Shanghai Astronomical Observatory
Chinese Academy of Sciences

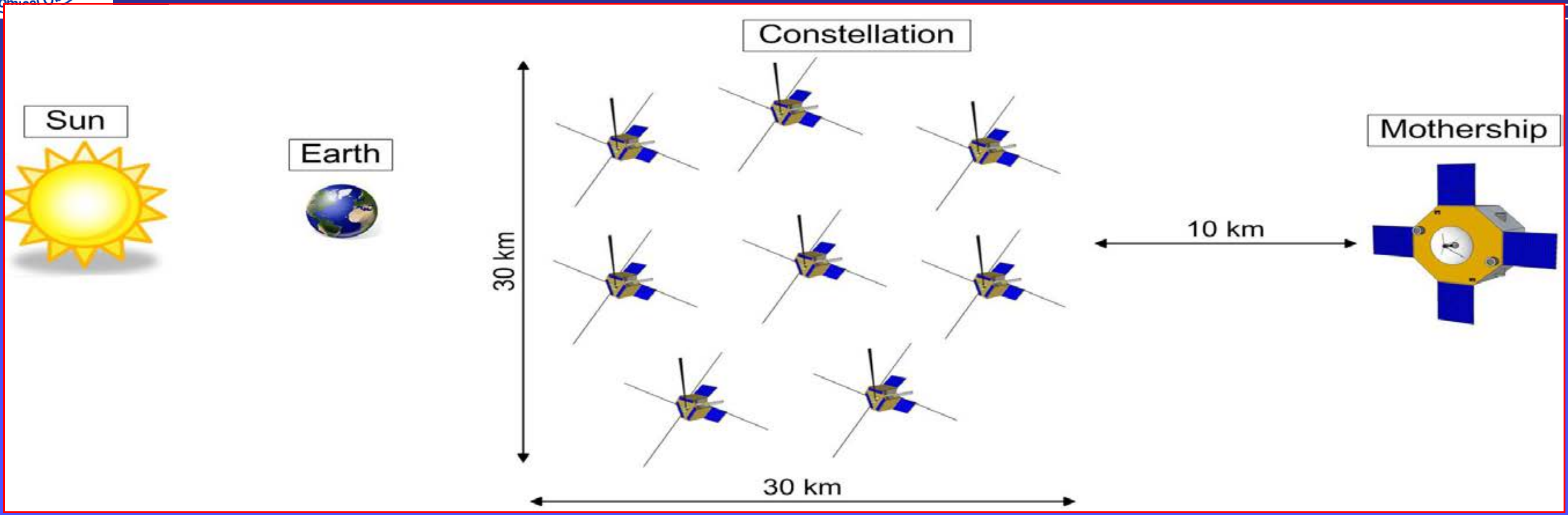
Low-Frequency Radio in Space

SULFRO – Space-Based Ultra Low Frequency Radio Observatory

Willem A. Baan – SHAO -CAS
Xiaoyu Hong – SHAO -CAS
Tao An – SHAO -CAS

On behalf of a large (worldwide) collaboration

Mission Profile – SULFRO Constellation Plan



- Mothership and 12 slowly drifting Daughters
- 'passive' formation flying
- 24/7 all-sky imaging interferometer => 4π all the time
- slowly drifting constellation – baseline projections & imaging quality
- frequency range 0.1 – 50 MHz
- Sun-Earth L2 Low-drift Lissajous (halo) orbit
- avoid RFI and ionospheric disturbances

Conclusions

24/7 omni-directional and targeted imaging in unexplored wavelength range

Multi-disciplinary science – solar, planetary, astronomy, cosmology

Large discovery space and prominent results

Low cost and weight using NanoSat & MicroSat platforms

Readily available technology with already high TRL values

The Time is Right for opening the last unexplored part of the EM spectrum

Already a collaborative project

Multi-country SURO (ESA-M 2011) & SURO-LC (ESA-S 2012) proposals
FIRST Explorer (2009 ESA pre-study)
DARIS concept (2010 ESA, pre-phase A study)
OLFAR concept (2013 STW, The Netherlands)

CN - Shanghai Astronomical Observatory (SHAO, CAS)
National Astronomical Observatory (NAOC, CAS)
Jiaotong Univ (Shanghai)
Shanghai Engineering Center for Micro-Satellites (CAS)
Institute for Satellite Engineering (#509, Shanghai)

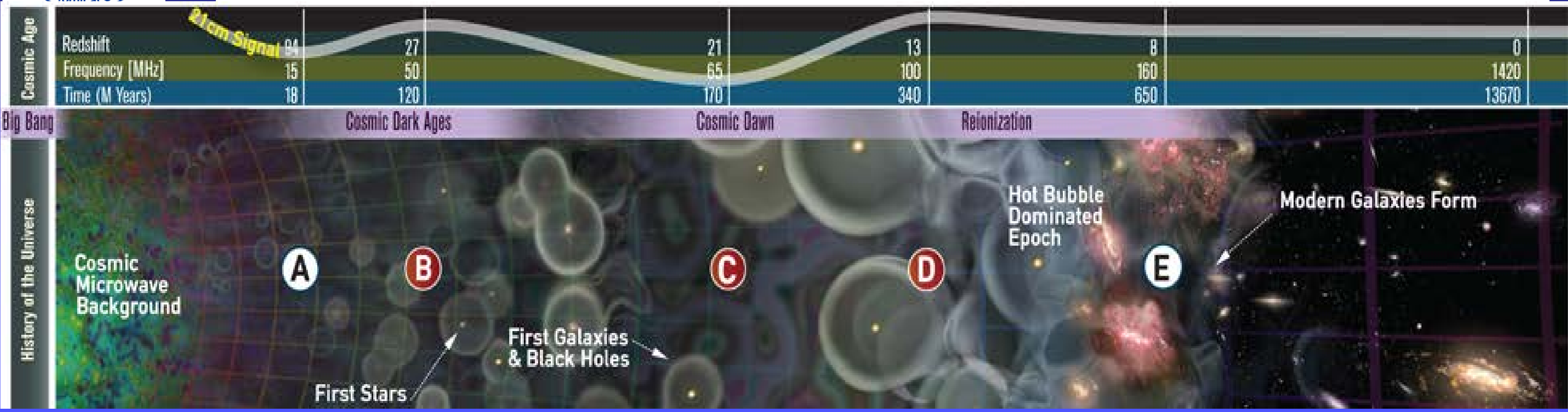
NL - ASTRON, Univ Twente, Univ Delft, ISIS Satellite Systems
SE - Inst. for Space Research, Linneaus Univ, Adarate AB
UK - Psi-tran, Space Enterprise Partnerships, Surrey Satellites (SSTL), Nat Physics Lab (NPL), Univ of Surrey
FR - Observatory of Paris

Supporting Scientists: 100+ from 17 countries & space agencies

Ultra-Low Frequency Science

- SULFRO addresses important Cosmic Vision questions
- Multi-disciplinary science objectives
  - 1st Dark Ages using highly **red-shifted 21cm emission**
  - 1st Birth and death of **extragalactic sources** through time
  - 2nd Constituents of the **interstellar medium** in the Galaxy
  - 2nd Monitoring/imaging of **planetary radio emissions**
  - **2nd Heliophysics** imaging of solar flares, CMEs, space weather
- Complement other space missions with high-freq radio imaging
- Complement ground-based facilities (21CMA, FAST, LOFAR, SKA)
- Completely unexplored frequency window => unforeseen discoveries

