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Beamformer Calibration With Distributed Reference Noise for the ALPACA Imaging Array

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***Abstract*—For wide-field astronomical phased array feeds, accurate beamformer calibration is required. Temperature variations and other environmental factors cause drifts in the phase and amplitude responses of the analog front end and RF-over-fiber signal transport system. To correct for these drifts and eliminate gain reductions and pattern drift in the formed beams, we have developed a distributed noise reference system that allows phase and amplitude recalibration. To validate the system, we use the reference system to correct the phase in a signal transport channel for the Advanced L-band Phased Array Camera for Astronomy (ALPACA) with a length of fiber inserted to mimic phase drifts.**

I. Introduction

Phased array feeds for radio astronomy allow for a wider instantaneous field of view than traditional single-horn feeds. A challenge in operating phased array systems is persistent calibration of beamformer weights. The beamformer weights compensate for channel losses, antenna interactions, time delays and other system deficiencies. To overcome drifts in the receiver signal paths and avoid the need for frequent on-sky recalibration, we have developed a distributed noise reference system that allows signal path phases and amplitudes for the Advanced L-band Phased Array Camera for Astronomy (ALPACA) [1] to be measured on the fly.

ALPACA, to be installed on the 100m Green Bank Telescope, has a 69 dual-polarization element phased array feed from which a real-time digital beamformer produces 40 dual-polarized beams. An RF-over-fiber (RFoF) link transports the signals from the telescope to the digital back end. Analog-to-digital conversion and frequency channelization is performed by 12 AMD/Xilinx RF system-on-chip (RFSoC) ZCU216 boards. Given the scale and complexity of the system, ALPACA requires multiple calibration modes for its various subsystems in order to maintain high quality beams. Once the ADCs in the digital back end are aligned, the relative amplitude and phase transfer functions of the RFoF signal transport links must be measured and corrected for drift. Our focus here is on validating the distributed noise reference system that will be used to make these measurements.

II. ALPACA System Calibration

Sources of varying time delays and amplitude drift in the ALPACA system include changes in the RFoF signal transport channels and variation in ADC sample timing from chip to chip and board to board. The ADCs must first be synchronized so that samples are aligned across all array channels. Once the ADCs are aligned, on-sky observations of a bright radio source are used to compute beamformer weights for each image pixel (or beam) over the PAF field of view. During operation, injected noise is used at two different levels in the signal chain to measure signal transport response and correct beamformer weights for system drift over time.

A. ADC Synchronization

At power-on, ZCU216 ADCs start sampling with an initial random relative phase. Multi-tile synchronization (MTS) and multi-chip synchronization (MCS) are used to discipline the ADCs to produce a synchronized sampling relationship across all ADCs that is re-established each time the system is power cycled. A common reference clock is distributed to each board's phase locked loop (PLL). A zero-delay configuration is used at each PLL to generate MTS clocking signals. These signals are then de-skewed in each RFSoC. This removes various sources of clock phase ambiguity between boards. To verify proper MTS and MCS alignment between synchronization attempts, a broadband noise signal is injected at each receiver board (call-out (1) in Figure 1) and the phase between each ADC pair is compared to the reference values from when the initial on-sky beamformer calibration occurred.

B. Initial On-sky Array Calibration

Initial calibration of a phased array feed is done by measuring the response to a bright calibrator source and using the maximum-SNR beamformer in "fixed-adaptive" mode [2]. Following standard practice for PAFs, the telescope is steered over a grid of pointing directions to place the calibrator source in the center of each beam position. The array output is correlated at each telescope steering direction. The on-source correlation matrix and an off-source noise-only correlation matrix are used in a generalized eigenvalue problem to find the maximum-SNR beamformer weight vector for each PAF image pixel. These are stored and used for astronomical observations over a period of days or weeks, referred to as a beamformer calibration epoch.

C. Initial Optical Fiber Calibration

To avoid having to frequently repeat the initial on-sky calibration, we measure the RFoF amplitude and phase response across all 1250 frequency bins during initial calibration, as a reference for use in rapid-update calibration during a beamformer calibration epoch. A noise distribution system injects identical broadband noise from a noise diode into each antenna signal path at call-out (2) of Figure 1. The transmitter board sends the noise over the RFoF link to the ZCU216 boards.

