Technology Issues for Square Kilometre Array Receiver Design

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***Abstract*—The acquisition of low-cost, low-noise, broadband receivers will be central to the success of the Square Kilometre Array (SKA), a radio telescope array aimed at probing the early universe between 0.2 GHz and 20 GHz. These receivers will most likely be integrated closely with feed assemblies and may support optical fibre interfaces. They must also be able to operate linearly in the presence of man-made interference. Here the challenge presented by a cost limited SKA is traced through to its implications on receiver design. The state of the art of relevant technologies is reviewed and possible future directions for the newly formed Australian SKA Working Group on Integrated RF Systems are presented.**

***Index Terms*—SKA, Radio Astronomy, RF Systems, Receiver Design, SoC, MMIC, RF-IC, Optoelectronics, LNAs, GaAs, SiGe, InP.**

I. INTRODUCTION

THE Australian Square Kilometre Array (SKA) Consortium has set up a working group on Integrated RF Systems to investigate enabling technologies for SKA receivers [1]. This paper explores the requirements of these receivers and identifies possible research directions that will lead to their fulfilment.

First, a general background of the SKA program and its goals is given. Second, the sensitivity of radio telescope systems, the prime specification for the SKA, is defined and discussed. Third, a first-pass attempt is made at modelling the requirements for SKA receivers. Fourth, a number of key issues, not immediately obvious in the model, are discussed. Finally, the state of the art of relevant technologies is reviewed and possible future research directions are suggested.

II. SKA BACKGROUND

A consortium of scientists and engineers representing eleven nations are working to bring the Square Kilometre Array into existence [1], [2], [3], [4]. It will have an effective collecting area of one square kilometre and may be spread over a continent (Fig. 1). When complete, it will be two orders of magnitude more sensitive than the best radio telescopes of today.

This quest for sensitivity is driven by humankind's desire to learn about the early Universe. To discern the events of a few billion years ago, astronomers need only point their telescopes toward the nearer quasars, a few billion light-years away. The finite speed of light presents humankind with a universal history book whose pages may be perused at leisure on any starry night. However, to discern the events of 10 or 20 billion years ago in the Universe's childhood, astronomers must look so far away that the radiation cannot even be detected with the world's most sensitive telescopes. Knowledge of the early universe is limited. The details of when and how the first stars and galaxies formed remain a mystery that cannot be solved without a very sensitive telescope such as the SKA.

Fig. 1. A possible layout of the SKA across Australia showing 300 stations connected by optimised cabling [39]. For this realisation, each station would be in the order of 250m in diameter.

III. TELESCOPE SENSITIVITY

The sensitivity of a radio telescope is a measure of the power density of the weakest radio source that it can detect. The sensitivity of the World's premiere radio telescope array, the Very Large Array (VLA) shown in Fig. 2, ranges from 7 to 48 micro Janskys (see definition below) per beam depending on frequency [5]. For comparison, the SKA aims to achieve sensitivities in the tens of nano Janskys per beam [6].

A. Astronomical Radio Sources

Radio astronomers measure the strength of radio sources in Janskys (Jy) where

$$1\,\mathrm{Jy} = 10^{-26}\,\mathrm{W.m^{-2}.Hz^{-1}}.$$

The choice of such a small unit reflects the relative weakness of astronomical radio sources. For example, an SKA receiver, with 10 GHz bandwidth, connected to a square kilometre of collecting area pointed at a 1 Jy radio source would receive only 10^{-10} W. At this power level, the energy would have to be collected and stored for a little over three thousand years until there was sufficient to power a 100 W light bulb for a second.

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Fig. 2. The Very Large Array (VLA) in Socorro, New Mexico. *Photograph by Dave Finley, courtesy National Radio Astronomy Observatory and Associated Universities, Inc. Available: http://www.aoc.nrao.edu/intro/vlapix/vlaviews.index.html*

B. Noise Sources in Radio Telescope Systems

As astronomical radio signals are weak, several sources of noise have a measurable effect on the sensitivity of a radio telescope. Common sources of noise in radio telescope systems include the receiving equipment itself; injected calibration signals; losses in the feed inputs and waveguides; ground radiation scattering into the feeds; atmospheric emission; and the microwave and Galactic background radiation [5].

