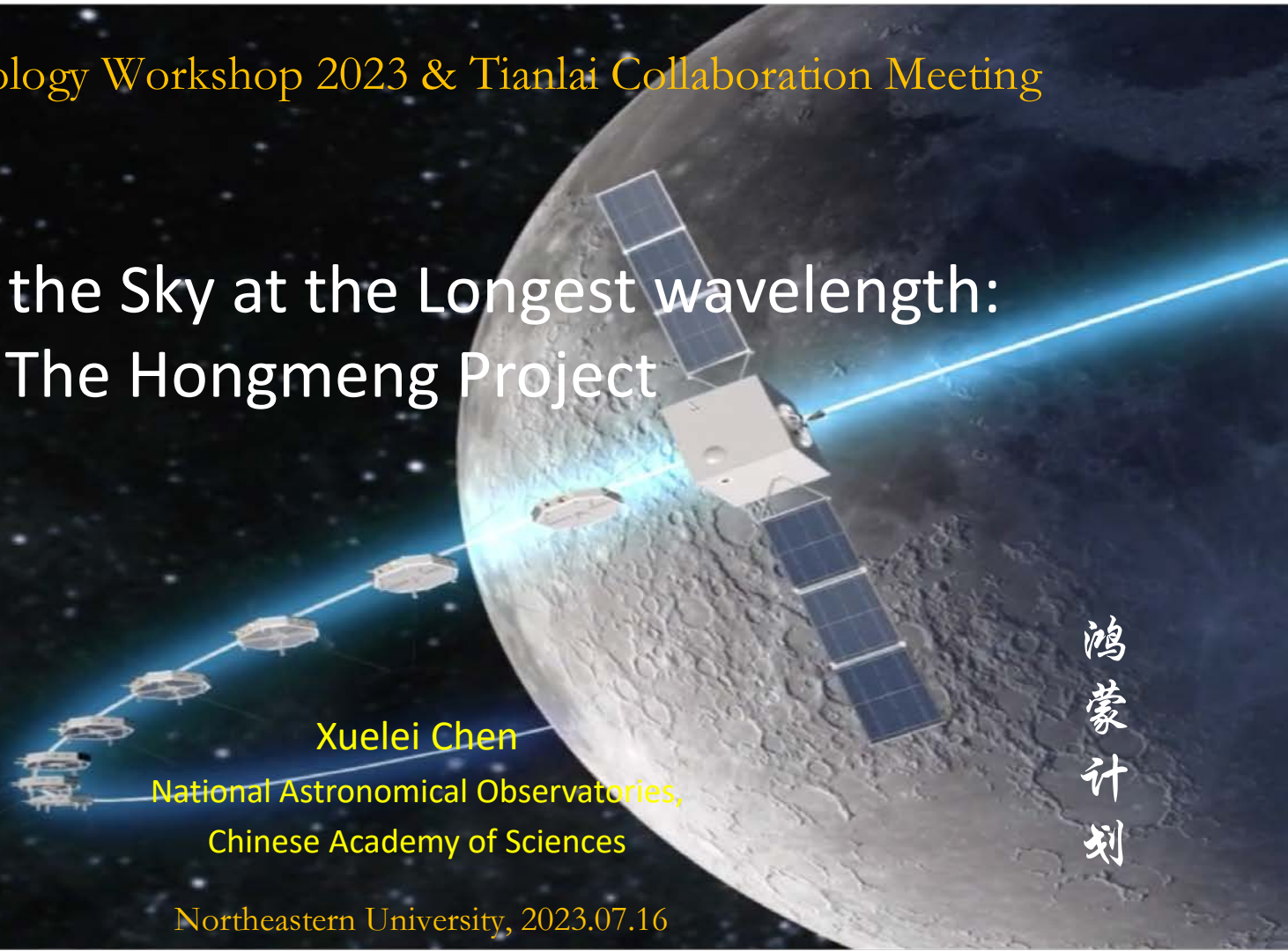
21cm Cosmology Workshop 2023 & Tianlai Collaboration Meeting

Discovering the Sky at the Longest wavelength: The Hongmeng Project



鸿蒙计划

Xuelei Chen
National Astronomical Observatories,
Chinese Academy of Sciences

Northeastern University, 2023.07.16

The DSL Chinese team

NSSC:


Jingye Yan


Li Deng


Lin Wu


Li Zhou

NAOC:


Yidong Xu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Yanping Cong

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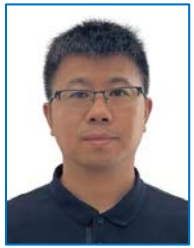

Xiaofeng Zhang


Xiaocheng Zhu


Zhongguang Yang

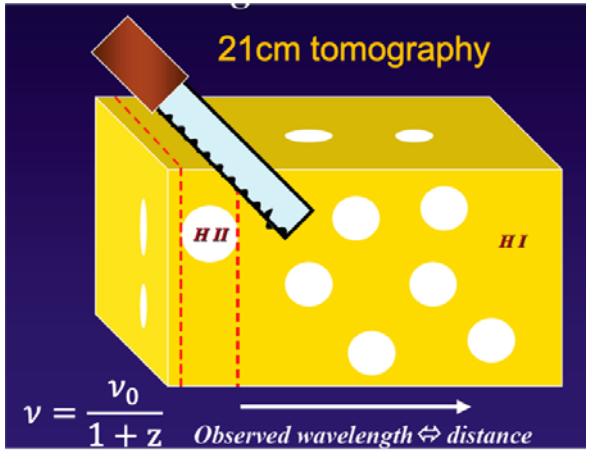

Yamin Wang

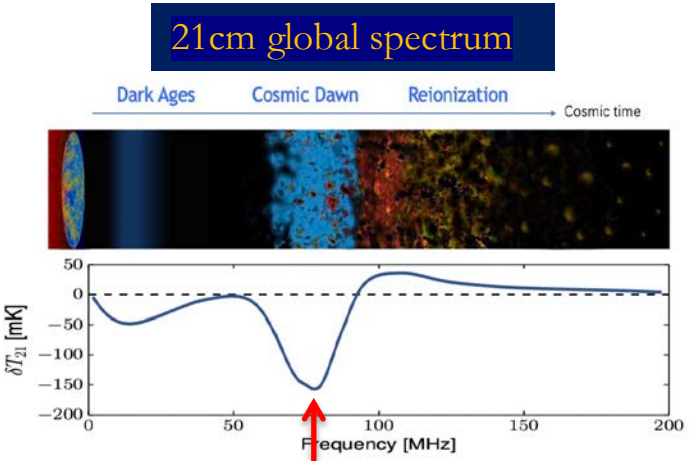

Jiangjiang Huang


Liu Liu


Tiantong Li

The Light in the Dark Ages—21cm line





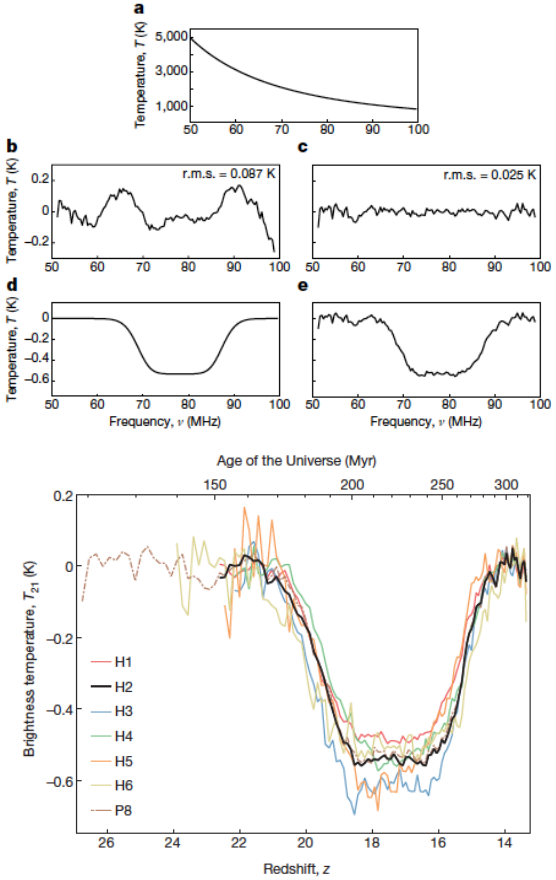
Cosmic Dawn signal
(XC& J. Miralda-Escude 2004, 2008)

