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Radio Astronomy in South Africa

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Abstract: Radio Astronomy in South Africa is currently undergoing rapid expansion and is already producing results that rival those from the optical observatories. Here its historical development and some recent installations are described in brief.

Early Radio Astronomy

Radio astronomy in South Africa started with a small group at Rhodes University around 1960. Its main activity was to monitor and understand the decametric radiation from Jupiter, for which John A Gledhill produced a theoretical model.

This group was led by Eddie Baart and Gerhard de Jager and produced a number of students who either pursued careers abroad in radio astronomy or were among the first radio astronomers to work at Hartebeesthoek.

With the great recent interest in radio astronomy generated by the MeerKAT telescope and the forthcoming Square Kilometer Array (SKA), this group has expanded greatly and since now has been known as the Rhodes Centre for Radio Astronomy Techniques and Technologies (RATT), headed by Justin Jonas and Oleg Smirnov.

Rhodes is involved in many of the ongoing surveys with MeerKAT and the extraction of different kinds of data from them. They also work on the combination of data from multiple antennas, that is, effectively turning a group of separate dishes into one huge dish by computers. They also study the output of HERA (Hydrogen Epoch of Reionization Array) that has its own special problems of data extraction. The goal of this experiment is to picture the Universe at different values of the redshift z, corresponding to the times over which the re-ionization took place.

Hartebeesthoek

The Radio astronomy observatory at Hartebeesthoek (normally abbreviated to HartRAO) started its existence in 1961 as NASA Deep Space Station 51 for receiving satellite signals. It was operated on NASA's behalf by the CSIR's (Council for Scientific and Industrial Research) National Institute for Telecommunications Research. The facility then consisted of a 26m antenna. George D Nicolson, one of the South African engineers involved, used it for radio astronomical research when it was not in use by NASA. On the withdrawal of the latter in 1974-5 it was transformed into a radio astronomy observatory within the CSIR under Nicolson. Rhodes University received 20% of the observing time. In 1988 it became part of the Foundation for Research Development, similarly to the SAAO. The FRD was later renamed the National Research Foundation.

Nicolson was director 1988-2003 and was succeeded in turn by Justin Jonas, Roy Booth and Michael Gaylard. HartRAO now forms part of SARAO (South African Radio Astronomy Observatory)

Fig 1. The Hartebeesthoek 26m radio telescope (Photo: HartRAO)

For radio astronomy purposes the receiving equipment had to be constructed anew. This included a gain-stabilised radiometer for mapping the Milky Way and making flux measurements on radio galaxies, a 256-channel spectrometer, equipment for the timing of pulsars and for Very-Long Baseline interferometry (VLBI). The latter permits the combination of telescopes far apart on the Earth to give ultra-high angular resolution. Receivers for celestial masers work at 4.7 and 6GHz (6.4 and 5 cms wavelength). Some of the projects included: mapping of the Milky Way at 960MHz (31cm wavelength) and 2300MHz (13cm). The second of these was of great importance to early studies of the 3° cosmic microwave background radiation by the COBE satellite – in removing the foreground radio emissions to reveal the Big Bang remnant radiation.

A particular subject well-suited to study with the 26m telescope is long-timescale variability. This has included the X-ray emitting binary star Cir X-1 which was also observed extensively at SAAO in the infrared. Distant galaxies with radio-emitting jets have been followed for variability.

Long-term monitoring of pulsars reveals little understood "glitches" or sudden changes in their periods.

Maser sources include hydroxyl radicals (OH) in the shells of matter given off by cool variable stars in the late stages of their evolution but also ammonia (NH3) found in the regions where stars are currently forming.

Accurate positional information of objects in the sky is now based on a network of quasars, which are extremely distant radio sources. This is the "International Celestial Reference Frame". Quasars are so distant that they do not show any appreciable relative movement, unlike the stars in the Milky Way galaxy that form the Fifth Fundamental Catalogue (FK5) and the like. The level of precision now attainable is a

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by-product of the VLBI programmes. It accurate to of order one thousandth of an arcsec.

VLBI has also allowed the position of the Hartebeesthoek telescope to be determined to below 1 mm. This is used to define the zero point for the country's geodetic surveys. It is found to be moving North at 25 mms per year as a result of the movement of the underlying African tectonic plate. A satellite laser ranger is also on-site.

