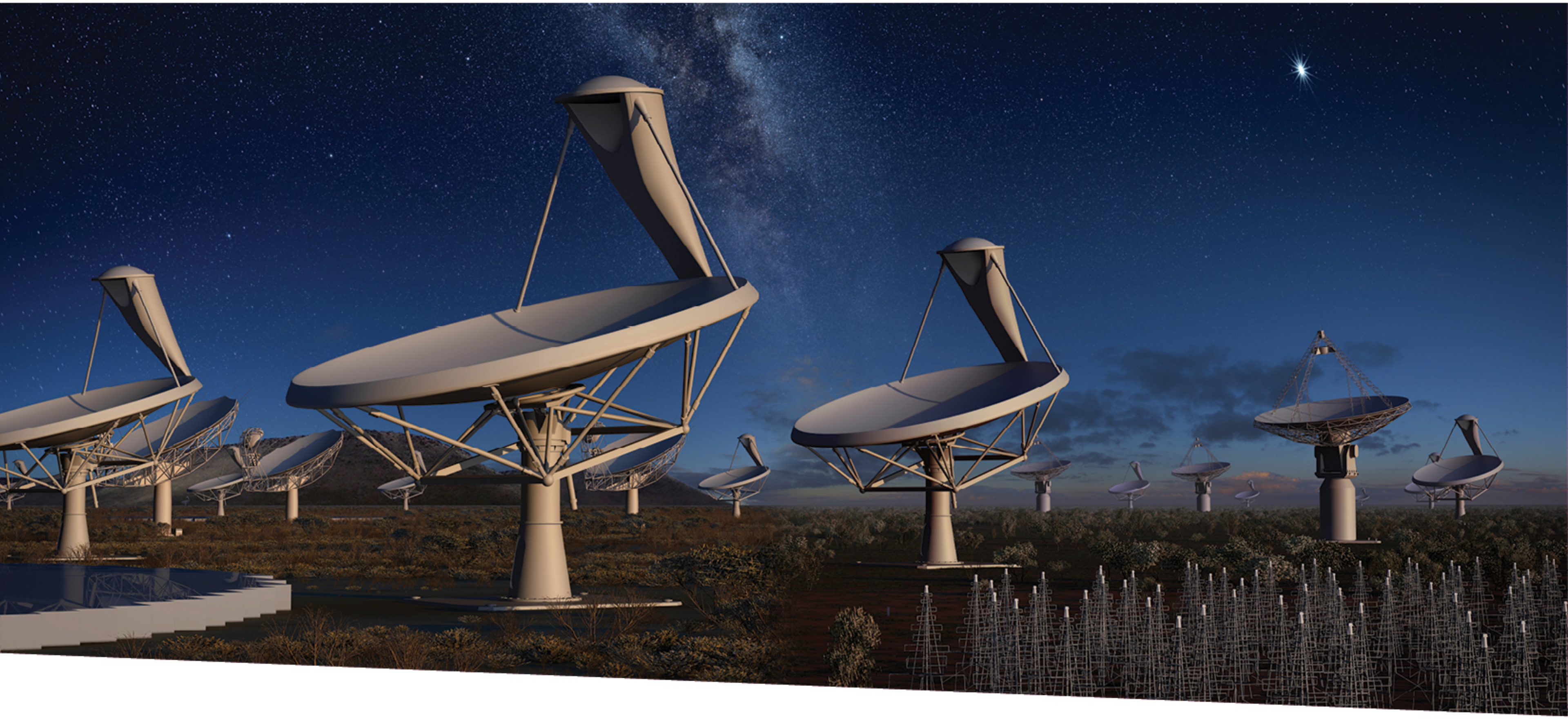
Future Array Technology and Design

Fourteenth Synthesis Imaging Workshop



SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

P. Dewdney

2014-05-19

Collaborators

Dave deBoer

Ger de Bruyn

Lisa Harvey-Smith

Justin Jonas

Mark Halpern

Greg Taylor

Steven Tingay

Introduction

- Astronomy is an exploratory science (over many dimensions).
- Science itself requires a multi-wavelength approach.
  - But technical specialisation is also essential.
  - The ideal situation is cross-training and experience:
    - Science, instrumentation and experimentation.
- The purpose of this talk is to illustrate the health of the field by examples of imaging arrays at both large and medium scales.
  - Hence the breadth of opportunity.
- There is room in radio astronomy for bright, early and mid-career scientists and engineers who see their future in the field.
  - Pure technology development and application.
  - Engineering.
  - Management.
  - International relations.

Introduction (cont'd)

- New technologies are the "life-blood" of radio astronomy:
  - Awareness of emerging technologies and innovation in other fields.
  - Constant flow and interchanges of people.
    - Innovation feeds off communication and interchange of ideas.
    - Participants do have to be mobile.
  - Assisted by:
    - Availability of demanding new projects.
    - Collaboration, especially international.
    - Involvement of industry.
- Organisation of each section (9 examples):
  - The science
    - questions being addressed,
    - measurements/observations are being planned or in use.
  - The technology
    - novel approaches, calibration schemes, foreground removal or similar.
    - Technical challenges
    - Key technical strategies, enabling technologies, or similar.
  - Status and/or recent result highlights.

SKA

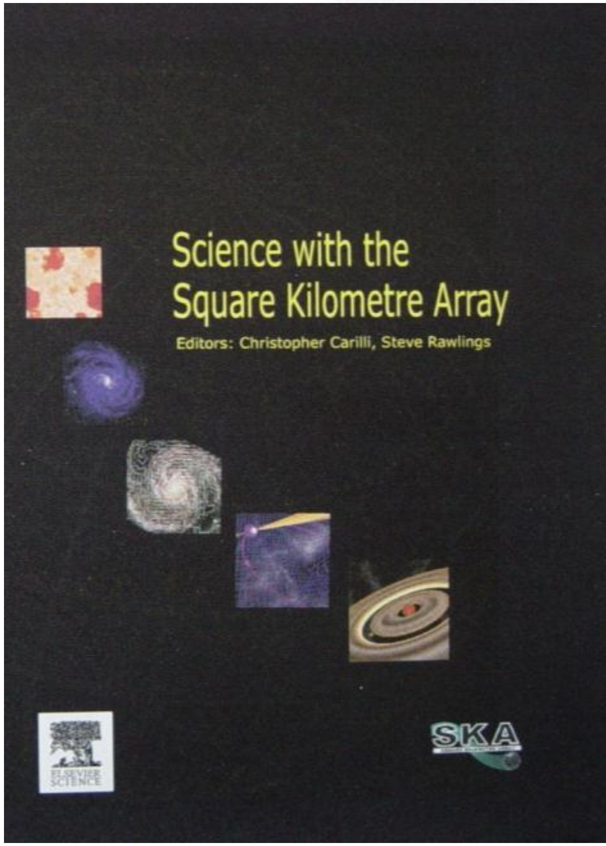
Square Kilometre Array

SKA

- More than a project – “recently minted” international observatory.
  - The SKA Organisation incorporated in the UK.
  - Headquarters at Jodrell Bank Observatory.
  - 50-60 employees, currently.
  - mandate to build next-generation telescopes in the cm-m wavelength range.
- Emphasis on sensitivity.
- Telescopes to be built in two phases:
  - SKA1 followed by expansion to SKA2.
  - SKA1
    - approx. 10% of SKA2.
    - outlined in the “SKA1 Baseline Design” (www.skatelescope.org).
    - currently consists of three telescopes, to be described.
- Global: Australia, Canada, China, Germany, Italy, New Zealand, South Africa, Sweden, Netherlands, United Kingdom

SKA2 Key Science Drivers

- ORIGINS
  - Neutral Hydrogen in the Universe from the Epoch of Re-ionisation to now
    - When did the first stars and galaxies form?
    - How did galaxies evolve?
    - Dark Energy, Dark Matter
  - Astro-biology
- FUNDAMENTAL FORCES
  - Pulsars, General Relativity and gravitational waves
  - Origin and evolution of cosmic magnetism
- EXPLORATION OF THE UNKNOWN
  - General purpose instruments.



Science with the Square Kilometre Array
(2004, eds. C. Carilli & S. Rawlings, *New Astron. Rev.*, **48**)

Context: Current & Future Suite of Great Observatories.

Square Kilometre Array (SKA):
m/cm/mm
Phase 1 2020

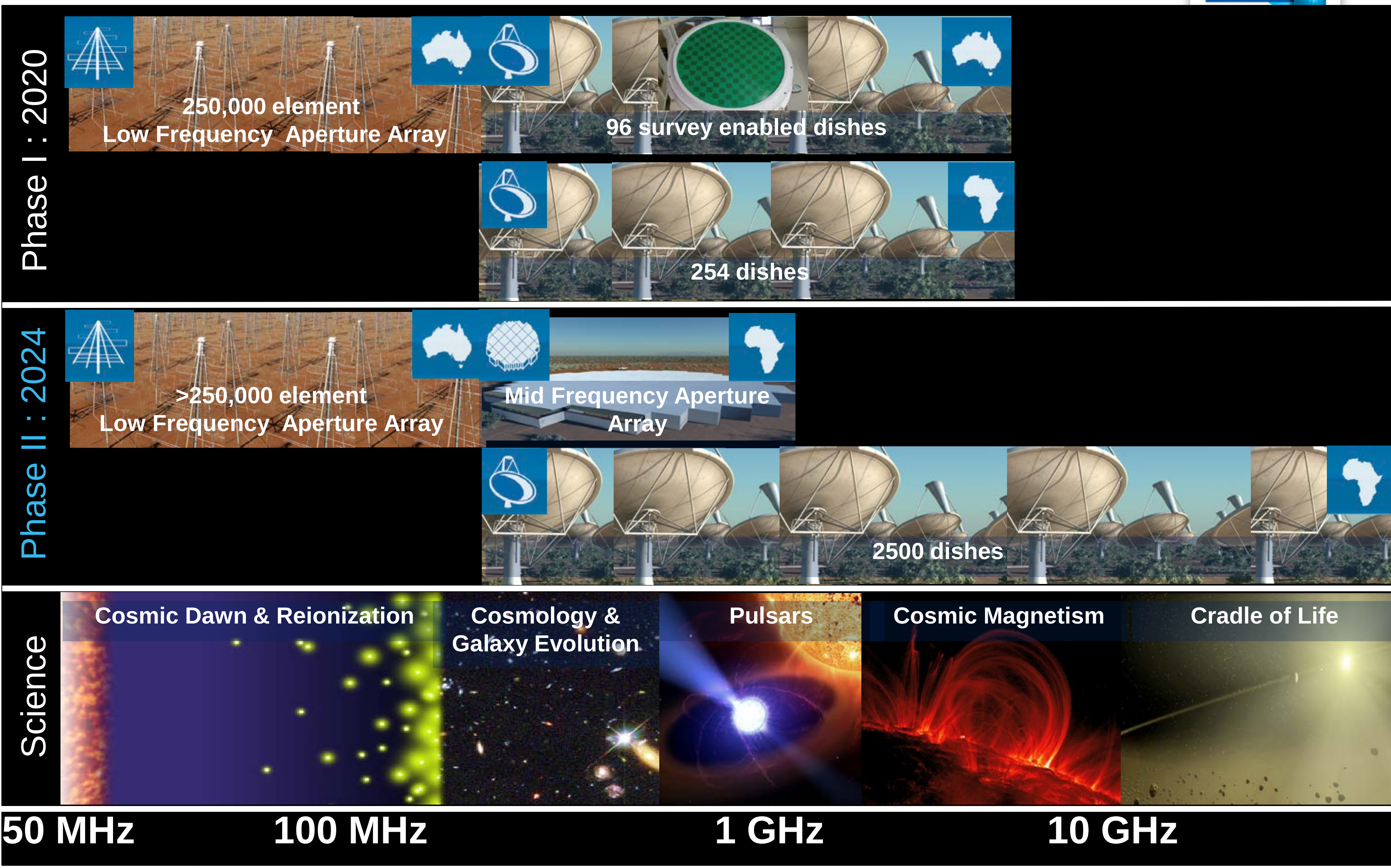
Atacama Large Millimetre Array (ALMA):
mm/submm
Inaugurated on 13th March 2013