large interferometer arrays

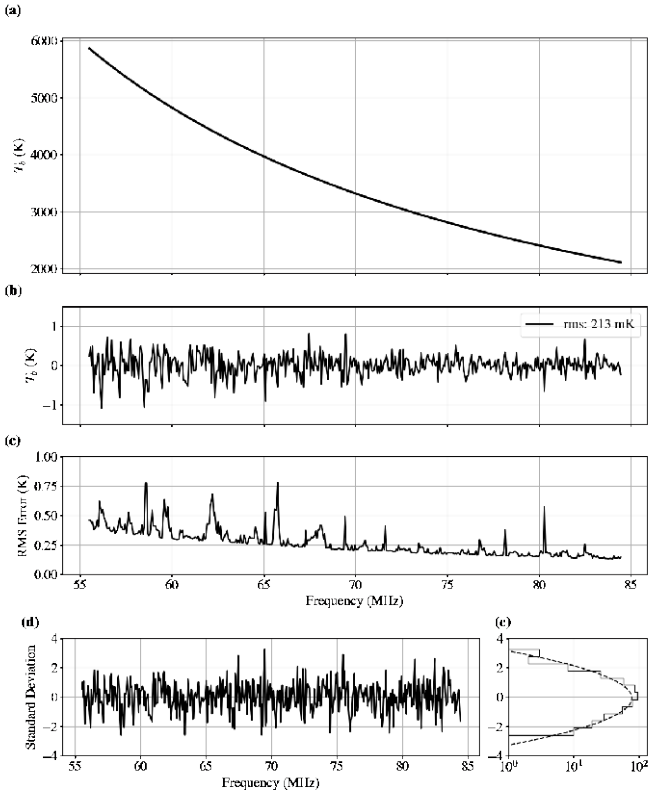
single antenna experiments

EDGES vs. SARAS Results

J. Bowman et al. 2018

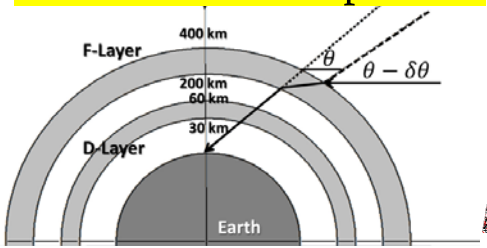


S. Singh et al. 2022



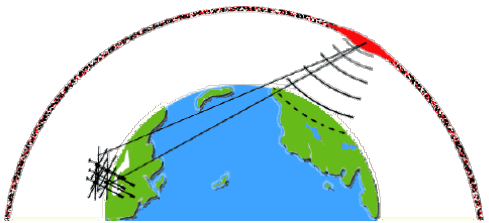
Difficulties of Ground Observation

Refraction and Absorption affects measurement precision

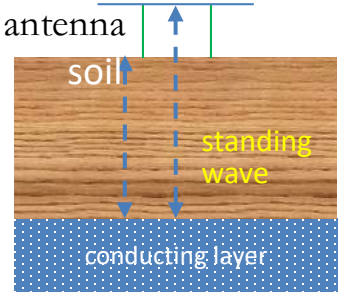


Vedantham & Koopermans (2015）, Shen et al. (2021)

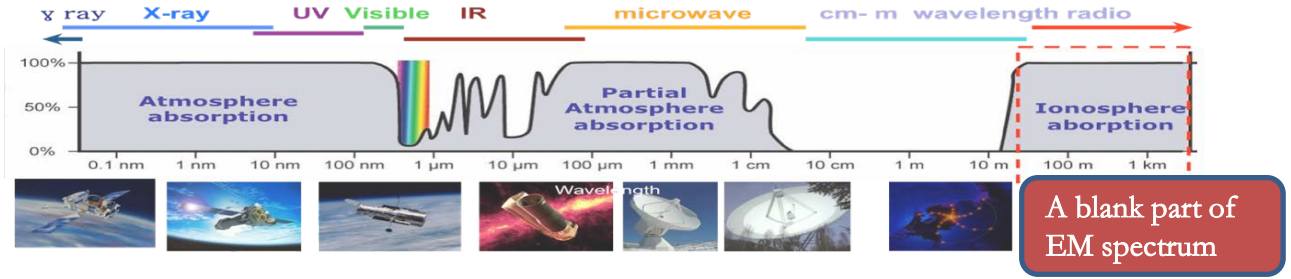
Reflection of RFI



Ground Reflection may generate false signal



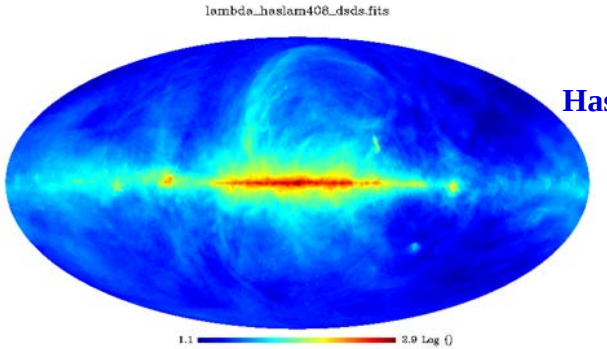
Bradley et al. (2019)



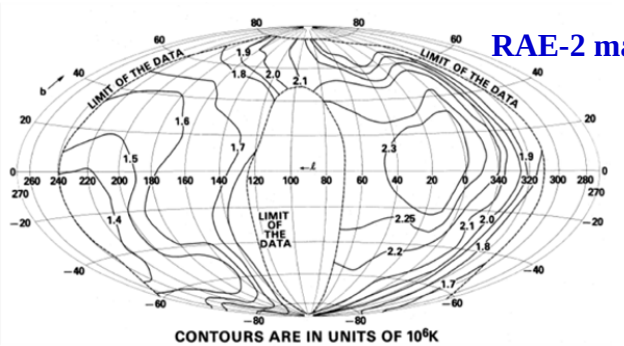
Space--avoid the ionosphere, RFI, ground reflection, and open up the last EM window

A blank part of the electromagnetic spectrum

Due to ionosphere absorption, the sky below 30MHz is still largely unknown

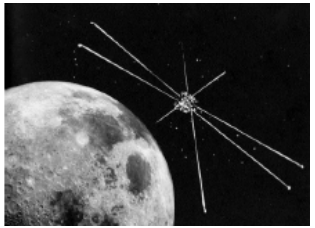


Haslam Map (408 MHz)

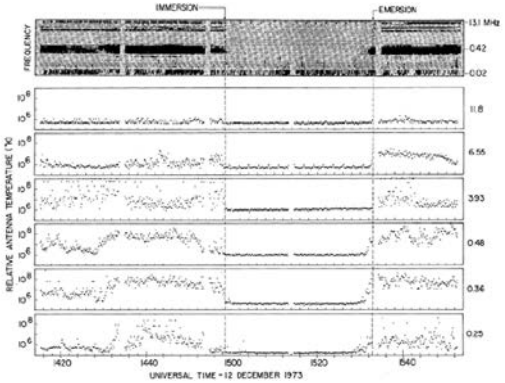


RAE-2 map (4.7 MHz)