Each source of noise power P_s may be modelled as an equivalent thermal noise source, and characterised with an *equivalent noise temperature* T_e [7]. Alternatively, each noise source may be characterised by its *noise figure*. Noise figure is a measure of the degradation in the signal-to-noise ratio between the input and output of a component. In radio astronomy systems it is difficult to define signal-to-noise ratio, as the desired signal is actually the noise power received by an antenna. Thus equivalent noise temperature is more commonly used in the analysis of radio astronomy systems.

It is convenient to quote an equivalent system temperature, T_{sys}, which represents the total noise power present in a given system. For the common sources of noise encountered in a radio telescope mentioned earlier

$$T_{sys} = T_{rx} + T_{cal} + T_{loss} + T_{spill} + T_{sky} + T_{bg}$$

where

T_{rx} = the receiver noise temperature;
T_{cal} = the noise contribution due to injected calibration signals;
T_{loss} = the noise contribution due to losses in the feed and input waveguide;
T_{spill} = the noise contribution due to the Earth's blackbody radiation scattering into the feed;
T_{sky} = the noise contribution from atmospheric emission; and
T_{bg} = the noise contribution from the microwave and Galactic backgrounds.

System temperature is often defined to include the noise contribution from the radio source under observation, T_a, in addition to the above components. In most practical situations, and in this work, this point is not important as $T_a << T_{sys}$. Fig. 3 plots the system temperature of the VLA, along with a breakdown into each of its components, based on values reported in [5]. A brief inspection reveals that the receiver itself is the dominant noise source, contributing between 50 and 70 percent of the system temperature depending on frequency.

C. A Measure of Sensitivity

The sensitivity of a single antenna radio telescope is defined by the smallest flux that it can detect. Detailed expressions for the limiting flux sensitivity of a single antenna telescope to a point source, ΔS, are derived in [8], [9] and [10]. These expressions often include a number of system specific factors. Seeking a general pattern useful in system design, one finds that the proportionality

$$\Delta S \propto \frac{T_{sys}}{A_e \sqrt{B\tau}}$$

holds for all configurations. Here A_e is the effective collecting area of the antenna, B is the bandwidth of the system and τ is the time over which the observation is averaged or integrated. By inspection, the numerator is representative of the unwanted noise power generated internally by the system. The denominator is representative of the desired noise power received by the antenna.

A more appropriate measure of sensitivity for antenna arrays, which are often used to image a source rather than probe it at a single point, is the r.m.s. error in a synthesised image, ΔI_m. Crane & Napier derive ΔI_m for an array of N antennas in [5]. For large N it is found that ΔI_m approaches the limiting flux sensitivity of a single antenna of equivalent effective collecting area. It follows that the proportionality for ΔS above will also hold for ΔI_m when N is large and A_e is taken to be the effective collecting area of the entire array (i.e. the sum of the effective collecting areas of each individual antenna).

Thus, for a given bandwidth and duration of observation, T_{sys}/A_e is a measure of the smallest detectable radio source for both single and many antenna telescope systems [8]. This may be inverted to give A_e/T_{sys}, a more intuitive metric that increases with improved sensitivity.

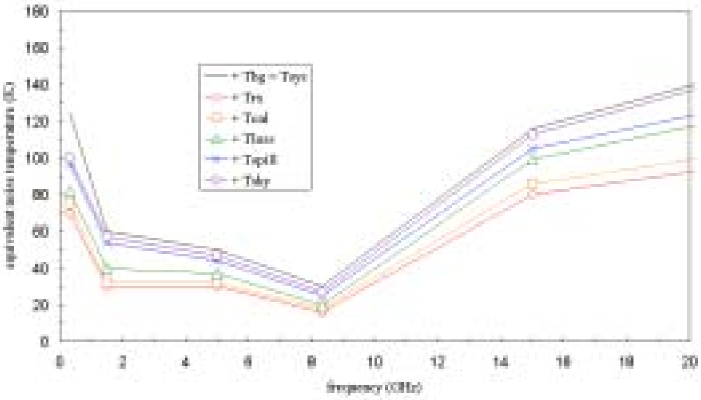

Fig. 3. The system temperature of the VLA (circa 1989) showing T_{sys} as a function of frequency and as an accumulation of its components. Plotted from data in [5].