Dark Ages and Epoch of Reionization



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

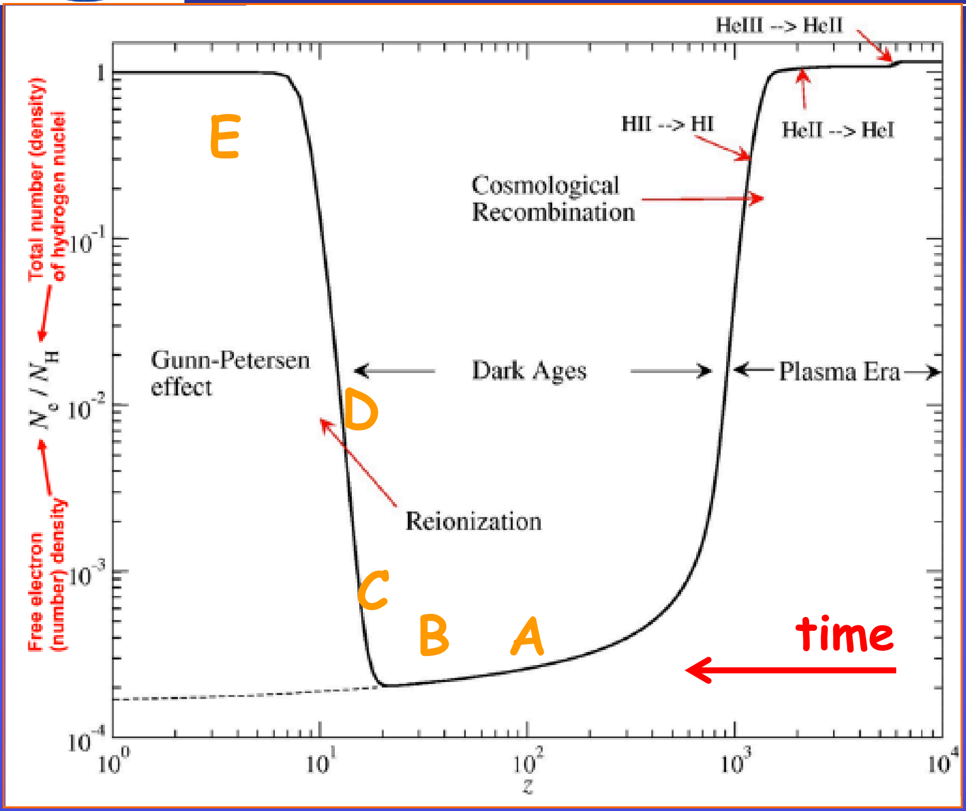
Stage B: Ignition of Star Formation - z = 30, the CMB photons and UV photons from first generations of stars absorbed by cold HI

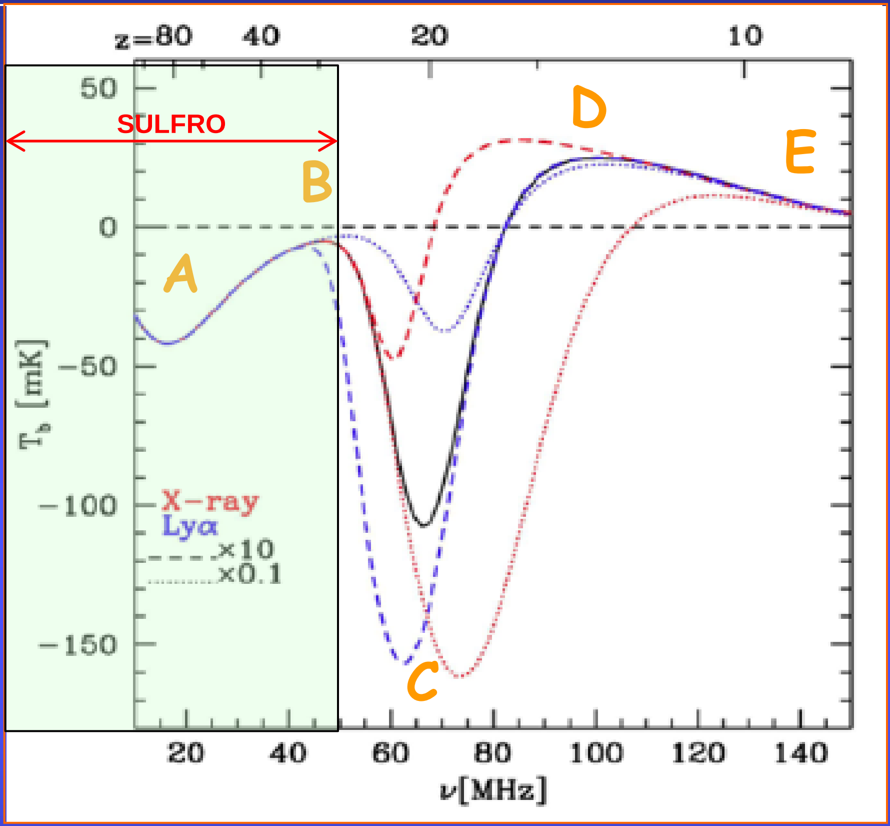
Stage C: The first Black Holes - z = 20, first Galaxies and accreting black holes heat HI bubbles in the IGM

Stage D: Hot Bubble Dominated – Around z = 13, stars and galaxies make hot ionized bubblesin 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





LF Radio = accurate tracker of the Dark Ages for z > 20

LF Radio completes the ground-based experiments

Life & Death of Radio Galaxies

Omni-directional Imaging of All Sky

3 arcmin at 10 MHz & 20 mJy sensitivity

1 arcmin at 30 MHz & 14 mJy sensitivity

=> Detect 2 million sources in 1 yr

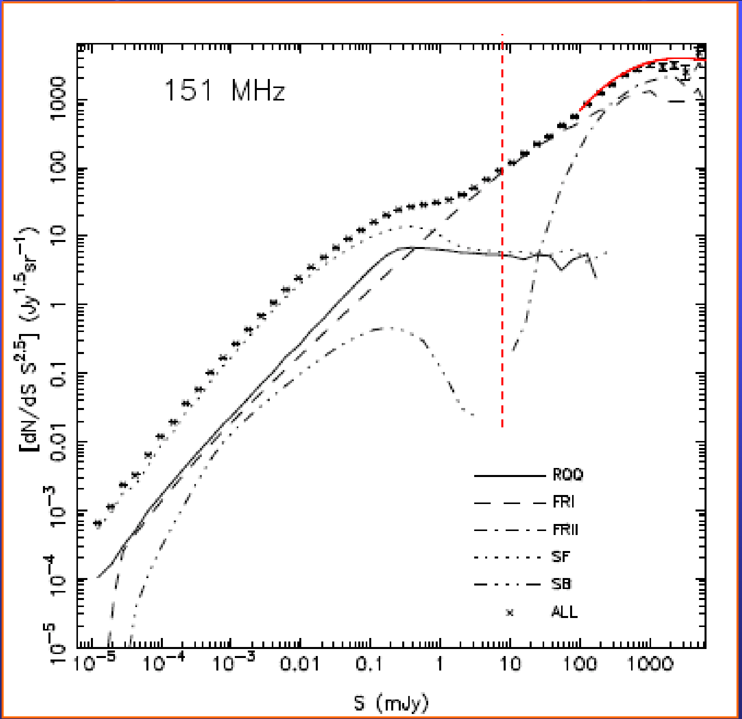
Source populations & evolution with time

