The Square Kilometre Array

Miguel Pérez-Torres (torres@iaa.es)  
(IAA-CSIC)
Great Observatories for the coming decade

ALMA: mm/submm

JWST: near-IR

E-ELT/TMT/GMT: optical/IR
...and the SKA
Commemorating the 50th anniversary of Karl Jansky’s discovery of radio waves from our galaxy.

Karl Jansky and his “merry-go-round” antenna — the first radio telescope with record of...
ELECTROMAGNETIC SPECTRUM SHOWING THE RADIO FREQUENCY SPECTRUM

RADIO FREQUENCY SPECTRUM

- Electric waves
- Radio waves
- Infra-red
- Visible light
- Ultraviolet
- X-rays
- Gamma rays
- Cosmic rays

Frequency Bands:
- VLF: Very Low Frequency
- LF: Low Frequency
- MF: Medium Frequency
- HF: High Frequency
- VHF: Very High Frequency
- UHF: Ultra High Frequency
- SHF: Super High Frequency
- EHF: Extremely High Frequency

Frequency Ranges:
- 9 kHz to 30 kHz
- 30 kHz to 300 kHz
- 300 kHz to 30 MHz
- 30 MHz to 300 MHz
- 300 MHz to 3 GHz
- 3 GHz to 30 GHz
- 30 GHz to 300 GHz
- 300 GHz to 3000 GHz
What is the SKA?

**Phase I**
- ~130,000 element Low Frequency Aperture Array
- 50 MHz, 100 MHz
- 2020

**Phase II**
- ~1,000,000 element Low Frequency Aperture Array
- Low Frequency Aperture Array
- ~200 dishes
- ~2500 dishes
- 2024

**Science**
- Cosmic Dawn & Reionization
- Cosmology & Galaxy Evolution
- Pulsars
- Cosmic Magnetism
- Cradle of Life
- Exploration of the Unknown

**Frequency Bands**
- 50 MHz
- 100 MHz
- 1 GHz
- 10 GHz
SKA Pathfinders - Northern hemisphere

Jansky Very Large Array (JVLA, USA)

Low Frequency Array (LOFAR, Europe)
SKA Pathfinders - Southern hemisphere

MeerKAT (South Africa)

GMRT (India)

ASKAP (Australia)

MWA (Australia)
The SKA challenge

- Revolutionise our understanding of the universe
- >4x angular resolution (JVLA)
- >10x sensitive
- > 100x survey speed
- Lifespan >= 50 yr; upgradable
- Use new receiver technology, signal transport and processing techniques, and computer power on unprecedented scales.
SKA Organisation

Australia (DoI&S)
Canada (NRC-HIA)
China (MOST)

India (NCRA/DAE)
Italy (INAF)
Netherlands (NWO)
New Zealand (MED)
South Africa (DST)
Sweden (Chalmers)
UK (STFC)
SKA Science

• **SKA**: one of the great physics machine of the 21st century

• **Science goals**:
  
  • Fundamental Physics: Gravity, DE, Magnetism
  
  • Astrophysics: Cosmic Dawn, First galaxies, galaxy assembly and evolution; protoplanetary disks, biomolecules, SETI+...
  
  • The unknown: transients; +...???
SKA1 Scope (March 2015)

- **SKA1-MID**
  - 70% of planned SKA1 dishes (133x15 m)
  - Integration of MeerKAT (64x13.5 m)
  - Deployment of Freq. bands 2, 5 and 1.
  - $B_{\text{max}} \sim 150$ km

- **SKA1-LOW**
  - 131000 antennas (50% of total planned)
  - Freqs: 50-350 MHz; $B_{\text{max}} \sim 65$ km
  - Pulsar search

- Negotiate ASKAP integration into SKAO
SKA1-MID, Karoo, South Africa:
133 SKA1+64 MeerKAT dishes. B_max \sim 150 \text{ km}
Bands: 1 (0.35 - 1.05 GHz), 2 (0.95 - 1.76 GHz), 5 (4.6 - 13.8 GHz)
SKA1-LOW, Murchison, Australia:
130000 dipoles (512 stations x 256 antennas/st), 50-350 MHz
B_max ~ 65 km; large concentration in the core
Hydrogen atom

