SKA and its computing challenges

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Summary

• The Project
• The Science
• Computing and Software
  • Telescope Manager
  • Low Frequency Aperture Array
  • Central Signal Processor
  • Science Data Processor
• Regional Centres
• Conclusions
The Project
Square Kilometre Array
3 sites; 2 telescopes + HQ
1 Observatory

Design Phase: > €170M; 600 scientists+engineers

Phase 1
Construction: **2018 – 2024**
Construction cost cap: €674.1M (inflation-adjusted)
Operations cost: under development (see below)

MeerKat integrated
Observatory Development Programme (€20M/year planned)
SKA Regional centres out of scope of centrally-funded SKAO.

Phase 2: start mid-2020s
~2000 dishes across 3500km of Southern Africa
Major expansion of SKA1-Low across Western Australia
HQ in UK; telescopes in AU & SA

- SKA1-LOW: 50 – 350 MHz
- Phase 1: ~130,000 antennas
- across 65km

SKA1-Mid: 350 MHz – 24 GHz
Phase 1: 200 15-m dishes across 150 km

Construction: 2018 – 2024; Cost cap: €675M
SKA Design Consortia

- Signal and Data Transport
- Telescope Manager
- Assembly, Integration & Verification
- Dish
- Science Data Processor
- Low-Frequency Aperture Array
- Central Signal Processor
- Infrastructure Australia
- Infrastructure South Africa

Exploring the Universe with the world’s largest radio telescope
Precursors

Exploring the Universe with the world's largest radio telescope
SKA Organisation: 10 countries, more to join

Australia (DoI&S)
Canada (NRC-HIA)
China (MOST)
India (DAE)
Italy (INAF)
Netherlands (NWO)
New Zealand (MED)
South Africa (DST)
Sweden (Chalmers)
UK (STFC)

Interested Countries:
• France
• Germany
• Japan
• Korea
• Malta
• Portugal
• Spain
• Switzerland
• USA

Contacts:
• Mexico
• Brazil
• Ireland
• Russia

Full members
• SKA Headquarters host country
• SKA Phase 1 and Phase 2 host countries

African partner countries
(non-member SKA Phase 2 host countries)

This map is intended for reference only and is not meant to represent legal borders.
STATUS OF INTERESTED COUNTRIES

- **Portugal**: Letters of support from Ministers of Science and Economy. Announcement imminent.

- **Germany**:  
  - MPG providing funding for a second SKA1-Mid prototype dish (first to go to site)  
  - Germany attended IGO meetings following positive re-engagement.

- **France**: Accelerated re-examination of Astrophysics section of National Science Infrastructure Roadmap. Engagement with industrial partners.

- **Spain**: Spanish State Secretary has written to D-G, supportive of joining SKA in near future.

- **Switzerland**: Swiss State Secretary requested observer status at SKA Board - granted; indication will join when an IGO.

- **Japan**: Attended SKA Board in November and March.

- **Korea**: Attended SKA Board in March.

- **USA**: Establishing radio astronomy strategy for Astro2020. Ongoing discussions with Director NRAO and DoE labs.
Future SKA governance structure

• IGO = ‘Convention’ agreed between governments
  • Government commitment: Long-term political stability, funding stability
  • A level of independence in structure
  • Availability of ‘supporting processes’ through Privileges and Immunities from members: functional support for project
  • ‘Freedom to operate’, specifically through procurement process, employment rules and so on
Operations Scope

SKA Observatory

Observatory Operations

Corporate Functions

Development Support

SKA Regional Centres

SKA Development Centres

In Scope

AUS Operator

SKAO AUS Office

GHQ

SKAO RSA Office

RSA Operator

Science Processing Centre

Science Processing Centre

Service Level Agreements

Memorandum of Understanding
Overall project timeline – to be confirmed

Key dates:
- Convention signing July 2017
- CDRs Q4 2017 – Q2 2018
- IGO enter into force July 2018
- SKA1 Construction approval early 2019
The Science
SKA—Key Science Drivers: The history of the Universe

- Cosmic Dawn
  (First Stars and Galaxies)
- Galaxy Evolution
  (Normal Galaxies z~2-3)
- Cosmology
  (Dark Energy, Large Scale Structure)
- Testing General Relativity
  (Strong Regime, Gravitational Waves)
- Cradle of Life
  (Planets, Molecules, SETI)
- Cosmic Magnetism
  (Origin, Evolution)

Exploration of the Unknown

Extremely broad range of science!
Era of Recombination

- Afterglow Light Pattern 400,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Big Bang Expansion 13.7 billion years
SKA1 capability vs state-of-the-art

Point-source sensitivity:
\(~4 - 20\) times state-of-the-art

Survey speed:
\(~10 - 100\) times state-of-the-art
Image Quality Comparison

- Single SKA1-Mid snap-shot compared to combination of snap-shots in each of VLA A+B+C+D
Science Working Groups