Startup and death of sources

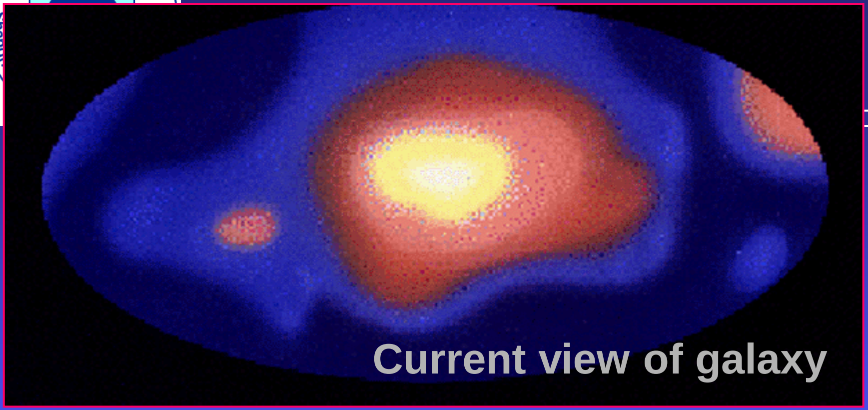
Feedback of Active Nuclei

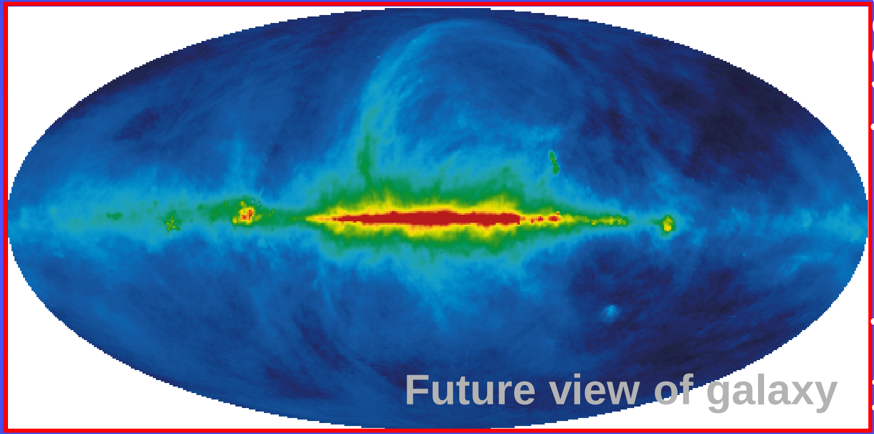
Relics of radio sources & cool holes in clusters (10^5 sources)

Transient phenomena

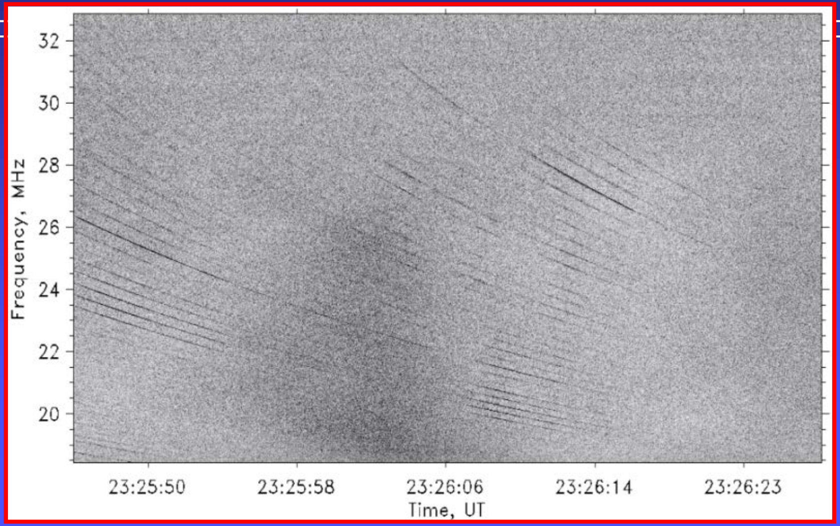


2nd Galactic Studies





Haslam et al 1982



Terrestrial detection of pulsar at low freq (Kharkov)

Galactic Interstellar Medium (Clumpy-Warm-Ionized)

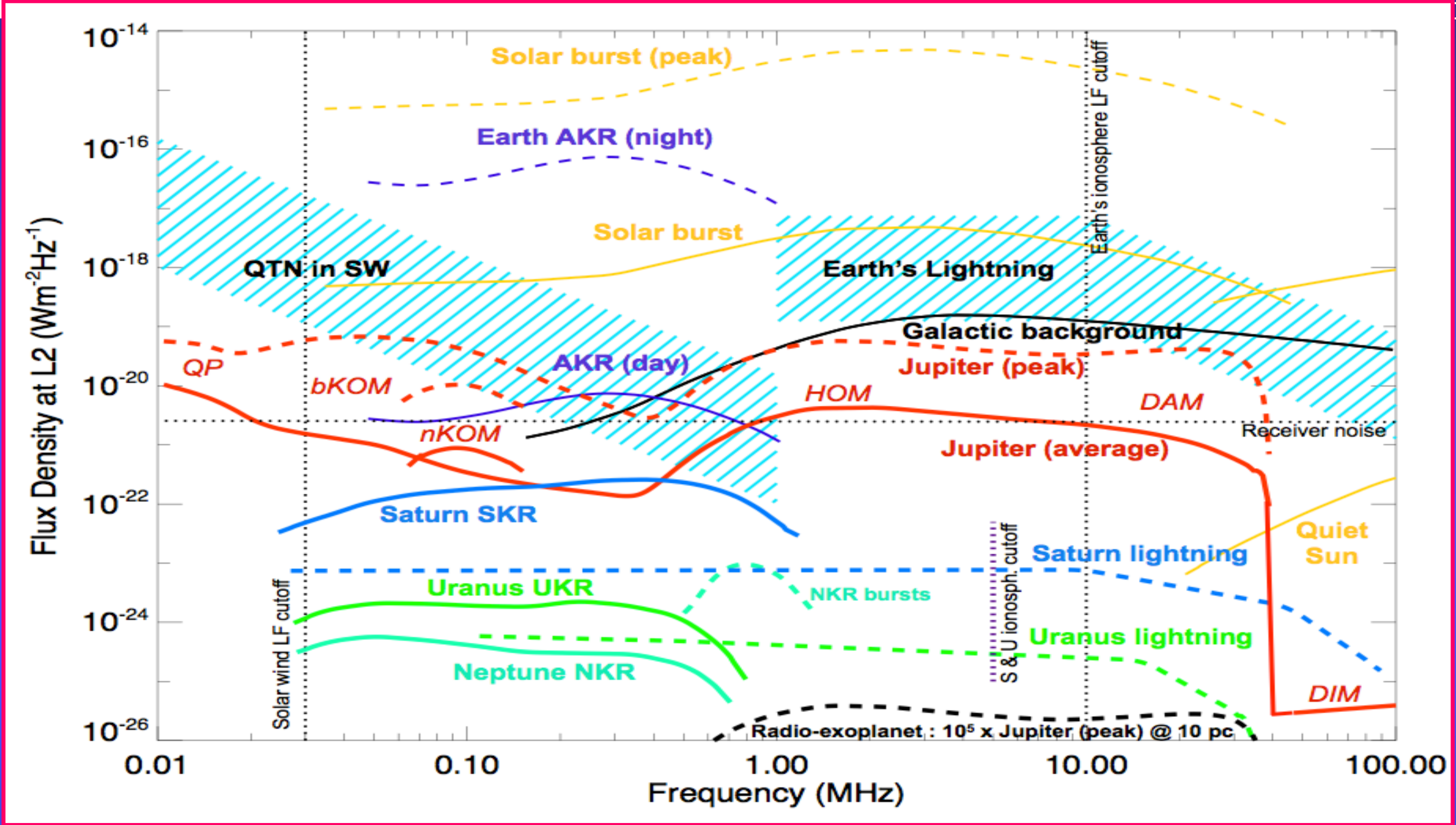
3D Origin of Cosmic Rays – nearby HII & SNR sources

