PROCEEDINGS OF SCIENCE

SKADS

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The Square Kilometre Array Design Study, SKADS, is an international programme partly funded by the Sixth Framework Programme of the European Community. It includes 26 partners from 9 EU countries and from 4 non EU countries. Aim of this research programme is to investigate and to develop new technologies, components, architectures and software algorithms applicable to the Square Kilometre Array: the next generation radio telescope. In particular, SKADS focuses on the Aperture Array technology because, even if it is probably the most expansive, compared to the other, is the most promising and versatile one, and, over all, the only one that can fully satisfy the strong astronomers' requirements in the SKA low frequency (i.e. less than 1GHz) band.

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[1] Speaker

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1. Introduction

The SKA Design Study is a 4 years international programme partly funded by the European Community Sixth Framework Programme. The project includes partners from 26 institutes in 13 countries. Aim of the research programme is to develop new technologies, components, architectures and software algorithms applicable to the Square Kilometre Array: the next generation radio telescope.

2. The SKA Design Study

2.1 SKA

The Square Kilometre Array [1] will be a distributed interferometer array with a total collective area of $10^6 m^2$ that will be spread over an area more than 3000Km wide. It will be probably located in the Western Australia or in the South Africa, the only two regions in the world sufficiently wide and at the same time with a very quiet Radio Frequency Interferences scenario. It will be able to work in a huge frequency band, from less than 100MHz to 25GHz, with a sensitivity up to hundred times better than with the existing radio telescopes, combined with both high resolution and large field of view. It will be a break instrument with the present and the past of radio astronomy, where big reflector antennas, up to 100m in diameter, have been used, because its huge collective area will be obtained with thousands of small and cheap antennas.

To synthesise the entire collective area, the signals of each antenna have to be amplified, conditioned, digitized and finally processed. So a massive use of low cost, both analogue and digital, electronics will be necessary, pushing the instrument in the direction of a "software telescope". Even if the SKA designers can take advantage of Moore's law, in particular for the digital processing hardware, an incredible effort they have to do in order to extremely reduce the cost of each antenna sensor, both from a mechanical and electrical point of view, and its, analogue and/or digital, link to the processing core. The overall SKA budget is in a range from 1 to 1.5 billion euros. The array construction will be completed in 2020, but just during the next decade, part of the array will be ready to give science at high level (SKA Phase 1).

2.2 The role of SKADS in the SKA design and prototyping phase

Since the hugeness and the complexity of the project, SKA is a world wide collaboration of several countries[1] led by an international steering committee and a jointly funded SKA project office. Vary institutions participating in the SKA are now designing and building prototype systems [2]. SKA will be based on the technologies demonstrated by these pathfinder telescopes and design studies. In the at present SKA reference design the collective area is subdivided in a central core, where the 50% of the total collective area is collected, and many remote stations to provide the necessary baselines. Regarding the antenna sensors, the selection process has identified 2 kinds of them capable to respect the heavy SKA requirements: small

[1] In alphabetical order: Argentina, Australia, Brazil, Canada, China, France, Germany, India, Italy, The Netherlands, New Zealand, Poland, Russia, South Africa, Spain, Sweden, United Kingdom and the United States.

dishes equipped by Single Wide Band Feeds (SWBF) and/or Focal Plane Arrays (FPA) in the upper frequency band (from about 1GHz to 25GHz) and Aperture Array (AA) in the lower frequency band, but only in the core (see Figure 1).

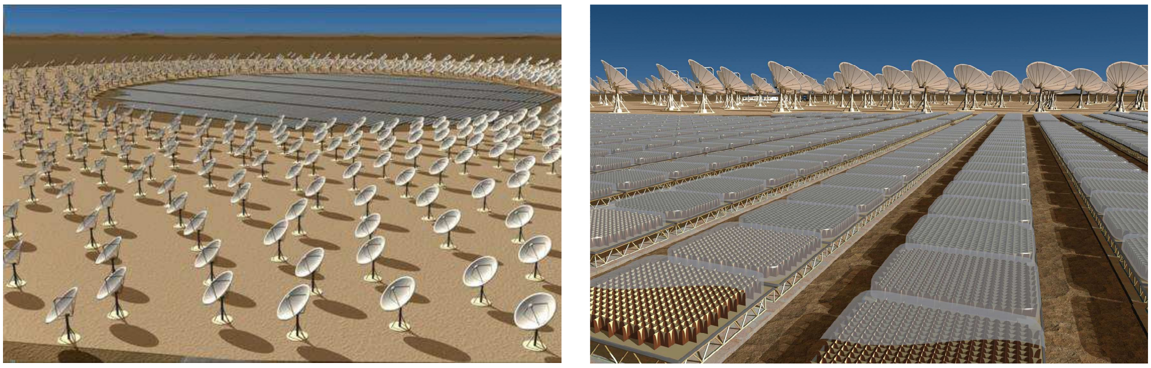


Figure 1: An artist impression of the SKA core (left) and a particular of the aperture array (right).

SKADS [3] focuses on the development of the AA[2] because it is a SKA key technology. In fact this kind of antenna sensor is the only one that can provide all the following features at the same time: high sensitivity, large Field Of View (FOV) and multibeam capability (see Figure 2, on the left). Moreover it can be used in combination with other kind of sensors, like small dish, because it's the fundamental element of the FPA technology, where, in simple words, an AA is placed in the focus of a dish[3] (see Figure 2, on the right).

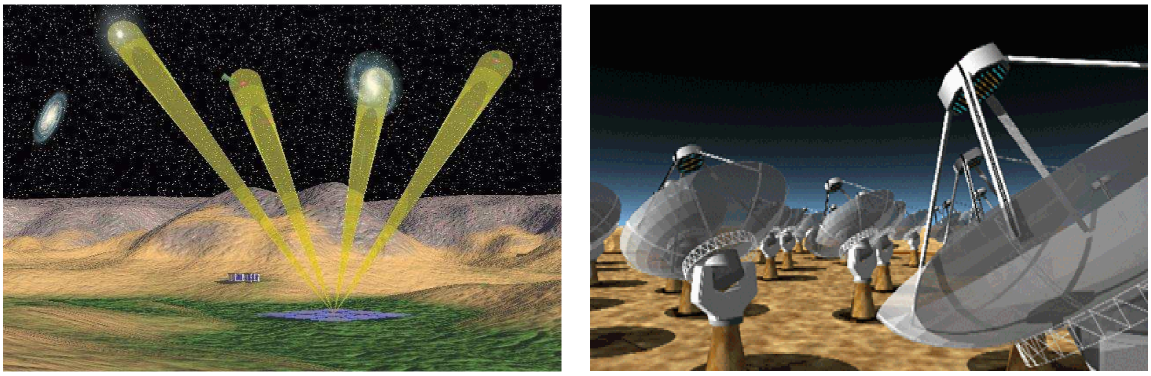


Figure 2: The aperture array technology used stand alone (left) and in combination with small dish reflector (right).

