



# **Memo 102**

## **Lessons Learned From Other Large Scientific Facilities**

Operations Working Group

06/08

# Report of the SKA Operations Working Group

## Lessons Learned From Other Large Scientific Facilities

The SKA will be one of the largest and most complex scientific facilities ever built. At other large facilities there are a variety of policies in place governing scientific access, administration, and science operations. With the goal of learning from the successes and failures experienced at these other facilities, especially those with an international basis, the OWG examined the organization policies and practices at the following facilities:

### FACILITIES

*ALMA* ( <http://www.alma.org/>): The Atacama Large Millimeter Array (ALMA) is an international astronomy facility under construction by a partnership between Europe, North America and Japan, in cooperation with the Republic of Chile. ALMA is funded by the NSF in the U.S. in cooperation with the Canadian NRC, in Europe by ESO and Spain. ALMA construction and operations are led on behalf of North America by the NRAO, which is managed by AUI, on behalf of Europe by ESO, and on behalf of Japan by the National Astronomical Observatory of Japan. ALMA is being built at a 5000 m high site in the Atacama Desert in Chile. When the current construction project is completed in 2012 it will consist of a total of 66 antennas operating at wavelengths between 0.8 and 3 mm. The Joint ALMA Observatory (JAO) is a Chile based service organization which conducts those activities needed to acquire, certify, and archive the scientific data and provides site maintenance and security. The JAO is not a legal entity and does not control any budgets. Interface with the global user community is through regional centers which administer proposals handling, user grants, scheduling, archival support, user assistance in data reduction, software development, module repair, student training, and in house research. ALMA was an outgrowth of the NRAO Millimeter Array and the European Large Millimeter Array projects. Funded ALMA design began in 1999, and construction in 2002. In 2005, the project was redefined and rebaselined with a substantial descoping and 40% cost increase. Reflecting the separate origins of the European, Japanese and North American projects, the partners have maintained independent management control of their activities and expenditures under separate project management structure, and it has been difficult to staff the top ALMA management positions. IP rights and other considerations restricted the flow of information vital to evaluating the prototype antennas. Observing time managed by the North American partner is likely to be open to all users, but the Japanese and ESO controlled time, will probably be restricted.

*LOFAR* (<http://www.lofar.org/>): The Low Frequency Array (LOFAR) is under construction in the northern part of the Netherlands. LOFAR construction is managed by the LOFAR Foundation Consortium which is a limited partnership under Dutch law. Operation will be managed by ASTRON and will include both Key Science Projects in recognition of contributions to the project as well as "open skies" time. Construction funding has been supported through a subsidy from the Dutch government Economic Affairs ministry using profits from natural gas extraction thus side-stepping normal astronomy funding channels. The guidelines for the subsidy did not permit funds to be used for LOFAR operations and data analysis, and consideration of how to fund this aspect of the project was deferred until later in the project development, which has led to considerable uncertainty in planning for operations and the impact to other areas of Dutch astronomy, especially radio astronomy. The location in northern Holland required by the unusual funding scenario is less than optimum for this wavelength range, and complex multi-disciplinary collaborations with geological and agricultural interests to use the shared networks have complicated negotiations with suppliers. Following a detailed engineering evaluation, the initial ambitious project had to be descoped to meet budget levels. After an anticipated 15 year lifetime, ASTRON has promised to dismantle LOFAR and return the land to a "nature reserve," but there are no plans or funds reserved for decommissioning.

*Pierre Auger Observatory* (<http://www.auger.org/>): Construction of the Pierre Auger Observatory is nearing completion at a site in western Argentina and a second even larger facility is planned in Colorado. The Pierre Auger Observatory consists of 1600 scintillator tanks plus 4 fluorescence detectors. Operation is centered around "The Collaboration" of 250 individuals, from 50 institutes in 16 countries. The collaboration is managed by a Collaboration Board of participating scientists appointed by the collaborating institutions, with support from a Finance Board. Fermi Lab provides

executive administrative support. U.S. and European institutes use different accounting rules resulting in a large overhead, but this has been more straightforward than trying to agree on a single accounting system. Contrary to recent trends in radio astronomy, scientists interact closely with the facility. Authorship reflects institutional financial support. More than 75% of the support comes from in-kind funding. Common funds are dispersed after competitive bidding. EPO has been important in recruiting good local staff.

