Development and Calibration of a X-band Dual Polarization Phased Array Radar

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***Abstract*—This paper describes the X-band dual polarization phased array radar developed at the University of Massachusetts. The high level system architecture is presented and an in-field calibration procedure is developed.**
Keywords - phased array, dual polarization weather radar, mutual coupling calibration

I. Introduction

The Microwave Remote Sensing Laboratory (MIRSL) at the University of Massachusetts has developed a low cost mobile X-band phased array weather radar, shown in Figure 1. The main limitation of currently operational meteorological radar systems is low temporal resolution. Long revisit time on the order of 5 min reduces the chance of observing quickly evolving phenomena such as tornadoes as well as issuing accurate warnings in advance. It is believed that electronically scanned antennas pose a solution to solve this restriction, but due to the high cost of narrow beam phased arrays, their implementation in weather sensing radar remains very limited [1] . Additionally, the system developed here provides dual polarization capability that significantly improves the quality of weather forecasts. However, this improvement can only be achieved if the radar is correctly calibrated. The RF performance of T/R modules utilized by the phased array system is expected to drift from its initial state due to several factors like temperature and component aging. This will induce an additional varying bias dependent on beam location. Therefore an efficient in-field array calibration method is crucial to assure proper radar operation.

Fig. 1. MIRSL phased array mobile radar.

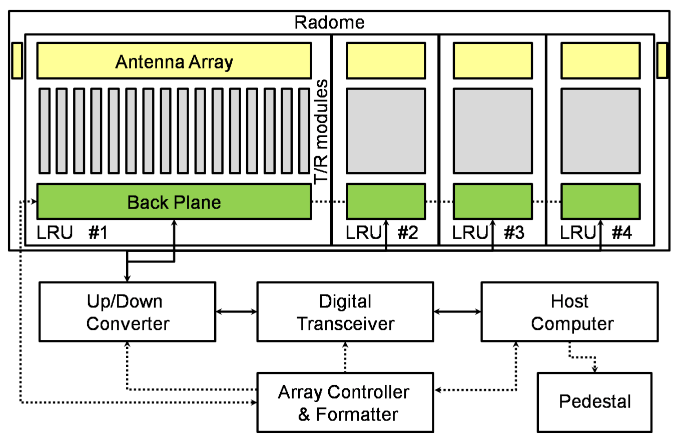

Fig. 2. MIRSL phased array radar block diagram and signal flow.

II. System overview

The MIRSL Phased Array Radar block diagram is shown in Figure 2. The system consists of the Phase-Tilt Antenna, Up/Down Converter, IF Digital Transceiver, Host Computer, Pedestal, and Array Controller/Formatter. The Phase Tilt Antenna subsystem was designed at the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) for use in distributed, collaborative, and adaptive sensing networks. This subsystem exhibits a modular design composed of four line replaceable units (LRU). Each LRU consists of a $0.27x0.56m$ passive antenna array, a set of 16 T/R modules, and a DC and signal distribution backplane shown in Figure 3. The linear array is a planar structure of 72 columns. Each column is a dual polarized subarray composed of 32 aperture-coupled microstrip patch antennas interconnected by series-fed networks for each polarization [2]. The central 64 columns of the antenna array are fed by dedicated T/R modules, while the remaining 8 outer columns are used as terminated dummy elements in order to minimize the effects of diffraction on the array's edges. The phase tilt antenna allows electronic scanning of ±45° in the azimuth plane, while scanning in the elevation plane is performed mechanically. This type of antenna architecture reduces the number of required T/R modules and hence significantly decreases the overall system cost and complexity.

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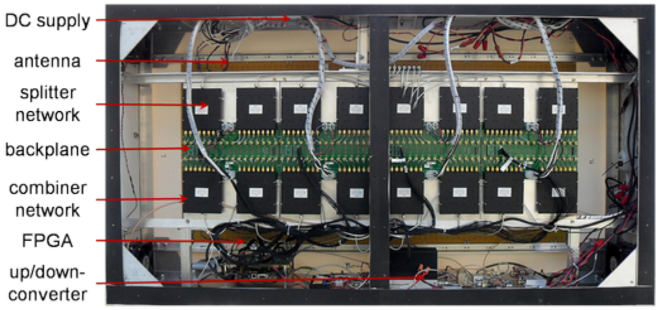

Fig. 3. MIRSL phased array radar RF and control subsystems.

TABLE I
MIRSL PHASED ARRAY RADAR PARAMETERS.

