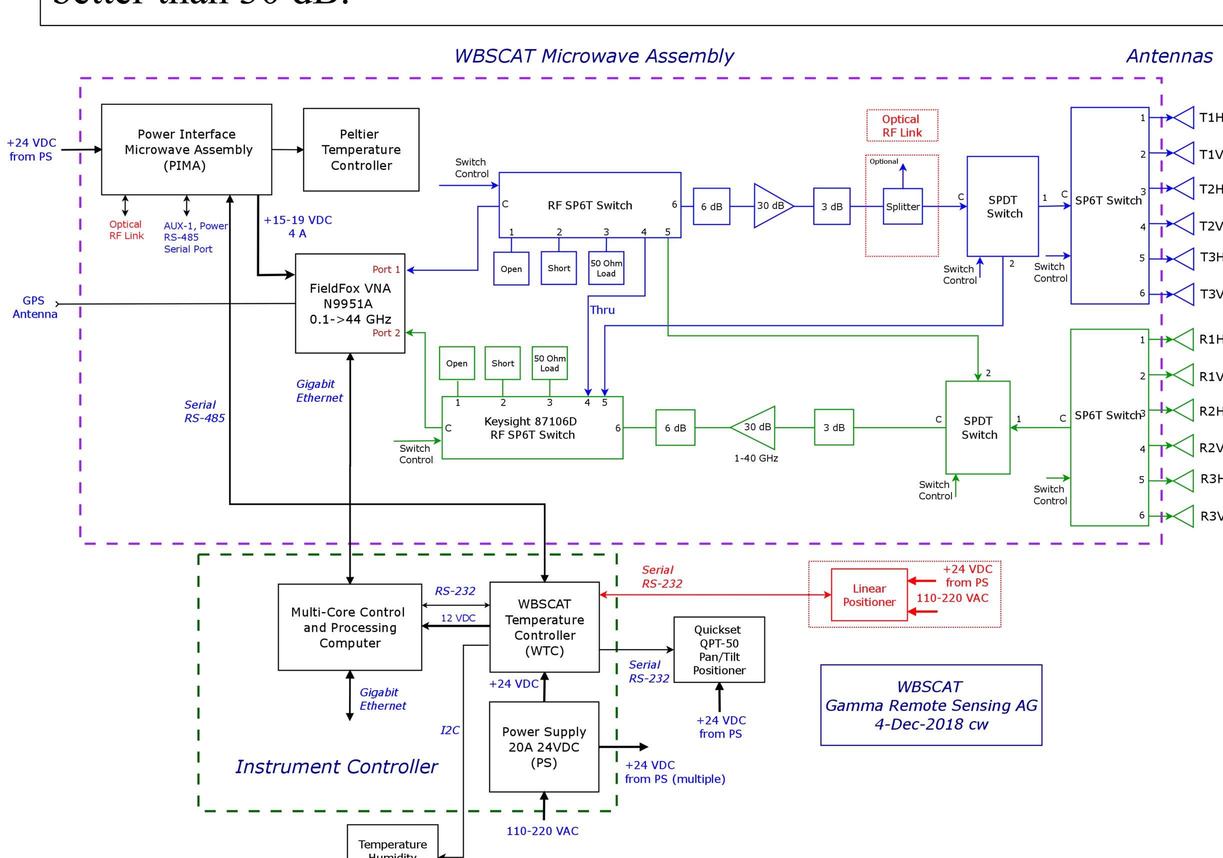

SnowScat 2D focused tomographic image of the tomo-target embedded in a 1-meter thick snow pack