European-Extremely Large Telescope (E-ELT)
Optical/Infrared (shown)
- Also TMT & GMT

Jansky Very Large Array (JVLA)
Fully Operational

James Webb Space Telescope (JWST)
Infrared
Due for launch 2018

Summary of the SKA Baseline Design



SKA1-low

LOCATION: Australia
ANTENNAS: 250,000 Log-periodic dipoles
FREQUENCY: 50 - 350 MHz

SCIENCE includes:

- Imaging the Epoch of Reionization (@ 5 arcmin scales with 1mK RMS)
- Statistical studies of the Cosmic Dawn
- Detections and studies of ‘hot jupiter’ exoplanets

SKA1-mid

LOCATION: South Africa
ANTENNAS: 190 15-m dishes plus 64 Meerkat 12-m dishes
FREQUENCY: 350 - 13800 MHz (*)

SCIENCE includes:

- Pulsar surveying and timing, to explore Gravitational Wave emission
- Cosmology and Galaxy studies (through HI, Continuum and OH)
- Studies of star formation, proto-planetary disks, cosmic magnetism, transients

SKA1-survey

LOCATION: Australia
ANTENNAS: 60 15-m dishes plus 36 ASKAP 12-m dishes
FREQUENCY: 350 - 4000 MHz

SCIENCE includes:

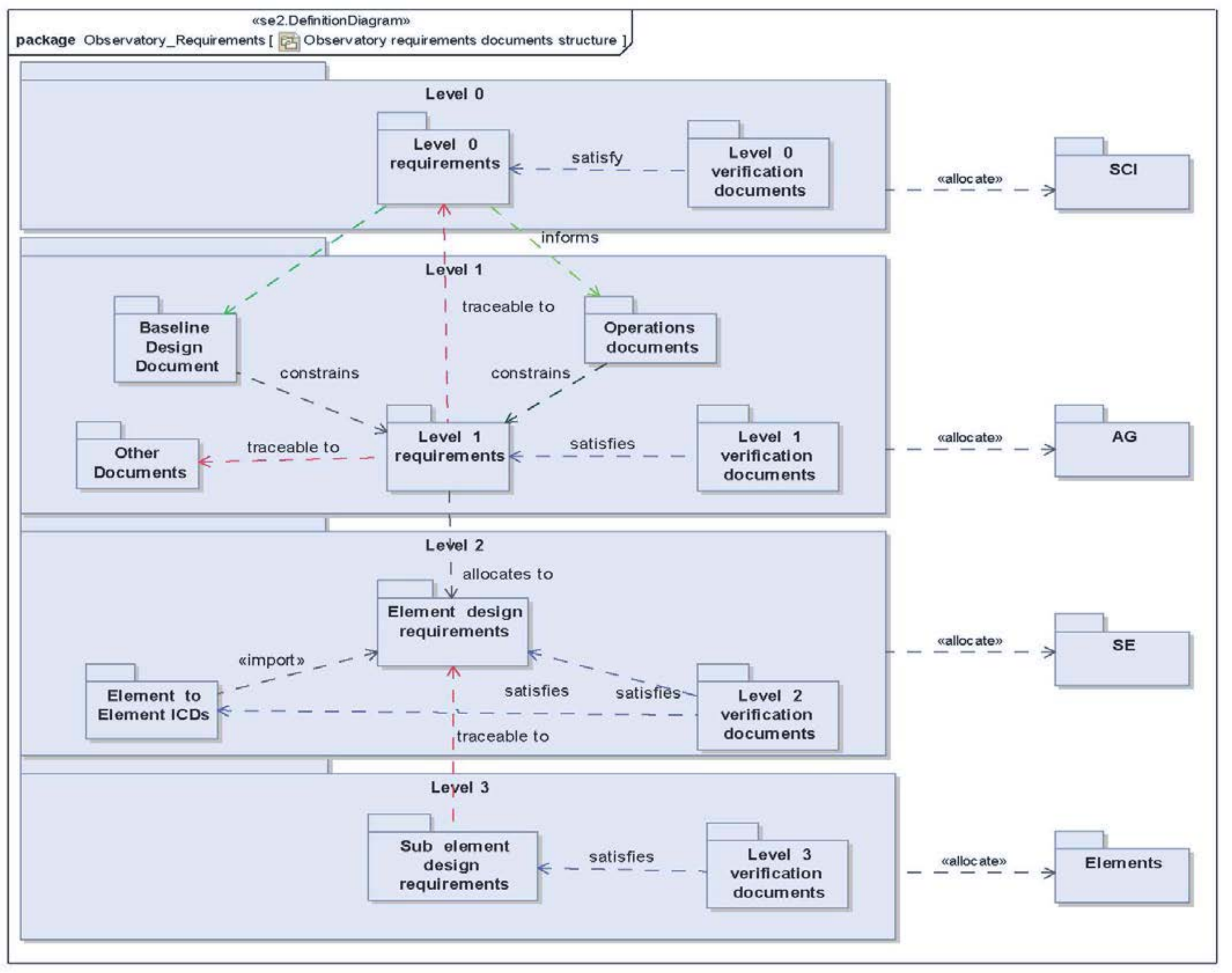
- Commensal wide field (~10,000 sq. deg. to all sky) surveys for Galaxy evolution studies and to establish a grid of Rotation Measures (>~300 per sq. deg.)
- Transient searches in image domain

Evolution from Baseline Design

'The Baseline Design'
Dewdney et al. 2013

Level 1 Requirements

Level 1 Requirements subject to change control
+
Level 0 Requirements



SKA Science Working Groups

Science Assessment Workshops

Epoch of Reionisation & the Cosmic Dawn [History of the Universe]
- *Working Group Chair:* Leon Koopmans
- *Project Scientist:* Jeff Wagg

Cosmology [History of the Universe]
- *Working Group Chair:* Roy Maartens
- *Project Scientist:* Jeff Wagg

Continuum Science [History of the Universe]
- *Working Group Chairs:* Nick Seymour & Isabella Prandoni
- *Project Scientist*: Jeff Wagg

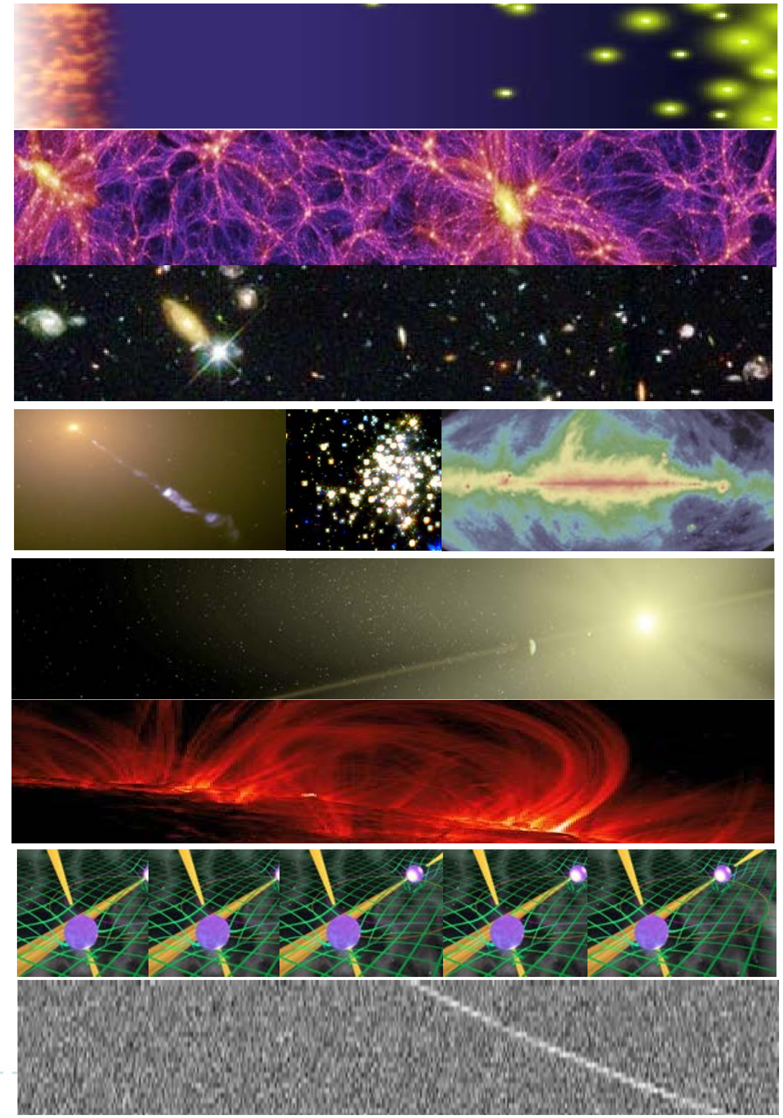
Galaxy Evolution - HI [History of the Universe]
- *Working Group Chairs:* Lister Staveley-Smith & Tom Osterloo
- *Project Scientist:* Jimi Green

Our Galaxy & The Cradle of Life [History of the Universe]
- *Working Group Chair:* Melvin Hoare
- *Project Scientist:* Tyler Bourke

Cosmic Magnetism [Fundamental Forces]
- *Working Group Chairs:* Melanie Johnston-Hollitt & Frederica Govoni
- *Project Scientist:* Jimi Green