Higher energy state

electron
proton

Hydrogen radio emission

Wavelength 21 cm
Frequency 1420 MHz

Lower energy state
Sky in the optical

Sky in H I
Sky in the optical

Sky at 408 MHz (~70 cm)
Does size matter?
Angular resolution

Human eye
1 arcmin

2 m optical
telescope (ground)
0.5 arcsec

HST
0.05 arcsec
Angular resolution
(Human eye vs. telescope)

Eye: 2mm
Wavelength = 580 nm
Angular resolution = 1 arcmin

versus

Yebes radio telescope: 40 m
Wavelength = 1 cm
Angular resolution = 1 arcmin
So what do we do?
Solution #1
Solution #2

Radio interferometry
Double slit experiment
A Course of Lectures on Natural Philosophy and the Mechanical Arts.
A single baseline has a sinusoidal sensitivity pattern across the sky, oscillating between constructive and destructive interference.
The oscillations in the sensitivity pattern have the same direction as the baseline, with a period determined by the baseline length in wavelengths.
12 Hour Synthesis Observation

UV Coverage

Point Spread Function
Radio Galaxy Hydra A at 330 MHz

VLA A-configuration

VLA A+B+C-configurations

Images courtesy of W.M. Lane
NGC 1614 @ 65 Mpc

VLA @ 4 cm
The European VLBI Network
...and the SKA
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 antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.

**Resolution**

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

<table>
<thead>
<tr>
<th>SKA1 LOW</th>
<th>SKA1 MID</th>
</tr>
</thead>
<tbody>
<tr>
<td>x1.2 LOFAR NL</td>
<td>x4 JVLA</td>
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</tbody>
</table>

**Survey Speed**

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.

<table>
<thead>
<tr>
<th>SKA1 LOW</th>
<th>SKA1 MID</th>
</tr>
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<tbody>
<tr>
<td>x135 LOFAR NL</td>
<td>x60 JVLA</td>
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</table>

**Sensitivity**

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.

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<tr>
<th>SKA1 LOW</th>
<th>SKA1 MID</th>
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<tbody>
<tr>
<td>x8 LOFAR NL</td>
<td>x5 JVLA</td>
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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.

www.skatelescope.org  Facebook: Square Kilometre Array  @SKA_telescope  The Square Kilometre Array

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.
Notional SKA1 KSPs

<table>
<thead>
<tr>
<th>SWG</th>
<th>Objective</th>
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<tr>
<td>CD/EoR</td>
<td>Physics of the early universe IGM - I. Imaging</td>
</tr>
<tr>
<td>CD/EoR</td>
<td>Physics of the early universe IGM - II. Power spectrum</td>
</tr>
<tr>
<td>Pulsars</td>
<td>Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection</td>
</tr>
<tr>
<td>Pulsars</td>
<td>High precision timing for testing gravity and GW detection</td>
</tr>
<tr>
<td>HI</td>
<td>Resolved HI kinematics and morphology of $10^{10}$ M$_{sol}$ mass galaxies out to $z \sim 0.8$</td>
</tr>
<tr>
<td>HI</td>
<td>High spatial resolution studies of the ISM in the nearby Universe.</td>
</tr>
<tr>
<td>HI</td>
<td>Multi-resolution mapping studies of the ISM in our Galaxy</td>
</tr>
<tr>
<td>Transients</td>
<td>Solve missing baryon problem at $z \sim 2$ and determine the Dark Energy Equation of State</td>
</tr>
<tr>
<td>Cradle of Life</td>
<td>Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc</td>
</tr>
<tr>
<td>Magnetism</td>
<td>The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields</td>
</tr>
<tr>
<td>Cosmology</td>
<td>Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.</td>
</tr>
<tr>
<td>Cosmology</td>
<td>Angular correlation functions to probe non-Gaussianity and the matter dipole</td>
</tr>
<tr>
<td>Continuum</td>
<td>Star formation history of the Universe (SFHU) – I+II. Non-thermal + Thermal processes</td>
</tr>
</tbody>
</table>

- All objectives originate with the science community
- Representative package of high-impact science deliverables for the first 5 years of science operations
- Maximize Commensality
SKA2 Configurations
Sensitivity comparison

- **SKA2**
- **SKA1-LOW**
- **SKA1-MID**
- **LOFAR**
- **JVLA**
Survey speed comparison

