Widefield Science and Technology for the SKA
SKADS Conference 2009
S.A. Torchinsky, A. van Ardenne, T. van den Brink-Havinga, A.J.J. van Es, A.J. Faulkner (eds.)
4-6 November 2009, Château de Limelette, Belgium

Active Antenna Design and Characterization

J.G. Bij de Vaate, L. Bakker, R. Witvers

Netherlands Institute for Radio Astronomy (ASTRON), P.O.Box 2, 7990 AA, Dwingeloo, The Netherlands
vaate@astron.nl

Abstract. System noise temperatures issues of antenna arrays are analyzed and improvements proposed. A test facility has been designed for the noise measurement of active antenna arrays: arrays with a high level of antenna and low noise amplifier integration.

1. Introduction

The Aperture Array (AA) as well as the Phased Array Feed (PAF) concepts for the realization of the Square Kilometre Array are both likely to rely on room temperature Low Noise Amplifiers (LNA) as the first active stage due to cost and design practicalities. Cryogenic cooling of the very large number of LNAs is not only expensive but will also impact the energy consumption and the weight of the system in the focus box (for PAFs). With the obvious drawback of the higher noise temperature at higher ambient temperature of the active device comes also a significant advantage: the LNA can be made physical very small and can be placed very close or even on the antenna, reducing interconnection losses. Furthermore the antenna impedance can be designed to match the optimal noise source of the LNA or vice versa. In this paper we define this as an *active antenna*: the antenna and the LNA *cannot* be separated at a fixed impedance interface, e.g. 50 Ω.

Not using an industrial accepted interface impedance is at the same time a disadvantage of the active antenna approach. Characterizing the antenna is still straightforward; however LNA noise figures cannot be measured directly with a classical noise figure meter. The importance of LNA and active antenna characterization has been recognized and attention has been paid to:

- Transistor and LNA noise parameters for which a tuner set-up has been installed.
- LNA characterization for which nitrogen cryogenic loads have been used for the measurements of differential LNAs.
- The measurements of active antennas. A large outdoor hot cold test facility has been build where antenna arrays up to 1,5x1,5m can be analyzed.

Figure 1 gives an example of an active antenna, in this case a Vivaldi realized on polyester foil, see Arts (2008), and a differential LNA, in this case a 70nm mHEMT monolithic microwave integrated circuit. The interface impedance, between antenna and LNAs is 150 Ω.

Based on the work above a roadmap has been derived for the achievable aperture array and phased array feed system noise temperature.

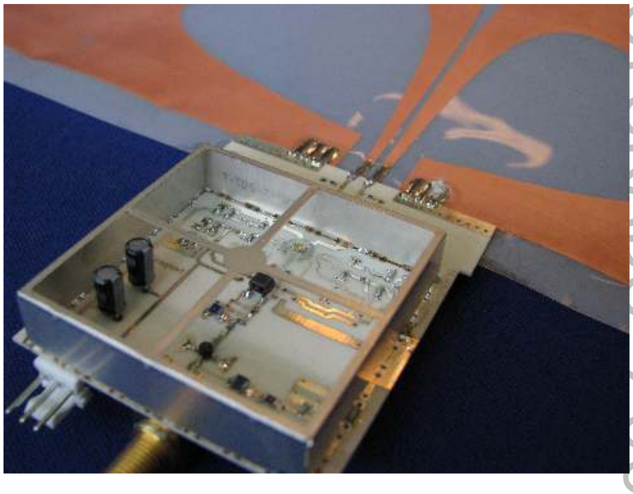

Fig. 1: Differential active antenna prototype

2. Technology Assessment

Low Noise Amplifiers for radio astronomy in existing systems are without exception based on III/V technology transistors, either Gallium Arsenide (GaAs) or Indium Phosphide (InP). These technologies offered the lowest noise temperatures and other performance criteria like cost, power consumption, linearity and integration density are not critical for traditional system. This is very different for the SKA Aperture Arrays. With ~ 10^8 LNAs cost and power consumption are crucial parameters as well. Furthermore, improvements in Silicon technology, driven by computer and telecom industry, offer aspects of interest for radio astronomy not only for the digital processing but also for the analogue building blocks. For the transistors we can distinguish three relevant variants for the LNA: 1) the High Electron Mobility Transistor (HEMT) in GaAs or InP, 2) the Silicon Germanium Hetero Bipolar Transistor (SiGe HBT) in Silicon and 3) the Complementary Metal-Oxide-Semiconductor Field Effect Transistor (CMOS FET) in Silicon. The minimum noise temperature, where the source impedance is equal to the optimal noise impedance, of HEMTs has been analyzed in detail by Pospieszalsky (1989). An approximation, relevant in radio astronomy receivers, for HEMTs is