RAE-2 satellite



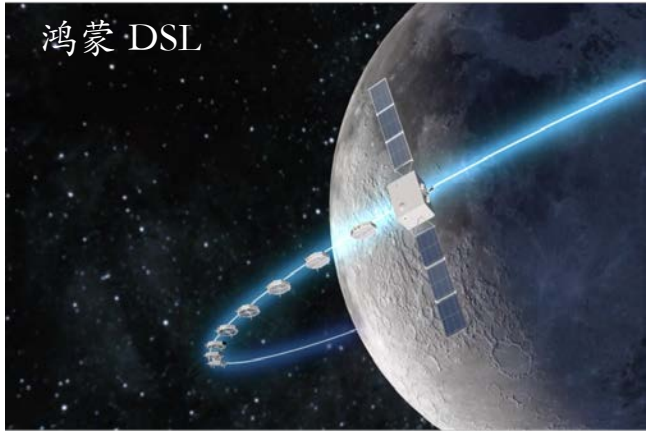
The Moon can block the radiation from Earth



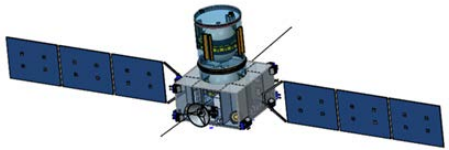
RAE-2 spectrum

DSL lunar orbit array （鸿蒙--Hongmeng)

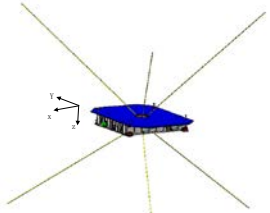
- lunar satellite: engineeringly simpler, no need for landing & deployment
- Lunar orbit period is about 2 hours, can use solar power
- Observe in the far side of the Moon, and transmit data back in the front side
- All flying on the same orbit, easy to maintain and communicate



DSL: 1 mother satellite (communication & data processing)
+ 8 daughter satellite (0.1-30 MHz interferometry & global spectrum)
+ 1 daughter satellite (30-120 MHz global spectrum)

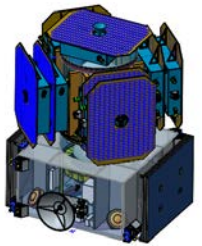


mother satellite



8 x low freq. daughter

1 x high freq. daughter

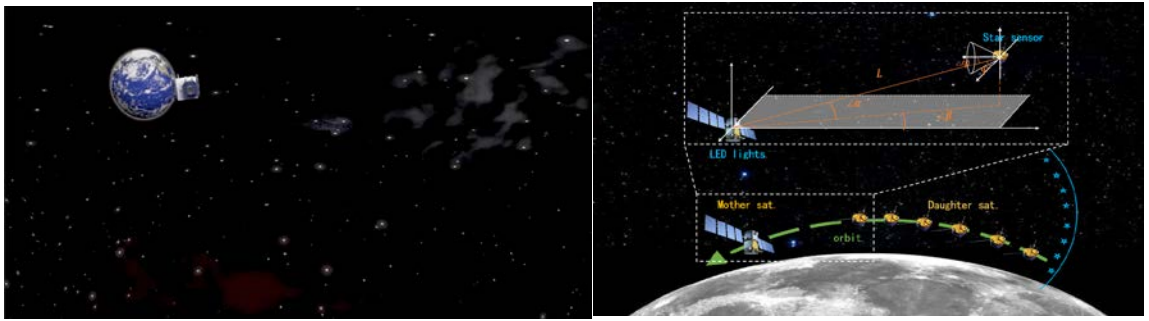


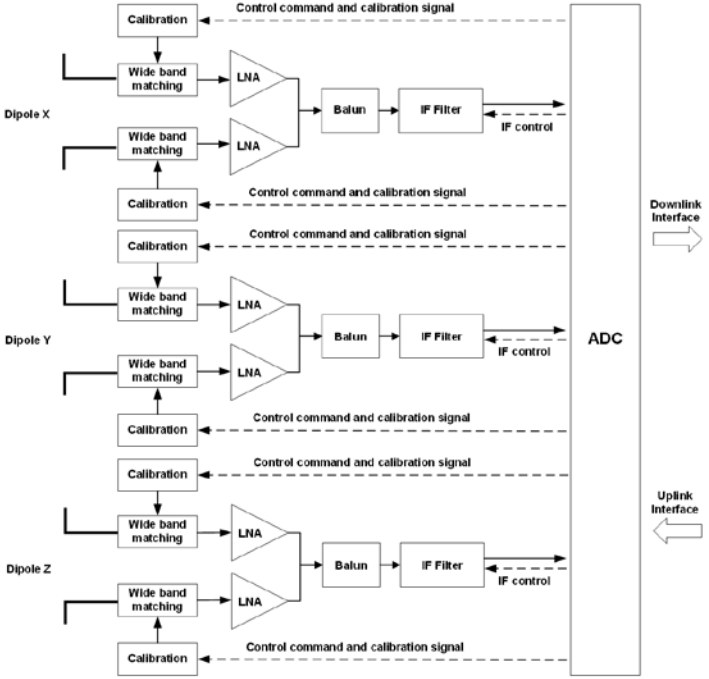
mother-daughter combo at launch

Interferometer Array Realization

A single rocket launch. No need for high precision adjustment of satellite positions, but do need high precision of relative position measurement

- **Synchronization, Distance Measurement (1 m), Data Communication: microwave link between mother and daughter satellites**
- **Angular position: mother satellite carrying blinking LED lamp, daughter satellites use star sensor to determine position (1m)**



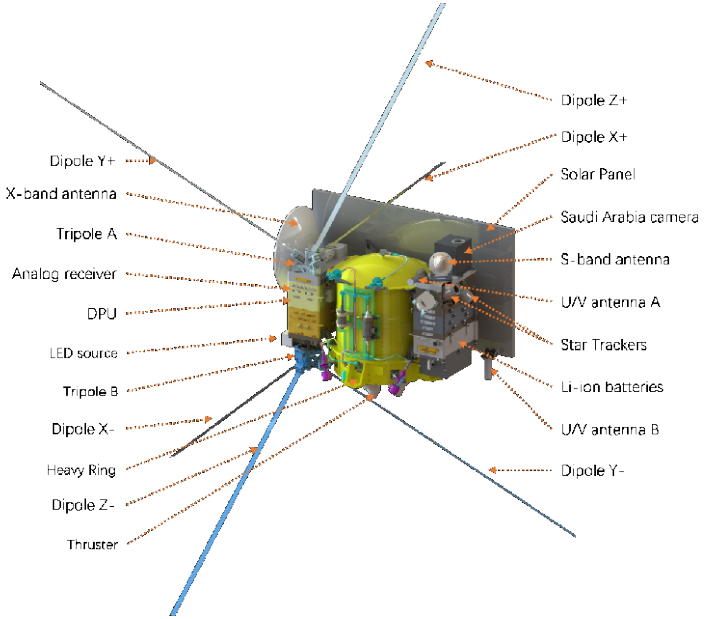


low frequency receiver

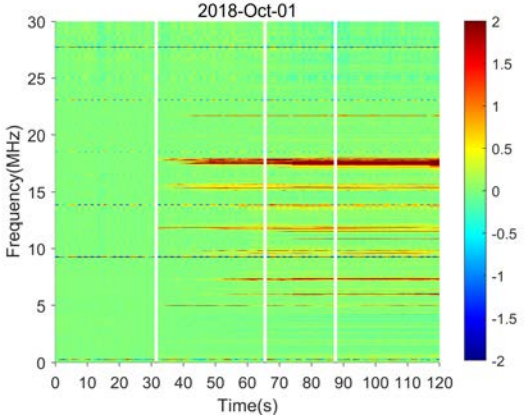
Chen et al., arxiv:2007.15794

Longjiang-2 pathfinder

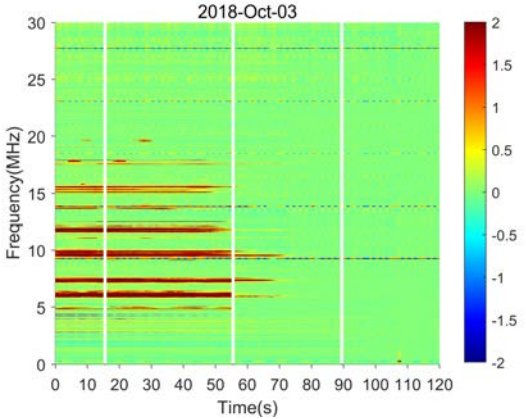
During the Chang’e-4 mission, the Longjiang satellite tested some of the key technologies for the DSL, and demonstrated the radio quietness at the lunar farside



J. Yan et al., Experimental Astronomy (arxiv:2212.09590)



(a) Egress on 2018 Oct. 01.

