The Square Kilometre Array: An international project to realize the world's largest radio telescope

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***Abstract*—The Square Kilometre Array is one of the most complex science projects ever conceived. The scientific drivers are important questions about the evolution of the early Universe, fundamental physics, study of galaxies and stars across time, formation of exo-planetary systems and astrobiology. The scientific requirements such as sensitivity and resolution are so hard that the required technology and the costs need a global effort. SKA is a project involving thousands of engineers, scientists, astronomers and construction specialists from 20 different countries. The telescope is a new concept radio interferometer consisting in two parts, with two different technologies for two different wavelength ranges, in the remote deserts of South Africa and Australia. In a first stage, SKA1, there will be about two hundreds 15m dishes and more than hundred thousand dipoles, grouped in stations, both connected via optical fiber to the central correlator. In a second stage the number of dishes and dipoles will be more than two thousand and up to one million dipoles respectively. The technological solutions, the controls of this complex system, the connections for data transfer, the big amount of data and the supercomputers to be used have no precedent in the history. In this paper I'll give an overview of the SKA system, with emphasis on design, architecture and organization of this challenging project.**

Keywords— Radioastronomy; Interferometry

I. INTRODUCTION

The new generation of instruments for Astronomy and, more generally, for Science, must answer to questions that are more and more complex. Until several decades ago, each observatory was able to conceive and realize a telescope, a photometer, a camera, a spectrometer, in order to pursue their own research. Later, the complexity of the scientific questions, the need to go deeper and deeper into the Cosmo in order to detect and study the most faint or the most distant objects of the Universe, with the aim to study the evolution of the Universe itself from the Big Band to the rise of the Life on Earth and in planets, has lead to the need to joint the efforts of different institutions. Bigger national telescope have therefore been realized as, for example, the Telescopio Nazionale Galileo (TNG) for Italy, in Canarias Islands, Spain. Inter Governative Organizations (IGO) have been created to realize the most powerful observatory in the world. For example the European Southern Observatory (ESO), which has been created in the sixties with the original aim to explore the southern sky. Now it is the bigger ground based observatory in the world, with the Head Quarter in Europe, the scientific organization in Europe and Chile, the telescopes in the driest deserts of Andes. Just to recall the most important instruments of ESO, the Very Large Telescope (VLT) consisting of four Unit Telescopes with main mirrors of 8.2m diameter, actually the bigger, or the Atacama Large Millimeter Array (ALMA), a radio interferometer born to observe at wavelength of millimeter and sub-millimeter, build at 5000m above the sea level in the driest desert of the world. The effort to realize ALMA has been so huge that ESO alone was not able to accomplish, and a new organization, Joint ALMA Observatory (JAO), with the National Radio Astronomy Observatory (NRAO), on behalf of North America, and National Astronomical Observatory of Japan (NAOJ) on behalf of East Asia, has been created. And the European Extremely Large Telescope (E-ELT), an optical telescope with a mirror 39m diameter in phase of design, to be constructed at 3000m above the sea level at Cerro Armazones, in Atacama, Chile.

All these projects are very complex. First, the location: generally are inaccessible deserts where no pre-existing infrastructures exist. Second, the instruments: the top of the technology to achieve the higher sensitivity in order answer to the big science. Third, the management: several nations, continents, personnel, and big organization. All these ground based world facilities for astronomy have to be considered complex systems.

One of the most complex projects for ground-based astronomy is the Square Kilometre Array (SKA). It will be a radio interferometer consisting of up to two thousands of dishes and up to a million low frequency antennas, to be build in two continents, South Africa for dishes (Fig.1), Australia for low frequency (Fig.2), thanks to an international cooperation of 10 member countries, around 100 organizations across about 20 countries, involving scientists and engineers.

II. THE SKA PROJECT

The concept of SKA has grown with the idea to answer to a simple question: "What size radio telescope would it take to permit us to read the history of the Universe as written in the language of its most abundant constituent, Hydrogen?" [1].

Fig 1 Artist impression of the central area of SKA at high frequency in South Africa. There will be a total of more than 2500 dishes spread over 3000 km.

But, at the same time, this concept has been developed to have the capabilities to probe the evolution of the galaxies, the star formation across time, the fundamental physics through the study of the signals of the pulsars, the gravitational waves generated by the merging of super massive Black Holes, the development of life into the Cosmo, the formation of planets in other stellar systems, the astrobiology, the Search for Extra Terrestrial Intelligence (SETI), and many other fields of Astrophysics, including the discovery of something new.