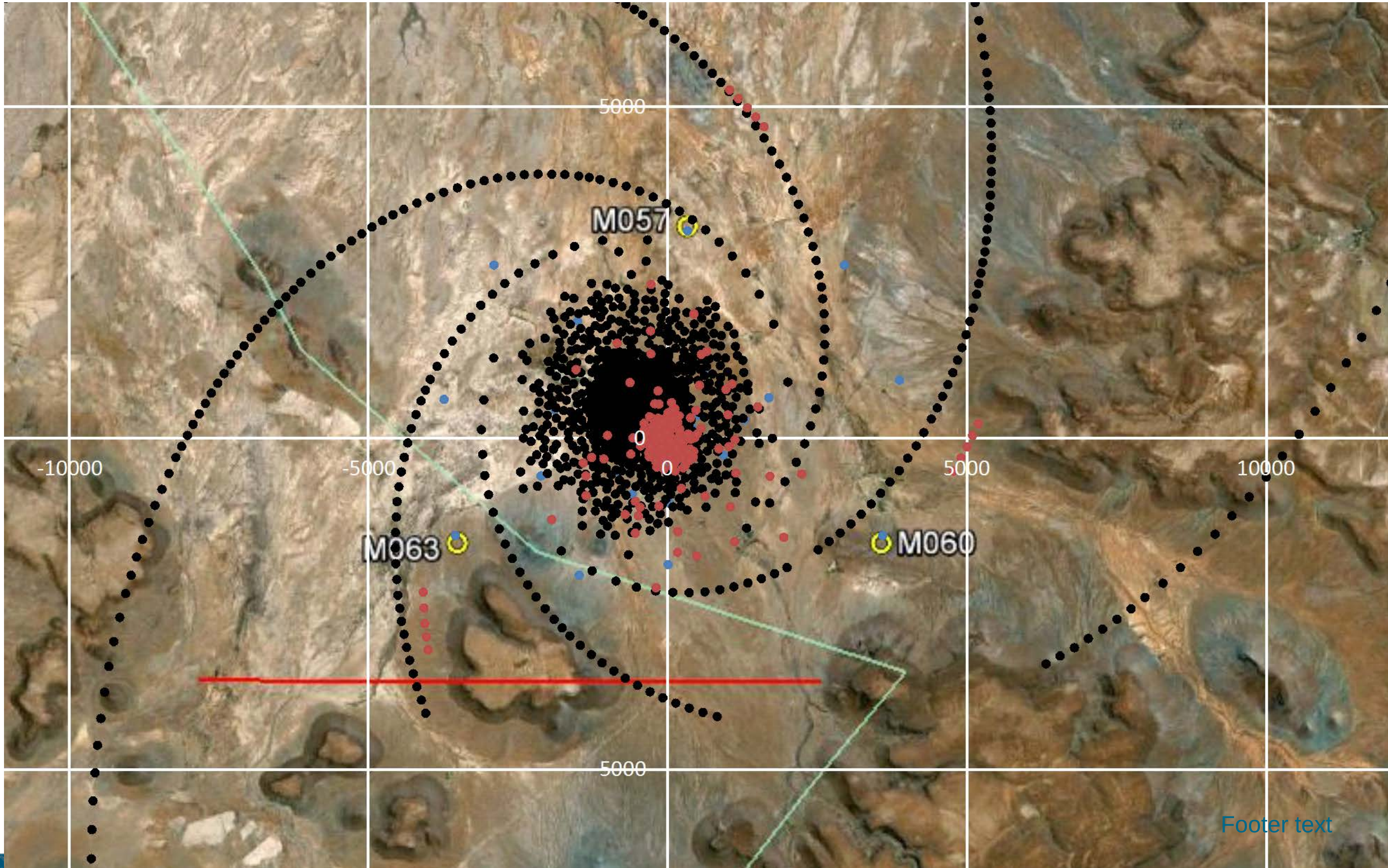
Pulsars & strong field tests of gravity [Fundamental Forces]
- *Working Group Chairs:* Ben Stappers & Michael Kramer
- *Project Scientist:* Jimi Green

Transients [Unknown Phenomena]
- *Working Group Chair:* Rob Fender
- *Project Scientist:* Tyler Bourke



Central SKA2 South Africa Core Site:

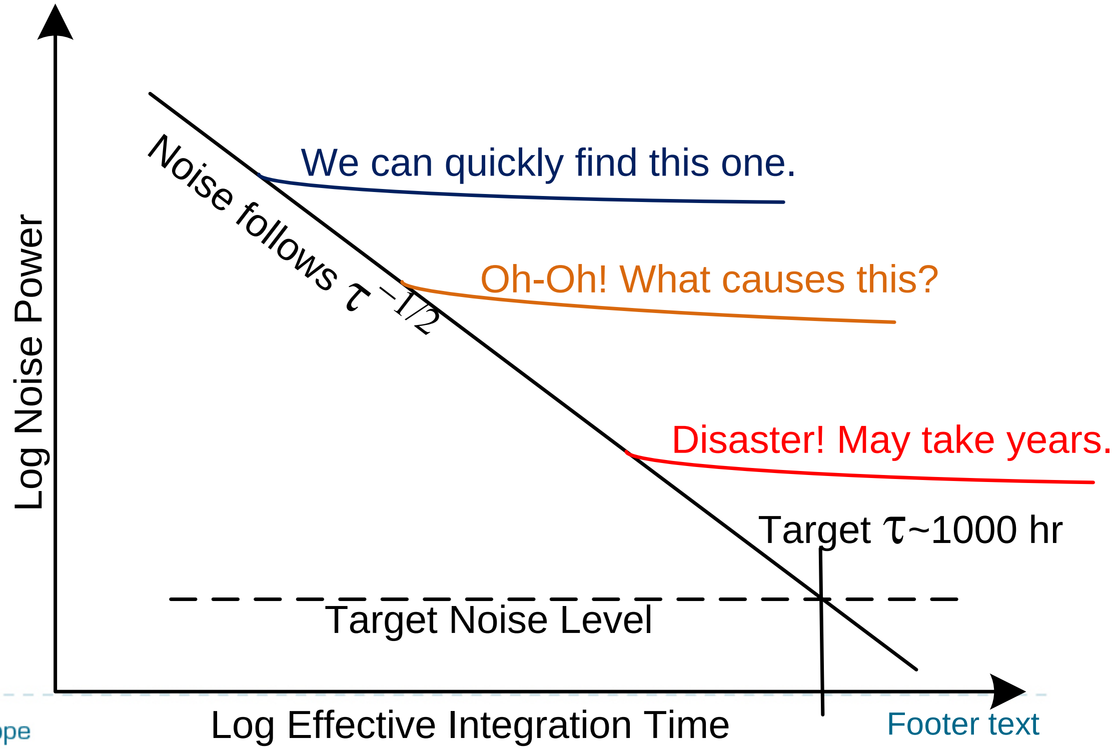
Potential Dish Array Transition from SKA1 (red) to SKA2 (blk)



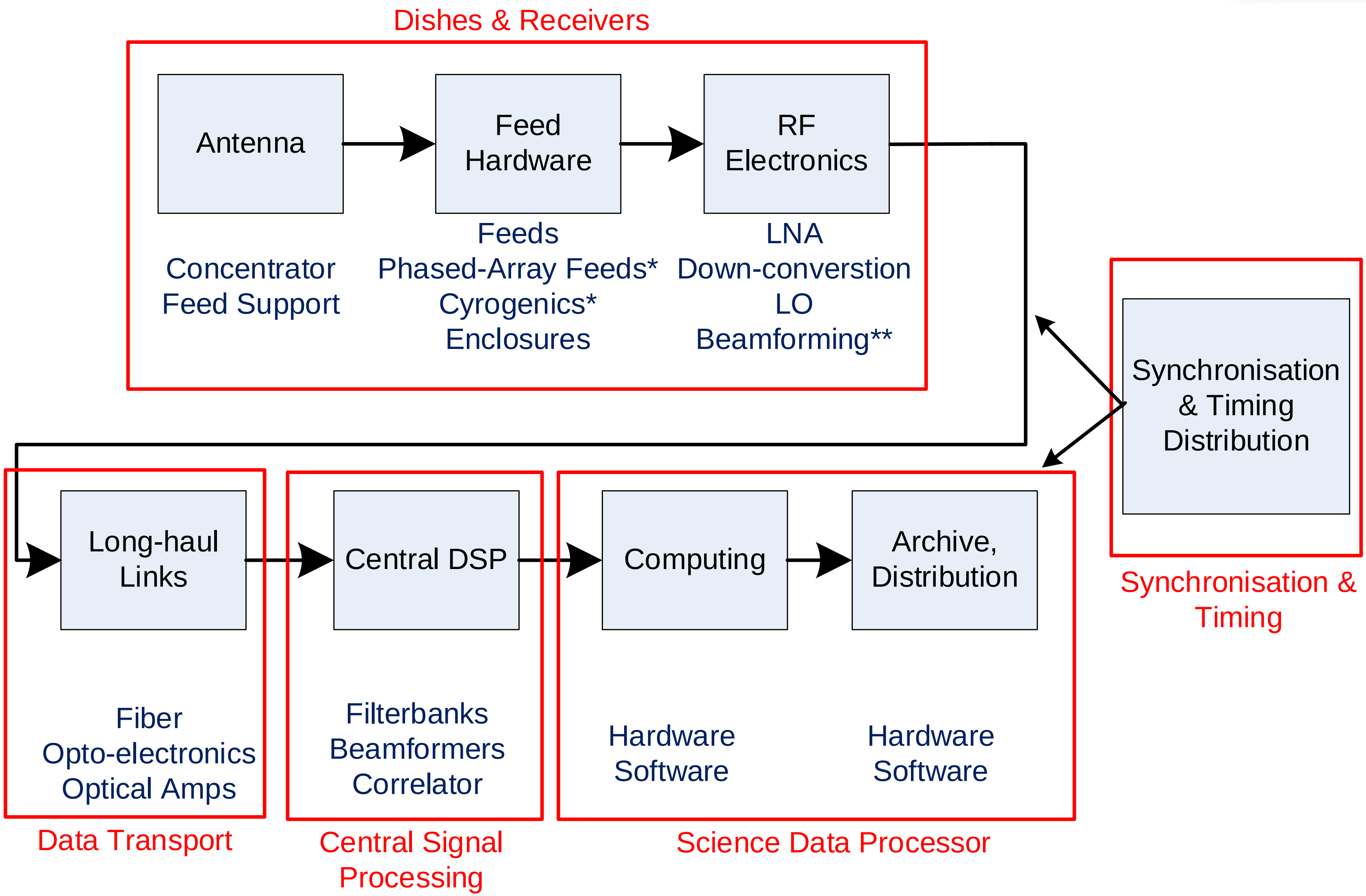
Challenge: Subtle Systematic Errors at High Sensitivity

- With the SKA2, the telescope should be able to reach 10's of nJy in continuum with 1000 hr integration.
  - SKA2 system requirement, not just a receptor requirement.
  - Dish performance is likely to play a limiting, if not dominant role.
- System-level systematic errors must be kept below the noise in the presence of sources ~$10^{7.3}$ times stronger in L-band images.
  - Applies only after all calibration and algorithmic steps have been taken.
  - How to verify???

