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Multiport Vector Network Analyzer Radar for Tomographic Forest Scattering Measurements

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***Abstract*— We describe a P-, L- and C-band radar, BorealScat, designed for polarimetric time-series measurements of forests. Radar tomography is implemented with a vertical antenna array, which provides measurements of the vertical scattering distribution. To minimize temporal decorrelation, the radar performs simultaneous measurements of the reflected signals using all array elements. The system is implemented using a 20-port vector network analyzer (VNA) and a stepped-frequency waveform. It has two 20-element arrays: one array optimized for P- and L-bands and one for C-band. The arrays are installed on a 50-m high tower and radar measurements are collected over a hemiboreal forest stand. We discuss several design issues and demonstrate some tomographic imaging capabilities. The multi-port VNA tomography results are compared with results from the system operating in the slower 2-port VNA measurement scheme.**

***Index Terms*— BorealScat, forest, polarimetry, radar, scattering, time series, tomography, vector network analyzer (VNA).**

I. Introduction

TIME-series radar measurements of forests can be used to investigate the effect of changing environmental conditions on microwave (MW) backscattering from forests. Understanding these effects is of great importance for improving retrieval algorithms for present and future satellite synthetic-aperture radar (SAR) missions. Temporal decorrelation of forest scattering is also of particular concern and needs to be investigated, since it may severely degrade the quality of repeat-pass SAR interferometry and tomography observables.

It is well known that soil moisture and air temperature affect the forest backscattering coefficient. However, only limited research has been performed to measure and understand such effects despite the large impact they may have on the retrieval accuracy.

Tower-based radars have been used in the past to measure long-term time series of radar backscatter and study the changes in forest backscattering [1], [2]. Tomographic measurements have also been performed with antenna arrays, enabling studies of vertical backscatter profiles. Data collections have mainly been conducted at P-band, motivated by the European Space Agency's BIOMASS mission, which is planned for launch in 2021. The primary mission objective is global forest biomass mapping and it will be the first-ever satellite SAR to operate in P-band (432–438 MHz) [3].

In the past studies [1], [2], tower-based radar measurements were conducted using a 2-port vector network analyzer (VNA) and a stepped-frequency waveform to generate range profiles after inverse Fourier transformation. A switching network was used to sequentially measure one channel (transmit–receive antenna pair) after the other. A drawback with this design is that forest vegetation may decorrelate during the measurement sequence due to displacements. This problem becomes increasingly severe for higher wind speeds and higher frequencies, where the signal is more sensitive to the smaller elements of forest canopies.

In this letter, we present a design based on a 20-port VNA, which decreases the measurement time when using multiple-antenna channels on receive. The design also enables simultaneous measurements of co- and cross-polarized backscattered signals with a little temporal decorrelation. Finally, we show example results that demonstrate successful tomographic measurements.

II. System Design

A. Requirements

The requirements that are important for the experiment design are as follows.

1) Allow the reconstruction of vertical backscattering profiles of the forest at all four polarization combinations (HH, VV, HV, and VH) at P-, L-, and C-bands.
2) The measurement duration should be short enough such that the effect of changes in the forest during the measurement are negligible.
3) The dynamic range must be large enough to sense changes in the forest among noise and sidelobes from direct coupling between transmit–receive antenna pairs.
4) The deflection of the antennas on the tower should not exceed a quarter of a wavelength during the measurement to avoid tomographic image defocusing.

Requirement 1 is met by suitably choosing the antenna models and designing the antenna-array configuration. Requirements 2 and 3 are met by choosing a suitable design of signals and measurement sequences and requirement 4 is met by a sturdy design of the tower structure and its foundation.

