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The SKA: A modern equivalent of the Antikythera Mechanism?

Richard Schilizzi
University of Manchester
Manchester, UK
E-mail: richard.schilizzi@manchester.ac.uk

The Square Kilometre Array is a large next generation radio telescope that promises to be many times more sensitive than the current most sensitive telescopes in the world and transform our view of the universe. It is a global mega-science project involving scientists and engineers from institutes and industry partners in more than 20 countries. The current status of the project is described and comparisons made with the Antikythera Mechanism and other larger scale projects in antiquity. Obvious conclusions are that the SKA is equivalent to the Antikythera Mechanism in being at the forefront of human ingenuity for its time, but it is much more advanced in terms of project complexity. However, the SKA is not obviously more complex in terms of management and planning compared to a project such as the Hagia Sophia church built in five years in the 6th century CE in present-day Istanbul.

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1. Introduction

The Square Kilometre Array (SKA) will be a radio interferometer with an aggregate collecting area of about 1 million square metres spread over at least 3000 km and operating in the frequency range ~70 MHz to 10 GHz (and possibly 30 GHz in the future). It is one of a small number of flagship astronomical instruments that will span the entire electromagnetic spectrum from radio to gamma rays, and beyond the electromagnetic spectrum to gravitational waves, cosmic rays and neutrinos, and whose collective aim is to chart the full history of the universe from its beginnings in the Big Bang to the present day.

Figure 1. Flagship astronomical instruments: in operation (ALMA), under construction (JWST, multiple ELTs), in the detailed planning stage (SKA), and in early planning (Athena).

The SKA had its genesis in 1991 with three publications in 1991 by Swarup, Noordam et al, and Wilkinson [1, 2, 3] on the need for a large collecting area radio telescope to study the neutral hydrogen content in the early universe, and its subsequent evolution. Underpinning these papers was the recognition that probing the fundamental baryonic component of the Universe much beyond the local Universe would require a substantial increase in collecting area. The translation of these ideas to a concept instrument began in 1993 with the establishment of a Large Telescope Working Group by the Commission for Radio Astronomy in the International Union for Radio Science (URSI) to study the next generation radio telescope. This was followed two years later with the first allocation of funds for engineering development, in the Netherlands, for aperture array technology. The first international engineering meeting was held in Sydney in 1996, and the first agreement to collaborate on SKA technology on a global scale was also signed in 1996. The SKA has evolved over the intervening years from a simple “hydrogen array” observing at frequencies near 1.4 GHz, to a multi-facetted science facility capable of answering many of the major questions in modern astrophysics and cosmology, physics, and astrobiology.

The SKA began as a global "grass-roots" initiative and now encompasses about 70 institutes in 20 countries. Work on the project is now managed by the SKA Organisation, a company established in the UK early in 2012 with funding agencies or government departments in eight countries as Members. The Board of the SKA Organisation is responsible for the oversight of the entire project. The Office of the SKA Organisation reports to the Board and coordinates the engineering, science, and site development work carried out around the world.

The project has attracted substantial national and regional funds for technical R&D, including major design/preparatory studies in Europe (SKADS and PrepSKA), the USA (Technology Development Program) and Canada as well as the design and construction of few-percent SKA scale pathfinder telescopes in a number of countries. Additional substantial funding is now being made available for the detailed design of the telescope in the Pre-Construction Stage (2012-5). The current project timeline has the telescope fully operational in 2024 at frequencies below 10 GHz.

A concerted effort by the science community in 2004 resulted in the publication of "Science with the SKA" (Carilli and Rawlings (eds), 2005), a 49-chapter compendium of the astrophysics and cosmology enabled by the SKA which provides the motivation for constructing the telescope. The science cases that set the envelope for the technical requirements have been summarised as science requirements for the telescope in a document called the Design Reference Mission (www.skatelescope.org).

The SKA will be sited in Australia and in Africa, with Western Australia as the location of the low frequency array and the Northern Cape Province in South Africa as the location of the central part of the dish array.

The following sections outline many of the aspects touched on in this introduction. Much of the material has been drawn from a number of key SKA publications [4, 5, 6]**.** The paper concludes with some reflections on the SKA and the Antikythera Mechanism, as well as large scale projects in antiquity.

2. Science, Engineering and Economic Context

To be successful in these modern times, large and expensive projects like those in Figure 1 have to satisfy a number of quite different and sometimes conflicting demands. First and foremost is the requirement to address what are preceived to be the fundamental scientifc challenges and thereby transform our understanding of the universe.

