THE ESA WIDEBAND MICROWAVE SCATTEROMETER (WBSCAT): DESIGN AND IMPLEMENTATION

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ABSTRACT

WBSCAT is a new terrestrial 1-40 GHz polarimetric scatterometer. This instrument, built for the European Space Agency, with additional support from ETH WSL, is currently an element of the ESA SnowLab project for continuous microwave measurements of snowpack in Davos-Laret Switzerland. WBSCAT is based on a compact Vector Network Analyzer (VNA), combined with calibration standards and low-noise amplifiers to increase sensitivity. A pan/tilt positioner provides the angular and spatial diversity required for measurement of radar cross-section, 3D tomographic imaging, and measurements of interferometric coherence. The instrument can apply angular diversity and aperture synthesis to increase radiometric accuracy and suppress clutter. In Davos-Laret, WBSCAT is suspended from a 2.2-meter linear rail positioner that provides additional spatial diversity for high-resolution 3D tomographic imaging.

Index Terms— snow, microwave scatterometer, aperture synthesis, time series, polarimetry, tomography

1. INTRODUCTION

WBSCAT is a new terrestrial microwave scatterometer supporting polarimetric observations over 1–40 GHz. This instrument has been 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. WBSCAT is part of the ongoing ESA SnowLab project at the CryoNet station Davos-Laret, Switzerland [2]. WBSCAT, like its predecessor, acquires fully polarimetric coherent backscatter data. WBSCAT began operation in December 2018 performing multiple daily measurements of snowpack and calibration targets. Both instruments are suspended from a 2.2-meter linear scanner (the TomoRail) inclined at 45 degrees and attached to the side of a 10-meter tower. This configuration permits linear aperture synthesis for tomographic snow profiling [3]. Both instruments utilize a pan/tilt positioner to scan in both elevation and azimuth. The WBSCAT antennas however, are located on the instrument frame with a radial offset along the line of sight (LOS) relative to the rotation axis, see Figures 1 and 2. This permits aperture synthesis by acquisition of data on a circular arc making 3D tomographic imaging possible. This paper describes the design and predicted performance of the WBSCAT instrument.

