Low Frequency Radio Astronomy

![Graphs showing different types of emission in radio astronomy](image)
### FCC Radio Spectrum

<table>
<thead>
<tr>
<th>Band Name</th>
<th>Range</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLF</td>
<td>10 kHz - 30 kHz</td>
<td>Cable Locating Equipment</td>
</tr>
<tr>
<td>LF</td>
<td>30 kHz - 300 kHz</td>
<td>Maritime Mobile Service.</td>
</tr>
<tr>
<td>MF</td>
<td>300 kHz - 3 MHz</td>
<td>Aircraft navigation, ham radio and Avalanche transceivers.</td>
</tr>
<tr>
<td>HF and VHF</td>
<td>3 MHz - 30 MHz</td>
<td>CB radios, CAP, Radio telephone, Radio Astronomy.</td>
</tr>
<tr>
<td>VHF Cars,</td>
<td>30 MHz - 328.6 MHz</td>
<td>Cordless phones, Televisions, RC Aircraft, police and business radios.</td>
</tr>
<tr>
<td>UHF radios, wireless</td>
<td>328.6 MHz - 2.9 GHz</td>
<td>police radios, fire radios, business cellular phones, GPS, paging, networks and cordless phones.</td>
</tr>
<tr>
<td>SHF</td>
<td>2.9 GHz - 30 GHz</td>
<td>Doppler weather radar, satellite communications.</td>
</tr>
<tr>
<td>EHF</td>
<td>30 GHz and above</td>
<td>Radio astronomy, military systems, vehicle radar systems, ham radio.</td>
</tr>
</tbody>
</table>
The Square Kilometre Array (SKA)

The SKA is a next-generation radio interferometer:
- 3 telescopes, on 2 sites
- Collecting area > 5 km² on baselines up to 3000 km
- Frequency range 50MHz - 14GHz
- Expected cost: >1.5 billion Euros

Compared to current instruments, SKA will be:
- ~100x more sensitive
- ~10⁶x faster surveying the sky

SKA uses innovative technologies
- Major ICT project...
SKA1 LOW - the SKA's low-frequency instrument

The Square Kilometre Array (SKA) will be the world’s largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

**Location: Australia**

**Frequency range:**

50 MHz to 350 MHz

**Antennas spread between stations:**

~130,000 antennas spread between 500 stations

**Total collecting area:**

0.4 km²

**Maximum distance between stations:**

65 km
How will SKA1 be better than today's best radio telescopes?

Astronomers assess a telescope's performance by looking at three factors - resolution, sensitivity, and survey speed. With its sheer size and large number of antennae, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.

The Square Kilometre Array (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

**RESOLUTION**

SKA1 LOW \( \times 1.2 \) LOFAR NL

SKA1 MID \( \times 4 \) JVLA

Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.

**SURVEY SPEED**

SKA1 LOW \( \times 135 \) LOFAR NL

SKA1 MID \( \times 60 \) JVLA

Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.

**SENSITIVITY**

SKA1 LOW \( \times 8 \) LOFAR NL

SKA1 MID \( \times 5 \) JVLA

Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.

As the SKA isn't operational yet, we use an optical image of the Milky Way to illustrate the concepts of increased sensitivity and resolution.
Low-frequency Array ("SKA-low"): The primary driver — Epoch of Reionization science targeting redshifts of 6 to >15 or < 90 to 200 MHz — is realizable using a dipole array that provides stable, wide-field imaging capabilities for three dimensional mapping of the cosmic web. Detection and mapping of the HI EoR signal is contingent on important studies now being done with experimental low-frequency arrays (MWA, PAPER, LOFAR), which will inform the design of SKA-low with regard to imaging algorithms, collecting area, and the configuration needed for mapping HI structure. SKA-low in turn can benefit from preparations for SKA-mid that include establishment of radio-quiet zones at the two candidate SKA sites and because there is considerable potential for joint use of required civil and digital infrastructure. Specific plans may be found in the Astro2010 submission by Backer et al. for HERA (Hydrogen Epoch of Reionization Arrays).

