21cm cosmology workshop

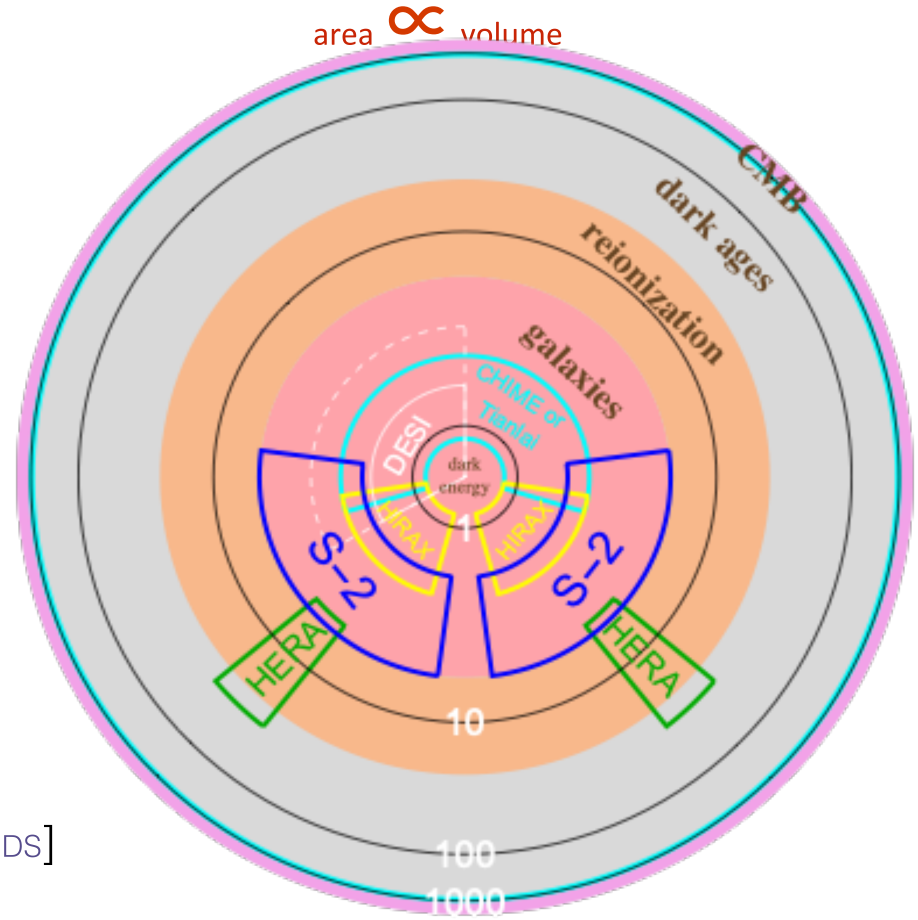
2019.10.22 Paris-Saclay

Tianlai and the lunar orbit array

Xuelei Chen
NAOC

Cosmic Cartography: uncharted

- parameter accuracy ~ $n_{mode}^{-1/2}$
- n_{mode} ~ volume



2D: CMB [SPT/ACT/S4]

large area galaxy imaging/spectroscopy

2D: single band imaging [APM]

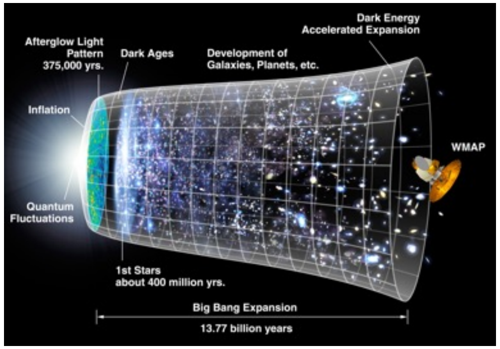
2D^{+}: + multi-band photo-z's [DES/LSST]

3D^{-}: + lo-res spectroscopy [PAU/JPAS/SphereX/MKIDS]

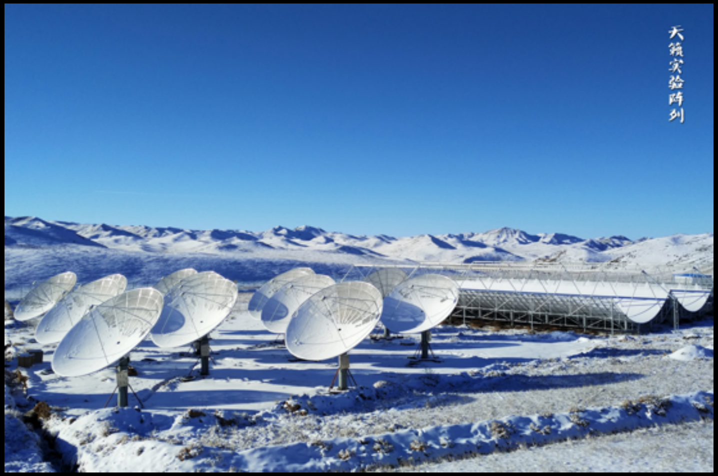
3D: + hi-res spectroscopy [APM/SDSS/DESI/4MOST/Euclid/WFIRST]

intensity imaging of galaxies/LSS

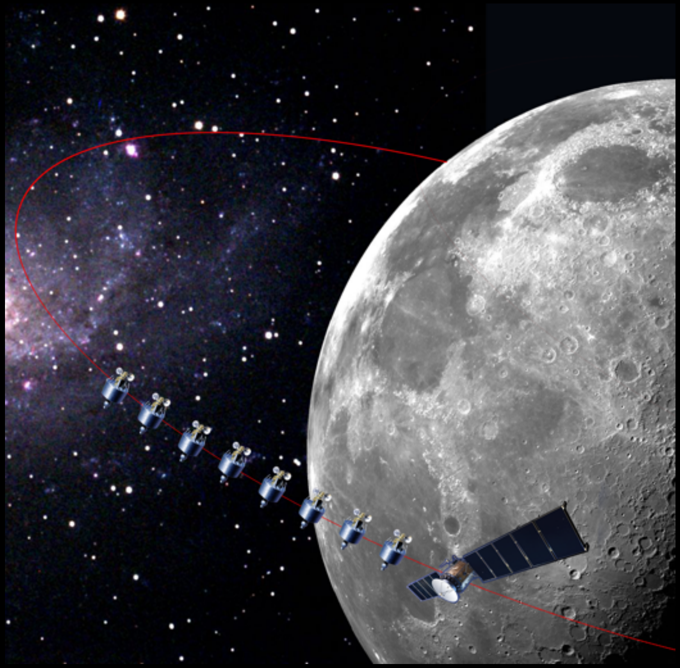
3D: + hi-res HydrogenIntensityMapping [CHIME/Tianlai/HIRAX/BINGO/SKA/S-2]



- The Status of the Tianlai Array



- Discovering the Sky at the Longest wavelength (DSL)



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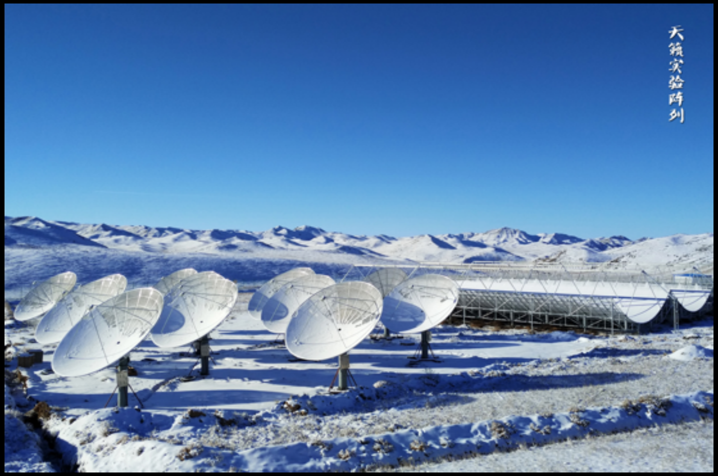
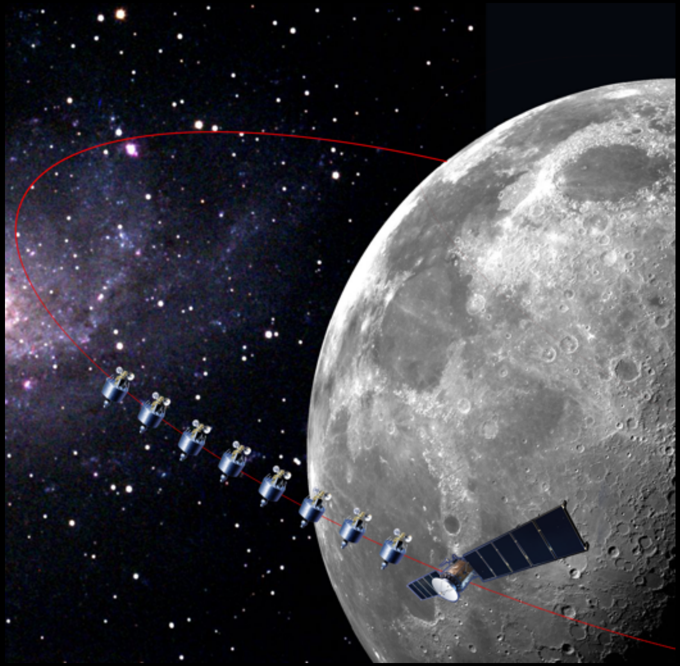
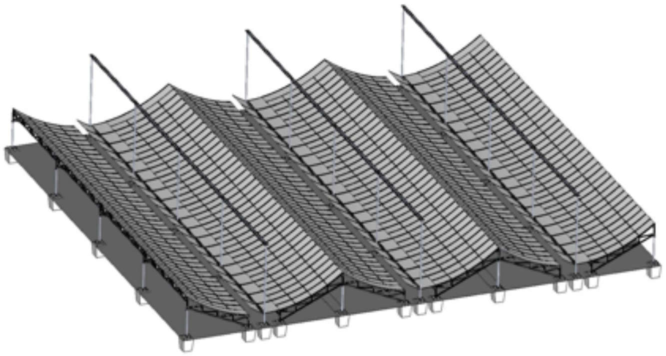


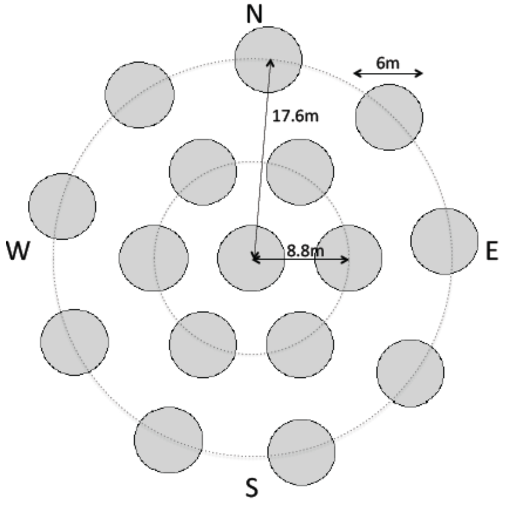


Hydrogen Intensity Mapping: The Tianlai Pathfinder

Pathfinders to demonstrate basic principle
and encounter all issues rapidly

- **Band** 685-810MHz ($0.77<z<1.3$)
512 frequency channels
($\Delta\nu$=125MHz $\delta\nu$=244kHz δz=0.0002)
tunable in 600-1420MHz ($0<z<1.5$)
- **Cylinder Array** 3 x 15m x 40m cylinders
96 dual polarization feeds
4 sec sampling
- **Dish Array** 16 x 6m dishes
16 dual polarization feeds
1 sec sampling
- **Pathfinder+ Cylinder Array**
216 dual polarization feeds
4 sec sampling
- **Proposed Full Cylinder Array** 8 x 15m x 120m
2048 dual polarization feeds
400-1420MHz

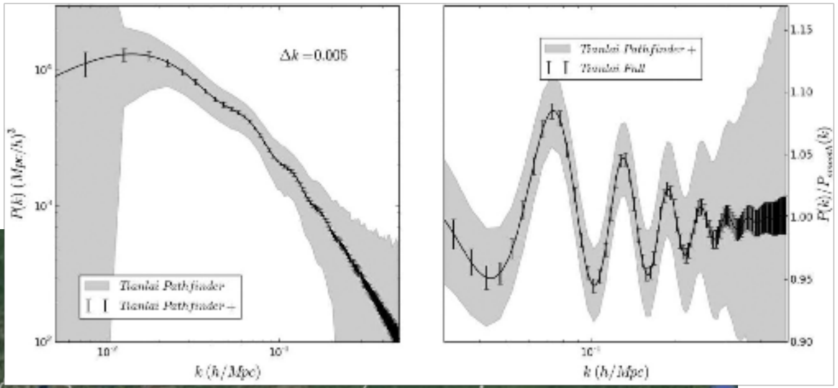


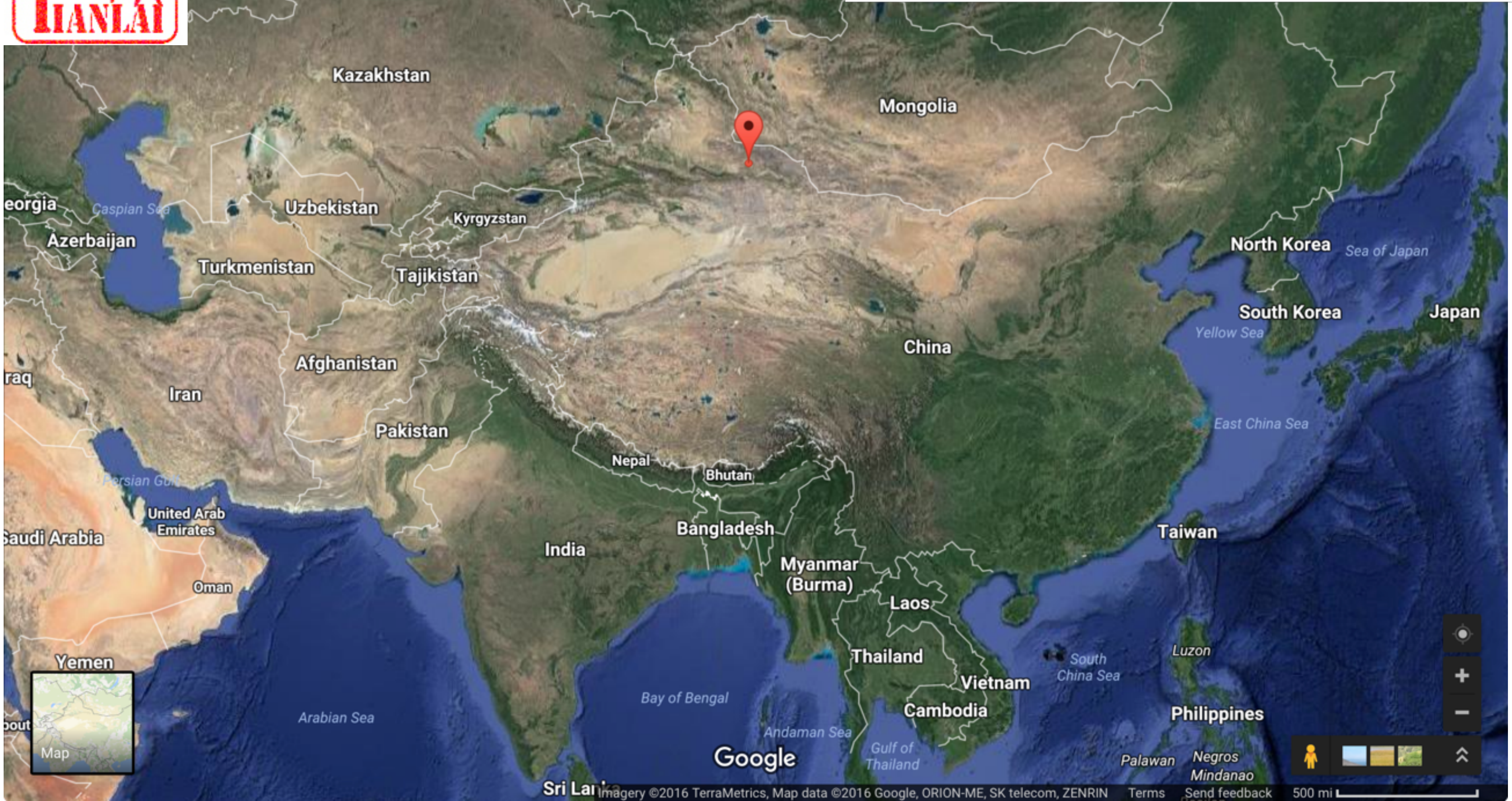


Hydrogen Intensity Mapping: The Tianlai Project

Tianlai ~ “*Heavenly Sound*”