Survey speed (m^4/K^2 deg^2) @ B_{Nom}

Frequency (GHz)
Angular resolution comparison

Resolution @ $B_{\text{Max}}$ (arcsec)

Frequency (GHz)

LOFAR
SKA1-LOW
SKA1-MID
SKA2
JVLRA-A
ALMA-C2
<table>
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<tr>
<th><strong>Headline Science with SKA</strong></th>
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</table>

<table>
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<tr>
<th><strong>The Cradle of Life &amp; Astrobiology</strong></th>
<th><strong>SKA1</strong></th>
<th><strong>SKA2</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Proto-planetary disks; imaging inside the snowline (@ &lt; 100 pc), Searches for amino acids.</td>
<td>Targeted SETI: airport radar 10^4 nearby stars.</td>
<td>Proto-planetary disks; sub-AU imaging (@ &lt; 150 pc), Studies of amino acids.</td>
</tr>
<tr>
<td><strong>Strong-field Tests of Gravity with Pulsars and Black Holes</strong></td>
<td><strong>SKA1</strong></td>
<td><strong>SKA2</strong></td>
</tr>
<tr>
<td>1st detection of nHz-stochastic gravitational wave background.</td>
<td>Discover and use NS-NS and PSR-BH binaries to provide the best tests of gravity theories and General Relativity.</td>
<td>Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.</td>
</tr>
<tr>
<td><strong>The Origin and Evolution of Cosmic Magnetism</strong></td>
<td><strong>SKA1</strong></td>
<td><strong>SKA2</strong></td>
</tr>
<tr>
<td>The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg2.</td>
<td>Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ z = 0.04.</td>
<td>The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg2.</td>
</tr>
<tr>
<td><strong>Galaxy Evolution probed by Neutral Hydrogen</strong></td>
<td><strong>SKA1</strong></td>
<td><strong>SKA2</strong></td>
</tr>
<tr>
<td>Gas properties of 10^7 galaxies, &lt;z&gt; = 0.3, evolution to z = 1, BAO complement to Euclid.</td>
<td>Detailed interstellar medium of nearby galaxies (3 Mpc) at 50pc resolution, diffuse IGM down to N_H &lt; 10^17 at 1 kpc.</td>
<td>Gas properties of 10^9 galaxies, &lt;z&gt; = 1, evolution to z ~ 5, world-class precision cosmology.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Detailed interstellar medium of nearby galaxies (10 Mpc) at 50pc resolution, diffuse IGM down to N_H &lt; 10^17 at 1 kpc.</td>
</tr>
</tbody>
</table>
# Headline Science with SKA

<table>
<thead>
<tr>
<th></th>
<th>SKA1</th>
<th>SKA2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>The Transient Radio Sky</strong></td>
<td>Use fast radio bursts to uncover the missing &quot;normal&quot; matter in the universe.</td>
<td>Fast radio bursts as unique probes of fundamental cosmological parameters and intergalactic magnetic fields.</td>
</tr>
<tr>
<td></td>
<td>Study feedback from the most energetic cosmic explosions and the disruption of stars by super-massive black holes.</td>
<td>Exploring the unknown: new exotic astrophysical phenomena in discovery phase space.</td>
</tr>
<tr>
<td><strong>Galaxy Evolution probed in the Radio Continuum</strong></td>
<td>Star formation rates (10 M_Sun/yr to z ~ 4).</td>
<td>Star formation rates (10 M_Sun/yr to z ~ 10).</td>
</tr>
<tr>
<td></td>
<td>Resolved star formation astrophysics (sub-kpc active regions at z ~ 1).</td>
<td>Resolved star formation astrophysics (sub-kpc active regions at z ~ 6).</td>
</tr>
<tr>
<td><strong>Cosmology &amp; Dark Energy</strong></td>
<td>Constraints on DE, modified gravity, the distribution &amp; evolution of matter on super-horizon scales: competitive to Euclid.</td>
<td>Constraints on DE, modified gravity, the distribution &amp; evolution of matter on super-horizon scales: redefines state-of-art.</td>
</tr>
<tr>
<td></td>
<td>Primordial non-Gaussianity and the matter dipole: 2x Euclid.</td>
<td>Primordial non-Gaussianity and the matter dipole: 10x Euclid.</td>
</tr>
<tr>
<td><strong>Cosmic Dawn and the Epoch of Reionization</strong></td>
<td>Direct imaging of EoR structures (z = 6 - 12).</td>
<td>Direct imaging of Cosmic Dawn structures (z = 12 - 30).</td>
</tr>
<tr>
<td></td>
<td>Power spectra of Cosmic Dawn down to arcmin scales, possible imaging at 10 arcmin.</td>
<td>First glimpse of the Dark Ages (z &gt; 30).</td>
</tr>
</tbody>
</table>
The Cradle of Life: Understanding planet formation