Addressing these fundamental challenges requires big machines that push the boundaries of what has been done before. But a balance of innovation and current state-of-the-art is needed in order that the schedule and budget remain predictable.

The funding climate is obviously crucial and dependent not only on the economic cycle but also national and supra-national (in the case of the European Union) requirements that large science projects contribute to the economic well-being of the funding countries directly though contracts, but also by stimulating innovation, and building capacity by training young scientists and engineers. In a global project, transfer of substantial funds across national boundaries to a central project organisation is not straightforward, and this often means that participation is by "in-kind" contributions.

3. Science

From the wider science case [7], a select set of investigations - Key Science Projects - have been identified [8] in which centimetre- and metre-wavelength observations are required to make fundamental progress in outstanding questions of modern astronomy, physics, or astrobiology. The five Key Science Programs are the following:

3.1 Probing the Dark Ages: As the first stars and galaxies formed, their ionizing UV radiation produced a fundamental change in the surrounding intergalactic medium, from a nearly completely neutral state to the nearly completely ionized Universe in which we live today. The most direct probe of this era, the Epoch of Re-ionization (EoR), and of the first large-scale structure formation, will be obtained by imaging neutral hydrogen and tracking the transition of the intergalactic medium from a neutral to ionized state.

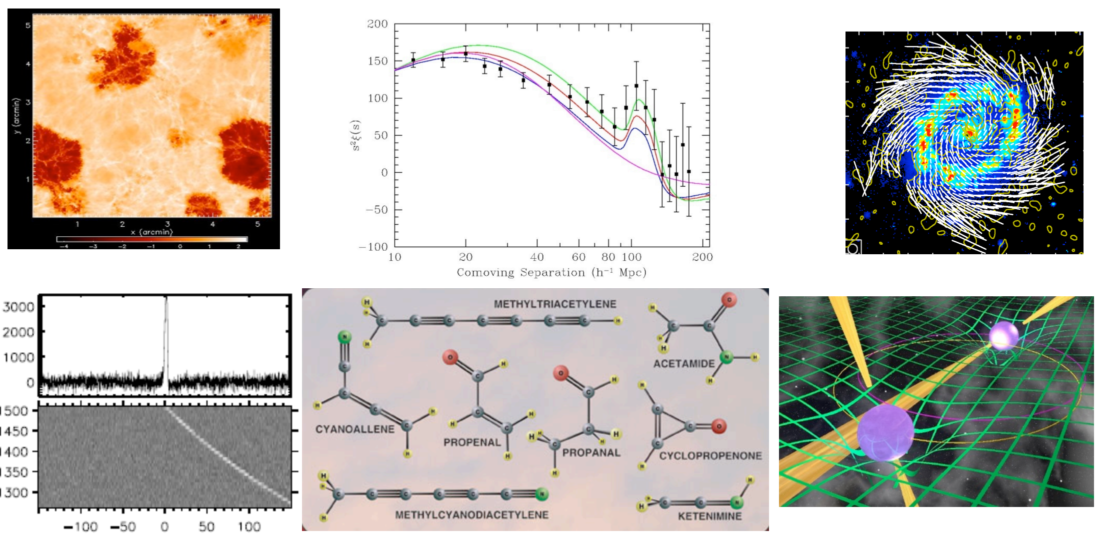

Figure 2. Key Science Projects for the SKA. Clockwise from top left: Probing the Dark Ages – simulation of the epoch of re-ionisation; Galaxy Evolution, Cosmology and Dark Energy – detection of the baryonic acoustic oscillations in the Sloan Digital Sky Survey; origin and Evolution of Cosmic Magnetism – magnetic field distribution in a spiral galaxy; Strong Field Tests of Gravity Using Pulsars and Black Holes – artist's impression of the double pulsar (neutron star binary) and associated distortions of space-time; Cradle of Life – complex pre-biotic molecules; and Exploration of the Unknown – a rotating radio transient.

