Low Cost Low Noise Phased-Array Feeding Systems for SKA Pathfinders

J.G. Bij de Vaate, L. Bakker, E.E.M. Woestenburg, R.H. Witvers, G.W. Kant, W. van Cappellen
R&D
ASTRON
Dwingeloo, The Netherlands
vaate@astron.nl

***Abstract*—Developments in radio astronomy instrumentation drive the need for lower cost front-ends due to the large number of antennas and low noise amplifiers needed. This paper describes cost reduction techniques for the realization of antennas and low noise amplifiers in combination with a noise budget calculation for array systems in the absence of cryogenic cooling.**

Keywords-phased-array feed; low noise temperature; antenna; low noise amplifier; radio astronomy

I. INTRODUCTION

A paradigm shift is about to happen in next generation radio telescopes. Where most current antenna systems are based on large reflectors with a single or a small number of feeds, new telescopes will require phased-array solutions or phased-array feed solutions. This requirement is driven by the key science projects described in [1] for frequencies below 10GHz. Besides the requirement for a significantly improved sensitivity, larger patches of the sky need to be observed instantaneously. Enhancing the sensitivity with two orders of magnitude over existing telescopes can be achieved with the realization of a Square Kilometre Array (SKA) collecting area [2]. Enhancing the Field of View, 20 up to 200 square degrees at 1GHz, can only be achieved by processing more beams. This can be realized with a Phased Array Feed (PAF) in the focus of a reflector e.g. forming 25 beams. Or with a full phased array or Aperture Array (AA), where the number of beams only depends on the available processing power. ASTRON is currently working on a PAF system for the Westerbork telescope array, fourteen 25 meter dishes, called Aperture Tile in Focus (APERTIF) [3]. Further within the EU-SKA Design Study (SKADS) an AA 144m^2 prototype, Electronic Multi Beam Radio Astronomy Concept (EMBRACE) demonstrator will be realized [4].

II. ANTENNA DEVELOPMENT

The design of the SKA, either with aperture arrays or with phased-array feeds, drives the development of low cost, low loss and high bandwidth antennas. The tapered slot or Vivaldi antenna has been identified as a very good solution to achieve the large frequency bandwidth. The Vivaldi antenna realization can be done either in stripline, microstrip or with differential outputs.

This work has been supported by EU-FP6 SKADS , NL-NWO APERTIF and NL-IS-PACMAN. The antenna foil production has been sponsored by MECO Equipment Engineers B.V.

Low loss Printed Circuit Board (PCB) materials are expensive, in particular important for the AA systems, and therefore two alternatives have been evaluated to overcome this, one in full metal, and one on polyester foil (Figure 1).The aluminum antenna is laser cut, 1mm thick, and will slide in position in extrusion bars forming a dual polarization grid. A low loss microstrip Duroid PCB feeds the antenna. The total cost of the antenna and the feed board are approximately 2€ for the antenna and 2€ for the feed board in modest volume, significantly lower than a PCB antenna realization.

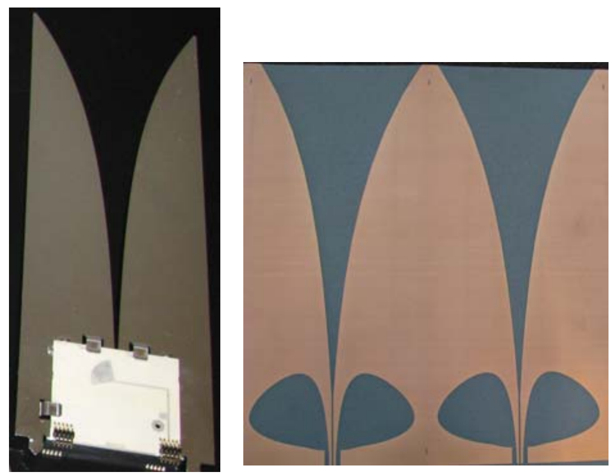

Figure 1 Aluminum antenna with duroid feed board (left) and Copper plated polyester foil antenna (right).