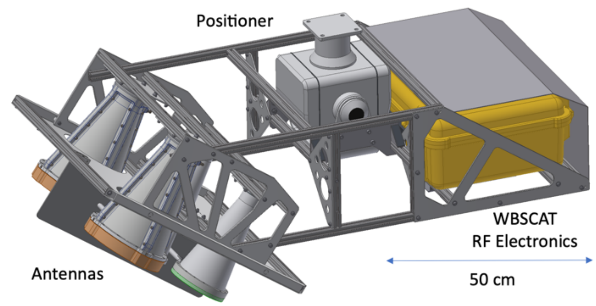

Figure 1: WBSCAT 3D model

Figure 2: WBSCAT hardware suspended from the TomoRail

2. INSTRUMENT HARDWARE

WBSCAT measures co- and cross-polarized backscatter using dual-linear polarized horn antennas. Data can be acquired in practically all-weather situations and over a wide temperature range of -40 to +50C. Based on our experience with SnowScat, the WBSCAT microwave components are enclosed in a temperature-regulated and well-insulated enclosure to improve radiometric and phase stability. The microwave electronics and computer that controls WBSCAT are housed in separate enclosures to minimize temperature variations and avoid potential RFI. WBSCAT utilizes a Vector Network Analyzer (Keysight FieldFox N9951A), covering frequencies up to 44 GHz, 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

```
VNA_FREQ_start:      16.
VNA_FREQ_stop:       40.0
VNA_FREQ_points:     4801
VNA_PWR_cal:         -16  #dBm
VNA_PWR_amp_cal:     -23
VNA_PWR_measure:     -16
VNA_IFBW_cal:        1.e3 #Hz
VNA_IFBW_amp_cal:    1.e3
VNA_IFBW_measure:    1.e4
VNA_CAL_method:      SOLT2
VNA_CAL_kit:         "8770S"
QPT_orientation:     INVERTED
WB_ANT_look_angle_start:        20.0
WB_ANT_look_angle_step:         10.0
WB_ANT_look_angle_num_step:        4
WB_ANT_azimuth_angle_start:     15.0
WB_ANT_azimuth_angle_step:        6.
WB_ANT_azimuth_angle_num_step:    5
WB_ANT_lk_ang0:       35.0
WB_TX_seq:       T3V T3H T3V T3H
WB_RX_seq:       R3V R3V R3H R3H
WB_cycle_count:    1
WB_cycle_interval:   60.
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Table 1: WBSCAT profile example

accurately measure the S-parameters of the low-noise amplifiers used in the receiver and transmitter signal paths. Mechanical microwave switches are used to select the standards for calibration of the VNA, select the amplifier calibration path, and select the transmit and receive antenna ports.

The instrument is controlled by an industrial PC utilizing CentOS 7 Linux enclosed in a weather-proof Pelican case. Software controlling the instrument is written in Python3. Communication with the VNA is over Ethernet utilizing the PyVISA API. A **keyword:value** text file, called the measurement profile, is used to specify data acquisition parameters. An example profile is shown in Table 1. Similar keyword:value parameter files are output for the calibration data parameters, and the acquired and processed data.

3. SYSTEM PERFORMANCE

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. The performance goal of WBSCAT is 0.5 dB uncertainty in the surface RCS. The looks N are obtained by a combination of spectral and azimuth diversity. The RSS uncertainty in the RCS is given by:

$$\Delta\sigma^0_{\mathrm{dB}} = \sqrt{(\sigma^2_{\mathrm{vna\_dB}} + (10\log(1 \pm K_p))^2)}$$

where:

$$K_p = \frac{1}{\sqrt{N}}\left(1 + \frac{2}{\mathrm{SNR}} + \frac{1}{\mathrm{SNR}^2}\right)^{\frac{1}{2}}.$$

In the case of WBSCAT, the SNR is significantly better than 30 dB over most natural surfaces, so that the uncertainty in the backscatter is nominally 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:

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

The antennas used in WBSCAT have broader bandwidth and wider beamwidth than the SnowScat antennas. This reduces the number of possible azimuth looks and leads to an increase in the RSS uncertainty (Figures 3 and 4).

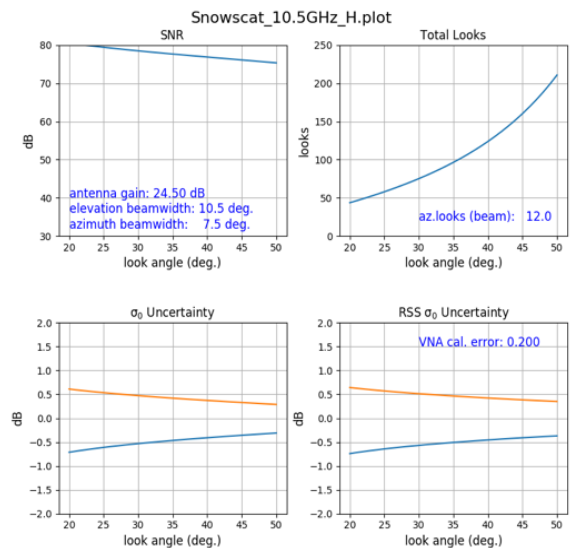

Figure 3: 10.5 GHz SnowScat effective number of looks (ENL) and RSS uncertainty of the RCS

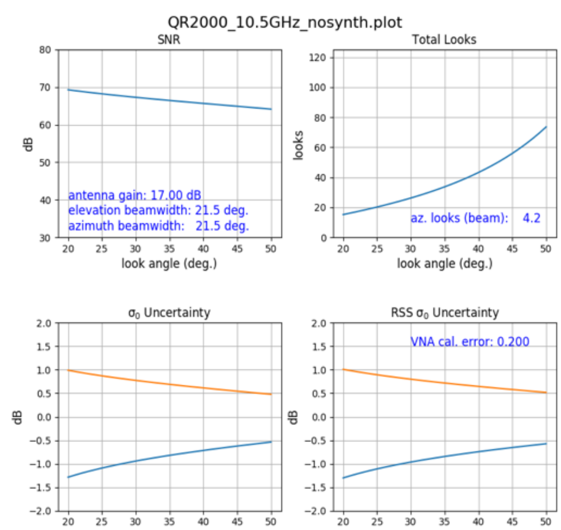

Figure 4: 10.5 GHz WBSCAT ENL and RSS uncertainty

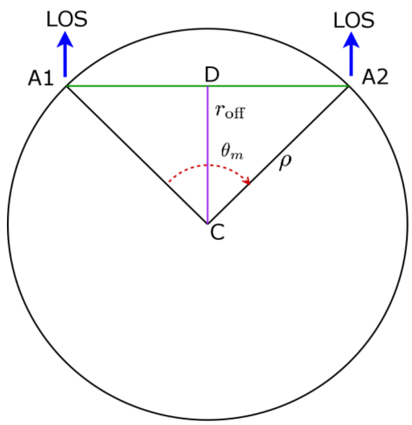

Figure 5: Circular scan geometry for aperture synthesis

The wide beamwidth of the WBSCAT antennas can be an advantage through the application of aperture synthesis to obtain a narrower effective azimuth beamwidth and hence more azimuth looks. This requires the antennas be moved away from the rotation axis to create a synthetic aperture; a circular arc perpendicular to the line of sight (LOS). An azimuth scan can then be focused to synthesize a beam substantially narrower than the physical antenna beam. In Figure 5, antennas A1 and A2 are located a distance ρ from the rotation center, with separation D, and perpendicular range offset r_{off}. The length of the synthetic aperture L_{sa} is determined by the antenna range offset and azimuth beamwidth θ_{az}:

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

The number of azimuth-looks l_{az_syn} obtainable by aperture synthesis is given approximately by:

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

