

STRATEGIC WORKSHOP

Final Report

Benefits of Research Infrastructures beyond Science

The Example of the Square Kilometre Array (SKA)

30 and 31 March 2010, Rome, Italy



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Organised by the COST Office

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Introduction – the context

The Square Kilometre Array (SKA) is an international radio telescope project incorporating a receiving surface of a million square meters, fifty times larger than the biggest receiving surface now in existence. This huge surface will be composed of many small antennas, divided into a dense inner core array which becomes more diffuse with increasing radius. In addition to the scientific challenges the discussion on this research infrastructure includes aspects covering the benefits *beyond* science. The SKA was conceived as a new international project to meet the future needs of radio astronomers. It will be used to address some of the more fundamental questions in contemporary physics and astronomy; including the nature of the first stars in the Universe, the cosmic history of the Universe, the nature of Dark Matter and Dark Energy, theories of gravity and black holes and the origin of cosmic magnetism. Beyond the science the SKA will be powered entirely by regenerative energy and apply data processing approaches of the next generation. All together it is an example of establishing scientific and technological leadership.

Mega-science infrastructure projects such as the SKA have the potential to seed or boost significant technological development, enhance capabilities and efficiencies across myriad industrial and educational sectors, as well as generate economic and social benefits to society. Indeed, beyond the benefits from the internationally-agreed SKA *science* projects, the benefits in terms of innovation, capacity and capability enhancement, and indirect societal impacts are expected to be significant and important. But how can the less tangible, indirect and non-scientific benefits to society best be incorporated into the decision-making processes for large-scale research infrastructure investments? COST wanted to support the development of assessment criteria for these non-scientific aspects of large–scale research infrastructures and convened this "Strategic Workshop" to stimulate an open debate on the topic.

The purpose of the COST Strategic Workshop "Benefits of Research Infrastructures beyond Science - the example of the Square Kilometre Array (SKA)" held in Rome on 30 and 31 March 2010 was to present the SKA project as an example of an international research infrastructure project which promises to offer multiple benefits – scientific and non-scientific – to people throughout the world and in all walks of life. Ultimately, and with contributions from industry, government and key stakeholders, the workshop sought to identify the conditions by which non-scientific benefits from large scale research infrastructure can best be integrated into investment decision-making.

The COST Strategic Workshop comprised four parallel break-out groups: Information and Communication Technologies, Green Energy, Global Science-Industry-Government Linkages and Human Capital. These parallel workshops explored how these technologies, education, society, economy and global cooperation etc will shape the future of big research infrastructures like the SKA. Presented here are four thematic reports summarising the findings of the workshop.

Executive Summary

The SKA research infrastructure is likely to become a lighthouse project for global cooperation in many "frontier" domains of the 21st century. To achieve the enormous potential that the SKA offers, in terms of increasing our understanding and knowledge of the universe, exploring new technologies and processes for communication and innovation, and testing viable solutions to secure energy supply, the SKA project requires long term political and financial support from governments and industry. Moreover, a secure location for the infrastructure needs to be selected - a location which will ensure the long term stability of the project and maximise the scientific, engineering, societal and socio-economic benefits which will be gained over at least the next 30 years.

The aim of the COST Strategic Workshop was to identify and classify the major benefits that can be accrued from the SKA project, and, by extension, other large scale infrastructure research projects of that nature. The highlights of the workshop conclusions can be summarised:

SKA: a major driver for innovation in ICT

To make the SKA research infrastructure function, revolutionary technology improvements need to be tested and validated. ICT innovations that are useful for the SKA will also be useful for all other activities that process large volumes of data retrieved from around the globe, including activities essential to the financial, communication, and environmental-monitoring industries.

Engineers for the SKA will have to challenge the ICT industry to innovate because the SKA's enormous infrastructure has to be built efficiently to save power and capital costs. The software and hardware that will drive it and make it 'smart' will need to be developed setting global standards for ICT engineering and construction. The expected benefits will involve not only signal processing, storage and computation, but also reliability and maintainability for remote SKA use, providing a backbone for development of the ICT commercial services.

SKA: accelerating progress in sensor technology and real-time monitoring

The SKA infrastructure will be a giant sensor network and signal processor. It will drive innovations in algorithms and software for 'on-the-fly' data manipulation and compression, flagging of transients and other notable signals, and enhanced processing of the selected data segments. This in turn should affect or spur the development of global sensor networks and real-time monitoring which is in turn useful for commerce and government.

SKA: driver for innovation in wireless communication

The SKA management has a unique opportunity to leverage the creation of this iconic scientific instrument into a development laboratory for worldwide communication infrastructure. The development of hardware of extremely low noise amplifiers (LNAs) and analog-to-digital converters (ADCs), will offer major advances in virtually all types of digital electronics and communication technologies.

SKA: a global model for 100% renewable energy

The SKA infrastructure will require a considerable amount of energy which is why adopting a 100% renewable energy strategy that is available 24/7 would set an important example for operating a large research infrastructure. The green energy solution for the SKA could accelerate important technology developments in the areas of energy generation, storage, distribution, efficiency and demand reduction. Moreover, the SKA can provide the most sophisticated ICT network that runs on locally-generated, renewable energy and if the system is designed larger than the energy needs of the SKA, it could even generate revenue to support some of its operational costs. Thus, the SKA has the potential, through its unique and challenging infrastructure requirements, to act as global project champion for sustainable development including green energy and green computing.

SKA: impact on human capacity building and employment

The biggest contribution of the SKA to human capacity development worldwide will most likely be in education and technological spin-offs. Its impact will be global, owing to the nature of the scientific collaboration, and the distributed aspects of the infrastructure itself. The SKA will provide employment and education opportunities in the construction and operation of the facilities, development, implementation and maintenance of the SKA-related ICT infrastructure, implementation of green energy, computing etc. Moreover, the role of the SKA as an international scientific endeavour needs to be echoed in its education and public outreach programme: it needs to shine globally while remaining flexible and open to the demands of local stakeholders.

SKA: a model for global mega-projects

If the SKA is to take a long term lead for future global science projects then it has the opportunity to lead in the development of a model for effective global research collaboration that focuses on long term benefits and gains, which go beyond the application of a strictly one to one *'just retoure'* model.

Conclusions

When decisions on large scale research infrastructures are being made, aspects beyond the respective excellent scientific cases need to be considered. These aspects should include topics like the use of sustainable energy sources, the development and building of human capacities, new communication strategies and technologies and, finally, that the project would generate incentives to enhance global and transcultural collaboration in communicating the advancement of knowledge for the benefit of mankind.

Information and Communication Technologies

Introduction

The SKA as a Scientific Instrument for the Future

The Square Kilometre Array will be the largest radio telescope in the world, having a total collecting area for cosmic radio waves comparable to a square kilometre of metal surface. This surface will be in the form of thousands of individual dish antennae and ground-level phased array antennae, spread out in clusters over a distance spanning several thousand kilometres. Acting as a single telescope, it will achieve spectacular angular resolution, 10 times better than the Hubble Space Telescope, although it will be sensitive to radio light rather than optical.

The radio universe is at least as interesting as the optical universe. Most of the objects imaged by Hubble are also radio emitters, including nebulae, galaxies, and individual stars, and in radio, these objects can be seen to much larger distances than optical objects without suffering from dust extinction. In addition, there are other sources such as rapidly spinning collapsed stars, beams of energetic particles in galactic nuclei, and cosmic rays that emit primarily in the radio. Cold interstellar gas emits only at radio wavelengths.

The Square Kilometre Array will be able to observe all of this at hundreds of times the sensitivity and survey speed of any previous radio telescope. Considering the countless discoveries made by existing instruments, including those leading to four different Nobel Prizes in radio astronomy, the science potential of the SKA is unimaginable.

The purpose of this break-out group was to articulate the significant and broader non-science benefits of Research Infrastructures in particular through contribution of the Information and Communication Technology (ICT), both current and future, with the Square Kilometre Array (SKA).



An overview of SKA components is shown in Figure 1 below:

Figure 1. ICT components of the SKA infrastructure.