The stakeholder is the scientific community with the scientific case; the requirements are given by sensitivity, frequency range, angular and temporal resolution needed to answer to the questions of the driving science. Among the different solutions, technical and economic reasons, as well as political reasons, since the global character of the project, drive the final choose.

The first idea leading to SKA dates back to 1993, when the International Union of Radio Science (URSI) promoted the formation of an international working group to define scientific and technical specifications for a next generation of radio observatory. In the years from 1995 and 2008 the participation of 11 nations was formalized and a Memorandum of Understanding was signed. The SKA Organisation (SKAO), lead by UK, was established in 2011 and the offices of the Headquarter are located at the Jodrell Bank Observatory, in UK. Participating Nations are Australia, Canada, China, India, Italy, New Zealand, South Africa, Sweden, the Netherlands and the United Kingdom, but more countries probably will joint the SKA Organisation in the next future.

The release of a radio interferometer with a total collecting area of one square kilometre is quite ambitious and expensive. The nature itself of interferometer, however, makes possible to build the array in different phases, to account for the budget

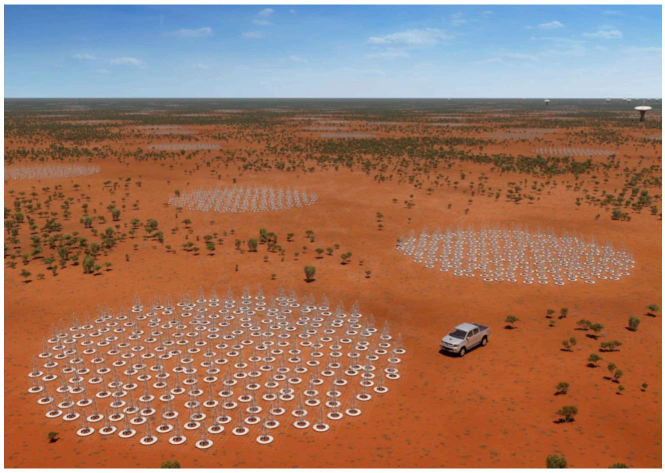

Fig 2 Artist impression of few stations of the low frequency aperture array of SKA, located in Western Australia. There will be a total of more than 2 million of dipolar antennas, grouped into stations with 256 dipoles each to form the array.

and the technology. A first phase is SKA1 [2], with a total collecting area less than 10% of the final and, at the end SKA (or SKA2). The requirement of expansibility to integrate new and old technologies, as well as incorporate pre-existing interferometers (the SKA precursors), adds complexity in the management of the project, in particular in the design process, giving, on the other hand, a “living” instrument.

The frequency covered by SKA1 spans over a wide range, from 50 MHz to 14 GHz. The technologies for the detection of low and high frequencies are not the same. At low frequency, tens to hundred MHz, simple dipoles are used, while at higher frequencies parabolic reflectors are more efficient. For the nature itself of the instruments, SKA is split into different arrays. For SKA1, there will be SKA1-mid at high frequency and SKA1-LOW at low frequency.

Among the radio interferometers, the SKA is the most complex. It is to be thought of as a single telescope that has a Headquarter in UK, where activities, observations and data release are planned, the two arrays SKA1-mid and SKA1-LOW, in South Africa and Australia respectively, and the data centre with many regional centres in all the participating countries.

III. THE TELESCOPE

The Observatory has its Headquarters in Jodrell Bank. SKAO performs the coordination of the operations, and is also responsible for engineering, science, site evaluation, and public outreach.

The organization of the operations, the control of the arrays, the data flow, the correlators and the data processors have the same structure, as shown in Fig. 4. The observations are performed by the dishes for SKA1-MID and the dipoles of LFAA for SKA1-LOW. Signals are locally converted and conditioned and sent to the correlators, which performs the correlations between each couple of detector (dishes for SKA1-MID or stations for SKA1-LOW). The correlated data (visibilities) are eventually sent to the Science Data Processor and sent to Regional Centres in each of the involved countries, which provides the scientific data (maps of the sky at different frequencies, timing for pulsars etc…) that will be used by the scientists.

A. SKA1-LOW

It is located in West Australia, in the Murchison Radio-astronomy Observatory (MRO), a desert region far from electromagnetic pollution due to human activities. It will operate at frequencies in the range 50-350 MHz. Although the radio frequency interferences (RFI) are a problem in the whole radio band, it is particularly important below 1 GHz where there is forest of strong interferences. The number of dipoles is about 130.000.

The main scientific goal at low frequency is the detection and the study of the highly red-shifted 21 cm (1420,405 MHz) hyperfine line of neutral hydrogen from the Epoch of Re-ionization and earlier, to study the distribution and the evolution of the matter from redshift z=28, corresponding approximately to 100 million years after the Big Bang up to the formation of the fists stars and galaxies. The foreseen signal is very low and in addition, the background is very high due to the strong galactic synchrotron emission.