Mid-frequency Array ("SKA-mid") (The focus of this Astro2010 paper): Galaxy evolution and cosmology, pulsars and gravity, cosmic magnetism, transients, extrasolar planets, and SETI require fast-survey capabilities from 0.3 to 10 GHz. A realizable system can be based on a large-N array of dish reflectors outfitted with single-pixel feeds and receivers, possibly enhanced by field-of-view expansion systems to increase survey speed. Further discussion is given below.
SKA-low site
The South African MeerKAT radio telescope, currently being built some 90 km from Carnarvon in the Northern Cape, is a precursor to the Square Kilometre Array (SKA) telescope and will be integrated into the mid-frequency component of SKA Phase 1. The SKA Project is an international enterprise to build the largest and most sensitive radio telescope in the world, and will be located in Africa and Australia.

**LOCAL PARTICIPATION IN THE CONSTRUCTION OF MeerKAT**

Stratosat Datacom (Pty) Ltd, the contractor for the design, manufacturing and acceptance of the MeerKAT Antenna Positioner, leads a technology consortium including international partners General Dynamics Satcom (GDSatcom, USA) and Vertex Antennentechnik (Germany).

At least 75% of the contract value will be spent in South Africa resulting in most of the MeerKAT antenna components being manufactured in South Africa.

Key local suppliers include Efficient Engineering (pedestals and yokes); Titanus Slew Rings (azimuth bearing), Tricom Structures and Namaqua Engineering (back-up structure), Westacor Engineering and General Profiling (receiver indexer); and Stratosat (reflectors).

Due to schedule pressure some of the components (such as the reflector panels, sub-reflector and receiver indexer) for the first two antennas were manufactured internationally. Since then, this function has been successfully transferred to local suppliers.

**TECHNICAL FACT SHEET**

**TIMELINE FOR MeerKAT CONSTRUCTION**

- **March 2014:** First antenna installed
- **June 2016:** 16 antenna array ready
- **End 2017:** 64 antenna array ready to do science
MeerKAT and SKA-mid array
MeerKAT ANTENNA
TOTAL HEIGHT: 19.5 m; TOTAL STRUCTURE WEIGHT: 42 TONS

The antenna consists of the main reflector (effective diameter 13.5 m) plus the sub-reflector (diameter 3.8 m). The main reflector is made up of 40 panels, made of aluminium. The sub-reflector is a single piece composite structure.

Lightning conductors around the reflectors protect the structure during lightning strikes.

The L-Band receiver and the UHF-Band receiver are mounted on the receiver indexer. The indexer can accommodate up to four receivers.

Steel support framework and connecting back-up structure.

The receiver indexer can rotate each receiver to the desired focal position.

The yoke and elevation bearing/actuator allows the reflectors to tilt up and down.

The azimuth bearing/actuator allows the structure to rotate in a horizontal plane.
MeerKAT’S MAKE-UP
(see annotated diagram on back page):
- The MeerKAT telescope will be an array of 64 interlinked receptors [a receptor is the complete antenna structure, with the main reflector, sub-reflector and all receivers, digitisers and other electronics installed].
- The configuration [placement] of the receptors is determined by the science objectives of the telescope.
- 48 of the receptors are concentrated in the core area which is approximately 1 km in diameter.
- The longest distance between any two receptors [the so-called maximum baseline] is 8 km.
- The main reflector surface is made up of 40 aluminium panels mounted on a steel support framework.
- This framework is mounted on top of a yoke, which is in turn mounted on top of a pedestal. The combined height of the pedestal and yoke is just over 8 m. The height of the total structure is 19.5 m, and it weighs 42 tons.
- The pedestal houses the antenna’s pointing control system.
- Mounted at the top of the pedestal, beneath the yoke, are an azimuth drive and a geared azimuth bearing, which allow the main and sub-reflectors, together with the receiver indexer, to be rotated horizontally. The yoke houses the azimuth wrap, which guides all the cables when the antenna is rotated, and prevents them from becoming entangled or damaged. The structure allows an observation elevation range from 15 to 88 degrees, and an azimuth range from -185 degrees to +275 degrees, where north is at zero degrees.
- The steerable antenna positioner can point the main reflector very accurately, to within 5 arcseconds [1,4 thousands of a degree] under low-wind and night-time observing conditions, and to within 25 arcseconds [7 thousands of a degree] during normal operational conditions.