The feed board can be avoided if a full differential solution will be used by feeding the tapered slot differential signals directly into a differential Low Noise Amplifier (LNA). Besides the costs reduction a performance improvement is possible due to a) the absences of feed board signal loss and b) a bandwidth improvement by avoiding the bandwidth limitation of the balun/feed board. The differential solution has been realized on polyester foil. The foil has been produced in two steps, first a Silver ink layer has been screen printed on the foil and on this layer an electrolytic process grows a Copper layer. The conductive Silver ink layer is already a reasonably good conductor, less than 10 Ω/square, but the plated Copper further improves the conductivity to milliohms/square. Both the screen printing and the electrolytic plating are continues processes with production throughputs up to 100 meter foil per hour. For a dual polarized array the foil needs to be folded in zigzag fashion. In a proto-type Expanded Poly Styrene (EPS) foam blocks are used to keep the foil in position. And to provide conductivity between continues antenna rows, clips are used, connecting the top and bottom of the antenna. The production cost of the antenna is approximately 0.75 € per antenna. Including foam and clips a cost of less than 2 € per antenna can be achieved.

For the antenna design infinite by infinite array simulations have been used. For large AA systems this will be sufficiently accurate, however PAFs, with a typical size of 8x8 elements drive the need for efficient finite by finite array simulation tooling [5]. Both presented antenna concepts achieve a 3:1 bandwidth in the dense regime. In the sparse regime, with an antenna spacing larger than λ/2, anomalies and blind scan angles appear in visible range.

III. LNA DEVELOPMENT

Radio astronomy traditionally uses cryogenic cooling to 20 kelvin or lower in order to reduce the noise temperature of the Low Noise Amplifier (LNA). Although low cost (micro) cooling is under investigation [6] it is generally assumed that cryogenic cooling cannot be afforded for aperture array systems. And will be difficult to implement in phased array feed systems due to the physical distribution and the large number of LNAs . Still a low noise temperature is crucial.

A. Phased-Array Feeds

For APERTIF the target system temperature is set to 50K. One of the main contributors to the system temperature will be the LNA which has to operate in the 1GHz-1.75GHz frequency range. The first approach is to use discrete devices for the LNA. The reference impedance of the antenna is 50 Ohm. A total gain of ~40dB is required to make the noise contributions of consecutive stages small, requiring a 3 stages design. Because of the RFI environment in Westerbork, linearity of the LNA is of great importance. Major sources of RFI are TV transmitter signals around 500MHz and 800MHz. In order to reduce the linearity requirements on the second and third stage, high pass filtering is applied after the first stage. The first stage is designed around a commercial off the shelf Avago ATF54143 pHEMT. High pass input/output matching is applied. The second and third stages are Avago MGA 53543 linear amplifiers. Equalization is applied to achieve nearly flat gain across the band of interest. S-parameter measurements are given in Figure 2. Measured gain of ~42dB and a S11 better than –7.5dB across the entire band was achieved. OIP2 of the first stage is 40dBm and OIP3 of the first stage is 25dBm. The measured noise temperature in 50 Ohm is ~40K at 1.4 GHz. The noise curve is given in Figure 3. The noise curve is nearly flat across the band of interest. The amplifier has a measured noise resistance (R_n) value of 3 Ohm at 1.4 GHz with $|G_{opt}|$=0.084 <G_{opt}=-99.8º. This design is an improved version of the LNA of which 112 are currently installed in the operational APERTIF prototype. The S-parameters and noise of the currently installed version are also given in Figure 2 and Figure 3.

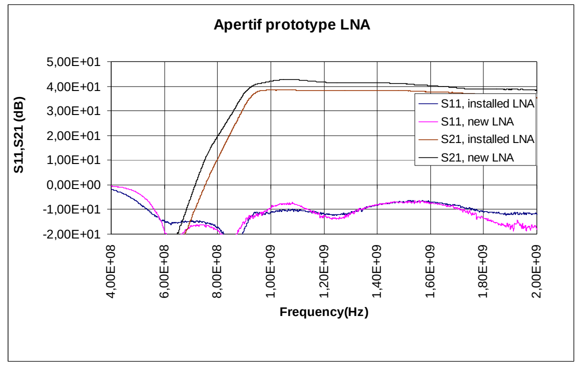

Figure 2 Measured S-parameters of the LNAs

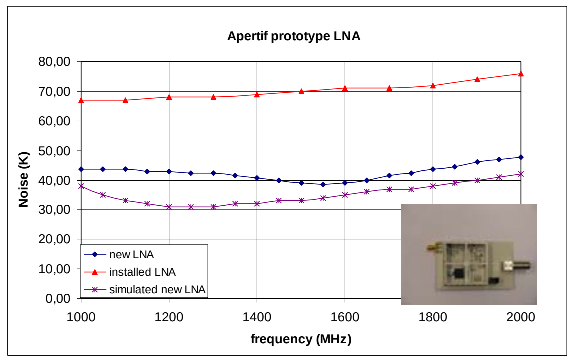

Figure 3 Measured and simulated noise. Inset: LNA currently installed in the telescope

