Calibration of Fully Polarimetric Wideband FMCW Instrumentation Radar at Sub-TeraHertz Frequencies

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Abstract— **This paper reports a calibration method of a wideband fully-polarimetric FMCW instrumentation radar operating at sub-terahertz frequencies. The proposed method corrects for both phase non-linearity and channel imbalances in the radar system.**

Keywords— ***Instrumentation radar; Millimeter-wave; Polarimetry; Terahertz; Calibration.***

I. INTRODUCTION

Radars operating at sub-terahertz frequencies is gaining significant attention due to their applications for a wide range of topics including high resolution radar imaging and concealed weapons detection [1]. Interest in operating radars at sub-terahertz frequencies is expected to continue as the demand for high-resolution, all-weather sensors that are also compact and lightweight continues to expand into new applications such as autonomous vehicles [2]. While significant attention has been directed towards the advancement of radar components at sub-terahertz frequencies [3], little attention has been directed towards studying the radar response of terrain at these frequencies.

An instrumentation radar is a key research tool in any phenomenological study of radar return from terrain. At microwave and low millimeter-wave frequencies, vector network analyzer-based (VNA) radars have been favorable instrumentation radars for ground-based testing [4,5]. While operating in stepped-frequency measurement mode, a VNA-based radar can measure the frequency response of distributed or point targets precisely, albeit completing its measurement over the desired frequency band in 0.5 to 1 second periods. At sub-terahertz frequencies, with signal wavelength less than 2-millimeter long, any movement of the target and/or the radar platform during the VNA's frequency sweep even if the movement is a small fraction of the radar wavelength will result in signal decorrelation and error in characterizing the target response. As a result, VNA-based radars at sub-terahertz frequencies are best suited for indoor testing of stationary targets. The frequency modulated continuous wave (FMCW) radar has been considered as the radar system of choice in many applications involving millimeter-wave and sub-terahertz frequencies due to the speed of measurement (20 μs to 200 μs) and the achievable high signal-to-noise ratio [1]. FMCW-based instrumentation radars are similar to VNA-based radar in that external calibration of the radar is needed to remove systematic errors in the measured radar response due to imperfections in hardware components. In this paper, we present a calibration technique for a fully polarimetric wideband FMCW instrumentation radar operating at 228 GHz that was recently developed at the University of Michigan [2]. This new system is used to characterize the radar response of road scenes under different surface conditions. The calibration technique addresses both polarimetric distortions and nonlinearities in the transmit chirp of the FMCW that impede the creation of high range resolution response.

II. SYSTEMATIC DISTORTIONS AND METHOD OF REMOVAL

A block diagram of the polarimetric FMCW instrumentation radar [2] is shown in Fig. 1. A chirp generation circuit is used to create a linear FM chirp at IF frequencies (3.150 to 3.70 GHz). The IF-chirp signal is then frequency up-converted using a 15.3 GHz LO (CW) signal and fed through an active frequency multiplier chain to generate the transmitted linear FM chirp signal spanning the frequency range 221.4 to 228 GHz. Switching between the different transmit V and H polarizations is enabled using a fast SPDT switch operating at an intermediate frequency band within the multiplier chain (around 77 GHz). A copy of the IF-chirp signal is also frequency up-converted using a 2nd LO (CW) signal operating at 13.8 GHz and is fed through a separate active frequency multiplier chain. This 2nd chirp signal is used to feed two dedicated subharmonic mixers in the receiver path in order to de-chirp directly the V and H components of the received radar signal after reflecting off of any given target. Through two subsequent chirp transmissions (V-H polarization sequence)

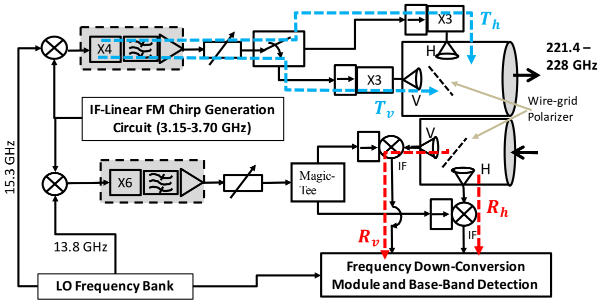

Fig. 1: Block diagram of the FMCW polarimetric instrumentation radar.

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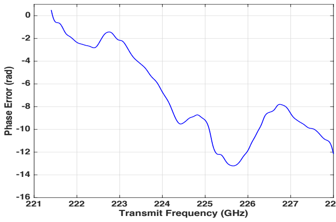

Fig. 2: Extracted non-linear phase error from target response at 9.4 m.

the entire scattering matrix of a target can be measured. Additional details of the new FMCW polarimetric instrumentation radar can be found in [2].