3.2 Galaxy Evolution, Cosmology and Dark Energy: Hydrogen is the fundamental baryonic component of the Universe. With a sensitivity to the 21-cm hyperfine transition of H I allowing detection out to redshifts $z > 1$, the SKA will both follow the assembly of galaxies as well as use their H I emission as a scale tracer for cosmological probes. One of the key questions is the assembly of galaxies; the SKA will probe how galaxies convert their gas to stars over a significant fraction of cosmic time and how the environment affects galactic properties. Simultaneously, baryon acoustic oscillations (BAOs), remnants of early density fluctuations in the Universe, serve as a tracer of the early expansion of the Universe. The SKA will assemble a large enough sample of galaxies to measure BAOs as a function of redshift to constrain the equation of state of dark energy.

3.3 The Origin and Evolution of Cosmic Magnetism: Magnetic fields likely play an important role throughout astrophysics, including particle acceleration, cosmic ray propagation, and star formation. Unlike gravity, which has been present since the earliest times in the Universe, magnetic fields may have been generated essentially *ab initio* in galaxies and clusters of galaxies. By measuring the Faraday rotation toward large numbers of background sources, the SKA will track the evolution of magnetic fields in galaxies and clusters of galaxies over a large fraction of cosmic time. In addition to elucidating the role of magnetic fields in galaxies and clusters of galaxies, the SKA observations will seek to address whether magnetic fields are primordial and dating from the earliest times in the Universe or generated much later by dynamo activity.

3.4 Strong Field Tests of Gravity Using Pulsars and Black Holes: With magnetic field strengths as large as 10^{14} G, rotation rates approaching 1000 Hz, central densities exceeding 10^{14} g cm^{-3}, and normalized gravitational strengths of order 0.4, neutron stars represent one of the most extreme laboratories in the Universe. Their utility as fundamental laboratories has already been demonstrated through results from observations of a number of objects. The SKA will find many new milli-second pulsars and engage in high precision timing of them in order to construct a Pulsar Timing Array for the detection of nanoHertz gravitational waves, probing the spacetime environment around black holes via both ultra-relativistic binaries (e.g., pulsar-black hole binaries) and pulsars orbiting the central supermassive black hole in the centre of the Milky Way, and probe the equation of state of nuclear matter.

3.5 The Cradle of Life: The existence of life elsewhere in the Universe has been a topic of speculation for millennia. In the latter half of the last century, these speculations began to be informed by observational data, including the discovery of organic molecules in interstellar space, and proto-planetary disks and planets themselves orbiting nearby stars. With its sensitivity and resolution, the SKA will be able to observe the centimetre-wavelength thermal radiation from dust in the inner regions of nearby proto-planetary disks and monitor changes as planets form, thereby probing a key regime in the planetary formation process. On larger scales in molecular clouds, the SKA will search for complex prebiotic molecules. Finally, detection of transmissions from another civilization would provide immediate and direct evidence of life elsewhere in the Universe, and the SKA will provide sufficient sensitivity to enable, for the first time, searches for unintentional emissions or "leakage."

3.6 In addition, recognizing the long history of discovery at radio wavelengths (pulsars, cosmic microwave background, quasars, masers, the first extrasolar planets, etc.), the international science community also recommended that the design and development of the SKA have **"Exploration of the Unknown"** as a philosophy. Wherever possible, the design of the telescope is being developed in a manner to allow maximum flexibility and evolution of its capabilities in new directions and to probe new parameter space (e.g., time-variable phenomena

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that current telescopes are not equipped to detect – radio transients). This philosophy is essential as many of the outstanding questions of the 2020–2050 era—when the SKA will be in its most productive years—are likely not even known today.

4.Technical requirements and design development

4.1 Snapshots of Science and Technical Requirements

Following on from the science case, the top-level science requirements are:

Frequency/wavelength range	70 MHz(4 m) – 10 GHz(3 cm)
Field of View	at least 1 square degree at 1 GHz
Sensitivity: effective collecting area /system temperature	10,000 m^2K^{-1}
Survey speed	10^{10} $deg^2m^4K^{-2}$

The related top-level technical requirements are:

Collecting area	1 million m^2
Overall size – longest baseline	at least 3000 km
Number of dishes	2500 - 3000
Number of low aperture arrays at low and mid-frequencies	250 each
Signal transport volume	up to 10 petabit/s (10^{16} bit/s)
Signal processing	exa-MACs (10^{18} multiply-accumulates/sec)
High performance computing	exa-flops (10^{18} floating point operations/sec)
Data storage capacity	exa-bytes (10^{18} bytes)
Power requirements	100 MW

The main elements of the system design are dishes + feeds & receivers, aperture arrays, signal transport, signal processing, synchonisation & timing, software engineering and algorithm development, high performance computing, data storage, and power delivery. The conceptual block diagram for the SKA is shown in Figure 3, artist's impressions of the central

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cores of the dish array, the low-frequency aperture array and the mid-frequency aperture array in Figure 4, and some pictorial highlights of the current design and prototyping efforts for antennas and feeds around the world are presented in Figures 5, 6 and 7. For an in-depth discussion of these and other areas of the system design, refer to the 2009 IEEE article by Dewdney et al [5].