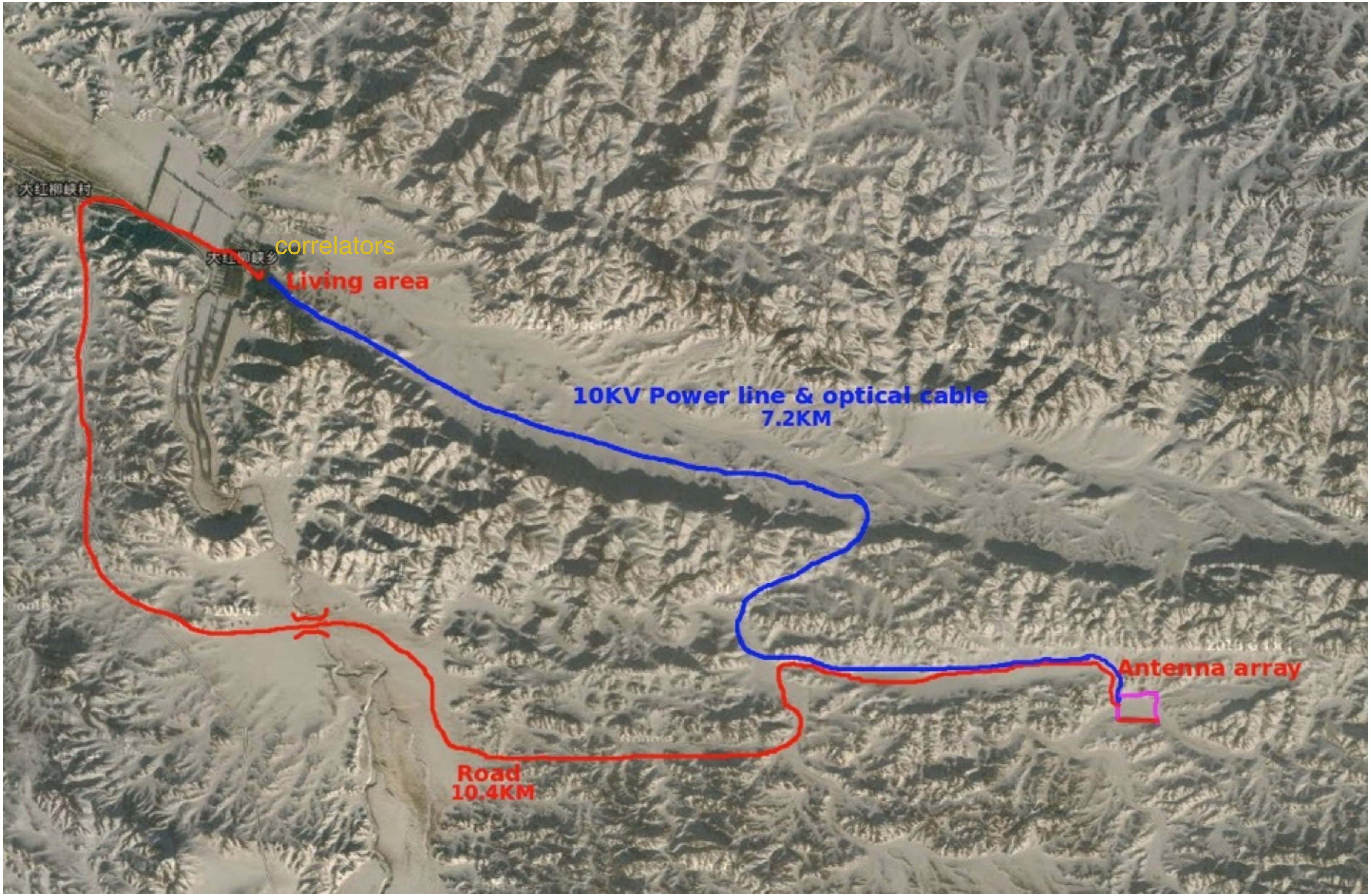
TIANLAI





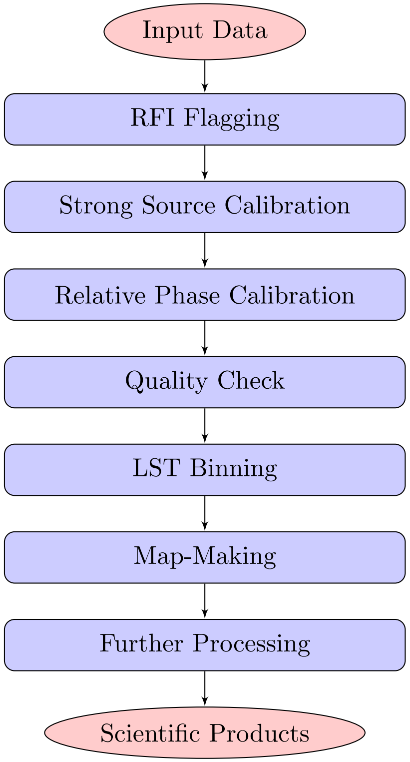
Hydrogen Intensity Mapping: The Tianlai Pathfinder

Hydrogen Intensity Mapping: The Tianlai Site



Tianlai data processing

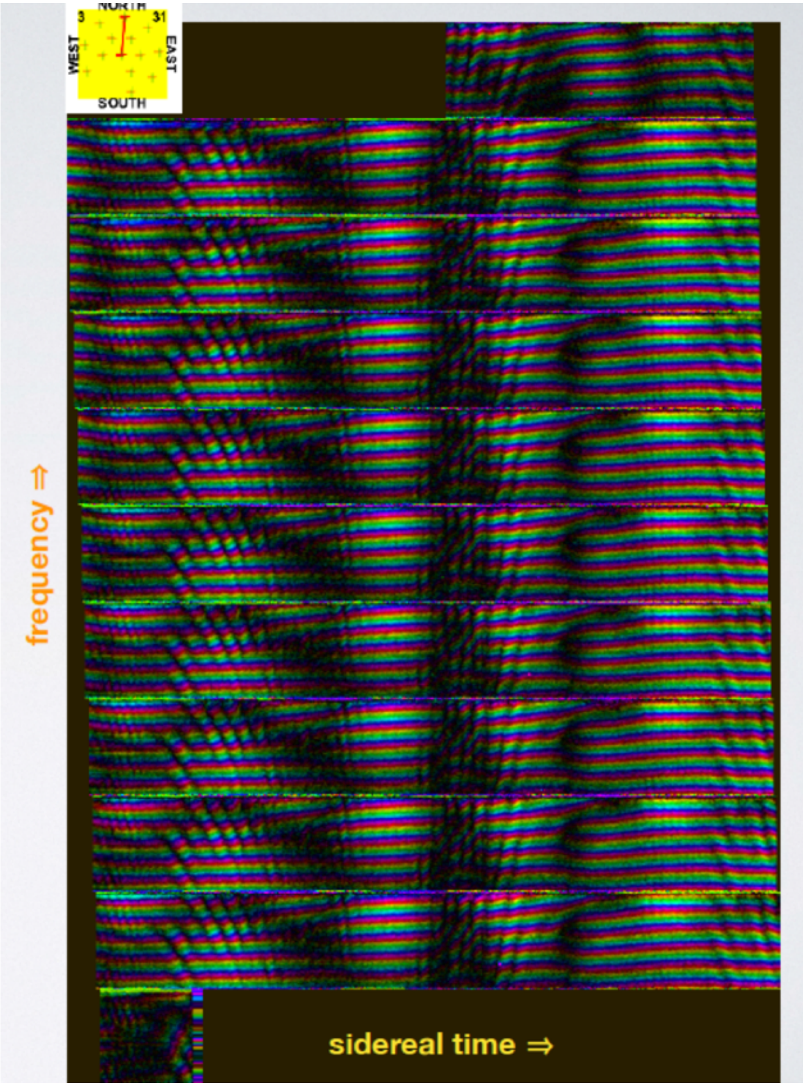
- Dish and Cylider array
- ~4TB data per day
- Multi-step
- Automatic pipeline
- Scalable
- Flexible



Zuo et al., *in preparation*

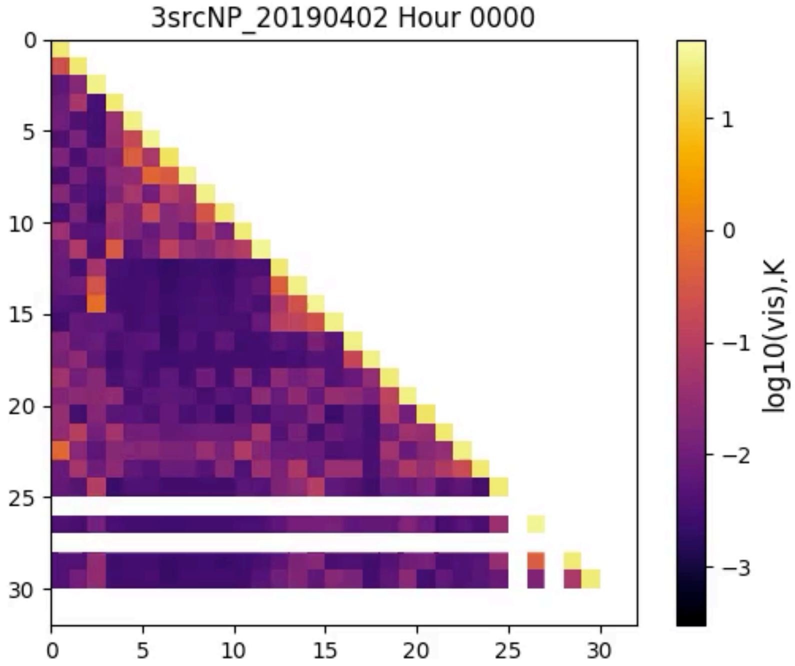
Tianlai Dish Array: highly-repeatable visibilities

- one visibility
- staring at NCP for 10 nights



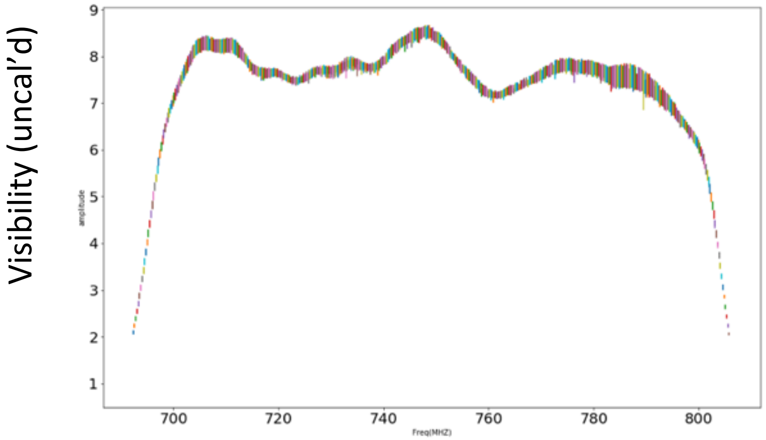
Tianlai Dish Array: correlation matrix movies

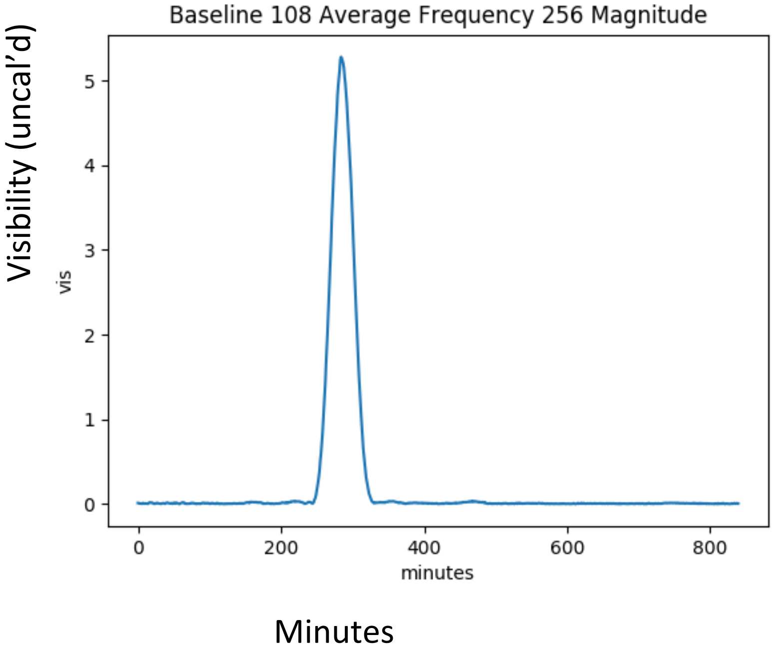
- 1 uncalibrated visibility
- quick-look at data quality over 25 days

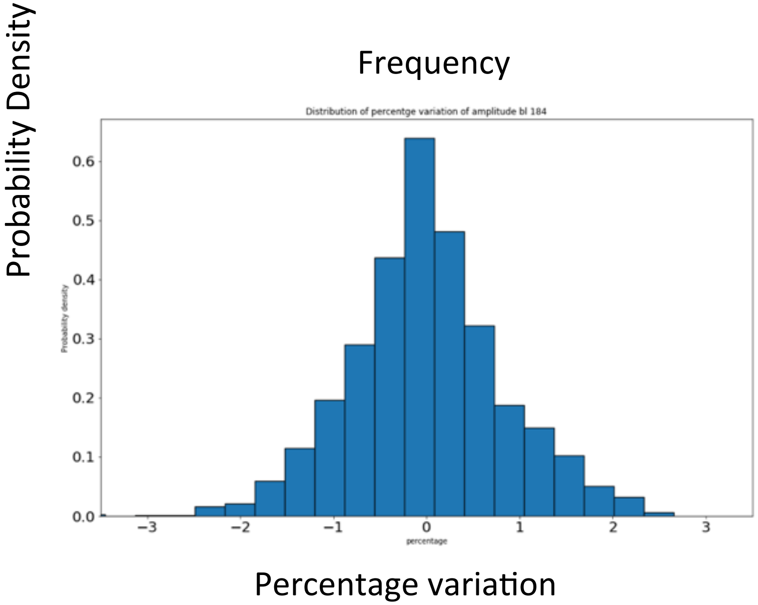


Tianlai Dish Array: Gain stability

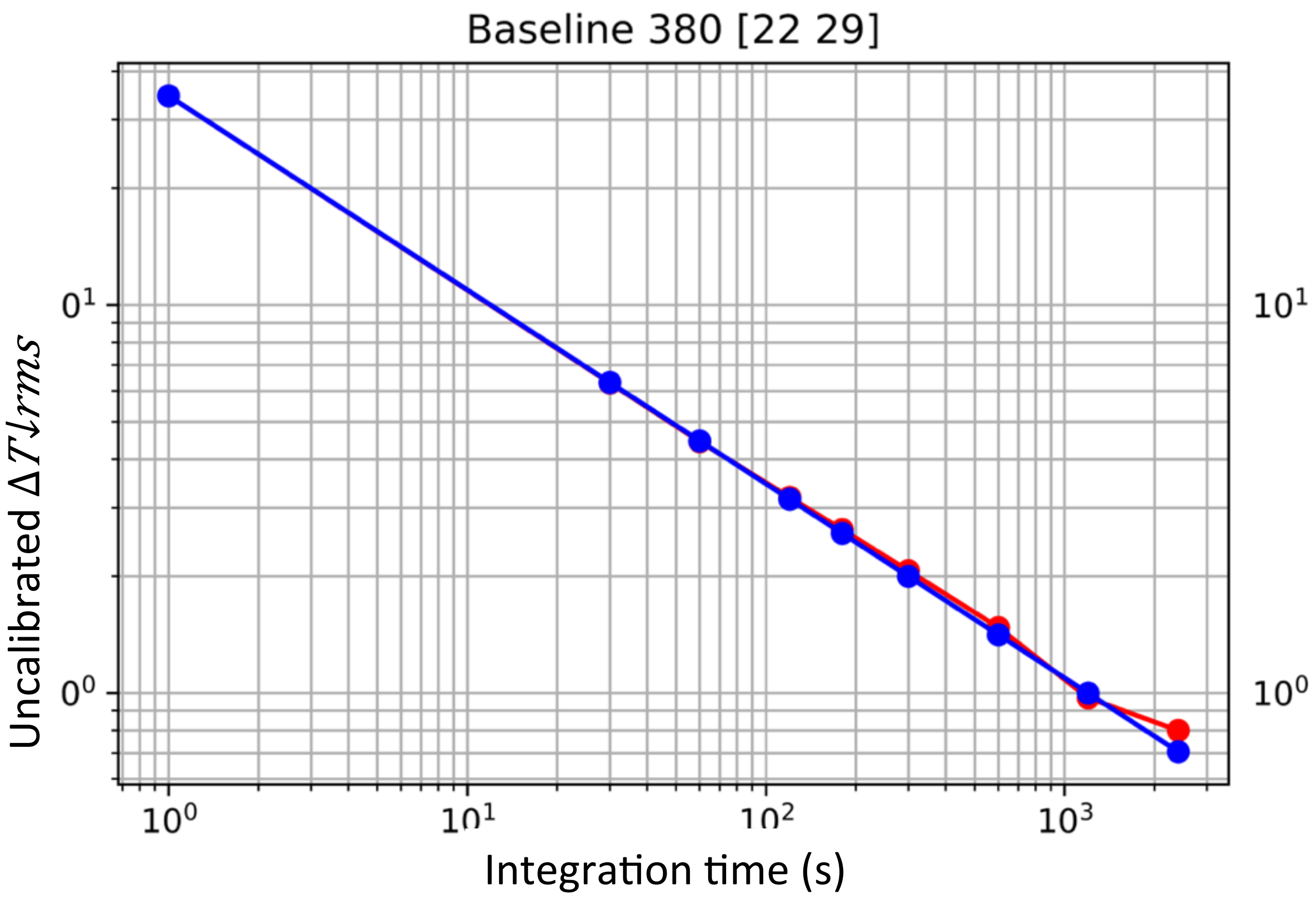
- Gain measured for 1 baseline using transits of Cas A over 11 days







noise integrates down



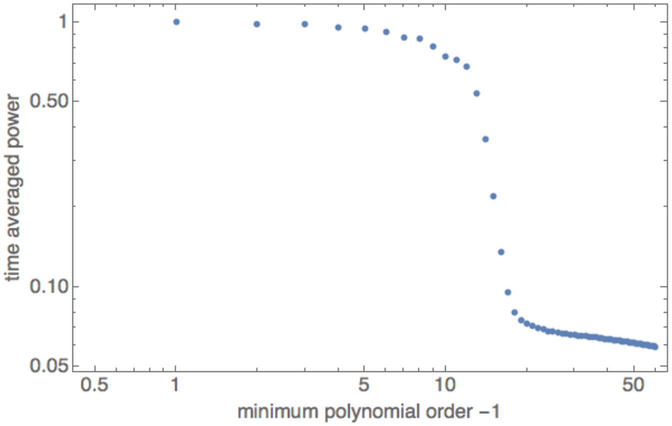
Tianlai Visibility: Foreground Subtraction