Simple dipoles are efficient at low frequency, with a maximum effective area proportional to λ^2, but are not directive. To overcome this problem, the *beamforming* technique has been developed. The dipoles are grouped in stations containing 256 sparse randomly spaced antennas, with typical distance of meters; the signal from each dipole, after conversion, is sent to a local correlator that apply a phase delay so that the signals from all the dipoles are coherent only in one direction of the sky, forming a *beam*. The signal from each station (beam) is then sent to the central correlator. The maximum distance between stations is about 40 km. It is important to note that the *beamforming* technique permits simultaneous observations in different positions of the sly. Only the current computing capabilities limits the possibility of simultaneous observations of the whole sky. The amount of data transported to the central correlator is impressive, reaching about 150 terabytes per second, corresponding to five times the current Internet traffic. Compared with the most sensitive interferometer operating at the present (LOFAR, in the Netherlands) SKA1-LOW will have an angular resolution 25% better, sensitivity 8 times better and a capability to observe large areas of sky (survey-speed) 135 times better.

B. SKA1-MID

It is located in South Africa, in a desert region north of Cape Town, Karoo. It will consist of a total of about 200 dishes, spread in an area 120 km wide. SKA1-MID will include the 64-dish array MeerKAT, a precursor of SKA, consisting of 64 dishes of 13 m of diameters, which is currently under construction. The Dish is a Gregorian offset telescope, that offer the maximum collecting area, with a secondary mirror about 5 m of diameter focusing the radiation to the feed system. SKA1-MID will operate at frequencies in the range 350 MHz- 14 GHz, divided in 5 observing bands. Single pixel receiver feeds at different bands are mounted in a rotating carousel, alternatively positioned in the focus. The signal is locally converted and conditioned and sent to the central correlator via optical fiber. The amount of data transported to the central correlator reaches about 2 terabytes per second and, compared with the most sensitive radio interferometer (JVLA, USA) SKA1-MID will have an angular resolution 4 times better, sensitivity 5 times better and a survey-speed 60 times better.

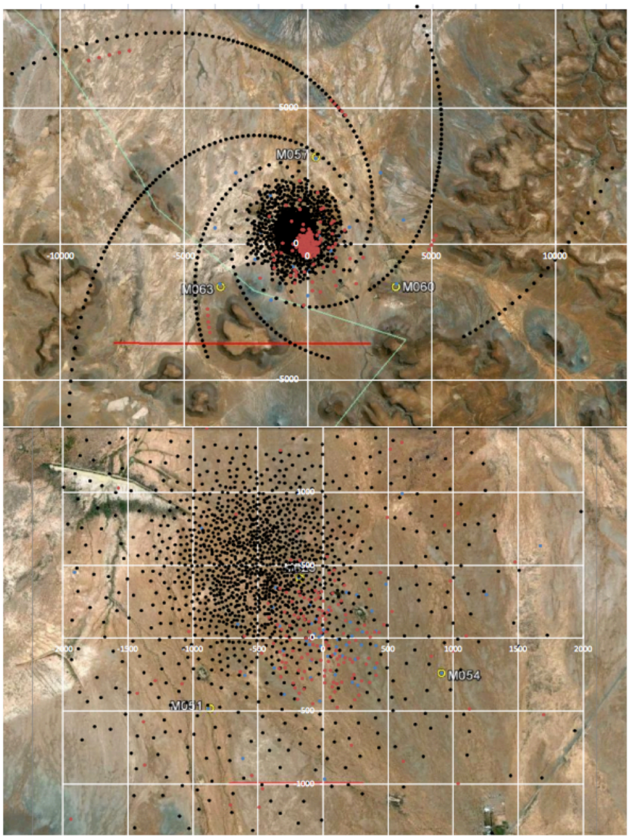

Fig 3. A possible SKA configuration including the SKA1-MID array. In the central area of the array (lower panel) the density of telescopes is higher and are pseudo-random distributed. Distant telescopes will be located in spiral arms (upper panel), with increasing distance, where optical fibers and power lines will be displaced. Red and black dots indicate SKA1-MID and SKA2-MID dishes respectively. Similar configuration is designed for SKA-LOW.