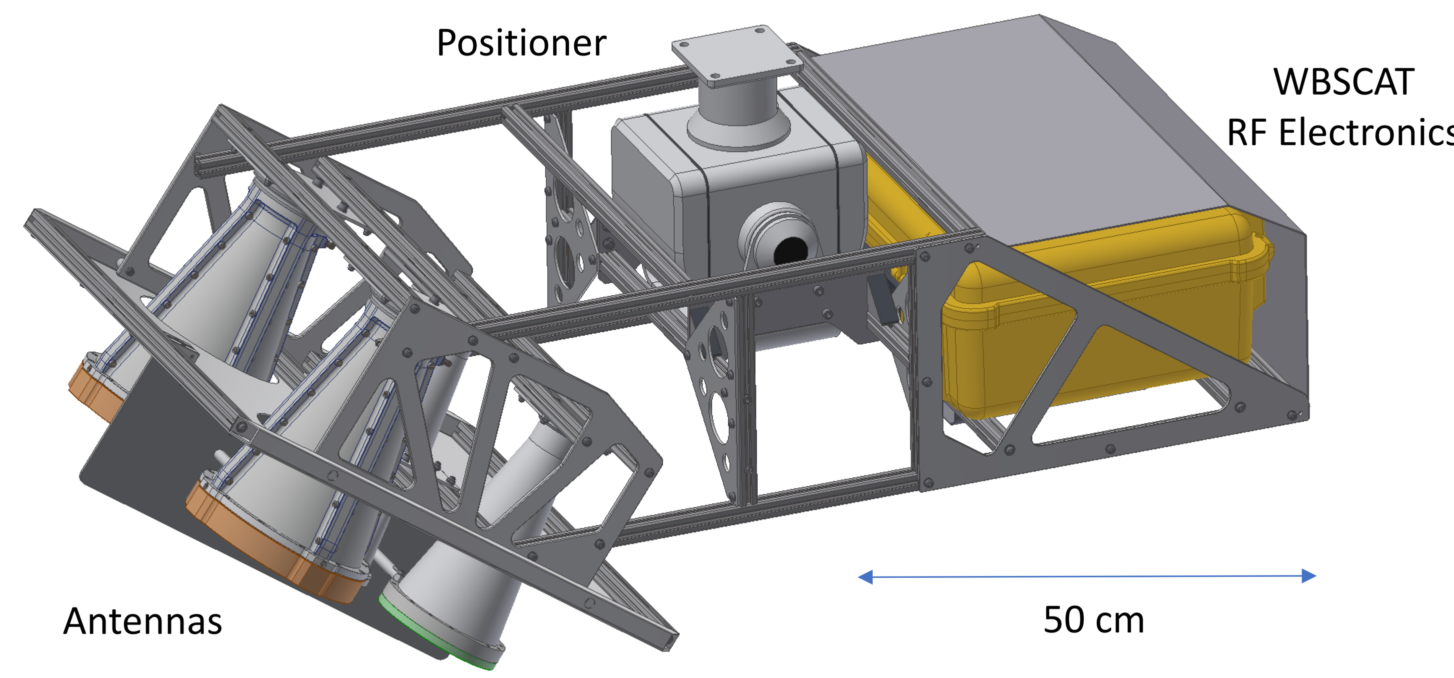
Snowscat vertical profiles over the 2017-2018 Winter Season, Davos, Switzerland

## WBSCAT Instrument Hardware

WBSCAT acquires fully polarimetric data in practically all-weather situations and temperatures, -40 to +50C. Based on our experience with SnowScat with respect to operation under severe environmental conditions, the WBSCAT microwave components are mounted in a temperature-regulated and insulated enclosure. The microwave electronics and computer that controls WBSCAT use separate enclosures to minimize temperature variations and avoid possible RFI. A Vector Network Analyzer (Keysight FieldFox N9951A), covering frequencies up to 44 GHz, is used for signal generation and coherent measurement of the backscattered signal. An external calibration network with discrete Short, Open, Load, and Thru (SOLT) standards is used to calibrate the VNA and accurately measure the low-noise amplifiers used in the receiver and transmitter. These amplifiers provide enough gain to overcome the high noise level of the VNA receiver. Quad-ridge horn antennas cover 1-6, 2-18, and 10-40 GHz with polarization isolation better than 30 dB.




