The MeerKAT radio telescope - the path to the SKA mid-frequency array

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ASSA Symposium – SAAO, Cape Town – 13th October 2012
Other things we do...
Brief History

- DACST/NRF workshop in 2000.
- First SA representation on ISSC in July 2001 (Berkeley).
- SKA SA project office established January 2003.
- Initial offer to host SKA in May 2003.
- First formal proposal submitted in December 2005.
- South Africa and Australia sort-listed in August. 2006 (Dresden ISSC meeting).
- Final proposal submitted September 2011.
- Face-to-face meeting with SSAC December 2011.
- SSAC recommendation receiver by Board of SKA Organization on 22 February 2012.
- Site Options Working Group considered split site implementations (April/May 2012).
- SKA Organization announcement on 25 May 2012.
- Vague blur ever since.
Finding a Site
Karoo Radio Astronomy Reserve

500 km
SKA Site Proposal

• 150 page main document with 10 sections:
  – Basic Infrastructure
  – Electric Power
  – Data Transport
  – Physical Characteristics
  – Radio Frequency Interference
  – Political, Socio-economic & Financial
  – Customs & Excise
  – Legal
  – Security
  – Working & Support Environment

• Over 500 annexures totaling 2 GB
The Team
Power
African Submarine Cable Systems
Weather and Troposphere
George Nicolson and “The Bid”
SKA Site Announcement
CONGRATULATIONS! WORKING TOGETHER, WE CAN REACH FOR THE STARS!
SKA antennas

Africa (mid-frequency)

Australia (low-frequency)
The “Core” in the Karoo
“Our commitment to the SKA is firm and steadfast. It is our hope that others will emulate this engagement”
Minister Naledi Pandor, SKA Forum 2011
The MeerKAT Programme

• Africa must have a legacy of a large radio telescope
  – Irrespective of the outcome of the SKA site competition
  – But not independent of the SKA
• MeerKAT is an SKA “precursor”
  – Engineering prototype
  – Early science (SKA “Phase 0”)
  – Largest radio telescope in southern hemisphere, one of largest in the world
  – Phased development: XDM, KAT-7, MeerKAT, SKA₁, SKA₂
  – MeerKAT will be the first 25% of SKA₁
    • Our strategy was successful!
System engineering & Design

• Science-led process
  – Science case
    ➔ User Requirement Specification
    ➔ Requirements Review
    ➔ System Specification
    ➔ Concept exploration and prototypes
    ➔ Concept and Preliminary design reviews (system)
    ➔ Subsystem specifications, design and reviews
MeerKAT SAC – June 2009

- Bruce Bassett
- Erwin de Blok
- Mike Garrett
- Michael Kramer
- Robert Laing
- Scott Ransom
- Steve Rawlings
- Lister Staveley-Smith
  – Also: Roy Booth, Bernie Fanaroff, Justin Jonas
Highlights of SAC meeting

• MeerKAT as per specifications provided to the SAC was an good instrument, but lacked defined niches and “killer apps”.
  – Legacy science also important
• Needs to be distinct from from VLA, ASKAP, GMRT
  – Extend to lower frequencies (580 MHz), limit to L/S-band to 2 GHz
  – Extend to X/Ku-band
  – Exclude C-band?
• Needs to capitalize on sensitivity and DR
  – Longer baselines
  – Extend to lower frequencies
• Needs to capitalize on extended, low-brightness sensitivity
  – Higher filling-factor in the core
• Capitalize on VLBI capability
# High Level Specifications

<table>
<thead>
<tr>
<th>Metric</th>
<th>KAT-7</th>
<th>MeerKAT Pre-SAC</th>
<th>MeerKAT Post-SAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\text{low}}$</td>
<td>1.2 GHz</td>
<td>700 MHz</td>
<td>580 MHz</td>
</tr>
<tr>
<td>$F_{\text{high}}$</td>
<td>1.95 GHz</td>
<td>10 GHz</td>
<td>15 GHz</td>
</tr>
<tr>
<td>$A_e/T_{\text{sys}}$</td>
<td>16 m$^2$/K</td>
<td>200 m$^2$/K</td>
<td>200 m$^2$/K</td>
</tr>
<tr>
<td>$\text{DR}_{\text{imag}}$</td>
<td>30 dB</td>
<td>60 dB</td>
<td>60 dB</td>
</tr>
<tr>
<td>$\text{DR}_{\text{spec}}$</td>
<td>30 dB</td>
<td>50 dB</td>
<td>50 dB</td>
</tr>
<tr>
<td>Xpol</td>
<td>-20 dB</td>
<td>-25 dB</td>
<td>-25 dB</td>
</tr>
<tr>
<td>BW</td>
<td>256 MHz</td>
<td>1 024 MHz (2 048 MHz)</td>
<td>1 024 MHz (4 096 MHz)</td>
</tr>
<tr>
<td>$N_{\text{chan}}$</td>
<td>4 096</td>
<td>32 768</td>
<td>32 768?</td>
</tr>
<tr>
<td>$T_{\text{int}}$</td>
<td>&lt;1 s</td>
<td>0.1 ms</td>
<td>0.1 ms</td>
</tr>
</tbody>
</table>
Configuration (64 antennas)
MeerKAT Science: UHF, L & S-band