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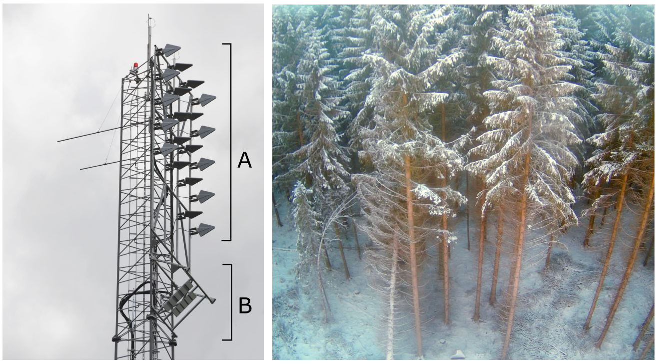

Fig. 1. (Left) Antenna arrays on the BorealScat tower. The top array is for P- to L-band measurements (A). The smaller, downwardly tilted array below is for C-band measurements (B). (Right) Forest as viewed by the C-band array 30 min before acquiring the measurements used for this letter.

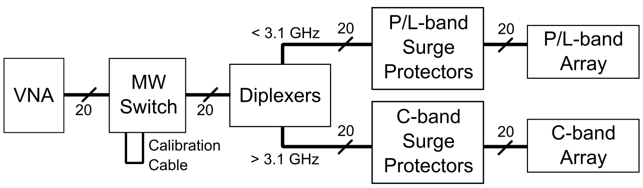

Fig. 2. Block diagram of the radar instrument. The VNA and MW switch are also connected to a controlling computer via Ethernet. All other components in the diagram are passive.

B. Test Site

The BorealScat station (Fig. 1) is located in the Remningstorp experimental forest site in southern Sweden (57° 27' 5" N, 13° 37' 35" E). The forest stand chosen for long-term observation is dominated by mature Norway spruce [*Picea abies* (L.) Karst.] on a flat terrain with a little undergrowth. Canopy heights vary from 25 to 27 m and the stand has an above-ground biomass density of approximately 250 tons/ha.

C. System Overview

The radar system consists of a VNA, MW switch, diplexers, surge protectors, antennas, and interconnecting coaxial cables (see Fig. 2). The antennas are grouped into two arrays, one for P- to L-band (Rohde&Schwarz HL040E) and the other for C-band (Cobham SA18–5.5VH), for reasons discussed in Section II-D. The 20-port VNA (Rohde&Schwarz ZNBT8) generates and emits the MW signal at one of its ports, which then passes through the switch to be routed to the corresponding antenna array by one of the 20 diplexers (Marki Microwave DPX-3). The diplexers passively route the signals to the P/L-band array for frequencies below 3.1 GHz and to the C-band array for frequencies above 3.1 GHz. The signal then passes through a surge protector and travels up the tower via a low-loss cable (Huber+Suhner Sucofeed 1/2″) to be emitted by an antenna. The purpose of the surge protectors is to route high currents arising from possible lightning strikes and charge build up on the tower to ground. The backscattered fields are sensed by all 20 antennas of the same array, and the received signals travel in the opposite direction in the system and are sampled in parallel by the 20-port VNA. No mechanical switching occurs during such a measurement.

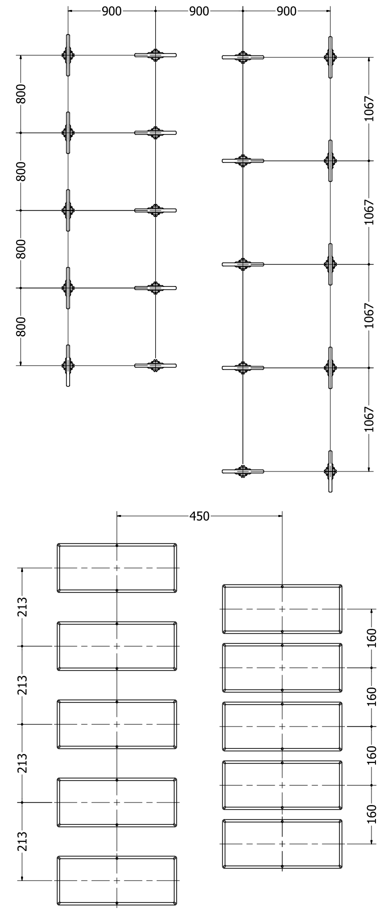

Fig. 3. Antenna configurations of (Top) P/L-band array and (Bottom) C-band array. The arrays are viewed from the front in the opposite direction of boresight. All dimensions are in millimeters. For the P/L-band array, log-periodic dipole antennas (Rohde&Schwarz HL040E) are used. For the C-band array, dual-polarized sector antennas (Cobham SA18–5.5VH) were used.

