The Science and Technology of the Square Kilometre Array

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Abstract. I discuss the science and engineering of the Square Kilometre Array (SKA), the next generation astronomical observatory for studying the structure and evolution of the Universe. I give an overview of the SKA Key Science areas and map them onto the instruments that are being developed for these investigations. I outline where the SKA is being built and how the international community is developing the project. I discuss a range of SKA pathfinder and precursor telescopes that are currently being built or are operational, helping to inform SKA engineering, ICT and astrophysics.

1. Introduction

This article follows the keynote presentation I gave at the “RADIO2014” conference. The presentation was a broad overview of Square Kilometre Array (SKA) science and engineering and, likewise, this written account is broad and shallow, given the limited length of the article.

When we humans gaze at the night sky, our eyes detect photons in a very narrow wavelength range, approximately 650 to 1200 nanometres. Consider the image in Figure 1, a photograph of the southern Milky Way (our Galaxy), which reveals huge amounts of gas, dust and stars in our Galaxy due to thermal emission processes associated with these objects.

As spectacular as Figure 1 is, it only reveals one small part of the information available to astronomers. Other parts of the electromagnetic spectrum, such as in the high energy photon regime (X-ray and gamma-ray) and low energy photon regime (radio waves) give very different information for the same objects. For example, when we look at the southern Milky Way in X-rays we see high-energy particles and processes such as the accretion of material onto Black Holes and other compact objects. At the other end of the electromagnetic spectrum, many objects and processes produce radio waves (wavelengths greater than approximately 1 millimetre) that can be studied using radio telescopes.

Modern radio telescopes are configured as arrays of individual elements (either small dish elements or low frequency antennas) and used as interferometers. See [1] for an explanation of interferometry. In this way, radio telescopes can be built with large collecting areas (and thus high sensitivity) with elements spread over large geographic regions (leading to high angular resolution imaging). Instruments such as the Australia Telescope Compact Array (ATCA: [2]) and the Low Frequency ARay (LOFAR: [3]) are examples of multi-element interferometers using dishes and low frequency dipoles, respectively.
Figure 1: The southern Milky Way, as seen from Australia’s SKA site in Western Australia, at wavelengths of light to which human eyes are sensitive (credit: the author).

The Square Kilometre Array (SKA) takes the idea of interferometry into new territory, with the construction of radio telescopes consisting of hundreds to millions of individual elements spread over hundreds to thousands of square kilometres.

2. The Square Kilometre Array (SKA) – the science

The SKA is a project to construct the largest and most sensitive radio telescope ever built, supported by an international community of 10 countries. A great deal of information on the SKA project, including material covered in summary form below, is available on the SKA web pages: http://www.skatelescope.org.

The science of the SKA is aimed at an exploration of fundamental astrophysics and physics and falls into five main areas:

(1) How do galaxies evolve? What is Dark Energy? Only approximately 5% of the content of the Universe is made up of baryonic material. The remaining 95% of the Universe is made up of Dark Matter (~25%) and Dark Energy (~70%), for which physics has no generally accepted explanation. The SKA will attempt to investigate the properties of Dark Matter and Dark Energy by watching how galaxies evolve over cosmic time, tracing the effects of Dark Matter in galaxies and by tracing the geometry of space-time and its relationship to Dark Energy.

(2) Was Einstein right about gravity? The SKA will be used to hunt for new pulsars, the rapidly spinning remnants of massive stars at the end of their lives. Pulsars have extremely strong gravitational fields and can be used as laboratories for tests of theories of gravity, including the highly successful general theory of relativity.
(3) What generates giant magnetic fields in space? Magnetic fields exist on all spatial scales in nature, including on the largest scales of hundreds of thousands or millions of light years (the scales of galaxies or clusters of galaxies). The origin of these magnetic fields is unclear as is their relationship to magnetic fields on much smaller scales. The SKA will be able to examine magnetic fields on all astrophysical scales, including the largest scales.

(4) How were the first stars and black holes formed? After the Big Bang, the Universe cooled to the point where neutral hydrogen filled the Universe. Over the first billion years of the Universe, this gas, acting under the influence of gravity, likely caused by Dark Matter, formed into the first luminous objects – stars, black holes and galaxies. Using low frequency radio waves, the SKA can look back in time into the first billion years to provide a unique view of this era in the Universe’s history.