- Low column density HI associated with the Cosmic Web and galaxy environments
- Ultra-deep narrow-field HI survey out to z=1.4 using gravitational lensing amplification
- High spatial dynamic range HI imaging of 1000 galaxies
- Ultra-deep narrow-field continuum surveys down to micro-jansky detection limits
- Mapping magnetic fields in clusters
- All-sky continuum survey at 600 MHz
- Pulsar timing and monitoring
- SNR detection and GRB follow-up
- OH mega-masers and Zeeman splitting
- Galactic gas dynamics and magnetic fields
MeerKAT Science: X & Ku-band

• **Future high-frequency upgrade**
• All-sky continuum survey at 8 GHz
• Detection of CO lines at high redshift
• Mapping of S-Z clusters
• Transients sources in the Galactic centre
An open invitation to the Astronomical Community to propose Key Project Science with the South African Square Kilometre Array Precursor

MeerKAT

R.S. Booth
Hartebeesthoek Radio Astronomy Observatory, P.O.Box 443, Krugersdorp 1740, South Africa
email: roy@hartrao.ac.za

W.J.G. de Blok
Department of Astronomy, University of Cape Town, Rondebosch 7700, South Africa.
email: edeblok@ast.uct.ac.za

J.L. Jonas
Rhodes University, Dept. Physics & Electronics, PO Box 94, Grahamstown 6410, South Africa
email: j.jonas@ru.ac.za

B. Fanaroff
SKA South Africa Project Office, 17 Baker St, Rosebank, Johannesburg, South Africa
email: bfanaroff@fanaroff.co.za

Proposal Submission deadline: March 15, 2010
MeerKAT TAC – Sept 2012

- Frank Briggs
- Simon Johnson
- Athol Kemball
- Robert Laing
- Joe Lazio
- Jay Lockman
- Andrew Lyne
- Roy Maartens
- Thijs van der Hulst
  – Also: Roy Booth, Bernie Fanaroff, Justin Jonas
MeerKAT Large Surveys

• Highest priority:
  – Deep HI field
  – Radio Pulsar Timing

• Compelling:
  – HI and continuum mapping of 30 nearby galaxies
  – Absorption line survey
  – Molecules in the EoR
  – Detecting fast transients and pulsars
  – HI survey of Fornax
  – X-band Galactic plane survey
  – Tiered continuum survey
  – Slow radio transient survey

• Also
  – VLBI
  – Cosmic Magnetism
MeerKAT Large Surveys

22 Countries
UK (26 Institutions, 89 individuals)

- ATC
- Birmingham
- Bristol
- Cambridge
- Dublin
- Durham
- Edinburgh
- Exeter
- Hertfordshire
- JCU
- Lancaster
- Leeds
- Leicester
- Liverpool
- Manchester
- MSSL
- Newcastle
- Nottingham
- Open U
- Oxford
- Portsmouth
- RAL
- Southampton
- Sussex
- Sussex
- UCL
- Warwick
Rest of EU (34 institutions, 93 individuals)

- Germany (8,24)
  - Bamburg
  - Bochum
  - Bonn
  - (ESO)
  - Jacobs
  - MPE
  - MPIfR
  - MPIA
- Netherlands (7,28)
  - Amsterdam
  - ASTRON
  - JIVE
  - Kapteyn
  - Leiden
  - Nijmegen
  - SRON
- France (7,19)
  - Bordeaux
  - Inst Ast
  - Marceille
  - Obs Paris
  - OCA
  - Orleans
  - Saclay
- Italy (4,9)
  - Cagliari
  - INAF
  - Padova
  - SISSA
- Sweden (2,4)
  - Chalmers
  - Onsala
- Spain (2,3)
  - IAA
  - Valencia
- Portugal (2,3)
  - Lisbon
  - UTL
- Poland (1,2)
  - Cracow
- Belgium (1,1)
  - Brussels
### Time Allocated – > 5 years

<table>
<thead>
<tr>
<th>Survey</th>
<th>L-Band</th>
<th>UHF</th>
<th>X/Ku-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep HI</td>
<td>5 000</td>
<td>5 000</td>
<td></td>
</tr>
<tr>
<td>Pulsar Timing</td>
<td>7 860</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 Galaxies</td>
<td>6 000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HI Absorption</td>
<td>2 000</td>
<td>2 000</td>
<td></td>
</tr>
<tr>
<td>EoR Molecules</td>
<td></td>
<td></td>
<td>6 500</td>
</tr>
<tr>
<td>Fast Transients</td>
<td>3 080</td>
<td></td>
<td>?</td>
</tr>
<tr>
<td>Fornax HI</td>
<td>2 450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X/Ku-band Galaxy</td>
<td></td>
<td></td>
<td>3 300</td>
</tr>
<tr>
<td>Deep Continuum</td>
<td>1 950</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow Transients</td>
<td>3 000</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>TOTAL</td>
<td>31 340</td>
<td>7 000</td>
<td>8 800</td>
</tr>
</tbody>
</table>