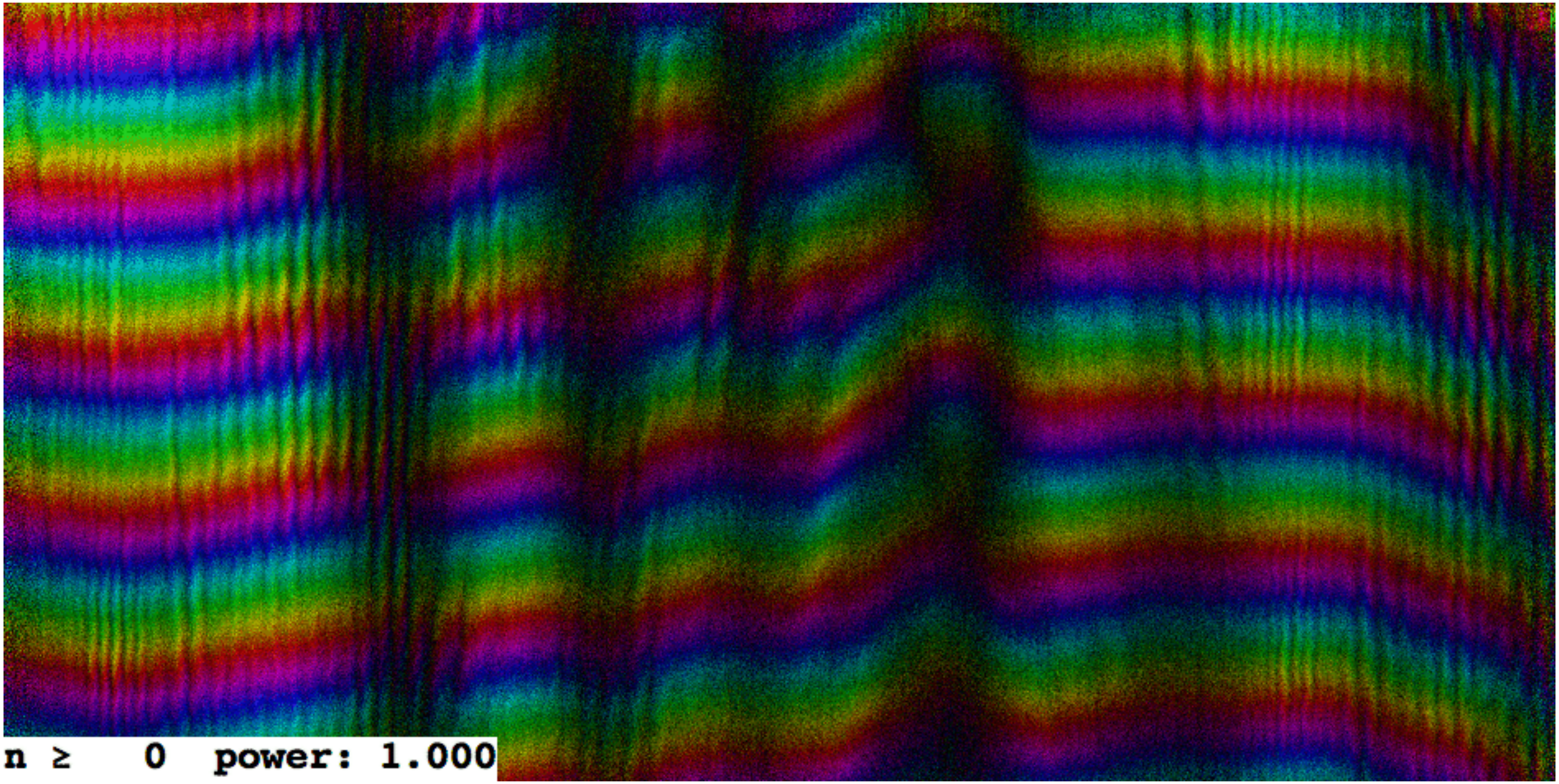
$$V[\nu]=\sum_{n=0}^{N} a_n P_n\left[\frac{2(\nu-\nu_{mid})}{\nu_{max}-\nu_{min}}\right]$$

$$k_{||} \approx \frac{2\pi}{\Delta R_{co}}(n+1)$$

10 night median averaged visibility discrete polynomial subtraction.

residuals n>60!



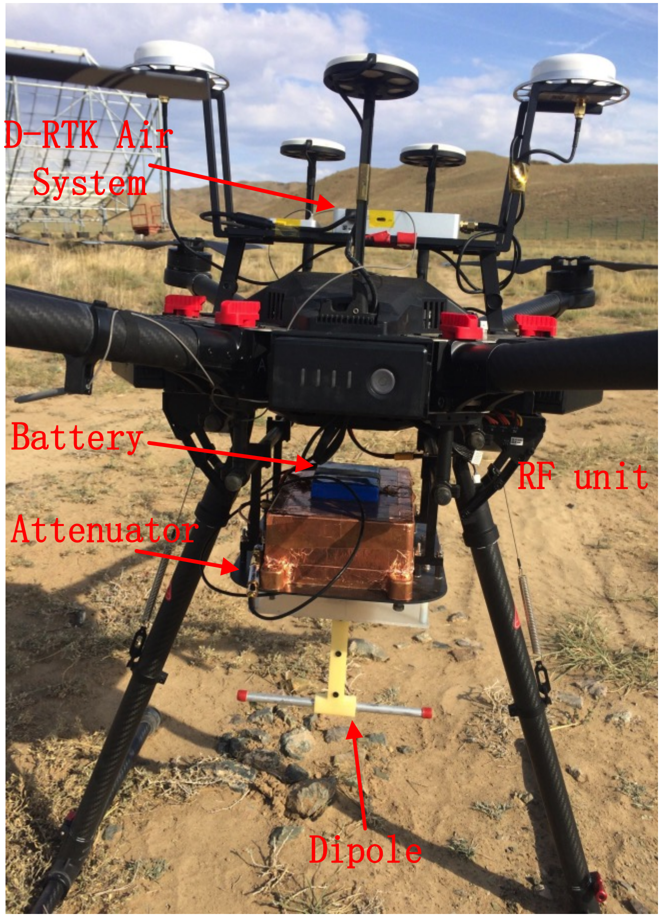


Beam Calibration Experiment with Drone

Juyong Zhang et al., in preparation

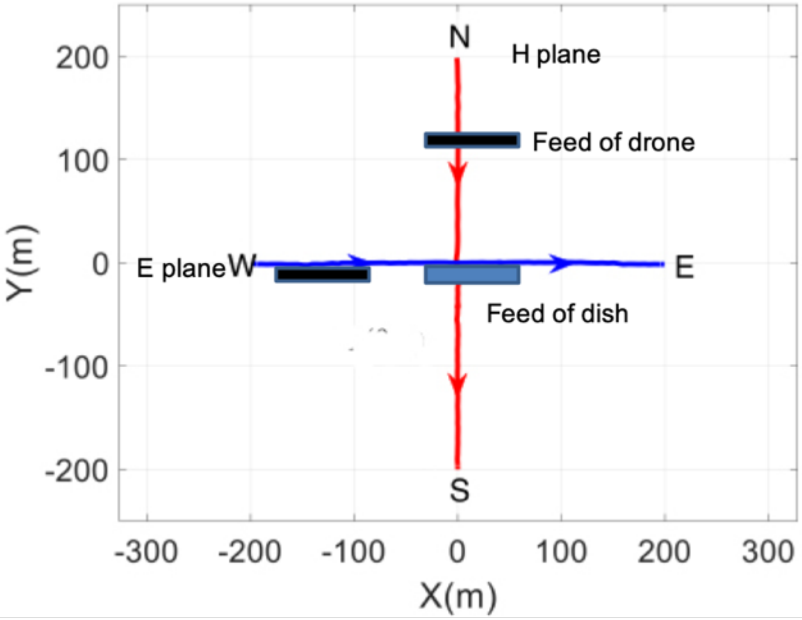
UAV

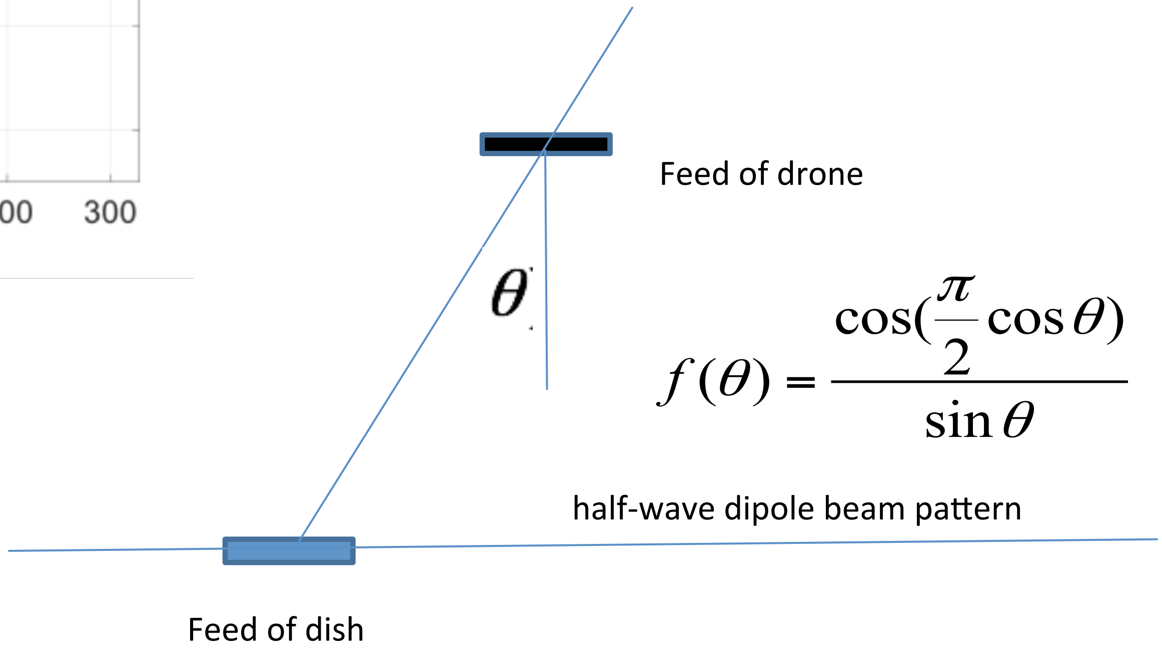
DJI Matrice 600 PRO



DJI Matrice 600 PRO	
Length	1.8m
Width	1.6m
Height	0.78m
Max Payload	6 kg
Usual Max Flight Height (Limited by Government)	500 m
Max Hovering Time	32 min(TB47S) 38 min(TB48S)
Hovering Accuracy	Vertical: 0.5 m; Horizontal: 1.5 m
Hovering Accuracy (With D-RTK)	Vertical: 2 cm; Horizontal: 1 cm
Payload (RF noise source, battery, dipole antenna)	0.7 kg