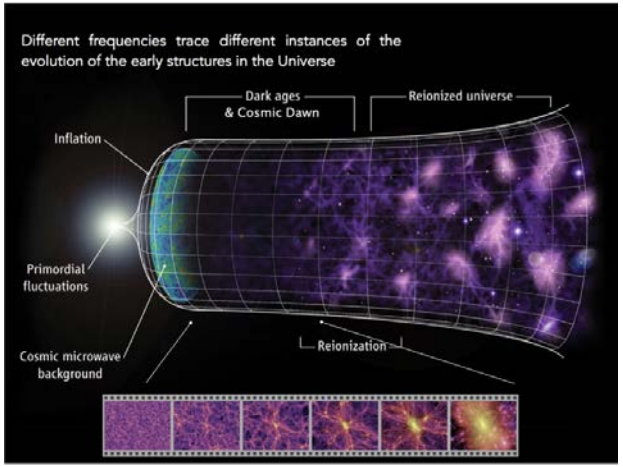


(b) Ingress on 2018 Oct. 03.

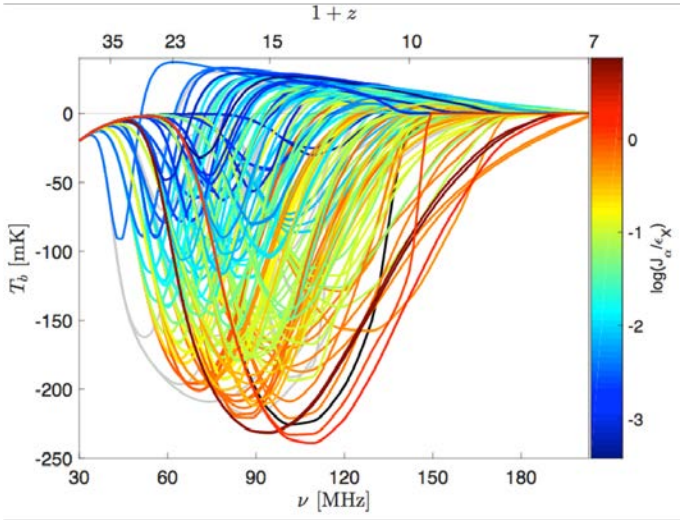
Science Case: Cosmic Dawn

- Measuring the primordial fluctuation would require large scale arrays (A_{eff} >10 km^2). The 21cm global specrtrum could be measured with single antenna and probe cosmic dawn and dark ages

- In a lunar orbit global spectrum, ionosphere & external RFI can all be avoided, and ground reflection will not producing features at the relevant delay space



Koopmans et al., arxiv:1908.04296

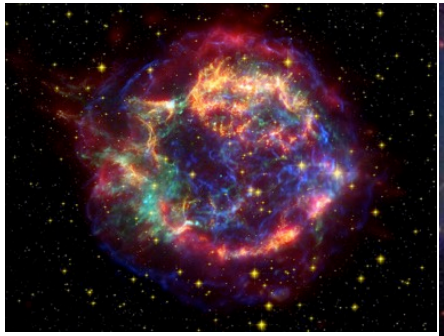


Cohen et al. (2018)

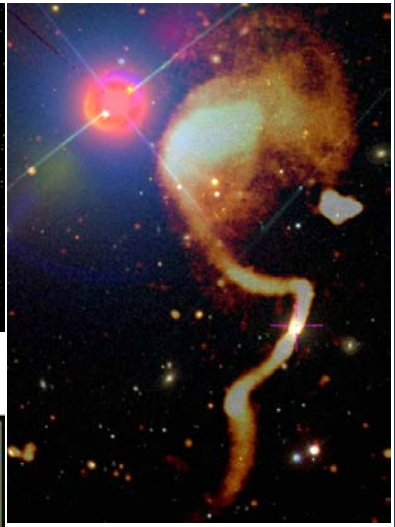
Science Case: Open Up A New Observational Window

What new objects will we see in the ultralong wavelength? What secret of the Nature will this observation reveal?

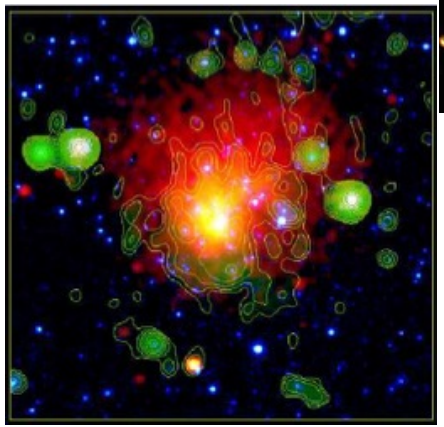
Potential of New Discoveries



supernova remnants



radio galaxies from the deep LOFAR image of Elais-N1 (Cyril Tasse)



cluster radio halo (Govoni et al 2015)

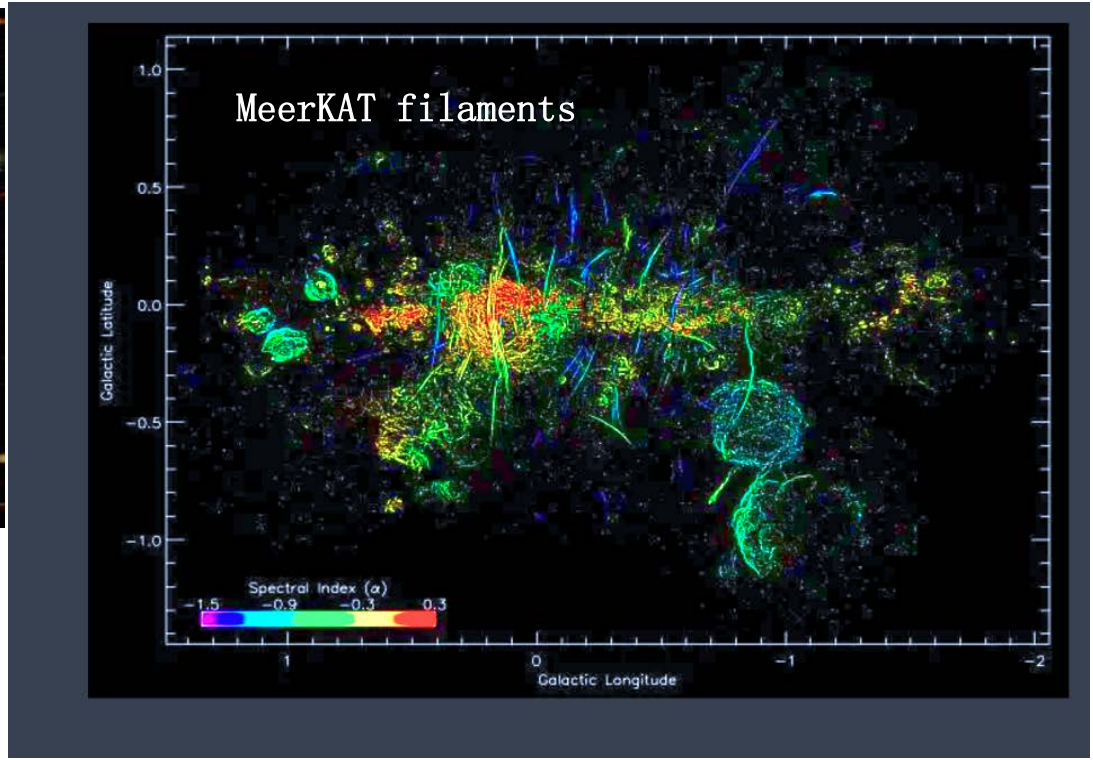
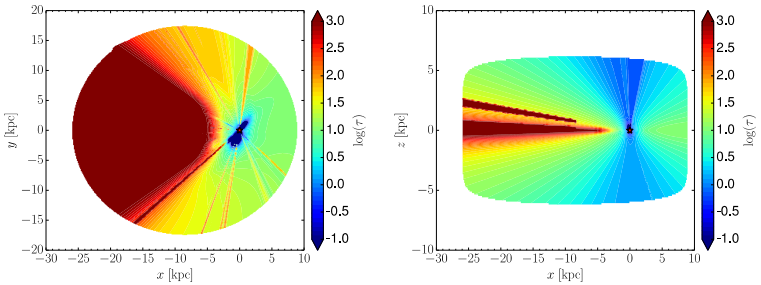