B. Aperture Array

An aperture array SKA system with a frequency range of 300 – 1000MHz with a dense, smaller than λ/2, spacing will require between 10 and 30 million antenna elements. This drives the need for integration and low costs IC processing technology. The low cost processing however should not compromise the noise temperature of the system; every 5 kelvin degradation calls for a 10% increase in collecting area in order to maintain the required A_{eff}/T_{sys} sensitivity (for T_{sys}=40K). Recent CMOS LNA designs [7] indicate that low noise temperatures at these frequencies are possible with mainstream technology, however with a somewhat high noise resistance (see section IV). A low noise temperature and a low noise resistance have been pursued with a state of the art Metamorphic HEMT GaAs process with a 70nm gate length from OMMIC. This process features an f_T of 250 GHz and with T_{min} ~ f/f_T a very low noise temperature should be possible. And R_n ~ transistor gate width (to a first order) drives the need for a relatively large first transistor.

Figure 4 gives a chip photograph of a realized differential LNA in the 70nm mHEMT process. This design gives, in simulation, 20K noise temperature with 150 Ohm source impedance [8]. 150 Ohm was chosen to be the compromise between achievable antenna impedance and relatively easy transistor noise match. The measurement of a differential LNA with non-50 Ohm input impedance is however not trivial [9], 20K could only be demonstrated for parts of the frequency band at this point in time.

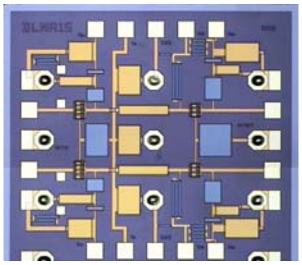

Figure 4 Photograph of differential LNA

IV. TSYS

A. Phased Array Feed System Noise Budget

The system noise temperature has several contributions. For the current operational system, 70K can be attributed to the installed LNA. Second stage contributions are ~5K. The antenna feed board and connectors between feed and LNA contribute an estimated additional 15K. The contribution due to noise coupling/mismatch is about 15K, spillover will contribute ~15K and sky noise an additional 3K. Accumulation of these contributions results in a system temperature of 123K. A central beam A_{eff}/T_{sys} measurement with the prototype PAF on an astronomical source resulted in 2.9, with weights set for maximum SNR. With a physical area of the dish of 490m^2, this would result in an efficiency of 73%. This is in line with expectation.

For the newly developed LNA we expect a 40K contribution due to the LNA. Second stage contributions are expected to reduce to 3K, because of a higher gain. The LNA will be integrated with a newly developed feed, reducing the contribution from feed and connector losses to an estimated 7K. The R_n value of the new LNA is improved compared to the currently installed version, reducing the noise coupling/mismatch contribution to 10K. Since the noise of the electronics is reduced significantly, the weights can be chosen such to reduce the spillover. This will likely reduce the spillover to <10K. A total system temperature of 73K is therefore expected.

For the final APERTIF system, the main improvement has to come from further reduction of the LNA noise contribution to 25K and some further improvement of R_n. To achieve the target 50K system temperature, the LNA even has to be reduced to 20K, while maintaining a low R_n value. This will be a challenging task. The noise contributors are summarized in Table 1.

	Current Prototype	New LNA	Final APERTIF
feed and connection loss	15	7	7
LNA + second stage (receiver)	75	43	28
Noise coupling/mismatch loss	15	10	7
Spillover	15	10	10
Sky noise	3	3	3
Total	**123**	**73**	**55**

Table 1: PAF noise contributions

B. Aperture Array System Noise Budget

The system noise budget of an AA system is in principle not different from the PAF, except for the spillover and coupling noise. A sufficiently large aperture array will not suffer from spillover noise. And in the case of a phased array feed each compound beam will have a constant noise coupling, whereas the noise coupling in the AA will vary with azimuth/elevation beam steering. The active reflection coefficient (Γ_{act}) determines the receiver noise temperature [10].

$$T_{receiver} = T_{\min} + \frac{4T_o R_n}{Z_o} \frac{\left|\Gamma_{act} - \Gamma_{opt}\right|^2}{\left|1 + \Gamma_{opt}\right|^2 \left(1 - \left|\Gamma_{act}\right|^2\right)} \quad \textbf{(1)}$$