A Field Station will consist of radio receivers at the foci of dish antennae, generally used for high frequency signals, and other radio receivers in one or more regularly-spaced phased arrays that are useful at low frequencies.

Each receiver has an amplifier and, not too far away, a digitiser, that represent the starting point of a long chain of signal processing. At the station, this processing might include filters to isolate the interesting frequency ranges and remove unwanted interference, and beam-formers to sum up and reinforce the signals, using time delays, that come from specific regions of the sky.

At the most fundamental level, a Field Station consists of sensors, digitisers, and computers, like any other sensor field or civic recording network. The processed signals are relayed to central computers over optical fibres that extend for hundreds and even thousands of kilometres, depending on how remote the Field Station is.

The central computers do more processing, this time multiplying and summing all of the signals from the Field Stations and a Central Core where more antennae are packed together. Eventually the data stream gets reduced in size, mostly by time-averaging, and stored in forms that are useful to astronomers.

Outcomes

The SKA Research Infrastructure

The research infrastructure surrounding the SKA will have enormous impact. As a coherent instrument, the SKA will pass high volumes of data through an interconnected network and have these data intelligently reduced to a manageable size in real time.

The data rate off the dishes will be around 1 Petabit per second (a Petabit is a number of 0-1 binary bits equal to 1 followed by 15 zeros). The phased array antennae will produce data at ten times this rate. The current rate of data movement on the world wide web is 30 Terabits/second (a Terabit is a number of bits equal to 1 followed by 12 zeros). Given the current growth rate of internet traffic, 50% per year (Minnesota Internet Traffic Studies, http://www.dtc.umn.edu/mints/home.php), the total internet traffic will also be about 1 Petabit/second when the SKA is built (between about 2020 and 2023).

Thus the data rate in the SKA will be larger than that circulating around the globe by the rest of humanity. Also at this time, there will be nearly a billion people collecting and thinking about this internet data. A similar number of computer processors, or arithmetic units, will be required to analyse and reduce the SKA data. Processor speed is not predicted to increase much in the coming few years because of energy losses from quantum mechanical effects.

The calculation rate in a computer chip increases only because the number of processors inside each one increases. If we consider the rate at which current computer processors do arithmetic, which is about one billion operations per second, then a billion processors will do calculations at a billion billion times per second. This number is 1 followed by 18 zeros, or an Exa-operation per second. The SKA will need this magnitude of processing power – comparable to that of the largest computers in the world at the time. The primary challenge of the SKA engineers will be to coordinate all of this data movement and arithmetic while the instrument operates.

The complexity of a system like this requires careful management to ensure peak performance throughout the expected SKA lifetime. Management before construction involves risk analysis and mitigation, systemic modelling for scientific verification, maintenance, and operation, and implementation of strategies for failure detection, identification and recovery ("FDIR").

After construction, much of the same software can be used again to monitor system performance and the impact of component upgrades. Such innovative design engineering will be only partly specific to the SKA; much of it will also be useful to other geographically distributed sensor networks. Additional software for monitor and control of the instruments, data processing and distribution, and further scientific verification, will be developed in advance of construction too, and then perfected during operation. Innovative management of the ICT infrastructure for the SKA will comprise a major part of the research in this project.

Another challenge will be to enable access to the data by astronomers from around the world. Stored data files, while reduced considerably from raw data, are likely to be too big to send to other continents by commercial internet. For example, a single data file corresponding to a large map of the sky could contain a Peta Byte of data. (A Byte is 8 bits and can be used to represent a number between 0 and 255. A Peta

Byte is a number of Bytes equal to 1 followed by 15 zeros.) Sending such a file over the internet to another continent could take a long time.

If we consider what may be a representative transfer rate at that time of 10 Gigabytes per second (most computers now access the internet at rates that are 1000 times slower), such a file would take 30 hours of uninterrupted movement. It would also have to be read off the SKA storage unit and written correctly to another storage unit in the retrieving country. Clearly the SKA represents more than a telescope. It is also a model for the future of global communication and information technology.

The SKA and Information-Communication Technology

Information and Communication Technology (ICT) is the backbone of the SKA. Engineers for the SKA will have to challenge the ICT industry to innovate because an enormous instrument like this has to be built efficiently to save power and capital costs.

The software that drives it and makes it smart will also be a challenge to write. In both cases, the technology of choice will likely be close to what is in the market place already, but there is still a need for innovation.

The term "market-adjacent" ICT has been suggested. This term refers to the use of hardware and software packages that are fundamentally based on commercial items, but it connotes a slight deviation from these standards in order to be more efficient in some ways. The telescope will be like the world wide web in its data and computer rates, but some of the operations it will be simpler and more repetitive than the web, allowing for reduction in complexity to save costs.

The SKA infrastructure, like any comparable ICT infrastructure in the financial, commercial, or government sectors, will have direct benefits to society through the training of technicians for development and operations, and through the attraction of new talent to ICT in general.

The SKA will hardly go unnoticed: an interest in Astronomy spans all cultures, ages, and demographies. For this reason, the SKA is an iconic project. It could affect international standards for ICT engineering and construction, and standards for innovation in hardware and software. It should affect or spur the development of global sensor networks useful for commerce and government.

There will also be environmental applications where natural events are detected and analysed in real time. We need smart, world-wide communications and the invention of relevant models, protocols, and microelectronics to handle the enormous future traffic of internet data that is connected with human knowledge and everyday activity.

The SKA is primarily an engineering project for the next ten years. Benefits to society from its ICT innovations will precede the astronomical discoveries eventually made from its antennae. SKA management has a unique opportunity to leverage the creation of this iconic scientific instrument into a development laboratory for worldwide communication infrastructure.

The technicians, scientists, and engineers that are assembled will inevitably think outside the box of their current project. The resulting Research Laboratory will be an engine for invention – a modern example of Thomas Edison's greatest contribution to society.

Innovations in Wireless Communication

The SKA will drive innovation in wireless communication through hardware development of extremely low noise amplifiers (LNAs), which are used to detect and amplify faint radio signals, and analog-to-digital converters (ADCs), which are used to convert the amplified signals into digital form for processing and storage. LNAs and ADCs are important in virtually all types of digital electronics and communications technologies.

A better LNA means a more sensitive receiver inside cell phones and relay towers, and that means better fidelity of the signals and longer range transmissions. The associated microelectronics is important for all wireless communication, and a good guess is that in 10 years, nearly everything that moves will have wireless capabilities.

Innovations in Algorithms for Signal Processing

The SKA will be a giant sensor network and signal processor. It will drive innovations in algorithms and software for on-the-fly data manipulation and compression, flagging of transients and other notable signals, and enhanced processing of the selected data segments.

These developments will be useful for financial and retail markets that have to adjust intelligently to changing conditions in the world, for surveillance in the recognition of license plates or faces in a crowd, for weather and traffic monitoring followed by active response during anomalies, for security and military actions that have to sense and respond to rapidly changing conditions in a large, interconnected arena, and for many other events and disturbances that require superhuman speed and analysis to initiate the appropriate response.

Innovation from the SKA will not only be widely applicable in other established fields, but they should also make possible an interconnected and supportive world that we cannot imagine today.

Industry Collaborations

The distinctive requirements for the SKA will necessarily involve collaborations with industry, which unlike the academic community, has the large scale of operation and the deep base of experience to develop, manufacture, install, and maintain what the SKA engineers and scientist invent. SKA project teams in all countries will benefit from close contacts with local and global industries as they seek to develop new methods and technologies for ICT through parallel and joint work.

Industrial collaborations will involve not only signal processing and computation, but also reliability and maintainability for remote SKA use. Reliability and maintainability is an important part of commercial ICT. The SKA will be even more demanding in this regard.

The SKA will consist of high-technology sites spread out over thousands of kilometres in desolate, barren land. Desert temperatures will cycle from extremely hot in the day to near-freezing at night. Water condensation and evaporation will follow. The exposed electronics will be subject to degradation, but it cannot be easily serviced. As a result, the most sensitive components will require extremely low failure rates and the ability to predict failures so that essential maintenance can be scheduled and cost-effective.