figure from *Astronomy* (Farhad Yusef-Zadeh/Northwestern University)

Example: Local Interstellar Medium

UltraLong wavelength Sky with Absorption Model (ULSA)



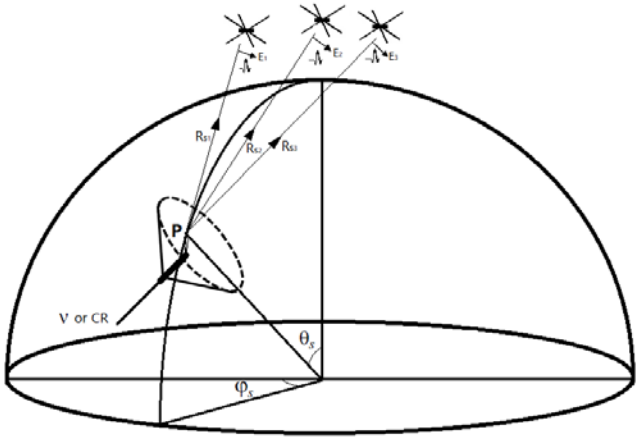
optical depth model

Y. Cong et al. 2021, ApJ, 914, 128

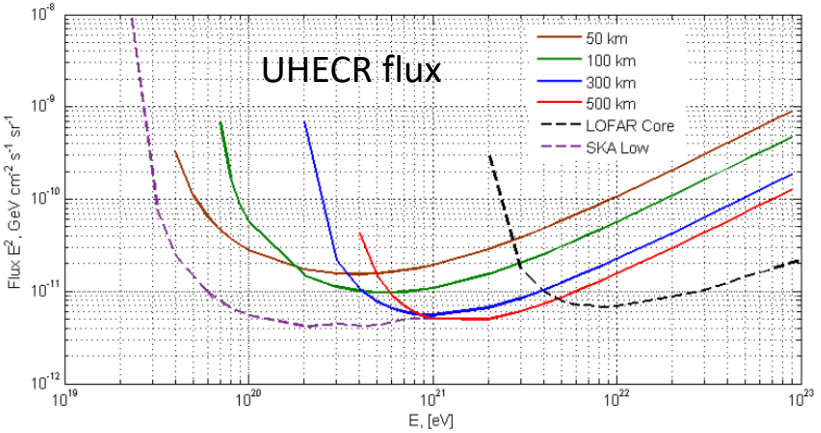
Reconstruction of the local ISM
(Y. Cong et al. 2022, ApJ 940, 180)

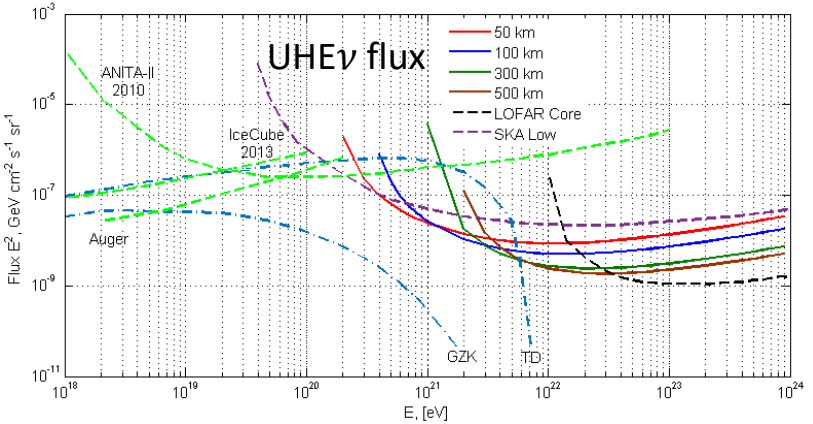
Moon as ultra-high energy cosmic ray/neutrino detector

The UHECR or UHEν generate particle shower, which produce a radio pulse through Askaryan effect.



