Progress of MUSER and Chinese IPS telescope for space weather

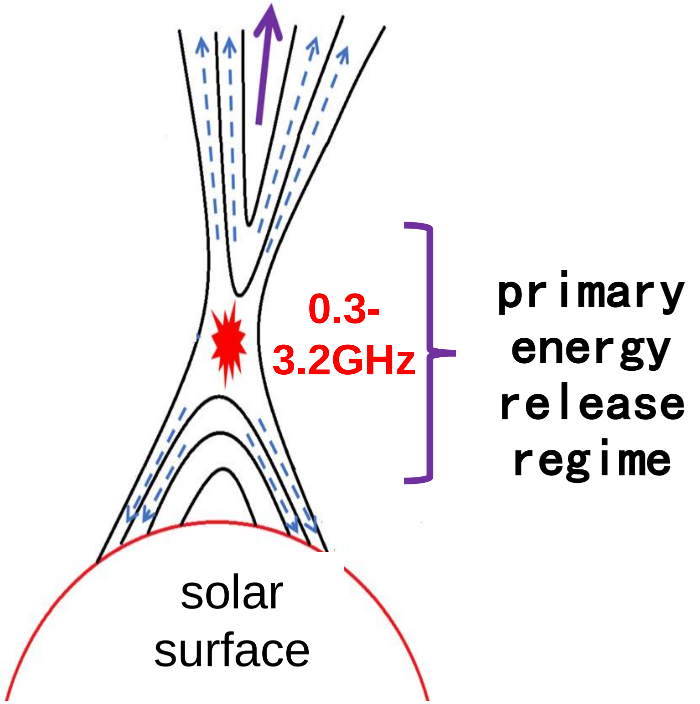
Wei Wang & Project team

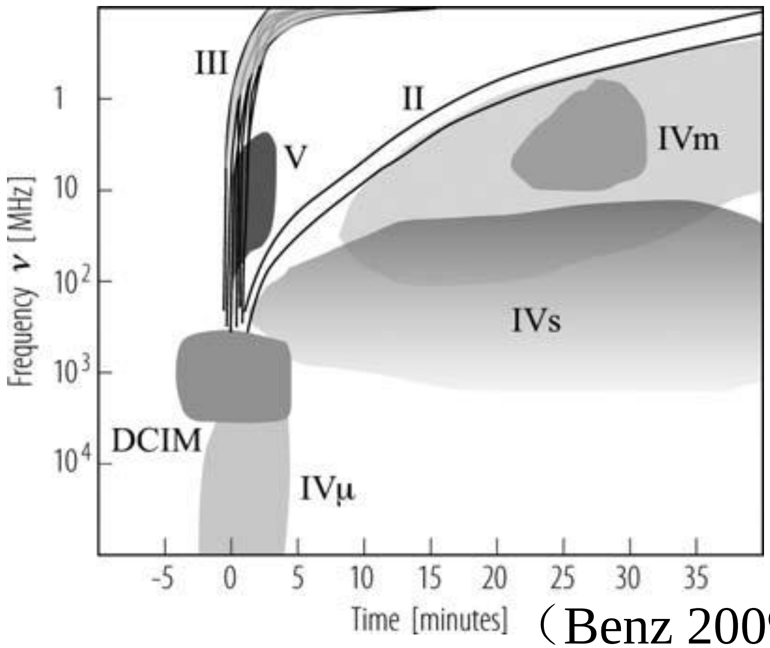
National Space Science Center, CAS
National Astronomical Observatories, CAS

outline

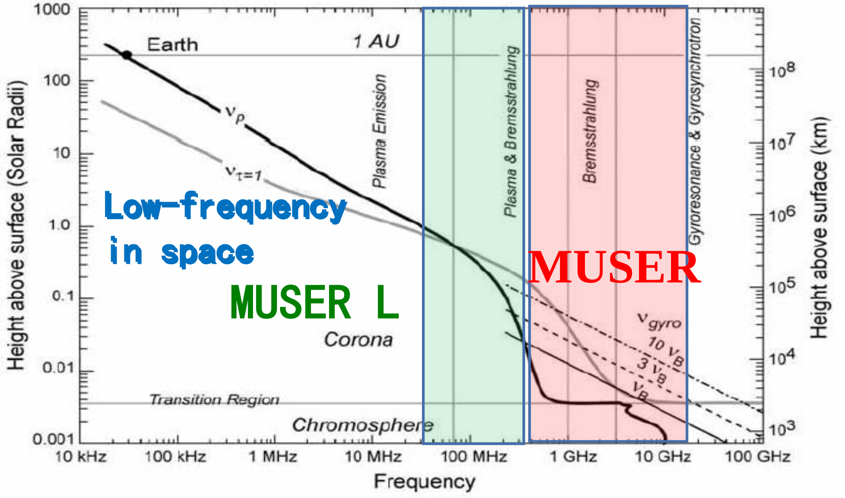
1. MUSER
    1. Introduction, calibration
    2. Observations
2. IPS telescope
    1. introduction, calibration
    2. Preliminary Observation
3. Summary

Developing Imaging-Spectroscopy Capacity





（Benz 2009）



(Gary & Hurford, 1999)