*HESS* (<http://www.mpi-hd.mpg.de/hfm/HESS/>): The High Energy Stereoscopic System is an array of four imaging atmospheric Cherenkov telescopes for stereoscopic observations of air showers in the 100 GeV energy range and is located in Namibia. Twenty-eight institutions and eight different funding agencies from five countries are involved in the collaboration which operates under a legally non-binding MoU with weighted voting rights. HESS staff who are located in Namibia remain under contract with their home institutions which are responsible for all costs of travel and sustenance of their employees. Broad oversight of scientific matters and organizational issues is provided by a Collaboration Board and evaluation of proposals for using the HESS facility is by an Observation Committee. Ownership of intellectual property rights are decided by the collaboration. Currently, neither data nor software tools data are made public and authorship for new data is open to all members of the collaboration. Local industry and universities play vital roles in the operation of HESS. Decommissioning plans are in place to be implemented after the expected 10 to 15 years of operations.

*ESO* (<http://www.eso.org/>): The European Southern Observatory is an inter-government agreement among 8 countries and exists as a legal entity. The ESO staff have privileges and immunities characteristic of other international organizations. ESO is limited to providing facilities located only in the southern hemisphere, and so does not impact directly on national and other European based national or regional facilities. The construction of new telescopes as well as new instrumental development is implemented through industrial and institutional contracts in the member countries. The direct responsibility for ESO operations rests with the Director-General who reports to a board consisting of one scientist and one administrative representative from each member country. Member states contribute to the operation of ESO in proportion to their GNP, but each council member has equal voting rights. Although there is no formal policy relating national contributions to the award of contracts or observing time, in practice there appears to be a close relation between the distribution of benefits and financial contributions, and it is widely perceived that this significantly increases the cost of providing new facilities and instrumentation to the European astronomical community. Little or no observing time is available to the international community, except through collaboration with European scientists, and until recently access to ESO data and archives was limited to European IP addresses.

*IRAM* (<http://iram.fr/>): The Institut de Radio Astronomie Millimetrique was established by the CNRS in France and the MPG in Germany, by merging, for political reasons, two independent initiatives: the German sponsored 30m mm radio telescope on the Pico Veleta in Spain and the French sponsored mm interferometer built on the Plateau de Bure in France. Since 1990 Spain has been a minor partner. IRAM Headquarters are located in Genoble, France and the Institut operates under French law with a Director who reports to a Board consisting of 3 members from each of the three partners. Expenditures and allocation of observing time is in the ratio of financial contributions. Limited observing time is available to the international scientific community, mostly by means of collaborations with scientists from Germany, France, and Spain.

*JPL DSN* (<http://deepspace.jpl.nasa.gov/dsn/>): Although the JPL Deep Space Network has a very different scientific role from radio astronomy, it has many technical and operational similarities to radio observatories, although high reliability is more important for DSN operations. Like the SKA, the DSN is an international operation. In addition to a site in California there DSN sites in Australia and Spain which are operated by local staff in support of missions from many countries. Maintenance and upgrades are treated like another mission and time is negotiated rather than scheduled in advance. Management of day-to-day operations is by contract which is cost effective, but long term planning suffers. The funding line is clean with all funding flowing from a NASA Program Executive to a DSN Project Manager. 25 to 30 year life cycle costs are considered when evaluating new initiatives, but there typically is little consideration of decommissioning costs. Future operational cost savings are anticipated with a move to more automation and single 24/7 presence at each site complex rather than at each individual antenna.

We also studied the two existing SKA Pathfinder:

*ASKAP* (<http://www.atnf.csiro.au/projects/aska/>): The Australian SKA Pathfinder is planned to consist of 30 to 45 twelve meter antennas equipped with FPAs to give a 30 square degree field of view field of view. It will be located at a remote site in Western Australia close to the site proposed by Australia to locate the SKA. With only a few technical support staff at the station, the primary site support will be provided from Geraldton, located about a 3 ½ hour drive, and regional science support in Perth, and high-level staff located in Marsfield. The site currently includes PAPER (Precision Array Probing the Epoch of Reionization), the MWA (Murchison wide Field Array) and CORE (Cosmic Reionization Experiment) all of which comprise the Murchison Radio Observatory (MRO). Extensive operations planning is already in place for end-to-end ASKAP operations from proposal handling through observing to data products, and is also being implemented at other ATNF sites. Unlike conventional radio telescopes, astronomers will interact with the ASKAP data base, and not with the telescope. Expected data rates up to 1 Tbps will be a challenge. Power costs alone may cost about AUD 4 M/yr.