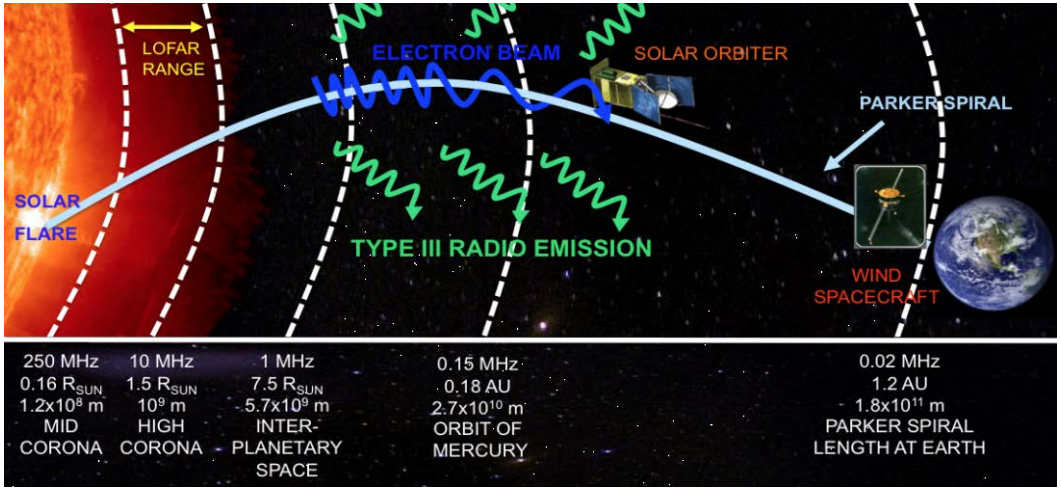
L. Chen et al. arxiv:2301. UHEν 11830



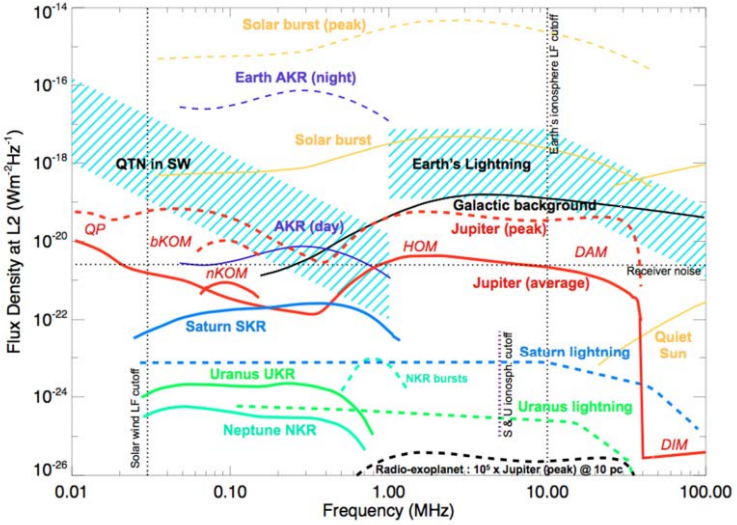


Science Case: Observing the Sun and Planets

- Lower frequency observation traces solar burst emission at larger distance from the Sun
- low frequency emission from giant planets reveal magnetospheric dynamics, solar wind - magnetosphere coupling, and electrodynamic coupling of the magnetosphere with planet's moons.



H.A.S. Reid (2015)



Mimoun et al.(2012)

Technology Challenges

- **Satellite formation fly in lunar orbit**

Automatic planning and control, cycle of array expanding and contracting (``breathing'')

- **Precision Measurement of Relative Positions, synchronization, and data communication**

The microwave based randing system and star-sensor systems have been tested. However, data rate is always a bottleneck

- **Electromagnetic interference (EMI) suppression and removal**

Design from scratch, careful schielding, use common oscillator to limit RFI to a small set of frequencies

- **High precision calibration**

Employ both internal and external calibrators

- **Imaging from orbit and with electrically short antenna**

new algorithm for interferometry from orbit

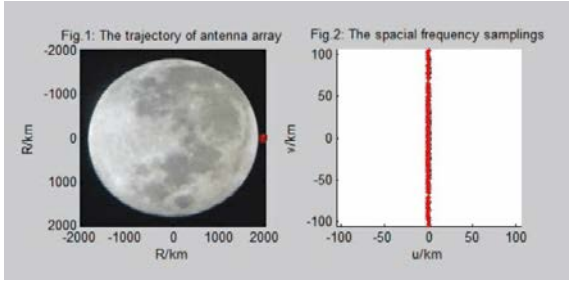
Synthesis Imaging with Lunar Orbit Array

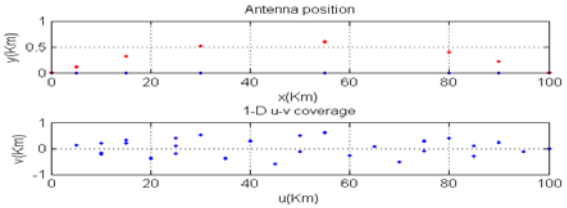
Interferometer Equation: $$V_{ij} = \int A_{ij}(\hat{k}) T(\hat{k})\ e^{-i\vec{k}\cdot\vec{r}_{ij}} d^2\hat{k},$$

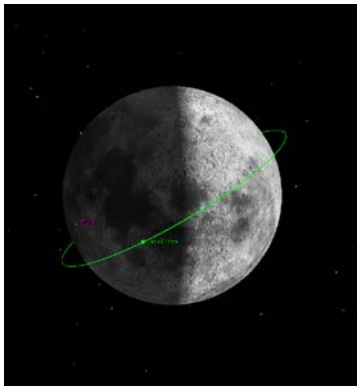
- **Conventional radio astronomy interferometer array: For nearly planar (2D) array, small field of view, small-w approximation:**

$$\frac{A(x,y)I(x,y)}{\sqrt{1-x^2-y^2}} = \int\int dudv V(u,v) e^{-i2\pi(ux+vy)} \qquad \text{(2D FFT)}$$

- **whole sky field of view**
- **mirror symmetry (can not distinguish two sides of planar baselines)—need 3D baselines**
- **Position-dependent blockage by moon**







Solution:invertion of linear mapping (Huang et al. 2018, AJ 156, 43)

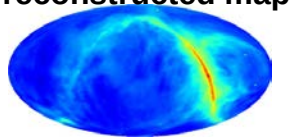
$$\mathbf{V} = \mathbf{B}\,\mathbf{I} + \mathbf{n} \qquad \hat{\mathbf{I}} = (\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{B})^{-1}\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{V}$$

Sensitivities

$$T_{\rm sys} = T_{\rm rcv} + T_{\rm sky}.$$

$$T_{\rm rcv} = 6.61 \times 10^3 \left(\frac{\lambda}{10\,{\rm m}}\right)^2 \left(\frac{2.5\,{\rm m}}{l_{\rm eff}}\right)^2 {\rm K}.$$

reconstructed map



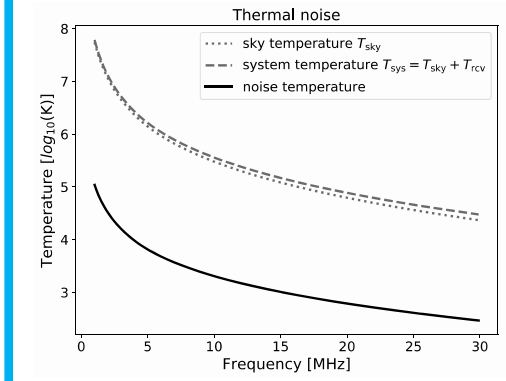
relative error

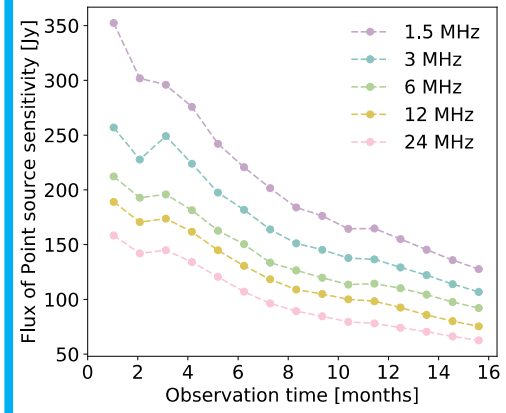
no noise

with noise

with noise & moon blocking

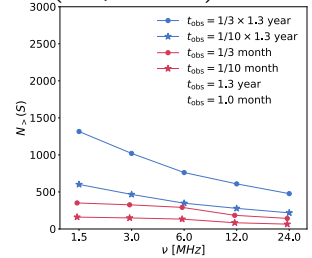
Y. Shi et al. 2021, MNRAS 510, 3046



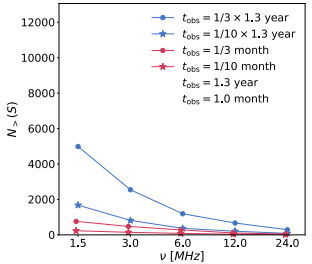


5 **σ** limit

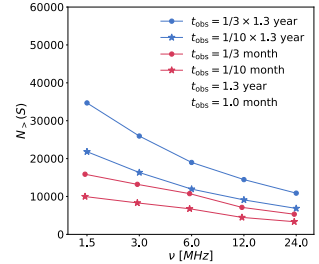
Detectable source (5σ, 8kHz)



VLSS model (Jester & Falck 2009)