Parameter	Specifications
Radar system dimensions [m]	1.47 x 0.82 x 0.30
Weight [kg]	82
Frequency [GHz]	9.3 - 9.4
Transmit power (peak) [W]	60
Pulse compression gain [dB]	up to 20
Duty cycle	up to 30%
Beam width [°]	2 (azimuth) x 3.5 (elevation)
Integrated cross-pol isolation [dB]	< -21
Range resolution [m]	> 37.5
Polarization	alternate H & V
Radar products	$Z_h, V, \sigma_v, Z_{dr}, \rho_{hv}, \phi_{dp}, \kappa_{dp}$

The T/R module architecture [3] can be broken down into four sets of components: control block, diversity switch, transmit, and receive channels. Operation of each individual T/R module is controlled by an independent FPGA. A custom-designed high power, four port diversity switch utilizes four GaAs SPST PIN diodes and provides an isolation between polarization channels in excess of 45 dB. The T/R module design uses a "common leg" architecture i.e. a 6-bit phase shifter, gain block, and 6-bit digital attenuator are shared between transmit and receive channels.

A FPGA based Array Controller/Formatter provides control and timing signals for all subsystems. Owing to the low peak power provided by solid state based T/R modules, implementation of pulse compression techniques is required. The transmitted nonlinear chirp is produced by an arbitrary waveform generator within the digital IF transceiver and is compressed by means of an inverse filter. The host computer generates all scanning settings, executes signal processing, and controls the data flow. Radar system specifications are shown in Table I.

III. System calibration

The proposed method is based on a well-established mutual coupling technique [4] [5], which presumes that the mutual coupling between pairs of adjacent elements is invariant to their position. However, this is only valid for certain element types in a large enough array. In our case, a common problem

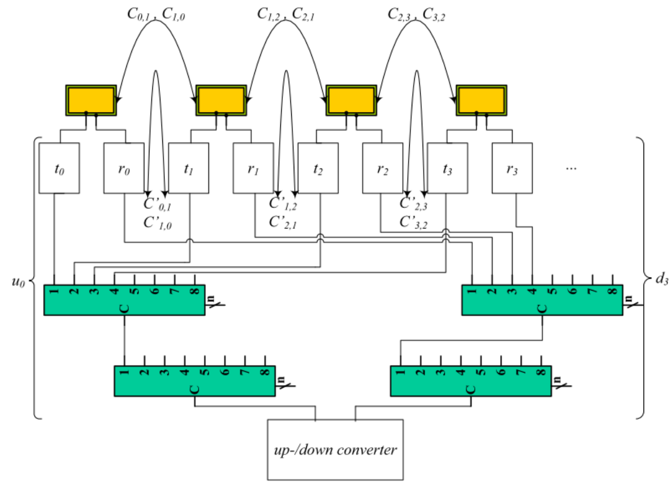

Fig. 4. Free space mutual coupling and transfer function which includes free space coupling and feed line/module effects.

encountered in patch antennas is an excitation of surface waves. The variance of mutual coupling between adjacent elements on order 0.5 dB in magnitude and 2 degrees in phase is to be expected. A solution to this problem, assuming that physical antennas do not change over time nearly as much as the active subsystems of phased array radar, was proposed in [6].

A. Mutual coupling calibration procedure

This calibration method assumes that each TR module is capable of both transmit- and receive-mode and can be independently controlled. If a small array in the presence of surface waves as shown in Figure 4 is considered then $C_{1,0} \neq C_{1,2}$ as well as $C'_{1,0} \neq C'_{1,2}$. Here $C_{m,n}$ denotes a free space mutual coupling and $C'_{m,n}$ is the measured complex value, which includes the free space mutual coupling and attenuation due to feed lines as well as gain provided by the TR module. The latter factor is measured right after initial array calibration is performed with a waveguide probe as described in [7]. The (m,n) index defines the number of TR modules in Tx- and Rx- mode respectively.