D. *Attacking Sensitivity Through Area*

It follows from the use of A_e/T_{sys} as a measure of sensitivity that one may increase the sensitivity of a radio telescope system by reducing its receiver noise temperature or by increasing its effective collecting area.

The first avenue has been pursued almost to its end at centimetre wavelengths. There is no more to be gained by solely reducing the system temperatures of today's radio telescopes. To achieve a reasonable increase in sensitivity there is naught to do but build a bigger radio telescope. Enter the SKA.

E. *Implications for SKA Receivers*

Even though the superior sensitivity of the SKA is achieved through its area, vigilance placed on T_{sys} may not be relaxed. There is a delicate tradeoff between the cost of building more antennas and the cost of lowering the noise temperature of radio receivers that must be explored for each telescope system design. The SKA explores a totally new domain of this tradeoff so special care must be taken in evaluating the different technologies proposed for the receivers and the antennas.

The science case for the SKA requests an A_e/T_{sys} of 2×10^4 at a frequency of 1.4 GHz and frequency coverage from 0.2 GHz to 20 GHz [6]. In order to investigate the implications of these requirements on SKA receiver design, let us construct a hypothetical and somewhat simplified model of the SKA.

Let this instrument consist of one square kilometre of effective collecting area at 1.4 GHz, all constructed from identical antennas. Let each antenna be fixed with a single feed and a single receiver such that the array's effective area varies as the inverse square of frequency as explained in [11]. Let the instrument be situated at sea level, pointing at the zenith and away from the Galactic plane. Let the air pressure be 1013 hPa and the relative humidity be 20%. Model the noise temperature contributions to T_{sys} arising from these parameters and estimate the rest, except for T_{rx}, by interpolating the contributions to the VLA's T_{sys} given in [5] and shown in Fig. 2.

This represents a somewhat crude model of the SKA, leaving the noise performance of its receivers as a free parameter. At 1.4 GHz, the assumed effective area of one square kilometre may be used to invert the A_e/T_{sys} requirement of 2×10^4 and arrive at a required T_{sys} of 50 K. From this may be subtracted all noise temperature contributions, except that of the receivers, as predicted by the model introduced above. This results in an upper limit for SKA receiver noise temperature of 19 K at 1.4 GHz.

A similar upper limit may then be calculated for other frequencies by scaling the assumed effective area by the inverse square of frequency and repeating the model calculations. Thus, upper limits of T_{rx} for a given A_e/T_{sys} may be plotted against frequency as in Fig. 4. Projected equivalent noise temperatures for gallium arsenide (GaAs) and cooled indium phosphide (InP) low noise amplifiers (LNAs) are also plotted in Fig. 4, giving a lower limit to achievable T_{rx} for a given technology. A receiver technology whose noise temperature is below the solid A_e/T_{sys} = 2×10^4 curve at 1.4 GHz meets the SKA science case requirement according to the given model. The sensitivity achievable at other frequencies with the same technology may be estimated by comparing it to the receiver noise temperature contours calculated for other values of A_e/T_{sys}.