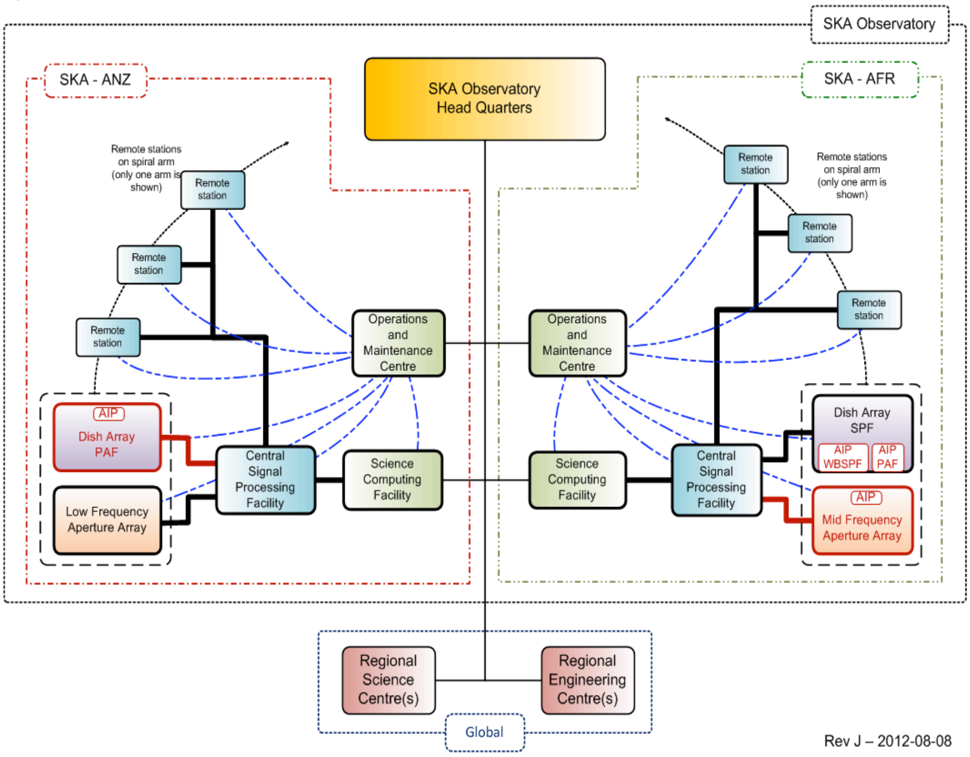

Figure 3. The conceptual block diagram for the SKA showing the design elements to be located in Australia + New Zealand (left-hand side) and in Africa (right-hand side). The low frequency array and a survey array (dish + phased array feeds) will be located in Australia while the dish array and mid-frequency aperture array will be located in Africa. Less-mature elements of the design are shown in red and are part of the Advanced Instrumentation Program (AIP). The Figure also shows the location and interconnection of major components, and the flow of data from the antennas to the signal processing facility, and off-site to a computer facility. Control interconnections between the Operations and Maintenance Centre and on-site components are not shown.

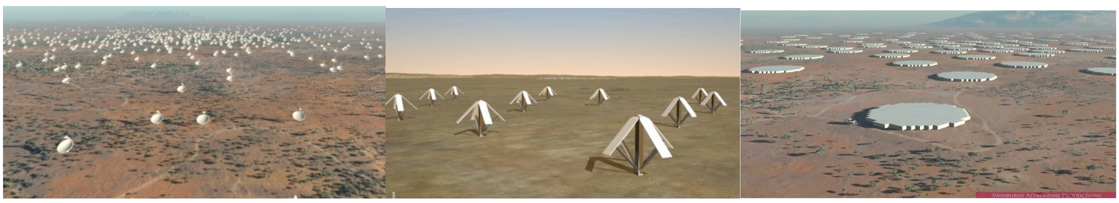

Figure 4. Artist's impressions of the core region of the dish array (left), low-frequency aperture array (middle), and mid-frequency aperture array (right). The dish and low-frequency aperture arrays constitute the Baseline Design, the mid-frequency aperture array is under development in the Advanced Instrumentation Program (AIP).