The complex sampled signal $x_{m,k}[n]$ at the mth array channel and in the kth frequency bin is an amplitude and

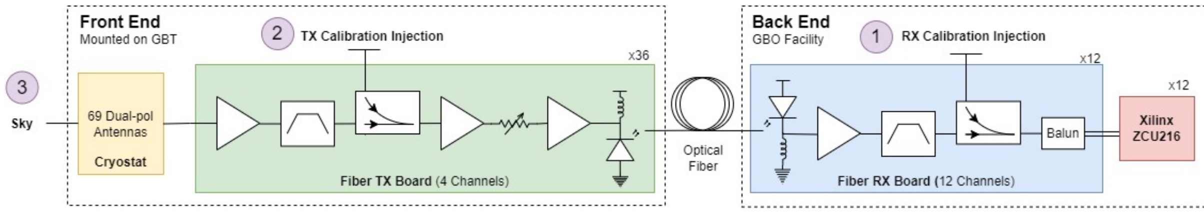

Fig. 1. Simplified signal transport chain for the ALPACA system. Calibration injection point (1) is broadband noise used to correct for drifts in the RFoF signal transport and (2) is also broadband noise used to verify ADC alignment.

phase shifted version of the injected white noise $z[n]$. The channel perturbation can be modeled as a complex vector $\boldsymbol{\alpha} = [\alpha_1 \dots \alpha_M]$, such that $x_{m,k}[n] = \alpha_m z[n]$. Since each antenna signal path sees the same injected noise signal, correlating $x_{m,k}[n]$ across all antenna channels leads to nearly rank-one matrix of the form $\sigma^2 \boldsymbol{\alpha}\boldsymbol{\alpha}^H$ for each frequency bin k. The principal eigenvector corresponding to the largest eigenvalue of the k-th covariance matrix provides an estimate $\boldsymbol{\alpha}_0$ of the signal transport complex phase and amplitude response.

D. Rapid-update Calibration

The purpose of the rapid-update calibration is to accommodate for gain and phase drift in the signal transport fiber links. Rapid-update calibrations will be done occasionally between or during telescope observations.

During rapid-update calibration, broadband noise is again injected as shown in Figure 1. The digital back end computes the array output voltage correlation matrix. As in the initial optical fiber calibration, the principal eigenvector of the correlation matrix provides an estimate $\boldsymbol{\alpha}_c$ of the current signal transport amplitude and phase response. The complex phase and amplitude drift since the last update in the mth array channel is $\alpha_{c,m}/\alpha_{0,m}$. To compensate for drift in the signal transport since the initial optical fiber calibration, the array beamformer weights for each image pixel over the PAF field of view are updated by dividing each coefficient by the corresponding measured amplitude and phase drift.

III. Experimental Results

Figure 2 shows results of a rapid update applied to a single RFoF channel. First, a baseline $\boldsymbol{\alpha}_0$ relative to a selected reference antenna channel is measured for each frequency bin, as represented by the blue line. We then added a 2-m length of fiber to the channel, simulating a time delay drift. In the frequency domain, the increase in delay for this channel relative to the reference channel appears as a phase ramp with a negative slope.

During rapid-update calibration, the phase drift in $\boldsymbol{\alpha}_c$ relative to $\boldsymbol{\alpha}_0$ was computed and removed from the sampled array output voltages (when used with the real-time beamformer, the correction will be applied to the beamformer weights rather than the array output voltages). Calibration removed the delay, resulting in a flat phase response shown by the red dotted line. The maximum error between the original undelayed phase response and the calibrated phase response is 0.006 radians.

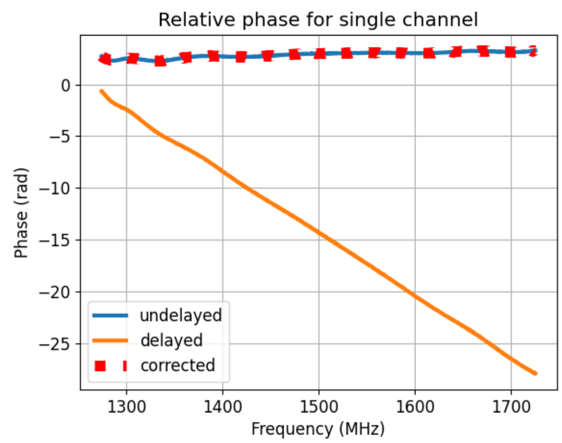

Fig. 2. Relative phase for one ALPACA signal transport channel. The blue line shows the original undelayed phase response. The orange line shows the phase response after adding a length of fiber to the channel. The red dotted line shows the corrected phase response after rapid update calibration.

IV. Conclusion

We have described a rapid-update calibration system for an astronomical phased array feed which will be used to correct phase drift in the signal transport lines. This calibration system will significantly extend the interval between necessary and time-intensive on-sky re-calibrations. In future work we will verify the system by using it to correct for phase drifts in the full ALPACA system and determine how often rapid-update calibration should occur.

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References

[1] M. Burnett, J. Kunzler, E. Nygaard, B. D. Jeffs, K. F. Warnick, D. B. Campbell, G. Cortes-Medellin, S. Parshley, A. Vishwas, P. Perillat, and D. A. Roshi, “Design and development of a wide-field fully cryogenic phased array feed for Arecibo,” in *2020 XXXIIIrd General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*, 2020, pp. 1–4.

[2] J. Landon, M. Elmer, J. Waldron, D. Jones, A. Stemmons, B. D. Jeffs, K. F. Warnick, J. R. Fisher, and R. D. Norrod, “Phased array feed calibration, beamforming, and imaging,” *The Astronomical Journal*, vol. 139, no. 3, p. 1154, 2010.