*MeerKat* (<http://www.ska.ac.za/>): MeerKat is being constructed in the Northern Cap Province of the Republic of South Africa. Current plan is for an array of 12 m antennas each equipped with single pixel wideband feeds covering the range from about 500 MHz to 3 GHz. An ambitious schedule calls for a seven dish array operating by 2009 and the full array of 50 or more dishes by 2012. The operation will be managed by the Hartebesthoek Radio Astronomy Observatory with a Science Center to be located in Capetown. The South African Parliament has passed the Astronomy Geographic Advantage Act to provide a Radio Quiet Zone around the MeerKat site.

In addition, we examined the following physics facilities which face many of the same operational challenges anticipated for the SKA:

*LIGO* (<http://www.ligo.caltech.edu/>): The Laser Gravity Wave Interferometer is a facility to detect gravitational radiation and is managed jointly by MIT and Caltech with facilities located in the states of Louisiana and Washington. Funding and oversight is provided by the U.S. National Science Foundation through a Cooperative Agreement. Approximately 300 scientists from 30 different institutions take part in the design, construction, and maintenance of equipment, as well as in executing the scientific program.

*DESI* ([http://www.desy.de/html/home/index\\_eng.html](http://www.desy.de/html/home/index_eng.html)): The Deutsches Elektronen-Synchrotron is one of the world's leading accelerator facilities. DESY operates 6 separate accelerators with a staff of more than 1500 people and a budget (2005) of € 170M.

*LHC* (<http://lhc.web.cern.ch/lhc/>): The Large Hadron Collider is a proton-proton collider being constructed at CERN at a cost of about € 3 billion. When it goes into operation in mid 2008 it will produce proton collisions with 7 TeV energy.

*ILC*: (<http://www.linearcollider.org/cms/>): The International Linear Collider is a planned collider that will provide electron/positron interactions with 500 to 1000 GeV energies which will require some 14,000 man years of effort at a projected cost of US\$ 7 billion. Planning for the ILC is led by a distributed Global Design Effort team which sets the strategy and coordinates worldwide prioritized proposal-driven R&D efforts. Approximately 2000 individuals located at more than 100 universities and laboratories in more than 20 countries around the world are involved in ILC development activities. Oversight, opportunity for the exchange of ideas, and the development of international funding mechanisms is provided by a body which includes the funding agencies and the ILC Steering Committee. Work packages are developed via MoUs between the ILC and individual institutes. An ILC Reference design was published in 2007 with a goal of delivering a Technical Design Report by the end of 2008 and to complete its work with an Engineering Design Report in 2010. At this time, the project will be re-organized around a more traditional central Project Management Office. Expressions of interest to host the ILC are expected in 2009. Projected power costs are US\$1 m/day. Partial support for the development of the ILC will come from a €5.0 M FP7 award. The goal is to be ready for construction by 2010 when the first results from the LHC will be ready. However, the elimination for funding from the U.S. and U.K. in 2008 will likely delay scheduled project milestones.

*ITER* (<http://www.iter.org/index.htm>): ITER is a joint international research and development project to demonstrate the scientific and technical feasibility of fusion power. The partners in the project, the ITER Parties, are the European Union (represented by EURATOM), Japan, the People's Republic of China, India, the Republic of Korea, the Russian Federation and the USA. ITER will be built by the ITER International Fusion Energy Organization which was established by the Joint Implementation Agreement (IIFEO) also known as the ITER organization Agreement. The work of the ITER Organization is supervised by a Council which meets at least twice per year and includes 4 members per party. The Council has any power it needs to carry out any functions of the ITER Organization within the scope of the Joint Implementation Agreement. Following two down selections, ITER will be constructed in Europe, at Cadarache in the South of France. Experimenters will work remotely. Funding to support ITER development was eliminated from the U.S. FY 2008 budget, in contravention of agreements with European and Asian partners.