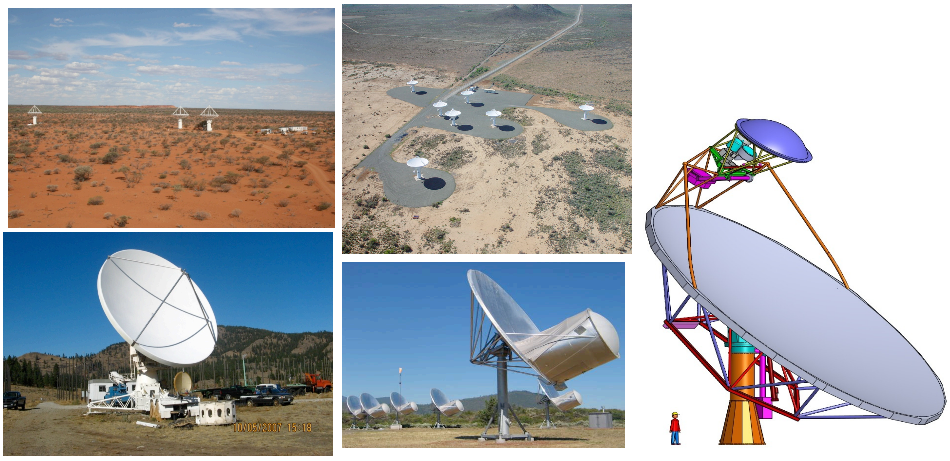

Figure 5. Baseline Design: dishes + single pixel feeds. Examples: clockwise from top left - Australian SKA Pathfinder 12m symmetric panelled dish with 3-axis rotation (36 deployed); MeerKAT Array (South Africa) 13.5m panelled dish (64 to be deployed); computer drawing of SKA Dish Verification Antenna #1, prototype offset-fed 15m composite dish with accommodation for both single pixel and phased array feeds (under construction); Allen Telescope Array (USA) 6m offset-fed hydro-formed dish (42 deployed); and Canadian 10m prototype symmetric composite dish.

Figure 6. Baseline Design: low frequency aperture array. Examples: left - aerial view of the central station for LOFAR in the Netherlands; right – one of the stations of the Murchison Wide-Field Array (MWA) in Australia.

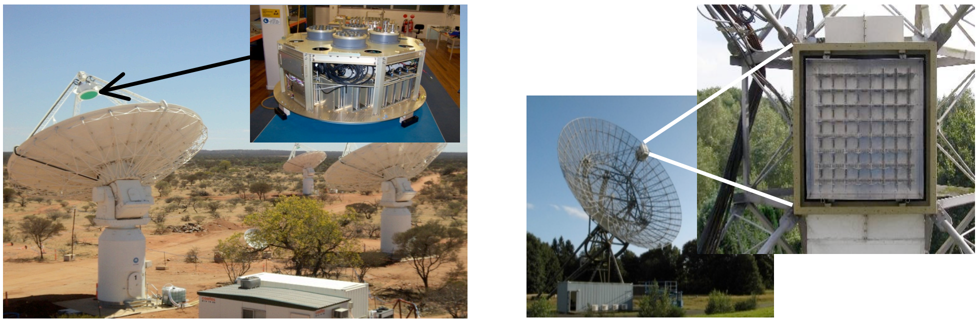

Figure 7. Advanced Instrumentation Program: dual polarisation phased array feeds for reflector antennas. Examples: left - chequer board array shown deployed on on of the ASKAP dishes; right: APERTIF Vivaldi array shown deployed on one of the Westerbork array telescopes.