$$T_{min} = 2\frac{f}{f_T}\sqrt{\frac{r_{gs}T_g}{g_{ds}T_d}}. \tag{1}$$

Where the noise properties of the intrinsic FET are represented by equivalent temperatures: T_g of r_{gs}, T_d of g_{ds} and $f_T = g_m/2\pi C_{gs}$.

The R_n, the sensitivity to noise mismatch, is given by:

$$R_n = \frac{T_g}{T_0}r_{gs} + \frac{T_d}{T_0}\frac{g_{ds}}{g_m^2}\left(1 + \omega^2 C_{gs}^2 r_{gs}^2\right). \tag{2}$$

Bardin (2009) analyzed the minimum noise temperatures for Silicon Germanium transistors, given by

$$T_{min} \approx T_a\eta_c\sqrt{\frac{1}{\beta_{DC}}\left(1 + 2\frac{g_m(r_b + r_e)}{\eta_c}\right) + 2\frac{g_m(r_b + r_e)}{\eta_c}\left(\frac{f}{f_T}\right)^2} \tag{3}$$

And for the R_n:

$$R_n \approx \frac{\eta_c}{2g_m}\frac{T_a}{T_0}\left[1 + 2\frac{g_m(r_b + r_e)}{\eta_c}\right] \tag{4}$$

Where the $\eta_c = I_C/g_m V_T$

According to Woerlee (2001), the T_{min} of a CMOS transistor can be approximated by

$$T_{min} = \frac{K}{T_0}\frac{f}{f_T}\sqrt{g_m(R_g + R_i + R_s)} \tag{5}$$

Where g_m is the transconductance, R_g is the gate resistance, R_i the real part of the input impedance and R_s the source resistance.

From the equations for HEMTs and CMOS FETs it can be easily seen that the T_{min} is directly dependent on f/f_T. Since AAs and PAFs are expected to operate at frequencies below 2GHz, this ratio is already small and benefits from the increase in f_T due to the smaller gate lengths (reduced C_{gs}) of new processes. Sub 100nm gate length processes, both in GaAs and in Silicon, demonstrated minimum noise temperatures below 10 kelvin at room temperature, Belostotski (2007) and this paper in the next section.

The T_{min} of SiGe transistors (3) also benefits from f/f_T, however for a high f_T, small base (r_b) and emitter (r_e) resistances one factor limits further reduction. In that case (3) can be simplified to T_{min}= $T_a/\sqrt{(\beta_{DC})}$. Only high β_{DC} processes can give very low T_{min} transistors, which is an additional constraint on the possible use of SiGe transistors.

For the R_n, given above in (2) for HEMTs and in (4) for BJTs, it is clear that both benefit from a large g_m, demanding large transistors, with the expense of power consumption.

3. Noise parameter measurements

For transistor characterization and system modeling it is important to know the full noise parameter set (T_{min}, Γ_{opt}, R_n). In order to measure these parameters a commercial noise parameter setup was recently acquired. The setup consists of a Maury tuner, a noise source and an Agilent PNA-X (Figure 2). The Maury software can determine all noise parameters with both a hot/cold and a cold only measurement. Furthermore different algorithms can be applied to determine the noise parameters. The measurement results are very repeatable. With this setup several packaged transistors were measured; the Avago ATF-34143 and ATF-54143 and a new OMMIC CGY-2106XHV 130nm GaAs transistor. All transistors were measured in one set of measurements where the same calibration was used. The preliminary measurement results are given in Figure 3. The OMMIC transistor seems to have a ˜5K better T_{min} compared with the ATF54143 currently used for the Apertif LNA (Bakker, 2009). More transistors will be evaluated in the near future, including bare transistor ones. Some future work on the tuner setup includes using a Liquid Nitrogen load, writing own tuner software and some error analysis. Also some further analysis is required to understand the variations in the T_{min} measurements.