2.3 SKADS history, funding and participants

The SKADS proposal was submitted to the EC in March 2004, almost 2 years after its conception (first meeting in late 2002). The contract with the EC was signed by the partners in

[2] Europe, thanks to pioneering work done in that field, especially by ASTRON with OSMA [4] e THEA [5] systems, has a leading role in the developing of that technology for radio astronomy.

[3] In that configuration it is possible to obtain a compromise between the dish capabilities and the phased array capabilities (i.e. FOV expansion and multibeam).

late 2005, when the funds started to flow, even if the formal project start (T0) was six month before (July, 1st 2005).

SKADS is co-funded by the EC through its sixth frame programme. What means co-funded? Typically, if the participants request a contribution by the EC, they have to contribute to the project funding at least with the same amount of funds, the so called “matching funds”. They can be money, man power or infrastructures (i.e. laboratories). For SKADS the contribution from the EC is a little more than 10M€, while the national matching funds are about 28M€.

1. ASTRON	2. University of Manchester	3. JIVE	4. Observatoire de Paris	5. INAF-IRA
6. Fundacion General de la Universidad de Alcalá	7. Max Planck Institut für Radioastronomie	8. Oxford University	9. CSIRO, Australia	10. Pushchino Radio Astronomy Observatory
11. National Research Council, Canada	12. National Research Foundation, South Africa	13. Torun Centre for Astronomy	14. Chalmers University	15. Cambridge University
16. Kapteyn Institute, Rijksuniversiteit Groningen	17. University of Leiden	18. Cardiff University	19. Glasgow University	20. Swinburne University of Technology
25. Université d'Orléans	26. Centre National de la Recherche Scientifique	28. University of Leeds	29. Universidad de València	30. OMMIC, France
31. IST/CENTRA, Portugal				

Figure 3: The SKADS participants (the highlighted ones are from extra UE countries).

The 26 SKADS partners are: 21 institutes and organizations from 9 EU countries[4] and 5 from 4 non EU countries[5]. After the project start, some Australian universities and one from South Africa resigned while the Portugal has entered into the programme.

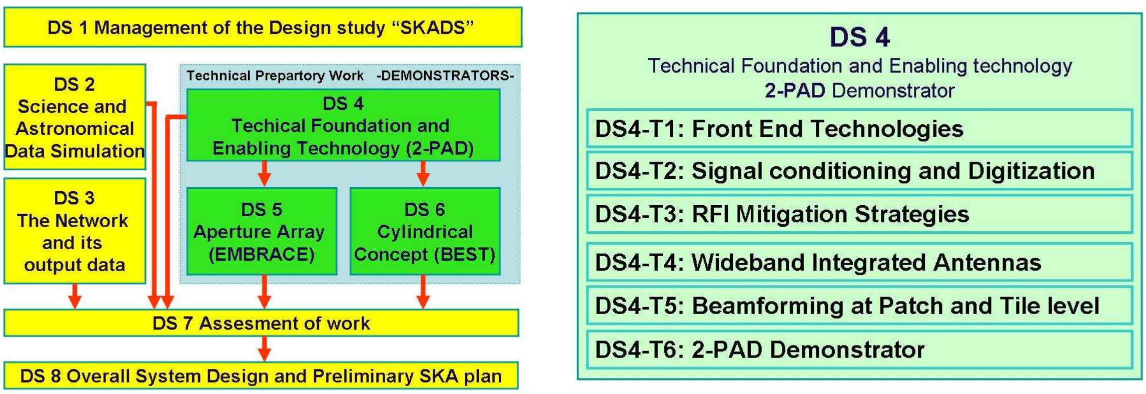


Figure 4: The SKADS structuring: the Design Studies (left) and the Tasks (right)[6].

[4] The Netherland, UK, France, Italy, Germany, Spain, Poland, Sweden and Portugal.
[5] Canada, Russia, South Africa and Australia.
[6] Example of the DS 4 task subdivision.

2.4 SKADS structuring

SKADS is structured in 8 main blocks called Design Study (see Figure 4, on the left). The yellow ones are feasibility and assessment studies (DS2, DS3, DS7 and DS8), while the green ones are the technical preparatory works (DS4, DS5 and DS6). The former group is concentrated on the design and costing of the SKA network and infrastructure and also on the overall assessment and project plan. The latter one focuses on software and hardware R&D of elements, components and architecture of and for a SKA station. Each DS from 2 to 8 has been subdivided into tasks, all having own objectives, milestones and deliverables. An example of a DS tasks subdivision is shown in Figure 4, on the right.

The role of the DS1, leaded by ASTRON (NL), is to provide the management of the overall project (i.e. funding and reporting) and the relations with the EC. The DS2 and DS3 are leaded, respectively, by JIVE (NL) and the University of Cambridge (UK). These two DS' are strongly linked each other, because both are related to the design of the overall SKA. In particular the scientists involved in DS2 have to establish the science that they are going to do with the SKA (Figure 5, (a)) and then, through simulations (b), they have to define the SKA specifications necessary to allow astronomers to do that science. For example, they have to define how large the core should be (c), how many antennas it has to include (d), how many remote stations are necessary and where they should be located (e) and again, they have to simulate the amount of the astronomical data to transfer from the remote stations to the central processing core. Moreover they have to define if it is necessary a single or multibeam system (g) with a large FOV or not (h). As said before, more of the previous points are in common, or related, to the DS3, because it is focused on the study of the inter-stations and intra-station data connection networks and the data handling. It is easy to recognize that both are strongly depended on where the stations will be located and how many antennas they will include and many other parameters mentioned before. DS3 takes care also of the study of the power line distributions among the stations and how to distribute the astronomical data to the end user astronomers located in different countries over the entire world.

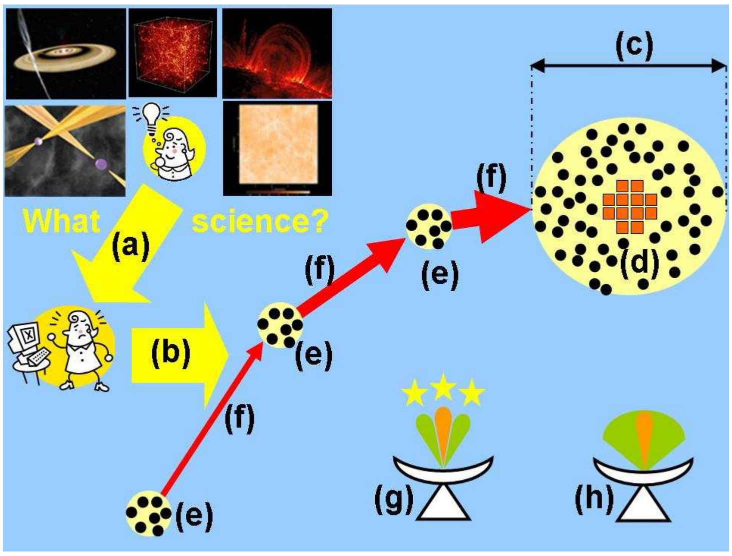


Figure 5: The DS2: From the desired SKA science to its configuration design.