Radio Transients

Strong pulsars – low frequency properties & spectral turnovers

Radio Recombination Lines - also foreground for EOR

2nd Planetary Studies & Space Weather



Radio Planets & Space weather – Earth, Jupiter, Saturn & Uranus

Complex spectral structures in 0.1 – 20 MHz range

Search for Jupiter-like Exoplanets in known systems

Imaging requires long interferometric baselines

2nd HelioPhysics & CMEs

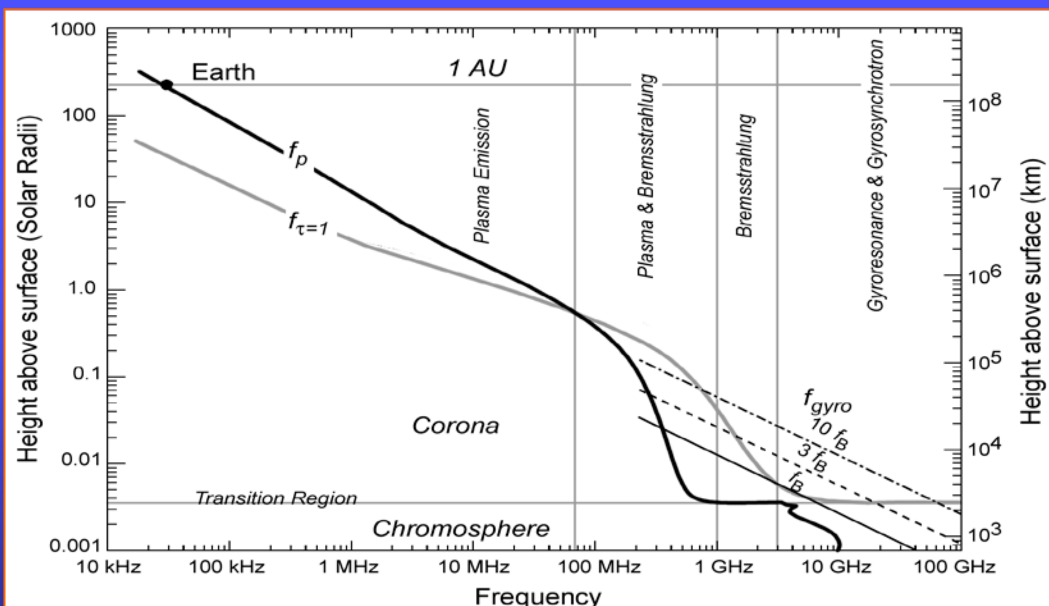
Imaging Solar activity at lower freq (3′ at 10 MHz)

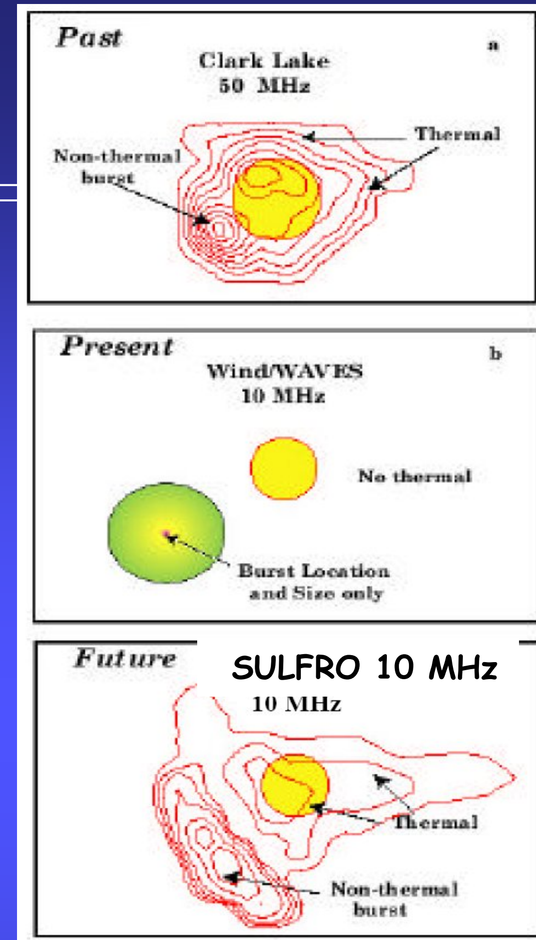
Imaging Type II (slow) & III (rapid) bursts

Imaging & tracking of CMEs beyond Earth distance

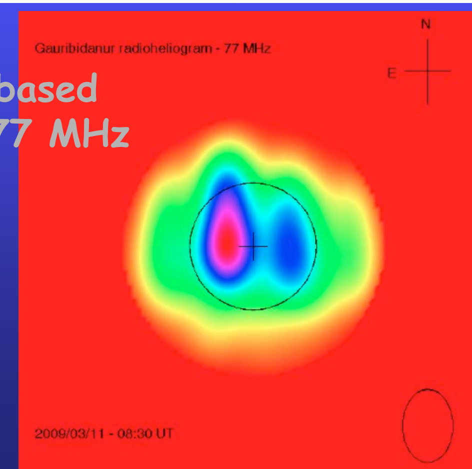
Coupling of different solar processes

Complementary to ground based arrays





Ground-based image at 77 MHz



Mission Profile (1) – launch concepts

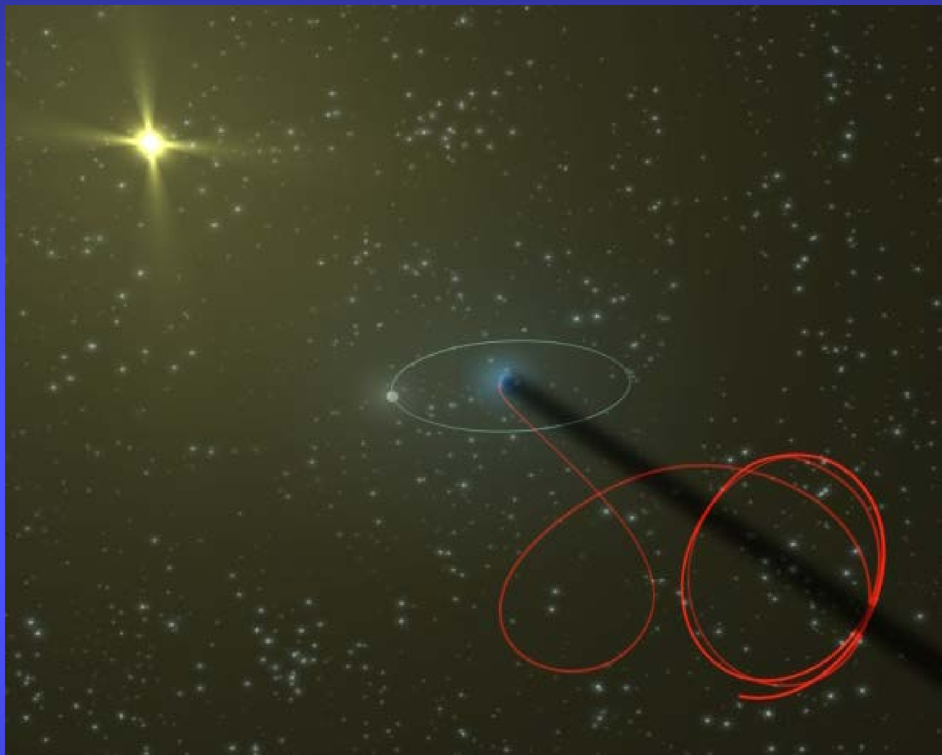
- Long March D2 or Vega-class launch
- Mothership => adapted Minisat (140 kg)
- 12 Daughters => stripped NanoSat (72 kg)