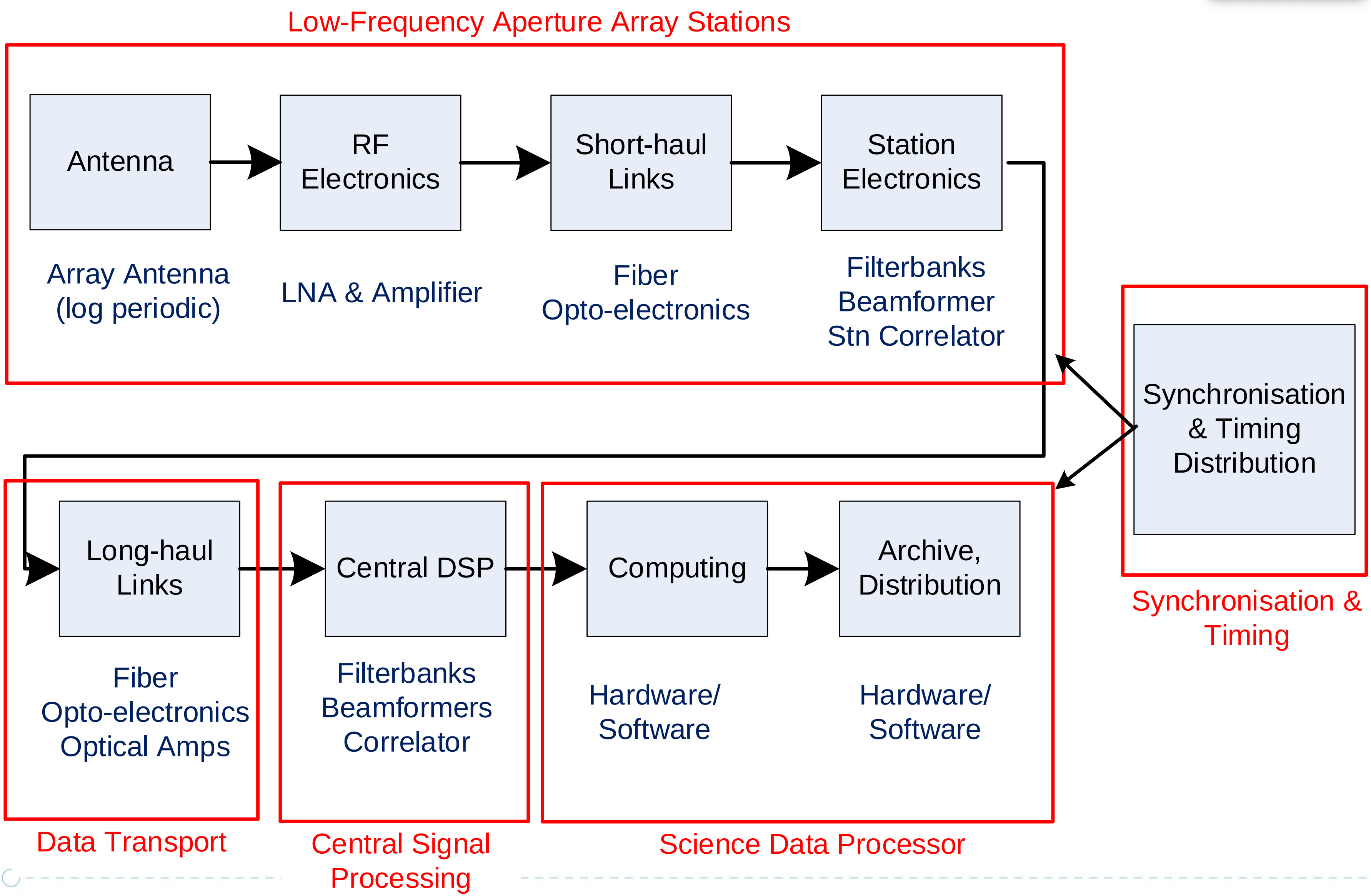
- Note that the SKA1 system must also be able to integrate for 1000 hr.
  - Separate SKA1 requirement.
- Impact of RFI on systematic effects?



Technology Opportunity Areas – SKA1-mid & Survey



Technology Opportunity Areas – SKA1-low



DVA1 – SKA Prototype with single-piece composite reflector

- Main reflector attached to mount May 7, 2014.
- Mount developed by U. California (Berkley), and the US TDP program.

- Main reflector: 15 x 18 m diameter.
- rms ~0.89 mm (unweighted)
  - Including damaged sections.
- Sub-reflector and feed platform to be attached early June.

ASKAP

Australian SKA Pathfinder

ASKAP: Introduction

What?

- ASKAP is a radio interferometer comprising 36 x 12m dish antennas located at the Australian SKA site. It is the precursor to and technology demonstrator for SKA1 survey.

How?

- Leveraging innovative frontend, backend and dish technologies, ASKAP will be a supremely fast survey telescope between 700-1800 MHz.

Why?

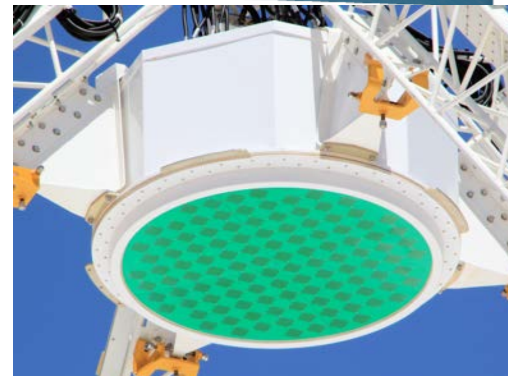
- ASKAP spectral line surveys will allow us to explore the history of gas in galaxies and to detect HI in the Milky Way, HVCs and local group.
- ASKAP continuum surveys will allow us to determine the formation, evolution and population of galaxies and the evolution of cosmic magnetic fields through cosmic time.
- At the same time, ASKAP will explore wide areas of uncharted parameter space through wide-area time domain surveys.

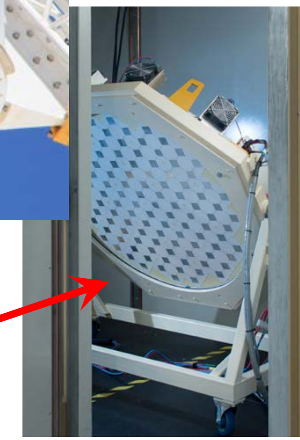
Who?

- ASKAP is part of the Australia Telescope National Facility run by CSIRO.
- ASKAP science teams comprise 360 scientists from 130+ institutions. 10 major surveys are planned.
- An Early Science program is planned with 12 antennas. This has distinct science goals from the 10 major surveys.

Key Technologies for ASKAP

- Phased Array Feed with 36 dual polarisation beams (FoV 30 square degrees).
- 3-axis dish rotation, to fix the orientation of PAF on the sky.
- The Petascale “Pawsey Supercomputing Centre for SKA Science” in Perth.
- Dedicated fast optical fibre link from observatory to supercomputer.
- Fully automated pipelining in near real-time (comparing images every 5 seconds).
- Extremely radio-quiet site, with legal protection.
- Active RFI mitigation (e.g. for satellites) using targeted nulls in the directional response of the PAF.





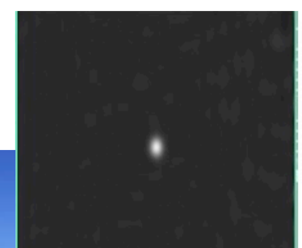
MkII PAF in the lab

Wide-field surveys require new approaches

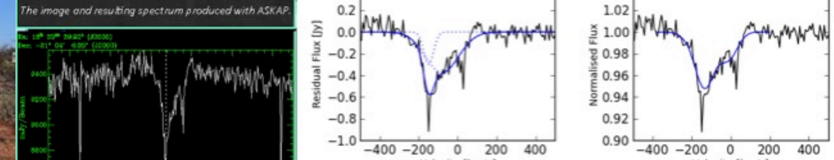
- High dynamic range with many bright sources in field will require in-beam calibration using a sky model
- Beam-forming methods will be refined to produce a stable, well-sampled and calibrated field-of-view
- Dish 3rd axis will contribute significantly to beam stability
- Survey strategy designed carefully to enable commensal continuum, transient, spectral line science where possible
- Powerful computers will process Terabytes of data every second through automated pipelines, delivering science data products directly to an archive.
- Science teams will access data from, and contribute value-added data products to, the ASKAP archive.

Project Description & Current Status

- All 36 telescopes, roads, airstrips, shielded control building, fibre networks and computing facilities are complete.
- ASKAP Commissioning & Early Science Team
  - Currently 12+ members (4 senior staff, 6 postdocs, 2 seconded from Sydney & Curtin Universities, plus additional support from engineering and software & computing teams)
  - Routinely observing commissioning experiments from remote operations centre in Sydney
- BETA 6-antenna test array: Milestones Achieved
  - Continuum image with nine dual-pol beams
  - Spectral line mode demonstrated
  - Other modes being commissioned



The image and resulting spectrum produced with ASKAP.



ASKAP Boolardy Engineering Test Array spectrum of PKS 183[illegible] compared with observations from other telescopes. Credit: CSIRO.

CHIME

Canadian **H**ydrogen **I**ntensity **M**apping **E**xperiment

THE UNIVERSITY OF BRITISH COLUMBIA

NRC · CNRC

UNIVERSITY OF TORONTO

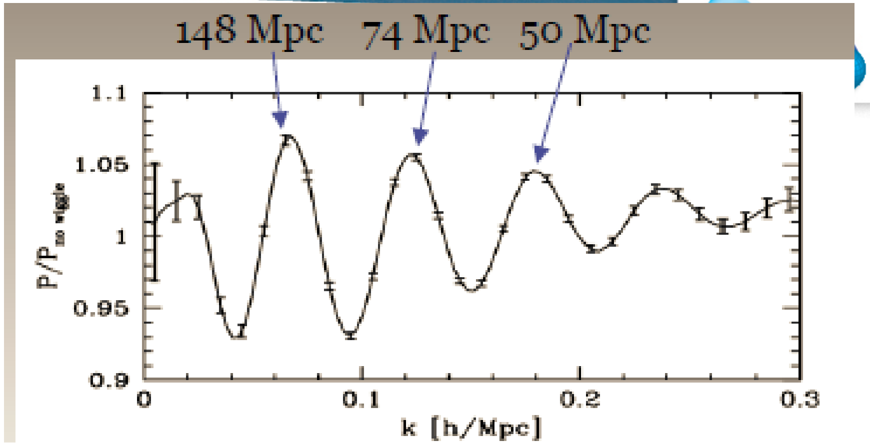
McGill

CHIME Science Goals

- Goal:
  - to observe baryon acoustic oscillations (BAO) by mapping the 3-D distribution of HI-line emitting gas.
  - BAO is the imprint of density variations at z~1 in the matter distribution of the universe first revealed in the CMB.
  - HI expansion history of the universe over the redshift range 0.7 to 2.5 (400-800 MHz).
  - 200 cubic Gpc with ~10 Mpc resolution.
- BAO angular size will be traced through this key epoch:
  - when cosmic acceleration appears to turn
  - when the Dark Energy driven transition from deceleration to accelerated expansion.
- Also an excellent transient radio source detector and pulsar timing facility.