Failure prediction and the failures themselves require self-healing to the extent that is possible. Selfhealing involves redundant parts of a wide variety of types, ranging from processors and memory elements inside each chip, to backup chips, power units, and cooling fans. Autonomous self-correction of software errors in the field will be needed too. What is learned about all of this will be useful for many years in other areas of ICT as worldwide infrastructure continues to increase in complexity and remote deployment.

The decades-long lifetime of the SKA also has implications for its design. It has to allow in-field upgrades, scalability of the electronics, including all of the detection, digitization, communication, and processing technologies, and expansion into other countries and continents as interest in radio astronomy grows. LOFAR in the Netherlands is a good example of this. It designed enough flexibility and capacity into its central computing system to handle the current expansion of field stations into other countries throughout Europe.

Software for the SKA

The software for the SKA is a major concern. It will be extremely complex to be able to sift intelligently through continuous signals that are overwhelmingly composed of sky noise and instrument noise. It has to make sophisticated maps without human intervention— something that is not yet done today at existing radio interferometers. There will be software for the front end near the telescopes that does monitoring, control, radio interference mitigation, basic calibration, and simple arithmetic to form beams of sensitivity in the sky.

There will be different software for the back-end that multiplies together all of the signals from each pair of antennae or station, adds these products up on a grid that keeps track of the relative antenna positions, and uses this grid to make maps of the sky in each frequency channel.

Other software will be needed for different uses of the telescope, such as the search for new pulsars (spinning collapsed stars), which requires all of the incoming radio waves to be added together with the

right time delays and then substantial sifting through the time series to find faint pulses that arrive at different times for different frequencies. There will also be software used by astronomers to analyse the maps that are kept in storage, long after the stream processing is finished.

This software is not only complex, but the development of it will be complicated as it will involve contributions from software experts and astronomers all over the world. There will be a need for record keeping and version tracking, notification of bug corrections and new developments, checking of accuracy and efficacy of new algorithms, and so on. This is done already for large commercial software enterprises, but it will be a challenge for the mostly academic community of radio astronomers building the SKA. Presumably the SKA operations office will also rely on industry participation for software maintenance.

Remote Power Generation for the SKA

In the desert environment of the SKA, solar and wind power is usually abundant, and it is naturally delivered to each remote station for local use. This is very different from fossil fuels that require transportation infrastructure to reach remote stations, and it differs from civilian power grids that rarely transport energy over large distances from power sources.

Solar and wind power is also likely to be cheaper in the next decade than these other forms. With solar and wind power, the SKA could be the most sophisticated ICT network that runs on locally-generated, renewable energy. Such operation will require significant research and innovation. Today there are no major computers or networks that run entirely off renewable energy. Highway telephones that run by solar-cell power are a common example of a network, but the power requirements for telephones are very low compared to an SKA antenna field, and there is not much computation involved on the highway.

Green energy also has to be compatible with sensitive radio telescopes. If photovoltaic cells emit very low levels of radio waves, a result perhaps of free electrons and currents on exposed surfaces, then that emission could interfere with the ultra-faint signals coming from space. Voltage converters and high power transmission lines emit radio waves too. Windmills have to be tested for radio emission. They stand high above the horizon if they are nearby, and each one contains a Megawatt-scale power generator that may be difficult to shield from virtually all electromagnetic emissions. Windmills also have moving blades that reflect radio waves.

Batteries are required for any variable power source, and they should be shielded as well. All of these power components should be far from the antennae, but not so far that power is lost in the transmission. The use of direct currents could help in this shielding, but this is incompatible with commercial power use. Innovations in these fields would open up markets for remote and local power generation.

Practical Matters: How would SKA Innovations actually get into the ICT World?

The SKA is more than a science project. It is a laboratory for innovations in radio communications, data transport, intelligent analysis, storage, and world-wide dissemination of knowledge. To have the greatest impact on civilization, the project should be as aggressive as possible in all of these fields. The creative energies of SKA scientists, engineers, and business partners will generate new ways of doing ICT that could revolutionise the world.

There have been many other big science projects over the last few decades, some much bigger than the SKA, and most of them have had significant non-science benefits that were not imagined at the start. NASA is a classic example, discussed in more detail below; of an organization with a science and engineering mission that has many important spin-offs to society.

The development at CERN of protocols that enabled the world wide web is another good example, as is the development at CSIRO of the algorithms that are necessary for modern wireless communications. The team of scientists working on the SKA will inevitably come up with new ideas that could change the way we do things. If these ideas can be developed and their organizations receive patents and industrial partners, then SKA innovations could spread to the marketplace with considerable profit potential.

The Example set by NASA of Research Infrastructure Benefits to Society

How might the SKA optimise its potential for benefits to society? The example set by NASA offers a few clues. NASA research connected with satellites and space flight has led to numerous spin-off benefits, including breast cancer screening technology, heart defibrillators, weather satellites, satellite monitoring of our environment and the effects of climate change, satellite communications for ATM machines and credit

card payments at gas pumps and other remote locations, and new technologies for increased crop yields and fishing (http://www.nasa.gov/50th/50th_magazine/benefits.html).

The list goes on: Teflon-coated fibreglass as a roofing material (1970s); portable cooling systems for medical ailments such as burning limb syndrome, multiple sclerosis, spinal injuries and sports injuries (1982); a lightweight breathing system for fire-fighters (1986); an advanced school bus chassis (1991); a mechanical arm for robotic surgery (1994); the DeBakey Left Ventricular Assist Device heart pump (1995); software to provide real-time knowledge of commercial aircraft positions using GPS (2000); a ballistic parachute system that has saved 200 lives already by lowering an aircraft to the ground in an emergency (2000); the Emulsified Zero-Valent Iron Technology to clean underground pollution (2005), painting restoration by oxygen bombardment, new and more effective tests for food poisoning now used by the Federal Food and Drug Administration, protective materials that coat the Statue of Liberty and the Golden Gate Bridge, multispectral imaging methods to analyse charred manuscripts, and more.

Technology transfer has been a mandate for NASA since the agency was established by the National Aeronautics and Space Act of 1958. The act requires that NASA provide the widest practical dissemination of information concerning its activities. It also provides NASA with the authority to patent inventions. Since 1976, the annual NASA publication *Spinoff* has described NASA's influence on society. Since 1990, NASA has recognised its "Government and Commercial Invention of the Year", and since 1994, NASA has recognised its "Software of the Year." Through these programs, publications, and awards, NASA has promoted a culture among its scientists and engineers that constantly looks toward wider society benefits of its inventions and ideas. Promotion like this could become part of the culture of the SKA as well.

Specific examples of NASA Policy Directives ("NPD") provide guidelines for the SKA. NPD 7500.2B is NASA's Innovative Partnerships Program, effective for five years starting in July 2009. It details dozens of program activities and cites specific laws that have bearing on them. The overview states: "This NASA Policy Directive establishes policy for the Innovative Partnerships Program (IPP). The IPP provides needed technology and capabilities for NASA's Mission Directorates' programs and projects through investments and partnerships with industry, academia, Government agencies, and national laboratories. The IPP also facilitates the transfer of technology developed by NASA for commercial application and other benefits to the Nation. The IPP seeks to stimulate innovation through non-traditional technology development and provides support to NASA's education and outreach activities."

To achieve maximum society benefits, the SKA needs an acceptable level of engineering risk and readily available council for patenting and commercialization of its innovations, either on its own or through industry partners. SKA scientists and engineers can be expected to invent great things, but a second step will often be needed to recognise the wider implications of these inventions and bring them to market for the common good.

The Example set by LOFAR of Network Infrastructure Benefits to the Netherlands

The Low Frequency Array (LOFAR) in the Netherlands is the first example of a nation-wide research network for high speed data transmission that links together instruments from a single project, a low frequency radio telescope. These links are now extending into neighbouring countries as the list of LOFAR participants grows. The network does more than deliver astronomical signals to a central computer, however. Also attached at the ends of this vast communication system are other detectors.

Geophones will be placed 10 meters below the surface to detect vibrations in all three directions. They pick up sounds from underground gas and oil reserves and enable the most detailed subterranean mapping that has ever been made.