- Sun Earth L2 => quiet RFI environment
- Disturbance free deployment to 30 km swarm
- Loose formation flying – swarm control
- Radio interferometry with sparse array
- Operations for 2 years (extendable to 3)

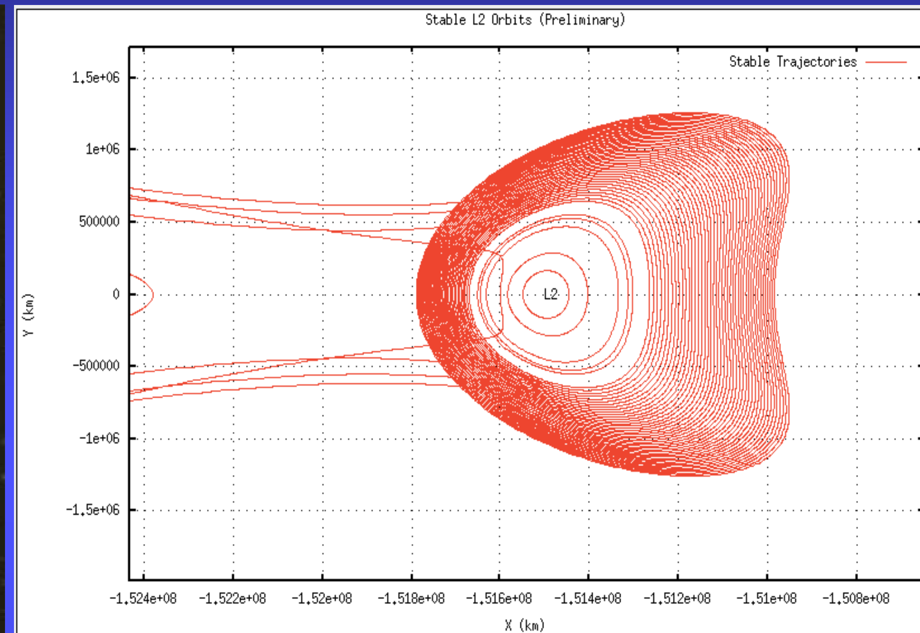
- High-speed ISL for wide-band observations
- Reduced data rate downlink (15Mbps-12m GRT)

Long March D2 (China)

Lissajous Orbit at Sun-Earth L2



Lissajous orbit around the second Sun-Earth Lagrange point (L2)