Technical Strategies

- 400-800MHz band
- 21cm from z ~ 0.8 - 2.5
  - **(7-2.6 Gyr)**
- Resolution: 1MHz, 13-26'
  - **3rd BAO peak resolved**
- Drift scan, no moving parts
  - **20,000 deg^2 coverage**
- 280 Dual-polarization feeds
  - (2560 channels)
- **Cosmic-variance-limited survey**

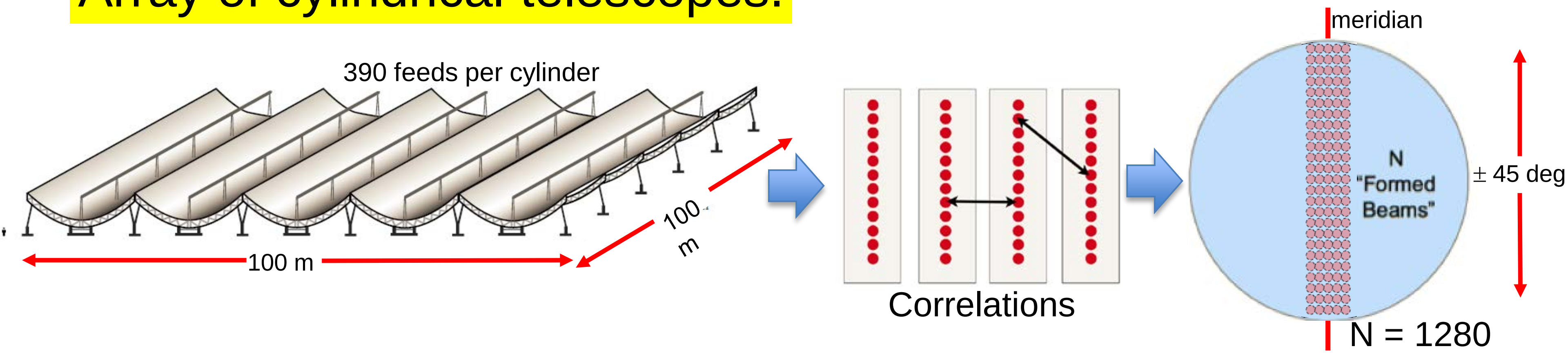


CHIME Experiment Parameters

Observing Frequency	800 to 400 MHz
Observing Wavelength	38 to 76 cm
Redshift	$z \approx 0.8$ to 2.5
System Noise Temperature	≤ 50K
Beam size	0.26° to 0.53°
Field of View, N-S	52° to 105°
Field of View, E-W	1.3° to 2.5°
Cylinder Size	100m × 20m
Number of Cylinders	5
Collecting Area	10,000 m^2
Antenna Spacing	26 cm
Number of Antennae per Cylinder	390
Number of Dual-Polarization Antennae	1950
Number of Antennae Summed before Digitization	2
Number of Digitizers	1950
Bandwidth of Channeled outputs	1 MHz

Design and Technology

- Array of cylindrical telescopes.



Output: ~N^2 vis in ~1024 frequency bands.
Raw data: ~17 TB/s, compressed: ~20 MB/s.

Location of Full Scale Telescope:
Now under construction.

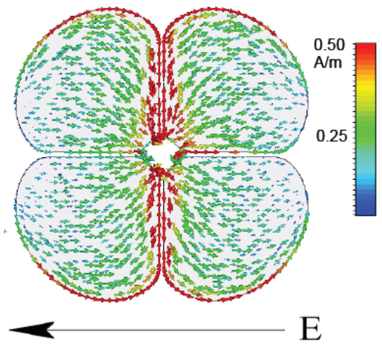
Prototype

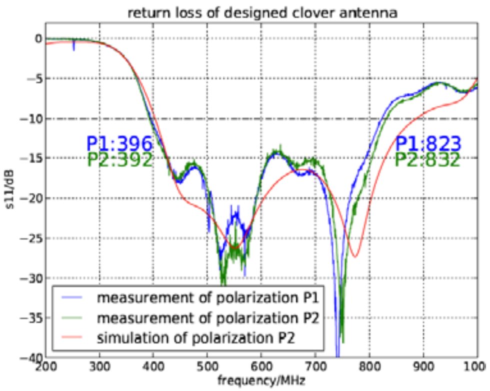
Radio Astronomy – a “Team Sport”

- Median age <30.

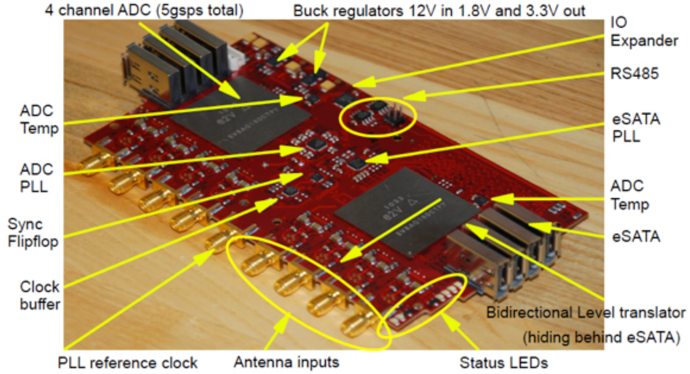
CHIME Status April 2014

Broad-band feeds designed and built;

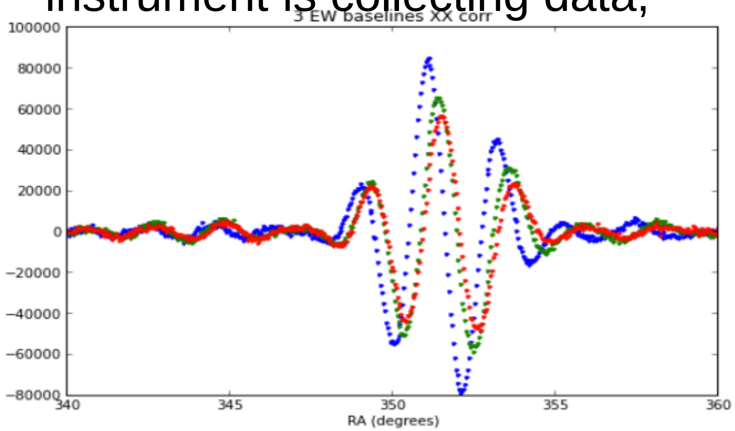




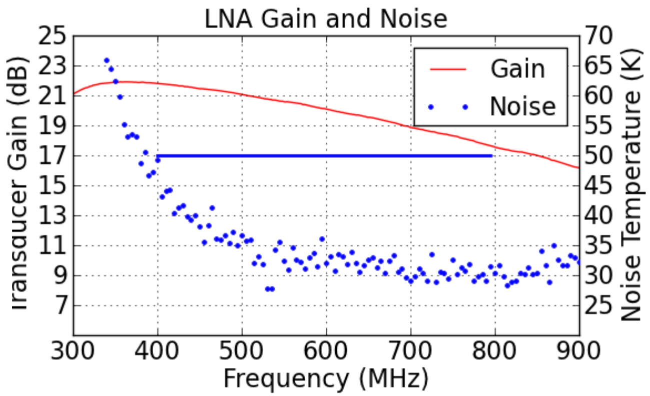
GS/s ADCs and custom FPGA correlator designed and built;



The pathfinder two-cylinder instrument is collecting data;



Low noise amplifiers designed and built;



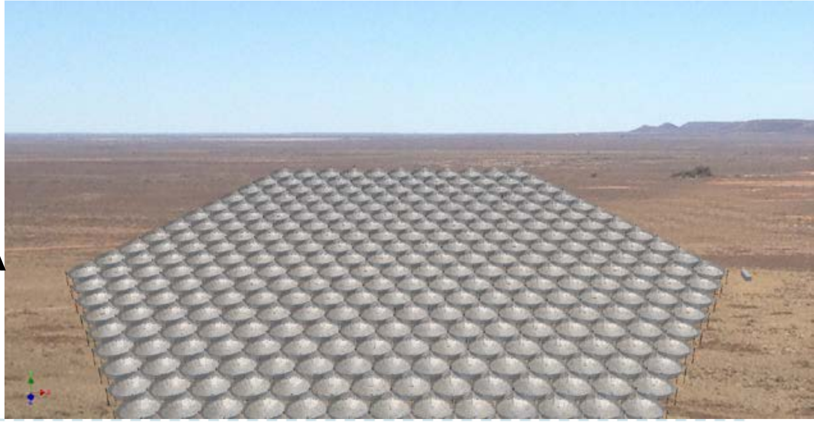
The full instrument is funded and site preparation has begun.

HERA

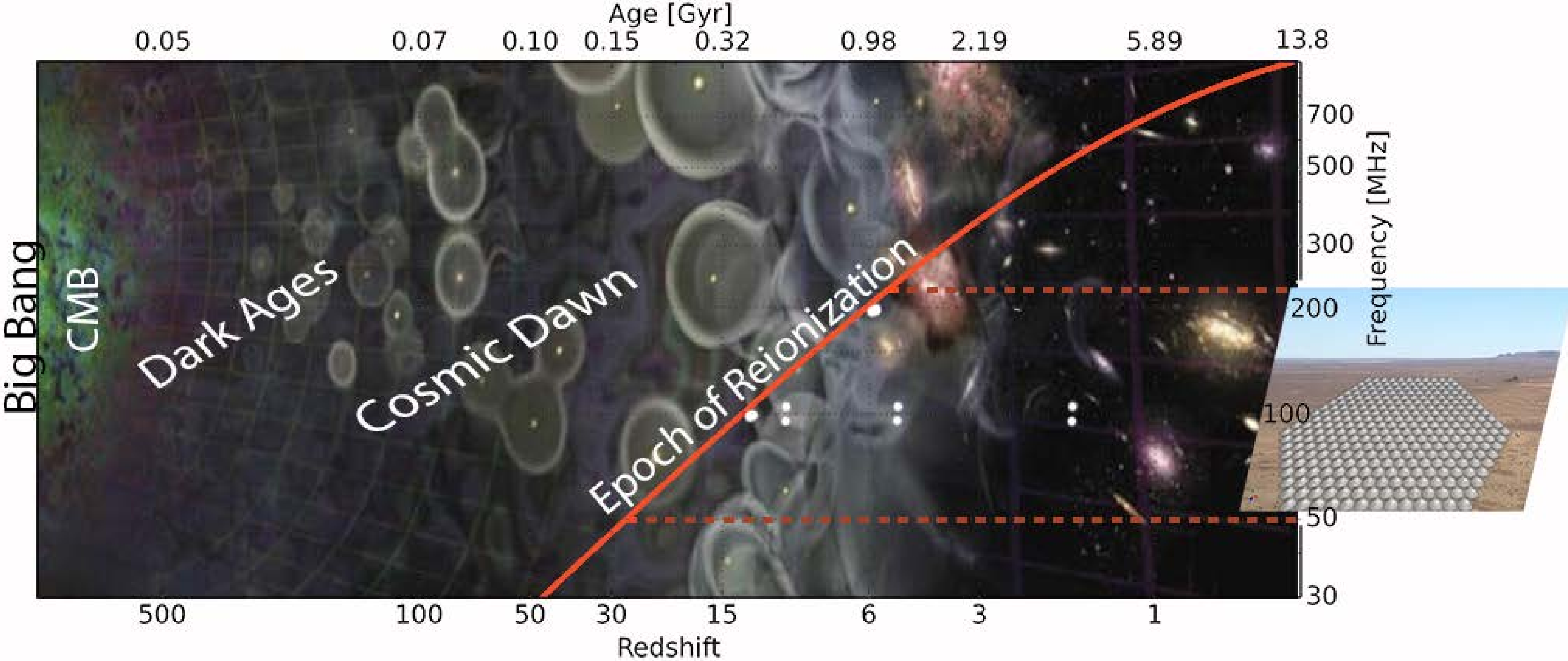
Hydrogen Epoch of Reionization Array

HERA Science

- HERA will detect and characterize the power spectrum of the epoch of reionization (EoR) to try and answer:
  - What objects first lit up the Universe and reionized the neutral IGM?
  - When did this occur in cosmic evolution.
  - How did the process proceed (what heating mechanisms, process feedback, scale-dependence)?
  - How did this lead to the large scale galaxy structure seen today?
- HERA is a focussed experiment, not a general facility.
- HERA is optimized to provide sensitivity on the spectral and spatial scales expected for the EoR signal.
- As a filled array out to about 300 m with 1.2 km outrigger baselines, HERA will also have excellent imaging capability.