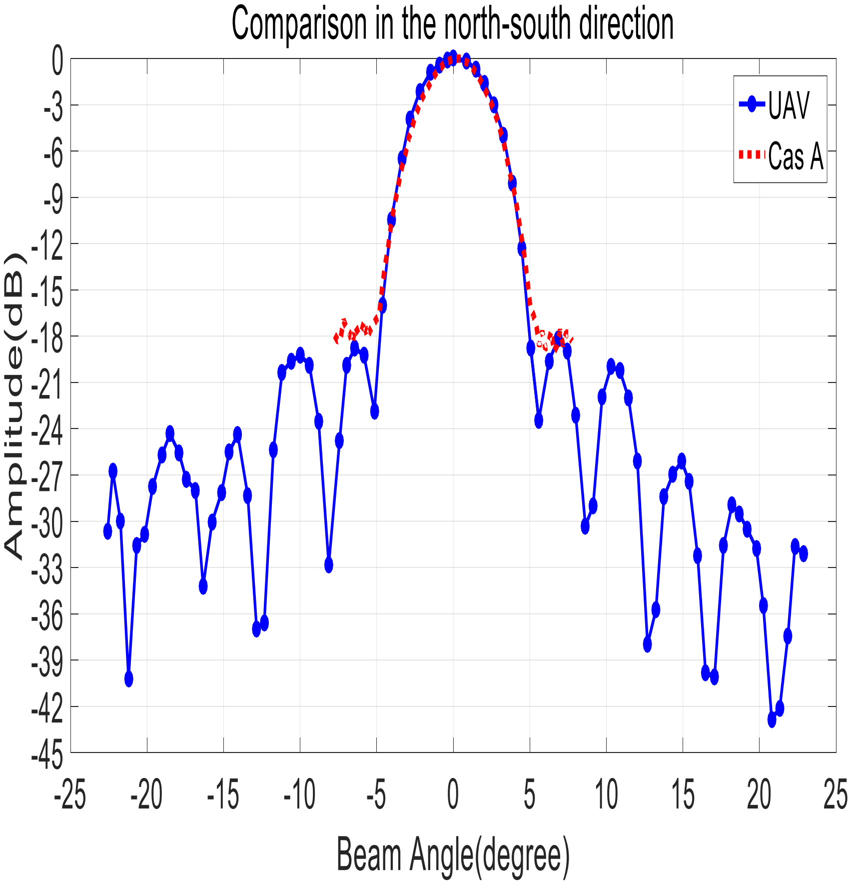
Measurement on H plane & E plane

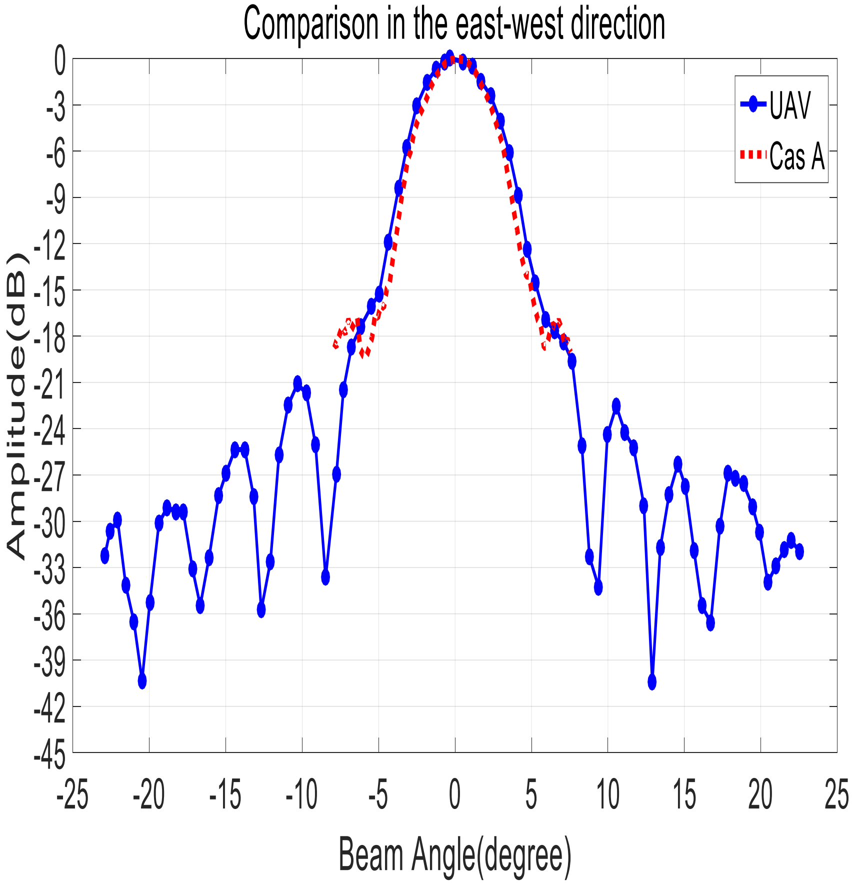


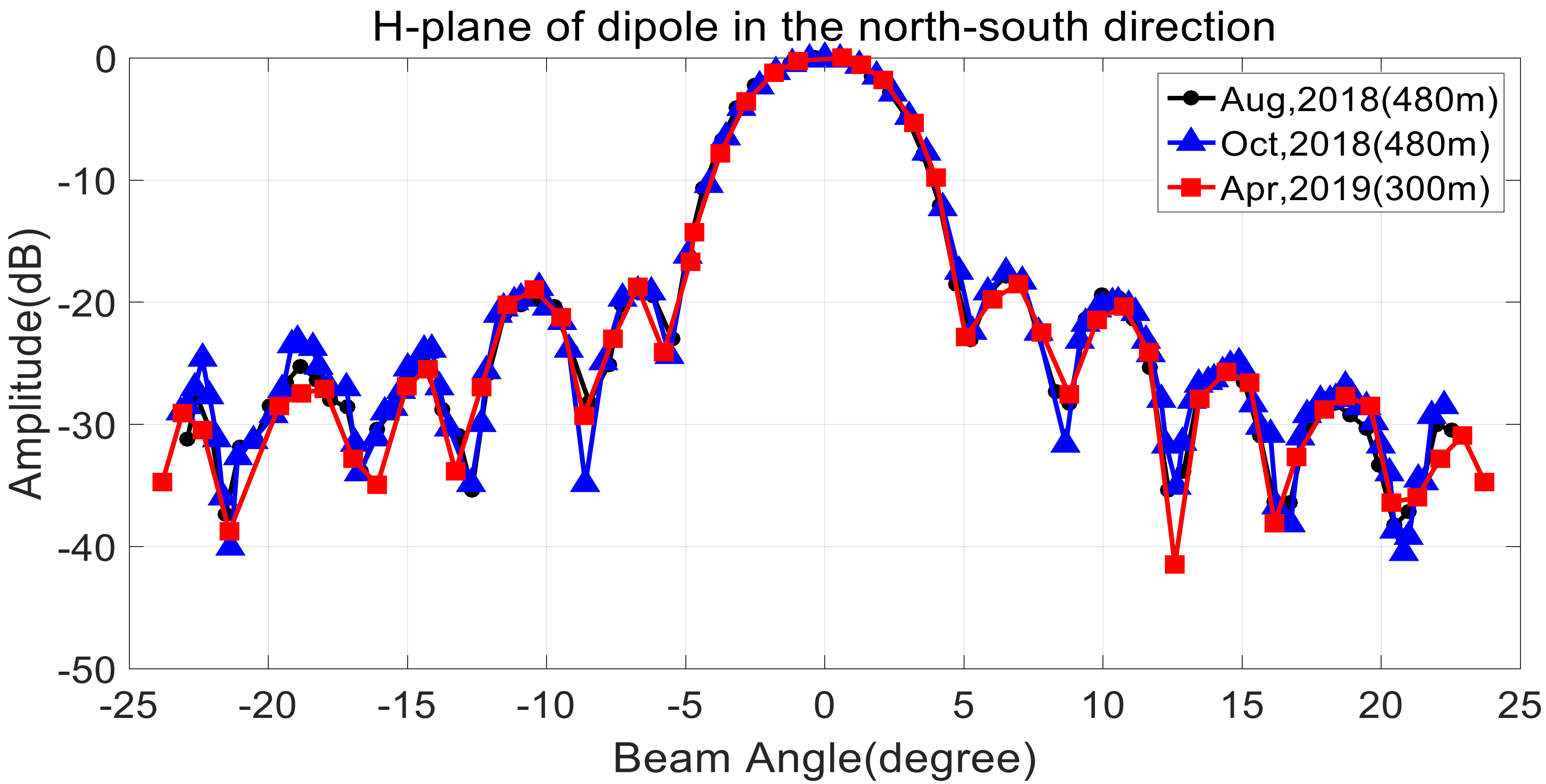


$$f(\theta) = \frac{\cos(\frac{\pi}{2}\cos\theta)}{\sin\theta}$$

half-wave dipole beam pattern


Comparison in the north-south direction
Amplitude(dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-36
-39
-42
-45
-25
-20
-15
-10
-5
0
5
10
15
20
25
Beam Angle(degree)
UAV
Cas A


Comparison in the east-west direction
Amplitude(dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-36
-39
-42
-45
-25
-20
-15
-10
-5
0
5
10
15
20
25
Beam Angle(degree)
UAV
Cas A

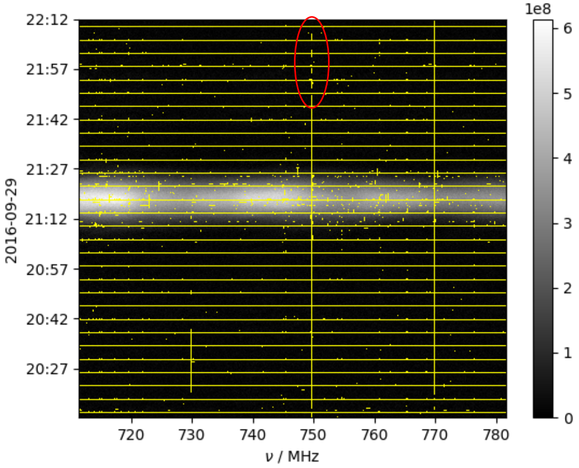

H-plane of dipole in the north-south direction
Amplitude(dB)
0
-10
-20
-30
-40
-50
-25
-20
-15
-10
-5
0
5
10
15
20
25
Beam Angle(degree)
Aug,2018(480m)
Oct,2018(480m)
Apr,2019(300m)

RFI Flagging

- **SumThreshold** Offringa et al. 2010

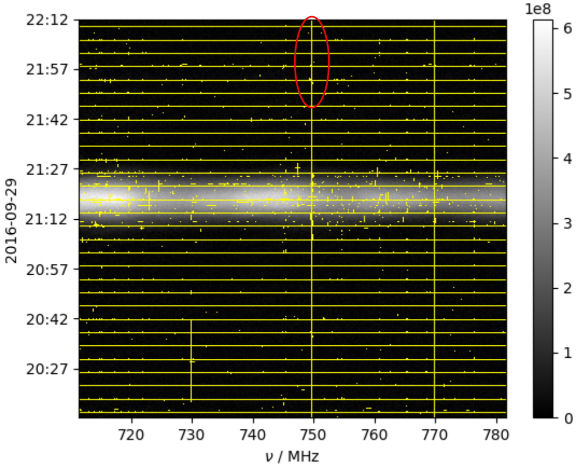
  Comare the sum of data samples with the given thresholds

$$\chi_i = \frac{\chi_1}{\rho^{\log_2 i}}$$



- **SIR operator** Offringa et al. 2012

  Effectively fill in the gaps in the previous results.



Calibration

- **sky point source calibration**

  Use an Eigenvector-based point source calibration method.

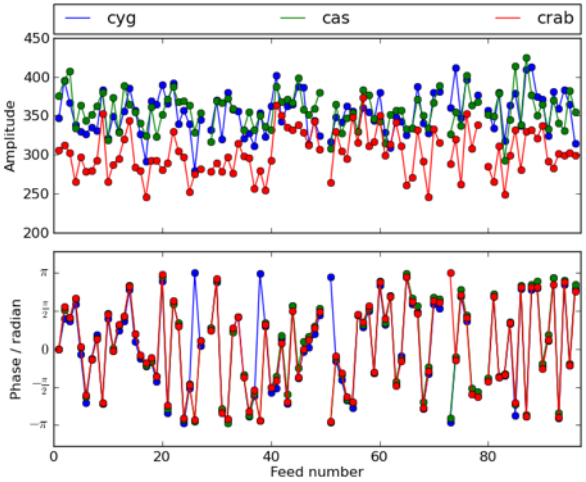
- **noise source calibration**

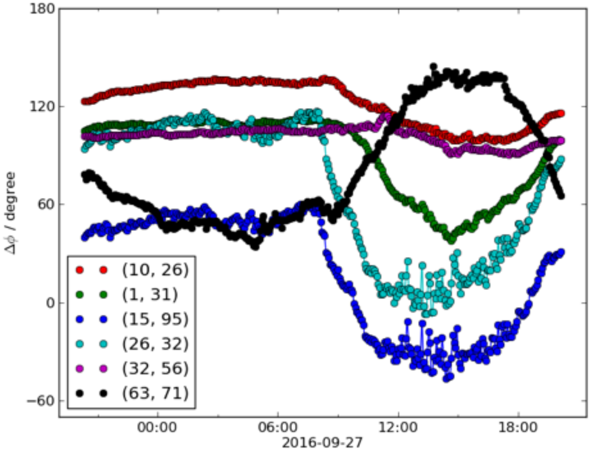
  Corrects for the time variation of the phase.

$$G_i = g_i A_i(\hat{\boldsymbol{n}}_0) e^{-2\pi i \hat{\boldsymbol{n}}_0 \cdot \boldsymbol{u}_i};$$

$$V_0 = S_c\, \boldsymbol{G}\boldsymbol{G}^{\dagger}.$$

Zuo et al. 2018





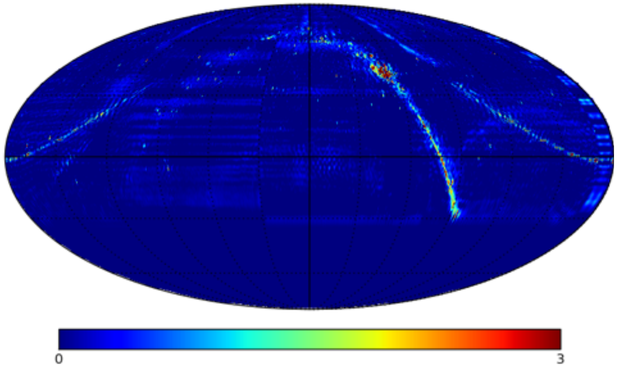
Map-making

Using the m-mode analysis method (Shaw et al. 2014, Zhang et al. 2016)

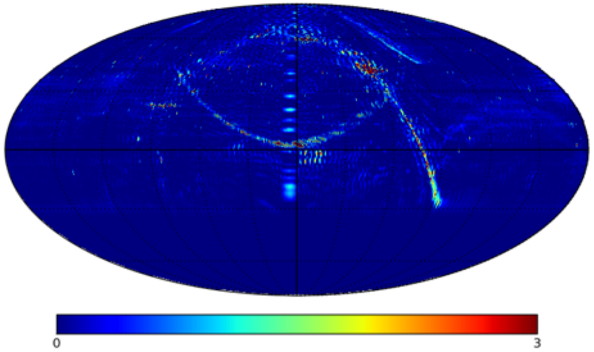
$$v_m^\alpha = \sum_l B_{lm}^\alpha a_{lm} + n_m^\alpha \Longleftrightarrow \boldsymbol{v} = \mathbf{B}\boldsymbol{a} + \boldsymbol{n}$$

$$\min \ \|\boldsymbol{v} - \mathbf{B}\boldsymbol{a}\|^2 + \varepsilon\|\boldsymbol{a}\|^2 \longrightarrow \hat{\boldsymbol{a}} = (\mathbf{B}^\dagger\mathbf{B} + \varepsilon\mathbf{I})^{-1}\mathbf{B}^\dagger\boldsymbol{v}$$

Tikhonov regularization



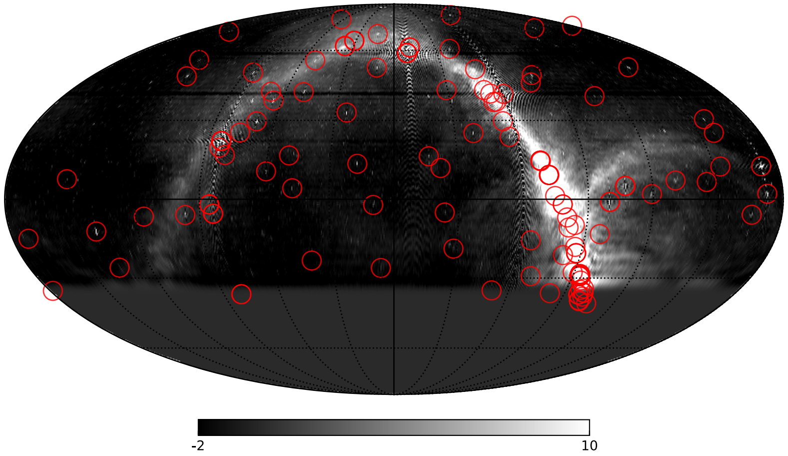
2016/09/27 – 2016/10/02



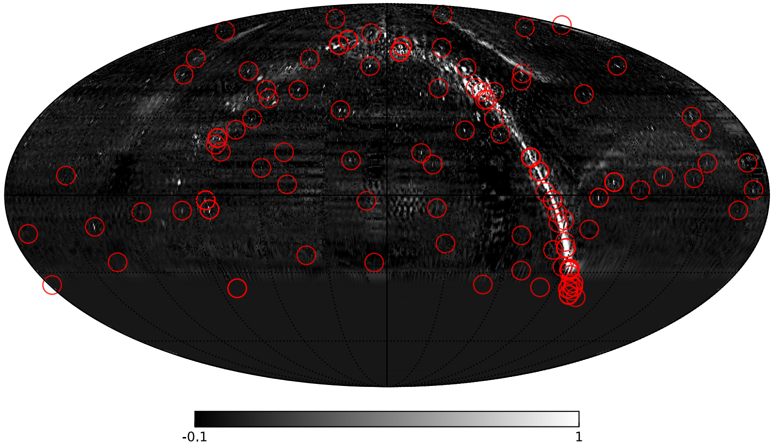
2018/03/22 – 2018/03/28

Map-making

simulated imaging map



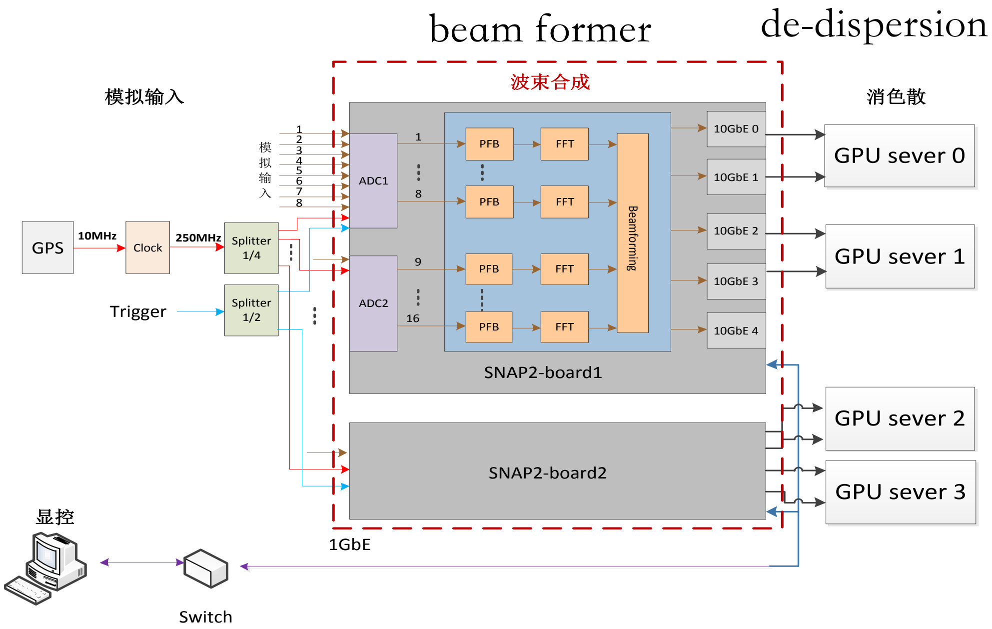
observation imaging map



Next: FRB search

◆**32-channel FRB backend**

--Install on site before the end of 2019



- 2 snap2 boards, each with 16 RF input ports (working separately)
- GPU de-dispersion