The Observatory also operates receivers for the Global Navigation Satellite Systems (GNSS) – GPS (USA), GLONASS (Russia) and Galileo (Europe).

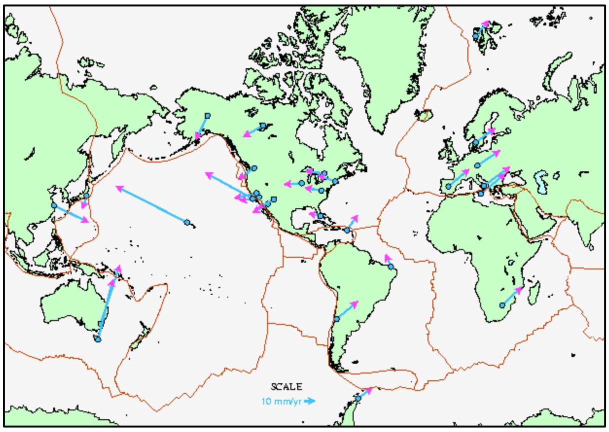

Fig 2. Annual movement of radio telescopes, measured by geodetic VLBI. The Hartebeesthoek telescope moves North-East at 2.5 cm per year. Tectonic plate boundaries are shown as brown lines (Photo: HartRAO web site).

The SKA Project

The Square Kilometer Array Observatory (SKA) is a well-publicised international project conceived in 1991. It will comprise a number of radio telescopes in South Africa and Australia having 1 km^2 of collecting area. Unfortunately it has taken a long time to reach fruition. It is now an intergovernmental organisation established by a treaty. The only other similar organization in astronomy is the European Southern Observatory.

The founding members who signed the treaty on 12 March 2019 are Australia, China, Italy, Portugal, the Netherlands, South Africa, and the United Kingdom. Each country has to ratify the treaty.

The SKA headquarters are at Jodrell Bank radio observatory in the UK. Dr Catherine Cesarsky is Chairman of the Board of Directors and Prof Phil Diamond is its Director-General. Bernie Fanaroff was the Director of the South African SKA project until 2016 and was succeeded by Rob Adam.

There will be two observing sites: (1) SKA1-MID, covering 350MHz to 24 GHz, in South Africa (2) Australia: SKA1-LOW, covering 50-300 MHz in Western Australia. This split is the result of intense competition between countries as to which should be the host.

The first phase, with about 10% of the total area is due to start in 2020. Full completion is hoped for about 2030

South African participation in the SKA is through SARAO, the South African Radio Observatory which manages all radio astronomy in South Africa including the facilities at Carnarvon in the Karoo and the older establishment HartRAO. The headquarters of this organisation are in Observatory, Cape Town.

SKA MID

This is the part of the SKA project based in South Africa (at Carnarvon). The current projection is that it will consist of 133 antennas combined with the 64 already existing ones of MeerKAT, for a total of 197.

The wavelength coverage of the receivers will be 350Mhz – 14GHz or 85 – 2 cms.

MeerKAT

The MeerkAT telescope is currently the major installation at the SKA site and has already made many unique contributions to astronomy. It is wholly South African owned. In its current form it is an array of 64 antennas on the SKA site located between Carnarvon and Brandvlei in the Groot Karoo. It was erected at a cost of R4.4 billion and was officially inaugurated in July 2018 by the Vice-President of South Africa, David Mabuza.

Fig 3. The MeerKAT Array at Dusk (Photo: SARAO.

MeerKAT has been functioning since 2018. By 2022 it will be expanded by another 20 dishes, half sponsored by Germany, at a further cost of R800 million. The extra 20 dishes to be installed will expand the distances up to 17km apart to increase the detail visible. They will also increase the sensitivity by about 50%. Ultimately, the MeerKAT will be merged into the SKA telescope.

Each antenna is 13.5m in diameter. The main “mirror” of each reflects the radio waves to the secondary that, in turn reflects them to the radio receiver. This design is

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called an "Offset Cassegrain", since in the traditional Cassegrain design the secondary is on the main axis of the primary. This version has the advantage that there is no metal in the incoming beam that may add to the background "seen" by the receiver.

The rms accuracy of the primary – a measure of its bumpiness – is 0.6mm.