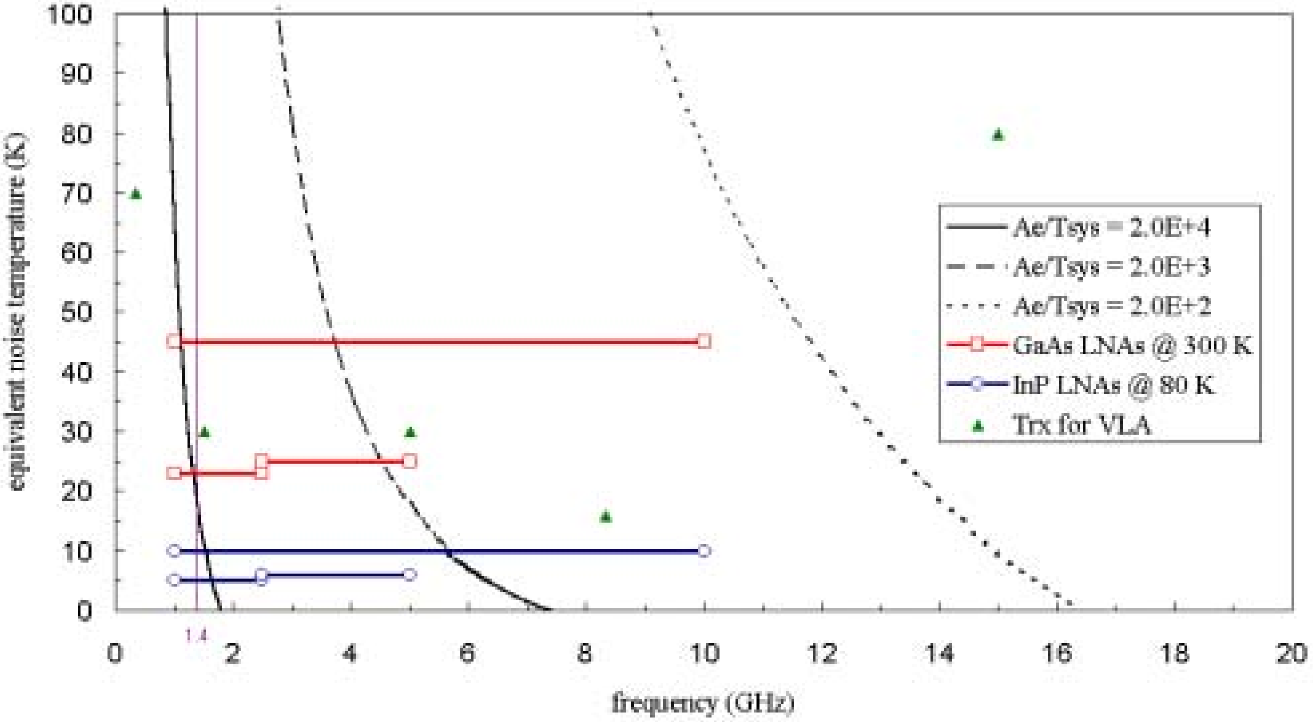

Fig. 4. Upper limits on SKA receiver noise temperature for three values of A_e/T_{sys}, plotted alongside representative receiver performance for three technologies: GaAs LNAs at 300 K, InP LNAs at 80K and the VLA's receivers circa 1989. The limiting receiver noise temperature contours are specific to observations made away from the plane of our Galaxy. The SKA was assumed to have a collecting area of one square kilometer, be constructed from a single type of antenna, and have a single type of feed and receiver optimised to match the given value of A_e/T_{sys} at 1.4 GHz; the Galactic background emission was modelled according to [38]; atmospheric emission was calculated using Miriad [12] for sea level assuming a temperature of 300 K, 20% relative humidity, and observation towards the zenith; other contributions to Tsys were interpolated from VLA data in [5]; VLA receiver performance was also taken from [5]; and LNA performance predictions for GaAs and cooled InP were taken from [23].

Referring to Fig. 4 shows that cooled InP LNAs satisfy the 1.4 GHz science case requirement for this SKA model, and that uncooled GaAs LNAs come very close. However, this model is quite specific and probably only applicable to designs employing concentrators (i.e. reflectors or lenses).