Another vibration sensor for shorter wavelength sounds is a micro-barometer, which will lie closer to the surface. Other sensors will monitor temperature, humidity, air pressure and sunlight to better understand the microclimate of potato fields and control the fungus Phytophtora. Tiny detectors with wireless communication capabilities that link them to the central network are being developed for this new science of precision agriculture. The commercial benefits of both subterranean mineral mapping and higher crop yields could far outweigh all of the costs of the network itself.

There is a treasure in untapped information all around us. The SKA network, like the LOFAR network, will provide a platform on which the most important and timely of all this information can be captured and processed for the benefit of society.

Conclusions

The SKA is an astronomy and engineering project for the next decade that has the potential to develop useful new methods for the detection, transport, and analysis of enormous volumes of data. These new methods will span a wide range of SKA components, from hardware radio receivers and optical transmission lines, to processors and software for streaming data analysis, to storage and dissemination in the world wide community. Channelling these innovations to benefit society will be a challenge, but there are other examples of science projects like this that can be used as a model.

Two important considerations about benefits to society will be the level of funding for the SKA program and the attitude and mission set by management. With adequate resources and a mission that has worldwide perspective on ICT, the SKA research infrastructure can be a force for revolutionary technology improvements. ICT innovations that are useful for the SKA will also be useful for all other activities that process large volumes of data retrieved from around the globe, including activities essential to the financial, commercial, communication, and environmental-monitoring industries.

List of experts

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Green Energy supply for the SKA

Introduction

The SKA will have considerable energy needs, summing up to a total of 100-200 MW. It is undesirable and might hurt the chances of the SKA realisation if the operation of the SKA adds to the global CO_{2^-} emission budget.

The goal of this break-out group was to define the benefits of a 100% renewable energy (RE) for the SKA and start the process of developing a serious scenario for the SKA. The most important issues that need to be tackled are:

- Can a 100% renewable energy scenario be technically realised, is there a need for conventional back-up power?
- What are the key technological issues that have to be addressed?
- What is the financial consequence of such a solution, how much will it add to the SKA budget?

Outcomes

The SKA a model for 100 % renewable energy

In the group consensus emerged early on that although a 100% renewable energy solution for the SKA might prove upfront costly and require to solve a number of technological challenges, the benefit of such a solution for the SKA energy needs will be substantial.

The COP-15 climate talks in Copenhagen attempted to reach a global framework agreement on reducing CO_2 -emissions, trying to set binding emission limits for each country. It failed in a spectacular way, which might show that this path is not the most promising way to reach the climate goals of limiting the earth temperature rise to 2°C.

Instead, focus should now be placed on increasing energy efficiency and the fraction of renewable energy in the energy mix, to move towards 100% renewable energy solutions for regions and countries. Such a policy would not concentrate on limiting economic activities to reduce CO_2 -emissions, but rather use to-day's green technologies in a beneficial way for the planet, generating jobs and adding to economic growth.

The SKA adopting a 100% renewable energy strategy would set an important example that this is indeed feasible. Such a perspective could add political and societal support for the project, outside the benefits to the scientific community

After detailed discussions consensus emerged in our break-up group that a 100% renewable energy solution is technically feasible, based on solar power harvested in solar thermal and photovoltaic (PV) power plants. Solar thermal power has the advantage that today heat can be more easily stored than electricity. On the other hand, solar thermal plants contain steam turbines that might present more of a challenge of RF interference with the sensitive detectors of the SKA than PV power that in principle does not need any moving parts, besides trackers that are used to follow the sun in the high-efficiency concentrated PV solutions. Possible RF interference from electrical inverters will have to be attended to.

Today, concentrated solar thermal power (CSP) presents the advantage of easy energy storage in the form of heat, which allows a 24/7 operation based on technologies available today. On the other hand, CSP has higher maintenance needs and might ultimately be more costly than PV whose cost comes down fast, following a steep learning curve: for each doubling of the globally installed PV power the cost of modules decreases by 20%, of systems by 15%. At present, annually about 1/3 to ½ of the total globally installed capacity is added, so that prices of PV systems do come down fast.

Therefore, the PV fraction of the SKA energy supply might be large, requiring the development of largescale electrical storage solutions, which might be based on water electrolysis producing hydrogen that can generate electricity in fuel cells, red ox-flow batteries that store positive and negative charges separately from the central membrane unit where electricity is produced, or more conventional solutions like NaS batteries that can be up scaled. Therefore, the green energy solution for the SKA could accelerate important technology developments that are needed anyway. This would add an important argument to the promotion of the SKA in the global society.

Outside the use of solar power, other forms of generating CO_2 -free electricity should be considered as well, based on local conditions. Geothermal energy can be easily harvested around the clock where it is easily available. Wind energy provides electricity at low cost, but it will have to be investigated if the RF noise of these turbines can be tolerated. Water energy is highly desirable where available.

Besides the technical issues, the financial consequences of a 100% renewable energy solution have to be included in the discussion. Today, solar power can be obtained at a system price below \$3/Watt, with a ¹/₄ duty cycle, i.e. about 2000h of operation annually in a good-sunshine region. Assuming this to come down to \$2/W in the near future, including the costs of storage, the SKA will be faced with an about \$ 1.2 billion to establish reliable power based on a total of 150 MW energy needs.

On the other side, an important advantage of solar, especially PV, power is the fact that there are only minimal operational costs. If the system is designed larger than the energy needs of the SKA, it could even generate revenue to support some of the operational costs of the SKA.

Global and political benefits of a green energy solution for the SKA:

- The SKA will play a global leadership role as an iconic scientific project, aspiring to run on 100% renewable energy 24/7. Hybrid solutions might sound technically attractive, but would risk the special appeal and the potential additional funding sources of a 100% renewable energy solution;
- The SKA will create a launching pad for reliable green power generation in remote areas without grid connection and thus provide a global test bed;
- The SKA will drive innovative solutions in generation, distribution, efficiency and demand reduction in a remote, harsh environment;
- The 100% renewable energy solution will save operational money to be spent on science instead of increasing fuel costs.

Societal benefits of a green energy solution for the SKA:

- The SKA will act as a trailblazer in the implementation of multi-scale, reliable energy generation and storage solutions through early competitive evaluation;
- The SKA will provide employment and education opportunities in implementation of renewable energy, and can deliver excess power to the local population;
- Spin-off research and technology developments will benefit societies, especially the 1.6 billion people currently without any access to electric power;
- The SKA will broaden societal awareness of renewable energy.

Technical opportunities of a green energy solution for the SKA

The SKA will innovate:

- Development and competitive evaluation of multi-scale renewable energy power storage solutions;
- Renewable energy generation and distribution free of radio frequency interference;
- Operation of multi-scale distributed renewable energy sources and storage sites

How to reach the 100% renewable energy target:

Demand site:

- Minimise energy needs through passive cooling systems and specific algorithms;
- Develop demand model for daily and yearly power needs;
- Provide technical assessment of potential local benefits.

Generation side:

- RF interference shielding issues (AC/DC lines), prevention of electromagnetic noise generation;
- Assess additional sources of renewable energy: wind, water, geothermal, biomass etc;
- Green energy provided from and into a local grid;
- Land use: amount, quality and suitability.

Storage:

- Key issue that will require additional technology development;
- 24/7 power needed, uptime may not be needed 100% of time.

Distribution:

- 100% renewable energy network has to be managed over 1000 km distances;
- Local distribution has to be provided.

Risk management:

- Core mission of the SKA cannot be compromised;
- Pathfinder project can serve as early model fort he final solution and help to provide roadmaps for key technologies;
- Management of a 100% renewable energy network over 1000 km size has to be developed;
- Local distribution has to be provided;
- Focus on base case, an economic and implementable model hat serves as reference point;
- Is 100% solar renewable energy in this area a unique selling point?
- Will the SKA get funded based on conventional energy?

Finance:

- Develop a competitive lifecycle cost model, with a fossil fuel power system as a starting point;
- Develop a competitive cost model of the entire system and during its full life cycle.