• Primary scientific community interface to the SKA
• Current SWGs represent a wide range of scientific areas:
  • Extragalactic Spectral Line (non-HI)
  • Our Galaxy
  • Solar, Heliospheric & Ionospheric Physics
  • Epoch of Reionization
  • Cosmology
  • Extragalactic Continuum (galaxies/AGN, galaxy clusters)
  • Cradle of Life
  • HI galaxy science
  • Magnetism
  • Pulsars
  • Transients
• Technique focused Working Group:
  • VLBI
• Topical Focus Group:
  • High Energy Cosmic Particles
Key Science Projects

• Key Science Projects (KSPs) are the science community’s highest priority science objectives which are:
  • Consistent with capabilities of the SKA1 design
  • Consistent with a realistic observing schedule filled at 50 – 75% for the first 5 years of scientific operations
• KSP policy currently progressing in context of IGO negotiations
  • Total access (sum of KSP + PI projects) approximately proportional to country’s contribution.
  • Mix of KSP/PI projects up to individual member countries
• Call for KSP proposals will happen during construction
  • Will need to allow time for organization and resourcing
  • Is anticipated to lead to large, multi-national teams.
SKA Computing and Software
Introduction

• SKA is a software telescope
  • Very flexible and potentially easy to reconfigure
  • Major software and computing challenge

• Computing challenges are significant
  • Science Data Processor (SDP) needs 25 PetaFLOPS/sec of delivered processing
    • Current estimate is that SDP needs 250 PFLOP/sec peak.
    • Tianhe-2 – 50 PetaFLOPS/sec peak.
    • Memory bandwidth is ~200 PetaBytes/sec
  • Pulsar Search is an additional 50 PFLOP/s of peak processing
  • Power efficiency required is ~40x better than Tianhe-2,

• Software challenges are also large
  • Feb 2017 costings have ~€90M of software.
System Overview

DISH

8.8 Tbits/s

TELESCOPE MANAGER

2x 5 Tbits/s

SIGNAL AND DATA TRANSPORT

~50 PFlop

CENTRAL SIGNAL PROCESSOR

~250 PFlop

SCIENCE DATA PROCESSOR

300 PB/yr

SKA Regional Centres

LOW-FREQUENCY APERTURE ARRAY

2 Pbits/s

2.1 Tbits/s

7.2 Tbits/s
Telescope Manager
Telescope Manager Overview
Telescope Management

- Dishes and Aperture Arrays
- Signal and Data Transport
- Infrastructure
- Central Signal Processor
- Science Data Processing
- Precursors

Telescope Management

Operator

Scientist

Engineer

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Low Frequency Aperture Array
Technical implementation

**Antenna:** Log Periodic

**No. of ant.:** 131,072 \(2^{17}\)

**Ant. Spacing, min:** 1.5m (av. ~1.9m)

**Station size:** 256 antennas

~40m dia.

**No. of stations:** 512

**Signal transport:** Analogue fibre

**Processing:** Digital

**Sample res.:** 8-bit

**Grouping:** 16 antenna per Tile

**Data routing:** Switched network
A Station...

- **Antenna**

  - Min. ant. spacing: 1.5m

- **A “Station”** – 256 antennas
  
  (beams sent for processing)

- **A “Tile”** – 16 antennas
  
  (processed in one module)

- **Low Frequency AA**: 512 Stations
- Antennas in a random pattern

~40mdia.
Low Frequency Aperture Array Overview

SKALA Antenna Arrays

RF over Fibre

Power & Interface

Central Processing Facility

Tile Processing module, TPM

ADCs

Spectral filters

Beamforming

COTS Data Network

MCCS

Monitor, Control & Calibration Servers

To Telescope Manager

To Telescope Manager

To Correlator

Screened Processing Facility

Remote Processing Facility

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Central Signal Processor (CSP)
Central Signal Processor Overview

Beamformer → Pulsar Search → Correlator → Control and Monitoring

Control and Monitoring → Pulsar Timing

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Correlator Beam Former (CBF)

- **Correlator:**
  - Channelise signal from every dish/aperture array station into fine frequency channels (65k)
  - Cross-correlate all channels for every pair of dishes/stations
  - Cross-correlations (‘visibilities’) passed to SDP for imaging

- **Beamformer:**
  - Forms multiple beams within the dish/station beam
    - 1500 beams for Mid and 750 for Low
  - Passes data to Pulsar Search/Timing engines/VLBI interface

- **Very large amounts of real-time processing:**
  - \( N_{corr} \sim B(N_{dish} \cdot \log_2(N_{ch}) + N_{dish}^2) \sim \text{PetaMAC/s} \)
  - \( N_{BF} \sim B \cdot N_{dish} \cdot N_{beam} \sim \text{few PetaMAC/s} \)