Finding a technology solution for SKA receivers is more complex when cost, alternative antenna technologies, and an unfixed collecting area are considered. Increasing the area of the array would lift the limiting receiver noise temperature contours, allowing the use of cheaper receivers with higher noise temperatures. Applying different antennas and/or feeds at different frequencies would enable the limiting receiver noise contours to be flattened with regard to frequency. In order to optimise the SKA, and hence its receivers, more data must be collected on the cost and performance of each proposed technology. This is currently being attempted through the construction of SKA demonstrators in Australia [1] [13] [14], the U.S.A. [15], the Netherlands [16], Canada [17] and China [18].

IV. SKA RECEIVER TECHNOLOGY ISSUES

As mentioned in § III.B., the receiver noise temperature can constitute between 50 and 70 percent of the overall system temperature in a contemporary radio telescope system. Receiver noise temperature, in turn, is mainly determined by the noise temperature of the first one or two amplification stages of a receiver's frontend [9]. One of the major issues for SKA receiver design will thus be the minimisation of the noise figure of its LNAs. However, there are a number of more subtle issues to address on the road to minimised noise figure and thus maximised sensitivity for a given collecting area and cost.

A. Which Semiconductor Process Should be Used?

Presently there are a handful of semiconductor processes suitable for application in the SKA frontend. Each comes with a variety of advantages and disadvantages that must be weighed against its cost. The costs of the various technologies vary over three orders of magnitude (Fig. 5) and their properties vary to a similar degree, leaving no obvious winning technology.

A qualitative assessment by De Vaate [20] suggested that silicon germanium (SiGe) has the most potential of meeting the performance and cost requirements of the SKA. It boasts noise figures competitive with GaAs and low power consumption, all at a third of the cost of GaAs or 5 percent of the cost of InP. The Dutch SKA collaborators have been pursuing SiGe solutions for their phased array SKA prototypes that require a relatively high number of frontends for a given collecting area [16].

American collaborators have opted to employ InP monolithic microwave integrated circuits (MMICs) in their paraboloid based SKA prototype, the Allen Telescope Array [15], [21]. The ATA LNA MMIC achieves a noise temperature of 23 K [22]. InP still yields premium noise performance for all semiconductor technologies, albeit for a premium price.

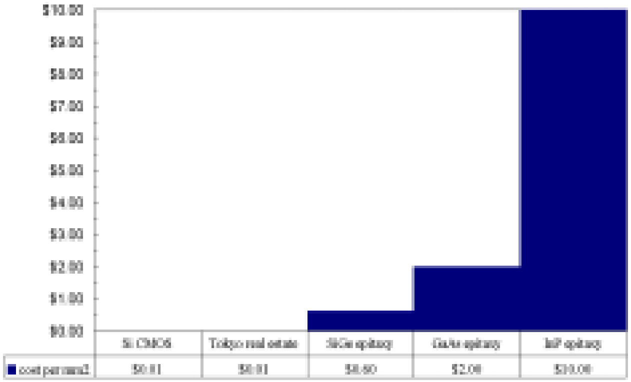

Fig. 5. A cost comparison of semiconductor technologies. Data from [19].

B. Should There be a Single Frontend for the Whole SKA Band?

The noise figure of an LNA may be traded for added bandwidth. One extreme would be to have a single SKA frontend with an LNA that covered the entire SKA frequency specification, from 0.2 to 20 GHz. Having a single frontend covering all frequencies would be cheaper and make for simpler system connections. On the down side, designing a broadband feed to cover the entire frequency range would be rather complicated.

The American SKA collaborators are pursuing the single frontend path and have designed a 0.5 to 11 GHz LNA for the Allen Telescope Array [22]. They have also explored the receiver noise temperature/bandwidth trade-off, simulating LNAs optimised for various bandwidths [23].

C. To What Degree Will the SKA Receiver Benefit from Integration?

The receivers for the SKA could be realised as custom-made MMICs. Alternatively, they could be constructed from commercial off-the-shelf products, such as the LNAs and discrete low noise transistors developed for the wireless communications industry.

