SURO-LC
Space-based Ultralong wavelength Radio Observatory

SURO Core Team:
ASTRON (NL)
Institute for Space Research (SE)
Psi-tran (UK)
Space Enterprise Partnerships (UK)
Surrey Satellite Technology (UK)
Introducing SURO-LC

- Space based low-frequency radio telescope: 0.1 to 70 MHz
  - 8+ Daughters with radio antennas - loose formation flying
  - Mothership for control, data correlation & ground communication
- SURO employs a low-drift Lissajous or halo orbit around Earth-Sun L2
- Opening the last unexplored frequency window
  - Avoid Earth ionospheric blocking (<30 MHz)
  - Avoid RFI and ionospheric disturbances (<70 MHz)
  - 24/7 All-sky Observatory
Lissajous Orbit at Sun-Earth L2

Distance 1.5 Mkm (0.01 AU)
Away from terrestrial RFI

VEGA launcher
1900 kg mass limit
A Working SURO Observatory

- Free-flying array using aperture synthesis imaging orbiting L2 and Sun
- Daughters with antennas and correlator onboard Mothership constitute payload
- “Passive formation flying”
- No complex & expensive control systems
- Allow slow drift & rotate of spacecraft
- Precise knowledge of positions & attitude using advanced metrology network
- High-speed intersatellite link (ISL) for data transfer to Mothership
- Mothership correlates science data and sends correlation matrices via Earth Link
- Actual imaging performed on the ground
- Resolution and sensitivity improves over time as the formation drifts
SURO-LC history

- Long history of “low-frequency space arrays”
  - Concept has been studied since mid 1980’s.
  - Solid science case, but all proposals failed
  - Technically infeasible or too expensive to maintain the formation

- SURO-LC employs “passive” formation flying
  - Looser control requirements makes satellite formations technically feasible & affordable

- SURO based on two separate passive formation flying ESA studies
  - FIRST Explorer (2009) and DARIS (2010)

- SURO was proposed to ESA as an M-class mission in December 2010 but not selected

- SURO-LC (low cost) was proposed to ESA as an S-class mission June 2012 & not selected

- Meanwhile => FACE mission proposal to ESA (tech demo), Sep 2012
Science to be done with SURO

• SURO addresses several ESA Cosmic Vision questions
  - How did the Universe begin and what is it made of?
  - What are the conditions for life and planetary formation in Universe?
  - How does the Solar System work?
  - What are the fundamental physical laws of the Universe?

• SURO has four primary science objectives
  - Detection of high red-shifted \textit{21cm emissions} from the Dark Ages
  - First low-frequency \textit{extragalactic survey} with high resolution and sensitivity
  - Monitoring and detection of non-thermal \textit{planetary radio emissions}
  - \textit{Heliophysics}: radio imaging of the Sun, solar flares, and CMEs

• SURO supports other space missions with high-res radio imaging

• SURO will cross calibrate ground-based facilities (LOFAR and SKA)

• By opening a new frequency band, SURO will make completely new and unforeseen discoveries
  - Happens each time a new frequency window is opened
Science Motivation for LF observatory

- Omni-directional radio interferometry observing all the time
- Application of existing antenna theory - three dipoles
- Multiple satellite stations - relaxed formation flying
- 'Far away' from Earth - Sun-Earth Lagrange point 2

- Address broad multi-disciplinary science goals

Observing Modes
- All-sky Imaging (10 MHz bw in 0.1 - 70 MHz range)
- Rapid Burst Monitoring (reduce bandwidth & interval to 100ms)
- Targeted Burst Monitoring (beamforming and sampling at 50 ms)
- Wide Band spectroscopy (running continuous - 5 min spectra)
Dark Ages and CMB

- Afterglow Light Pattern: 380,000 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
Dark Ages and the Epoch of Reionization

**Stage A: The very Dark Ages** - Until \( z = 40 \) the hydrogen in the universe continues to absorb the CMB radiation field.