For an ideal FMCW radar, the de-chirped signal of a given target is a CW signal whose frequency (known as the beat frequency) is constant and proportional to the range to the target while the strength of the signal is representative of the target reflectivity. In general, systematic distortions in polarimetric FMCW radar are: (a) non-linearity in de-chirped signal, (b) coupling between the orthogonal polarization ports (V & H) of the antennas resulting in polarization contamination, and (c) channel imbalances that correspond to variations in transmit and receive signal paths, as denoted by T_v, T_h, R_v, and R_h in Fig. 1. The phase of an ideal de-chirped signal is linear function of time. Phase non-linearity in the de-chirped signal of an actual system results in a point target being represented by multiple beat frequencies, as shown in Fig. 3, which in turn degrades range resolution. Causes of phase non-linearity include non-linearity in creating the FM chirp at low frequencies and frequency dispersions in subsequent RF components of the active frequency multipliers. We have developed a procedure to extract the non-linear phase error for all polarization combinations by isolating the de-chirped signal of a target at known range through software gating, unwrapping the phase of the signal, and finally subtracting the ideal linear phase from the actual unwrapped phase. Example of non-linear phase error is shown in Fig. 2 for the HH radar channel. Similar responses were observed for the other channels. In addition, an empirical model was developed for the non-linear phase error as function of frequency. This model is valid for all frequency chirp rates. This model is used to remove the non-linear phase errors from all target responses and achieve the desired range resolution. Since the SPDT switch in the transmit path has port-to-port isolation exceeding 35 dB and both Gaussian Optics antennas of Fig. 1 have high polarization isolation exceeding 30 dB, then polarization contamination in this system is negligible and need not be characterized. As a result, a simplified technique for characterizing channel imbalances and calibrating the polarimetric radar data is used [4]. This technique requires the measurement of a metallic sphere and any depolarizing target (actually theoretical response is not necessary) to determine the channel imbalances.

III. VALIDATION

Polarimetric measurements of three point targets were performed in an anechoic chamber. The FMCW radar was set to operate over 5.4 GHz bandwidth and the targets were two identical 2.5 cm Trihedrals (theoretical RCS = 0 dBsm) at close proximity of each other (about 10 cm apart in range) followed by a 5.1 cm metallic sphere (theoretical RCS = -27 dBsm). A comparison between the phase-corrected response of all targets using the empirical model of phase error and the uncorrected response is shown in Fig. 3. The three targets can be clearly isolated and placed at actual distances from the radar. A 2nd experiment was performed on a small metallic dihedral titled at 22.5°. The dimensions of the dihedral as well as its theoretical response can be found in [5]. The polarimetric calibration technique in [4] was used to calibrate out channel imbalances in the measured dihedral response. Calibrated dihedral data agrees well with theoretical response: σ_{vv}^{Cal}= -5.9 dBsm (σ_{vv}^{Thry}= -5.9 dBsm), σ_{hv}^{Cal}= -8.2 dBsm $\angle 5^{o}$ (σ_{hv}^{Thry}= -5.9 dBsm $\angle 0^{o}$), σ_{vh}^{Cal}= -5.9 dBsm$\angle 3^{o}$ (σ_{vh}^{Thry}= -5.9 dBsm$\angle 0^{o}$), σ_{hh}^{Cal}= -6.0 dBsm$\angle -179^{o}$ (σ_{vv}^{Thry}= -5.9 dBsm $\angle 180^{o}$).

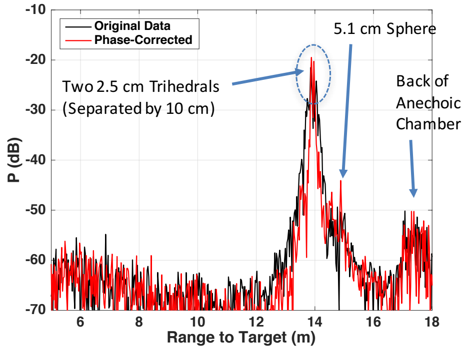

Fig. 3: De-chirped time-domain signal of 4 targets and the corresponding

IV. CONCLUSIONS

Accurate calibration method of fully-polarimetric, wideband FMCW instrumentation radar operating at 228 GHz has been implemented. The radar and the corresponding calibration method will be used to accurately measure the scattering matrix of different targets at this frequency band.

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