The DS4, DS5 and DS6, in order leaded by the University of Manchester (UK), ASTRON (NL) and INAF-IRA (IT), are the technological preparatory works or, better, the three SKADS demonstrators. In Figure 6 are explained the acronyms of the demonstrators and the main technological areas where their R&D activity is focused. Thanks to these three complementary demonstrators, the overall SKADS R&D activity is well distributed at each SKA system level. We will entry more in detail about the demonstrators in the follows sections.

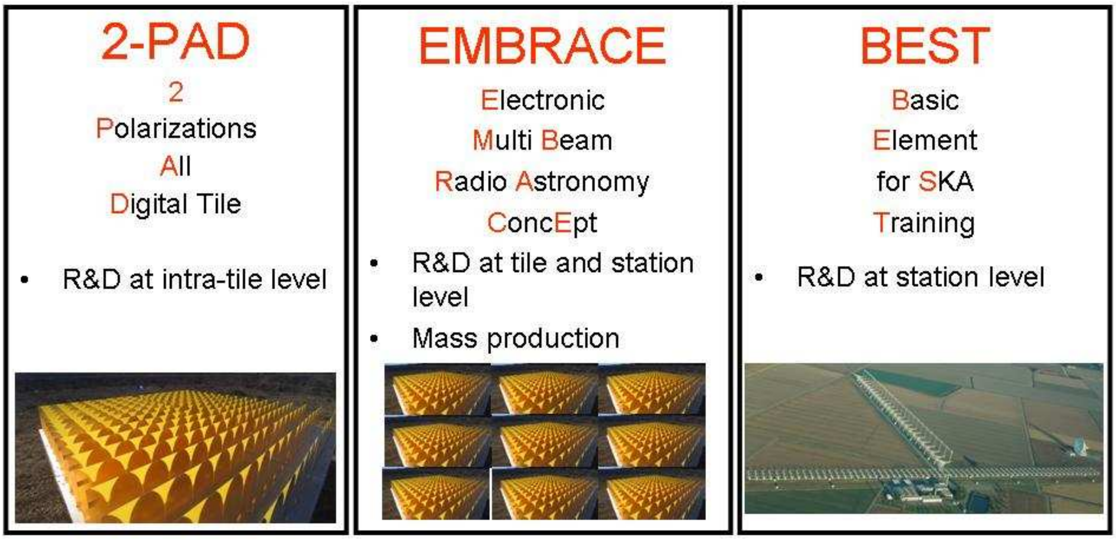
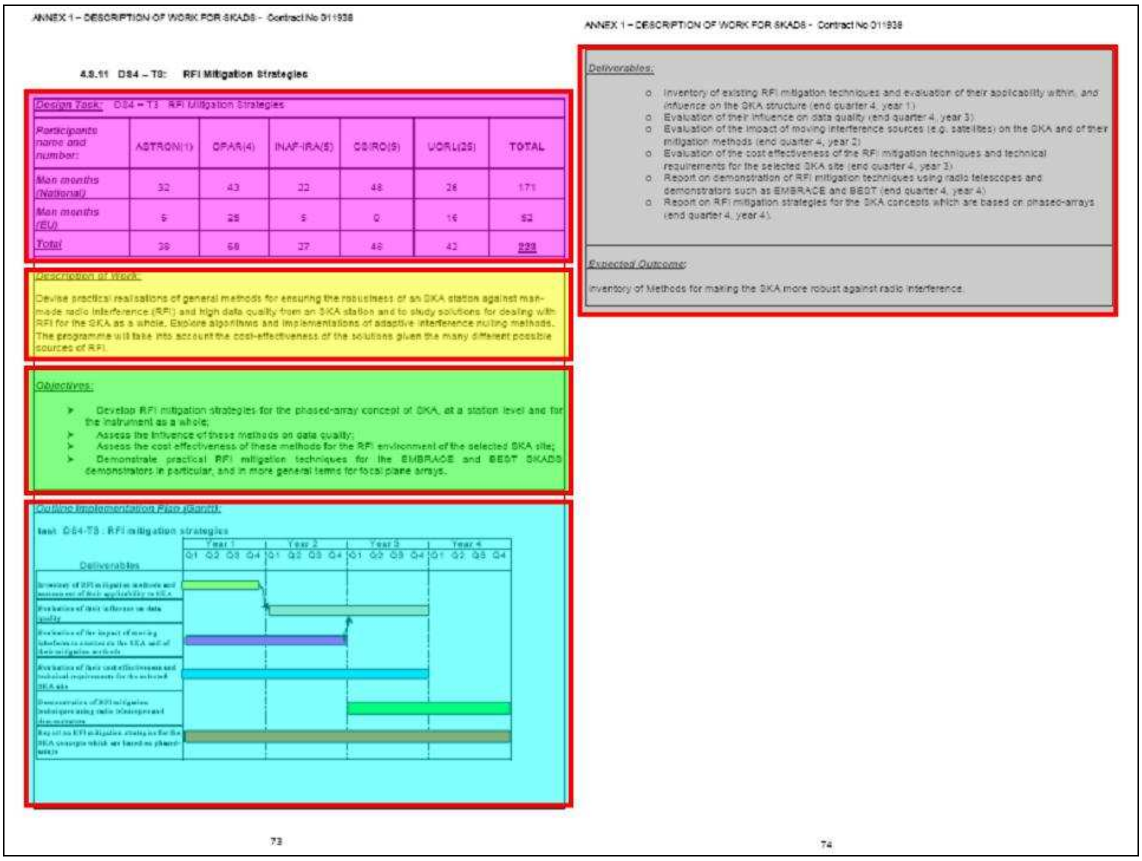


Figure 6: DS4, DS5 and DS6: the SKADS demonstrators.

The last two Design Studies have to continually asses the whole programme of work and to organise the mid-term and final design review (DS7, leading participant: OPAR–FR) and to produce the SKA overall system design and a preliminary project plan (DS8, leading participant: University of Manchester–UK).

2.5 The DoW

The Description of Work [6] is probably the most important SKADS document. It includes a complete description of: the overall project, the participants, each Design Study and each Design Study Task. In particular for each task (see Figure 7) it is shown: who are the participants and their employed resources (pink highlighted), a brief description of the activity (yellow highlighted), the objectives (green highlighted), a Gantt chart (blue highlighted) and the deliverables and expected outcomes (gray highlighted).