D. Antenna Array Design

A large vertical aperture, yielding a resolution in elevation much finer than the antenna beamwidth, is synthesized by a vertical column of antennas. Grating lobes in the antenna-array gain pattern after digital beamforming result in ambiguous radar returns in elevation. These ambiguities must be separated far enough in elevation such that a tomographic profile from the forest below can be reconstructed unambiguously. This requires the vertical spacing of antennas in the vertical column to be smaller than the physical dimensions of an antenna element. The virtual array concept is therefore used: an equivalent virtual phase center is synthesized by a transmit–receive antenna pair when the distance between the physical transmitting and receiving phase centers is small compared with the physical extent of the observed scene [4]. The resulting antenna array designs are shown in Fig. 3.

The resolution in azimuth is determined by the antenna beamwidth. Fields scattered from the forest are then coherently integrated over the resulting resolution cell. This cell may be wide in azimuth as long as the virtual array is vertical (as for P- and L-bands). This results in coherent integration over the same height interval, preserving resolution in elevation. A tilted array (as for C-band) requires a narrower beamwidth

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TABLE I
FREQUENCY BANDS AND BEAMWIDTHS USED BY BOREALSCAT

Band	Centre frequency, f_c [MHz]	Bandwidth, B [MHz]	Frequency step, Δf [MHz]	Half-power antenna beamwidth
P	435	30	0.5	E-plane: 68° H-plane: 114°
L	1307.5	135	0.5	E-plane: 60° H-plane: 98°
C	5410	320	0.5	Azimuth: 10° Elevation: 35°

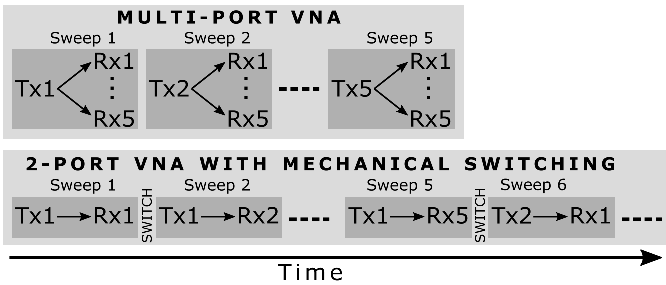

Fig. 4. Timing diagram comparing a multiport VNA tomographic measurement and a 2-port VNA measurement where antenna routing is done using mechanical switches. The multiport VNA allows parallel reception of scattered fields, resulting in a shorter measurement time.

in azimuth (see Table I) to avoid integrating fields scattered from different heights.

E. Measurement Sequence

The VNA generates a stepped-frequency continuous-wave signal with the frequency steps of Δf to cover the bandwidth B centered at the frequency f_c. The total number of frequency steps N depends on the bandwidth as $N = B/\Delta f + 1$. The frequency step size Δf was fixed to 0.5 MHz to give an unambiguous range of 300 m, necessary to observe the range extent of the forest and allow time for signal propagation in cables. The frequency bands and antenna beamwidths are listed in Table I.

To reconstruct a tomographic profile, the received signals from all transmit–receive antenna pairs contributing to the virtual array are needed. For columns of five antennas, five frequency sweeps are needed if the receiving antennas can be sampled in parallel, as can be done with the 20-port VNA. A 2-port VNA with mechanical switching between all transmit–receive pairs requires at least 15 frequency sweeps to complete a virtual aperture, as well as time taken for mechanical relays to switch. This is illustrated in Fig. 4. Both the measurement methods were carried out by the same multiport VNA setup for comparison. The 2-port VNA measurement scheme was replicated by measuring one transmit–receive antenna pair at a time. A 15-ms delay was inserted between frequency sweeps to simulate a typical mechanical relay-based MW switch routing VNA ports to different antennas in the array.

F. Calibration Reference Cable

The purpose of the MW switch shown in Fig. 2 is to route any of the 10 transmit ports on the VNA to any of the 10 receive ports via a cable to form an internal calibration loop. By passing the transmitted signal through this loop to the receiver, the ratio method for internal relative calibration can be applied [5]. The switch and the calibration cable are situated in a temperature-controlled hut, so their impulse responses are assumed to be constant with time. This increases the precision of measurements by compensating for temporal drifts in VNA measurement characteristics. Such a relative calibration of all transmit–receive pairs is carried out every 30 min.