In the second phase of SKA, the array will be extended to other African countries (Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia and Zambia), to reach very high angular resolution (of the order of milliarcseconds). The dishes will be equipped with phased array feed (PAF) in the focal plane, which create 30 separate (simultaneous) beams with the beamforming technique to give a field of view of 30 square degrees. In addition, Mid-frequency aperture array antennas (MFAA), currently under development, will be installed in South Africa. It will cover a frequency range between SKA-MID and SKA-LOW, starting from around 400 MHz. As for LFAA, the detectors will consist of dense array of contiguous dipoles, whose signals will be combined with the technique of the *beamforming*.

C. SKA Precursors

New generation radio interferometers have been installed, or are currently being installed, in the sites of Australia and South Africa. At MRO (Australia) there are two SKA precursors, one at low frequency, the Murchison Widefield Array (MWA), operating between 80 and 300 MHz, and the Australian SKA Pathfinder (ASKAP), consisting of 36 12 metre dishes, equipped with PAFs operating between 700 MHz to 1.8 GHz. At Karoo (South Africa) the MeerKAT array is already under construction. The 64 dishes will be included into SKA1-MID.

D. Array Configuration

The angular resolution of a telescope is given by the ratio λ/D, where λ is the wavelength and D the diameter of the aperture of the telescope. Given the big wavelength at the radio band, the resolution is very low even for the biggest radiotelescope. However, since the signal can be easily treated electronically, the possibility to correlate signals from two telescopes increases the resolving power, as D is the distance between them (baseline). Radio interferometers include large number of telescopes. Each couple of telescopes is sensitive to particular fringe spacing, and the wide range of baselines, and therefore spatial frequencies, simulates a single larger telescope whose size is given by the maximum distance between the elements. The best images of the sky can be obtained when the elements of the array are distributed in a pseudo-random configuration. Short baselines give sensitivity to the large angular scales, while long baselines determinate the angular resolution of the array. In the arrays of SKA, the density of the elements falls off approximately as a Gaussian distribution, with the higher concentration at the centre. Distant telescopes/stations are located in spiral arms, optimizing their distribution and the path of the signals and electric power.

IV. Managing the Complexity

The SKA is a complex telescope, a challenge both in terms of science and technology, as well as organisation, being a project involving several scientific organisations and industrial companies spread in the world, with different laws and social background. Broadly speaking, the complexity involves:

- definition of the scientific goals, and therefore scientific requirements;
- definition of the sites for the management, the arrays and the data processing;
- definition of the instrument, with a clear Product Breakdown Structure end definition of the “Arrays”, the “Elements” and “Sub-Elements”;
- definition of the interfaces between Elements and, inside them, Sub-Elements;
- definition of consortia for the design process;
- development of the technology for all the devices, including dishes, dipolar antennas, receivers, feeds, correlators, communication systems, optical fibers etc…, in order to match the requirements;

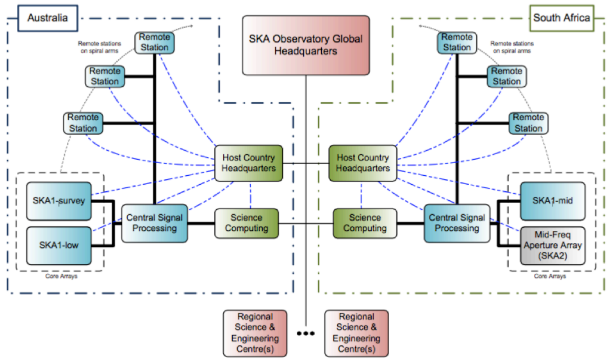

Fig. 4. Schematic view of the SKA Observatory. The Headquarter of the Observatory is located in Jodrell Bank (UK), the two arrays in Australia and Africa and the overall organisation is shown.

- definition of the software for control and monitoring of the system, for the data transfer between receivers and correlators, for the correlators and, last but not least, the Science Data Processor, which is the Element that produces scientific data;
- definition of the procedures for the observations, of the Science Key Project and the rules from call for proposals to observations and data release;
- definition of an Inter Governative Organisation (IGO) and all the rules for a smooth construction and running of the telescope.

A. The Design process

1) The Consortia

At the moment of writing, SKA is in the pre-construction phase, which began in 2013 and shall end in 2019. The goal is to converge towards a solid, reliable final design before starting construction. This process started after the design document [2] was released, with the analysis of the requirements and the definition of the Product Breakdown Structure of SKA. Eleven consortia have been formalized in 2013. They are: Assembly, Integration and Verification (AIV); Central Signal Processor (CSP); Dish (DSH); Infrastructure in Australia (INAU); Infrastructure in South Africa (INSA); Low-Frequency Aperture Array (LFAA); Mid-Frequency Aperture Array (MFAA); Science Data Processor (SDP); Signal and Data Transport (SaDT); Telescope Manager (TM) and Wideband Single Pixel Feeds (WSPF).