The initial coupling values between TR modules $C_{m,n}$ for the digital attenuator and phase shifter set to first state can be calculated as follows:

$$C_{m,n} = \frac{C'_{m,n}}{u_m d_n} \quad \text{for } 1 < m,n < N \quad \text{and} \quad m \neq n \tag{1}$$

where u_m, d_n is a contribution of the feed lines, connectors, and power dividers, as well as phase shifter and attenuator set to first state, i.e. 0° phase shift and $0dB$ attenutation. We assume here that even if the u_m, d_n RF response changes due to the temperature drift or aging of TR modules, it affects all phase shifter-attenuator states of the TR module under test by an identical offset from the reference point. N is the number of TR modules. $m(m-1)$ measurements are required to fully describe the mutual coupling characteristics of the phased array under test expressed in (2). Note that diagonal elements of C matrix are not defined.

$$C = \begin{bmatrix} C_{1,1} & \cdots & C_{1,N} \\ \vdots & \ddots & \vdots \\ C_{N,1} & \cdots & C_{N,N} \end{bmatrix} \tag{2}$$

Here the derived C matrix contains only free space mutual coupling values that remain constant as long as no physical change to the antenna array occurs. It enables monitoring of system health and ideally phase and amplitude misalignment compensation, which is the aim of the in-field self calibration procedure.

For two arbitrary receive modules and a common transmit module, $C^{'}$ can be defined as:

$$C^{'}_{m,n} = t_m[i]u_m C_{m,n} r_n[j] d_n \tag{3}$$

$$C^{'}_{m,l} = t_m[i]u_m C_{m,l} r_l[j] d_l \tag{4}$$

where $t_m[i], r_n[j]$ are the contribution of the phase shifter and attenuator of the m-th transmitter and n-th receiver in the i-th and j-th state respectively.

The receiver correction factor $R[0]_{n,l}$ can then be expressed as:

$$R[0]_{n,l} = \frac{C^{'}_{m,n}/C_{m,n}}{C^{'}_{m,l}/C_{m,l}} = \frac{d_n}{d_l} \tag{5}$$

The quantity $R[0]_{n,l}$ applied to the receiver of l-th TR module makes the signal received by this element look like the signal received by the n-th element. Note that the contribution of the utilized transmitter is canceled out in computation of $R[0]_{n,l}$. Hence, it is possible to use part or all of the available transmitters in the array in order to refine the calculation of $R[0]_{n,l}$ by averaging:

$$R[0]_{n,l} = \frac{1}{N-2}\sum_{m=1}^{N} \frac{C^{'}_{m,n}/C_{m,n}}{C^{'}_{m,l}/C_{m,l}} \qquad m \neq n \wedge m \neq l \tag{6}$$

Similarly, one can define the transmitter correction factor $T[0]_{n,l}$ as:

$$T[0]_{n,l} = \frac{C^{'}_{n,m}/C_{n,m}}{C^{'}_{l,m}/C_{l,m}} = \frac{u_n}{u_l} \tag{7}$$

A more precise measurement of $T[0]_{n,l}$ can be obtained by averaging measurements over multiple available receivers:

$$T[0]_{n,l} = \frac{1}{N-2}\sum_{m=1}^{N} \frac{C^{'}_{n,m}/C_{n,m}}{C^{'}_{l,m}/C_{l,m}} \qquad m \neq n \wedge m \neq l \tag{8}$$

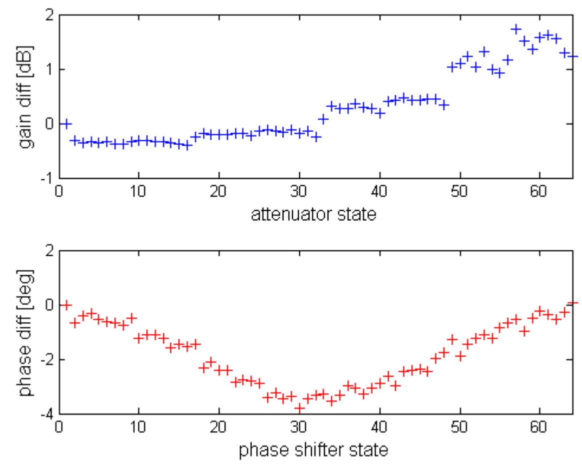

Fig. 5. Comparision of NF probe and mutual coupling calibration methods. The reference signal was transmitted using one of the dummy elements. Both calibration methods are in good agreement with respect to each other.

B. Calibration verification

The initial array characterization was performed with an external near field waveguide probe as described in [7]. In order to reduce the time of this procedure, only a subset of 128 combinations of phase and attenuation settings out of the available 4096 states for every single TR module was tested. At the beginning the attenuator was set to its first state, while phase shifter was switched through each of its 64 states. In the second step the phase shifter was fixed in its first state, while attenuator was switched through each of its 64 states. Finally, the remaining phase shifter and attenuator combinations were computed by appropriate multiplication of the measured states. This procedure was repeated in all 4 modes of radar operation (TxH, TxV, RxH, RxV). Although this method enables accurate array characterization, it requires external calibration equipment and several hours of measurements.