◆**192-channel FRB backend**

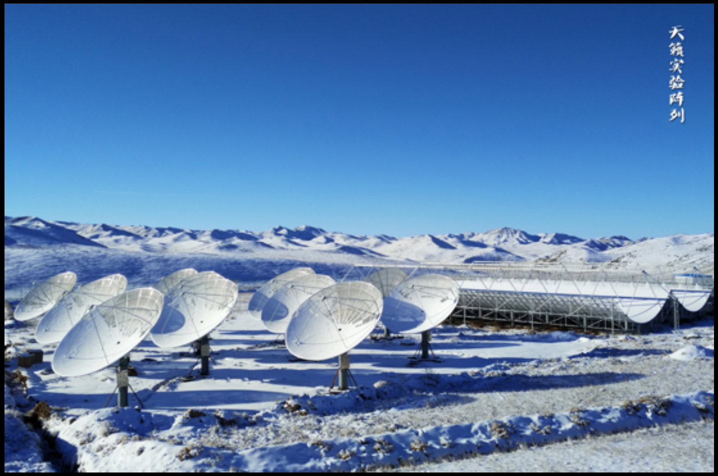
--2020

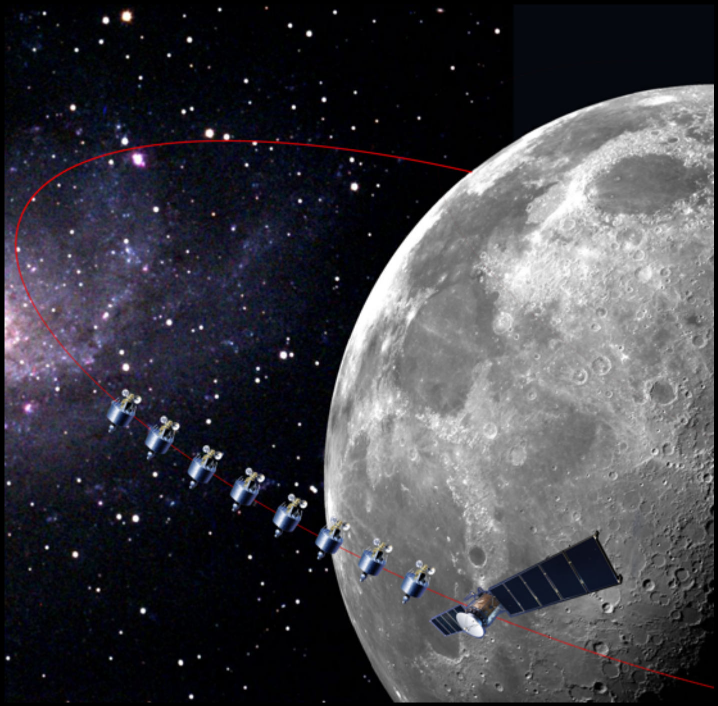
Tianlai Summary

- The Tianlai pathfinders have been operating for a few years, validation analysis in progress
- Prelimnary results indicate the arrays are stable
- FRB search backends coming soon

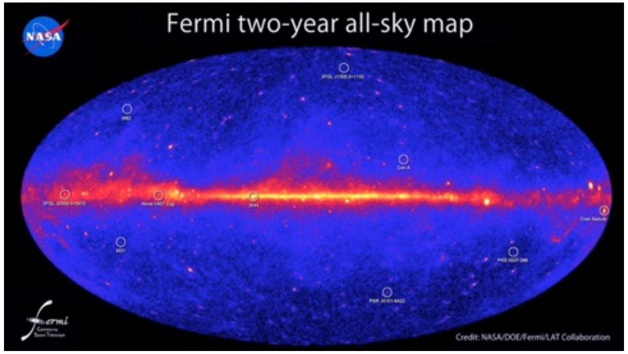
- The Status of the Tianlai Array

- Discovering the Sky at the Longest wavelength (DSL)

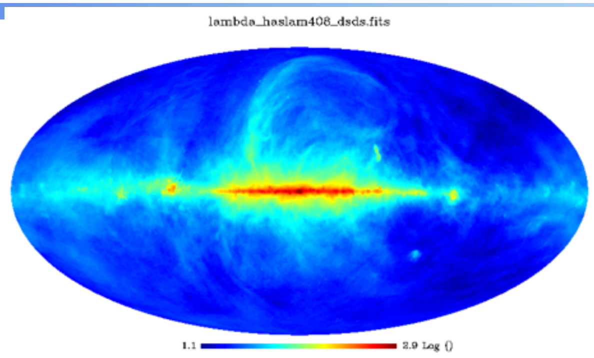




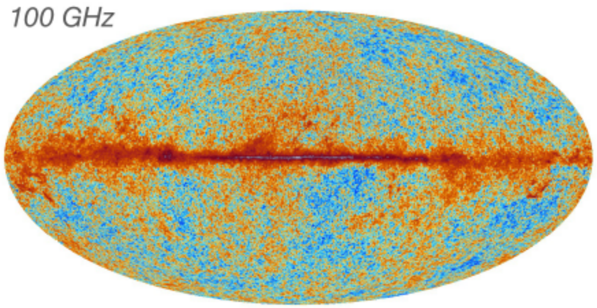
Sky in different wavelengths



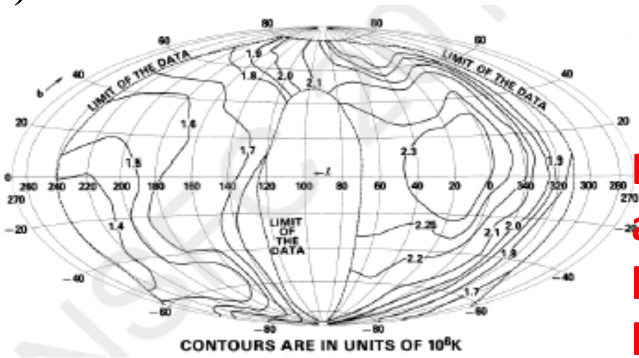
Gamma-ray Sky Map (Fermi Satellite)



408 MHz Sky Map

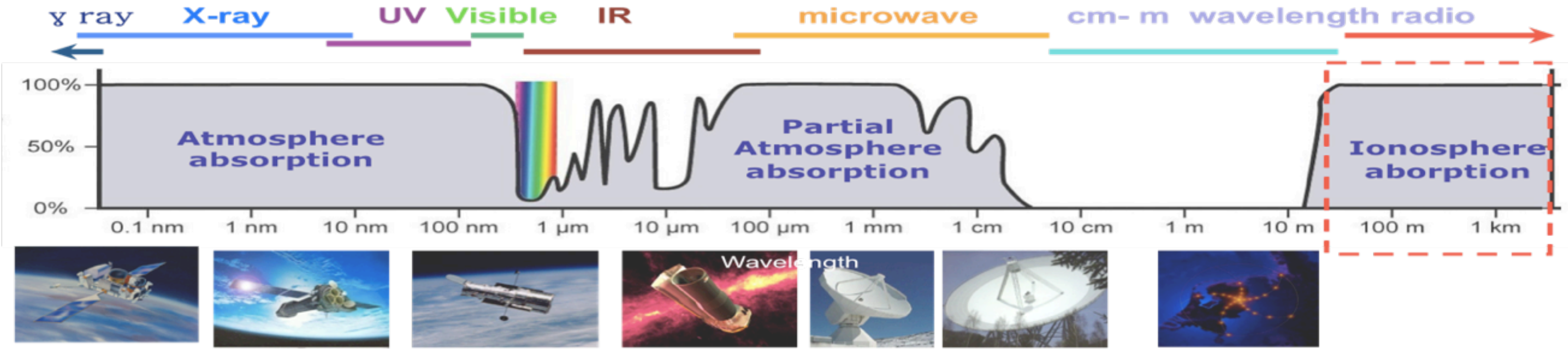


mm Sky Map (Planck Satellite)

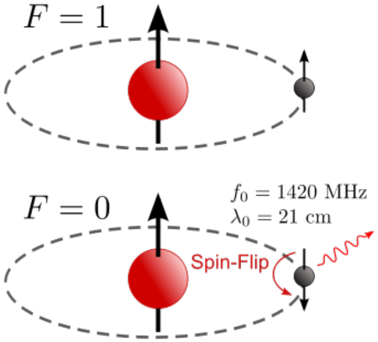


Low Frequency (RAE-2 satellite)

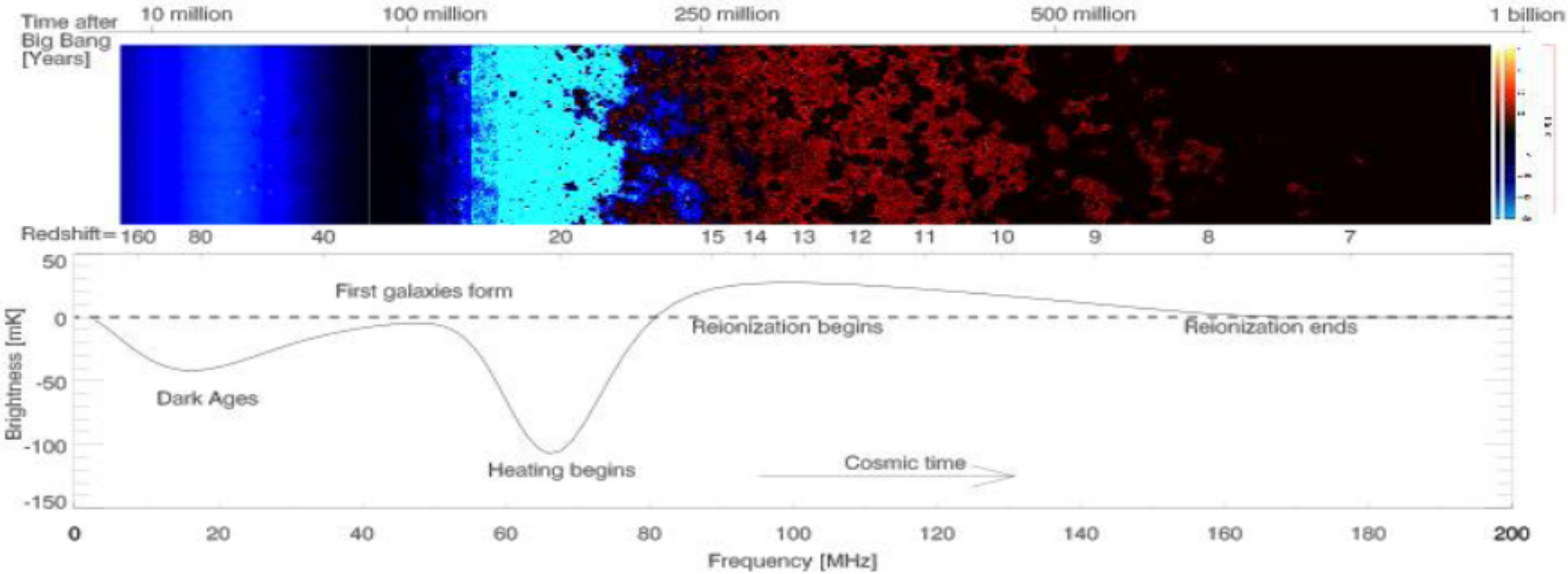
Due to ionosphere absorption, the sky below 30MHz is still largely unknown



The Light in the dark age——21cm line

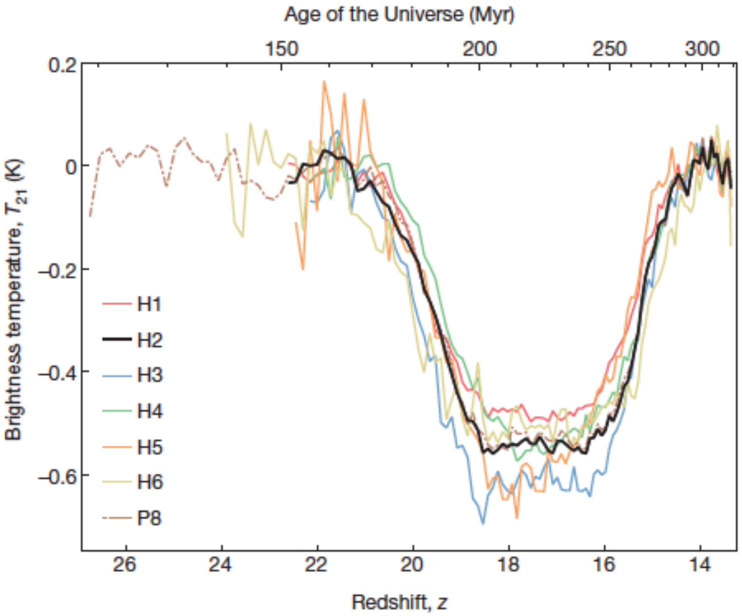


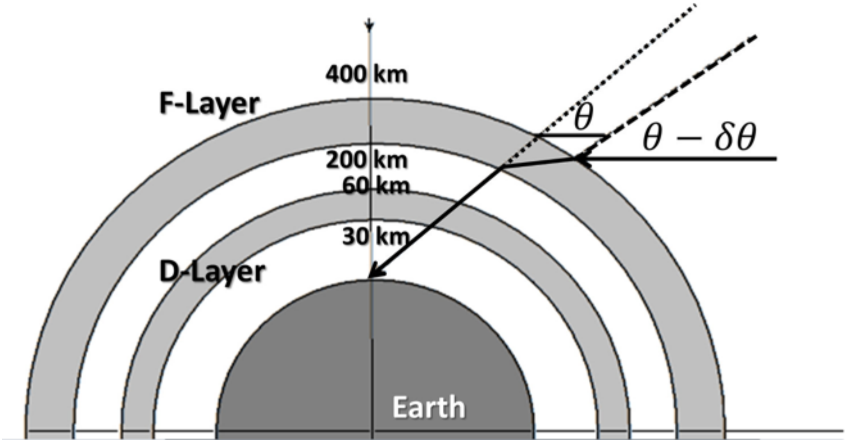
- **Neutral Hydrogen** （HI） produce spectral line of 1420MHz in Frequency or **21cm** in wavelength, superimposed on the radiation background
- **Strong Absorption line** can be produced by **Dark Age** and **Cosmic Dawn** （XC & J. Miralda-Escude 2004,2008)
- These are now redshifted to **low frequencies**

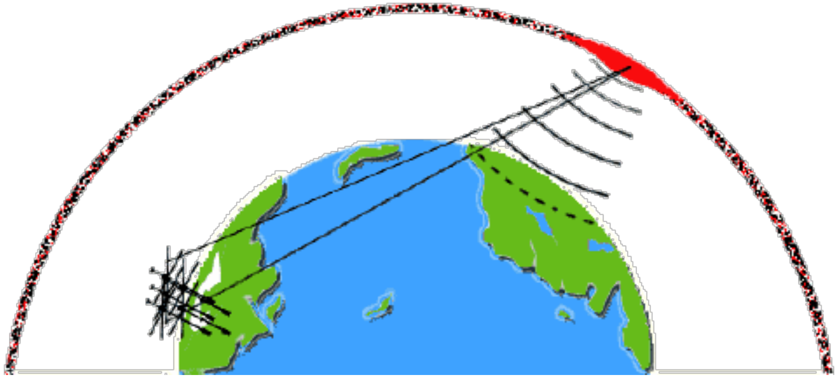


New Results from the EDGES Experiment

Bowman et al. 2018, Nature

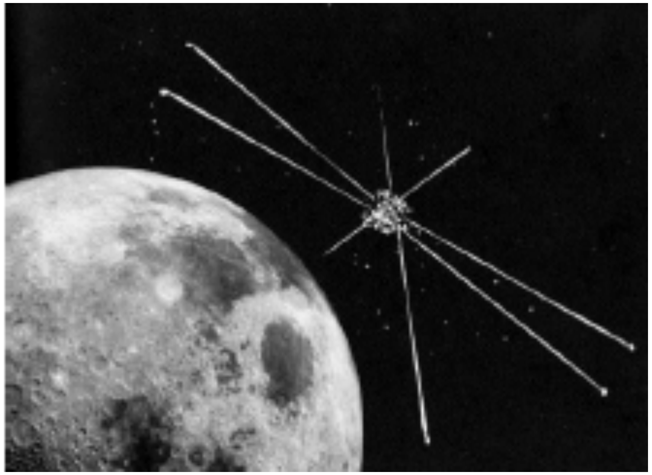


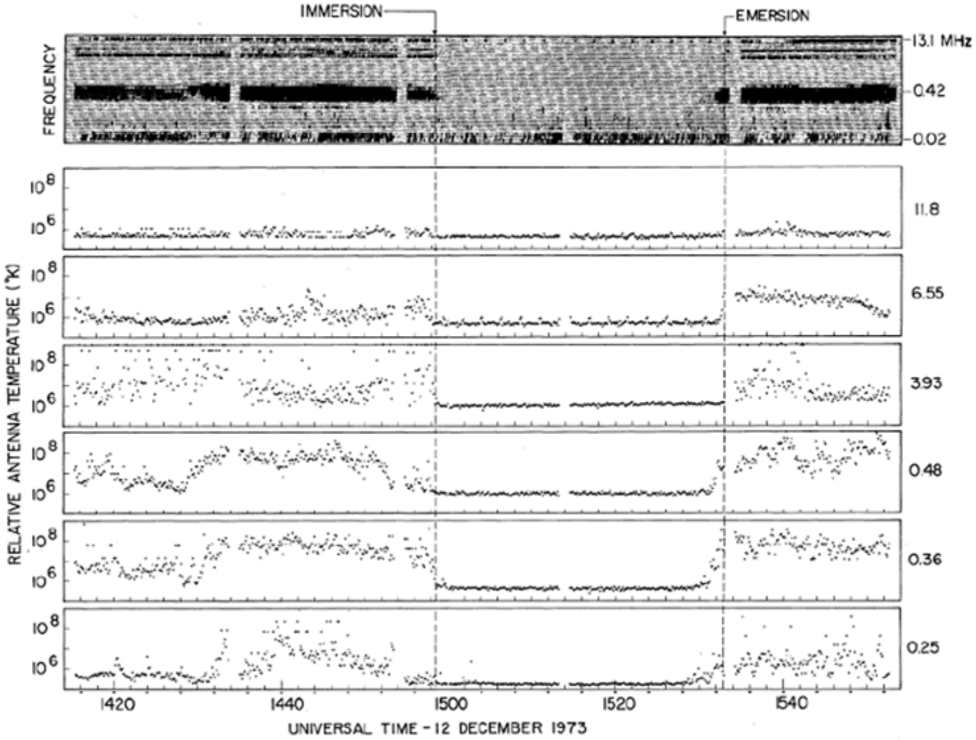




Vedantham & Koopermans (2015)