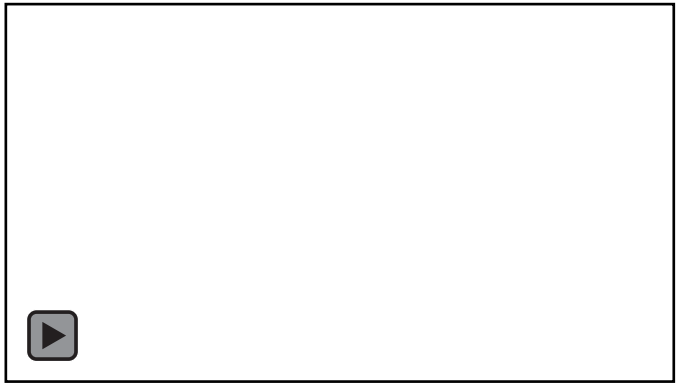
GLEAM model (Franzen et al. 2019)

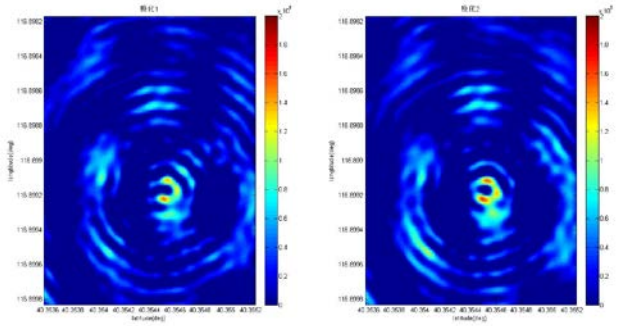


SSM model (Huang et al. 2019)

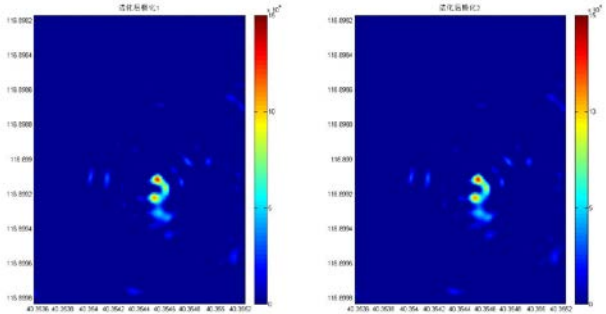
UAV test of Interferometry Imaging

3 drones, 2 noise source





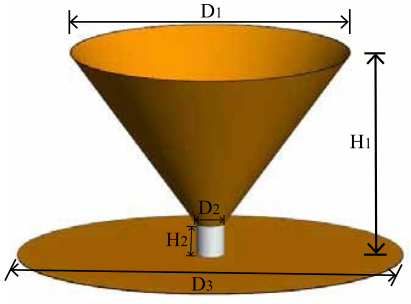
Reconstructed Dirty Map



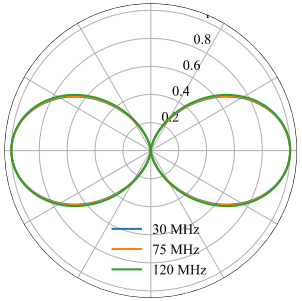
Cleaned Map

Global Spectrum Measurement

Frequency-independent antenna



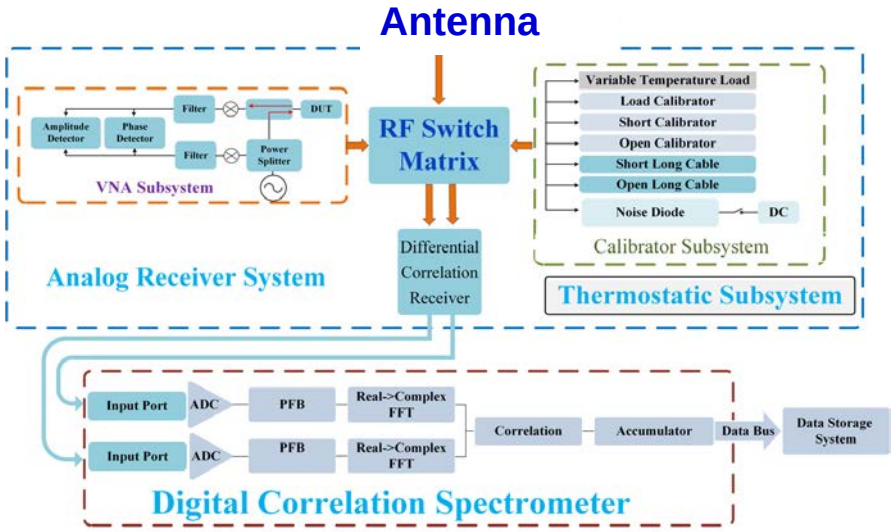
antenna



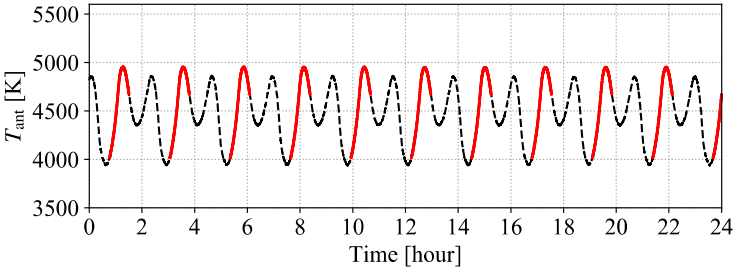
beam

frequency gradient of beam

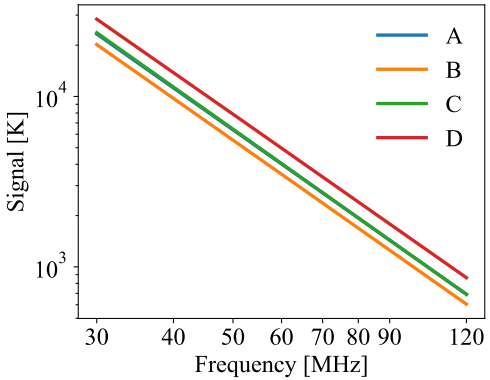
Receiver System with high precision internal calibration



Global Spectrum simulation

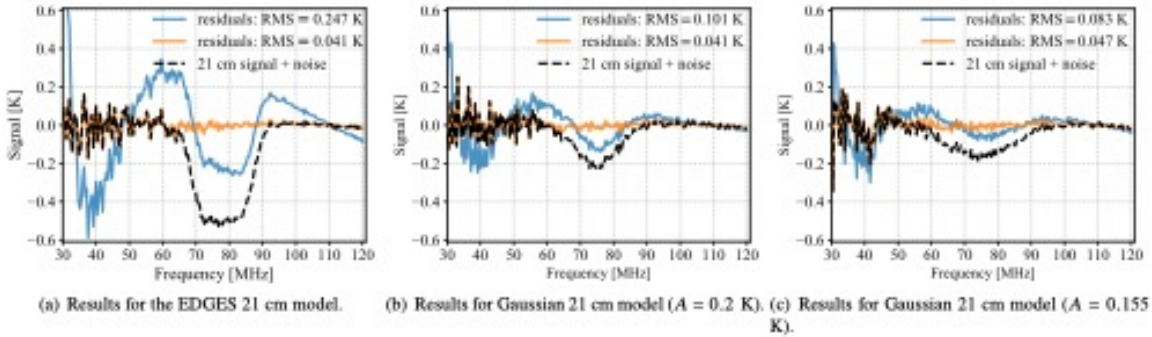


simulated T_{ant} variation at 60 MHz



Average spectrum at 4 different segments of orbit

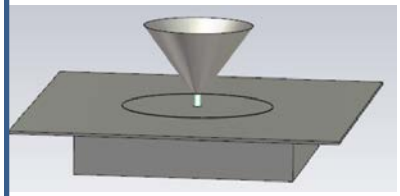
Fitting with a smooth foreground model

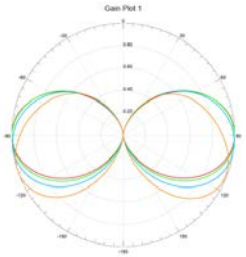


(a) Results for the EDGES 21 cm model. (b) Results for Gaussian 21 cm model (A = 0.2 K). (c) Results for Gaussian 21 cm model (A = 0.155 K).