**Stage B: Ignition of Star Formation** - \( z = 30 \), the CMB photons and UV photons from first generations of stars absorbed by cold HI

**Stage C: The first Black Holes** - \( z = 20 \), first Galaxies and accreting black holes heat HI bubbles in the IGM

**Stage D: Hot Bubble Dominated** - Around \( z = 13 \), stars and galaxies make hot ionized bubbles in IGM causing of HI 21cm emission

**Stage E: Ionization** - IGM becomes completely ionized by stars and galaxies after which HI 21-cm signature disappears.
21 cm HI signature of Dark Ages

21cm transition of neutral Hydrogen is accurate tracker of the ionization history during Dark Ages of the Universe

SURO completes the story after ground-based experiments
All Sky Surveys

Omni-directional Imaging of All Sky
3 arcmin at 10 MHz & 30 mJy sensitivity
1 arcmin at 30 MHz & 20 mJy sensitivity

=> Detect 2 million sources in 1 yr

Source populations and their Evolution
Nuclear startup sources
  (numerous at z = 20)
Long-term evolution of radio sources and AGN feedback (lower energy component)
Relics of radio sources
Cool holes in clusters ($10^5$ sources)
Galactic Studies

Galactic Interstellar Medium
Local clumpy Warm Ionized Medium
(RAE-2 & IMP-6 sats 1975, 2002)

3D Origin of Cosmic Rays - nearby HII & SNR sources
Radio Recombination Lines - also foreground for EOR
Strong pulsars - low frequency properties & spectral turnovers

Transient phenomena
Planetary Studies

Radio Planets = Solar planetary magnetospheric emissions
- Earth, Jupiter, Saturn & Uranus- solar wind interaction
Complex spectral structures in 0.1 - 20 MHz range
Search for Jupiter-like Exoplanets in known systems
HelioPhysics & Solar Weather Studies

- Solar activity at lower freq
  - Radio Imaging - 3' at 10 MHz
- Imaging Type II (slow) & III (rapid) bursts
- Imaging and tracking of CMEs to larger distances into space than before
- Resolution complementary to ground based arrays

![Graph showing frequency vs. height above the solar surface]

**Past**
- Clark Lake
- Non-thermal burst

**Present**
- Wind/WAVES
- Burst Location and Size only

**Future**
- SURO 10 MHz
- Non-thermal burst

Ground image at 77 MHz
Mission Profile (1)

• New Vega launcher (or Rockot)
• Mothership with cargo of 8 daughters
  - Total dry mass 500 kg
  - Total wet launch mass 1910 kg
• Mothership
  - Adaptation of the LISA Pathfinder - Minisat
  - LISA PF chemical main engine to reach SE L2
  - Disturbance free deployment of daughters
• Daughters
  - Stripped version of SSTL SNAP nanosat
  - High-speed ISL (8x60 Mbps)
  - Wide-band observations for high sensitivity
• SE L2 selected for quiet RFI environment and low relative satellite drift rates
  - Sufficiently close to Earth for high-speed ground communication (15 Mbps using 12 metre stations)
• Operations for 2 years (extendable to 3)
Launch Concepts

Solar Wind stabilization Daughters and Mother Daughters based on small satellite technology
Disturbance-free deployment
Thrusters for orbit corrections within group

SURO-LC (S-class 2012) concept (SEP & SSTL)

SURO (M-class 2010) concept (EADS Astrium)
Mission Profile (2)

• **DAUGHTER RELEASE and CONFIGURATION**

• At L2 release/jettison mechanical containment for daughters
• Daughters and Mothership remain attached until disturbance rates minimized using Mothership micro-propulsion
• Precision manoeuvring by Mothership before release
• Release daughters from electro-magnetic containment

• Sun-pointing orientation for all - passive attitude control
• Eight daughters drifting slowly in spherical distribution (30 km)
• Active control only at edge of constellation (< 1 m/s for lifetime)
• Micro-propulsion systems and micro-momentum wheels on daughters and Mothership
• Knowledge of inter-satellite separation for science operation
SURO-LC Constellation Plan

