Calibration and Validation of the CASA Phased Array Antenna

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Abstract—**This paper describes the calibration and validation of one-dimension scanned phased array antenna for an X-band weather radar being developed at the Engineering Research Center for the Collaborative Adaptive Sensing of the Atmosphere (CASA). The antenna aperture is based on a linear array of vertical subarrays. Each subarray is fed by a separate Transmit/Receive (T/R) module which provides phase, amplitude and polarization diversity. The characterization and calibration of the array are based on single element measurements obtained from a portable near-field probe test system. The calibration is validated by measuring the antenna radiation pattern in a near-field antenna range. In addition, thermal stability tests are performed to estimate the system performance loss.**

Keywords- ***Calibration; Phased Array; Electronic Scanning Antennas; Radar; T/R module; CASA***

I. Introduction

Recently, the NSF Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) developed the first prototype of an active phased array antenna for weather radars. One of the center's goals is to implement a distributed network of short-range solid state radars to improve the sensing of the near-surface atmosphere [1]. Such system has the potential to create high spatial and temporal resolution observations from weather phenomena. The phased array radar system being developed in CASA is based on a low-cost, low-power, one dimensional dual-polarization phased array antenna that operates at a center frequency of 9.36 GHz and bandwidth of 60 MHz. The antenna is mounted in a tilt gimbal, allowing the radar to perform electronic scanning in azimuth and mechanical scanning in elevation direction. Such system is called the Phase-Tilt Antenna Array [2].

As a part of the antenna development program, the center has been exploring ways to characterize, calibrate and evaluate effectively the antenna performance using low cost solutions as an alternative to the expensive near-field (NF) antenna range facilities. This paper will focus on the characterization and calibration of an active phased array using a portable NF probe measurement system designed by CASA. The process is validated with measurements of the far-field radiation pattern obtained from a near-field antenna test facility. Another aspect that has been included is the evaluation of the antenna performance at different temperatures.

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II. System Description

The antenna aperture consists of a linear array of 72 vertical subarrays. The inner 64 subarrays are active elements that are fed by dedicated T/R modules, which provide amplitude, phase and polarization diversity. In addition, the aperture has 4 passive subarrays at both edges that are used to reduce the edge diffraction effects and no uniform mutual coupling. Both the amplitude and phase of each active element can be individually adjusted to control the beam steering angle and aperture amplitude distribution in the azimuth direction.

The vertical subarray used in the aperture consists of a linear array of 32 dual linear polarized aperture coupled microstrip patch antennas that are interconnected by series-fed networks in each polarization port [3]. The spacing between elements is 17 mm ($0.53\lambda_0$) in both azimuth and elevation plane. This value restricts the maximum scanning angle to ±62.5° in azimuth, where the first grating lobe is located. The excitation of each subarray is controlled in the T/R module with a 6-bit 32dB digital attenuator and 6-bit digital phase shifter. Each T/R module has a Field Programmable Gate Array (FPGA), which creates the control signals from commands that are sent from the Array Controller. As a part of the control logic, the FPGA's memory is configured as a look-up table, where calibrated settings for the attenuator and phase shifter are stored [4].

Another key aspect of design is the antenna cooling system. The array is equipped with an inexpensive forced air cooled system that prevents the T/R modules from excessive heat. A voltage-controllable fan array that forces cool air to circulate from the antenna base to the top, passing through the T/R modules is used. This system allows the T/R module temperature to be controlled by the fan speed.

III. Characterization and Calibration Scheme

A. *Characterization*

The characterization scheme is based on single element measurements that are performed in the reactive near field zone [5] . The process consists in positioning a near-field probe exactly in front of each subarray, and measuring all possible combinations of gain and phase that are realizable by adjusting the attenuator and phased shifter in the element under test. This procedure is repeated until all the subarrays are measured.