SKA Brand Strategy with a 100% renewable energy power supply:

- The SKA is not only a tool for radio-astronomy, but also the first global demonstration of 100% renewable energy power provided on a large scale, available 24/7;
- Stakeholders may apply to be allowed to participate, like in the project DESERTEC in Europe;
- Strategic partners on financing and technology developments will have to be identified;
- Spin-offs are expected to emerge in green energy development and system optimization.

The SKA will be a trailblazer in exciting science, allowing us to learn more about the cosmos, and in developing the future energy system on earth, that will have to be based 100% on renewable energy use to be long-term sustainable.

Conclusions

A 100% renewable energy option for the SKA appears to be technically feasible today. Important further improvements, especially in storage, can be expected before the implementation phase starts. Developing a 100% renewable energy option for the SKA will allow adding an important argument to the benefits of realising the SKA.

The SKA and earlier projects like Pathfinder will provide important examples of the world energy supply system of the future. Paying higher up-front construction costs will relieve the energy burden from future

operational cost budgets. There is a serious chance that the SKA will get only funded when based on CO_2 -emission free energy supply.

List of experts

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Global Science-Industry-Government Linkages

Introduction

The purpose of the COST Strategic Workshop was to articulate the significant and broader non-science benefits of Research Infrastructures in particular through experiences and involvement, both current and future, with the Square Kilometre Array (SKA). Moreover, we intended to capture to capture, discuss, prioritise and describe routes through which such broader benefits may be realised.

Outcomes

Industrial engagement is crucial to the overall success of the SKA

The SKA Office is currently planning a global mapping exercise of industrial capabilities on a national or group country basis following the guidelines issued by the PrepSKA. The results of this mapping will show where there are significant strengths but also more importantly show where there is limited industrial expertise and indeed may show where there are currently gaps.

A number of companies have already been involved in Pathfinder projects, some of which have been given public sector support to develop a variety of early stage demonstrator technologies. Once the mapping exercise has been competed it would be useful to extend this funding model to fill gaps in expertise and avoid reliance on single company capabilities which could make overall success over dependant on one or two key players.

There was agreed value in extending this model to give a balance of capabilities across all of the SKA requirements.

Some procurement models can act as a real barrier to maximising effective broad impact from such a large project. There are examples where companies successful with winning contracts to carryout preliminary studies are then in turn excluded from participating in any second stage development, however there are approaches that avoid this problem. Therefore, it was a common feeling in the group that procurement needs to be open and take a long term view to be able to realise the maximum long term impact over and above the value of initial contracts. In other words, become more than a simple 'Just retour' model.

Industry engagement is maximised through facilitation and the development and growth of industry networks where current information on SKA can be communicated. Clearly defined outline opportunities and timescales are needed so that industry can decide how much effort of engagement is relevant to their individual business opportunities.

Where such early industry groupings have been formed they need some small public sector funding but can quickly become self financing and lead to short term benefits in helping with inter company trading between members leading to increased trust and a willingness to work together.

Building on these industry networks it would be positive to see both virtual and physical networking opportunities developed to bring existing and new SKA engagers whether from scientific, industrial or government communities together to hear progress reports and share ideas moving forward.

To realise the broader benefits of developing technologies which are of use to other sectors the SKA should look early to see where best practice already exists in this area and set up a suitable model early and see it as not an integral part of the SKA. It would be viewed as negative to see this activity merely tagged on at the end.

What are the motivators for industrial engagement?

The SKA can inspire individuals, team, organizations and governments to be part of a global fellowship which will last beyond their involvement, whatever the scale, in such a prestigious scientific project.

The profit and benefits' to all those involved will be realised over long timescale and the broadest sense building capacity and long term stability for those who engage.

The SKA offers a massive leap forward in our understanding of the Universe and how it was formed and as such can 'open the blinds to the universe'.

It can in turn act as a self motivator and model for other global mega-projects.

It has the potential for individuals and nations to gain international recognition for their contributions.

The SKA necessitates leadership and strategic direction from all its stakeholders and therefore raises the credibility of all those involved.

The benefits above the science can have much wider economic and socio-economic benefits which will provide solutions for future global challenge areas including communication, transport and energy, as well as support scientific and engineering skills development.

The project can play an important role as a vehicle for science diplomacy, reinforcing global cooperation and solidarity.

What are the challenges which the SKA should overcome to maximise the impact of the SKA provide leadership for future large science projects?

Such a global project needs participation from many nations and there must be early recognition of the importance to respect cultural differences whilst maintaining diversity amongst all project partners.

There are not insurmountable challenges in developing and agreeing necessary legal governance frameworks, tax systems, labour laws and agreeing how the IP generated will be fairly attributed. There was concern that the legal profession will need to act in new ways to prevent these issues becoming a hindrance to the overall success of the project.

There is an immediate need to provide substantial resource, both staff and budget, to fund the global promotion of the SKA, what it has achieved to date and what the future holds.

The procurement process should focus on long term benefits and gains which go beyond the application of a strictly one to one 'Just retoure' model.

It is essential to define how we will successfully deal with the ever-increasing scale and scope of "Big Data" and the systems integration, central to all mega-science project challenges.

There are potential problems if the project attracts insufficient funding or that the funding model does not buffer against funding and exchange rate fluctuations.

The project as a whole relies upon the building of trust and commitment and that to realise this effectively needs the SKA to deliver clear and concise messages of a shared vision that everyone can sign up to.

What will successful linkages and international engagement look like?

As a source of global pride the SKA has the potential to harness the excitement and create as great a sense of global fellowship and manned space flight or the Hubble Space Telescope Through this sense of pride it can in turn bring the world together across the scales of government, regional and local levels.

The creation of the global agreement models necessary to ensure the success of the SKA will in turn create best practice models, framework sand agreements for new collaborations allowing future projects to move forward in shorter timescales.

It will also require the development of international agreements on partnership between industry and scientific research which can act as best practice.

The SKA has the potential, through its unique and challenging infrastructure requirements, to act as global project champion for sustainable development including green energy and green computing.

The novel technologies and engineering challenges set by the SKA will in turn lead on to for wider uses in market sectors outside of astronomy, research and science.

As a flagship science project with global awareness the SKA will help in attracting and inspiring young people to be interested and get involved with science.

Partnership will necessitate an open approach to bring in new research groups and disciplines and build on an expanding global scientific community ensuring inclusive collaboration.

If the SKA is to take a long term lead for future global science projects then it has the opportunity to lead in the development of a model for effective global research collaboration. One option could be formation of a global version of European Research Infrastructures Consortia (ERIC).

Ideally the funding model arising for the SKA will have a banking facility that deals with both exchange rate and funding fluctuations.

The overall success of forming effective global linkages will ensure a 'win – win' situation for all who get inspired and involved.

What actions are now needed by those involved with the SKA to enable effective linkages to be realised?

The SKA needs to establish a formal global entity with a brand and a shared vision so that it is recognised internationally outside of the astronomy and research community.

Part of the key messages moving forward should include clear descriptions of the substantial successes and benefits from all those who have been part of the project so far.

The steps forward need to be defined in clear steps, with key decisions taken to include designs concepts and costs get government and industry buy-in

The communication plan for both government and industry needs to clearly demonstrate the multiplier effect on the spending chain and the powers to build capacity rather than focus on short term procurement opportunities.

The SKA can create a platform for renewed global relationship post financial crisis

It can provide leadership for the development and growth of industry clusters, national and international that 'really work'.

The SKA through its own experiences should share with the broader community new perceptions and understandings of risk to include technical, political and financial risks.

Conclusions

The Square Kilometre Array, as a large scale global project at the forefront of science, does, by its very nature necessitate international collaboration by, scientists, industry and governments all from the earliest stages.

The SKA to date has been led in the main by the science community through long standing networks of researchers and by enhancing these capabilities by growing the collaborations to bring in new research partners from across the globe.

The success and benefits to date of bringing together these communities with governments and small scale industry engagement should not be underestimated. These benefits should be articulated and communicated as part of the key messages moving forward.

However to ultimately realise the SKA as a successful research infrastructure, the project now needs to focus in its key message including the broader impact, both economic and socio-economic, so that the project can bring to both gain commitment from governments on funding, locations and secure the long term stability for the telescope to maximise the scientific and engineering knowledge to be gained over the next 30 years of operations.