- Daughters slowly drift back and forth through constellation
- Changing baselines and projections
- Positions and orientations known for radio interferometry
- Passive Formation flying
  - Relaxed station keeping requirements
  - Passive control through ‘shuttlecock’ design
Mission Profile (3)

- **SATELLITE DESIGNS**

- **Attitude and Orbit Control System (AOCS)**
- LISA PF functionality (main propulsion, attitude sensors & control)
- LISA PF micro-propulsion system
- SSTL SNAP nano-sat platform (mini-reaction wheels & micro-prop)
- Solar Wind (sailing) stabilization for Daughters & Mothership

- **On-Board Data Handling (OBDH)** distributed over Daughter & Mothership - Daughter links with Mothership for data

- **Telemetry (TT&C)** - linking with all Ds & Mothership for ranging and position data
- **Mothership** - Fixed X-band high-gain antenna (15 Mbps - 12 m GS)
- Objective: Three or more ground stations
Daughters: Minimalist version of SSTL SNAP small satellite

Mothership: Stripped down LISA Pathfinder platform for mothership
Mission Profile (4)

• **SCIENCE PAYLOAD & OPERATION**

  • Daughter payload of three orthogonal dipoles (0.1 - 70 MHz)
  • *On-board processing of baseband signal 3>10 MHz (8bit > 1 bit)*
  • RFI Mitigation – burst detection
  • Inter-satellite links (ISL) with 60 Mbps (0.7-1 GHz)
  • Independent Daughter transmissions (FDM)
  • Mothership correlates streaming data - visibilities and spectral data to be downlinked

• Stringent EMC requirements for Daughter and Mothership

• Four observing modes – triggering by burst detection
Dipole Antenna Performance

- Three orthogonal dipole antennas about 3m tip-tip
- System Noise dominated by Galactic background
- Blanking/Nulling Terrestrial Interference at L2
- Proven deployment mechanism (has never failed)
**Daughter Science Payload**

*JUICE mission to Jupiter (IRF Uppsala & Tohoku U)*

Inputs from 8 x 3 dipole antennas (8 bit)

Digital Down Conversion per antenna and polarization

RFI mitigation and Burst detection

1-bit conversion baseband signal for transmission to Mothership

(2, 4, or 8 bits for smaller bandwidth)

FFT engine produces full bandwidth all-sky spectra
Mothership Payload

ISL data input from daughters (0.7 - 1 GHz; 60 Mbps)
Earth Link Tx/Rx data and command communication (X-band)
Time keeping for constellation
Science data processing - Cross- and Auto-Correlation
Metrology Control system
Fourier transform – cross correlation (FX correlator)
- Omni-directional (patch) imaging using narrow-band correlation
- Source brightness distribution with all Stokes information
Distributed array with 3 dipoles at 8 (9) stations & 28 (36) baselines
Multiple observations with drifting configuration improve imaging capability (PSF)

PSF point spread function in (w)-direction for 10 snapshots & many snapshots
Mission Profile (5)

• **RANGING & METROLOGY**

• Daughters and Mothership communicate with all using omni-directional antennas (2.4 GHz < 1 Mbps) (control & housekeeping)
• TDM and CDM techniques for unambiguous point-to-point linking
• Data headers allow simple ranging (L/10 = 0.4m @70 MHz)
• Multi-lateration metrology in 'timestep' => 30 x improvement in ranging and orientation measurement uncertainty
• Position & collision avoidance processing using 1 GHz processor
• Closed form solution for clock offsets, clock drifts, relative distances and velocities gives 3D relative locations of Daughters using single reference clock
Daughter Communication

Ranging & Metrology to determine position relative to others (CDM)
Payload data - 50 (60) Mbps in separate bands 0.7 - 1 GHz (FDM)