The advantage of the Lunar Orbit

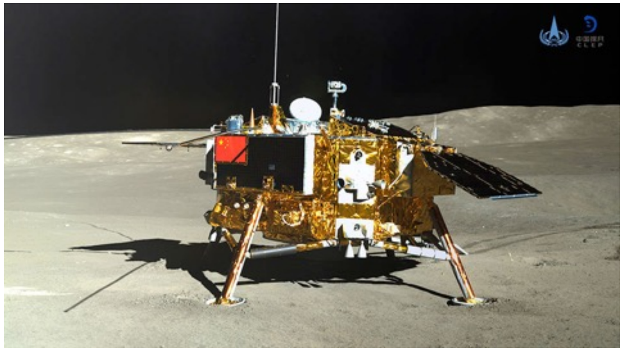




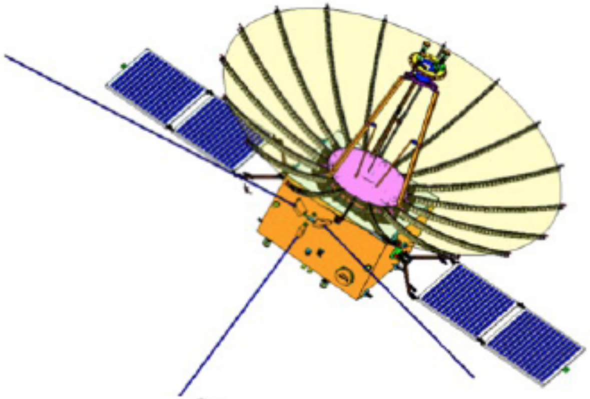
RAE-2 satellite and its spectrum measurement

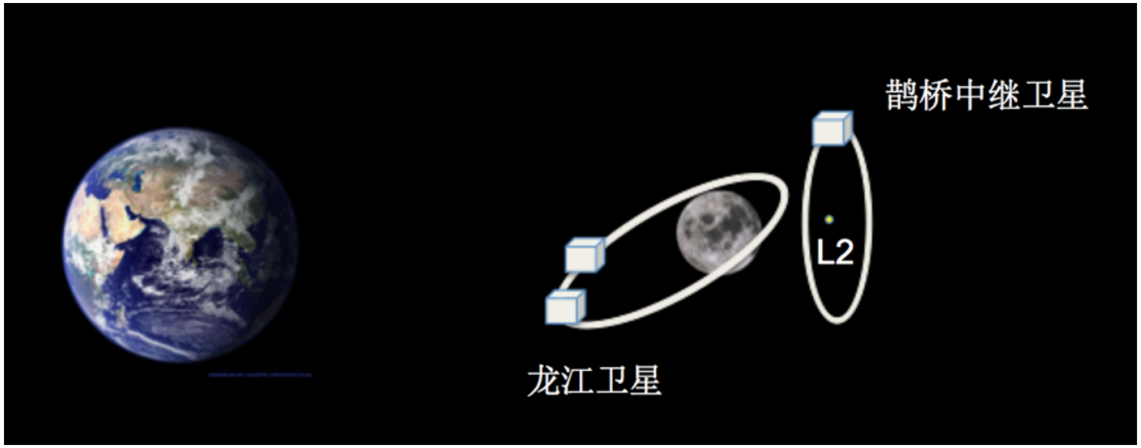
- The Moon can block the radiation from Earth
- Lunar surface—need to solve the problem of data transmission relay, and power supply during long lunar night
- lunar satellite: observe in the backside of moon, and transmit data back in front side
- Lunar orbit period is a few hours, can use solar power

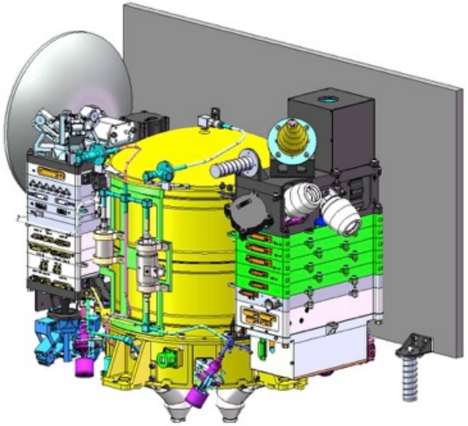
Experiments during CE-4 mission



- **CE-4 Lander**
- **Netherland-China Low frequency Experiment (Relay Satellite)**
- **Longjiang Orbiting satellites (piggy-back on relay satellite launch)**

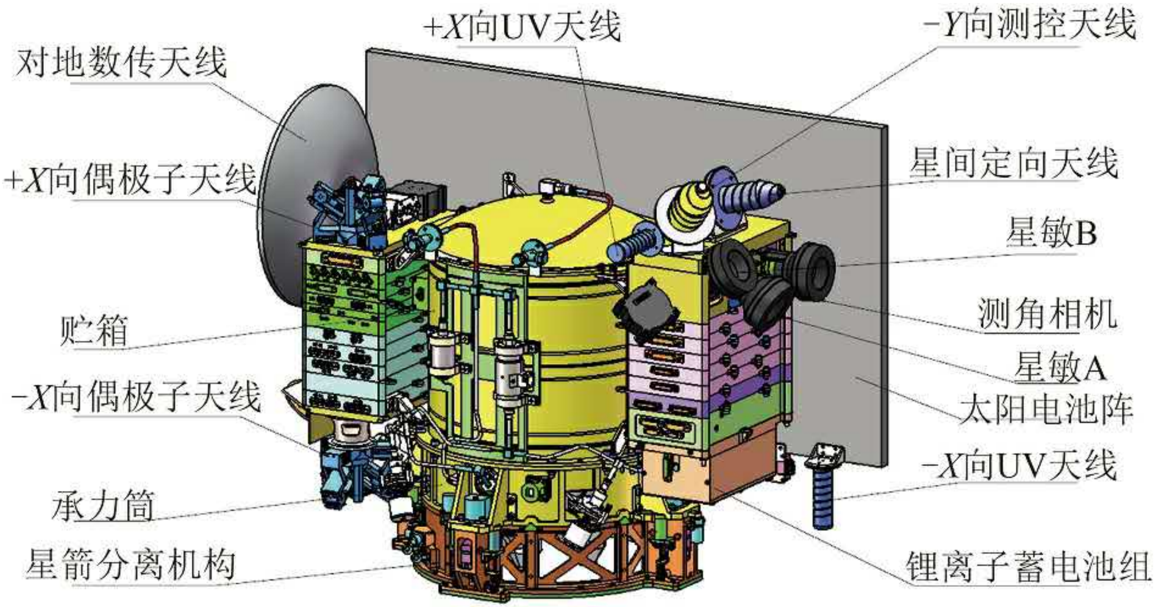






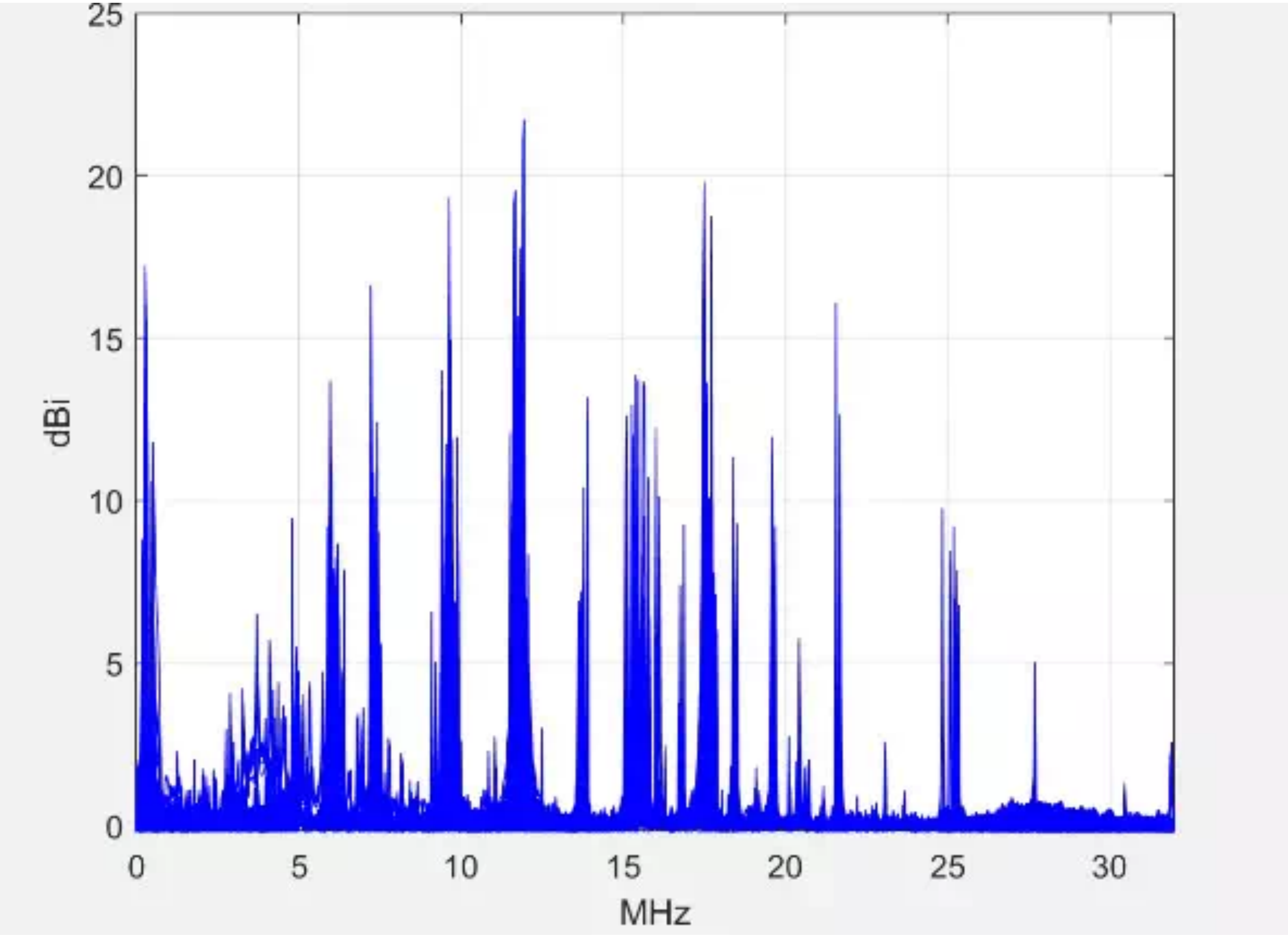
- Longjiang:
- Orbit: 21 hour elliptic orbit, 350 – 13700 km
- working time per orbit: 10-20 min.

- LJ-1 lost shortly after launch

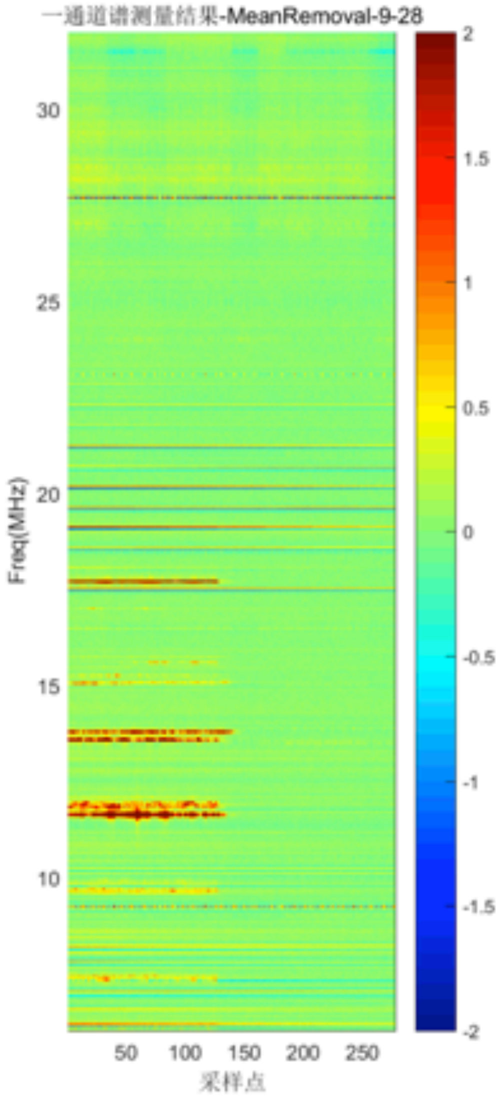


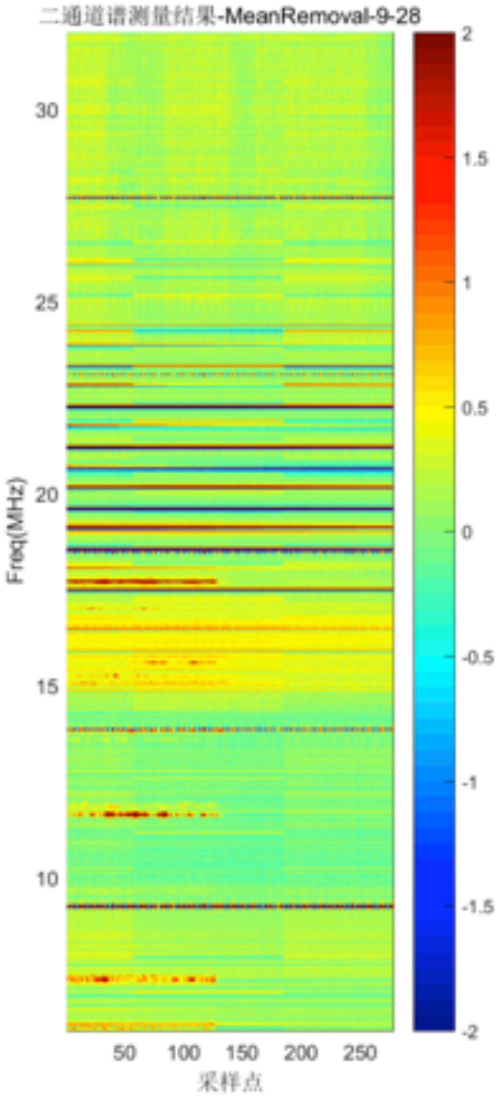
Problems

- **self-generated RFI**



Result


一通道谱测量结果-MeanRemoval-9-28
Freq(MHz)
30
25
20
15
10
50
100
150
200
250
采样点
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2


二通道谱测量结果-MeanRemoval-9-28
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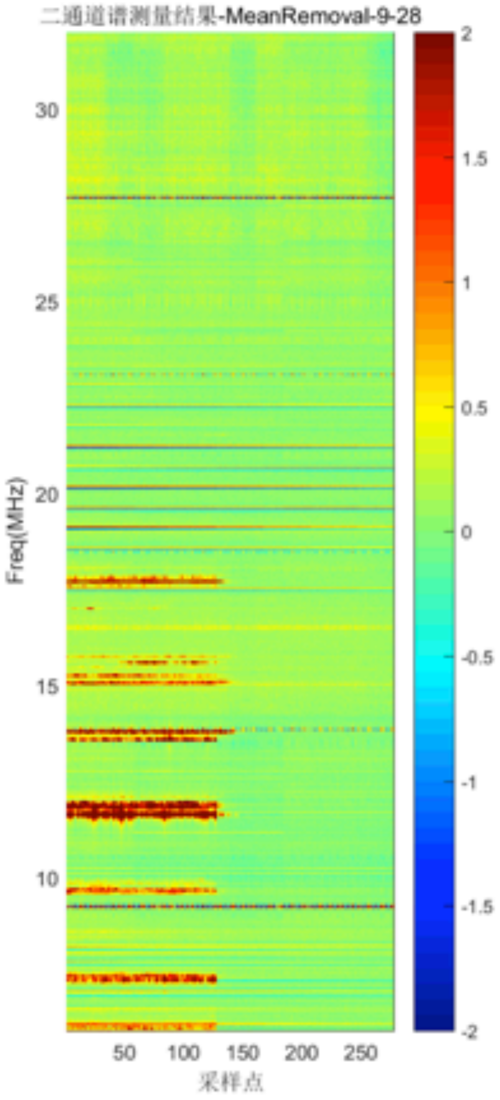
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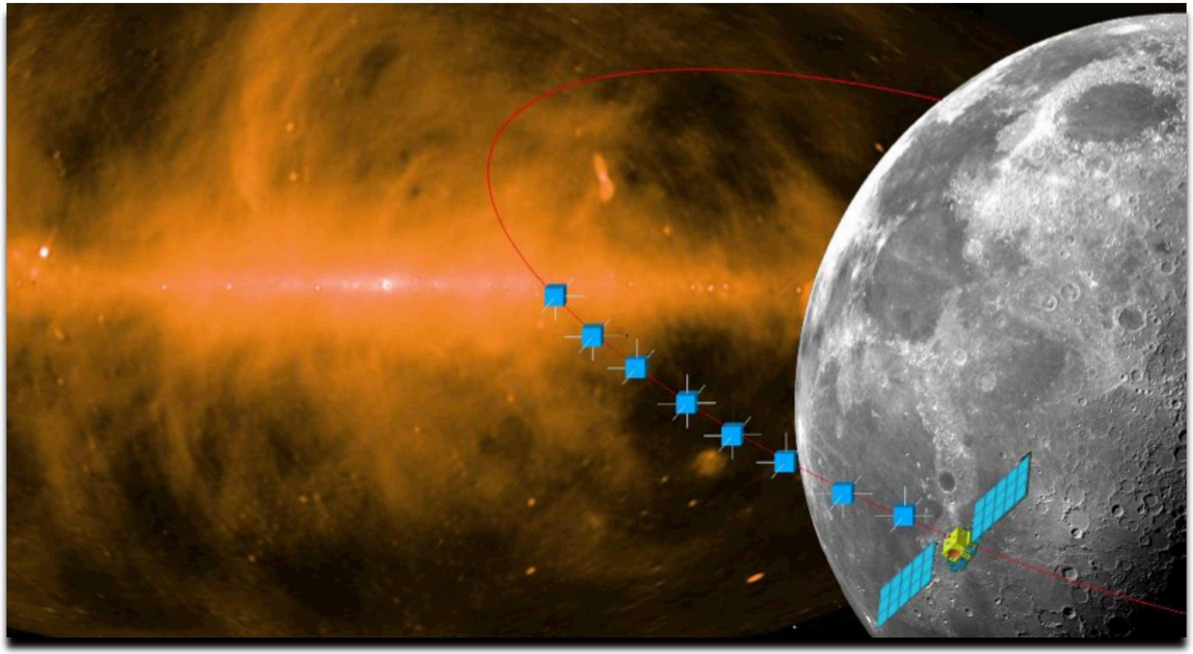
-2

