Arecibo Focal Phased Array
Feasibility Study and Instrument Concept Design

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Abstract

We are developing the next generation instrumentation for the Arecibo radiotelescope, consisting of an L-band focal phased array feed (PAF) with an effective field of view (FOV) of approx 20 arcmin in diameter. In 2010 and in part of 2011, as part of this development, we made a feasibility study to address two issues, in particular, necessary to implement this technology: first, to determine the available FOV of a PAF system with the Arecibo shaped optics, and second, the development of a suitable cryogenic concept with the potential of reaching a receiver temperature of 35K. We are presenting the results of this feasibility study and the system concept design of the Arecibo cryogenic phased array feed (AO-PAF).

1 Introduction

Phased array feeds (PAF) are of great interest for radio astronomical applications, in which survey speed is now becoming a driving force [1]. PAF systems, when located in the focal plane of a radio telescope, have the potential of simultaneously accessing the available field of view (FOV) of the optics, henceforth, realizing its full survey speed, [2, 3]. As survey speed varies with the square of the telescope sensitivity [4], expressed by the ratio of effective to system temperature, A_{eff}/T_{sys}, large aperture radio telescopes are very well suited to implement PAF systems to increase survey speed by one or two orders of magnitude. This is the case of the Arecibo's 300m diameter radio telescope.

We are developing the next generation of astronomical instrumentation based on a phased array feed capable of providing the highest sensitivity over an extended field of view (FOV) equivalent to 40 beams overlapping at half-power in L-band (approx. 20 arcmin in diameter). With a target receiver temperature of 35K, and a 300 MHz instantaneous bandwidth digital beam former, the PAF will provide a factor of 21 increase in survey speed compared with that of a single pixel L-band receiver. The development of this new instrument requires the assessment of two critical aspects for the particular characteristics of the Arecibo radio telescope: the FOV performance of a PAF with Arecibo's shaped optics, and suitable cryogenics concept capable of reaching the receiver temperature goal. The final implementation relies on 300 MHz instantaneous bandwidth digital beam former technology, currently being developed by others groups [5, 6]. We will present the most current results form the Arecibo PAF feasibility study, including the FOV assessment, cryogenics design concept and the overall system design concept of AO-APAF.

2 Field of View Assessment

The Arecibo radio telescope has spherical primary reflector surface and a dual shaped reflector corrector system specifically designed to correct the spherical aberration and provide a nearly uniform aperture illumination, (Fig. 1, *left*). The effect of this shaping is a net reduction of the FOV; while the AO shaped optics works remarkably well when the feed is located at the designed focus point, it loses efficiency rapidly when the feed is displaced from the ideal position. As the feed moves (scans) in the focal plane of the telescope optics, the corresponding beam moves in the sky by a given amount related to the plate scale of the optics. On the right of Fig. 1 we show the scanning losses for different frequencies, as a function of the corresponding sky beam displacement in beam widths. The figure indicates, in particular, the regime of operation for the Arecibo L-Band Focal Array camera (ALFA), corresponding to a three-HPBW separation for the outer beams at 1.4 GHz and with approximately 0.8 dB of scanning loss.

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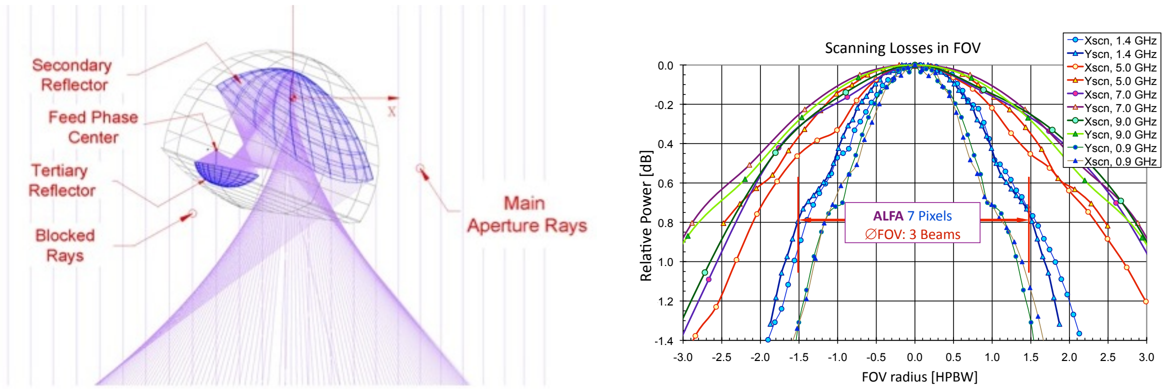

Figure 1: *Left:* Ray tracing of the secondary and tertiary reflectors of the Arecibo Shaped Gregorian Optics. *Right:* Scanning loss at the focal plane of AO shaped optics as a function of sky beam displacements, for different frequencies.