- Measuring grain growth through planetesimal phase
- Resolving proto-planetary disks at 100 pc (SKA1) or 300 pc (SKA2) inside the snow/ice line, sub-AU scales with SKA2

(Hasegawa & Pudritz 2012)
• Detection thresholds for planetary and airport radars at 15 pc
Detectable stars with airport radar power $\sim 10^4$ with SKA1
Detectable stars with TV transmitter power $\sim 10$ with SKA2
Finding all the pulsars in the Milky Way...


- ~40,000 normal pulsars
- ~2,000 millisecond psrs
- ~100 relativistic binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars

- Timing precision is expected to increase by factor ~100
- Rare and exotic pulsars and binary systems: including PSR-BH systems!
- Testing cosmic censorship and no-hair theorem
- Current estimates are ~50% of population with SKA1, 100% with SKA2
Detection thresholds for discrete GW source detection; the first discoveries with SKA1, “GW astronomy” with SKA2
Galaxy HI Evolution: out to z ~ 1 with SKA1 and z ~ 5 with SKA2

(Simulations: Schaye et al. 2010, Images: Oosterloo 2014)

- Understanding galaxy assembly and the baryon cycle
  - Determine the impact of galaxy environments
  - Probe gas inflow and removal, diffuse gas $N_{\text{HI}} < 10^{17} \text{ cm}^{-2}$
  - Measure angular momentum build-up
Precision Cosmology with SKA2 HI

- Detect $10^{8.9}$ galaxies with $<z> \approx 1$, $10^{7.9}$ with $<z> \approx 2$
- Compare Euclid (2020+5?) target of $10^8$ spectra with $<z> \approx 1$
- SKA2 will provide an unrivaled capability for precision cosmology!
The Transient radio sky

A Population of Fast Radio Bursts at Cosmological Distances
D. Thornton et al.
Science 341, 53 (2013);
DOI: 10.1126/science.1236789

- Four celestial “FRB” events now detected (after first “Lorimer” burst):
  \[ S = 0.5 \text{ – } 1.3 \text{ Jy}, \Delta t = 1 \text{ – } 6 \text{ msec}, \text{DM} = 550 \text{ – } 1100 \text{ cm}^{-3} \text{ pc} \]
- Estimated event rate: \(1 \times 10^4\) sky\(^{-1}\) day\(^{-1}\)
- Completely unknown origin, possibly at cosmological distances
Galaxy Evolution Studies in the Radio Continuum: Understanding the Star Formation History of the Universe

(Murphy et al. 2014)

- Unmatched sensitivity to star formation rates ($10 \, M_\odot/yr$) out to $z \sim 4$ with SKA1 and $z \sim 10$ with SKA2
- Resolved (sub-kpc) imaging of star forming disks out to $z \sim 1$ with SKA1 and $z \sim 6$ with SKA2
NGC 6964: same scale

Optical (stars)

radio 21cm (hydrogen gas)
Cosmology with SKA: Integrated Sachs-Wolfe effect

• Constraining non-Gaussianity of primordial fluctuations with the Integrated Sachs-Wolfe effect: correlation of foreground source populations with CMB structures
  – Uniquely probing the largest scales

(Raccanelli et al. 2014)
Cosmology with SKA: Baryon Acoustic Oscillations

(Blake & Moorfield)

- Constraining Dark Energy models with redshift-resolved BAO measurements
  - Discrete detection is complementary with SKA1, cutting edge in SKA2
  - Intensity mapping is higher risk but world-class, even with SKA1
Cosmology with SKA: Baryon Acoustic Oscillations

- Constraining Dark Energy models with redshift-resolved BAO measurements
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Cosmology with SKA: Matter Dipole versus CMB Dipole

(Schwarz et al. 2014)

- Sensitive constraints on isotropy and homogeneity
  - Unique tests of isotropy at $z \sim 1$
  - Measure cosmic matter dipole with high precision
Cosmology with SKA: Redshift space distortions

- Constraining modified gravity and curvature with discrete HI galaxy surveys
  - Discrete detection is complementary with SKA1, cutting edge with SKA2
HI surveys of the EoR, Cosmic-Dawn & Dark Ages

CMB displays a single moment of the Universe. Its initial conditions at \( \sim 400,000 \) yrs.