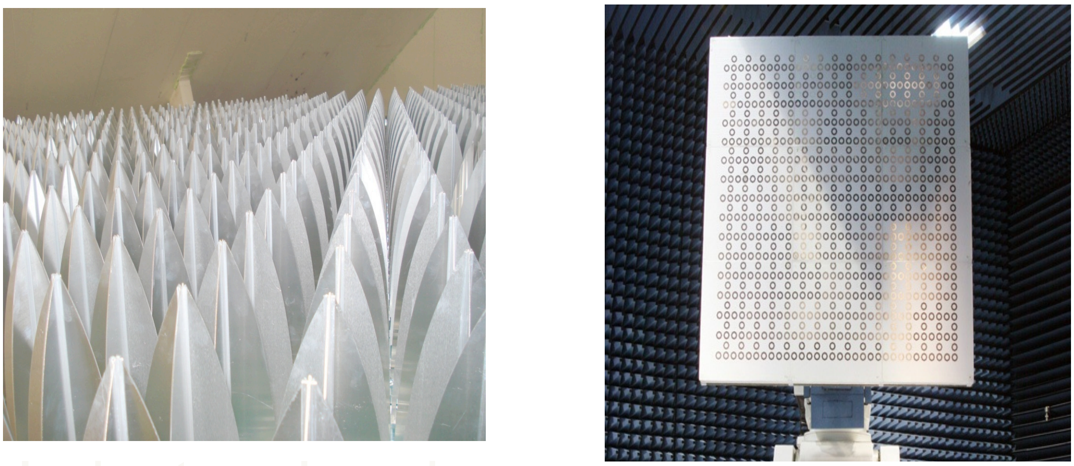

Figure 8. Advanced Instrumentation Program: mid-frequency aperture array development. Left: 80 square metres of the EMBRACE Vivaldi array developed by ASTRON in the Netherlands and partners. Right: 16x16 finite array of Octagonal Ring Antenna (ORA) elements (University of Manchester).

5. Technical development schedule

The SKA schedule can be divided into five separate stages as described below. It should be emphasised that the schedule for stage B and beyond is currently under revision.

A. *Telescope System Design (2008-2012)* in which the initial telescope system design was completed and a Project Execution Plan for Stage B developed. Establishment of the SKA organisation as a legal entity, and selection of the site.

B. *Pre-Construction Stage (2013-2015*) in which final preparations will be made for the start of Phase 1 construction in 2016. This will include system requirements reviews, preliminary and critical design reviews and additional prototyping where necessary. Site infrastructure preparation and initial rollout will occur. System design of the Advanced Instrumentation Program technologies, not included in the baseline design, will continue throughout this period.

C. *Phase 1 Construction, Verification, Commissioning, Acceptance, Integration & First Science (2016-2020)* in which Phase 1 is rolled out and integrated and first science is carried out as part of the commissioning process, starting in 2018 with a sub-array of Phase 1. Science operations with Phase 1 will begin in 2020.

D. *Phase 2 Construction, Verification, Commissioning, Acceptance, Integration & First Science (2020-2024)* in which the construction of the full SKA is completed.

E. *Science operations begin with full array at mid and low frequencies (2024→)*

6. Site selection

Following the short-listing in 2006 of sites in Western Australia and Northern Cape Province in South Africa as acceptable locations for the SKA core, a series of studies of the characteristics of these sites was carried out in preparation for final selection of the site in 2012. These studies included highly sensitive measurements of the radio quietness in the central region as well as selected remote stations, establishment of Radio Quiet Zones covering the central ~200km diameter region, studies of the array configuration, the costs of infrastructure deployment and operations, the impact of physical characteristics of the sites on the design, characterisation of ionospheric turbulence, characterisation of tropospheric water vapour turbulence, and a risk analysis of the science environment with respect to long term interference potential.

Figure 9. The locations of the SKA sites in South Africa (left) and Australia (right).

The decision on the SKA location in 2012 created an "SKA Observatory" with two sites, Australia and Africa. The low-frequency array will be located in Australia, as well as an SKA Phase 1 Survey Telescope incorporating the pre-cursor instrument, ASKAP, and its AIP technology of Phased Array Feeds. The mid-frequency dish array will be located in South Africa and associated countries and will incorporate MeerKAT. If a decision is made to include the AIP mid-frequency Aperture Arrays in SKA Phase 2, they will also be located in South Africa. The incorporation of the pre-cursor telescopes in South Africa and Australia in SKA Phase 1 will maximise the initial science return.

7. SKA Organisation

The SKA Project was transformed on 1 January 2012 from a collaboration amongst academic institutes to a formal organisation registered in the UK as a Company Limited by Guarantee. There are currently (December 2012) nine Members of the Company – Australia, Canada, China, Germany, Italy, Netherlands, New Zealand, South Africa, and UK. The Members own the Company and each Member appoints two representatives on the Board, with the Board being responsible for the operation and solvency of the Company.