where θ_{scan} is the scatterometer azimuth scan extent converted to radians, and L_{az} is the effective azimuth aperture width of the antenna calculated from the measured 3-dB beamwidth θ_{az}. In this expression for l_{az_syn}, the spacing between uncorrelated samples has been increased by a factor of 1.5 relative to the theoretical value, to account for a reduction of the effective aperture due to a processor-defined window function or antenna pattern.

SnowScat and WBSCAT are stepped-CW radars. The VNA measures the calibrated magnitude and phase of the received signal at a set of discrete frequencies. A Fast Fourier Transform (FFT) is applied to the measured data to obtain range profiles. A Kaiser window, tuned to reduce range sidelobes by 60 dB or more, and corrections for transmission delay and losses are applied to the acquired data prior to calculation of the FFT.

The range profile contains the magnitude and phase of the

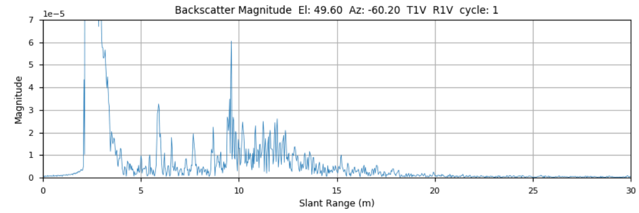

Figure 6: WBSCAT range profile 1-6 GHz using QR800 antennas. Note the strong antenna crosstalk signal at the start of the echo..

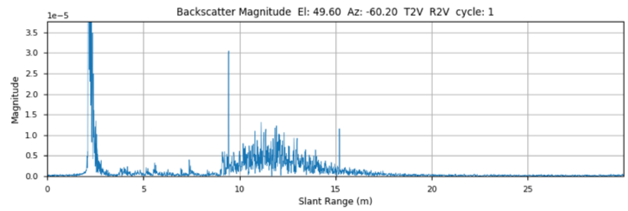

Figure 7: WBSCAT range profile 3-18 GHz using QR2000 antennas. Note cross-talk in the near field and reflection from the sphere calibration target near 9 meters slant range

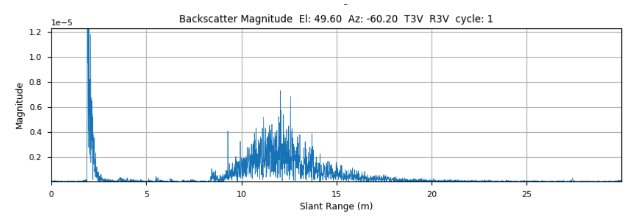

Figure 8: WBSCAT range profile 16-40 GHz acquired using the QR18000 antennas

backscatter as a function of distance from the scatterometer. Included in the range profile are crosstalk between the transmitting and receiving antennas and reflections from the support structure. WBSCAT uses ferrite-loaded microwave absorber behind the antennas to suppress reflections from the support structure, especially at frequencies below 6 GHz. Adding microwave absorber between the antennas was not a viable approach to reduce crosstalk because of the reduction of the field of view and distortion of the antenna patterns. Figures 6-8 show range profiles for three frequency bands covering the full frequency range.

Antenna motion perpendicular to the LOS (angular diversity) causes decorrelation of the backscatter and can be used to obtain additional azimuth looks. Aperture synthesis improves azimuth resolution for clutter suppression. Application of angular diversity without focusing is viable when the antenna beam is sufficiently narrow to avoid spurious reflections (clutter) from contaminating the RCS measurement.

The expected scatterometer performance based on simulation is summarized in the Tables 2-4. The estimated uncertainties of the RCS measurements assume that the VNA is well calibrated (~0.2 dB). In the simulation, the WBSCAT is situated 8m above the ground. Angular diversity is essential for getting sufficient looks due to the wide antenna beamwidths.

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

Table 2: WBSCAT performance for 1.5, 3.2, and 5.5 GHz, 90-degree azimuth field of view

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

Table 3: WBSCAT performance for 3.2, 5.5, 10.5, 13.8, and 17.5 GHz, 90-degree azimuth field of view

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

Table 4: WBSCAT performance 10.5, 13.8, 17.5, 25, and 39 GHz, 60-degree azimuth field of view

For example, the 10-40 GHz (QR18000) antenna has an aperture of less than 5 cm, resulting in a beamwidth between 40 and 18 degrees (Table 4). Given a 60-degree scan, it is possible to get approximately 24 azimuth looks at 17.5 GHz by moving on a 48.5 cm radius arc orthogonal to the LOS.

4. CONCLUSIONS

WBSCAT is a new wideband (1-40 GHz), polarimetric scatterometer operating over a wide range of environmental conditions and temperatures -40 to +50 C. This VNA-based radar can acquire calibrated, coherent, fully-polarimetric measurements of radar backscatter. The WBSCAT antenna configuration permits scanning the antennas over a circular arc with the look vector orthogonal to the LOS. When the antenna pattern is broad, resulting in significant clutter from the support structure, azimuth aperture synthesis improves directionality. In cases where the clutter is minimal, angular diversity provides additional azimuth looks without requiring focusing. In either case, the WBSCAT design can acquire sufficient looks to meet the 0.5 dB goal for uncertainty in radar backscatter. WBSCAT has been mounted at Davos-Laret on 2.2m linear scanner (TomoRail), inclined at 45 degrees, to obtain high-resolution 3D tomographic images of snowpack.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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