In order to characterize the array, a portable near-field (NF) probe measurement system was custom built. The system consists of a single-axis linear positioner that carries an open ended waveguide as a near-field probe, and a vector network analyzer to measure the S-parameters. These devices are interfaced to a computer, which also controls the T/R modules, processes the data and records the measurements. The entire process is controlled by the user with the help of a GUI developed in C programming language. In order to minimize the alignment errors, the linear positioner is parallel attached to the antenna support structure, with the near-field probe aligned to the center of the subarrays, as illustrated in Fig 1. The separation distance between the probe and antenna is chosen to be one wavelength to minimize the coupling effect due to other subarrays. The network analyzer is connected between the RF manifold (transmit or receive) and the NF probe to measure the end-to-end gain transfer function (S_{21} parameter).

The characterization starts by first placing the NF probe in front of the subarray under test (SUT) and measuring the S_{21} parameter, with that element in either transmit or receive mode and the remaining array subarrays terminated in matched loads. In order to save time, the attenuator and phase shifter are only switched through a subset of 128 of the possible 4096 states, initiating the measurements with the attenuator in the state zero (0 dB) while the phase shifter is switched through each of its 64 states, and then setting the phase shifter to state zero (0 degrees) while switching the attenuator through each of its 64 states. The remaining 3968 states are obtained as follow:

$$S_{21}^{m}(n,att,phs,t)=\frac{S_{21}^{m}(n,att,0,t)S_{21}^{m}(n,0,phs,t)}{S_{21}^{m}(n,0,0,t)} \quad (1)$$

where m represents the operation mode (TH, TV, RH, or RV), n is the SUT index (n=1,2,3,..,64), att and phs are the attenuator and phase shifter states (0,1,2..,63), and t is the temperature index. The parameters $S_{21}(n,att,0,t)$, $S_{21}(n,0,phs,t)$ and $S_{21}(n,0,0,t)$ represent three of the 128 measurements recorded for the subarray n at a specific frequency. This data reconstruction scheme allows the characterization time to be reduced by a factor of 32 compared to full measurements.

B. Calibration

The purpose of the calibration is to use the S_{21} measurements to determine the proper setting that should be applied in the attenuators and phase shifters to obtain the desired antenna excitation as indicated by the measurements. To find the antenna calibration settings, an error minimization algorithm is used. The algorithm searches in the characterization files of each element the best approximation for the attenuator and phase shifter states that minimize the norm between the measured gain $S_{21}(n,att,phs,t)$ and the desired gain S_{21des} for that particular element. The S_{21des} is the scaled product of the complex excitation coefficient A_n, which depends on the desired aperture distribution function and the scanning angle. Formally, this is expressed as

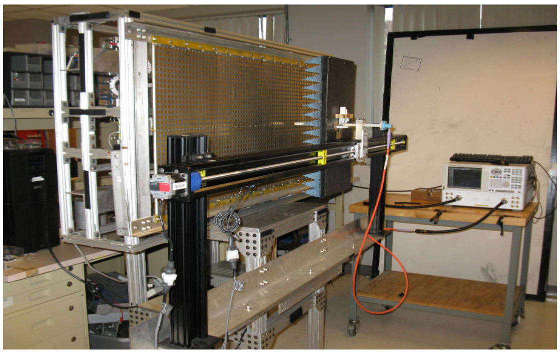

Figure 1. Antenna characterization system

$$[att^{m}(\theta),phs^{m}(\theta)]=\text{argmin}\left\| S_{21}^{m}(n,att,phs,t)-S_{21des}^{m}(n)\right\| \quad (2)$$

$$S_{21des}^{m}(n)=A_n\cdot\left|S_{21ref}^{m}\right|=a_n e^{jnkd\sin(\theta_0)}\left|S_{21ref}^{m}\right|$$

where a_n is the amplitude distribution coefficiente, k is the wavenumber (rad·m^{-1}), d is the inter-element spacing (m), θ_0 is the scanning angle (rad), and S_{21ref} is a gain scaling factor. This last value represents the maximum gain that can be implemented by the array elements to obtain an uniform aperture distribution. S_{21ref} should be chosen less than or equal to the minimum gain found among the T/R modules, when the attenuator and phase shifter are in zero state. This can be expressed as $S_{21ref}^{m}\le\min(S_{21}^{m}(n,0,0,t))$.