1 yr = 8 760 hr
MeerKAT Phase 1 (2016)

- 64 x 13.5 m gregorian offset antennas
  - >> 220 m²/K (300 m²/K goal)
- 8 km maximum baseline
  - 70 % in < 1km diameter core
- 0.9-1.726 GHz (following ECP) cryogenic single-pixel receiver (L-band)
  - Multiple feed indexer
- Direct digitization
  - DFX architecture
Future Phases

• 580-1000 MHz (UHF-band)
• 8-14.5 GHz (X/Ku-band)
• Aspirations (contingent on money and/or technology availability):
  – 20+ km baselines
  – 1.5-3 GHz for NanoGrav
  – 5-22 GHz wideband receiver
• SKA-mid Phase 1
Concept exploration:

- Antenna geometry
  - Symmetric centre-fed / Gregorian offset
- Receivers
  - Octave / wide bandwidth
  - Cooled / uncooled
  - Single / multiple pixel
- Array configuration
  - Number of dishes
  - Distribution of dishes
- Signal conditioning and digitization
  - Heterodyne / direct RF
  - Location of digitizer (digital or RF signal transport)
- Software
  - Custom / consortium
MeerKAT with Offset Gregorian
Comparison of beam patterns
• Extensive trade off between optical and mechanical aspects of antenna
  – Mechanical tolerance impacting optical performance

• Materials testing and component durability
  – Accelerated environmental and operational tests

• Receiver cryogenic refrigeration options
  – Stirling cycle vs G-M cycle
MeerKAT dish concept
## Performance @ 1420 MHz

<table>
<thead>
<tr>
<th></th>
<th>JVLA</th>
<th>ASKAP</th>
<th>SKA-Survey</th>
<th>MeerKAT</th>
<th>SKA-Mid</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{dish}}$</td>
<td>27</td>
<td>36</td>
<td>96</td>
<td>64</td>
<td>254</td>
</tr>
<tr>
<td>$D_{\text{dish}}$</td>
<td>25 m</td>
<td>12 m</td>
<td>(15 m)</td>
<td>13.5 m</td>
<td>(13.5 m)</td>
</tr>
<tr>
<td>$T_{\text{sys}/\varepsilon_a}$</td>
<td>47.3 K</td>
<td>62.5 K</td>
<td>62.5 K</td>
<td>29.4 K</td>
<td>29.4 K</td>
</tr>
<tr>
<td>$N_{\text{beam}}$</td>
<td>1</td>
<td>30</td>
<td>30</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>BW</td>
<td>1 GHz</td>
<td>300 MHz</td>
<td>300 MHz</td>
<td>750 MHz</td>
<td>750 MHz</td>
</tr>
<tr>
<td>$A_e/T_{\text{sys}}$</td>
<td>280 m$^2$/K</td>
<td>65 m$^2$/K</td>
<td>271 m$^2$/K</td>
<td>311 m$^2$/K</td>
<td>1 236 m$^2$/K</td>
</tr>
<tr>
<td>SS m$^4$K$^{-2}$ deg$^2$</td>
<td>17 368</td>
<td>127 312</td>
<td>2 210 286</td>
<td>73 510</td>
<td>1 157 857</td>
</tr>
</tbody>
</table>
Commissioning and early science

KAT-7 Full Science Operations

- First dishes QTP + ATP
- Continue dish ATP as they roll out
- August 2016: All dishes complete

- Commission first array release
- Science verification
- Commission second array release
- Science verification
- Commission third array release
- Science verification

- Array release 1
- Imaging, Tied array
- + Pulsar Timing
- + Transients, Fly's eye, VLBI

- Correlator modes available
- Early science: Imaging, Tied array
- Early science: Imaging, Tied array, Pulsar timing
- Full operations ??

2013 2014 2015 2016 2017 2018 ...

- Dishes available
- 2 6 35 64
Cen B
Cir X-1 - off
Cir X-1 - on
HUDF & NVSS contours
NGC 3109 (neutral hydrogen)
Single Baseline OH spectrum
Vela Single Pulse Baseband
Klerefontein Support Base
Site Complex extension for MeerKAT

- Dish Assembly shed
- Pedestal integration shed
- Bunkered & RFI shielded processor building and power room
Grid power to site
Carnarvon S/S upgrade to 10 MVA
10 Gb/s to the heart of the Karoo

Broadband InfraCo container arrives at Carnarvon SKA POP Station

New overhead optical fibre cable being installed between Hutchinson and Carnarvon as part of Broadband InfraCo’s long-haul fibre network
On-Site power & data reticulation
Road network near core
The President at KAT-7