Fig. 2: Photograph of the noise parameter test set-up

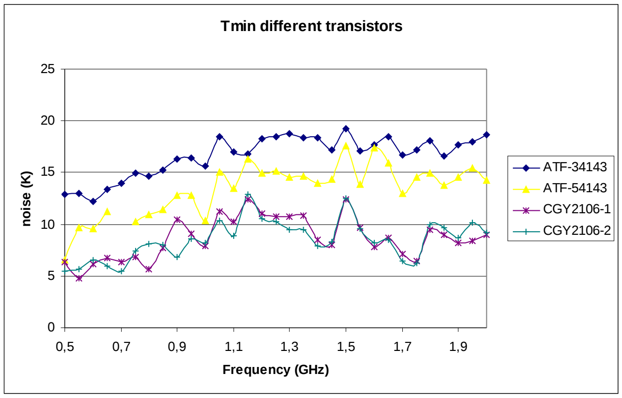

Fig. 3: Measured minimum noise temperatures

Table 1: Tsys contributions AAs at 1 GHz

	Current Prototype	Final AA (goal)
feed and connection loss	20	10
LNA + second stage (receiver)	65	18
Noise coupling/mismatch loss	10	8
Spillover	0	0
Sky noise	4	4
Total	**99**	**40**

4. Active Antenna Noise Temperature

Various aperture array and phased array feed prototypes have been realized, with the following system temperatures: THEA in Bij de Vaate (2002) gave 170K, EMBRACE in Kant (2010) gives ˜100K and APERTIF, a PAF system, in Bakker (2010) gives 78K starting with 123 in the first iteration. Figure 4 plots these results including projections for these systems based on the following for AAs:

- Second stage loss can be reduced significantly when more front-end gain can be applied. This is only possible at a low RFI site, clearly one of the requirements of a SKA site.
- Feed loss can be reduced by bringing the LNA closer to the antenna.
- LNA noise temperature will improve with new sub-10 kelvin transistors.

Table 1 gives the components of the AA system temperature. The noise coupling in this table is specific for array antennas and deals with the correlated coupled noise to adjacent antennas which gives a beam steering dependent noise contribution, see Maaskant (2007). Improvements on PAFs are possible with an improved LNA, reduced spill-over and reduced feed loss. More LNA results can be found in Bhaumik (2010) and Garcia (2010).

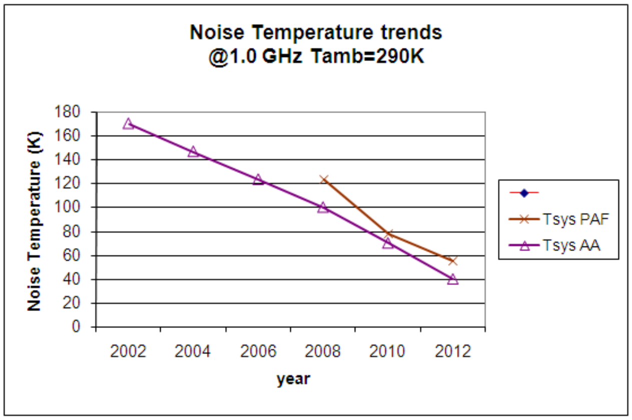

Fig. 4: System noise temperatures trends

5. Active Antenna Characterization

The sensitivity of an astronomical receptor can be determined with terrestrial or extraterrestrial sources as a measure for effective collecting area divided by the system noise temperature: A_{eff}/T_{sys}. A direct measurement of T_{sys} is normally not possible and can only be derived from careful modeling of the antenna effective area. And vice versa: the effective area can be derived if the system noise temperature is carefully modeled. To overcome this issue a hot/cold antenna measurement facility has been designed and constructed. The facility is in particular important when the elements of the active antenna, the antenna and the LNA cannot be measured directly, e.g. when a differential antenna is directly coupled to a differential LNA or when interface impedance levels are non 50 Ω. Furthermore the influence of noise coupling can be measured when a full array is tested rather than individual elements.

Figure 5 gives a photograph of the realized facility. The hot noise source consist of a roof cover with RF absorbing material which functions as an 'outdoor temperature' noise source applied to the full aperture of the antenna. The sky functions as the cold load when the cover is rolled away. Removing the cover is in principle sufficient however in order to avoid noise pick-up from the ground and from nearby objects, a metal shielding has been designed. Simulations at 500MHz, considered to be the worst case frequency, showed that the noise picked up from the ground and potential nearby trees is limited to 5K for an isotropic radiator. Details of the analyses can be found in Enthoven (2007).