The procedure described by (2) is repeated at different scan angles until covering the radar scanning region from -45° to 45°. Ultimately, several calibration settings are obtained for the same elements. These values are arranged as beam-tables and stored in the T/R module memory for later use. The antenna pattern is created after sending beam commands from the Array Controller to the T/R modules.

IV. CALIBRATION TEST ON RECEIVE

This section reports the results obtained from the calibration tests of a receive array at the frequency of 9.36 GHz. Characterization was performed with the NF probe measurement system inside an anechoic chamber at room temperature. Measurements made in both polarizations were used to calibrate the antenna aperture with a 25 dB Taylor tapering. Two different methods were used to evaluate the antenna calibration: single element measurements and direct measurement of the radiation pattern. In the single element measurements, the calibrated gain and phase of each element is measured with the NF probe measurement system. Comparison between measured and theoretical data (S_{21des}) is used to calculate the RMS amplitude and phase errors, which are the main indicators of the performance. The second method is based on the measurement of the far-field radiation pattern in a planar NF antenna range. For that case, the sidelobe level is used as performance indicator.

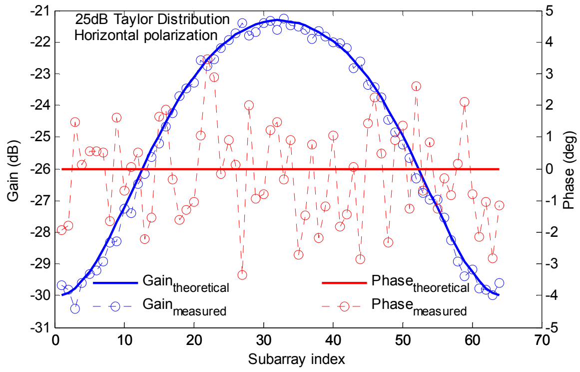

Figure 5. Aperture distribution measured with the NF probe

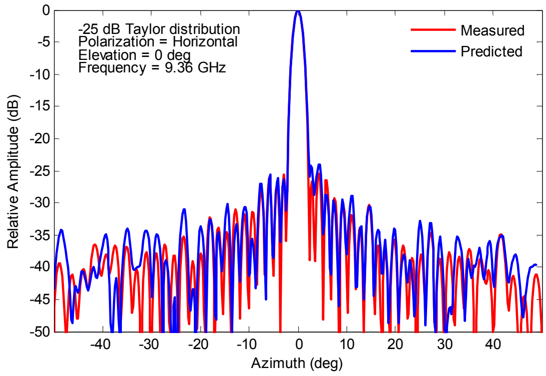

Figure 4. Comparison of the predicted far-field radiation pattern obtained from single element measurements and far-field measurements

The measured results of the complex gain, S21mes, obtained from single element measurements for a calibrated receive array in the horizontal polarization and theoretical values are shown in Fig. 2 The RMS errors obtained from the characterization and calibration scheme were 0.25dB in amplitude and 1.56° in phase. The results are good considering the attenuator and phase shifter quantization effects, which limit the perfect implementation of the gain and phase. Single element measurements can also used to predict the far-field radiation pattern in the azimuth direction if the embedded element pattern, *Pe(θ),* is known. The far-field radiation pattern can be calculated from the product of the embedded element far-field pattern and the array factor as

$$P_a(\theta) = P_e(\theta)\sum_{n=1}^{64} S_{21mes}(n)e^{jnkd\sin(\theta)} \qquad (3)$$

A comparison of the predicted and the direct measurement of the far-field radiation pattern obtained from a NSI planar near-field measurement system in the azimuth direction is shown in Fig. 3. The sidelobe levels obtained in both patterns meets the design requirements of -25dB.