Each antenna weighs 42 tons and all must be driven in lockstep to follow a particular part of the sky. They are located within a range of 29m to 8km from each other and their layout must cover all azimuth angles to obtain coverage at each position angle on the sky. Their separations control how fine is the detail that can be observed – close spacing gives the coarse detail while far spacing gives the fine.

Fig 4. A single MeerKAT antenna. The radio signals bounce off the big dish onto the smaller one at right and then into the receiver just below the small one (Photo: SARAO).

The receivers at present cover 1.0 to 1.75GHz (30cm to 17cm wavelength – the so-called L-band). Ultimately there will be three interchangeable receivers on each antenna to give coverage from 2cm to 50cm.

MeerKAT Observing Programmes

MeerKAT is mostly devoted to carrying out large programmes of a survey nature. These often involve several collaborators from different countries: most astronomical facilities worldwide welcome such international collaboration.

LADUMA: Looking at the Distant Universe with the MeerKAT Array – ultradeep survey of neutral hydrogen in the early universe.

ThunderKAT: Hunt for dynamic and explosive radio transients with MeerKAT – e.g. γ-ray bursts, novae and supernovae; new types of transient radio sources.

MeerKAT DEEP2 Survey (Mauch et al, *Ap J* **888**, 61M, 2020). This survey was made at a wavelength of 23cm and took 130 hours. The faint objects are very distant galaxies that account for most of the star formation in the universe. These results show that the rate of star formation at its maximum around 3.5 million years after the Big Bang was even larger than previously believed.

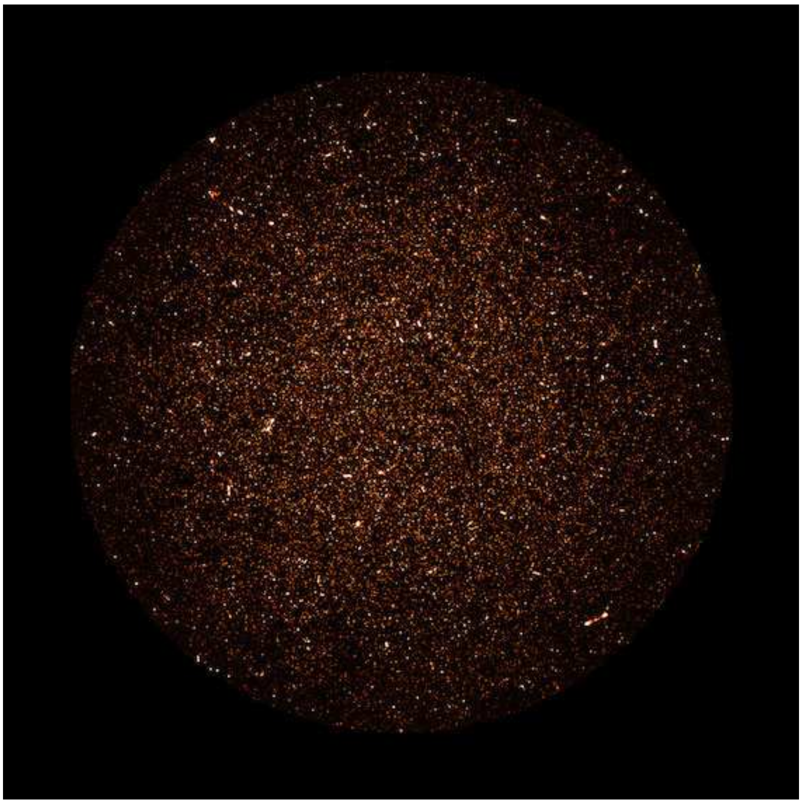

Fig 5. MeerKAT DEEP2 Survey. This image is the deepest survey ever made at these frequencies and is the deepest image of distant star-forming galaxies (Photo: SARAO).