## RECOMMENDATIONS

The OWG met in Manchester, UK on September 29, 2007, to hear presentations on many of these facilities. In addition R. Ekers visited the Pierre Auger facility in March, 2007, and R. Schilizzi and C. Greenwood visited DESY and ITER in October, 2007. This report is based on the oral and written presentations prepared by the WG members and discusses issues and strategies derived from the experiences of these other facilities as they might be appropriate to planning for SKA operations. We also profited from the OECG report Organizational Approaches for International Megascience Projects, OECD/GC (95)80 and from discussions with the VLA/EVLA and ALMA operations staff.

*The governance model:* Strong central project management of the SKA will be important, as the founding partners often want to keep control. Two equal partners may result in a difficult management structure. International organizations like ESO, IRAM, and CERN and national organizations such as NRAO and ATNF with strong central management and control of operating funds have been very effective. Bilateral or multilateral partnership with separate funding and management lines, such as planned for ALMA may not be effective for a complex facility such as the SKA. While governments will want to remain involved to oversee and to protect their investment, the direct management of SKA operations should be delegated to a single managing authority which appoints a Director who has the responsibility and authority normally associated with the Observatory Directors including central budget and technical control as well as decision making authority.

To maintain continuity of the support staff, attractive working conditions must be negotiated in the early phase of the negotiations for siting. Barriers to spousal employment will need to be identified and minimized. To the extent possible, staff from different sponsoring countries doing the same work need to feel that they are being treated equitably taking into account the different circumstances that they and their families will face when they return to their home country. Cultural differences, at all levels, among partners and the host community will be a challenge and need to be addressed early on. Continued face-to-face interactions may minimize the adverse effects of cultural diversity. The SKA may need to establish a legal entity sooner rather than later, and to clearly identify an SKA Champion to represent the project to the international community.

*Early identification of operating and pre-operating costs:* Basic annual operating costs of the SKA including administration, routine and emergency maintenance of the antennas, instrumentation, and computers, site protection and maintenance, personnel and equipment safety, proposal handling, time assignment, scheduling, telescope control, grant administration, student and user training, leases, EPO, and power consumption are likely to be at least 5 percent of construction costs. Some savings will be possible, if the SKA is used mostly or entirely to support a staff based observatory program such as an all sky HI survey, and not as a user based facility. To the extent possible, automated non attended execution of pre-scheduled observations as is already practiced at some existing facilities will help keep operating costs low. Life cycle costs might be minimized by generous spending during construction to maximize reliability and minimize maintenance, but there is the danger the construction costs might grow out of proportion to the scientific returns.

As discussed below annual instrument refurbishment costs are likely to be at least 2 to 3 percent of construction costs and the cost of user support another 2 to 3 percent per year. Pre-operations must start before construction is finished to hire and train operations staff, to develop

operational procedures, and to prepare both the scientific community for routine science operations. Funding agency requirements and diverse practices may make it difficult to minimize administrative costs.

With total annual operating costs probably close to 10 percent of construction costs, full lifecycle costs of the SKA will be several times the construction costs. All partners will need to recognize the need to secure a commitment for the effective operation of the SKA at least for several decades, more likely for 40 to 50 years if the SKA becomes the effective facility that we anticipate. The actual construction of the SKA itself is likely to last over the better part of a decade. This may require a new paradigm for funding whereby a fixed level of funding, plus inflation is required over many decades. In the first years, the funding is largely for construction, and in later years for operations, with an interim period when construction is being completed but some limited “pre-operations” is possible.

*Provision for adequate upgrading funds:* Many radio telescopes now operate over a wider range of wavelengths and with far better performance than originally anticipated by their planners. In fact, the scientific problems being addressed today with some of our older instruments were unknown at the time the instruments were originally built. This has been possible by introducing new techniques for fabricating and adjusting surface panels, by exploiting the rapid development of electronic and computing technologies and by the introduction of innovative new algorithms. This will be especially true for the SKA, since it may take so long to build, that by time it is finished, some instrumentation will be obsolete and much will be learned from early science operations. Constant upgrading will be necessary, in order to maintain state-of-the art performance. One of the advantages of ground-based telescopes is the capability of easy and continual refurbishment, but at the expense of significant increased operating cost. As is well known, the VLA for example, while adding new frequencies, and adopting powerful new imaging techniques, is still using a correlator system that is literally decades out of date, greatly limiting both the continuum and spectroscopic capability. In order to maintain the effectiveness of the instrument over its expected long lifetime, regular upgrades of the instrumentation and new software development will be needed on a continuing basis. Even an investment of 2 to 3 percent of construction costs per year would imply a turnover time of decades, so it will be a challenge to keep the SKA performance at the state of the art. Although currently astronomical telescope upgrades are usually based on proposals for additional external funding, the physics facilities often have a fixed annual budget to insure that their facility remains at the state-of-the art. Software development is very labor intensive and subject to large uncertainties in manpower and thus costs. Tight management of software development is essential to controlling operating costs, but will be difficult to achieve, especially if software development is distributed among the regional centers.