Measurements of the far-field radation pattern were also made at different scanning angles to validate the calibration scheme. Fig. 4 and 5 show the azimuth patterns for both polarizations when the beam is steered to 0, 15, 30 and 45

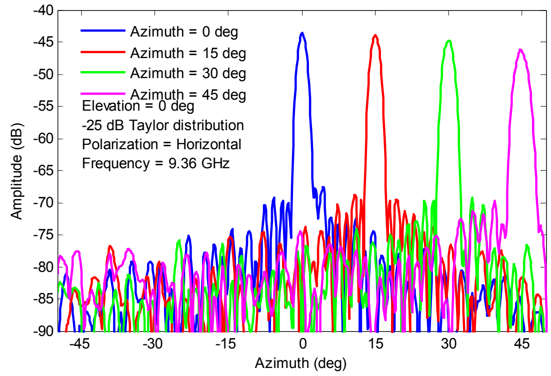

Figure 3. Measured far-field radiation pattern for different scanning angles in the horizontal polarization

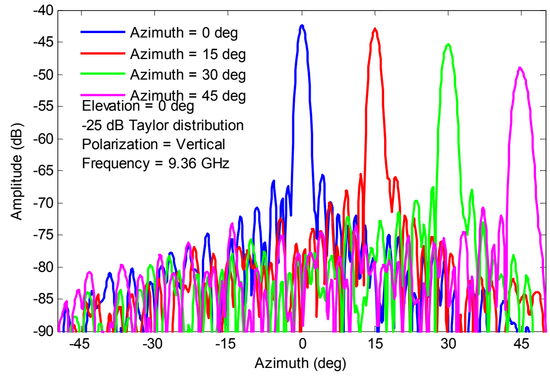

Figure 2. Measured far-field radiation pattern for different scanning angles in the vertical polarization

degrees. In both cases, the amplitude of the main beam is affected by the array element pattern. Fortunately this effect did not affect in the relative sidelobe level, which is still around -25dB in all patterns.

V. Calibration Test On Transmit

In order to maximize the power efficiency of the transmit array, all transmit modules must be operated in the saturation region. In addition, the transmit array must use an uniform aperture distribution to deliver the maximum avalible output power. This leads to the array losing the ability to control the gain. Having not gain control, the phase is the only parameter that needs to be characterized. To measure the transmit array in saturation, an extra test is performed before the array characterization. The test consists in measuring the output power variations of each element versus the antenna input power with the NF prove. Measurements provide the minimum power (P_{in1dB}) that should be applied in the antenna input to achieve the 1dB compression power. Once this boundary is found, an input power level grater than P_{in1dB} is applied to the antenna and the phase of each element is characterized.

Fig. 6 shows the average output power from 64 elements in both polarizations sensed with the NF probe versus the antenna input power. The standard deviation of the sensed output power was 0.92 dBm and 0.74 dBm for V and H polarization, respectively. The variance of these parameters is due in part to the interconnection losses between the T/R modules and the