III. SIGNAL PROCESSING

A. Range Profiles

The received signals are dominated by strong mutual coupling between antennas in the array. To separate the return from the forest from direct antenna coupling, and also to isolate the returned signal by the incidence angle, the frequency-domain signals (S-parameters) measured by the VNA must be transformed into the time/spatial domain by inverse discrete Fourier transformation to form complex range profiles (scattered power density versus range). Due to the limited bandwidth, the strong direct antenna coupling peaks in the range profiles cause large sidelobes in the forest region of the range profiles. These sidelobes can be reduced at the cost of poorer resolution by applying a Hamming window in the frequency domain first. This window also suppresses sidelobes in the range due to the forest response. The resulting complex range profile can further be compensated for free space loss by multiplying it with the squared range to a pixel in a tomographic image.

B. Phase Calibration

The components and cables between the VNA and the antennas result in a time delay in the transmitted and received signals, causing systematic phase errors. These phase errors may also vary as the low-loss cables leading up the tower are exposed to varying environmental conditions. Trihedral corner reflectors were therefore placed on-site to act as stable reference targets. For P- to L-band, a trihedral reflector with short sides of 5.1 m was installed in the forest, and for C-band, a single reflector with short sides of 0.7 m was installed near the base of the tower.

C. Reconstruction of Tomographic Profiles

Tomographic profiles were reconstructed by a coherent back-projection of the recorded complex range profiles. This involves interpolations and calculations of Euclidean distances, making the reconstructions computationally intensive. Although faster FFT-based reconstruction methods exist, they are not suitable when the spatial extent of the scene is on the order of the antenna-scene distance, as is the case in this experiment.

To form a focused image, the phases of the range profiles must be accurate to within a fraction of a wavelength, which even the trihedral corner reflectors on site cannot provide. The residual phase errors, corresponding to a time delay, of each transmit–receive antenna pair were therefore estimated using an autofocus algorithm that optimizes for maximum image

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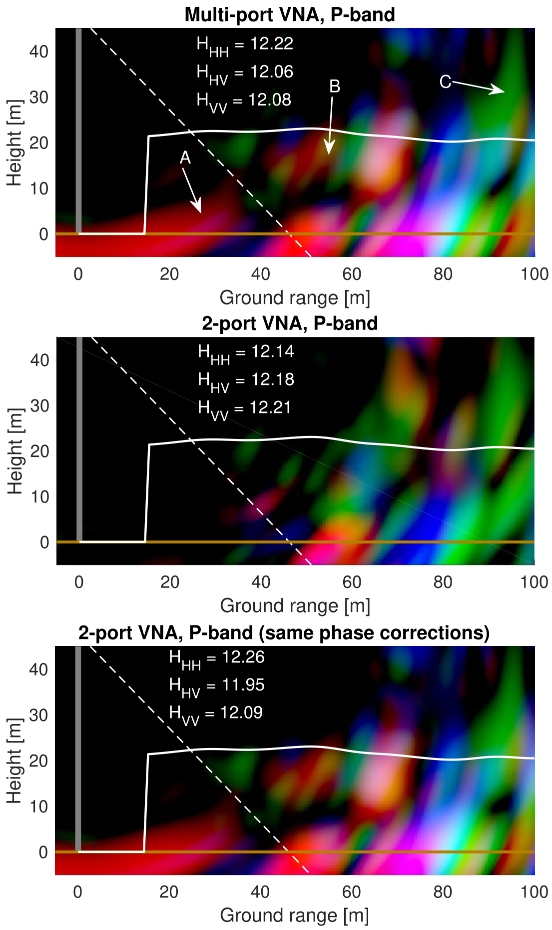