ANNEX 1 – DESCRIPTION OF WORK FOR SKADS - Contract No 011938

4.8.11 DS4 – T3: RFI Mitigation Strategies

Design Task: DS4 – T3 RFI Mitigation Strategies						
Participants name and number:	ASTRON(1)	OPAR(4)	INAF-IRA(5)	CSIRO(9)	UORL(25)	TOTAL
Man months (National)	32	43	22	48	26	171
Man months (EU)	6	25	5	0	16	52
Total	38	68	27	48	42	223

Description of Work:

Devise practical realisations of general methods for ensuring the robustness of an SKA station against man-made radio interference (RFI) and high data quality from an SKA station and to study solutions for dealing with RFI for the SKA as a whole. Explore algorithms and implementations of adaptive interference nulling methods. The programme will take into account the cost-effectiveness of the solutions given the many different possible sources of RFI.

Objectives:

- Develop RFI mitigation strategies for the phased-array concept of SKA, at a station level and for the instrument as a whole;
- Assess the influence of these methods on data quality;
- Assess the cost effectiveness of these methods for the RFI environment of the selected SKA site;
- Demonstrate practical RFI mitigation techniques for the EMBRACE and BEST SKADS demonstrators in particular, and in more general terms for focal plane arrays.

Outline Implementation Plan (Gantt):

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Deliverables:

- Inventory of existing RFI mitigation techniques and evaluation of their applicability within, and influence on the SKA structure (end quarter 4, year 1)
- Evaluation of their influence on data quality (end quarter 4, year 3)
- Evaluation of the impact of moving interference sources (e.g. satellites) on the SKA and of their mitigation methods (end quarter 4, year 2)
- Evaluation of the cost effectiveness of the RFI mitigation techniques and technical requirements for the selected SKA site (end quarter 4, year 3)
- Report on demonstration of RFI mitigation techniques using radio telescopes and demonstrators such as EMBRACE and BEST (end quarter 4, year 4)
- Report on RFI mitigation strategies for the SKA concepts which are based on phased-arrays (end quarter 4, year 4).

Expected Outcome:

Inventory of Methods for making the SKA more robust against radio interference.

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Figure 7: The description of a task as presented in the DoW.

The employed resources for every task are expressed in Man Months. In order to explain what Man Months means we have to introduce another concept before: the FTE. A FTE is a Full Time (Expert) researcher dedicated for one year to a project. It can be considered as a measurement unit for human and funds resources that a participant can request to the EC and/or that the EC requires as Matching Funds. A FTE is quantified as about 85K€ per year[7]. From its definition, a FTE can be not only one researcher fully dedicated to the project for one year (a), but also an half time researcher who is dedicated to the project for two years (b), or again, two full time researchers who are dedicated to the project only for half year each one (c), or two half time researchers who are dedicated for one year (d) and any other possible combination you can find (e)!

A Man Month can so finally be defined as a FTE employed for a month, instead of one year. In the DoW it was preferred to adopt the Man Months definition because with this unit is easier to subdivide the work activity[8]. Finally, using the MM definition is also possible to have an idea of the funds efforts of each participant for every task[9].

[7] This value should correspond to a mean value of UE researchers' salaries.

[8] For example: 7MM correspond to 0.5833333FTE, but the former expression is more useful than the latter.

[9] In the Dow you the MM are distinguished between National and EU: the first ones are equivalent to national matching funds and the second ones to funds received by EC.

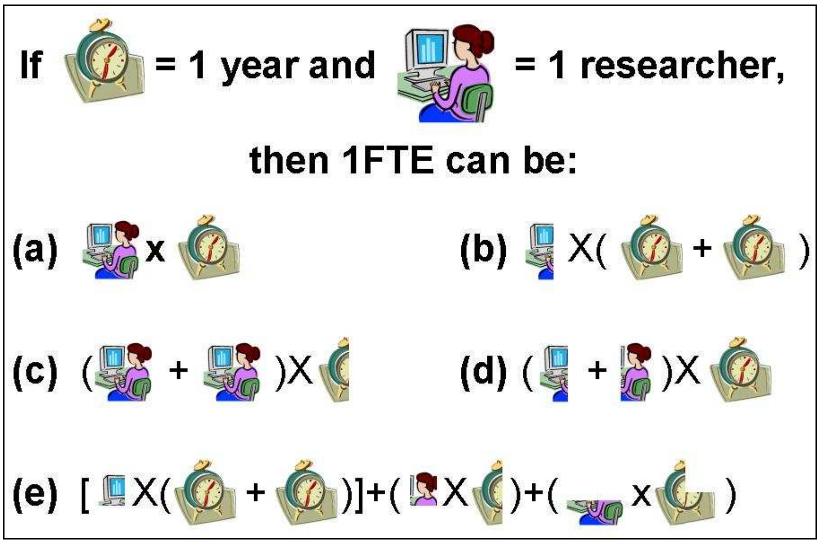


Figure 8: The FTE equation.

2.6 Project reporting and timing

Every three months a report on the activity of each task and design study has to be produced, while every year, a report on the whole SKADS project, the so called Annual Report, as to be produced. These documents are very important because they are used by the EC to check the project progress.

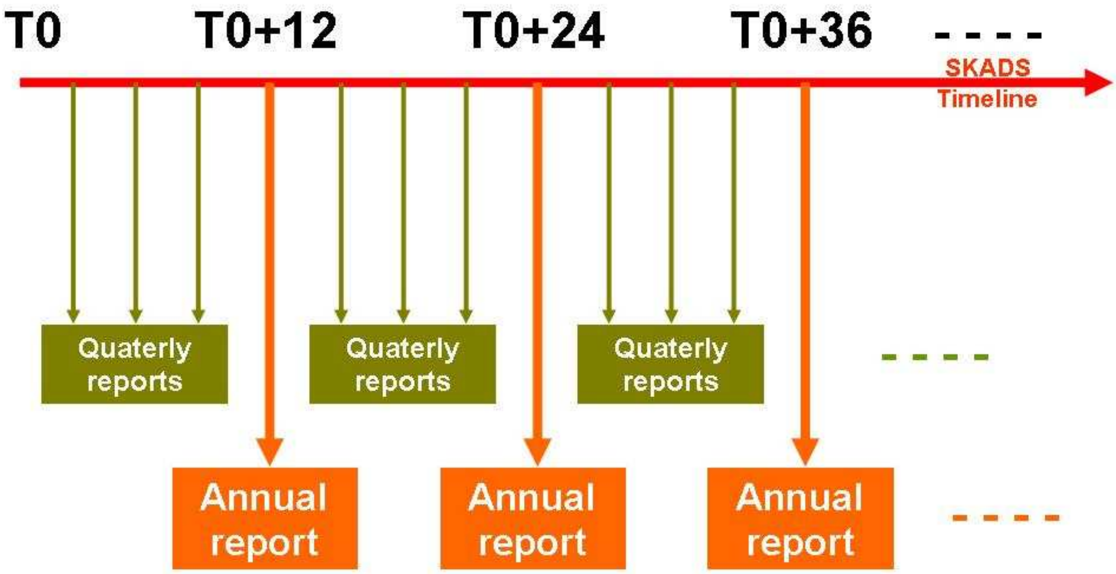


Figure 9: The SKADS reporting plan.