Lunar Orbit Array DSL

An interferometer array with one mother satellite and 5~8 daughter satellites, on a 300km circular orbit

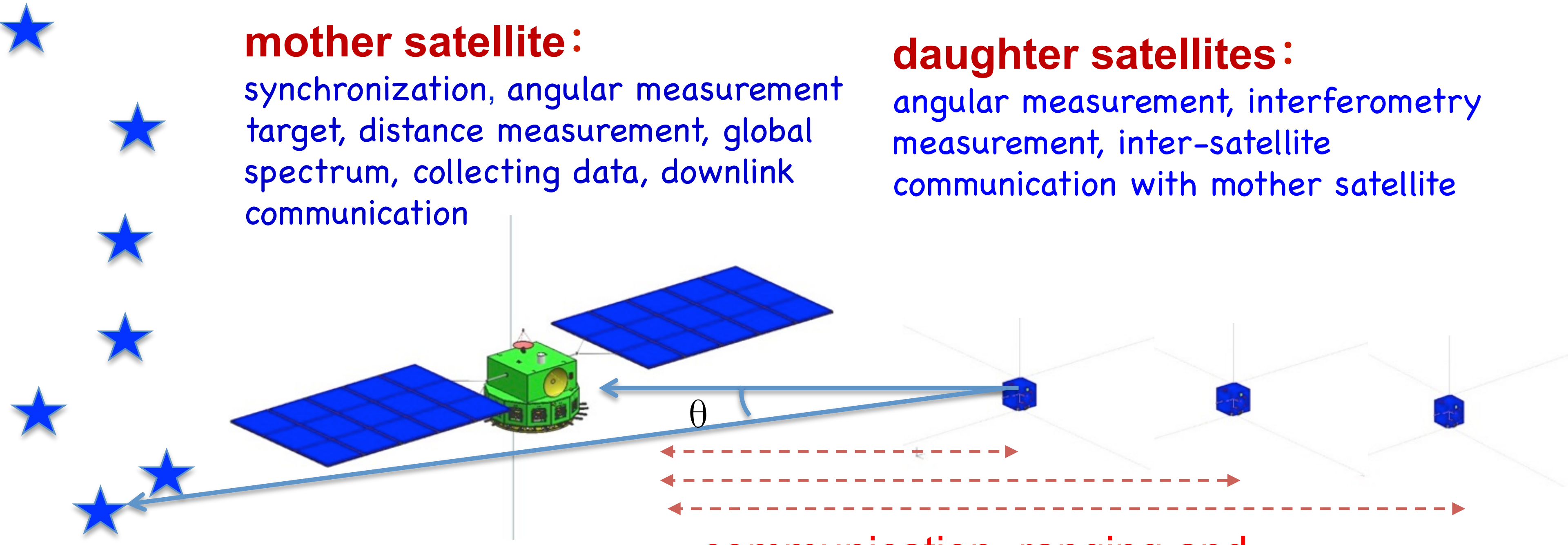


- **To obtain high resolution sky map at ultralong wavelength, openning up new window in eletromagnetic spectrum**
- **high precision measurement of global spectrum, to probe dark age and cosmic dawn**

Interferometer Array Realization

No need for high precision **adjustment** of satellite positions, but do **need** high precision of **relative position measurement**

- Synchronization, Distance Measurement, 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



mother satellite:

synchronization, angular measurement target, distance measurement, global spectrum, collecting data, downlink communication

daughter satellites:

angular measurement, interferometry measurement, inter-satellite communication with mother satellite

Star background for angle measurement

communication, ranging and synchronization through microwave link

Key Technology and Challenges

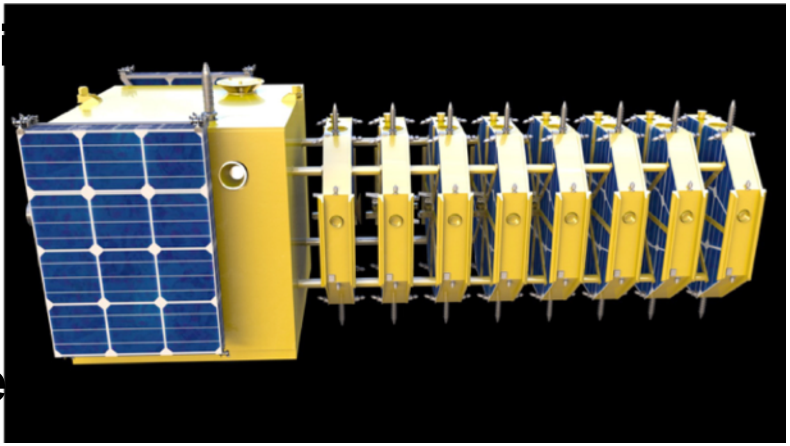
① **Satellite Formation Fly in lunar orbi with large variation on scales**

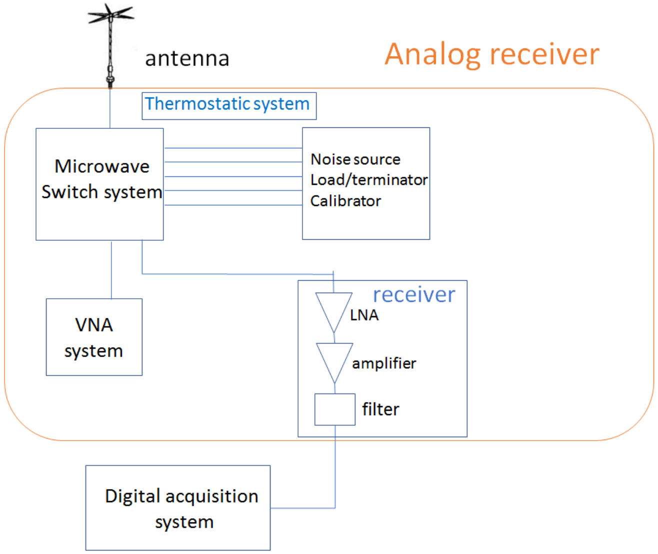
② **Precision Measurement of Relative Positions and synchronization**

③ **High precision calibration of phase and amplitude**

④ **Imaging algorithm with large field of view, 3D baseline distribution, and time-dependent blockage**

⑤ **Electromagnetic interference (EMI) suppresion and removal**





antenna

Analog receiver

Thermostatic system

Microwave Switch system

Noise source
Load/terminator
Calibrator

VNA system

receiver
LNA
amplifier
filter

Digital acquisition system

Spectrometer

Some Key Parameters

System	Parameter
Number of Satellites	1 mother＋ 5~8 daughters
Orbit	300km lunar cirlcular orbit， about 30^0 inclination
Baselines	0.1~100km
Sensitivity	〈0.1K@30MHz（1 year integration,1MHz BW）
angular resolution	〈0.2 degree@1MHz， 0.012 degree@30MHz
Individual	
Polarization	3 linear polarization
Frequency	1MHz~30MHz（interferometry incl. spectrum） 30MHz~120MHz（global spectrum）
Baseline prescision in each direction (1σ)	〈 1m
Synchronization	〈3.3ns
Inter-satellite data communication	〉20Mbps each daughter satellite

System Performance Analysis

Angular Resolution

$$\theta \sim \frac{\lambda}{D}$$

ISM and IPM scattering

$$\vartheta_{\mathrm{ISM}} \approx \frac{30'}{(\nu/\mathrm{MHz})^{2.2}\sqrt{\sin b}},$$

$$\vartheta_{\mathrm{IPM}} \approx \frac{100'}{(\nu/\mathrm{MHz})^{2}}$$

Diffraction Limit

	10 km baseline	30 km baseline	100 km baseline
1 MHz	1.7°	0.57°	0.17°
10 MHz	0.17°	0.057°	0.017°
30 MHz	0.057°	0.019°	0.0057°

The angular resolution is limited by scattering, 100km baseline sufficient

Dispersion and Scattering

$$\Delta t = 4.15 \times 10^{3}\ \mathrm{DM}\ (\nu/\mathrm{MHz})^{-2}\ \mathrm{s}$$

Observing pulsars and FRBs would be hard due to very large dispersion delays

Depolarization

$$\Delta\psi_{\mathrm{RMS}} = 2.6 \times 10^{-13}\ \lambda^2\ \Delta N_e\ \lambda^2 a\ B_{\parallel}\sqrt{L/a}\ \mathrm{rad},$$

At this frequency, linear polarization is greatly reduced by depolarization. Circular polarization may be observable.

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 array, small field of view, small-w approximation: 2D FFT

$$V_{ij}(u,v,w) = \int \frac{\mathrm{d}l\,\mathrm{d}m}{n} A_{ij}(l,m) T(l,m)\, e^{-i2\pi[ul+vm+w(n-1)]}$$

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

- For large FOV, or non-planar array, needs to take into account of the w-term:

3D Fourier transform: $V(u,v,w)e^{-i2\pi w} = \int \frac{I(l,m)\,\delta\sqrt{1-l^2-m^2}-n}{\sqrt{1-l^2-m^2}} e^{-i2\pi[ul+vm+wn]} dl\, dm\, dn$

w-projections: $V(u,v,w) \otimes \mathcal{K}^*(u,v,w) = V(u,v,0)$

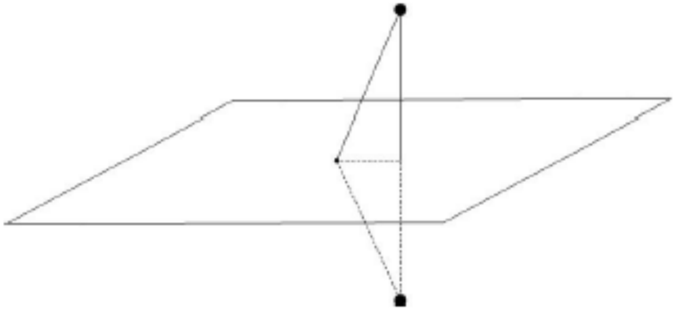
$$\mathcal{K}(u,v,w) = \int e^{-i2\pi w(\sqrt{1-l^2-m^2}-1)}\, e^{-i2\pi(ul+vm)}\, dl\, dm$$

w-stacking: $\frac{I(l,m)\,(w_{\max} - w_{\min})}{\sqrt{1-l^2-m^2}} = \int_{w_{\min}}^{w_{\max}} e^{i2\pi w(\sqrt{1-l^2-m^2}-1)}\, \mathcal{F}^{-uv}\, [V(u,v,w)]\, dw$

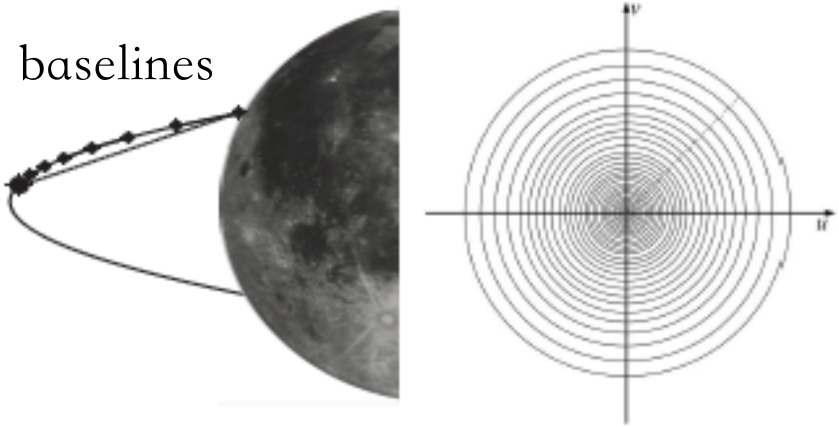
Problems

But here we face the following problems:

- whole sky field of view,
- problem of mirror symmetry,
- 3D distribution of baselines
- Position-dependent blockage



mirror symmetry



Kill two birds with one stone:
3D baselines actually solves
the mirror symmetry problem 🙂

Position-dependent blockage by moon:
visibility for each baseline has different
part of sky blocked by the Moon!

Image Reconstruction

- Fundamentally, the relation between the sky intensity and visibility is a time-dependent (but known) linear map.

$$\mathbf{V} = \mathbf{B}\,\mathbf{I} + \mathbf{n}$$ B=A S(t) I, S: screening by Moon

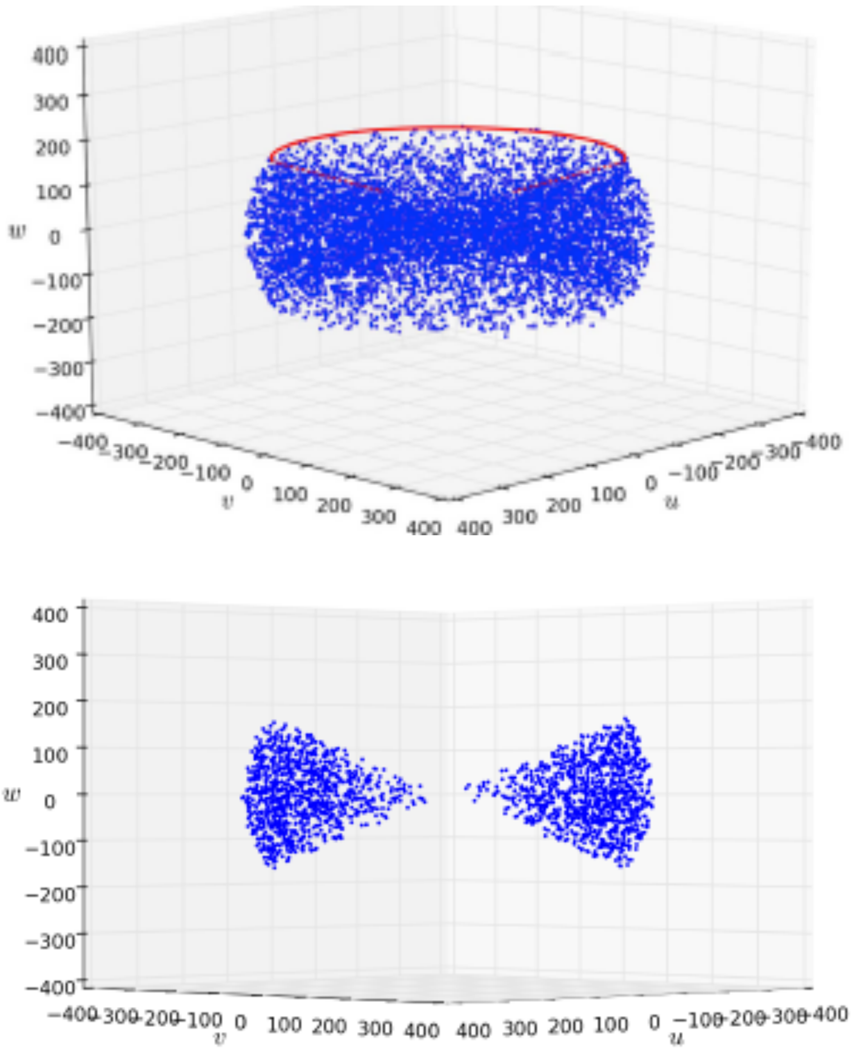
- So one can invert the map and obtain the image.