8. Funding

Funding for the current Pre-Construction Stage is being made available by the Member Organisations under two headings: 1) a direct contribution to the operating costs of the Office of the SKA Organisation, and 2) national funding of Work Package design activity by academic institutes and industry. A total of about €90M is expected to be spent in this phase, about 30% on SKA Office operations and 70% on Work Package design.

The target cost for Phase 1 of the telescope construction was set four years ago at €350M. This is currently under revision as the consequences of the dual-site Observatory are analysed. The target cost for the full SKA, again set four years ago, was €1.5B. This will also be revised as more understanding of system costs is gained during the Pre-Construction Stage.

9. State-of-the-art projects now and in antiquity

9.1 Are the SKA and the Antikythera Mechanism comparable?

The SKA, like any of the Flagship Projects mentioned in section 1, is a worthy successor to the Antikythera Mechanism as a science and engineering instrument. The SKA will be a device to transform our view of the universe by observing hitherto unknown phenomena in the new parameter space enabled by the telescope, or by observing known phenomena more accurately in the hope of finding deviations from expected behaviour which might lead to refinement of current physics or to new physics.

The Antikythera Mechanism embodied the state of the art astronomical and mechanical knowledge of the time. It could be used to make predictions of eclipses in the future but it was not obviously a machine to make discoveries. Its purpose has been the subject of a number of the contributions to this Workshop. In my view it is likely we will never know whether it was a philosophical or religious demonstration of the workings of the heavens, a device to demonstrate the power of the Greek Empire, an advanced prototype for some other machine, or something else.

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There is also an obvious difference in scale in terms of physical size and in project complexity. So I would argue that the SKA is a modern equivalent to the Antikythera Mechanism in terms of its use of state-of-the-art science and technical knowledge, but that in terms of the level of organisation of human endeavour required to bring a project to completion, the SKA has more in common with the big architectural constructions in antiquity than with the Antikythera Mechanism.

9.2 Big Projects in antiquity

Constructions like the Great Pyramid at Giza, the Great Wall of China, the Parthenon in Athens, and the Hagia Sophia in Constantinople (present-day Istanbul) were all large and complex projects to devise and execute. What do we know about these flagship projects [9, 10]?

Figure 10. Clockwise from top-left: The Great Pyramid at Giza, the Great Wall of China, the Parthenon in Athens, and the Hagia Sophia church in Istanbul (Constantinople).

The Great Pyramid was completed in 2230 BCE as a burial place for the Pharaoh Khufu (Cheops in Greek). Construction took at least 10 and possibly 20 years and estimates of the workforce involved range up to 50000 skilled workers. One study suggests an average workforce of about 15000 and a peak workforce of 40000. The cost is unknown.

The first sections of what became the Great Wall of China were begun in the 7th century BCE and were continued for two thousand years by several Chinese Emperors. A very rough estimate of the peak workforce is 1.8 million [10], a substantial fraction of which is thought to have been soldiers. Again there is no information on the cost.

The Parthenon in Athens was commissioned by Pericles and constructed from 447 to 432 BCE. It is not known how many people were involved, or the cost.

The Hagia Sophia (Church of the Holy Wisdom) in Constantinople/Istanbul was commissioned by the Emperor Justinian I in 532 CE and completed five years later in 537 CE by a highly skilled workforce of 10000 at a cost of 20000 pounds of gold. There is more known about the the Hagia Sophia so let us dwell briefly on this structure.

9.3 Hagia Sophia

It was the main church of the Byzantine Empire for 916 years until 1453 CE, and the main Ottoman Mosque for the subsequent 482 years until it became a museum in 1935. The Byzantine or Eastern Roman Empire was one of the most powerful and long-lasting empires that has ever existed. It exerted cultural, religious, economic and military influence throughout the Mediterranean and the near-East and profoundly influenced the medieval development of western Europe.

9.3.1 Design

The design of the Hagia Sophia is symbolic, incorporating a round dome of state power on the square base of a Christian church. With a length, width and height of 75 x 70 x 56 m and a 30 m diameter dome, it is a spectacular building. The dome is of particular interest. Its "penditive" design transfers the downward thrust of the circular cross-section of the cupola via spherical triangles to the corners of the square supporting structure (Figure 11). The use of this design for the dome is believed to have been unprecedented at the time.