FOV assessment of phased array feeds (PAF) has been made on prime focus paraboloid optics, such as the BYU 19-dipole element PAF located on the prime focus of a NRAOs 20m diameter paraboloid antenna [7], or measured reported for the CSIRO checkerboard PAF also at prime focus of a paraboloid reflector [8, 9]. In 2010, during the AO-PAF feasibility study, a characterization and measurement of the available FOV of Arecibo radio telescope (AO) shaped optics was made, using the BYU 19-element dipole PAF.

In order to measure the AO FOV, we took advantage of the hexagonal element layout of the (19 elements) PAF, by putting the array on a 3 degrees-of-freedom positioner, and then we moved it in a hexagonal mosaic pattern, in the focal plane of the AO optics, hence simulating a large format array (approx 1.4m in diameter).

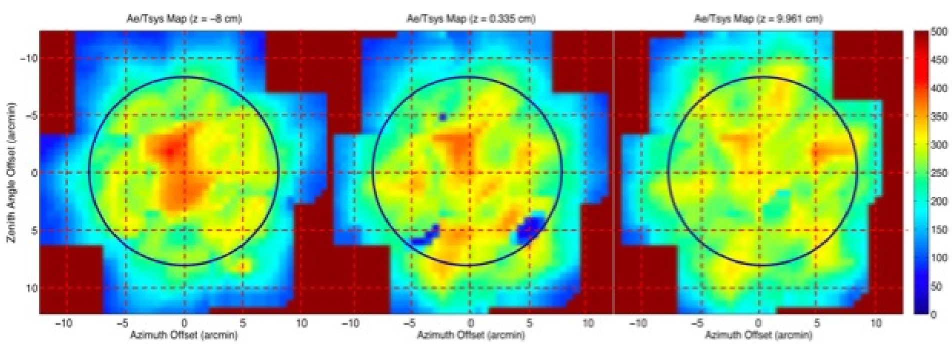

Figure 2: Measured sensitivity maps for three different z-focus positions. Reference circle is 8-arcmin in radius.

Fig. 2 shows the measured sensitivity (A_{eff}/T_{sys}) maps for three different values of focus for the combined mosaic positions. These results reveal that the PAF location that maximizes available FOV, is close to the exit pupil of the telescope optics. Although the available FOV is larger at the exit pupil of the telescope, peak sensitivity is lower. This indicates that there is a critical tradeoff between sensitivity and size of FOV that must be considered for optimal location of an astronomical PAF on the Arecibo telescope.

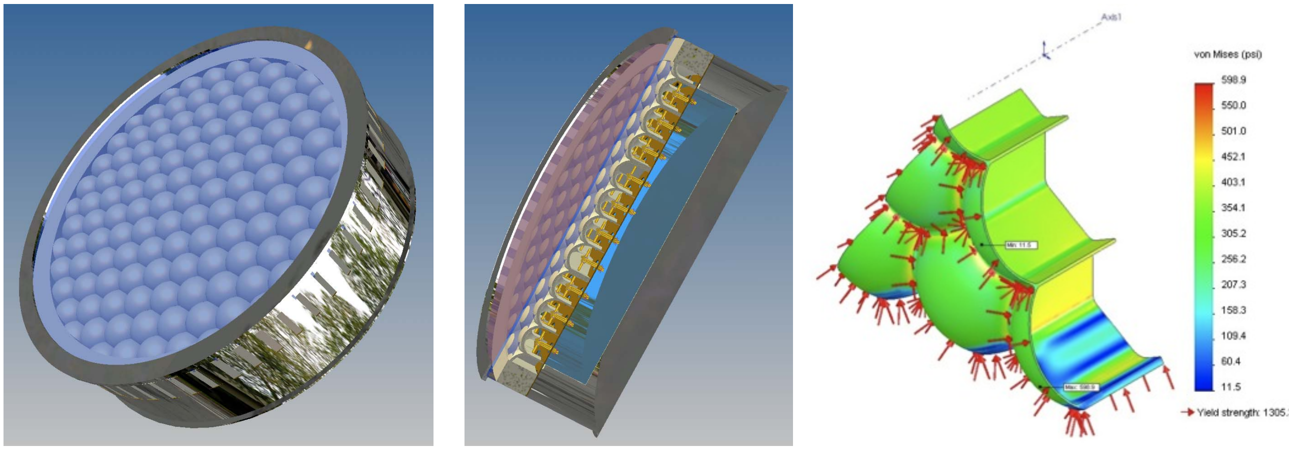

Figure 3: *Left:* AO-PAF Cryostat perspective view. *Center* Cut out detail showing the cryo-window , the 70K section and dipole elements+LNAs at 15K. *Right:* Vacuum stress analysis of the teflon honeycomb window.