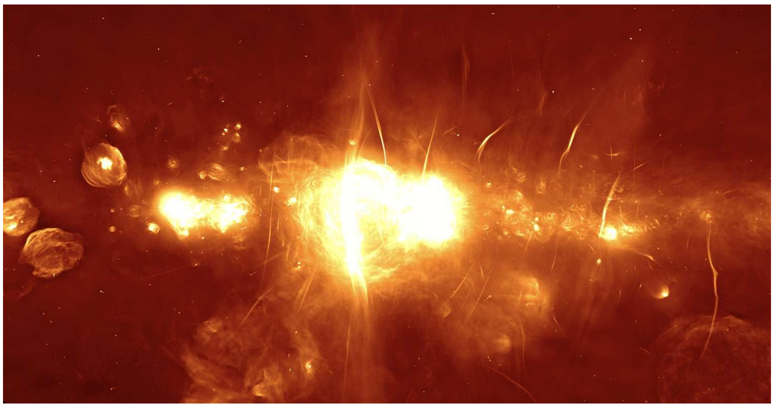

Fig 6. MeerKAT radio image of a 2° x 1° region around the Galactic Centre. Especially notable are the many filaments, a manifestation of synchrotron radiation from high-energy electrons spiraling along magnetic field lines (Photo: MeerKAT, SARAO).

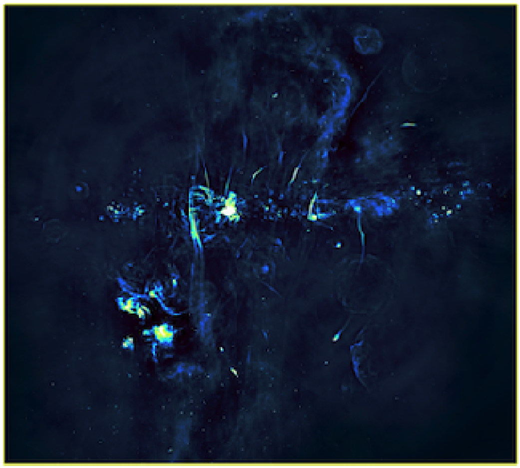

Fig 7. A radio image of the central portions of the Milky Way galaxy at 23cms. The plane of the galaxy is marked by a series of bright features, exploded stars and regions where new stars are being born, and runs horizontally through the image. The black hole at the centre of the Milky Way is hidden in the brightest of these extended regions. The radio bubbles discovered by MeerKAT extend vertically above and below the plane of the galaxy. Many magnetised filaments can be seen running parallel to the bubbles. (Adapted from results published in Heywood et al. (Nature ***573****, 235, 2019; Photo: SARAO.).*

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KAT

Fig 8. The Karoo Array Telescope (KAT) is an array of 7 antennas intended as a demonstrator project. Since MeerKAT (more KAT) started working it has been mothballed.

C-BASS

The C-Band All Sky Survey (C-BASS) is mapping the whole sky in temperature and polarization at 4.76GHz (6.3cm), with an angular resolution just 45 arcmin. The Southern part is being conducted at Klerefontein, just outside Carnarvon, away from the site of the other radio telescopes. Its main aim is to allow accurate subtraction of the Galactic synchrotron radiation that contaminates the 3° Cosmic Microwave Background polarization experiments observed at much shorter wavelengths by the Planck satellite.

C-bass also includes a Northern part at the Owens Valley Radio Observatory in California. This portion has already been completed.