ABOUT MeerKAT – HOW IT WORKS:
- Electromagnetic waves from cosmic radio sources bounce off the main reflector, then off the sub-reflector, and are then focused in the feed horn, which is part of the receiver.
- Each receptor can accommodate up to four receivers and digitisers mounted on the receiver indexer. The indexer is a rotating support structure that allows the appropriate receiver to be automatically moved into the antenna focus position, depending on the desired observation frequency.
- The main function of the receiver is to capture the
### MeerKAT TECHNICAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of antennas</td>
<td>64</td>
</tr>
<tr>
<td>Configuration</td>
<td>Offset Gregorian</td>
</tr>
<tr>
<td>Diameter of main reflector (dish)</td>
<td>13.5 m</td>
</tr>
<tr>
<td>Diameter of sub-reflector</td>
<td>3.8 m</td>
</tr>
<tr>
<td>Surface accuracy (main and sub-reflector combined)</td>
<td>0.6 mm RMS (root mean square)</td>
</tr>
<tr>
<td>Wind optimal (mean/gust)</td>
<td>10/15 km/h</td>
</tr>
<tr>
<td>Wind operating (mean/gust)</td>
<td>35/48 km/h</td>
</tr>
<tr>
<td>Wind stow (gust)</td>
<td>68.4 km/h</td>
</tr>
<tr>
<td>Wind survival 3 sec gust</td>
<td>144 km/h</td>
</tr>
<tr>
<td>Azimuth speed/range</td>
<td>2 deg/s [-185 to +275 deg]</td>
</tr>
<tr>
<td>Elevation speed/range</td>
<td>1 deg/s [15 to 88 deg]</td>
</tr>
<tr>
<td>Lowest elevation</td>
<td>15 deg</td>
</tr>
<tr>
<td>Continuum imaging dynamic range at 1.4 GHz</td>
<td>60 dB</td>
</tr>
<tr>
<td>Line-to-line dynamic range at 1.4 GHz</td>
<td>40 dB</td>
</tr>
<tr>
<td>Mosaicing imaging dynamic range at 14 GHz</td>
<td>27 dB</td>
</tr>
<tr>
<td>Linear polarisation cross coupling across -3 dB beam</td>
<td>-30 dB</td>
</tr>
<tr>
<td>Sensitivity UHF-Band (0.58 - 1.015 GHz)</td>
<td>220 m²/K required</td>
</tr>
<tr>
<td>Sensitivity L-Band (0.9 - 1.67 GHz)</td>
<td>220 m²/K required</td>
</tr>
<tr>
<td>Sensitivity X-Band (8 - 14.5 GHz)</td>
<td>200 m²/K required</td>
</tr>
<tr>
<td>Aperture phase efficiency</td>
<td>0.91 [at 14.5 GHz]</td>
</tr>
<tr>
<td>Surface accuracy</td>
<td>0.6 mm RMS</td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>5” [optimal conditions, 20 min]; 25” [normal conditions, 24 h]</td>
</tr>
<tr>
<td>Pointing jitter</td>
<td>&lt;15” RMS</td>
</tr>
<tr>
<td>Reflector noise contribution</td>
<td>&lt;1K</td>
</tr>
<tr>
<td>Reflector reflecting efficiency</td>
<td>&gt;99.5% (main and sub)</td>
</tr>
<tr>
<td>Indexer</td>
<td>4 receivers, 1 min switchover</td>
</tr>
</tbody>
</table>
Simulated radio emission from the cosmic web

We assume synch. emission from electrons accelerated by DSA:

\[ P(\nu) \propto \xi_e(M) \rho V_s^3 B^2 A_s \]

(Hoef't & Brüggen 07)

Maximum accel. efficiency - 0.07%
Magnetic fields -μG (clusters) to ~nG-100nG (filaments)

FV, Ferrari, Bruggen+15 a,b FV 2016
Further, gas infall may explain extended, sometimes lopsided, HI disks and warps. The sensitivity of the SKA is required to probe cold accreting gas to $z > 0.5$ and in a range of environments.

While the star formation rate evolves significantly from $z \sim 1$, the HI mass density remains effectively constant. Ongoing gas accretion and conversion to molecular form must be important, but the processes are not yet understood in any detail. Absorption-line studies currently measure the HI mass density beyond $z = 0.24$, but they do not reveal how gas is distributed relative to galaxies' star formation nor do they reveal the sequence of accretion and consumption. Only the SKA will have the sensitivity to extend our view to $z \sim 1$ and beyond.

The HI line in absorption will also be a powerful tool for tracing the HI content of galaxies to much higher redshifts ($z > 4$) and along with circumnuclear environments.