In the DoW every milestone or deliverable or Gantt chart uses T0 as reference date and it corresponds to the formal start of the project: July, the 1st 2005. Since the programme has 4 years duration, it will be end in July 2009. An important SKADS date is the midterm review[10]: there the EC will deeply cheek the project progress.

3. The SKADS demonstrator

3.1 EMBRACE

The main goal of the DS5 is to build an aperture array station composed by 300 tiles. The system will be located in the Netherland, next to the Westerbork Synthesis Radio Telescope (WSRT). This way it will be possible to compare EMBRACE to a standard dish antenna of the WSRT array, both in total power and in interferometer measurements. To test the system behaviour at longer baseline, a second smaller station of about one hundred square meters (i.e. 100 tiles), will be built in France, at the Nancay Observatory.

EMBRACE will be the evolution of the first generation AA developed by ASTRON: THEA, THousand Element Array. One of the biggest challenges for EMBRACE will be the tile cost reducing exercise: a new tile will have to cost less than 1000€, less than an order of magnitude than the cost of a THEA tile. In each tile, the incoming signal is received by 64 Vivaldi antennas, arranged in a dense array configuration. After that the signals are amplified and, thanks to new, especially designed by ASTRON, beam former chips, combined in order to obtain two independent analogue beams (the red ones in Figure 11), which are sent to the remote receivers through low cost 75Ohm coaxial cables.

The signals came from the tiles as first combined, 4 by 4, and the resulting signals entry in a double conversion receiver, which converts the input bandwidth 400-1600MHz, in a 100-200 MHz Intermediate Frequency (IF) output band. Now the signals are ready to be sent to a LOFAR like digital back end, where up to 8 digital beams (the blue ones in Figure 11) can be created inside a single analogue one.

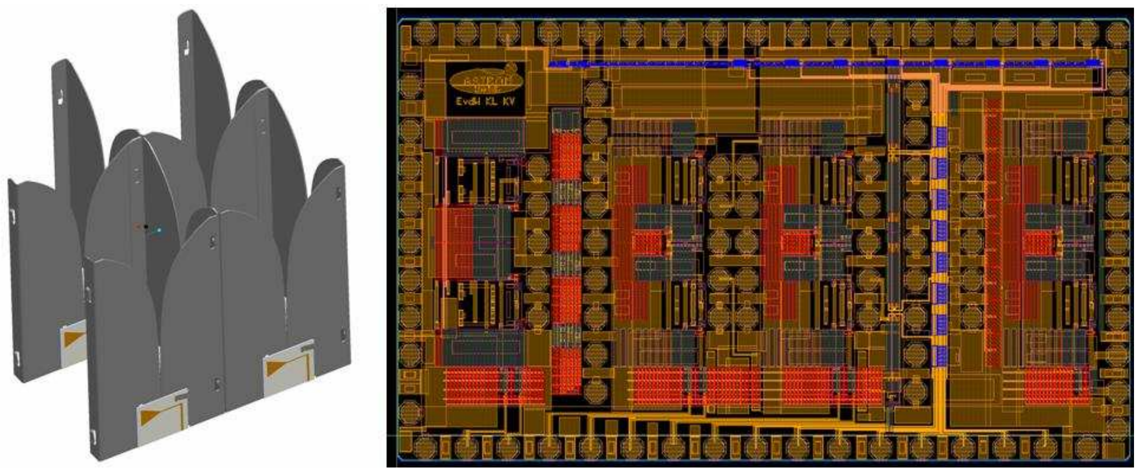


Figure 10: The newest aluminium Vivaldi antennas (on the left) and the analogue beam former chip (on the right), both are outcomes of the ASTRON team.

[10] The SKADS midterm review was held at the Observatoire de Paris on September, the 14th 2007.

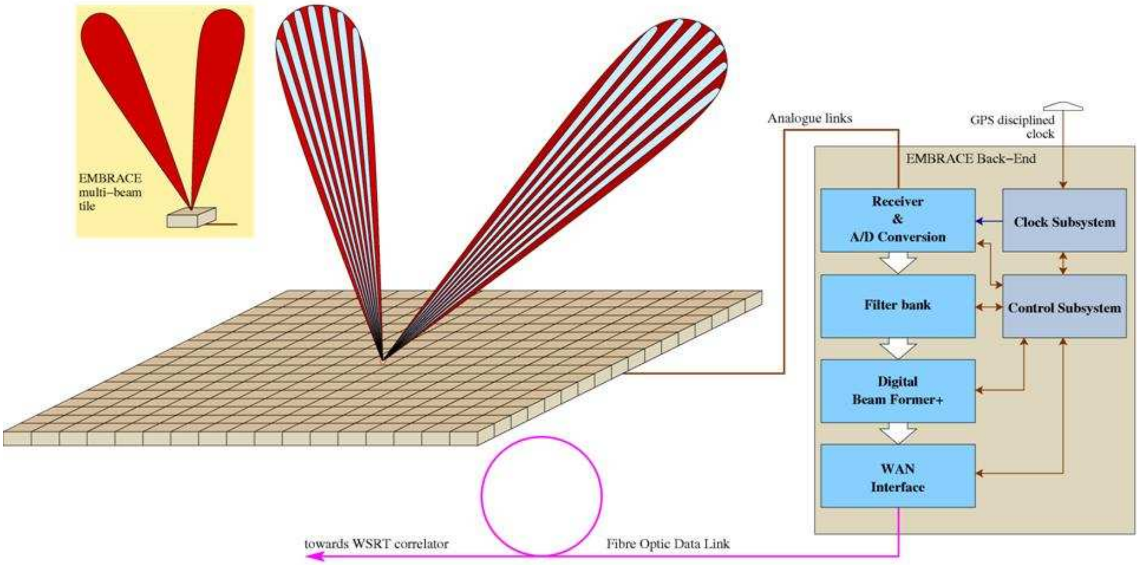
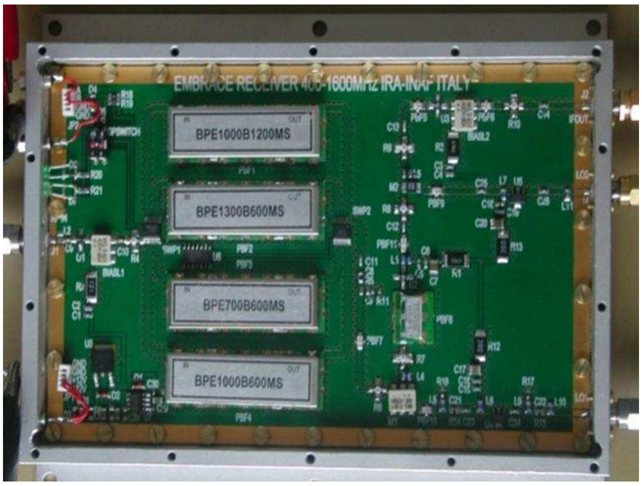


Figure 11: EMBRACE general overview.