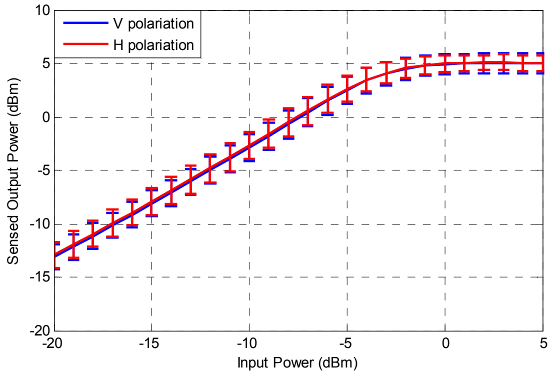

Figure 6. Average output power and error bars versus input power

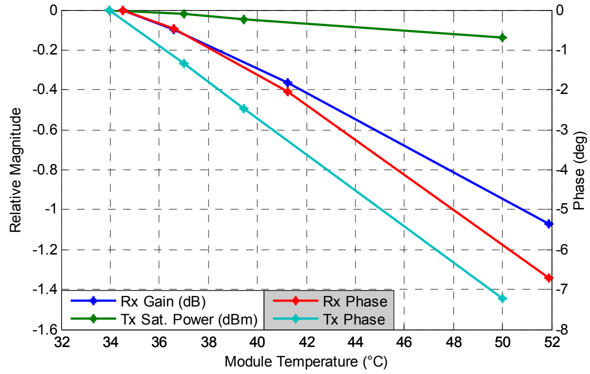

Figure 7. Realtive gain, phase and saturation power performance versus module temperature

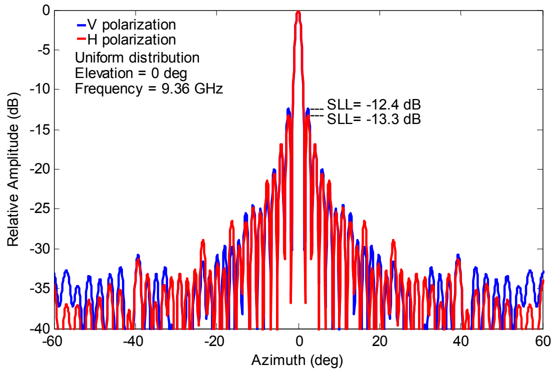

Figure 8. Far-field radiation pattern for the transmit array

array elements, which is realized with push-on SMP connectors. The average P_{in1dB} is around -2dBm. Above this point, any power level will be enough to saturate the modules.

Since the transmit array is limited to operate to a maximum duty cycle of 30%, the evaluation was only performed with the NF probe test system. The measurement of the direct far-field radiation pattern was not performed due the lack of a test facility to measure pulsed antenna. Both the characterization and calibration were performed for an input power of 0 dBm. Fig. 7 shows the far-field radiation patterns obtained from single element measurements. The patterns achieved peak sidelobe levels of -12.4 dB and -13.3 dB in the vertical and horizontal polarization respectively. The peak sidelobe level for the vertical polarization exceeds in 0.9 dB the expected value for a uniform distribution. This degradation is due the RMS amplitude errors of the implemented gain, which can not be calibrated.

VI. Antenna Stability

The stability test consists in measuring the S_{21} performance of a calibrated array at different temperatures. To perform this test, the arrays was calibrated for a temperature of 34 °C, then the temperature of the active components was varied by steps up to reach 54° C. Temperature control was realized with the air cooling system and measurements at steady-state were performed at each array element with the NF probe.

The relative gain (gain loss), phase and Tx saturation power (power loss) performance versus module temperature are shown in Fig. 8 for both Tx and Rx arrays. Measurements are normalized to the operating temperature of 34 °C. According the results, the receive gain and phase decay at a rate of 0.061 dB/°C and 0.38 deg/°C respectively. The total gain loss is about 1 dB in the range. In contracts, the Tx saturation power and Tx phase vary in at rate of 0.009 dB/°C and 0.45 deg/°C respectively, while the total power loss is 0.14 dB in the range of interest.

VII. Summary

This paper has described the characterization and calibration of an active phased array antenna for the CASA phase-tilt radar. The array was fully characterized for all operation modes, at different frequencies and temperatures. The calibration scheme was successfully tested with a NF probe measurement system and verified in a planar NF antenna test facility. For the Rx array, gain and phase corrections were applied to set a -25 dB Taylor distribution. Low RMS amplitude and phase errors were achieved after measuring the implemented aperture. For the Tx array, an uniform aperture distribution was used. All modules were driven in the saturation region, allowing only phase corrections. Due the lack of gain control a moderate RMS amplitude errors in the aperture excitation of both polarizations were obtained.

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