From the industry perspective, the science involved in the SKA is compelling, but the engineering solutions (e.g. applying the outcomes of science and technology to the design, development and manufacture of the end product) predominate industry thinking, particularly as they apply to future commercial outcomes.

The SKA can be a beacon of 21st century inclusive collaboration in such a way that it becomes a transformative influence on global geopolitics if it is managed efficiently and effectively and yet remains open to the participation of young scientists from across the world.

Also the SKA cannot be created without early stage engagement with industry to develop and provide novel technologies and engineering solutions and the manufacturing capabilities which will be needed not only for the core telescope but also for scientific instrumentation, IT and data handling, power supplies and the necessary infrastructure to make such a project to be built and networked over an extensive foot-print in a series of geographically remote locations to be both built and run.

The key messages distilled from this workshop theme were as follows:

- Governments will need to see convincing arguments clearly setting out the benefits of the project
 as it encompasses all of those who engage with it. Business cases should include inspirational yet
 tangible goals wherever possible supported by both numerical justification and clear focused narrative cases illustrated with sound examples form other areas.
- Industry will need to receive clear messages on the value of engaging with the SKA over and above the potential value of contracts to be placed, in terms of realising the value of global fellowship gained through collaboration, kudos and pride in being a part of a successful groundbreaking science project and use of core technology platforms to build new business opportunities to make their futures more sustainable in both other research infrastructure investments but also in broader market sectors.
- There is an opportunity for innovation, with potential long-term global impact, for organising a global collaboration in a way that successfully manages all elements of risk, including financial risk, in order to deliver a massive infrastructure for global use.

To make both of these key areas effective will need the SKA to focus quickly now, create a global brand awareness for the project and get government, industry and the public interested and updated on the excitement and potential that the SKA can bring.

List of experts

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Human Capital

Introduction

The Square Kilometre Array (SKA) is one of the largest earth-based science projects ever proposed. As such it is also one that involves many international partners. The SKA, if built, will employ thousands of people from a range of professions. People are needed to design, build, operate the SKA as well as run all the associated services. Builders, caterers and administrative staff as well as scientists, engineers, IT specialists, communicators, etc. will be employed in this endeavour. In addition to these staff, a number of employment opportunities will arise around demand created by the existence of the facility: tourism might flourish around the sites of the telescope and science centres, education professionals will be needed to develop curriculum material related to the SKA, its science might inspire popular culture, etc.

The telescope itself will be distributed geographically over 3000 km but it will not be fully operated on site. Astronomers using the SKA for scientific research will do so from their home institutions or from foreseen SKA Science Centres, giving the telescope a truly global presence. At present, 19 partner countries in the SKA comprise 8 European countries (France, Germany, Italy, the Netherlands, Poland, Spain, Sweden and the United Kingdom), and 7 major world players in astronomy (Australia, Canada, China, India, Russia, South Africa and the United States of America) representing more than half the world population¹. The science centres in each of the partner regions will serve as beacons of this scientific enterprise.

A number of professions will benefit from working for, with, on the SKA, or as a result of a spin-off of its development. The potential of this major scientific facility to contribute to the development of human capital globally is one of its strongest selling points in times when 'blue-skies' research comes under increasing pressure to deliver economic justifications. The main goal of this break-out group was to discuss how the SKA could at best realise this potential.

Outcomes

A framework was proposed to discuss human capacity development (HCD) aspects of the SKA in terms of time, location and type of profession. Although the potential reach of the SKA in terms of skills development for all the areas mentioned was acknowledged, the group chose to focus on Science, Engineering and Technology (SET skills that would grow in more than one country as a consequence of the SKA being built).

This framework is reported here for the record and as an illustration of the broadness of skills and knowledge the SKA has the potential to stimulate.

	Locally ²	Regionally ³	Globally
Preparation			
Construction	Support and administrative staff Construction workforce Civil Engineering	Civil Engineering Environmental Aware- ness	
Operation	Support and administrative staff Tourism and other non- technology-driven spin-offs		Environmental Awareness

Table 1. Non-SET Human Capital (skills and general knowledge) potentially stimulated by the presence of the Square Kilometre Array.

Support and administrative staff: The SKA will be an international project, with stakeholders from government agencies, the private sectors and academia. Working in such an international environment at the

¹ July 2009 estimate from the CIA World Factbook

https://www.cia.gov/library/publications/the-world-factbook/

² Locally means around the site of the telescope and around each SKA Science Centre

³ Regionally means on the scale of several countries at least

interface of the stakeholder communities requires certain skills from the support and administrative staff in every location.

Construction workforce and civil engineering: The construction of a high-tech facility will equip construction workers with valuable experience and skills for future employment. The installation of new communication infrastructures required for the SKA is expected to be particularly valuable. Although civil engineering arguably belongs in the SET skill set it was not discussed further and therefore is mentioned here.

Tourism and other non-technology driven spin-offs: The SKA facilities (science centres) could attract a large number of visitors. This will lead to a number of small-scale business opportunities locally, which are expected to develop governance and business skills, as well as drive community development. This can be coupled with outreach efforts, creating a sense of ownership of the telescope and of its outcomes. The sites of the radio antennae of the SKA are also expected to attract tourists, and radio quiet zones will need to be protected. Other radio telescopes (the VLA in New Mexico or Jodrell Bank in the U.K.) do attract some tourism, which is suitably managed. Such models might be applicable to the sensitive parts of the SKA.

Environmental Awareness: During the construction phase we will be presented with an opportunity, if not an obligation, to build the telescope and the science centres in the most environmentally friendly way possible. Proper communication of this construction policy is expected to raise awareness of environmental issues in each of the countries concerned.

Once built, the SKA will 'see' and 'hear' the cosmos but this is only possible if no man-made radio waves interfere with the faint signals coming form the far reaches of the universe. This again presents us with a real opportunity to reach out and engage the global community in a dialogue about human influence on the environment.

Challenges

A list of challenges for present-day science was discussed. These issues are pressing not only for the development of new science but threaten the pool of SET skills needed for the sustainability of today's scientific communities and the knowledge-based economy. References in support of these points have been added by the Chair. These were not mentioned at the meeting itself.

The challenges mentioned below form part of a complex reality. There are many excellent programmes addressing aspects of these issues in various countries, often with excellent results. It was acknowledged throughout the discussion that while it is not the main purpose of the SKA to tackle these issues, it could significantly enhance existing programmes and be a source of inspiration to imagine a future with better possibilities.

Lack of interest in Science, Engineering and Technology among young people

It is well known that in spite of an interest in technological gadgets, young people shy away from studying science at school and even more so when it comes to choosing a profession. This problem seems to affect most countries worldwide. See also [1-3].

Image of Science

Science is not seen as attractive for young people. It is seen as scary, difficult, uninteresting, dull, etc. It is also sometimes seen as dangerous. See also [4].

Image of scientific professions

Scientific careers are mostly seen as unattractive. Two major contributing factors are: the image of scientists and the working conditions of scientists.

Scientists are often depicted with glasses and a lab coat and described as lonely, socially awkward, ageing, white, and male. Figure 1 show the first page of results of a Google image search for 'scientist'. While this is not a scientific result, young people's perceptions of scientists has been researched extensively [5,6], and while there is a notable improvement in recent years, mainly due to television series and movies [7,8], the mainstream image of a white male in a lab coat remains prevalent. The stereotype may amuse young children but as long as young people don't identify with that character, it may influence young people against choosing a scientific career. The UK's Science Council warns [9], "Many young people still have preconceived ideas about science subjects leading solely to laboratory jobs and wearing a white coat."

Some participants pointed out that more monetarily rewarding professions such as business, medical and legal professions appear much more appealing to young people and parents.



Figure 1: Google image search for 'scientist'.

Reluctance of scientists to engage with the public

It was reported in the discussion that in some research environments, outreach and involvement in education other than tertiary education is commonly perceived as a waste of precious research time, or even as charity work. In addition to this deeply rooted reluctance is a common discomfort among scientists to engage directly with members of the public. It was also pointed out that not all scientists are good communicators and that offering training was advisable. See also [10, 11].