WBSCAT microwave electronics




## Performance Analysis

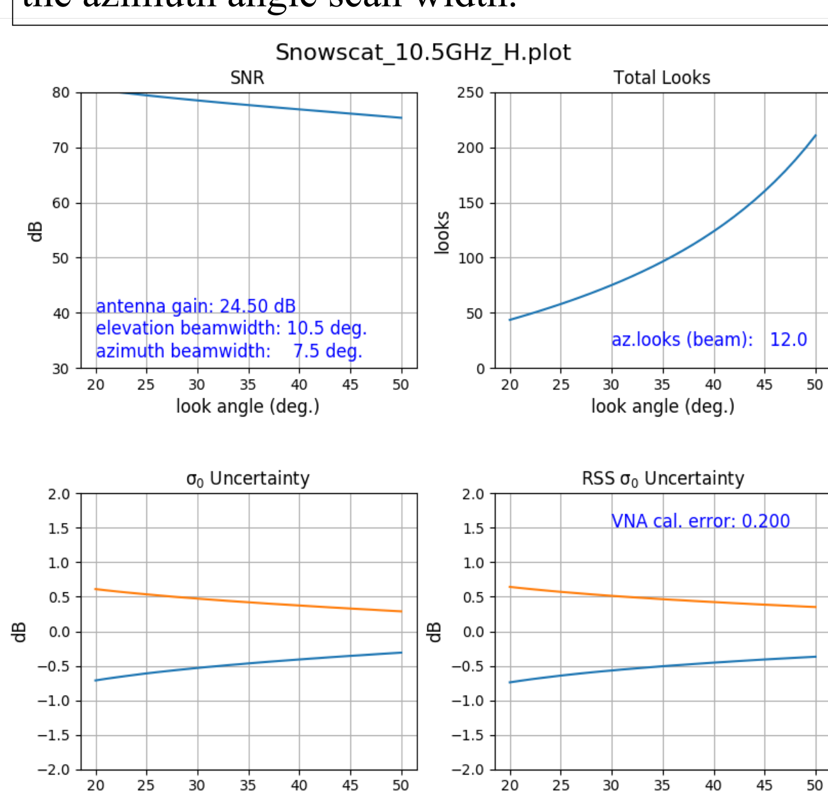
WBSCAT acquires measurements of the radar cross-section coefficient (RCS) of the surface as a function of incidence angle by combining independent samples of radar backscatter ("looks") to reduce radar speckle and thermal noise contributions. The performance goal of WBSCAT is 0.5 dB uncertainty in the RCS of the surface. The looks are obtained by a combination of spectral and azimuth diversity.

$$\Delta\sigma^0_{\mathrm{dB}} = \sqrt{(\sigma^2_{\mathrm{vna\_dB}} + (10\log(1 \pm K_p))^2)} \quad \text{where} \quad K_p = \frac{1}{\sqrt{N}}\left(1 + \frac{2}{\mathrm{SNR}} + \frac{1}{\mathrm{SNR}^2}\right)^{\frac{1}{2}}$$