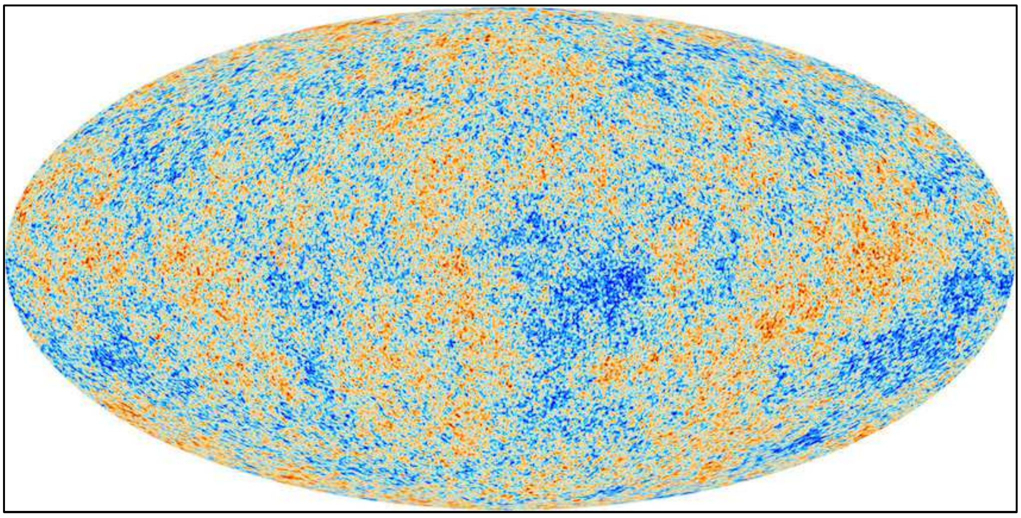

Fig 9. The three degree radiation left over from the Big Bang as measured by the Planck satellite at millimeter wavelengths that cannot be observed from within the Earth's atmosphere. Measurements at 5GHz (6cm) and other wavelengths are necessary to separate radiation arising in our own galaxy from that due to the Big Bang. This and the next map are in "Galactic Coordinates" so that the "equator" corresponds to the Milky Way.

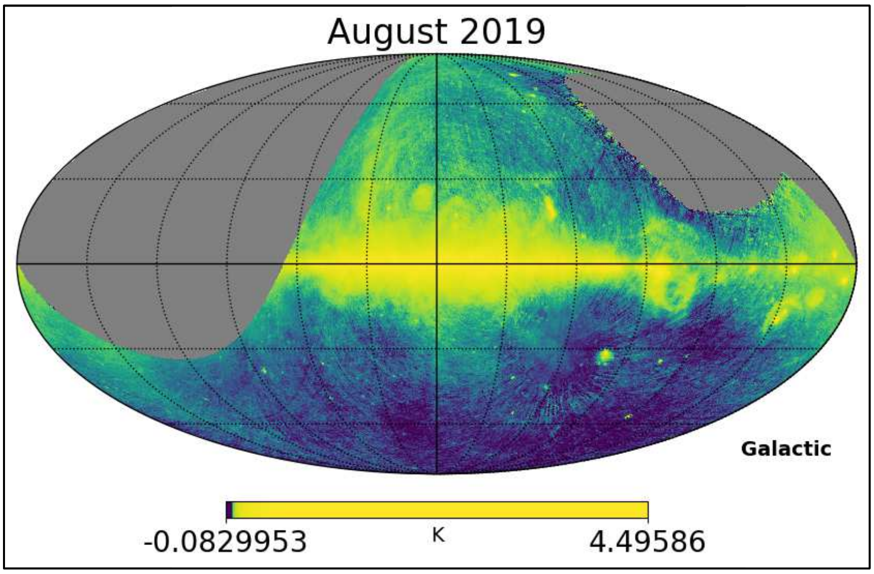

Fig 10. The Southern hemisphere data from C-BASS at 6cm to date. Most of this is "Synchrotron Radiation" whose effects extend to the mm-region wavelengths observed by he Planck satellite). The bar at the bottom is "antenna temperature", a measure of brightness used by radio astronomers (courtesy Prof J Jonas, Rhodes University).

Fig 11. The C-bass antenna at Klerefontein near Carnarvon. It has a diameter of 7.6m and was donated by Telkom.

The survey is a collaboration between the University of Oxford, University of Manchester, the California Institute of Technology, the Hartebeesthoek Radio Astronomy Observatory (HartRAO), and the King Abdulaziz City for Science and Technology.

Interferometry – The Key Technology used in Radio Telescope Arrays

Fig 12. The support buildings at the SARAO site, including the Karoo Array Processor Building where powerful computers assemble the signals from the individual antennas (Photo: SARAO).

Whether considering the SKA, the MeerKAT, HERA or HIRAX, The combination of the signals from the individual antennas to make one large antenna is a very complex process requiring state-of-the-art computers. The relative positions of each antenna surface have to be known to a small fraction of a wavelength. Technically, the correlations between the signals from each antenna (the fringe visibilities) undergo a “spatial Fourier transform” to make a radio picture of the relevant part of the sky.

For MeerKAT “the receiver outputs are digitized immediately at the antenna 2 x 1712 million times per second and the digital data streams are sent to the Karoo Array Processor Building (KAPB) via buried optical fibre cables. The antenna signals are first processed by the Correlator/Beamformer (CBF) digital signal processor. Data from the CBF is passed on to the Science Processor computer cluster and disk storage modules. The MeerKAT antenna data is also made available to a number of user-supplied digital backends via the CBF, including pulsar and fast radio burst (FRB) search engines, a precision pulsar timing system, and a SETI (Search for Extraterrestrial Intelligence) signal processor. A time and frequency reference (TFR) system provides clock and absolute time signals required by the digitizers and other telescope subsystems. This TFR system comprises two hydrogen maser clocks, two rubidium atomic clocks, a precise crystal oscillator, and a set of GNSS (Global Navigation Satellite Syatem) receiver systems for time transfer with UTC.