Application specific MMICs yield high bandwidth, high performance and highly integrated designs. Most SKA collaborators have been researching the path of custom MMICs and thus many advances have been made in circuit topology, cooling, biasing and packaging arrangements in the radio astronomy context. It is possible that, in the future, the entire receiver frontend may be integrated into a single IC and mounted directly on an antenna.

However, with the SKA achieving its sensitivity predominantly through area increase, the application of commercially available discrete components should not be ruled out.

D. Should the SKA's Receivers be Cooled?

Cooling a receiver reduces the thermal noise it generates and thus improves its noise temperature. However, the cost-benefit function for cooling receivers has not been fully explored in the domain relevant to the SKA. For the SKA, cooling devices must be cheaper and more reliable than those currently used in radio astronomy receivers. It is likely that cooling will only be feasible for SKA designs using concentrator antennas.

V. STATE OF THE ART

Following is a summary of international and Australian research that is relevant to the design of receivers for the SKA.

A. International

1) Investigation of Silicon Processes: The philosophy of high integration levels, high-density packaging and low cost materials has been explored [20]. It was concluded that an improved SiGe process is the most likely process candidate for a single chip front-end for performance and cost reasons. A thorough assessment of the possibilities and the developments in the silicon processes was recommended.

The shortcomings of conventional silicon technology in the integrability of RF functions at high GHz frequencies have been explored [24]. Silicon micromachining techniques have been proposed as potential solutions to the integration of RF passives and to reduce substrate losses and cross-talk on silicon.

2) *Receiver System Design:* Conceptual designs of the analogue receiver for an SKA based on phased array technology have been produced [25]. In the process, a spreadsheet based tool for the conceptual design of receiver systems for radio telescopes was produced.

3) Amplifier Topology Studies: Systematic methods for generating wide band CMOS low-noise amplifier topologies have been developed [26]. New topologies were found that had promising noise and intermodulation properties.

4) Packaging and Matching: A low noise amplifier with direct noise and power matching to an antenna, without intermediate matching to a standard 50 Ω characteristic impedance, has been designed and characterised [27]. Simulation yielded a bandwidth of 2 octaves and a noise temperature of 35 K, indicating that it would be possible to make a design for a wide band low noise amplifier that is directly matched to an antenna. However, an improved measurement setup is required before this design can be reliably characterised.

5) Multi-element MMIC Array Feed Elements: Prototype Multi-element MMIC array architectures have been prototyped and their application as feed elements for radio telescopes has been explored [28].

6) Noise Figure Optimisation: LNAs under development at Caltech and JPL for radio astronomy and deep space communication have continued to show excellent performance. This group recently produced a world record 2 K noise temperature cryogenic LNA, operating over 4 to 8 GHz, whose performance has been verified in four different laboratories [22].

B. Australia

1) Robust Receivers: Experiments have been conducted with the aim of determining which components of a receiver system limit its dynamic range [29]. This has helped form conclusions regarding the design of receivers that remain linear in the presence of interference.

2) Cryogenic InP LNAs: As part of the Australia Telescope Millimetre-Wave Upgrade, cryogenically cooled (20 K) receivers using low-noise amplifiers based on InP MMIC technology have been developed [30]. Local experience has been developed in MMIC design, simulation, cooling, and testing. Experience has also been gained in packaging MMICs and integrating them into working radio astronomy systems.

3) Matching: A first pass investigation has been made into the benefits of matching LNAs directly to an antenna impedance rather than the standard intermediate 50 Ω system impedance. Simulations have yielded promising results, however definitive experiments are yet to be made.

VI. FUTURE DIRECTIONS

The future will open up many more avenues for optimising the SKA's receivers. Here the possibilities of System-on-a-Chip (SoC); electro-optical integration; and smart packaging and matching are put forward. These research areas are suggested in view of their relevance to the SKA and their potential for synergy with industry.

A. System-on-a-Chip (SoC)

A current focus of the semiconductor world, as evidenced by the International Technology Roadmap for Semiconductors (ITRS) [31], is the maximisation of the functionality of a single integrated circuit. There is a strong effort to provide not just single functions, but entire systems on a chip.