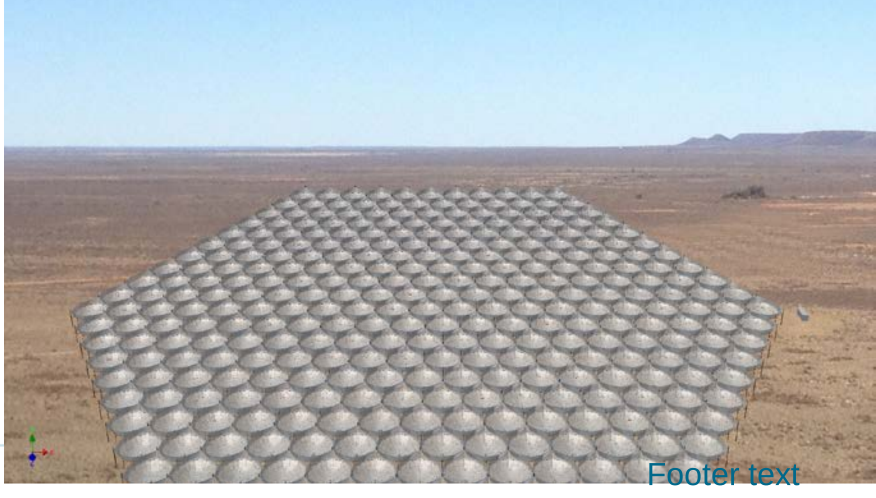
HERA Science



Redshift of EoR defines the frequency range of the telescope.

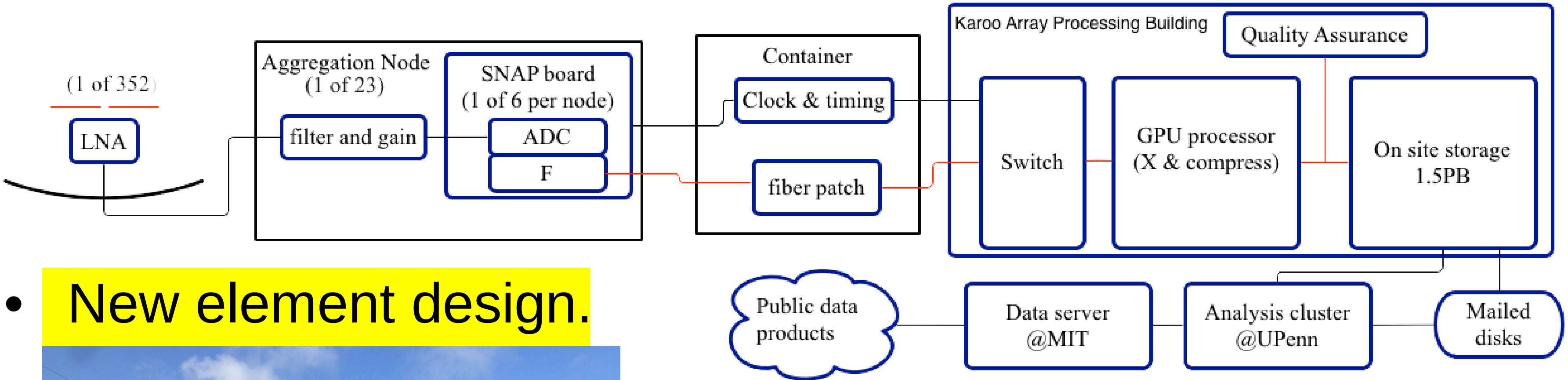
Enabling Technologies, Technical Strategies

- HERA relies on an optimized design for a focussed strategy of EoR Power Spectrum detection and characterization.
  - Interferometers natively measure the power spectrum: the layout can then be optimized to multiply sample the desired spatial scales.
- HERA uses a 14-meter low-cost fixed zenith antenna.
- Staged build to 352 elements
- HERA is located near the South African SKA site.
- Utilizes CASPER hardware developments (in addition to creating a new CASPER board called "SNAP".



Design and Technology

- Node architecture, with digitization/F-engine in the field.
- 10 GbE from node to X-engine/processing at central location



- New element design.

Project Description & Current Status

- Design and prototyping well underway.
- Funds for building first antennas on-site.
- Collaboration amongst:
  - Arizona State University
  - Academica Sinica Institute for Astronomy and Astrophysics
  - University of California Berkeley
  - University of California Los Angeles
  - Cavendish Laboratory - University of Cambridge
  - University of Kwa-Zulu Natal
  - Massachusetts Institute of Technology
  - National Radio Astronomy Observatory
  - University of Pennsylvania
  - SKA South Africa
  - University of Washington
- Proposals in for full funding.

LOFAR

LOw-Frequency ARray

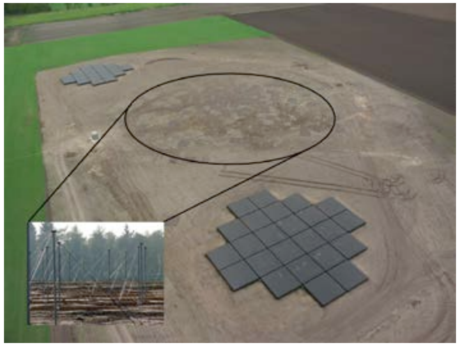
The LOFAR observatory: overview May 2014

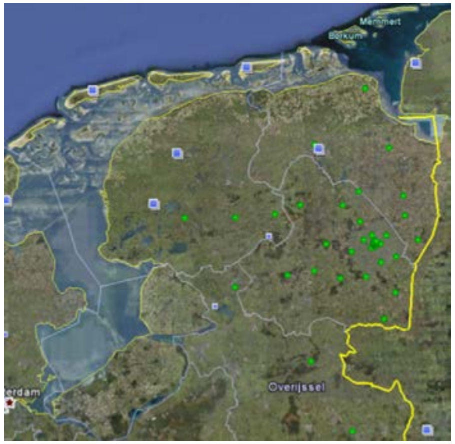
(summary prepared by Ger de Bruyn)

See van Haarlem etal, 2013, A&A, 556A, 2V

- Frequency coverage: 10-90 MHz (LBA) and 110-250 MHz (HBA)
- 70 phased-array 'stations' with 24, 48 or 96 tiles (HBA) and 96 dipoles (LBA)
- GPU-correlator ('Cobalt'): ~ 350 Gbit/s inputs,   ~100 TB/night correlator products
- Multi-beaming: e.g. 8 digital beams of each 12 MHz (fully tunable)
- Pulsar and Fast transients: Tied-array + Fly's eye mode

- Configuration: hierarchy of scales → 70 stations distributed over:
  - Superterp: 0.35 km   - 6 stations (x2, HBA'S split)
  - Core: 2 km - 18 more stations (x2)
  - NL-array : 120 km - 14 stations
  - European: 1200 km - 8 stations (+4 more in 2015 → 2000 km)





LOFAR key technical and software developments

- Multi-beaming hardware and software
- Sophisticated RFI mitigation software *(Offringa etal, 2013)*
  (typical RFI losses in both LBA and HBA bands <5%)
- Sophisticated pulsar and fast transients pipeline
- New fast direction-dependent selfcalibration *(Kazemi & Yatawatta, SAGEcal)*
- Giga-pixel imager, excon (*Yatawatta*)
- Ionospheric screen fitting (*Intema etal, vdTol, Rafferty, Mevius, rapid maturing*

Receiver modes

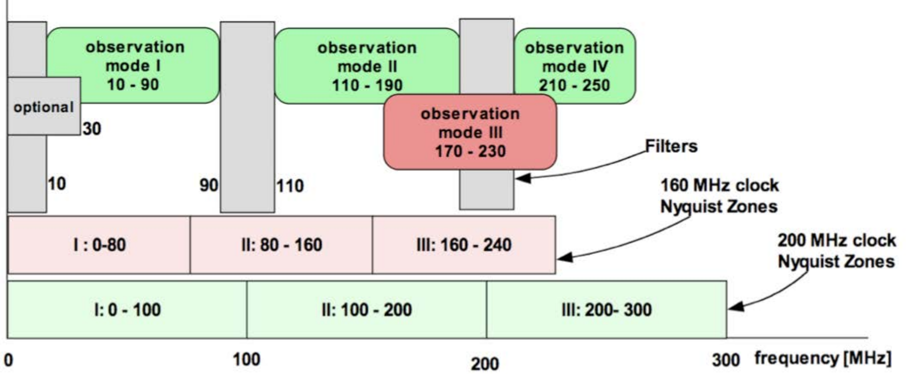
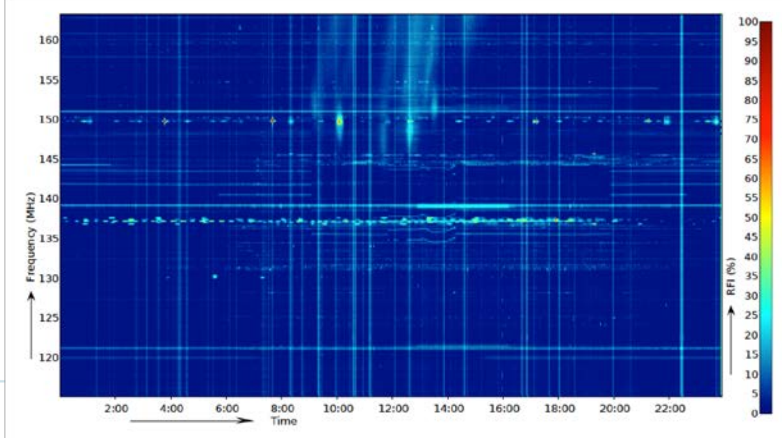


Figure 10 *Selection of Nyquist zones is used to select the observed band in the station.*

A day in the life (at 1s, 1 kHz)

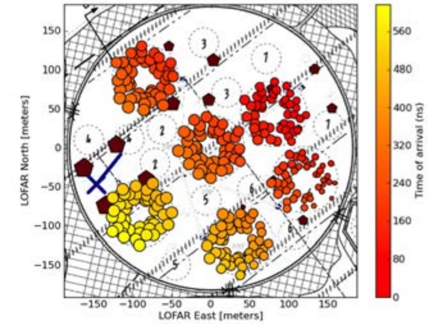


LOFAR key design features

- Salient instrumental specifications
  - Spectral resolution down to <1 kHz (e.g. Carbon recombination lines)
  - Frequency range > octave ! (20-200 MHz)
  - 96 'MHz-beams' on sky
  - Primary (digital) stationbeams (NL-array): HPBW ~ 2^o - 10^o
  - Angular resolution from 1^o to 0.2"
  - Sensitivity ~100 μJy (after 8h, 60 MHz in HBA band)
  - Typical observation: 2 beams from 30-78 MHz, 1s, 8h synthesis, or
    1 beam from 115-185 MHz, and 6 flanking beams of 4 MHz
- Observing modes
  - Interferometric, Full Stokes,
  - Multi-beaming (all sky in LBA-band, within (20^o) tile beam in HBA-band)
  - Tied-array (up to 128 beams), Fly's eye mode, ..
  - Transient Buffer Boards (few seconds, piggybacking, baseband sampling at 5 ns)