Fig. 5. Tomographic backscattering profiles at P-band during a 6 ± 1 m/s average wind speed with lexicographic color coding (red = HH, green = HV, and blue = VV). (Top) Resulting tomogram from a multiport VNA measurement. (Middle) Resulting tomogram from a 2-port VNA measurement. (Bottom) Result from a 2-port VNA measurement if the same autofocus phase corrections as in the first image are used. The channels were scaled from -25 to -10 dB for HH, from -35 to -25 for HV, and from -28 to -15 dB for VV. Image entropy values for the individual HH, HV, and VV intensity images are denoted by H_{HH}, H_{HV}, and H_{VV}, respectively. The gray line indicates the location of the tower and the brown line lies at ground level. The dashed white line indicates the -3-dB antenna gain boundary in the vertical plane and the solid white line shows the canopy height as in 2014. The annotations show the ground response (A), forest (B), and sidelobes (C).

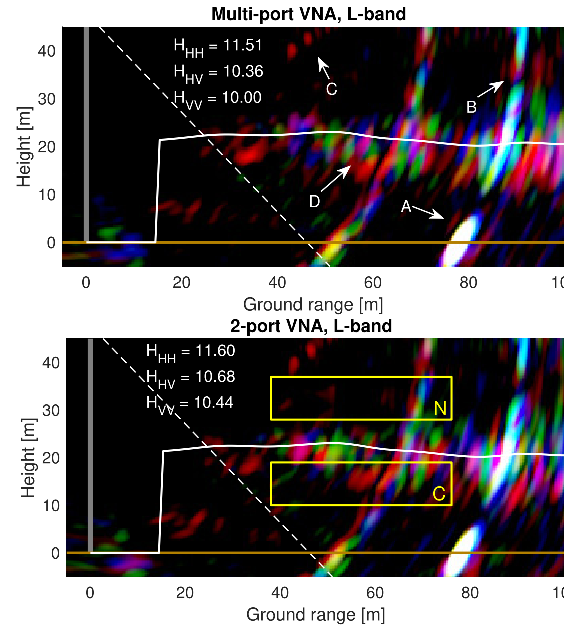

Fig. 6. Tomographic backscattering profiles at L-band during a 6 ± 1 m/s average wind speed with lexicographic color coding (red = HH, green = HV, and blue = VV). (Top) Resulting tomogram from a multiport VNA measurement. (Bottom) Resulting tomogram is from a 2-port VNA measurement. The channels were scaled from -38 to -25 dB for HH, from -43 to -30 for HV, and from -40 to -27 dB for VV. The annotations show the trihedral corner reflector (A), sidelobes of the corner reflector (B), an ambiguous response of the forest (C), and the forest canopy (D). The yellow rectangles show the clutter (C) and noise (N) regions from which the CNR is estimated.

contrast by minimizing the Shannon entropy in the resulting tomographic profile [6]. The absolute-squared value of the complex pixels in the back-projected image is computed to obtain vertical backscattering profiles.

Two image focusing quality metrics were used: the image intensity entropy and clutter-to noise ratio (CNR). The CNR was estimated by taking the ratio of the averaged intensity of a region over the forest (clutter) and a region with nothing but open air (noise). A defocused image will produce sidelobes, resulting in a lower CNR.

IV. Results

Examples of tomographic backscattering profiles reconstructed using measurements from BorealScat are shown in Figs. 5–7. The acquisitions were made on December 18, 2017 during the time period 09:13 to 09:15 CET, when the air temperature was -0.7°C at ground level and the average wind speed was 6 ± 1 m/s. The limited signal bandwidth and coherent nature of the reconstructions result in speckled images, especially at the P-band where the bandwidth is the lowest. The forest is present from a ground range of approximately 15 m from the tower and vertically up to 25–28 m. This is indicated by the canopy height profile, derived from the 95th percentiles from an airborne LiDar-derived point cloud acquired in 2014. Tomograms were individually autofocused, except for the bottom tomogram in Fig. 5.

At P-band (Fig. 5), the backscatter appears to originate from both the ground and the canopy. The response from one of the trihedral corner reflectors can be seen at a ground range of 78 m in purple (VV and HH). Large differences can be seen between the tomograms from multiport VNA measurements and 2-port VNA measurements if individually autofocused. However, when the same phase corrections from autofocusing based on the multiport VNA data were used on both the data sets, nearly identical tomographic profiles were reconstructed. The autofocus algorithm is therefore not very robust for low-resolution imaging during wind, but phase corrections from quieter times can be used instead.