The Medicina SKA team is also involved in the design of EMBRACE, and in particular is responsible of the design of its receiver (see Figure 12). The design, prototype and testing phase have been carried out at the Medicina laboratories. Right now ASTRON is starting to integrate it with other subcircuits in order to start the mass production necessary for the full array.



- RFin 400-1600 MHz
- IFout 100-200 MHz
- LO1=1400-2600 MHz
- LO2=2850 MHz
- Input ports ESD protected
- RF/IF equalization
- RF High Selectivity Filter bank
- TTL/CMOS controls
- Low Power for driving LO Typ. 2dBm
- No OL Phase Noise degradation
- High Reliability
- Substrate FR4, 1.6mm, 1Oz. Cu
- Standard Euro Dimension (160x100)

Figure 12: The IRA-INAF EMBRACE receiver (on the left) and its main features (on the right).

3.2 BEST

The Basic Element for SKA Training [7] is based on the re-instrumentation of about 8000m^2 of the Northern Cross radio telescope (see Figure 13), one of the largest low frequency arrays in the northern hemisphere, located in Medicina, nearby Bologna (IT).

Figure 13: Aerial view of the Northern Cross radio telescope.

Such a prototype extension is comparable with the effective collecting area of a future proposed SKA station (about 10000m^2). Io order to reduce the risks, the re-instrumentation will be faced in three successive steps with increasing size [8]. The first one (BEST-1) corresponds to 4 new receivers installed on one cylindrical reflector of the North/South arm, while the second one (BEST-2), correspond to a further extension of 8 N/S cylinders (32 receivers). The last one, BEST-3, will involve also the East/West arm, where 24 new receivers will be installed on 6 sections of its long focal line, meanwhile the total number of the N/S cylinders re-instrumented will become 14. At the end of the re-instrumentation process, a total amount of 80 new receivers spread on both arms will be available; this way good instantaneous u-v plane coverage could be obtained. The first two steps are already completed (BEST-1 in late 2004 and BEST-2 in summer 2007), while the last one is planned to be completed in late 2008.

Thanks to new low noise fronts, the RF signal at 408MHz comes, through analogue optical links 700 meters long, directly in a central protected and shielded receiver room. This way the system reliability and maintainability are considerably improved [9]. There, the signals are converted by new receivers at IF level (30MHz) and then sent to a digital acquisition system and to the back end (see Figure 16).

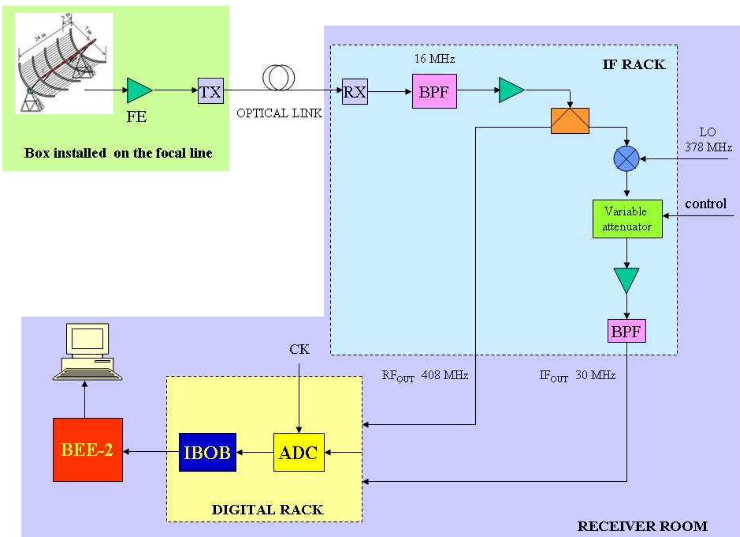


Figure 14: BEST general architecture.

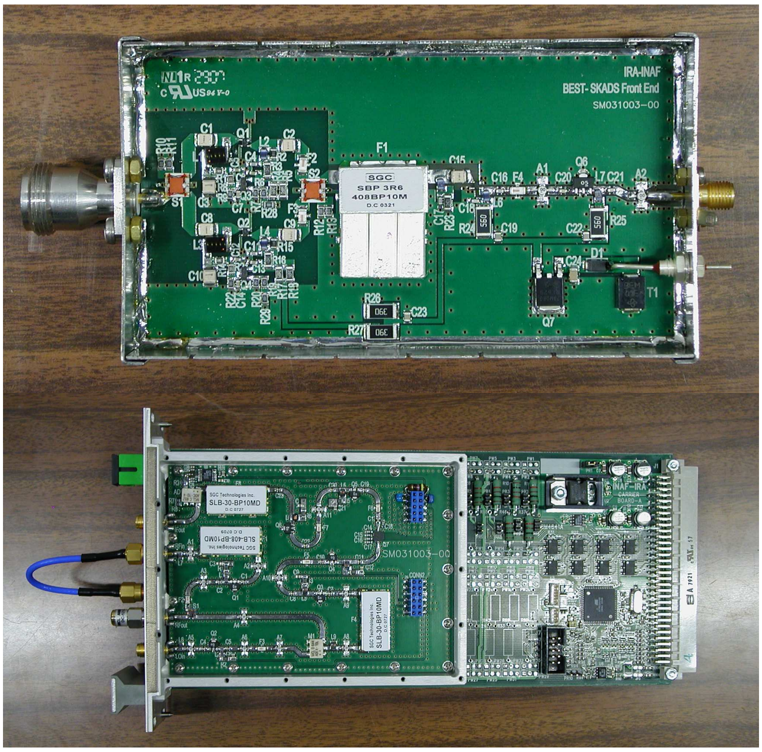


Figure 15: New IRA-INAF/SKADS low noise front end (upper)[11] and the new RF to IF receiver (lower)[12].