The aims of the System-on-a-Chip (SoC) movement in the wireless communications arena are clear. By integrating transceivers, RF engineers hope to reduce die count, packaging complexity and cost whilst increasing performance and reliability of their designs [32]. However, the increased difficulty of RF isolation and other caveats prolong the debate over just how much RF systems can benefit from integration.

The provision of full SoCs incorporating many diverse semiconductor technologies may lie beyond the horizon of even the SKA. However, single pairs of technologies are already beginning to be combined. Already we have seen the combination of RF and BiCMOS technology [32]. RF and optical functions have also been successfully combined on the same substrate.

B. Electro-optical Integration

The use of optical signal transport has become common in radio astronomy. At present, the common LO signal of the Australia Telescope Compact Array (ATCA) is distributed to each antenna by means of RF modulated light transmitted over single mode optical fibre [33]. Digitised data samples from each antenna of the ATCA are also returned to a central site for processing by optical means. The Allen Telescope Array (ATA) will optically transmit each antenna's RF signals to a central site for digitisation and processing [15].

A further permutation has been suggested which would involve optical sampling at the antenna and then quantisation at a central site [34]. Such a system would remove the need for local oscillators and would allow the simultaneous digitisation of the entire SKA bandwidth.

With all this work on optical signal distribution, it is likely that there would be some benefit derived from integrating an RF frontend circuit with its own optical interface. Recently Yap reported the monolithic integration of an optoelectronic electroabsorbtion modulator with an HBT driver circuit on a semi-insulating InP substrate [35]. The measured bandwidth was 30 GHz and it was observed that the performance of the HBT was not degraded by the regrowth and modulator/HBT circuit fabrication procedures.

The ITRS predicts that electro-optical integration will be provided in a process compatible with mainstream silicon by 2004 [31], thus substantially reducing its cost. Whilst this target sounds bold, a key milestone on the road towards it was achieved in the last year.

At present, more expensive direct band-gap semiconductor processes such as InP and GaAs are necessary for integrated light detection and generation. However, it has recently been shown that GaAs can be grown on silicon through a relatively inexpensive process [36], [37]. Thus, GaAs could be deposited wherever a high performance transistor or optical component is required within a standard silicon process. This would not only make SKA design easier, but open up a whole new range of commercial optical applications that have been ruled out thus far solely due to their high cost. It may do for integrated optoelectronics what SiGe has done for integrated RF.

C. Smart Packaging and Matching

The main incentives here are the reduction of parasitic elements attributed to packaging and the possible increase in bandwidth between each system element, especially the LNA and the Antenna. Some basic work in this field has been performed by both the Australian and Dutch SKA collaborators. Smart packaging is also becoming a key focus area for industry as integration levels rise [31].

VII. CONCLUSION

A picture of the SKA receiver design challenge has been painted with a broad brush. The SKA is an instrument that predominantly employs enhanced collecting area to achieve supreme sensitivity. Receiver design will still play an important part, but design choices will be driven slightly more by cost than performance.

Initially, a first order model of the required receiver noise temperature for the SKA was presented. Although illuminating, it is not yet useful for making receiver design choices for the SKA. The model must be extended to cover cost as well as performance. The economies of scale generated by the SKA should also be investigated.

A number of critical receiver technology issues have been raised. These include the choice of an appropriate semiconductor process; the determination of how many frontends should be used to cover the entire SKA band; the exploration of to what degree SKA frontends benefit from integration; and the determination of whether or not SKA receivers should be cooled.

Finally, three additional future directions for the Australian SKA Integrated RF Systems Working Group were identified that are relevant to both the SKA and industry. These are:

a) System-on-a-Chip (SoC);
b) electro-optical integration; and
c) smart packaging.

The radio science community should discuss the relevance of these directions to the SKA and to Australian industry in general. The SKA Working Group on Integrated RF Systems can then construct a Technology Roadmap for SKA receiver design, especially that applicable to the proposed Australian SKA demonstrators [13], [14].

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