2.1 Cryogenic Concept

The cryogenic concept that has been developed for the AO-PAF consists of a 1.6m diameter cryostat with a 1.3m diameter window, (see Fig. 3, left), with a two stage cryo-cooler system. The vacuum window consist of a teflon honeycomb structure sitting on a 70K-stage ground plane. the cell size is large enough to accommodate each of the 92 dual polarization dipole elements that form the phased array feed, (see Fig. 3, center). Each dipole and dual LNA set are attached to the second, 15K, stage, not shown in the figure. On the right of Fig. 3 we show a vacuum stress analysis of the teflon honeycomb window. A multilayer IR filter sits between the honeycomb structure and a Kapton vacuum seal. The dual polarization and LNA are encapsulated on a push-on connector carrier that is captured mechanically and thermally to a 15K stage sink, but disconnect and detach easily at room temperature. we are developing a prototype to test the large vacuum window concept and the mechanism for connecting the dipole+LNA package.

2.2 AO-PAF Systems Architecture

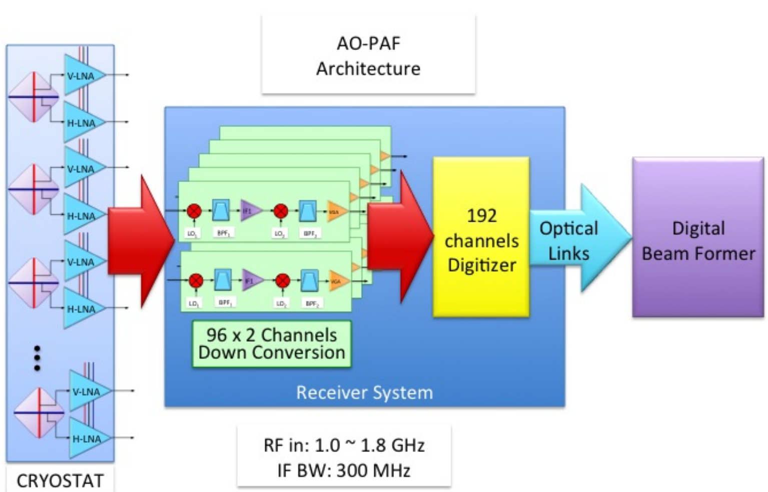

Figure 4: System architecture of AO-PAF.

Fig. 4 shows the system architecture for the AO-PAF. It consists of a cryogenic front-end with 92 dual wide-band dipole antenna elements with a pair of LNAs, one per polarization, cryogenically cooled to 15K. The signals channels from the front-end then go to the receiver system. Two options are being considered: a double downconversion system or a I/Q receiver for each channel. Although the antenna elements are capable of 600 MHz bandwidth, the instantaneous (digital beamformer) system bandwidth is 300 MHz. The receiver system then connects with the digitizer. The receiver system and digitizer will be mounted on the AO Gregorian platform, with the digitizer properly shielded on the second floor of the platform for RF interference. The output of the digitizer will connect to fiber optics links that connect with the control room, and the digital beam forming system and back-end spectrometers.

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References

[1] J. R. Fisher and R. F. Bradley, Full sampling array feeds for radio telescopes, in *Proc. SPIE, Radio Telescopes*, H. R. Butcher, Ed., Jul. 2000, vol. 4015, pp. 308318, SPIE.

[2] T. Oosterloo, M. Verheijen, W. van Cappellen, L. Bakker, G. Heald, and M. Ivashina, "Apertif - the focal-plane array system for the WSRT". *Widefield Science and Technology for the SKA* SKADS Conference 2009.

[3] M. V. Ivashina and J. D. B. A. van Ardenne, A way to improve the eld of view of the radiotelescope with a dense focal plane array, in *Proc. 12th Int. Conf. Microwave and Telecommunication Technology*, 2002, pp. 278281

[4] J.M. Cordes, Survey Metrics, *SKA Memo Series*, No. 109, 2009.

[5] ____ "ASKAP Digital Signal Processing Systems System Description and Overview of Industry Opportunities" *The Australian SKA Pathfinder Project*, www.atnf.csiro.au/projects/askap

[6] A. W. Gunst, "Cost and power usage evaluations for the various processing architectures: A Hardware and Operational Cost Comparison of Two Architectures for Large Scale Focal Plane Array Beamforming and Correlation". *SKA Memo Series*, No. 110, Feb, 2009, www.skatelescope.org/pages/memos

[7] K.F. Warnick, B.D. Jeffs, J. Landon, J. Waldron, D. Jones, J.R. Fisher, and R. Norrod, Beamforming and imaging with the BYU/NRAO L-band 19-element phased array feed. *13th International Symposium on Antenna Technology and Applied Electromagnetics and Canadian Radio Sciences Meeting*, Banff, AB. Canada, 15-18 Feb, 2009.

[8] D. B. Hayman, T. S. Bird, K. P. Esselle, and P. J. Hall "Experimental Demonstration of Focal Plane Array Beamforming in a Prototype Radiotelescope" *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 6, JUNE 2010

[9] J.D. Bunton and S. G. Hay, Achievable field of view of chequerboard phased array feed. *International Conference on Electromagnetics in Advanced Applications (ICEAA)*, 2010.