(5) Are we alone? The SKA will be sensitive enough to detect stray radio emission from communications systems that may exist on other planets, assuming that those transmitters are similar to those developed by humans on earth. Thus, the SKA will provide the best yet search for extraterrestrial signals. Further, the SKA will be used to explore the process of planetary system formation and studies of astrobiology, some of the fundamental building blocks of life (as we know it) in the Universe.

All of these science drivers require very high sensitivity and very good angular resolution over a substantial range in radio frequency, from ~100 MHz to ~10 GHz. As such, the science requirements translate into a very challenging set of technical requirements. The next section of this paper briefly discusses the technology required for the SKA.

3. The Square Kilometre Array (SKA) – the technology
The SKA will be built in two locations, Southern Africa and Western Australia. Both locations have been chosen because they have very low levels of interference from human activities that produce radio waves (mobile phones, telecommunications, industry activity, automobiles etc) many orders of magnitude stronger than the astronomical signals sought. Both these locations are therefore remote.

The SKA will also be built in two stages, Phase 1 and Phase 2. Phase 1 is nominally approximately 10% of the full SKA scope, with the remaining 90% slated for construction in Phase 2. The breakdown of SKA construction is as follows:

**Southern Africa, Phase 1:** An array of approximately 250 dishes of order 13 m diameter, operating in the 0.35 – 3.0 GHz frequency range, will be built using traditional single pixel feed technologies. This telescope is known as SKA-mid.

**Western Australia, Phase 1:** An array of approximately 100 dishes of order 12 m diameter, operating in the 0.65 – 1.7 GHz frequency range, will be built using a new technology known as Phased Array Feeds (PAFs). Whereas single pixel feeds give a single field of view, PAFs provide a large number of independent fields of view, covering a large area of sky compared to a comparable single pixel feed telescope. This telescope is known as SKA-survey.

Additionally in Western Australia, a low frequency radio telescope will be built using approximately 200,000 dipole antennas operating in the frequency range 0.05 – 0.35 GHz. The low frequency telescope is inherently a very large field of view instrument and is known as SKA-low.

**Southern Africa, Phase 2:** SKA-mid will be expanded to approximately 2,700 dishes. An additional instrument will be built in Phase 2, consisting of approximately 250 stations made of dense aperture arrays, similar to the low frequency array but at higher frequencies.

**Western Australia, Phase 2:** SKA-low will be expanded to approximately 2,000,000 dipole antennas.

The exact specifications for each telescope are to be determined over the next few years in the final SKA design stage. Each of these instruments are of a scale never before constructed and offer technical challenges across electrical and electronic engineering (RF and digital systems), power...
engineering (provision of electricity to significant remote infrastructure), civil engineering, information and communication technologies (computing and advanced networking), and algorithm development.

The scale of the SKA is such that we do not embark directly upon its construction. Three official SKA Precursors are being built on the two SKA sites. In Southern Africa, MeerKAT is being built as a Precursor for SKA-mid. In Western Australia, the Australian SKA Precursor (ASKAP: [4]) is being built as a Precursor for SKA-survey and the Murchison Widefield Array (MWA: [5]) has been built as a Precursor for SKA-low and is currently the only one of the three Precursors to be operational for science. These Precursors are proving the science and technology for the SKA, in advance of SKA construction. An additional SKA Pathfinder not located at one of the SKA sites is LOFAR, based in The Netherlands.

Finally, in preparation for SKA construction, the international community is funded to undertake the final coordinated SKA design and prototyping activities, an official project phase known as pre-construction. Pre-construction will continue for three or four years, resulting in tender-ready specifications for SKA construction. Pre-construction activities make heavy use of industry collaborators and the eventual SKA construction will engage industry at a fundamental level, as the scale of construction is well beyond the capabilities of astronomical research institutes.

4. Conclusions
The SKA is the biggest ever project in radio astronomy and one of the largest mega-science projects currently being pursued around the world; it is an international endeavour to pursue fundamental physics and will have many technological spin-offs that are likely to have significant impact outside astronomy or physics.

5. References
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