**Figure 1**—Simulation of a Milky Way-size halo at $z = 2$ being fed by cold streams of gas ("cold mode accretion," Keres et al. 2009, arXiv: 0809.1430). Gas temperature is color coded from blue ($\sim 10^4$ K) to yellow ($\sim 10^6$ K). The circle indicates the virial radius of the halo. SKA HI observations are required to understand the role of cold accretion in galaxy formation.

**AGN and Star Formation:** Both star formation (SF) and AGN evolve strongly with time, reaching a peak near $z \sim 2$, but it is unclear what the relation is between SF and AGN. Did the first massive black holes (MBHs) form before or after the first galactic-scale assemblies of stars? What is
View showing 10% of the full MeerKAT First Light radio image. More than 200 astronomical radio sources (white dots) are visible in this image, where prior to MeerKAT only five were known (indicated by violet circles). This image spans about the area of the Earth’s moon.
Deep galaxy surveys have revealed that the global star formation rate (SFR) density in the Universe peaks at $1 \leq z \leq 2$ and sharply declines towards $z = 0$. But a clear picture of the underlying processes, in particular the evolution of cold atomic ($\sim 100$ K) and molecular gas phases, that drive such a strong evolution is yet to emerge. MALS is designed to use MeerKAT's L- and UHF-band receivers to carry out the most sensitive ($N(\text{H}\, I) > 10^{19}$ cm$^{-2}$) dust-unbiased search of intervening H I 21-cm and OH 18-cm absorption lines at $0 < z < 2$. This will provide reliable measurements of the evolution of cold atomic and molecular gas cross-sections of galaxies, and unravel the processes driving the steep evolution in the SFR density. The large sample of H I and OH absorbers obtained from the survey will (i) lead to tightest constraints on the fundamental constants of physics, and (ii) be ideally suited to probe the evolution of magnetic fields in disks of galaxies via Zeeman Splitting or Rotation Measure synthesis. The survey will also provide an unbiased census of H I and OH absorbers, i.e. cold gas \textit{associated} with powerful AGNs ($> 10^{24}$ W Hz$^{-1}$) at $0 < z < 2$, and will simultaneously deliver a blind H I and OH emission line survey, and radio continuum survey. Here, we describe the MALS survey design, observing plan and the science issues to be addressed under various science themes.
LOFAR Stations

Dipole ‘tiles’ for 110-240 MHz
Dipole array for 10-80 MHz

Tautenburg, Germany
Faraday Tomography of the Local Interstellar Medium with LOFAR: Galactic Foregrounds Towards IC342

C.L. Van Eck¹, M. Haverkorn¹, M.I.R. Alves², R. Beck³, A.G. de Bruyn⁴,⁵, T. Enßlin⁶,⁷, J.S. Farnes¹, K. Ferrière², G. Heald⁸,⁹, C. Horellou⁹, A. Horneffer³, M. Iacobelli⁴, V. Jelić¹⁰,¹¹, I. Martí-Vidal⁹, D.D. Mulcahy¹¹, W. Reich³, H.J.A. Röttgering¹², A.M.M Scaife¹¹, D.H.F.M. Schnitzeler³, C. Sobey¹³,⁸,⁴, and S.S. Sridhar⁵,⁴

¹ Department of Astrophysics/IMAPP, Radboud University, PO Box 9010, NL-6500 GL Nijmegen, the Netherlands; * e-mail: ...
1500 new pulsars: A full local census of radio emitting NSs

- One hour pointings
- 150 MHz optimum frequency
- 20 beams simultaneously
- Limited in gal. plane by scattering
- Weak nearby MSPs
- Possibly exotic systems
ABSTRACT

We present the first limits on the Epoch of Reionization (EoR) 21-cm HI power spectra, in the redshift range $z = 7.9 - 10.6$, using the Low-Frequency Array (LOFAR) High-Band Antenna (HBA). In total 13.0 h of data were used from observations centred on the North Celestial Pole (NCP). After subtraction of the sky model and the noise bias, we detect a non-zero $\Delta_1^2 = (56 \pm 13 \text{ mK})^2$ (1-$\sigma$) excess variance and a best 2-$\sigma$ upper limit of $\Delta_{21}^2 < (79.6 \text{ mK})^2$ at $k = 0.053 \text{ h cm}^{-2} \text{Mpc}^{-1}$ in the range $z = 9.6 - 10.6$. The excess variance decreases when optimizing the smoothness of the direction- and frequency-dependent gain calibration, and with increasing the completeness of the sky model. It is likely caused by (i) residual side-lobe noise on calibration baselines, (ii) leverage due to non-linear effects, (iii) noise and ionosphere-induced gain errors, or a combination thereof. Further analyses of the excess variance will be discussed in forthcoming publications.