2) The Interfaces

Each consortium has the task of design a particular element. However, the interfaces between elements are among the most important parts of the project. In each array, there are two main streams of data. The first is the control and monitor (C&M) data flow for the management of the observations, monitoring of the status, maintenance and other. This involves TM, the SaDT with the optical fiber connections, the Infrastructures (INAU or INSA) the receptors (LFAA, MFAA od DSH) with the LMCs and the receivers and the structure of the receptor itself. This example gives the complexity of the simplest group of interfaces for a specific task. The second example is about the interfaces for the acquired data. This more complex and involves the feeds that acquire and amplify the RF signal, the receivers that digitalize the signal and sent via optical fiber (SaDT) to the central correlator (CSP).

3) Interaction between groups

Engineering meetings have been held each year during the pre-construction phase. They are an important moment to discuss the status of the project, to meet people working in different consortia, discuss about interfaces and organize future works. In addition, each consortium has a tight schedule and regular meetings are held via teleconferences, both for Management and for System Engineering. Exchange, revision, discussions of documents, better definition of requirements and of interfaces, hardware and software development and tests are the major activities of the engineering teams. The work is quite heavy but, at the same time, it gives the security of a robust approach.

4) Costing revision

A continuous analysis of the costs is performed in order to align the design with the cost cap of 650 M€ for SKA1. A re-baseline was necessary in 2014, after the definition of the scientific priorities that occurred after the conference "Advancing Astrophysics with the SKA" [3,4] held in Naxos, Sicily, Italy.

5) Towards the construction of SKA

The CDR of all the Elements and of the SKA itself is planned in 2019, and then there will be a "bridge period" of few months from the end of the pre-construction phase, when the consortia will be formally released, and the beginning of the construction phase, that will start with the first construction contracts being awarded, in 2020.

B. The role of Italy in the Design phase

Italy is involved in four consortia, namely DSH, LFAA, CSP and TM. The National Institute for Astrophysics (INAF) leads all the Italian activities, including the industrial companies.

In the DSH consortium there are four Sub-Elements, namely the Dish Structure (DS), the Single Feed Pixels (SPF), the Single Feed Pixels Receiver (SPFRx) and the Local Monitor and Control (LMC). The leader of the team developing DSH.LMC is the author of this paper. DSH.LMC is the interface with TM and the other sub-elements of the Dish. It is the central brain of the Dish: it has the responsibility of the communication with the TM, receiving the commands for operating modes, setup of the Dish and the other sub-elements, sky coordinates and more. It monitors, aggregates the information and reports to TM the status of each sub-element and of the whole Dish. All the metadata necessary for calibration purposes are sent to TM.

The work of LMCs is mainly software and requires a continuous interaction with the other LMCs and TM. For this reasons working groups involving people of different consortia have been created, in order to share a common software platform across SKA as well as exchange of codes and problem solving. This approach gives a further security and solves for the problem of a big community sparse around the world.

From the perspective of a research institution as INAF, the responsibility to lead DSH.LMC gave us the opportunity to acquire a deep knowledge of the control systems for large astronomical facilities, as well as system design and modeling and software architecture. Thanks to the collaborations started during this period with other groups inside the project and with the Tango Control System collaboration [5], the LMC team can now lead the development of control systems for other important projects.

C. Preparation for Science

Scientists are conscious of the complexity of the SKA and exited by the potentiality of the instrument. Science Working Groups (SWGs) have been created, including scientists from all over the world, in order to discuss and get ready for the observations and data analysis. There are 13 SWG to date, including science from the Sun to the Cosmology. One of the main goals is the definition of Key Science Projects (KSPs) for the SKA. Part of the community is working with SKA pathfinders and precursors, the last being includes in the SKA.

Shared risk observations will start after a period of commissioning that should start in 2022, followed by science verification in 2014. Normal PI observations and KSP should start in 2015.

V. The Technological Challenge of SKA

The complexity of the system is a big challenge. SKA involves many countries and different institutions and industries in the entire world, with thousands among scientists and engineers working on its realization.

The location of the two arrays, in two desert regions, is a problem for the accessibility, the infrastructure, including power management, data transport, deployment and maintenance. Dishes and antennas are designed to work in extreme conditions for at least 50 years. Dishes have to be deployed in almost inaccessible regions and their design must take into account agile transport and installation.

The management of the huge data amount (hundred of terabytes per second) and the data transport (about one order of magnitude more than the current global internet traffic) are one of the biggest technological challenges of SKA and require exceptionally high-speed computer.

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