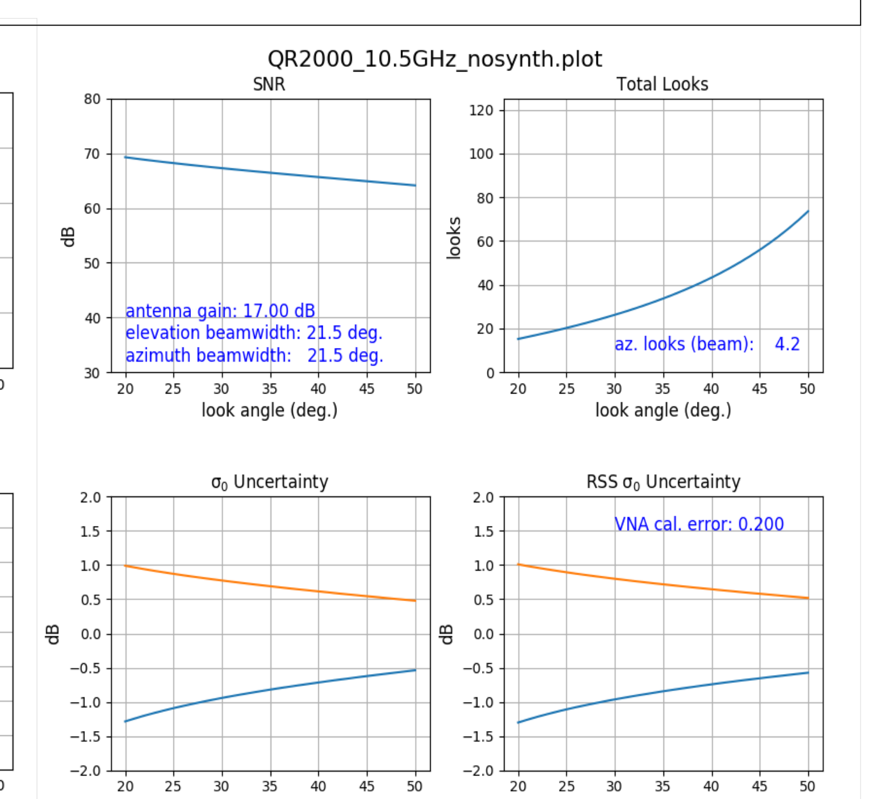
In the case of WBSCAT, the SNR is significantly better than 30 dB over natural surfaces, so the uncertainty in the backscatter is dominated by speckle noise. Spectral diversity uses data acquired over a spectral window with bandwidth B to measure backscatter from samples spaced ~c/2B in slant range. The number of range-looks on level terrain for an angular elevation span $\Delta\theta_{elev}$ is a function of the specified bandwidth B, instrument height h, and the look angle θ:

$$N_r \approx \frac{2hB}{c\cos\theta}\Delta\theta_{elev}\tan\theta$$

Spatial diversity requires scanning the radar beam over a range of azimuth angles. In this mode, each azimuth look is obtained by illuminating a different region on the ground. The number of azimuth looks $N_{az}$ is given by $\theta_s/\theta_{az}$, where $\theta_{az}$ is the antenna beamwidth and $\theta_s$ is the azimuth angle scan width.




SnowScat 10.5GHz SNR, Total Looks, and RSS uncertainty of the measurement of $\sigma_0$




WBSCAT 10.5GHz SNR, Total Looks, and RSS uncertainty of the measurement of $\sigma_0$

| | Snowscat 10.5 GHz H-Pol | Snowscat 10.5 GHz V-Pol | Snowscat 17.5 GHz H-Pol | Snowscat 17.5 GHz V-Pol | WBSCAT 10.5 GHz | WBSCAT 17.5 GHz |
|---|---|---|---|---|---|---|
| Azimuth Ant. Beamwidth (deg.) | 7.5 | 10.5 | 5.0 | 6.0 | 21.5 | 10.0 |
| Ant. Gain (dB) | 24.5 | 24.5 | 26.0 | 26.0 | 17.0 | 21.0 |
| Azimuth Looks | 12 | 8.6 | 18 | 15 | 4.2 | 9.0 |
| SNR (dB) | 77.7 | 79.14 | 71.7 | 72.5 | 66.5 | 64.7 |
| ENL | 96.5 | 68.9 | 144.8 | 120.6 | 33.7 | 72.4 |
| RSS Uncertainty (dB) | -.466 +.507 | -.592 +.533 | -.427 +.400 | -.460 +.428 | -0.845 +.719 | -.579 +.522 |