HI emission from the Dark Ages, Cosmic Dawn & EoR traces an evolving “movie” of baryonic and DM structure formation at \( t_{\text{univ}} < 10^9 \) years.

• Gathers Spanish efforts aimed at making Spain part of SKA

• Contact person: Lourdes Verdes-Montenegro (IAA-CSIC)
Spanish participation in SKA Science groups

Epoch of Re-ionization

- Diego Herranz (IFCA), A. Rubiño (IAC), J. M. Rodríguez (IAC)

Extragalactic Continuum (galaxies/AGN, galaxy clusters)

- Antxón Alberdi (IAA)
- Miguel Pérez-Torres (IAA)
- Iván Agudo (IAA)
- Fatemeh Tabatabaei (IAC)

Cosmology

- Enrique Martínez-González (IFCA)
- Diego Herranz (IFCA), Olga Mena (UV-CSIC)
- Jose A. Rubiño (IAC), Ricardo Génova (IAC)

HI Galaxy Science

- Lourdes Verdes-Montenegro (IAA)
- Bjorn Emonts (CAB)
- J. Sánchez-Almeida (IAC), J. Beckman (IAC)

Cosmic Magnetism

- Iván Agudo (IAA)
- Eduardo Battaner (UGR)
- Josep Miguel Girart (IEEC)
- F. Poidevin (IAC)

Our Galaxy

- Antxón Alberdi (IAA)
- Rainer Schöedel (IAA)

Transients

- Miguel Pérez-Torres (IAA)
- Iván Agudo (IAA)
- Eric Kuulkers (ESA)
- Simone Migliari (ESA)

Extragalactic spectral line
Cradle of life
Pulsars
Solar, heliospheric and ionospheric physics
SPANISH CONTRIBUTION TO SKA PRE-CONSTRUCTION

- 11 Spanish research centres and 12 companies participate in 7 SKA Pre-construction Consortia (~2 M€ Feb 2014):

- Instituto de Física de Cantabria (CSIC)  
  Dish

- Dpto. de Ingeniería de Comunicaciones (Universidad de Cantabria)  
  Dish

- Universidad Pública de Navarra (UPN)  
  Dish

- Instituto de Astrofísica de Andalucía (IAA-CSIC)  
  Science Data Processor; Infra-SA&AUS

- Fundación Centro de Supercomputación Castilla-León (FCSCL)  
  Science Data Processor

- Barcelona Supercomputing Center  
  Science Data Processor

- Observatorio Astronómico Nacional (Instituto Geográfico Nacional)  
  Dish

- Plataforma Solar de Almería (CIEMAT)  
  Infra-SA, Infra-AUS

- Universidad Politécnica de Madrid  
  Central Signal Processor

- Universidad de Granada  
  Synchronization and Data Transport

- Universidad Politécnica de Valencia  
  Synchronization and Data Transport

Under discussions:

- Institut de Ciències de l’Espai (CSIC)  
  Telescope Manager
SPANISH CONTRIBUTION TO SKA PRE-CONSTRUCTION

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- TTI Norte
- Anteral
- 7 Solutions
- Das Photonics
- ISDEFE
- GTD
- iGrid-TD
- Arraela
- Aora Solar Spain
- CSP Sunless
- Torresol Energy
- GMV

- Dish
- Signal & Data Transport
- Central Signal Processor
- Science Data Processor
- Telescope Manager
- Infrastructure - Australia
- Infrastructure - South Africa
• Make aware the whole Spanish astronomical community

• Show the interests of our community and our ability to successfully exploit the SKA capabilities

• 120 researchers involved

• 29 chapters

• SKA Science Headlines well represented
The SKA in one slide

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Phase II

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- ~200 dishes
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Science

- Cosmic Dawn & Reionization
- Cosmology & Galaxy Evolution
- Pulsars
- Cosmic Magnetism
- Cradle of Life
- Exploration of the Unknown