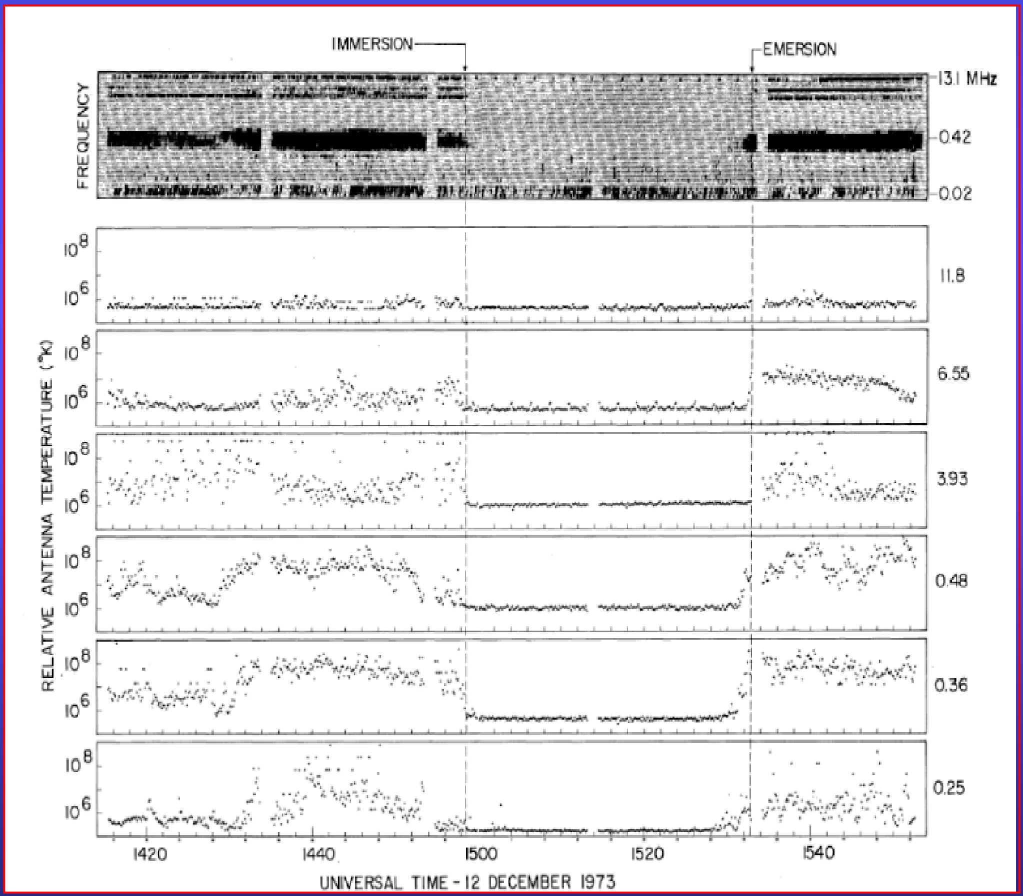


Distance 1.5 Mkm (0.01 AU)
reduced terrestrial RFI

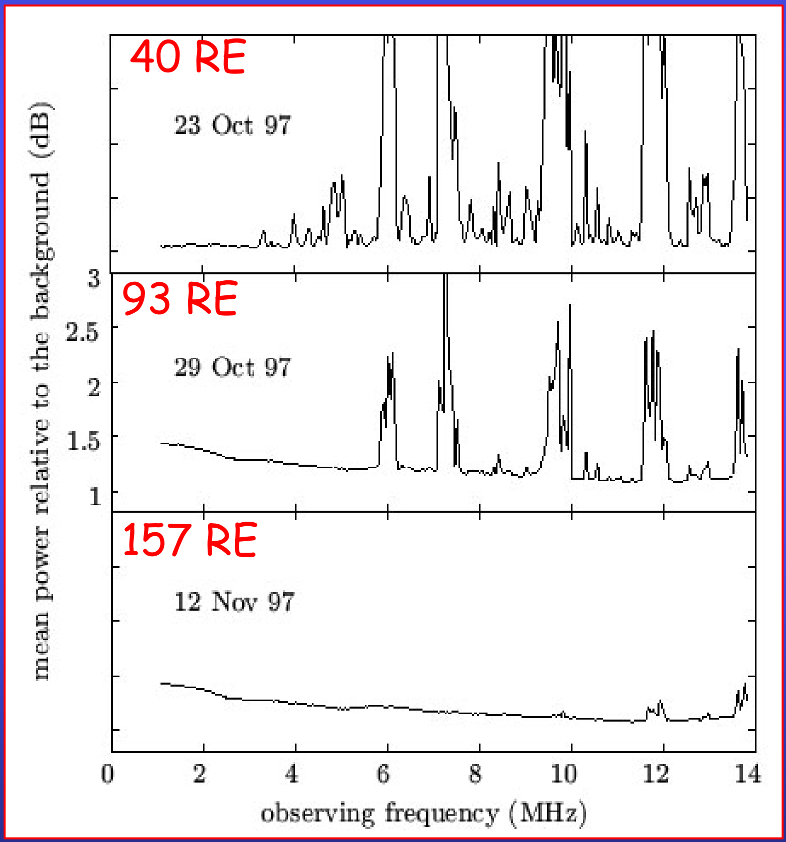
Mission Profile (1) - Hiding from RFI

SE L2 location at 1.5 Mkm = 235 RE

RAE B (1973), Lunar orbit, Kaiser 1975



WAVES instrument on Wind



G. Woan, ESA study SCI(97)2

Mission Profile (1) - Alternatives

Swarm of identical NanoSats

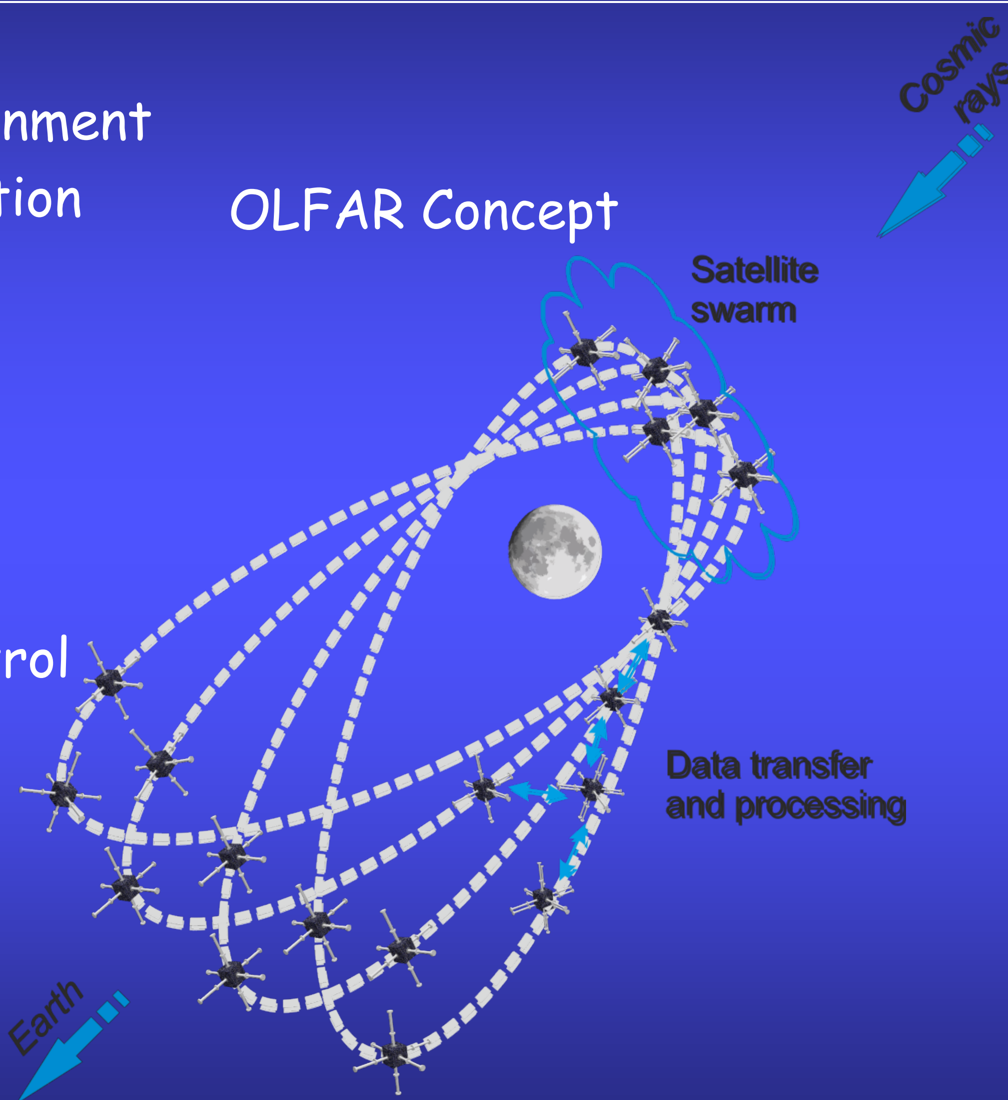
Lunar orbit => quiet RFI environment

High-speed ground communication

Operations for multiple years

Repeated insertions

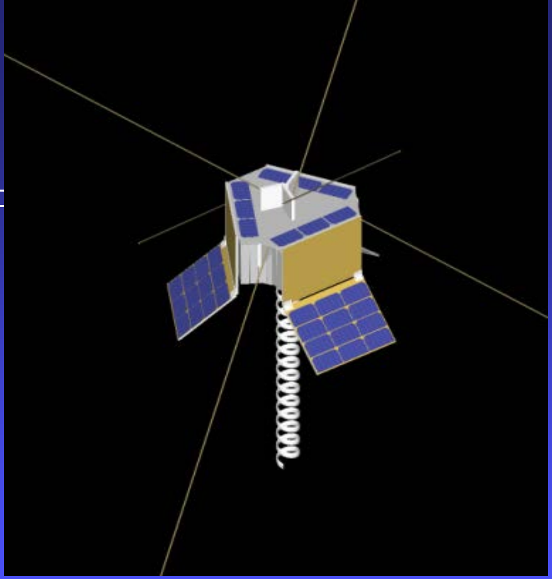
OLFAR Concept



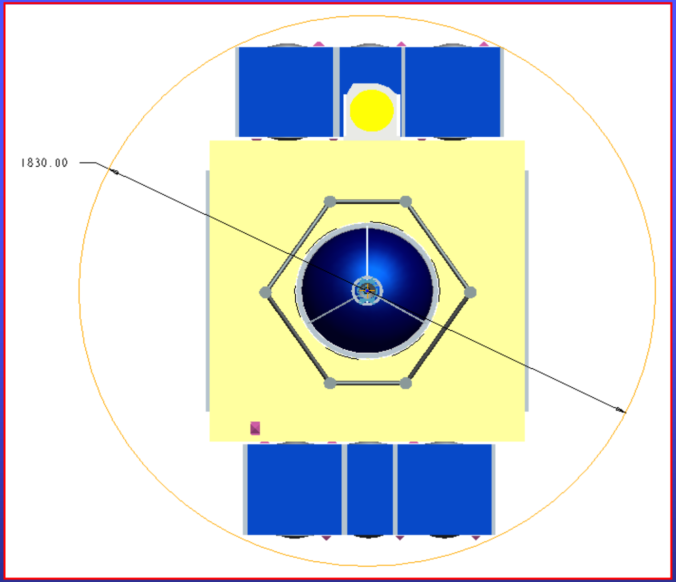
Disadvantages (?)