*Conflicts between commissioning and early science:* While the construction staff may desire an extensive commissioning period devoid of scientific users, the active participation of experienced skilled users can expedite and enhance the commissioning exercise as well as produce early scientific results that will draw attention to the availability of the SKA as a productive scientific instrument.

*Cost effective procurement and the implications of tariffs and “juste retour.”* Procurement costs at international facilities may be artificially inflated by the lack of competitive bidding due to requirements of *juste retour* or import duties charges. It will be difficult to minimize procurement costs and at the same time maintain equitable balance between financial contributions and contracts or /work packages. It will be important to develop mechanisms to equitably and realistically recognize in-kind contributions, and to negotiate import tariff fees prior to committing to the host country.

*Innovative sources of power:* Power costs to run the SKA will be large, perhaps dominated by the large computing needs of the SKA. One estimate is that the power consumption for computing alone might require tens of MegaWatts of power costing about € tens of millions, or comparable to that projected for the ILC. Use of innovative power sources, e.g., wind, solar, thermal, may appear attractive and politically correct, but may not result in any cost savings. Windmills, in particular, are to be avoided as they are good reflectors of RFI. Rather it will be important to minimize power consumption by careful engineering and the use of low power consumption devices.

*Access rights to the facility and to data?* Practices and procedures governing access to using large scientific instruments and access to their data varies widely among fields, and to an extent within fields subject to national and regional cultures and policies. Radio astronomy has for the most part

adopted an “open skies” policy, but some facilities are more open than others. The private optical observatories and ESO typically have a more restricted policy. The high energy observatories, HESS and Pierre Auger are used only by members of the “collaboration” who contribute to the financial and intellectual health of the facility. Although in the U.S., it is government policy, that the U.S. national observatories are open to all scientists based on scientific merit alone, independent of their national or institutional affiliation, in practice, this policy is not uniformly followed. More over, where an open skies policy is followed, it has created a perceived unbalance between the number of U.S. and foreign users, and threatens the possible closing of some major unique facilities. The situation for ALMA is unclear, and the assignment of time by EU, NA, and Japan TACs may operate under different rules. While access through the NA TAC may be officially open, it is hard to see how scientists from the EU or Japan can receive time through this process, if the EU and Japan TACs have a more restricted policy. Funding agencies in other countries, have questioned the merit of supporting telescope users whose governments have not contributed to the design and construction of the SKA.

*Models for user interaction and support:* The nature of user interaction with the instrument varies widely among existing astronomical facilities, but there is a general trend toward remote use by the user and even to eliminate completely any user interaction at the time observations are made. The high energy facilities, such as HESS and Pierre Auger, however, are an exception and members of the collaboration team take an active part in taking data with the facility. Hands-off-observing will allow the facility to operate at maximum flexibility and may reduce operating costs, especially considering the remote location of the SKA. But, there may be long term dangers in isolating the scientific community from the instrument. Regardless of the user model, support for scientists to use the SKA will be needed to build and maintain a viable user community, including the training of new scientists. While SKA global user support may not come from the same funding lines as the SKA construction or basic operations, it is still a real cost that ultimately comes back to the same sources – the national funding agencies. A carefully crafted and easy to navigate web site will greatly enhance the visibility and impact of the SKA

*Actual facility operation and operations budgets may differ from planned operation and planned budgets.* Project management tools must be developed early in the project. From the beginning, it is important to listen to the engineers who may be more realistic than the scientists in planning for operations. Do not separate R&D activities and personnel from maintenance and operations. Otherwise, it can be difficult to retain a high quality maintenance staff. It will be important to minimize administrative costs, especially the hidden costs normally associated with international projects. Smoothly running 24/7 operations, as will be appropriate for the SKA needs to be balanced with keeping operating costs under control. The costs related to operation of a complex high tech facility located at a remote site should not be underestimated.