Comparison of Snowscat and WBSCAT performance without aperture synthesis

## WBSCAT Azimuth Aperture Synthesis

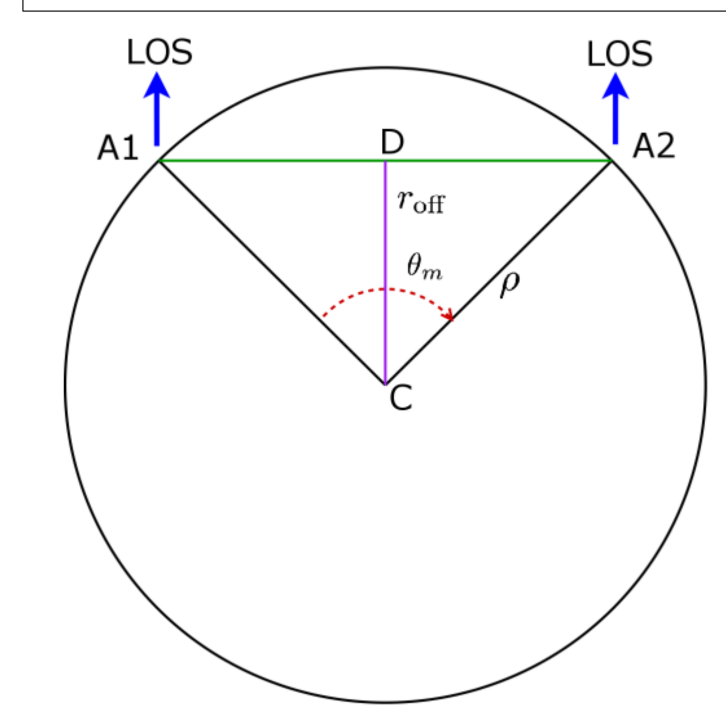
The WBSCAT antennas have a wider beamwidth than Snowscat resulting in fewer possible azimuth looks. The radial offset of the WBSCAT antennas permits processing of aperture scans to synthesize a beam that is substantially narrower than the physical antenna beam. In the figure below, antennas A1 and A2 are located a distance $\rho$ from the rotation center, have separation distance D, and a perpendicular range offset of $r_{\mathrm{off}}$. The length of the synthetic aperture is determined by the antenna geometry and azimuth beamwidth:

$$L_{sa} = 2r_{\mathrm{off}}\sin\frac{\theta_{az}}{2}$$

The number of azimuth looks that can be obtained by aperture synthesis $l_{az\_syn}$ is given by:

$$l_{az\_syn} = \frac{3\pi r_{\mathrm{off}}\,\theta_{\mathrm{scan}}}{L_{\mathrm{az}}}$$

where $\theta_{\mathrm{scan}}$ is the scatterometer azimuthal scan angle converted to radians, and $L_{az}$ is the effective azimuth aperture of the antenna calculated from the measured 3 dB beamwidth $\theta_{\mathrm{az}}$. In this expression the spacing between uncorrelated samples has been increased by a factor of 1.5 relative to the theoretical model to account for reduction of the aperture due to application of a window function.




Circular scan geometry for aperture synthesis

| MVG QR800 Quad-Ridge Horn | 1.5 GHz | 3.2 GHz | 5.5 GHz |
|---|---|---|---|
| Azimuth Ant. Beamwidth (deg.) | 76.3 | 40.0 | 34.0 |
| Ant. Gain (dB) | 7.0 | 12.0 | 13.0 |
| Azimuth Looks (Real-Aperture) | 1.2 | 2.25 | 2.65 |
| Azimuth Looks (Synthetic Aperture) | 6.3 | 7.0 | 10.3 |
| Range Looks | 8.0 | 8.0 | 8.0 |
| SNR (dB) | 75.0 | 75.6 | 70.5 |
| Total ENL | 50.5 | 56.5 | 82.5 |
| RSS Uncertainty (dB) | -.688 +.606 | -.620 +.578 | -.545 +.496 |