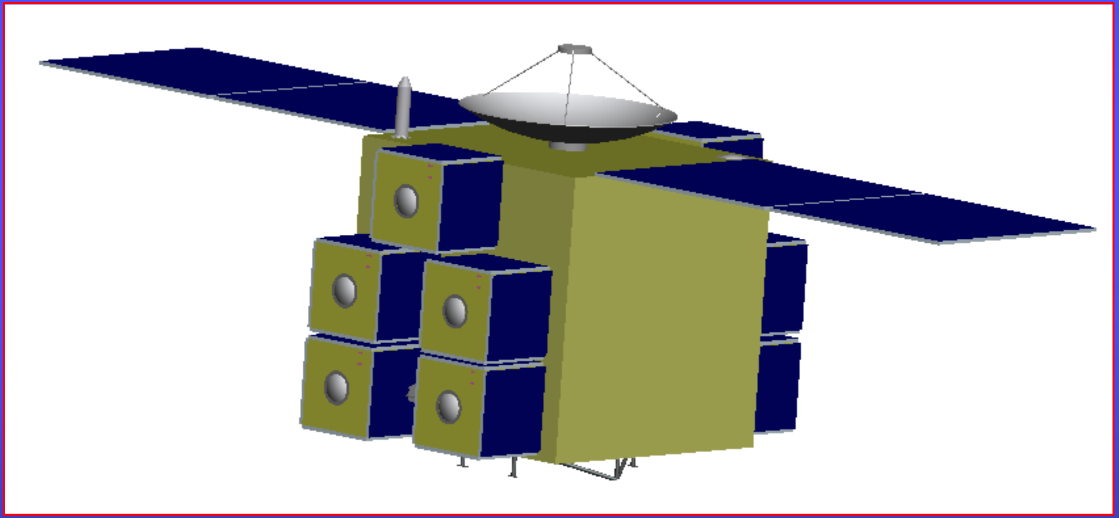
- most of orbit unused
- active swarm and orbit control
- precise in-orbit deployment

MP(2) - SULFRO Platforms



Stripped MiniSat and NanoSats
Solar Wind stabilization Daughters and Mother
Disturbance-free deployment
Thrusters for orbit corrections within group



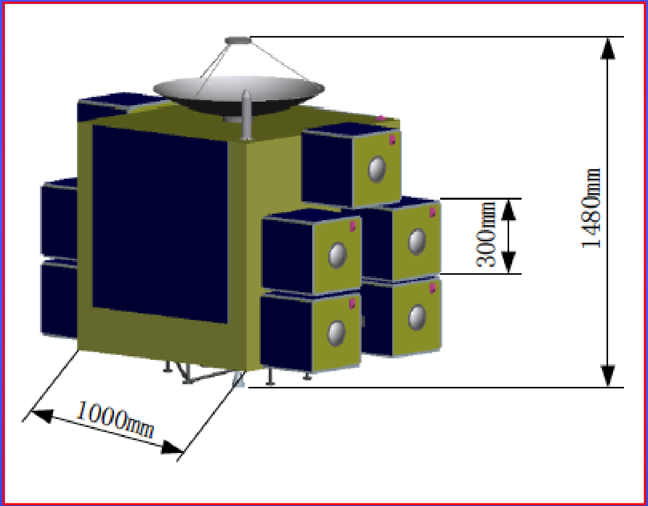


SULFRO - SAST100 concept (SHA Inst. Sat. Eng. 509)

Mission Profile (2) – Launch & release

- Precision maneuvering by Mothership using micro-propulsion
- Disturbance-free release using electro-magnetic containment

- Sun-pointing orientation – passive attitude control
- Active control at edge of spherical swarm & collision avoidance (lifetime < 1 m/s)
- Micro-propulsion systems and micro-momentum wheels
- Accurate knowledge of inter-satellite separations



- Release and loose formation flying and passive attitude control require further verification

Mission Profile (3) – Control & Comm

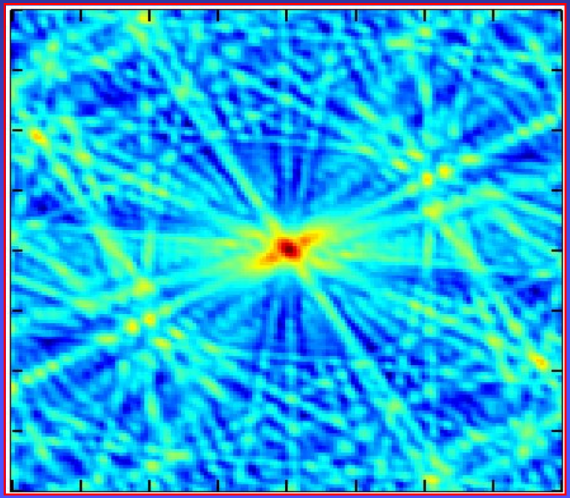
- Attitude and Orbit Control System (AOCS)
  - Sensors & control - micro-propulsion + mini-reaction wheels
  - Solar Wind (sailing) stabilization for Daughters & Mothership
- Data Links & Telemetry (TT&C)
  - TDM & CDM Inter-satellite links for data (60+ Mbps) (TRL)
  - Clock distribution and linking ALL for ranging and position data
  - (Multiple) Fixed X-band high-gain antenna (15 Mbps)
  - Three or more ground stations
- Ranging & Metrology & Swarm Control
  - Control & housekeeping using patch antennas (2.4GHz)
  - Multi-lateration metrology in 'timesteps' (30 x improvement)
  - Position & collision avoidance processor
  - Closed form solution (clock offsets & drifts, relative distance, and velocity) for 3D relative locations single reference clock

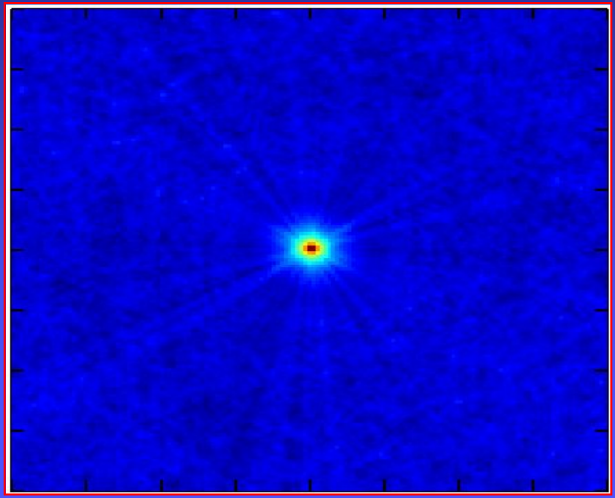
M Profile (4) – Science payload

- Daughter/Mothership On-Board Data Handling (OBDH)
- NanoSat payload of three orthogonal dipoles (0.1 – 50+ MHz)
- On-board processing of 3-10 MHz BW
- RFI Mitigation – burst detection
- 12 independent Inter-satellite links (ISL) with 60 Mbps
- Central or distributed proc => correlation of streaming data
  => download visibilities & spectral data
- Stringent EMC requirements for all components

- Science Observing Modes
- All-sky Imaging
- Rapid Burst Monitoring (reduce bandwidth & increased sampling)
- Targeted Burst Monitoring (beamforming & increased sampling
- Wide Band spectroscopy (running continuous – integrated spectra)

Omni-Directional Imaging w Sparse Arrays





PSF point spread function on sky improves with time

for 10 snapshots & many snapshots

FX Correlation: Fourier transform – cross correlation

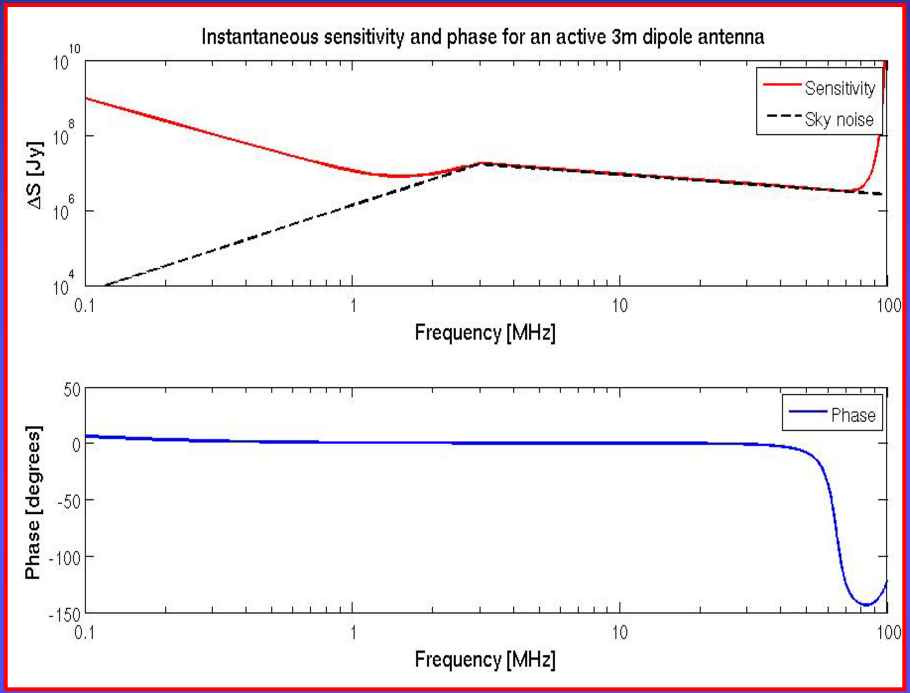
– Omni-directional (patch) imaging using narrow-band correlation