Key Science Programs + some results

Cycle 0 (Dec12-Nov13), Cycle 1 (Nov13-May14) Cycle 2 (May14-Nov14)
Open time fraction in Cycle 2: 10% and ramping up

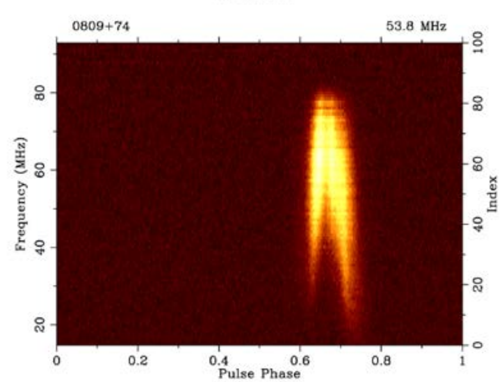


CR radio flash arrives at superterp: arrival colour-coded
Nelles etal, arXiv 1304.097

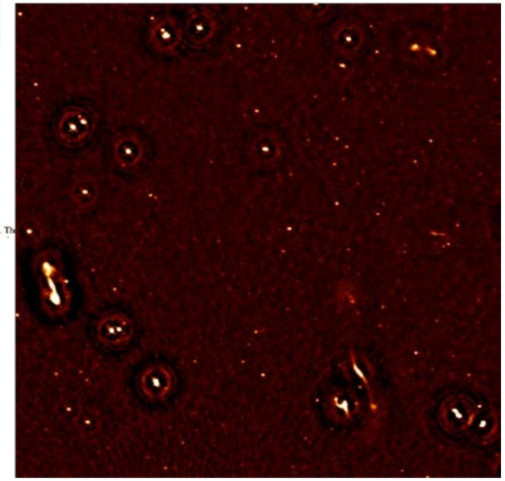
- Calibration/shake-out survey: 20,000 □º: MSSS, finished *(Heald etal)*

- Epoch of Reionization: ~300h integrations
- Surveys: Dec >0º surveys in LBA and HBA
- Transients: fast or slow
- Pulsars
- Magnetism, polarimetry (RMSF$_{HBA}$~1 rad/m^2)
- Solar science
- Solar system, IPM, Exoplanets, SETI
- Ionospheric science (see AJDI* 7-Mar-2014)

A&A 556, A2 (2013)



LOW frequency pulsar profiles (Kondratiev etal, see van Haarlem etal)



Deep image of NCP, 115-175 MHz (60 hours, 6" PSF, ~ 40 μJy noise) Yatawatta etal, in preparation

*Astron Jive Daily Image: www. astron.nl/dailyimage,
Check out for previews of many early LOFAR results !

MeerKAT

"Meer" Karoo Array Telescope

MeerKAT: Science Questions

- Ten large survey projects supported by 360 scientists from 121 institutions in 22 countries:
  - Cosmology and Galaxy evolution: deep (in both flux and brightness) HI surveys (emission and absorption), deep polarization surveys, high-redshift CO surveys.
  - Tests of general relativity: pulsar surveys and timing.
  - Ultra-high energy objects: fast and slow transient surveys.
  - Galactic ultra-compact HII regions: continuum survey, atomic and molecular line surveys.
- New observational parameter space being probed.
  - Similar sensitivity to VLA, ~4x survey speed, high-fidelity imaging (64 antennas, clean and stable primary beam).
  - Multiple tied array beams for pulsar and fast transient surveys.
- SKA Precursor (on site selected for SKA1-mid).

Enabling Technologies, Technical Strategies

- Very compact OMTs (small fraction of volume of VLA equivalents, hence lower cooling requirement).
- Extensive use of computational electromagnetics to optimize Gregorian reflector design.
- Direct sampling of RF signal directly after the LNA – no heterodyne stage.
- DSP based on CASPER packet-switched architecture.
- Use of commodity SOIC technology to build compute clusters matched to the needs of interferometric calibration and imaging.
- Use of inexpensive digital storage media (custom designed disk arrays).
- Development of “third generation” calibration and imaging algorithms.
- Use of “traditional” G-M cryogenics optimized for low power and low maintenance.

Design and Technology

- Medium-size offset Gregorian reflectors (13.5 m).
- G-M cooled single-pixel receivers.
- Direct RF digitization.
- Packet-switched DSP architecture.
- Commodity compute and data storage platforms.
- "3G" calibration and imaging algorithms.

- Technical challenges:
  - Low cost antenna manufacture.
  - Low-power/low-maintenance cryogenics.
  - High performance wideband receivers.
  - Elimination of self-generated RFI.
  - Pulsar search engine requiring large number of tied array beams and massive real-time compute.

Project Description & Current Status

- Description of the project structure, collaborating institutions, etc.
  - MeerKAT a project of SKA South Africa, a business unit of the National Research Foundation. 100% funded by RSA.
  - MeerKAT Large Surveys supported by 121 institutions worldwide. Some of these institutions are involved in technology development.
  - A substantial human capital development programme is associated with the project, supporting local students and foreign post-docs and visiting scientists.
- Short description of status.
  - All infrastructure elements practically completed (e.g. power, data, buildings, antenna foundations).
  - First antenna erected.
  - Prototype L-band receiver and digitizer delivered, UHF-band this year.
  - Correlator/beamformer, science data processing software and control and monitoring system development all on track.
  - Completion of all 64 antennas with L-band and UHF-band capability 2016/2017.

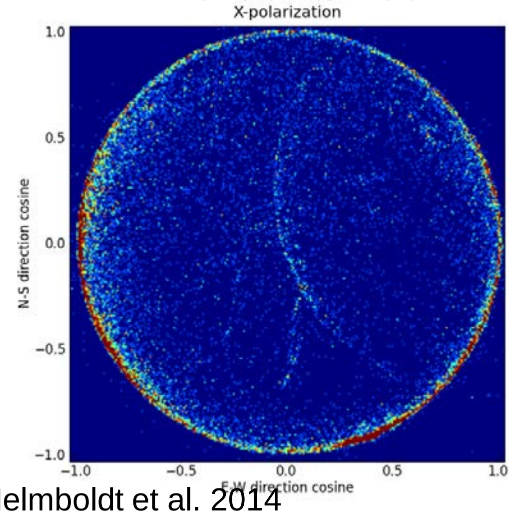
LWA

Long Wavelength Array

Science Questions

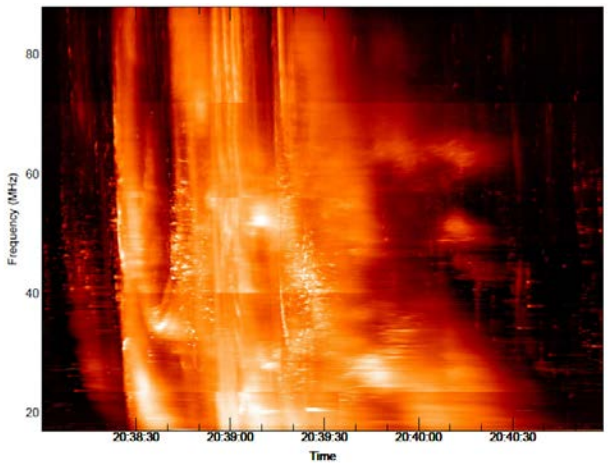
- The Long Wavelength Array (LWA) will explore the Universe at low frequencies (10-88 MHz), including:
  - Cosmic Explosions (GRBs, Magnetars, Flare Stars, etc..)
  - RRATs, Pulsars, Gravitational Waves
  - Cluster Halos and Relics, and the Cosmic Web
  - Cosmic Dawn through redshifted HI
  - Ionospheric and Space Physics including meteors

Meteor Stream



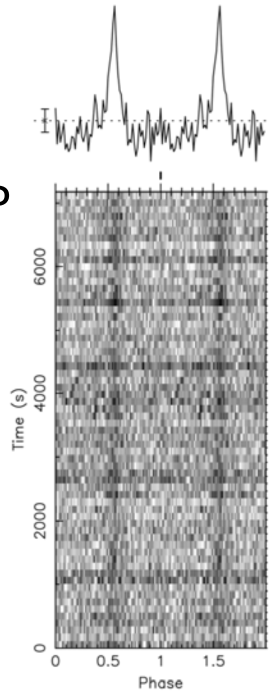
Helmboldt et al. 2014

Solar Flare



White et al. in prep.

MSP

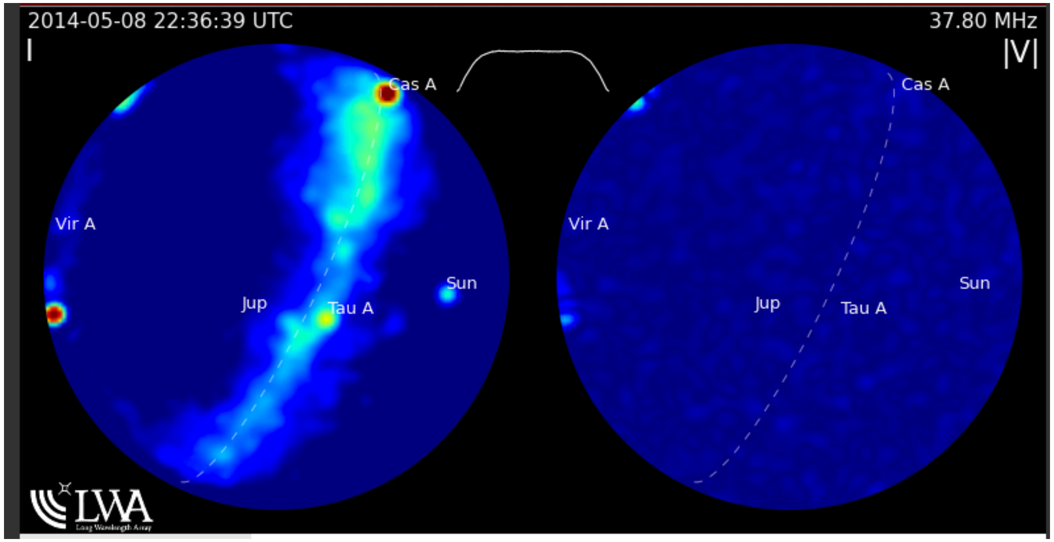


Dowell et al. 2013

Enabling Technologies, Technical Strategies

- New Technology realized by First Station (LWA1)
  - Galactic noise dominated low frequency antenna
  - Large N array (33,670 baselines!)
  - Sensitive, all-sky imaging for over 11,000 hours
  - Software development (LWA Software Library)
- Outreach/Science
  - LWA TV (http://www.phys.unm.edu/~lwa/lwatv.html)

Real time view of the sky over LWA1



Design and Technology

- LWA1 is 5 telescopes in one
  - All sky imaging by combining all 260 dipoles with 70 kHz bandwidth
  - 4 independently steerable beams (each 2 tunings of 16 MHz)
  - SEFD ~6 kJy at zenith : S_{min} ~ 5 Jy (5σ, 1 s, 16 MHz, zenith)

Project Description & Current Status

- LWA1 is operated by UNM, VT, NRL
  - Funded by NSF through the University Radio Observatory program.
  - Over 50 projects on going.
  - Users meeting July 10+11 in Albuquerque, new users welcome!
  - Next proposal deadline August 15, 2014 see lwa.unm.edu.
- LWA-OVRO construction completed, now commissioning .
- LWA-Sevilleta under construction, additional funding needed to complete (additional station).
- LWA Future
  - LWA1 demonstrates successful station design, low risk.
  - LWA1 has excellent spectral (100 Hz) and temporal (50 nsec) resolution.
  - Improve spatial resolution to arcsecond level by adding stations.
  - Improve sensitivity to mJy level by adding stations.