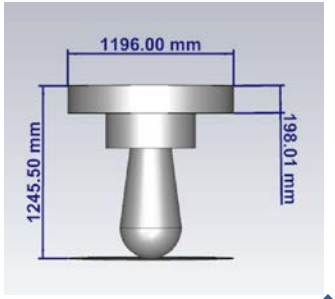
Y. Shi et al. (2022), ApJ 929, 32

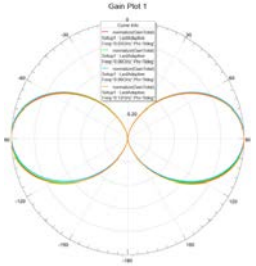
Antenna Design with the satellite body

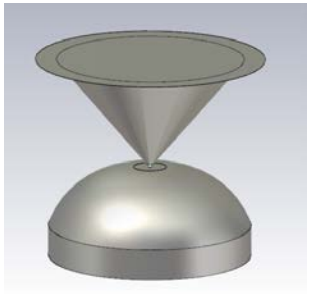


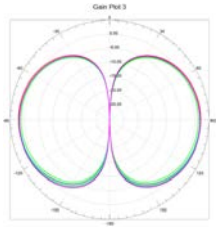


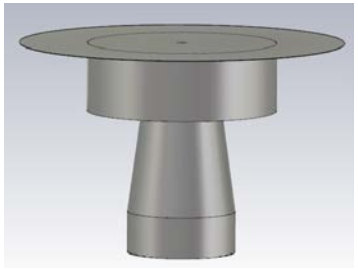
The satellite body (thick box) affect beam pattern

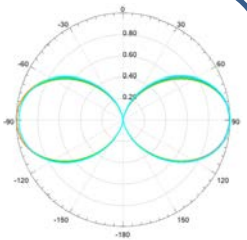










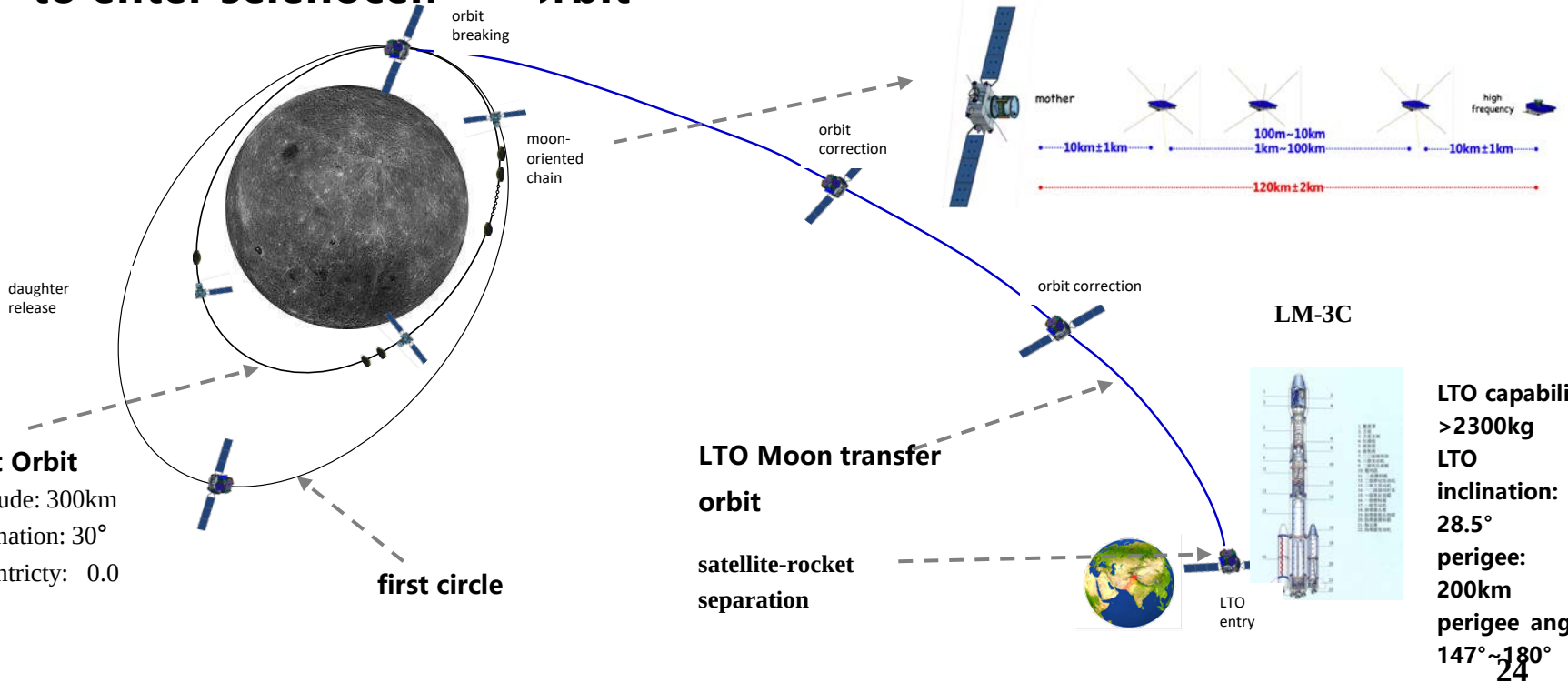


Requirements and Parameters Summary

Science	Observable	Measurement	Parameter	Payload
cosmic dawn and dark ages	21cm global spectrum (high precision 30-120 MHz, good precision 0.1-30 MHz)	30MHz–120MHz single antenna measurement	frequency band：30-120MHz sensitivity：<0.1K@80MHz (1MHz channel, 10 min integral) spectral resolution：<100kHz Antenna Beam non-chromatic: no sidelobe	**1 daughter satellite**
High Resolution whole sky survey, open up last window in EM spectum	1-30MHz whole sky map and source catalogue	multi-satellite interferometry taken with daughter satellites, data communication and processing on mother satellite, Position determination by ranging and angular measurement. Downlink to Ground	band：1-30MHz spatial resolution：<0.18° @1MHz，0.012° @30MHz antenna: 3 polarization Tsys：＜120% Tsky（1-30MHz） gain stability < 0.02dB/°C Amplitude Error：0.5dB Phase error：50° baselines：100m–100km ranging error：≤1m angular error：≤2" clock synchronization error：3.3ns communication range：10km-120km	**8 daighter satellites with interferometric spectrometer, inter-sat communication, ranging and synchronization, star sensor; 1 mother satellite for communication system, correlator, calibration source**
solar and planet ultralong wave radiation	monitoring of continuum spectrum for solar radio burst and planetary radio	Time Allocation or Event triggering	frequency band：0.1-30MHz dynamic range：60dB time resolution ： second spectral resolution：≥8192	

Launch Plan

- **Launch & Transfer Orbit Design:** **One LM-3C rocket launch to place the satellite assembly into LTO orbit, spacecraft breaking to enter selenocentric orbit**



Project Status

- PI: Xuelei Chen (NAOC)
- Technology Chief: Jingye Yan (NSSC)
- Satellite Platform: Xiaofeng Zhang (IAMC)

- First proposed in 2015 as a China-Europe joint project

- Intensive Study (2018-2020) successfuly completed

- Applying for entering Engineering Phase, aiming for a mission launch in 2026

X. Chen et al. arxiv:1907.10853

Chen et al., arxiv:2007.15794

International Collaborations Welcome!

- The project is completely open to international collaboration

- We envision an international science team, with different subject PIs from around the world

Thanks!