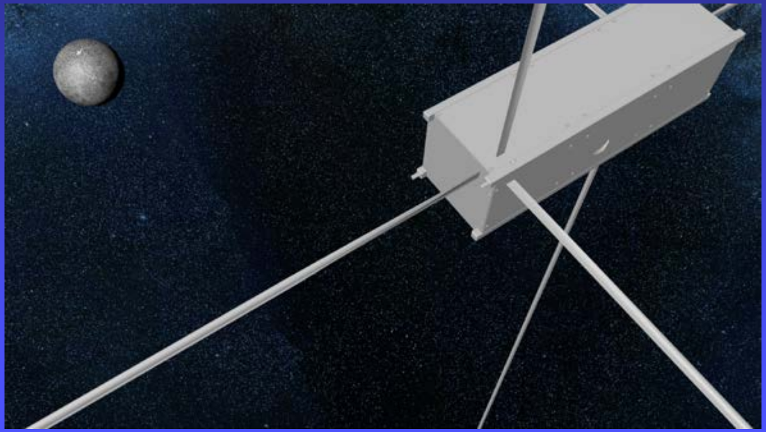
- Source brightness distribution with all Stokes information

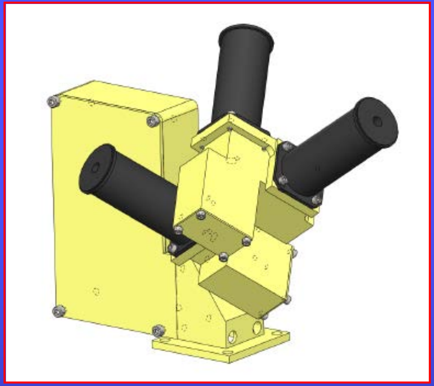
Sparse antenna array with 12 stations and 66 baselines

Drifting antenna configuration improves imaging PSF

MP(4) - Dipole Antenna Performance



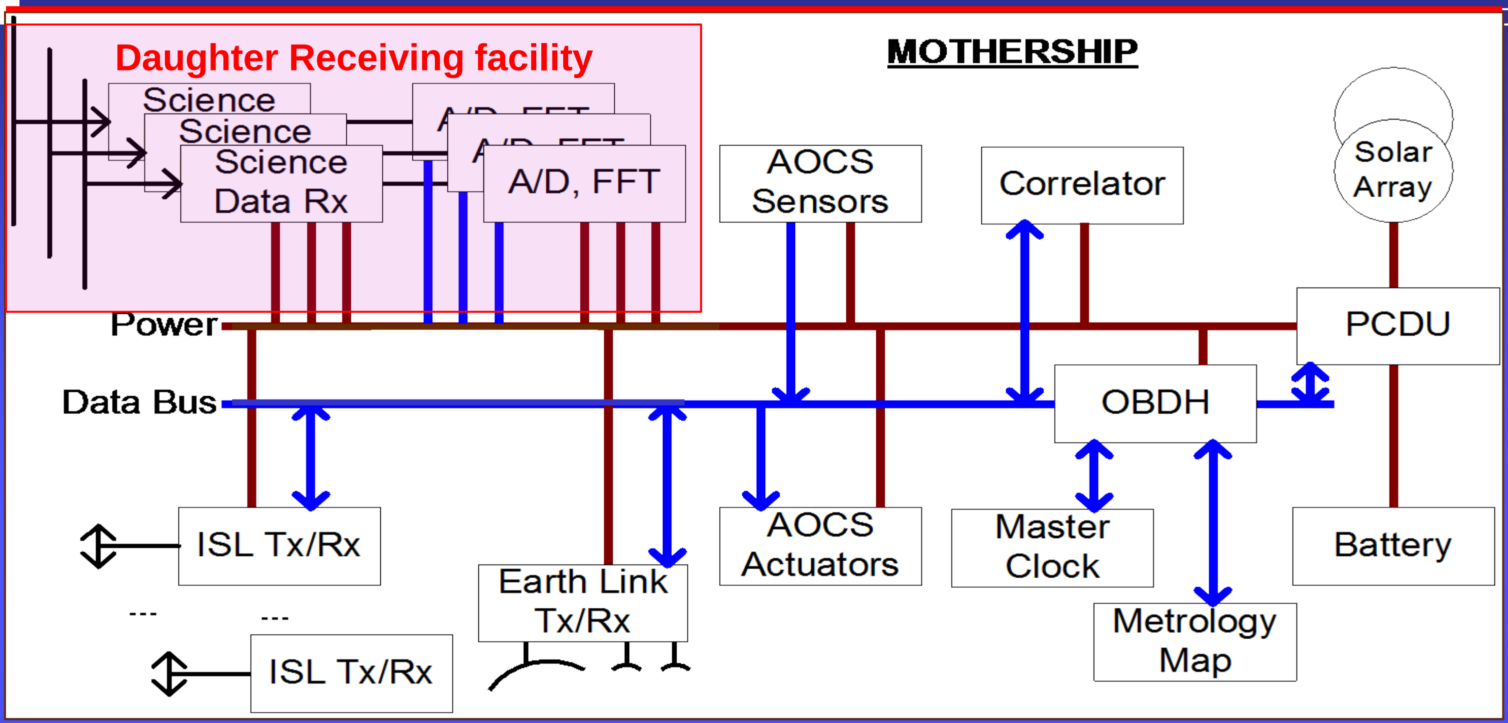




SRC – PAS Poland

- Three orthogonal dipole antennas (2 x 1.5 m)
- System Noise dominated by Galactic background
- Blanking/Nulling - Terrestrial RFI - mitigation
- Proven deployment mechanism (has never failed)
- Receiver design to be used for Juice Mission (IRFU)

MP(4) - Mothership Function Payload



ISL data input from daughters (60 Mbps)

Time keeping for constellation

FPGA science data processing – cross- and auto-Correlation

Earth Link Tx/Rx data and command communication (X-band)

Metrology & ranging & control system

Project Costs

Preliminary Estimates

Payload	40	M RMB	(5 M€)
Daughter hardware (12)	70.7	M RMB	(8.7 M€)
Mothership hardware	190.5	M RMB	(23.8 M€)
Launch CZ-2D	80	M RMB	(10 M€)
Management & operations	20	M RMB	(2.5 M€)
Margins	60	M RMB	(7.5 M€)
Total	461	M RMB	(57.6 M€)

Our Cost picture => Hardware and Launch in China
=> Payload development in Europe
=> High TRL technology readily available

Timescales => Shorter than guidance timeline

‘When a plan comes together’

Using small satellite technology – increase number of stations
Using innovative metrology / sensing techniques
Using existing NanoSat / MicroSat platform technology
Hardened FPGAs for Daughters and Mother processing
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
Disturbance-free release mechanism
Solar wind (sailing) stabilization of stations

Putting existing know-how/knowledge together in a new/better way

谢谢你