The principal goals of BEST are: to produce low cost, high performance, easily replicable technology; to investigate beamforming algorithms for RFI rejection and multibeam techniques; to give the possibility to test concepts, algorithms and technologies on a large demonstrator where there are, at the same time, high sensitivity and high RFI level; to give the possibility to do science with a 1% SKA demonstrator and finally, but not the least, to transfer quickly all of those things to EMBRACE and 2-PAD.

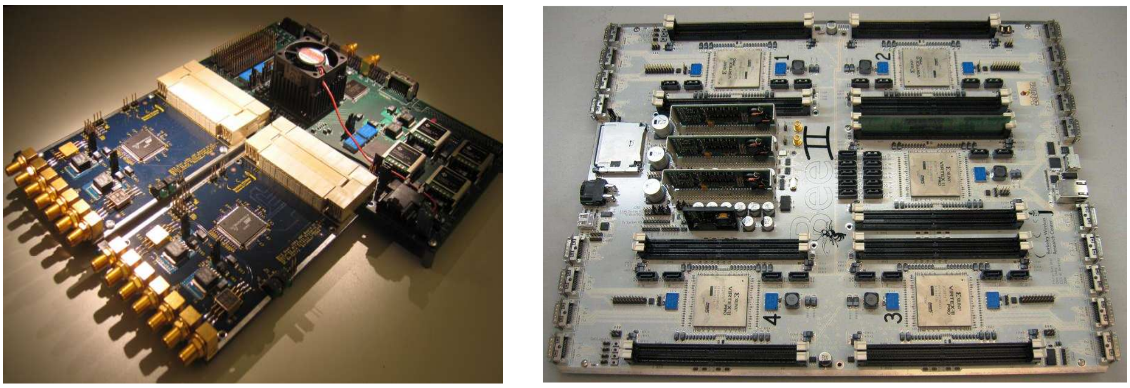


Figure 16: BEST-2 digital acquisition system (ADC board on the left) and digital processing back end (FPGA board on the right)[13].

[11] The first of the three FE stages is a balanced LNA.
[12] Thanks to a system called “carrier board”, each receiver can be fully remotely controlled by LAN through a micro processor installed on board.

BEST-1 has been running from late 2004 and many important results has just obtained. Here only two of them are mentioned: the comparison between the simulated and measured antenna temperature and a RFI rejection test.

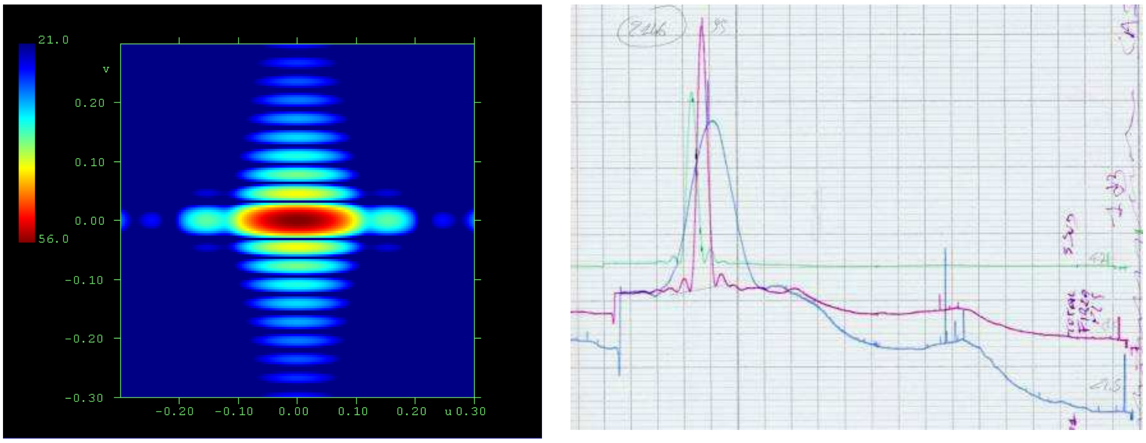


Figure 17: BEST-1 2-D power pattern simulation (left) and received transit of a calibrator (right).

Thanks to the BEST-1 readiness, we were able to check on the field the antenna temperature distribution calculation proposed by the International SKA Project Office, as a guideline to compare all the SKA antenna sensors [10]. The simulated antenna temperature was obtained through an ad hoc code, which integrate the proposed brightness temperature distribution, with the BEST-1 power pattern obtained through GRASP simulations [11]. Meanwhile, to obtain the measured one, we observed with BEST-1 the transits of some strong calibrators[14]. For the RFI rejection test see the next Figure 18.

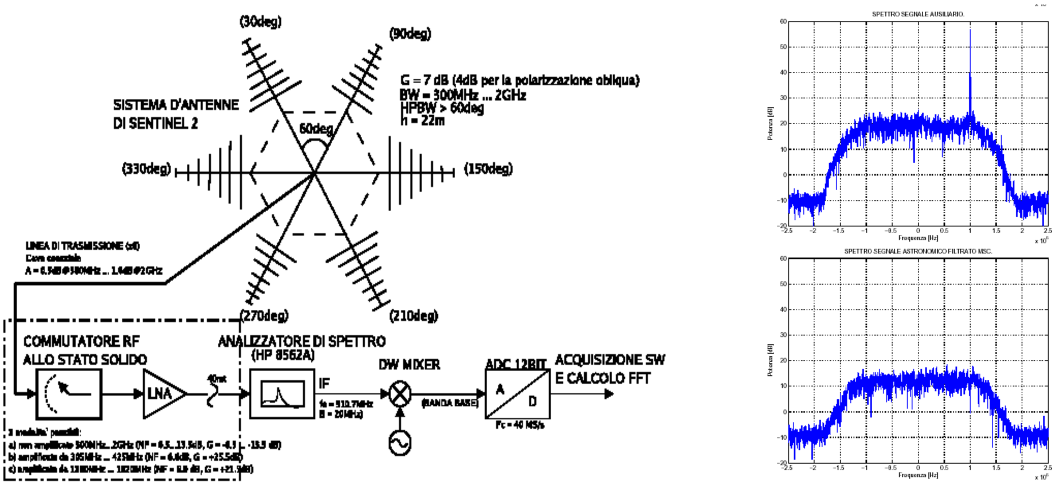


Figure 18: RFI excision test through the Multiple Side Lobe Canceller Algorithm: the corrupted spectrum (on the right, upper) and the cleaned one (on the right, lower) and the reference antenna used: the Sentinel system (on the left), mounted on the RFI monitoring tower of the Medicina station.

[13] This acquisition system, called BEE2, has been developed by Berkeley University for the Allen Telescope Array: the US-SKA demonstrator based on small dishes.

[14] Cassiopeia-A and Virgo-A.