MWA

Mileura Wide-Field Array

Science Questions

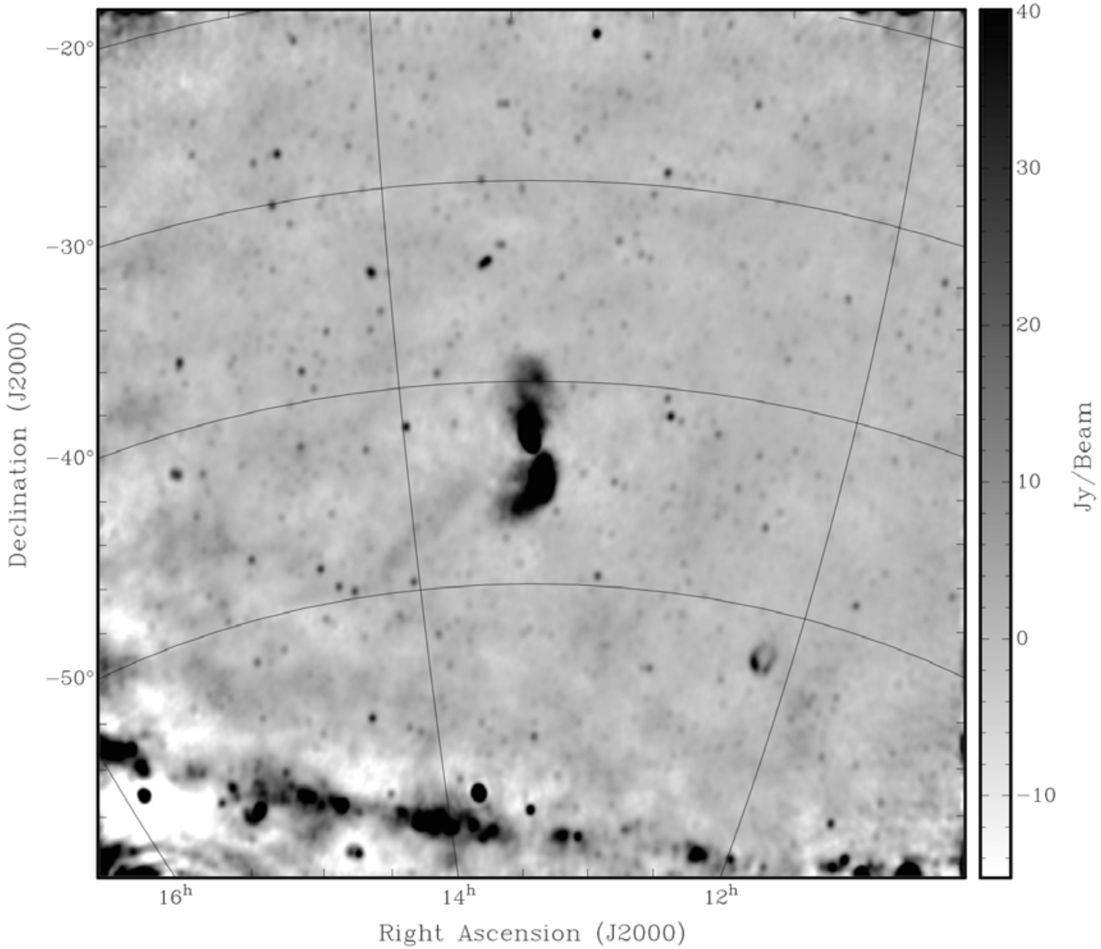
- 1st of the three SKA Precursors to be operational
- Four main science themes:
  - measurement or constraint of the Epoch of Reionisation power spectrum;
  - transients and variables;
  - galactic and extragalactic surveys;
  - solar and heliospheric science.
- The full MWA science case is detailed by Bowman et al. 2013, PASA, 30, 31.
- Detailed MWA system description published by Tingay et al. 2013, PASA, 30, 7.
- System features:
  - 80 – 300 MHz frequency range, dual polarisation;
  - Extremely wide fields of view (at FWHM): 610 sq. deg. at 150 MHz;
  - Large-N array (128 5mx5m aperture array stations) provides excellent *u-v* coverage, imaging performance and surface brightness sensitivity;
  - Special features such as a Voltage Capture System for high time resolution science.

Recent Science Highlights

RIGHT: Image of Centaurus A and surrounding field at 118 MHz, from McKinley et al. 2013, MNRAS, 436, 1286.

Other recent highlights:

- Low frequency variable and transient survey: Bell et al. 2013 MNRAS, 438, 352;
- Large-scale polarisation survey: Bernardi et al. 2013, ApJ, 771, 105;
- The Murchison Widefield Array Commissioning Survey: A Low-Frequency Catalogue of 14,121 Compact Radio Sources over 4,300 Square Degrees: Hurley-Walker et al. 2014, PASA, submitted



Enabling Technologies, Technical Strategies

- The MWA takes advantage of advances in a number of dimensions
  - Superb radio-quiet location at the Murchison Radio-astronomy Observatory (MRO), particularly in the FM band;
  - Aperture array technology: no moving parts; simple deployment; simple operations and maintenance;
  - Large-scale GPU-based correlator;
  - Long-haul offsite data transport with dedicated 800 km 10 Gbps link;
  - 9 PB data archive at the $80m Pawsey supercomputing centre in Perth.
- The MWA itself is critically enabling SKA pre-construction activities for SKA-low, by hosting verification systems for SKA-low technologies.

Design and Technology

The enabling technologies provide:

- Benefits:
  - Wide fields of view;
  - Excellent imaging performance;
  - Simple remote operations model;
  - Flexible, software-defined system;
- Technical challenges
  - Maintenance of very high long-haul data rates;
  - Very large archived datasets requiring large-scale HPC resources for data processing;
  - Wide-field, direction-dependent, time-dependant calibration and imaging, including precision characterisation of primary beam effects;
  - Monitor and control of many thousands of instrumental parameters;

Project Description & Current Status

- Construction complete December 2012; Commissioning complete June 2013; Science operations commenced July 2013;
- MWA consortium: 13 institutions from four countries led by Curtin University: Australia; USA; India; and New Zealand.
- Time allocation is under Open Skies policy, with six month semesters and an independent time assignment committee:
  - Details at http://www.mwatelescope.org
  - As of May 2014: 14 refereed papers published; six submitted; four in collaboration review; and 16 in preparation;
  - Operations funding secured through 2015;
  - Extension/upgrade planning currently underway. Double collecting area and double maximum baseline length?
- Close connection with SKA-low development via funded pre-construction activities. $A5m in funding to Curtin University to leverage MWA lessons for Low Frequency Aperture Array and Central Signal Processing SKA pre-construction work packages.

PAPER

Precision **A**rray **P**robing the **E**poch of **R**eionization

PAPER

- PAPER seeks to detect the power spectrum of the epoch of reionization (EoR) to constrain:
  - What objects first lit up the Universe and reionized the neutral IGM?
  - When did this occur in cosmic evolution
  - How did the process proceed (what heating mechanisms, process feedback, scale-dependence)?
  - How did this lead to the large scale galaxy structure seen today?
- PAPER is a focussed experiment, not a general facility
- PAPER is optimized to provide sensitivity on the spectral and spatial scales expected for the EoR signal
- PAPER dipoles are movable to trial different configurations.
- PAPER+US-MWA teams transitioning to HERA.

Current Status

- Collaboration among:
  - UC Berkeley
  - UPenn
  - NRAO
  - SKA-SA
  - U KwaZulu Natal

PAPER-32 (2011)

- Observed 92 days
- -80 dB (mK^2) suppression of foregrounds

PAPER-64 (2012)

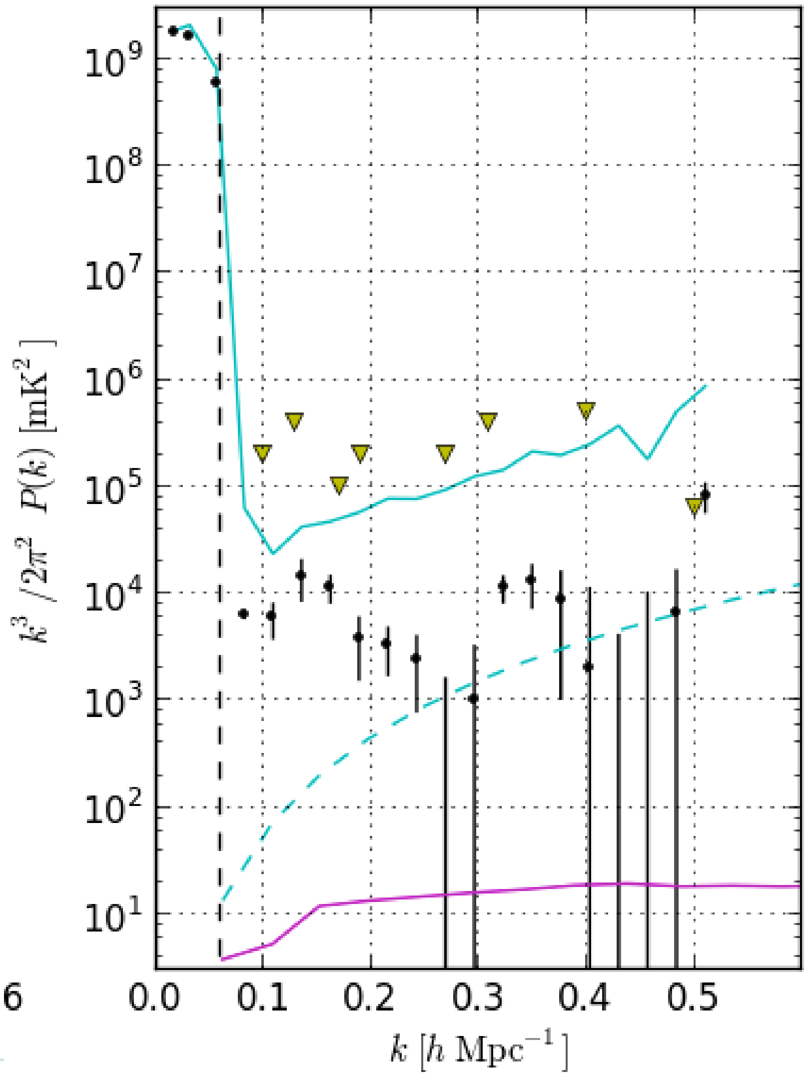
- Observed 172 days uninterrupted

PAPER-128 (2013)

- observing now for second season

Current State of EOR measurements

- PAPER-32 deployment, 92 days, 164 MHz (z=7.7)
- Black dots show final limit with 2σ error bars
- Magenta is fiducial model from Lidz et al. (2008)
- 9 orders of magnitude (in mK^2) of foreground suppression
- Upper limit: $(41\ mK)^2$, see Parsons et al. (2013)



PAPER

End