During the discussions, institutions where engagement with the general public is seen as a positive thing were mentioned as examples of best practice, e.g. the Perimeter Institute in Waterloo, Canada or the Hubble Space Science Institute in Baltimore.

Lack of awareness of science

The general knowledge of basic science is very low among the general public. It is also confined to facts. Science is generally perceived as a dogma based around indisputable 'truths', as opposed to a research process driven by curiosity, discovery and the will to solve problems. See also [12].

Lack of science in general culture

Highly educated people are expected to know arts and literature, but not so much science. To quote Posamentier [13] "math is the only subject about which adults can cheerfully exclaim they know nothing, and still be thought intelligent and even educated."

The term 'culture' often refers to artistic human creations and excludes science, engineering and technology.

Lack of scientific literacy

The capacity of critically evaluating scientific information and making decisions is increasingly needed in every day life. Examples include scientific evidence in legal affairs or scientific agendas becoming political debates, e.g. stem cell research, or climate change [14]. Therefore, it is important that the stakeholders and decision-makers, i.e. the general public, are equipped to evaluate the information they are presented

with [15]. Martin & Tang [16] mention an "increased capacity for problem-solving" as a direct benefit of publicly funded research.

Lack of basic science in education

Science education in its traditional form based on textbooks and disconnected to every-day life sustains the poor image of science. Primary school teachers often lack confidence to teach science, and so propagate their disinclination to the learners [17-19]. It has also been shown that gender-related apprehension to engage in science is often transmitted through teachers [20]. For those reasons, science education, already suffering from poor representation on most curricula, is kept at a minimum by teachers. See [21].

Retention of students

Students who have chosen to study science or engineering often do not pursue academic careers. Figure 2 illustrates this point from a recent Royal Society report [22]. For the SKA, it is essential that enough astronomers be trained to make use and benefit from this great facility.



Figure 2: Transition points in typical academic scientific careers following a PhD. Source: the Royal Society [22]

Reasons for this drain are complex and this particular point is delicate; a scientifically and technically skilled workforce is also a contribution to society. The possible lack of qualified astronomers is therefore more of an issue of the academic career path.

Potential impact of the SKA on SET Skills worldwide

The SKA, by its scale and its scope has the potential to inspire generations of young people with science. It can do so not only because Astronomy is attractive, but also because through astronomy it opens the door to many fields of science, engineering and technology development.

If the SKA, using astronomy, acts as an attractor for young people to go into science, it can contribute to reinforce the scientific communities in all the disciplines mentioned in figure 3.



Figure 3. Astronomy links science, technology and culture. Source: IAU [23]

Means to realise the human capital development potential of the SKA

In view of the abundance of outreach initiatives acting at local, regional and international levels, the SKA needs to be aware of what exists, learn from other programmes, collaborate with them, and build on successful models of outreach and education. The SKA cannot carry this entire out by itself even with a dedicated percentage of its funding dedicated to outreach and education. The project can, however, act as a facilitator, a platform for exchange and dissemination across a network of outreach partners. Those partners can be individuals, organisations, education authorities, etc.

In order to fulfil this role appropriately, SKA education and outreach needs to find balance between a topdown (e.g. prepare and disseminate compelling outreach resources) and a bottom-up approach (e.g. coordinate efforts with local education authorities), as shown in figure 4.

The challenge is to optimise this process, to develop effective ways of sharing best practices, to connect different initiatives, to find out what is needed, what exists and how to best share it. Some novel means to achieve this objective include new media communication, citizen science, novel science visualisations, etc.

Recommendation: Facilitate and network education and outreach initiatives feature the SKA in their activities. Proactively engage with the public. Bottom-up approach: be responsive to demands from outreach programmes and educational institutions. Top-down approach: provide high-quality visuals and information to be used freely by science communication and connect outreach communities worldwide.

	Locally	Regionally	Globally
Preparation		Science Centres Education departments	IYA 2009 network Data mining and data visu- alisation technologies Engineering tenders
Construction	Stimulate ICT at school Engineering role models Civil engineering and tech- nicians	Universities more attractive owing to involvement with the SKA Clusters of expertise	All of the above plus Electronic and software en- gineering Computer science Engineering industries Tech support
Operation	Maintenance and Tech support	Same as above Technological spin-offs	Citizen science All of the above Tech support

Table 2. Opportunities presented by the SKA for socio-economic development, for improving the uptake of SET studies, and strengthening SET skills. They are color-coded by target audience as follows: Red = Young people, Blue = Higher Education, Green = Industry.

Education and Research

It is urgent to inspire young people today to make sure there is a sufficiently large pool of trained scientists, engineers and technicians by the time the SKA is ready to be operated. If we want many PhD students in 2025, we need to inspire 10-year olds and younger today. Therefore the SKA project needs to start working with education authorities as early as possible.

NASA outreach has been tremendously successful to the point where most people around the world (not only in the U.S.) believe that all astronomy is related to NASA. Moreover, NASA has invested massively in training teachers in the U.S. and from abroad. This has reinforced their image tremendously among young people [24] (teachers are powerful multipliers) and brought innovative science teaching methods and top-ics to the classroom. The reason for this success is that substantial funding (a fixed percentage of the science budget [25, 26]) has been invested in education and outreach for many years.

The SKA can build on this success and take this model a step further with the help of existing programmes and with the support of new media technologies. The SKA can bring a substantial contribution to current efforts to bring astronomy on the school curriculum in a number of countries. The SKA must strive to be seen as an accessible partner for such programmes as they benefit the SKA as well in the long term. School curricula are decided at local levels so for the SKA to contribute, a bottom-up approach is required.

The amount of data generated by the SKA will make it available for high-school science projects. Real science experiences are thrilling for young people, and if they discover something, chances are that those learners will pursue a science career. Radio experiments should be designed, that can be used as hands-on experiments at university. A radio equivalent of the Galileoscope⁴ could make radio astronomy familiar from the level of primary school.

Recommendation: Mobilise substantial investment in education through close collaboration with education authorities around the world. Tune the education initiatives to specific target groups: Teachers, young

⁴ http://www.galileoscope.org/

children and learners from primary, middle and secondary school. Proactively seek ways in which SKA data can be used at school.

General Public

The SKA could, with proper outreach be turned into a 'brand', like the Hubble Space Telescope (HST). The HST has earned global fame owing to the dramatic astronomical images it has generated. This has also led to a number of consumer products like coffee-table books, calendars, etc. A facilitating factor for this success, in addition to the substantial investment in outreach, has been the intellectual property of the HST data and images. Instead of seeing an open copyright policy as a threat, HST has mobilised private initiatives that have greatly contributed to its image and its omnipresence in the media.

If the SKA becomes a brand like the HST, opportunities to profile the SKA brand in mainstream media will arise. Not everyone is interested in the SKA as such but almost everyone has a natural liking for astronomy. It is astronomy therefore, that should be used to profile the SKA.

While the HST has achieved a great deal, the general public is ripe for more. The SKA can go beyond the dissemination of astronomical images and the communication of results. It should make the scientific method part of its communication, making scientific thinking more accessible and familiar to the general public.

The SKA will produce vast quantities of data, some of which will most certainly be suited for citizen science projects. Evidence suggests that people's motivation for contributing to citizen science is the satisfaction of contributing to real science [27]. With the expected increase in Internet penetration worldwide, more and more new Internet users can be inspired to take part in citizen science programmes.

Each of the SKA science centres should be a local platform for SKA outreach, responding to the interest of the region, while disseminating best practice and resources designed all around the world.

Recommendation: Practice a proactive outreach and an open copyright policy on science results. Develop very attractive visuals. Keep a vigilant eye on possible citizen science projects. Go beyond compelling visuals: embed scientific thinking and the scientific method in the outreach.

SET Professions

The requirement for new technology development of the SKA presents the community with opportunities for technological spin-offs. These can happen on various scales.