Keywords: cosmology: theory - large-scale structure of Universe - observations - diffuse radiation - methods: statistical - radio lines: general - cosmology: dark ages, reionization, first stars

1. INTRODUCTION

During the Epoch of Reionization (EoR) hydrogen gas in the universe transitioned from neutral to ionized (Madau et al. 1997). The EoR is thought to be caused by the formation of the first sources of radiation and hence its study is important for understanding the nature of these first radiating sources, the physical processes that govern them and how they influence the formation of subsequent generations of stars, the interstellar medium (ISM), intergalactic medium (IGM) and black holes; see e.g. Furlanetto et al. (2006); Morales & Wyithe (2010); Prichard & Loeb (2012); Natarajan & Yoshida (2014); McQuinn (2015) for extensive reviews of the EoR.

Current observational constraints suggest that reionization took place in the redshift range $6 \lesssim z \lesssim 10$, with the lower limit inferred from the Gunn-Peterson trough in high-redshift quasar spectra (Becker et al. 2001; Fan, et al. 2003, 2006), and the upper limit of the redshift range currently being set by the most recent Planck results, which yields a surprisingly low value of the optical depth for Thomson scattering, $\tau_e = 0.058 \pm 0.012$ (Planck Collaboration 2016). This small optical depth mitigates the tension that exists between the higher optical depth values obtained by the WMAP satellite (Page et al. 2007; Komatsu et al. 2011; Hinshaw et al. 2013) and the other probes. The current range can easily accommodate photo-ionisation rate measurements (Bolton & Haehnelt 2007; Calverley et al. 2011; Becker et al. 2011), Intergalactic Medium (IGM) temperature measurements (Theuns et al. 2002; Bolton et al. 2010; Becker & Bolton 2013), observations of high-redshift Lyman break galaxies at $7 \lesssim z \lesssim 10$ (see e.g. Oesch et al. 2010; Bouwens et al. 2010; Bunker et al. 2010; Bouwens et al. 2015; Robertson et al. 2015) and observation of Lyman-α emitters at $z = 7$ (see e.g. Schenker et al. 2014; Santos et al. 2016).
Imaging Spectroscopy of Type U and J Solar Radio Bursts with LOFAR

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ABSTRACT

Context. Radio U-bursts and J-bursts are signatures of electron beams propagating along magnetic loops confined to the corona. The more commonly observed type III radio bursts are signatures of electron beams propagating along magnetic loops that extend into interplanetary space. Given the prevalence of solar magnetic flux to be closed in the corona, it is not clear why type III bursts are more frequently observed than U-bursts or J-bursts.

Aims. We use LOFAR imaging spectroscopy between 30–80 MHz of low-frequency U-bursts and J-bursts to understand why electron beams travelling along coronal loops produce radio emission less often. Radio burst observations provide information not only about the exciting electron beams but also about the structure of large coronal loops with densities too low for standard EUV or X-ray analysis.

Methods. We analysed LOFAR images of a sequence of two J-bursts and one U-burst. The different radio source positions were used to model the spatial structure of the guiding magnetic flux tube and then deduce the energy range of the exciting electron beams without the assumption of a standard density model. We also estimated the electron density along the magnetic flux rope and compared it to coronal models.

Results. The radio sources infer a magnetic loop 1 solar radius in altitude, with the highest frequency sources starting around 0.6 solar radii. Electron velocities were found between 0.13 c and 0.24 c, with the front of the electron beam travelling faster than the back of the electron beam. The velocities correspond to energy ranges within the beam from 0.7–11 keV to 0.7–43 keV. The density along the loop is higher than typical coronal density models and the density gradient is smaller.

Conclusions. A more restrictive range of accelerated beam and background plasma parameters can result in U-bursts or J-bursts, causing type III bursts to be more frequently observed. The large instability distances required before Langmuir waves are produced by some electron beams, and the small magnitude of the background density gradients make closed loops less facilitating for radio emission than loops that extend into interplanetary space.