- Based on custom FPGA processing platforms
Pulsar Search

• General processing pipeline requires ~50 PFLOPS/sec.
• Baselined heterogeneous design to achieve best combination of hardware & software firmware.
• Two beams per compute node in current design.
• 250 server nodes in Australia and 750 in South Africa
• Dual redundant 10 & 1 gig networks.
• Each Node (1000 in total):
  • Low Power CPUs
  • GPUs
  • FPGA boards
  • 10 Gig inputs
  • > 1 Tbyte RAM &/or SSDs
2+ Gbps in / beam
Real-time dedispersion, 6000 DM trials
2+ Gbps * 6000 out

1.5 Gbps in
8Mpt point FFT
10.7 ns per sample
1.5 Gbps out

1000 candidates in
256 kB/folded candidate
380 GB/obs out

1.5 Gbps in
85 * 4 Mpt convolutions
1.5 Gbps * 5 out
Science Data Processor
Science Data Processor Overview
Graph driven data flow
Computing Limitations

- Arithmetic Intensity $\rho = \text{Total FLOPS}/\text{Total DRAM Bytes}$
- The principal algorithms required by SDP (gridding and FFT) are typically $\rho \approx 0.5$
- Typical accelerators have an $\rho \approx 5$
  - For example, NVidia Pascal GPU architecture has:
    - Memory bandwidth $\approx 720 \text{ GB/sec}$
    - Floating point bandwidth $\approx 5,000 \text{ GFLOPS/sec}$
- Hence, the computational efficiency $\approx 0.5/5 \approx 10\%$
  - So, because of the bandwidth requirements, we have to buy 10 x more computing than a pure HPC system would require.
  - Unless the vendors improve the memory bandwidth...
Computing Requirements

• ~25 PetaFLOPS/sec total sustained
• ~200 PetaByte/s aggregate BW to fast working memory
• ~50 PetaByte fast working storage
• ~1 TeraByte/s sustained write to storage
• ~10 TeraByte/s sustained read from storage
  • ~ 10000 FLOPS/byte read from storage
• Current power cap proposed is ~5MW per site.
Data Management Challenges

• All Top500 HPC systems have been designed for High Performance Computing (by definition).

• There is a new term – High Performance Data Analytics (HPDA) to reflect systems like SKA

• Must ensure the data is available when and where it is needed.

• CPU’s must not be idling waiting for data to arrive
  • Data must be in fast cache when it is needed.

• Need a framework that supports this.
  • Looking at a variety of prototypes
Addressing Power

- Need to achieve a FLOPS/Watt 5-10 times better than current greenest computer.
- Need a three pronged approach:
  
  **Algorithms**
  
  Pursue innovative approaches to cut processing times

  **Hardware**
  
  Look at accelerators, hosts, networks and storage.

  **Testing**
  
  Using real algorithms and fully instrumented systems
Software

• Budget of ~€90M on manpower for software development across the whole telescope.
  • Need professional practices for development, testing, integration and deployment.
  • Need to unify the processes across the world-wide team of developers.
  • Need world-leading expertise in a number of areas.

• Delivered system will not be static
  • SDP hardware and software will be updated periodically.
  • Key input for development will be the scientific and software community through the regional centres.
SKA Regional Centres
Regional Centre Overview

• In April 2016 the SKA Board agreed the principal of regional centres
• Modelled on the LHC Tiering system
• Not part of SKA, or funded by SKA, but:
  • Essential to generate science
  • Coordinated with assistance from SKAO and accredited with SKAO
• Principle functions
  • Take data products generated by SDP and turn them into science
  • Support regional astronomers with their data processing.
  • Act as a centre for domain expertise.
Regional Centre Concept:

Science Processing Centre

Regional Centre 1

Regional Centre 2

Regional Centre N

Users

Users

Users

Users

Users

Users

Observatory

User Community
Regional Centre Network

- 10 year IRU per 100Gbit circuit 2024-2033 (2015 est.)
- Guesstimate of Regional Centre locations

Fibre Cable Systems – SKA relevant

Major NREN Paths – SKA relevant
What will Regional Centres do?

• Provide a nexus for resources
  • Scientific expertise
  • Software expertise
  • Access to computing resources - but direct ownership of is not a requirement
• Provide support for scientific development
  • Provide future, subject-specific pipelines
  • Contribute to common efforts in visualization, stacking, co-adding?
• Provide access to data
  • Ensure security and adherence to SKA data policies
  • Play a defined role in hosting and distributing archives
• Provide local (time zone) user support, proposal access, information, training and outreach activities
• Liaison with SKA Observatory and NRENs
  • Need to ensure sufficient and affordable network capacity is procured and provisioned in a timely fashion
Conclusions

• SKA will be the world’s primary radio telescope in the metre and centimeter bands.
• It is a huge computational and software challenge
• Traditional HPC is not a good match because the problem is bandwidth dominated.
  • SKA is seen as a key programme in global IT development
  • Showcases a major development area of High Performance Data Analysis (HPDA).
• Software complexity is also beyond what has been achieved in astronomy previously.
  • Quality is paramount and good processes essential