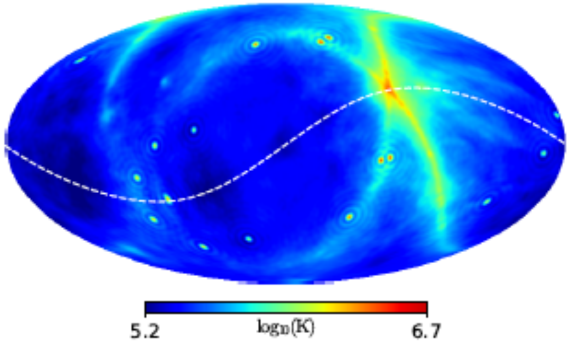
$$\hat{\mathbf{I}} = (\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{B})^{-1}\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{V}$$

- Spherical Harmonic Expansion can be employed to reduce computation

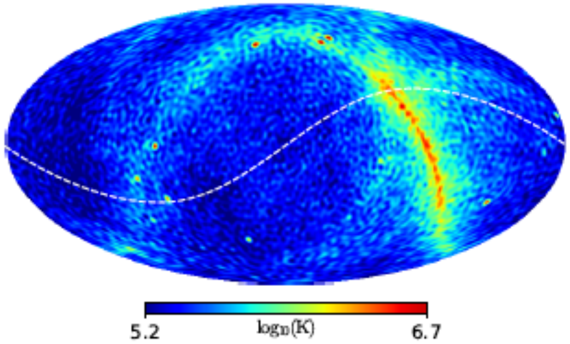
Break mirrow symmetry by 3D baselines

3D baseline distribution

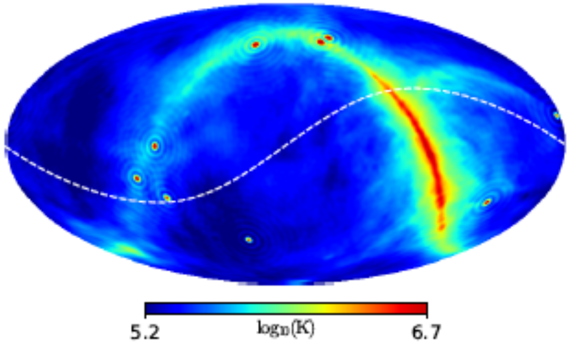




planar
baselines



70%
planar
baselines

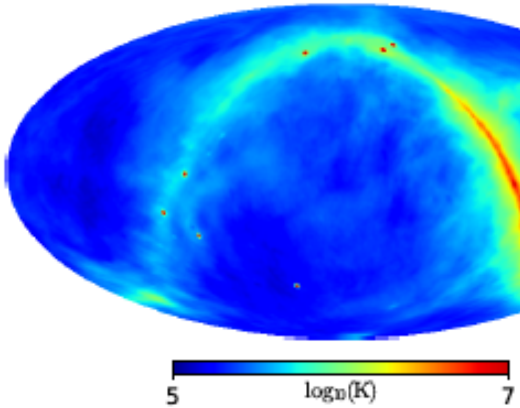


full 3D
baselines

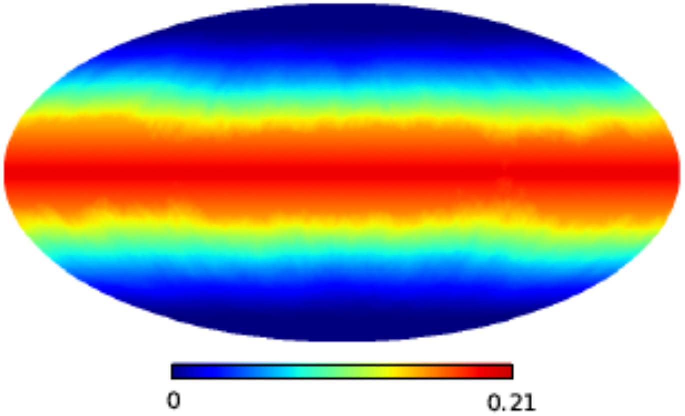
Reconstruction Results

Q. Huang et al.:
AJ 156, 43 (2018)

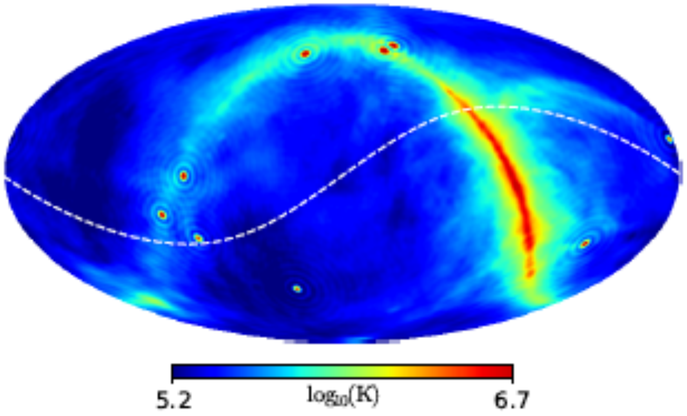
input map



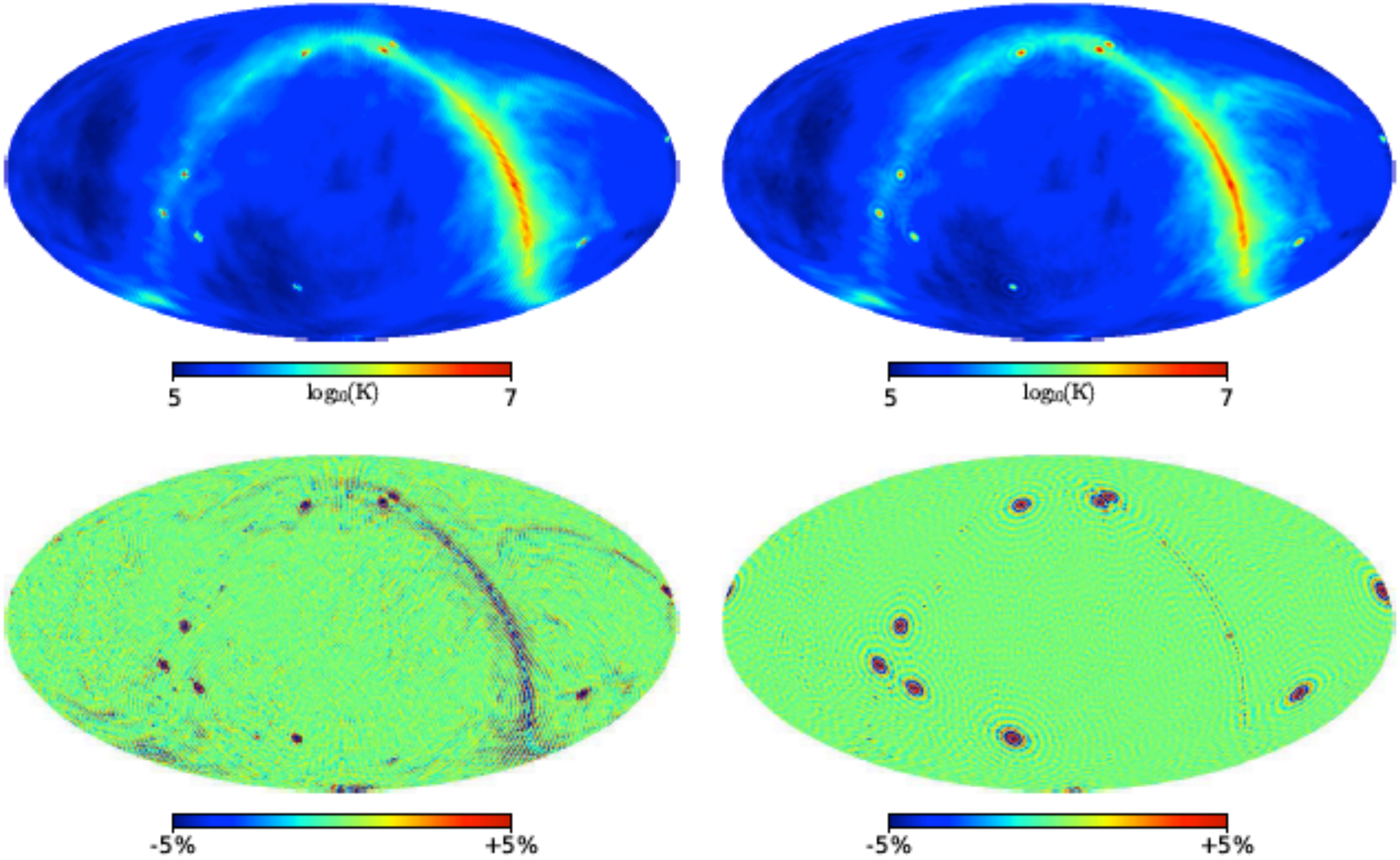
blockage



reconstructed map



Errors in the reconstruction result



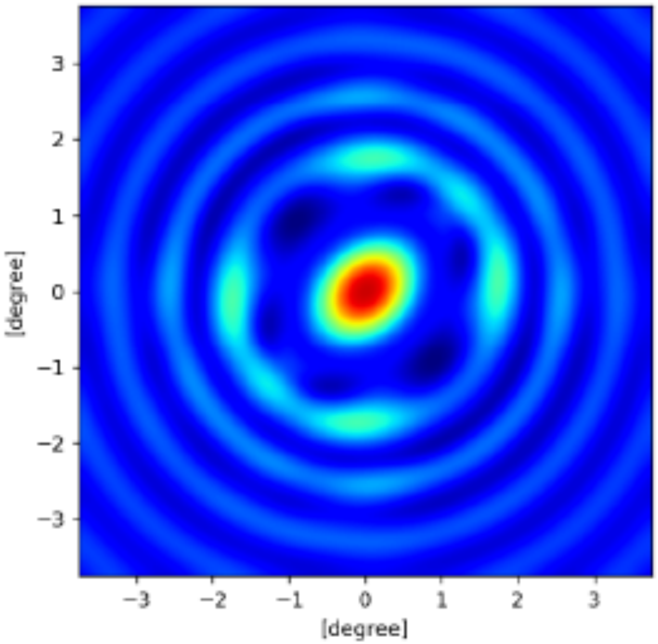
pixel space reconstruction

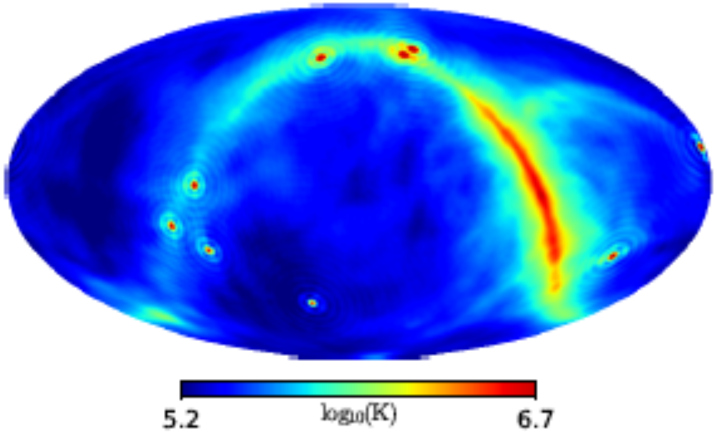
harmonic space reconstruction

Reconstructed Map

Relative Error

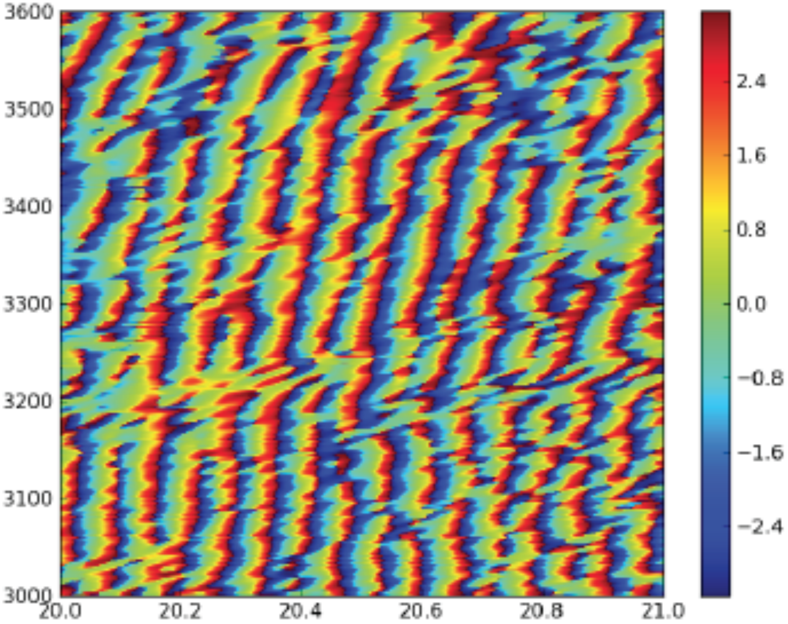
Image with asymmetric baselines





Problems to be solved

- Effect of noise and sensitivity
- Varying Sources
- Antenna Directionality
- Error in Position Measurement and Synchronization
- Calibration Method
- Reflection of the Moon
- Optimal Strategy



Simulated fringes (Zuo et al. in progress)

Project Status

- Currently undergoing intensive study, look for 2023-2025 launch.

- PI: Xuelei Chen (NAOC), Technology Chief: Jingye Yan (NSSC)

- International Collaboration Welcome!

- Interested researchers welcome to join the Science Working Group, to discuss the science cases and key technologies

- An ISSI-BJ forum report has been put published (arxiv:1907.10853). Also discussed in *Peering into the Dark (Ages) with Low-Frequency Space Intergerometers* (ESA Voyage 2050 white paper, arxiv:1908.04296)

太空 | TAIKONG

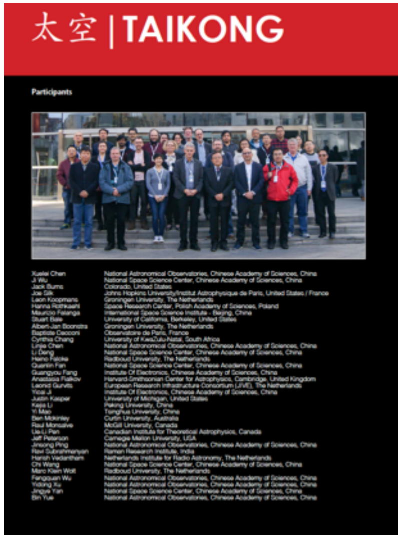
ISSI-BJ Magazine

No. 14 July 2019

国际空间科学研究所 - 北京

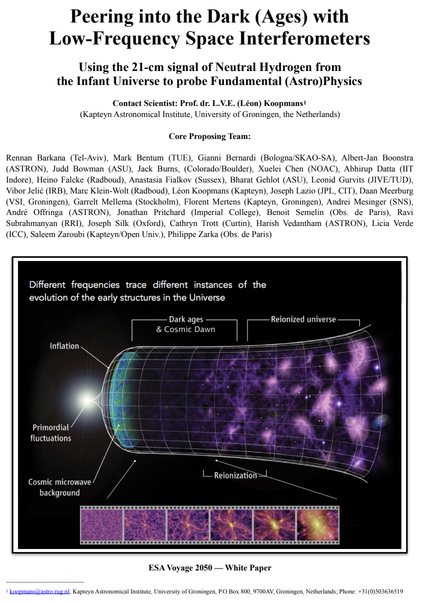
DISCOVER THE SKY BY LONGEST WAVELENGTH

WITH SMALL SATELLITE CONSTELLATION



太空 | TAIKONG

Participants



Peering into the Dark (Ages) with
Low-Frequency Space Interferometers

Using the 21-cm signal of Neutral Hydrogen from
the Infant Universe to probe Fundamental (Astro)Physics

Contact Scientist: Prof. dr. L.V.E. (Léon) Koopmans[1]
(Kapteyn Astronomical Institute, University of Groningen, the Netherlands)

Core Proposing Team:

Rennan Barkana (Tel-Aviv), Mark Bentum (TUE), Gianni Bernardi (Bologna/SKAO-SA), Albert-Jan Boonstra (ASTRON), Judd Bowman (ASU), Jack Burns, (Colorado/Boulder), Xuelei Chen (NOAC), Abhirup Datta (IIT Indore), Heino Falcke (Radboud), Anastasia Fialkov (Sussex), Bharat Gehlot (ASU), Leonid Gurvits (JIVE/TUD), Vibor Jelić (IRB), Marc Klein-Wolt (Radboud), Léon Koopmans (Kapteyn), Joseph Lazio (JPL, CIT), Daan Meerburg (VSI, Groningen), Garrelt Mellema (Stockholm), Florent Mertens (Kapteyn, Groningen), Andrei Mesinger (SNS), André Offringa (ASTRON), Jonathan Pritchard (Imperial College), Benoit Semelin (Obs. de Paris), Ravi Subrahmanyan (RRI), Joseph Silk (Oxford), Cathryn Trott (Curtin), Harish Vedantham (ASTRON), Licia Verde (ICC), Saleem Zaroubi (Kapteyn/Open Univ.), Philippe Zarka (Obs. de Paris)

Different frequencies trace different instances of the evolution of the early structures in the Universe

ESA Voyage 2050 — White Paper

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[1] koopmans@astro.rug.nl; Kapteyn Astronomical Institute, University of Groningen, P.O.Box 800, 9700AV, Groningen, Netherlands; Phone: +31(0)503636519

Thanks!