WBSCAT performance for 1.5, 3.2, and 5.5 GHz, 90-degree azimuth field of view (Side-looking/Synthetic Aperture mode)

| MVG QR2000 Quad-Ridge Horn | 3.2 GHz | 5.5 GHz | 10.5 GHz | 13.8 GHz | 17.5 GHz |
|---|---|---|---|---|---|
| Azimuth Ant. Beamwidth (deg.) | 43.0 | 34.0 | 21.5 | 16.0 | 10.0 |
| Ant. Gain (dB) | 9.0 | 13.0 | 17.0 | 18.3 | 21.0 |
| Azimuth Looks | 2.1 | 2.7 | 4.2 | 5.6 | 9.0 |
| Azimuth Looks (Synthetic Aperture) | 7.0 | 7.5 | 12.4 | 12.1 | 9.6 |
| Range Looks | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| SNR (dB) | 68.2 | 70.5 | 66.5 | 64.4 | 64.7 |
| Total ENL | 60.7 | 82.5 | 99.6 | 97.4 | 77.2 |
| RSS Uncertainty (dB) | -.629 +.561 | -.545 +.496 | -.500 +.460 | -.505 +.464 | -.561 +.509 |

WBSCAT performance for 3.2, 5.5, 10.5, 13.8, and 17.5 GHz, 90-degree azimuth field of view (Side-looking/Synthetic Aperture mode)

| MVG QR18000 Quad-Ridge Horn | 10.5 GHz 1.0 GHz BW | 13.8 GHz 1.0 GHz BW | 17.5 GHz 1.0 GHz BW | 25 GHz 1.5 GHz BW | 39 GHz 1.5 GHz BW |
|---|---|---|---|---|---|
| Azimuth Ant. Beamwidth (deg.) | 40.0 | 32.9 | 32.0 | 22.0 | 18.0 |
| Ant. Gain (dB) | 12.0 | 13.8 | 15.0 | 16.5 | 18.5 |
| Azimuth Looks | 1.48 | 1.82 | 1.87 | 2.72 | 3.33 |
| Azimuth Looks (Synthetic Aperture) | 18.9 | 20.1 | 24.8 | 24.4 | 31.1 |
| Range Looks | 8.0 | 8.0 | 8.0 | 12.1 | 12.1 |
| SNR (dB) | 60.5 | 59.7 | 58.8 | 55.1 | 50.4 |
| Total ENL | 152 | 162 | 200 | 294 | 376 |
| RSS Uncertainty (dB) | -0.419 0.394 | -0.408 0.385 | -0.376 0.358 | -.361 +.351 | -0.378 0.371 |

WBSCAT performance 10.5, 13.8, 17.5, 25, and 39 GHz, 60-degree azimuth field of view (Side-looking/Synthetic Aperture mode)

## Conclusions

- WBSCAT is a new wideband (1-40 GHz), polarimetric scatterometer operating over a wide range of environmental conditions and temperatures -40 to +50C
- The instrument uses a calibrated VNA to provide coherent measurement of radar backscatter
- Circular track aperture synthesis provides directionality and azimuth spatial resolution to increase radiometric accuracy and achieve the 0.5 dB uncertainty requirement
- The system can be mounted on a rail, inclined at 45 degrees, to obtain 3D tomographic imaging of scattering volumes including snow packs and vegetation

## References


[1] O. Frey, C. L. Werner, R. Caduff, and A. Wiesmann, "Tomographic profiling with SnowScat within the ESA SnowLab Campaign: Time Series of Snow Profiles Over Three Snow Seasons," in Proc. IEEE Int. Geosci. Remote Sens. Symp., 2018, pp. 6512–6515. [Online]. Available: http://ieeexplore.ieee.org/document/8517692

[2] Reza Naderpour, M. Schwank, C. Mätzler. "Davos-Laret Remote Sensing Field Laboratory: 2016/2017 Winter Season L-Band Measurements Data-Processing and Analysis," Remote Sens. 2017, 9, 1185.