BEST-2 has been completed just prior of the midterm review, where the Italian SKADS team shown its “first light” obtained through the transit observation of the Cassiopeia-A, with each all the 32 receivers in total power mode.

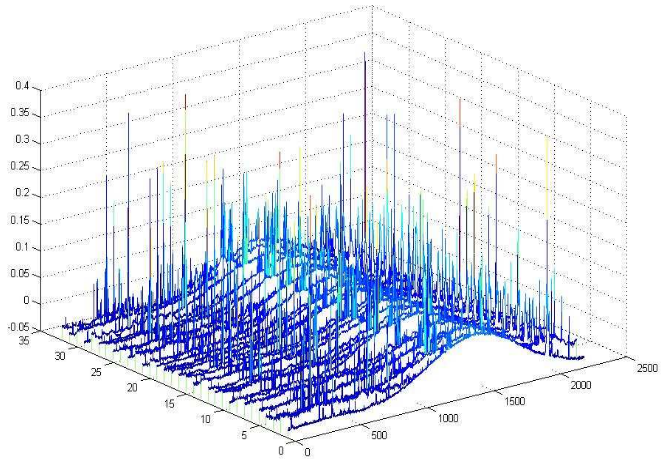


Figure 19: BEST-2 first light. On the right axis there is the time, on the left one the receivers and in the vertical one the relative amplitude. The BW was the full 16MHz, where strong RFI take place. The vertical peaks are due to them: a heavy real RFI environment to check the RFI rejection!

Thanks to the wide collecting area available on the Northern Cross radio telescope, besides the ones employed for the BEST system, the cylindrical concentrator could be also a useful test bed for a lot of deliverables of other tasks: as the LNA chip produced in the DS4-T1 or the antennas developed in the DS4-T4 and so on. The Northern Cross could offer a cheap and quick opportunity to check the behaviour of EMRACE and 2-PAD sub-elements as FPA (see Figure 20).

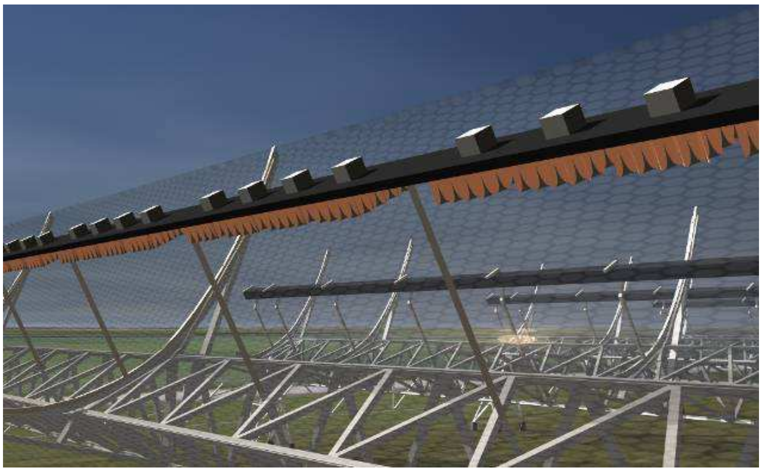


Figure 20: An artistic view of the Northern Cross as test bed for FPA technology.

3.3 2-PAD

As just mentioned, the first AA generation was THEA, and EMBRACE can be considered the second one. The main goal of the design study 4 is to understand if 2-PAD could become the third AA generation. The main difference between EMBRACE and 2-PAD is that in the latter there is not any analogue beam former at any level, it is all digital. The signal that comes out from each antenna is digitised at once and then, every signal conditioning is digital.

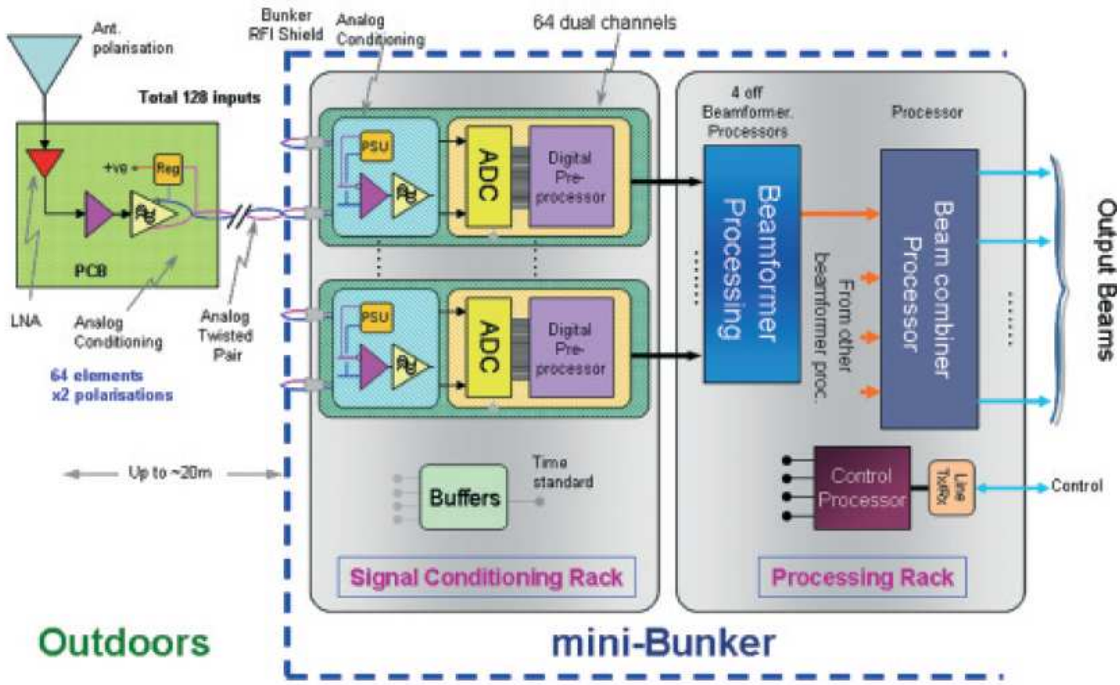


Figure 21: 2-PAD system architecture.

This concept forces the AA capability at its highest reachable limit in terms of flexibility and performances (i.e. the FOV of the entire instrument remains the same of the single antenna, since there is not any analogue array factor that reduces it). 2-PAD would be the so far dreamed by the astronomers "software telescope", where only the computing processing power is the limiting factor.

2-PAD will be designed as a sum of the outcomes of all the DS4 tasks (see Figure 4, on the left), but the results of each task will be very useful even if they are considered stand alone. For example, if the DS4-T1 designs a LNA with very good performances and at low cost, that device could be adopted by many other SKA receiver systems, even if they are not all digital. DS4 is late in SKADS timeline due to national funding delay, the first hardware outcomes are expected in 2008 and 2-PAD is planned to be build in 2009.

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