“The massive computing and digital signal processing systems located at the KAPB are housed in a large shielded chamber to prevent radio signals from the equipment interfering with the sensitive radio receivers. The KAPB itself is partially buried below ground level to provide additional radio frequency interference (RFI) protection, and to provide temperature stability. The KAPB also houses a power conditioning facility for the entire site, including three diesel rotary UPS units that provide an uninterrupted power supply to the whole site.

“A long-haul optical fibre transfers data from the KAPB to the Centre for High Performance Computing (CHPC) and SARAO office in Cape Town, and provides a control and monitoring link to the SARAO operations centre in Cape Town. Telescope data processing and reduction is executed on computing facilities provided by the MeerKAT SP systems, and on other high performance computer facilities provides by MeerKAT users.”

HIRAX

HIRAX, a future installation, stands for Hydrogen Intensity and Real-time Analysis Experiment.

Fig 13. Prototype antennas for HIRAX under test at Hartebeesthoek (Photo credit: SARAO).

HIRAX is similar in intention to HERA but concentrates on redshifted 21-cm neutral hydrogen radiation from material dating back 2-6 billion years, i.e., the more recent Universe where the Hubble expansion changed from decelerating to accelerating.

The Expansion of the Universe is known to be accelerating due to the effects of the mysterious Dark Energy and Dark Matter.

Its frequency coverage will be 400-800 MHz or wavelengths of 38-75cms, that is, at shorter wavelengths than HERA. It will have 1024 semi-fixed antenna of 6m diameter (in 2020s) and will map 1/3 of the sky daily over 4 years

HIRAX will also search for "Fast Radio Bursts" – little understood transient radio sources. Also pulsars.

It is managed by UKZN with many other national and international participants

HERA[1]

Fig 14. Artist's impression of the Hydrogen Epoch of Reionization Array (HERA) when completed (Image: University of California, Berkeley website).

One of the most exciting cosmological projects at present, this telescope is dedicated to understanding the large-scale structures formed during the earliest observable stages of the Universe. It asks which objects first lit up the intergalactic medium by reionizing the neutral hydrogen and at what redshifts this occurred.

Ultimately HERA will have about 350 fixed dishes of 14m diameter and it is currently being developed in phases. Promising results have already been obtained from the first 47 dishes to have been completed. It functions as an interferometer, scanning about 440 square degrees of the sky. The signals are processed in the Karoo Array Processor Building.

Hydrogen radiation has an un-redshifted wavelength of 21cm and this telescope will be able to observe it when redshifted into the range 600 to 1200cm, corresponding to z = 6 to 30. HERA's direct aim is to extract the large-scale structure of the primordial inter-galactic medium at different redshifts.

[1] 2017 DeBoer, DR et al, https://iopscience.iop.org/article/10.1088/1538-3873/129/974/045001

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The signal from hydrogen at the epoch of reionisation is expected to be very weak and must be separated from foreground contamination by essentially all foreground objects. This can possibly be done for a range of angular and spatial scales.

HERA is funded by the National Science foundation (USA) and the Gordon and Betty Moore Foundation. The HERA collaboration consists of Arizona State University, Brown University, Cambridge University, the Massachusetts Institute of Technology, the National Radio Astronomy Observatory, Scuola Normale Superiore (Pisa), Square Kilometre Array South Africa (SKA SA), University of California at Berkeley, the University of California at Los Angeles, the University of Pennsylvania, and the University of Washington. Participating South African institutions include Rhodes University, the University of KwaZulu-Natal, the University of the Western Cape and the University of the Witwatersrand.

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Fig 15. Paper was a relatively simple precursor array located on the SKA site with the same aim as HERA. It was too small and insensitive to achieve the desired aim and has now been superseded (Photo: University of California Berkeley Astronomy Website).

Acknowledgments

Prof Justin Jonas (Rhodes) and Dr Fernando Camilo (SARAO) are thanked for providing information. The web sites of SARAO and other institutions have also provided useful information.