Small, much specialised businesses whose first customer is the project itself before finding a niche market in the high-tech industry is a possibility. Such small companies often cluster around academic centres where the new technology was originally developed. They form clusters of expertise (see table 2), which can have a big impact regionally, creating jobs and attracting qualified people to the region. Such centres can be very productive with appropriate support and intellectual property policies from universities and science centres.

On the other hand, groundbreaking technologies could emerge from the SKA; the World Wide Web came out of CERN or Wi-Fi technology came out of radio astronomy. The impact of technological innovations is often unpredictable and the question remains open as to how to stimulate the emergence of such world-changing technologies.

Recommendation: Provide favourable conditions for innovation and support for the setting-up and long-term success of technological spin-offs.

IYA and amateurs

The most successful science outreach exercise ever is probably the International Year of Astronomy in 2009 [28], which resulted in a global participation and reached of millions of people worldwide. The network of the IYA is still very active and the SKA should make use of the momentum of the IYA to inform the public and disseminate outreach and educational resources. The SKA can gain access to this network and invite them to join the project's outreach programme, thereby mobilising thousands of volunteers from over a hundred countries, ready to work and translate materials into many languages.

The IYA network has members from all professions from scientists to teachers, amateur astronomers and astronomy enthusiasts. Engaging with them will give a sense of proximity to the science of the SKA. Amateurs can become the SKA's best ambassadors among the general public.

Recommendation: Liaise with the international office of the IYA and begin reaching out to the community of IYA volunteers as soon as possible.

Uniqueness of the SKA

The SKA can become the first international scientific infrastructure with education and outreach embedded in its development form the earliest stages, inspiring young people in time for them to become users of the telescope, or engineers and scientists working with the SKA.

In terms of implementation of outreach and education initiatives related to the SKA, the following question was raised: 'What differentiates the SKA from other large scientific infrastructures?'

Like space telescopes, the SKA will not be operated on site. Unlike space telescopes, telescope operations will be networked and distributed. This is a major asset for the international visibility of the SKA and presents as many opportunities of public engagement and sense of ownership of the SKA – and of science – in society as there are SKA science centres.

Most opportunities in table 2 above are global and this is one of the strongest points of the SKA in terms of human capacity development. This needs to translate into positive brain circulation (as opposed to brain drain) and active participation from the scientific communities in every country. It was echoed by many participants that the international SKA collaborations could help stimulate new or small astronomy groups at universities worldwide, in particular in developing countries.

The language of science is global and the SKA presents an opportunity to use scientific diplomacy to stimulate development and international cooperation. This form of cooperation goes beyond diplomacy based on common interests: the SKA can contribute significantly to a culture of global collaboration, to global engagement and ownership of science.

The SKA will likely be so data prolific that it presents a real opportunity to invite the public and students to take part in the real hands-on science like no other infrastructure before.

The SKA is expected to contribute significantly to the development of new energy and communication technologies as well as data processing, science visualisation and imaging, pioneering technological innovation around each of its science centres. Such developments are expected to benefit the global knowledge-based economy beyond scientific research and academia.

For the first time, developing world will potentially be an active contributor to fundamental research on an unprecedented scale. Emerging and developing countries can become active contributors in the production and exchange of knowledge, stimulating their participation in the global knowledge-based economy.

Finally, if the SKA outreach is done well, it will undoubtedly lead to the mobilisation of additional funds and investments in education, outreach and human capacity development initiatives. The SKA can pull in additional resources for human capacity development from existing programmes (with funds and people invested in the collaboration) or new development funding invested in some regions because of their involvement in high-profile international science.

Key Issues and difficulties

Convince funders to build the SKA

The SKA project needs to reach out to governments and increase the awareness of the SKA and its potential benefits – scientific and non-scientific alike – as soon as possible to maximise its chances to be funded and built.

It is important to communicate that the SKA can also play a pioneering role as test bed for other global scientific endeavours and infrastructures to do with e.g. climate change, global health, etc.



Figure 4. Top-down and bottom-up roles of SKA establishments (science centres or other).

Top-down and bottom-up, from local to global

The SKA is a large project on the scale of earth-based scientific research infrastructures but it is not so large in comparison with, e.g. projects in the private sector. It is therefore crucial that the ambitions of the SKA remain realistic. The SKA is a scientific instrument, not an education programme all on its own. Having said that, the SKA represents a fantastic opportunity and a platform on which to build science education and outreach worldwide.

Undoubtedly, many independent science education initiatives will seize the opportunity presented by the SKA to design new curricula and educational materials. It is therefore paramount to liaise well with such programmes and work in collaboration with them. Internationally, the opportunity to disseminate such resources is great but presents a linguistic challenge. The SKA public outreach needs to collaborate and support such initiatives with knowledge and access. With appropriate strategic leverage, SKA science centres can act as multipliers and help small outreach efforts yield very high return on investment.

The role of the SKA as an international scientific endeavour needs to be echoed in its education and public outreach programme: it needs shine globally while remaining flexible and open to the demands of local stakeholders. A bottom-up approach is essential to ensure this happens. The whole is greater than the sum of the parts and the reach of the SKA can be maximised if it plays a facilitating and networking role, as well as provides communication products: images, films, etc. to support the development of educational resources.

Images in astronomy

One of the reasons why astronomy is so attractive is the ever-growing collection of breathtaking astronomical images. Radio astronomy does not (yet) produce such images⁵. The superposition of various wavelengths on one image using, e.g. optical, infra-red, X-ray and radio can produce very beautiful results but some new visualisations of the radio universe will need to be produced. New technologies and the increased resolution of the SKA will potentially open a new domain of astronomical visualisation, whose aesthetic quality is yet to be unravelled.

⁵ This statement should be understood in comparison with optical images. The VLA for example already produces beautiful images.

Sustainability

It is crucial to develop an education and public outreach strategy that goes beyond the time-limited hype of superlatives. A number of "wow" aspects of the SKA were mentioned (see Appendix II) but it was underlined that each one of these needs to be tailored to the target audience and that there is always a need to update impressive comparisons and metaphors.

The SKA needs visible, tangible goals, which will contribute to consolidate its status as (i) a rich subject for educational resources and (ii) a global scientific endeavour useful to all in some way.

Conclusions

The biggest contribution of the Square Kilometre Array to human capacity development worldwide will most likely be in education and technological spin-offs and its impact can potentially be nearly global, owing to the nature of the scientific collaboration, but also to the distributed aspects of the infrastructure itself.

Education and outreach can be embedded in the project from early stages, maximising its impact. The nature of SKA science and technological infrastructure is prone to get children and young people excited about science and technology. Building on existing successes, e.g. NASA and the Hubble Space Telescope, the SKA can potentially become part of our culture, using its popularity to expose the general public to scientific thinking. The vast network of volunteers and professionals engaged in astronomy for the International Year of Astronomy 2009 represent a natural vehicle for SKA outreach.

Technological spin-offs will undoubtedly emerge from the development, building and use of the SKA, potentially of a world-changing nature.

In addition, the construction and operation of the SKA facilities will most likely impact local and regional skills development outside of science, engineering and technology.

The SKA can benefit society for a very long time, suitable for the long-term investment it requires. If successful the SKA can mobilise funds from other sources, targeted at education and development and private commercial initiatives around the topic of the SKA (books, tourism, etc.).

These benefits can be particularly relevant for emerging and developing nations, who can actively take part in cutting-edge science and knowledge production for the first time on such a grand scale.

List of experts

First Name	Last Name	Organisation	Country
Roy	Booth	National Research Council	ZA
Louis	Brennan	Trinity College Dublin	IE
Philip	Diamond	University of Manchester	UK
Graham	Durant	Questacon	AU
Kevindran	Govender	South African Astronomical Observatory	ZA
Soccorsa	Le Moli	INAF- National Institute for Astrophysics	IT
George	Miley	Leiden University	NL
Jordi	Molas-Gallart	INGENIO (CSIC-UPV)	ES
Carolina	Odman	Leiden University	NL
Giancarlo	Setti	University of Bologna	IT
Olive	Shisana	Human Sciences Research Council	ZA
Julia	Stamm	COST Office	BE

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Giampaolo	Vettolani	INAF	IT

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