*The impact to existing national and institutional facilities:* The annual operating cost of the SKA is likely to be about € 100 M per year, and will constitute a significant fraction the funds spent worldwide in operating radio telescopes. It is well known that the start of operation of major new national radio astronomy facilities, such as the NRAO VLA and VLBA has had a pronounced negative impact to the health of the university operated facilities in the US. More recently, ramping up for the operation of ALMA, LOFAR, and ASKAP has had significant impact to the ongoing operation of the facilities, at NRAO, Westerbork, and the ATNF, respectively. With the expectation of the SKA coming on line in the near future, some other major new facilities such as eMERLIN and EVLA may be raided to support the SKA, and the operation of other newly planned facilities such as the ATA, MWA, LWA, etc may be compromised. While the SKA will have unequalled sensitivity, for at least some decades to come, it will have limited resolution and frequency coverage, and so will address only a limited range of problems considered by radio telescopes. It will be necessary to provide and maintain effective operation of these other important radio astronomy facilities both to provide complementary resources and where the next generation of scientists will be trained.

*Balance between operations and maintenance:* Efficient 24/7 operation of the SKA will require a careful balance between maintenance time and observing time. Well run radio telescopes, generally are able to use about 70 percent of the time for productive scientific observations, but technical personnel will use all the time that they can get for development, testing and maintenance of both

hardware and software. To the extent possible, single point failures must be avoided. Soft failures, such as from individual antennas or receivers can be tolerated. Automated fault detection and repair are desirable.

*Software development is a capital expense and should not be deferred to operations:* Inevitably, construction costs of major scientific facilities exceed budget planning, either due to unrealistic budgeting, or to project escalation. It is tempting under these circumstances, to defer software development to the operations phase. This results both in increased operations cost and delay in implementing the software required to run the system and to optimize the data return.

*Plan for possible partner withdrawal:* Long term budget planning will naturally involve an assumed contribution level from all of the partners. It is often claimed that funding for international projects are more secure due to the nature of international commitments that have been established. But, these commitments, typically have fixed period, and in the worse scenarios, countries may unpredictably drop out claiming fiscal exigency, and there is no higher authority to regulate any such capricious actions. The recent announcement that the UK plans to withdraw from GEMINI; the drastic cuts proposed by the U.S. and the U.K. for the ILC; and the unilateral reduction in funding for ITER by the U.S. are examples of how national priorities can take precedence over international commitments to the detriment of the international project.

*Maintaining stakeholder and regional involvement.* Support for SKA operations will continue to compete for resources with complementary institutional, national, and regional projects. The SKA will not only demand considerable operating funds, but will also draw on a significant fraction of the intellectual resources of the global radio astronomy community. It is important that all stakeholders buy-in to the SKA operations plan in advance of construction, and in order to maintain a healthy user base, to insure the continued support of national and regional groups, and to exploit their expertise, there must be continued meaningful involvement in SKA operations throughout the global radio astronomy community. This might be might take the form of a set of regional and institutional support centers as was described in SKA Memo No. 84 and as is being implemented by ALMA. Continued involvement of individuals through membership on governing boards and advisory committees, in observing time allocations, and of institutions via work packages will be important in maintaining community support for the SKA; but it is important that local and individual agendas not take priority over the effective operation of the SKA, and that intellectual property rights be preserved. Establishment of policies to account for intellectual property rights and in-kind contributions as well as the structuring of collaborations should occur early in the project planning. Consideration of intellectual property rights are more likely to be an issue with industrial contractors, for example relating to antenna design, than to university providers of computing algorithms. Policies to deal with participants who do not or cannot deliver promised work package products should be considered, although there are probably few legal options, and in practice it will probably be necessary to absorb the losses and move on. Progress will be more important than justice.

*Plan for decommissioning:* Powerful as it will be, even with regular refurbishment, the SKA will not remain competitive indefinitely. Other major radio telescopes have had a 30 -50 year effective lifetime. Current environmental protocols may require having a plan in place for decommissioning and returning the land to its previous state. This could be very expensive. It will be important to determine in advance of committing to a site, who will be responsible for and the costs of decommissioning, and to insure that such funds will be available, and not come at the expense of the following generation of radio telescopes