Fig. 5: Photograph of the realized hot cold test facility

The hot-cold active antenna results of an APERTIF prototype are given in Figure 6. Position 1 and 2 are two different positions in the facility. The frequency plot clearly shows the RFI from mobile communications, a local radar transmitter and broadcasting stations. The measured noise temperature in the 'quiet' bands is very close to the simulations.

6. Conclusions

The viability of the SKA strongly depends on the achievable noise temperature, which is a direct measure of the cost of the system when a specified A_{eff}/T_{sys} needs to be achieved.

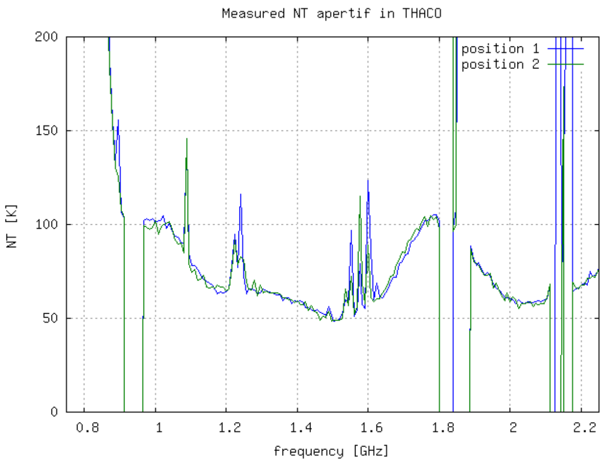

Fig. 6: PAF prototype noise temperature measurement

Based on the analyses in this and cited papers 40 kelvin system noise temperature for an aperture array with room temperature LNAs is shown to be feasible. But in order to achieve this, specific design effort with new transistor processes in a combination with antenna simulations is needed. The proposed test facility will support the development with direct active antenna measurements.

References

Bakker, L., van Cappellen, W., "Phased Array Feeds on dishes: system design, subsystem design and experimental results," 2010, in *Proc. Wide Field Science and Technology for the SKA*, Limelette, Belgium, S.A. Torchinsky et al. (eds), ASTRON, ISBN 978-90-805434-5-4

Bij de Vaate, J.G., Kant, G.W., 2002, "The Phased Array Approach to SKA, Results of a Demonstrator Project," IEEE European Microwave Conference, Milan, Italy

Bij de Vaate, J.G., Bakker, L., Woestenburg, E.E.M., Witvers, R.H., Kant, G.W., van Cappellen, W., 2009, Symposium on Antenna Technology and Applied Electromagnetics and the Canadian Radio Science Meeting, ANTEM/URSI

Bardin, J.C. 2009, "Silicon-Germanium Heterojunction Bipolar Transistors For Extremely Low-Noise Applications," PhD Thesis (Caltech, Los Angeles)

Bhaumik, S., George, D., "Review of Square Kilometre Array LNA technologies and topologies," 2010, in *Proc. Wide Field Science and Technology for the SKA*, Limelette, Belgium, S.A. Torchinsky et al. (eds), ASTRON, ISBN 978-90-805434-5-4

Belostotski, L., Haslett, J.W., 2007, "Sub-0.2dB Noise Figure Wideband Room-Teperature CMOS LNA With Non-50 Signal-Source Impedance," IEEE Journal of Solid State Circuits, Vol. 42, No. 11

Enthoven, B.C., Maaskant, 2007, R., "Design of a Hot-Cold Test Facility," SKA-ASTRON-RP-397, ASTRON memo

Garcia-Perez, O., et al., "FIDA3: A Novel Active Array for the Mid-SKA," 2010, in *Proc. Wide Field Science and Technology for the SKA*, Limelette, Belgium, S.A. Torchinsky et al. (eds), ASTRON, ISBN 978-90-805434-5-4

Maaskant, R., Woestenburg, E.E.M., 2007, "Applying the Active Impedance to Achieve Noise Match in Receiving Array Antennas," IEEE Antennas and Propagations International Symposium, Hawaii

Kant, G.W., van der Wal, E., Ruiter, M., Benthem, P., "EMBRACE System Design and Realisation," 2010, in *Proc. Wide Field Science and Technology for the SKA*, Limelette, Belgium, S.A. Torchinsky et al. (eds), ASTRON, ISBN 978-90-805434-5-4

Pospieszalski, M.W., 1989, "Modeling of Noise Parameters of MESFETs and MODFETs and Their Frequency and Temperature Dependence," IEEE Transactions on Microwave Theory and Techniques, Vol. 37, No. 9