Nominal observing bandwidth 10 MHz
Daughter transmits raw data from three dipoles
Mother produces correlation matrices for transmission to Earth
We love it when a plan comes together

Using small satellite technology - increase number of Daughters
Using innovative metrology /sensing techniques
Using existing satellite platforms
Newest hardened FPGA processing chips for daughters and mother
Using proven radio interferometry techniques
High-gain antennas between satellites
Reduced data rate to Earth
Using mitigation algorithms for terrestrial radio interference
Implement burst detection techniques
Use omni-directional antennas for all-sky imaging
Concepts for disturbance-free release mechanism
Solar wind (sailing) stabilization of Daughter and Mothership

Putting existing know-how/knowledge together in a new/better way
<table>
<thead>
<tr>
<th>PROGRAMME ELEMENT</th>
<th>COST M€</th>
<th>COMMENT</th>
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<tbody>
<tr>
<td><strong>Payload</strong></td>
<td></td>
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<tr>
<td>Daughter Spacecraft (8)</td>
<td>2.5</td>
<td>Antenna and receivers</td>
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<tr>
<td>Mothership</td>
<td>2.5</td>
<td>Correlator</td>
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<tr>
<td><strong>Platforms and System</strong></td>
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<tr>
<td>Daughter Spacecraft (8)</td>
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<td>Adapted SNAP platform</td>
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<tr>
<td>Mothership Platform</td>
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<td>Adapted LISA platform &amp; propulsion</td>
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<tr>
<td>System Design &amp; Demos</td>
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<td>Excludes Phase A/B1 estimated M€1</td>
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<td><strong>Sub-total Industrial Cost</strong></td>
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<td>M€78 with 20% margin</td>
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<td>Vega launch</td>
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<td>Science Operations</td>
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<td>For 2 year’s nominal</td>
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<td>Consortium Management</td>
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<td>Meetings and T&amp;S</td>
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<td><strong>Services Total</strong></td>
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<td>M€37.95 with 10% margin</td>
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<td><strong>Total Industrial &amp; Services</strong></td>
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<td><strong>Total + Margins</strong></td>
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Summary

• SURO opens an entirely new frequency window for astronomy and space physics
  - High profile science topics (cosmology)
  - Make new and unforeseen discoveries

• SURO science case attractive to large research community
  - astronomy, astrophysics & cosmology, space physics

• SURO employs passive formation flying and small satellites technologies to make the mission affordable
  - Pathfinder for future formation flying missions

• Benefits from previous investments
  - Formation flying technologies
  - Space science instrumentation
  - Micro and nanotechnology
SURO-LC (Low-cost)
ESA Small-Class Call - June 2012 - not selected
5 yr project - flight in 2017
Investigation of other paths outside ESA towards realization

“We will not give up and your support is welcome!”
Organisation of SURO-LC

SURO worldwide science community, organizations, space agencies and small aerospace companies in Australia, China, France, Germany, India, Italy, Japan, Netherlands, Poland, Russia, Sweden, UK, and USA
• **Australia** – Commonwealth Science and Industrial Research Organisation (CSIRO)
• **China** – National Astronomical Observatory of China, Shanghai Astron. Observatory, Shanghai Jiao Tong U
• **France** – Centre National de la Recherche Scientifique, CNRS
• **Germany** – German Long Wavelength Consortium GLOW
• **India** – Raman Res. Inst. RRI, Nat. Center Radio Astronomy NCRA
• **Italy** – INAF, UNOBO, ISA
• **Netherlands** – Netherlands Institute for Radio Astronomy
• **Poland** – Space Res. Center, Polish Academy Sciences SRC PAS, U Zielona Gora, Jagiellonian U Karkow
• **Russia** – AstroSpace Center, Lebedev Physical Institute
• **Sweden** – Swedish Institute of Space Physics (IRF)
• **United Kingdom** – Mullard Radio Astronomy Observatory
• **United States** – JPL, Univ Colorado, NASA