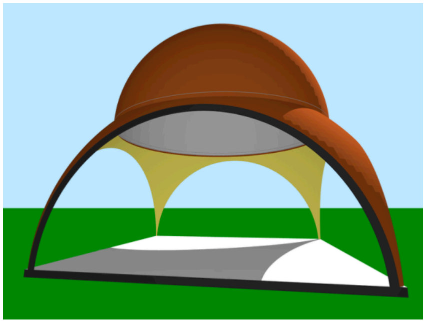

Figure 11. Model of the support structure for the dome of the Hagia Sophia [9].

9.3.2 Project management

The leaders of the Hagia Sophia project were Anthemius of Tralies and Isodore of Miletus, the most acclaimed "architects" of the day, but better described as engineers with a deep knowledge of physics, mathematics, and structures. They reported directly to Emperor Justinian. The workforce of 10 000 included the best artisans from all over the world, and were divided into two teams of 50 master builders and 5000 workers, one team under each architect. The bulk of the cost of the project is said to have gone towards salaries for the workforce. The Emperor had material brought from all over the empire including porphyry from quarries in Egypt, green marble from Thessaly, black stone from the Bosporus region and yellow stone from Syria.

The scope and duration of the project was dictated by the Emperor and reflected his desire to see the building completed in his lifetime. This will have restricted design changes and required tight time and people management. The dome was completed within 3 years which was a major feat of engineering and planning.

The impact of earthquakes was minimized by creating a light flexible building; crushed brick was used in the mortar for high tensile strength, while the bricks were hollowed and made of light-weight clay from Rhodes. However, even these precautions did not mitigate the risk entirely; an earthquake in 557CE caused the dome to collapse. But with a redesign and rebuild from 558-562 CE and additional strengthening actions following subsequent earthquakes, the dome and the whole structure has withstood the test of time since then.

9.4 Project management then and now

Although we have no detailed records of the management of the Hagia Sophia project, Procopius, a contemporary historian writing about the construction, notes that Anthemius "regulated the tasks of the various artisans and prepared in advance designs of the future construction" [11]. We can safely assume that project management in modern times is much the same as in ancient times, albeit with more sophisticated tools available.

Obvious differences between non-military projects then and now are the source and singularity of funding, and the degree of international collaboration. Having a Pharaoh or Emperor as the project director and provider of funds clearly can have the advantage of concentrating resources and shortening timescales.

Acknowledgements

Many people around the world are part of the international SKA project. I would like to acknowledge their contributions, direct and indirect, to the contents of this paper. I would also like to thank the organisers of the meeting for conceiving the idea of relating ancient and modern astronomical instruments in what was a most interesting conference. Finally, I'd like to thank Tasso for turning 60!

References

[1] Swarup G., 1991, Current Science, 60 (2), 106-108

[2] Noordam, J. E., Braun, R., de Bruyn, A. G., 1991, Netherlands Foundation for Radio Astronomy Note nr 585 (available on www.skatelescope.org)

[3] Wilkinson, P. N., 1991, Proceedings of IAU Colloquium 131, ASP Conference Series, Vol. 19,T.J. Cornwell and R.A. Perley (eds.), 428-432.

[4] Schilizzi, R. T., Dewdney, P. E. F., Lazio, T. J. W., 2008, Proceedings of the SPIE, vol 7012, 70121I1-13

[5] Dewdney P. E. F., Hall P. J., Schilizzi R. T., Lazio T. J. L. W., 2009, Proceedings of the IEEE, vol 97, No 8, 1482-1496

[6] Schilizzi, R. T., Dewdney, P. E. F., Lazio, T. J. W., 2010, Proceedings of the Conference on Wide Field Astronomy & Technology for the Square Kilometre Array, November 2009 (Eds. Torchinsky S. et al), 15-22

[7] Carilli C. and Rawlings S. (eds), "Science with the SKA", 2004, New Astronomy Reviews, Vol. 48, Nos 11-12, 979-1606

[8] Gaensler, B.M. 2004, "Key Science Projects for the SKA" SKA Memorandum 44 (www.skatelescope.org)

[9] Wikipedia (Great Pyramid at Giza, Great Wall of China, Parthenon, Hagia Sophia and references therein)

[10] "The History of Project Management" by Mark Kozak-Holland, Multi-Media Publications Inc., ISBN-13: 9781554891061

[11] "Buildings", Procopius of Caesarea, translated by H. B. Dewing, published in the Loeb Classical Library, 1940, see Wikipedia (Procopius, The buildings, LacusCurtius)