Graceful performance degradation is one of the biggest advantages of phased array technology. Damaged TR modules can be scheduled for replacement at the most convenient time without prolonged radar down time. However, new TR modules have to be calibrated once installed in the array system. The performance of a mutual coupling based calibration is compared to the near field waveguide probe method in Figure 5. Here, a pulsed signal generated by a radar transceiver was first up-converted and then radiated using one of the dummy elements. All TR modules except the one under test were switched off. The calibration procedure resembles the one described in the previous paragraph, i.e. characterization of 64 states of phase shifter, was followed by equivalent measurements of a digital attenuator in the module under test. The received signal was then down-converted, digitized, and analyzed. Both calibration methods are in good agreement with respect to each other. The root mean square error of phase and amplitude measurement is 2.15° and $0.71dB$ respectively. The difference in the measurement is partially caused by the

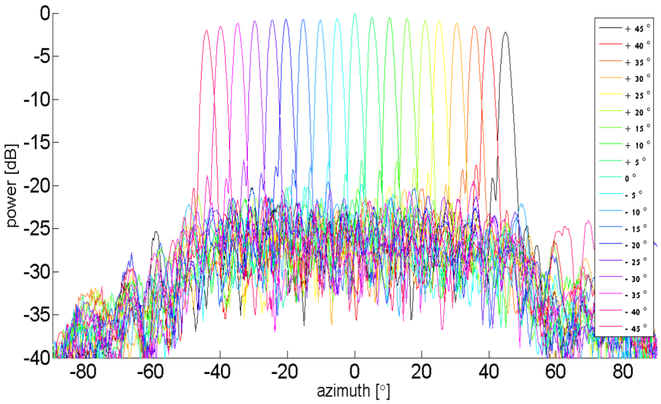

Fig. 6. Azimuth scans of a beacon located 85 m from the array..

temperature dependence of RF performance. The gain and phase of the Rx channel decay at a rate of $0.016dB/°C$ and $0.6deg/°C$ repectively. The near field waveguide probe method is also affected by the alignment errors [7]. On the other hand, the mutual coupling based calibration is sensitive to the signal to noise ratio parameter. In Figure 5 one can notice that the deviation between measurements increases as SNR decreases. Finally, the up/down converter stability was monitored over a calibration switch located in front of the splitter network.

Practical implementation of mutual coupling based calibration method reveals several limitations. Sufficient SNR has to be guaranteed over the entire dynamic range of MUT without setting LNA in a saturation region. Hence correction factors derived in equations (6) and (8) can be obtained only by averaging a limited number of measurements. Furthermore, it is important to record the temperature of calibrated modules. This will allow control of the transmitted power level as well as receiver gain. The biggest benefit provided by this calibration method is that it does not require external equipment. Additionally, it takes into account the influence of all radar subsystems and not only the array itself. Eventually, it is expected that the entire system can be fully calibrated on the order of minutes.

The TR module characterization data was used to compute calibration factors for 91 beams. Then the accuracy of the near field waveguide probe method was verified using a pyramidal horn located in the far field. Beam patterns with 1 degree of separation were measured in-field using simultaneous mechanical and electronic scanning. The radar was moved mechanically in azimuth over range ±90 degrees, while switching beams electronically over range ±45 degress from array broadside. In receive mode, RF signal at 9.36 GHz was fed into the horn antenna from an external signal generator. For the Rx array, gain and phase corrections were applied to set a -25 dB Taylor distribution, but due to TR module failure the desired sidelobe reduction could not be achieved. In transmit mode, signal received by the horn antenna was downconverted to 60 MHz and transmitted over a long IF cable back to radar data acquisition card. The measurements are affected by multipath effect. The two way 6dB beam width equals 1.6° at broadside and increases to 2.6° at beam angle ±45°. The measured beam patterns in receive mode are shown in Figure 6.

IV. Conclusion

This paper has described the hardware architecture of a dual-polarized, solid-state X-band phased array weather radar. The array system was fully characterized using a near field probe measurement system. The accuracy of this characterization was verified using a pyramidal horn located in the far field. An in-field calibration scheme based on a mutual coupling method has been proposed and its performance has been tested. It poses an attractive solution for a rapid in-field calibration. Care has to be taken to meet SNR requirement and to avoid driving receivers in saturation region.

Acknowledgments

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