At L-band (Fig. 6), the backscatter appears to originate from the canopy only, except for the corner reflector response. Differences can be seen in the canopy region for the tomograms from the two measurement schemes. But this is simply due to the fact that the measurements were taken approximately 2 min apart. Defocusing due to temporal decorrelation results in sidelobes, as can be seen above the forest canopy for the 2-port VNA measurements at HH. This is reflected in higher image

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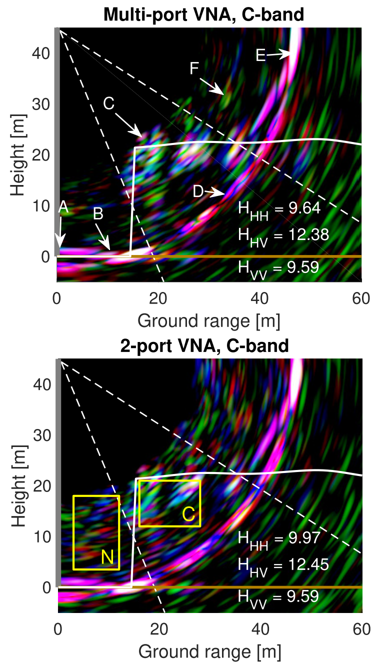

Fig. 7. Tomographic backscattering profiles at C-band during a 6 ± 1 m/s average wind speed with lexicographic color coding (red = HH, green = HV, and blue = VV). (Top) Resulting tomogram from a multiport VNA measurement. (Bottom) Resulting tomogram from a 2-port VNA measurement. The channels were scaled from -44 to -30 dB for HH, from -50 to -36 for HV, and from -44 to -30 dB for VV. Annotations indicate the ground (A), a trihedral corner reflector (B), the forest (C), sidelobes of the corner reflector (D), an ambiguous response of the corner reflector (E), and sidelobes of the forest response (F).

TABLE II

CNRs IN DECIBELS AT L- AND C-BANDS COMPARING THE TOMOGRAPHIC RECONSTRUCTION QUALITY OF MEASUREMENTS FROM THE MULTI-PORT AND 2-PORT VNA MEASUREMENT SCHEMES

Polarisation	L-band		C-band	
	Multi-port VNA	2-port VNA	Multi-port VNA	2-port VNA
HH	5.6	4.5	6.5	1.7
HV	3.1	2.2	6.6	3.7
VV	2.3	1.9	8.7	4.6

entropy values (lower contrast) for the 2-port VNA measurements than the multiport VNA measurements.

At C-band (Fig. 7), only the upper canopy within the 3-dB beamwidth of the antennas scatters the incoming wave, except for the small corner reflector at a ground range of approximately 16 m. Significantly, more sidelobes can be seen for the 2-port VNA measurements above the canopy and in between the canopy and the tower. There is evidence of significant temporal decorrelation exhibited by the slower 2-port VNA measurement scheme even at such a low wind speed. Sidelobes due to temporal decorrelation (mainly due to wind) can be seen even for the multiport VNA measurement scheme at HV-polarization. The entropy values agree that a multiport VNA measurement scheme is more robust to temporal decorrelation due to wind. Table II shows that the CNR is higher for all polarizations at L- and C-bands when using a multiport VNA for tomographic imaging, with C-band showing the largest improvement in the CNR.

V. CONCLUSION

A multiport VNA-based radar for tomographic forest scattering measurements was described. The first experimental results of vertical backscattering profiles were shown for P-, L-, and C-bands and compared with what would have been the result if a 2-port VNA with mechanical VNA-antenna routing was used instead. The multiport VNA results showed that even at wind speeds as low as 6 m/s, advantages were obtained for P- and L-band tomographic reconstructions and significant defocusing due to temporal decorrelation was avoided at C-band.

The system has been collecting data since December 2016 and will continue to do so. Future work will include the analysis of backscatter variations with time, temporal coherence, and variations of vertical backscattering profiles with time. Improvements will be made in tomographic reconstruction quality and efforts will be made to reduce the computational complexity of reconstructing images.

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