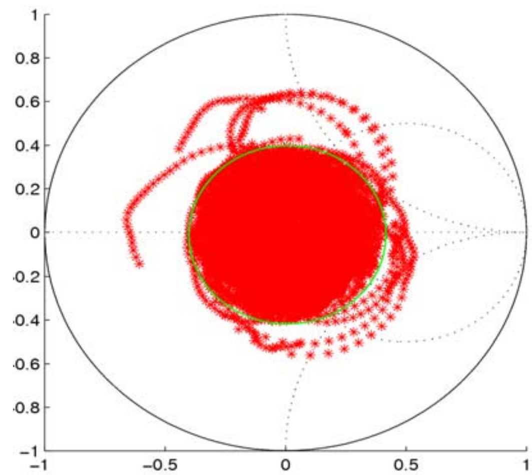

Figure 5 Measured active reflection coefficient of centre element of an 8 by 8 array for freq=0.5 – 1.5GHz and scan angle 0 – 45^o

Due to (1) and the active reflection coefficient variation for a typical Vivaldi array, plotted in Figure 5, the receiver noise temperature will vary over scan angle. A Γ_{opt} in the centre of the Smith chart and a R_n=2.5Ω will give a ΔT_{rec} of 6K.

	Current Prototype	Final AA (goal)
feed and connection loss	20	10
LNA + second stage (receiver)	60	16
Noise coupling/mismatch loss	10	6
Spillover	0	0
Sky noise	8	8
Total	**98**	**40**

Table 2 AA noise contributions

In Table 2 the noise contributions for AA systems are summarized (valid for 0.5-1 GHz) [11]. The target for the 10K better LNA as compared to the PAF LNA is justified with, a) lower frequency and b) a full system realization in 2020 whereas the APERTIF system will be operational in 2011. In any case achieving the projected AA T_{sys} will require significant research.

V. CONCLUSIONS

Low cost low noise feeding systems have been discussed for phased array feeds and aperture arrays. Developments for two SKA pathfinder systems indicate that room temperature wide band feeding systems achieving system noise temperatures of around 50 kelvin will be possible with careful design. Further research will be required to lower this to 35 or 40 kelvin.

REFERENCES

[1] C. Carilli, S. Rawlings, "Science with the Square Kilometre Array", New Astronomy Reviews, Vol. 48, Elsevier, December 2004

[2] R. Schillizi et.al., "Preliminary Specifications for the Square Kilometre Array", memo100, Dec. 2007, www.skatelescope.org

[3] W.A. van Cappellen, J.G. Bij de Vaate, M.V. Ivashina, L. Bakker and T. Oosterloo, "Focal Plane Arrays Evolve", URSI General Assembly, Chicago, Illinois, USA, August 7-16, 2008

[4] P.D. Patel, G.W. Kant, E. van de Wal, A. Ardenne, "Towards Completion of Aperture Array Developments –EMBRACE Update", URSI-General Assembly, Chicago, August 2008

[5] R. Maaskant, R. Mittra, A. Tijhuis, "Fast Solution of Large-Scale Antenna Problems Using the Characteristic Basis Function Method and the Adaptive Cross Approximation Algorithm", IEEE Trans. Antennas and Propag., Vol. 56, No. 11, November 2008

[6] F. Schreuder, J.G. Bij de Vaate, "Localized LNA Cooling in Vacuum", THERMINIC workshop, Nice, France, September 2006

[7] L. Belostotski, J.W. Haslett, "Sub-0.2dB Noise Figure Wideband Room-Temperature CMOS LNA With Non-50 Ω Signal-Source Impedance", IEEE Journal of Solid-State Circuits, Vol 42, Issue 11, pg 2492-2502, Nov. 2007

[8] J. Morawietz, R.H. Witvers, J.G. Bij de Vaate, E.E.M. Woestenburg, "Noise Characterization of Ultra Low noise Differential Amplifiers for Next Generation Radiotelescopes" European Microwave Conference Munchen, Germany, Oct. 2007

[9] L. Belostotski, J.W. Haslett, "A Technique for Differential Noise Figure Measurment of Differential LNAs, IEEE Transactions on Instrumentation and Measurement, Volume 57, Issue 7, pg 1298-1303, July 2008

[10] R. Maaskant, E.E.M. Woestenburg, "Applying the Active Impedance to Achieve Noise Match in Receiving Array Antennas", IEEE Antennas and Propagation International Symposium, pg 5889-5892, Hawaii, June 2007

[11] E.E.M. Woestenburg, J.C. Kuenen, "Low Noise Performance Perspectives of Wideband Aperture Phased Arrays", The Square Kilometre Array: An Engineering Perspective, Experimental Astronomy, Vol .17, Nos. 1-3, pg89-99, 2004