- **Bremsstrahlung**
- **Gyroresonance**
- **Coherent emission**
  - ★ **Plasma emission**
  - ★ **ECME**

$$\nu_p = 8.98\times10^3\sqrt{n_e}$$

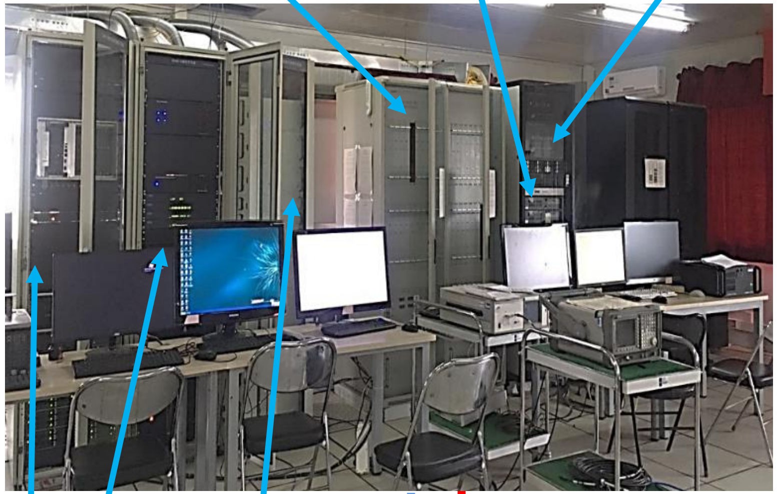
$$\nu_{\tau=1} \approx 0.5 n_e T_e^{-3/4} L^{1/2}$$

$$\nu_B = 2.8\times10^6 B$$

- The Sun is an effective accelerator
- During solar flares/CMEs, thermal/non-thermal particles at the Sun can be accelerated to high energy as revealed in HXR/γ-rays and in radio regime
- where the acceleration (or primary energy release) take place? how many particles are accelerated? how they are accelerated? associations between X-rays and radio? etc.

Mingantu Spectral Radioheliograph — MUSER

- MUSER constructed in 2009-2013 by National Major Scientific Research Facility Program
- MUSER being upgrated to add MUSER-L in 2019-2023 by Meridian II project.
- Since 2022 MUSER & Team moved from NAOC to NSSC due to re-organization of SKL by CAS.



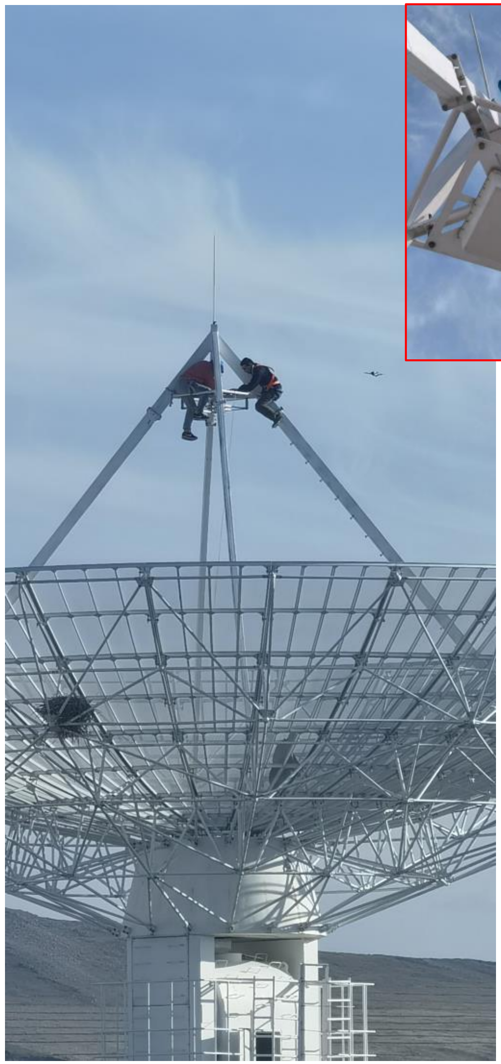
optic cables (3.4km, 2.5m underground)

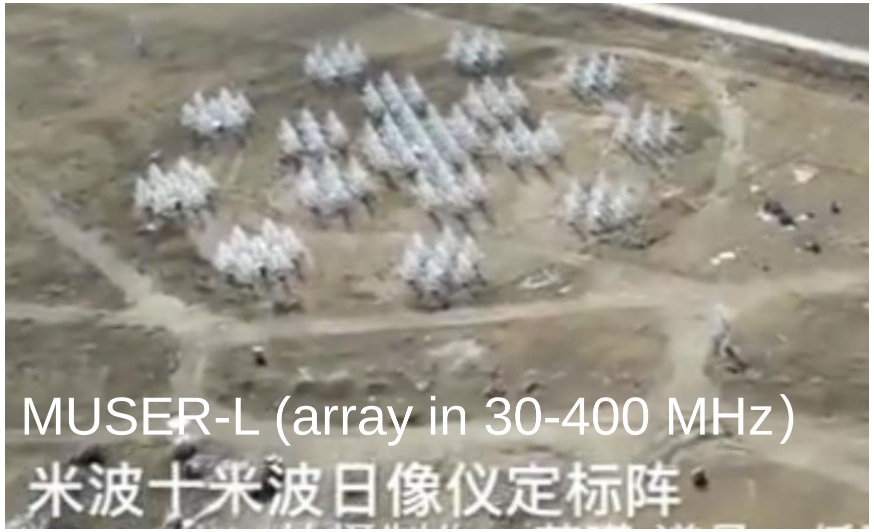
MUSER situation

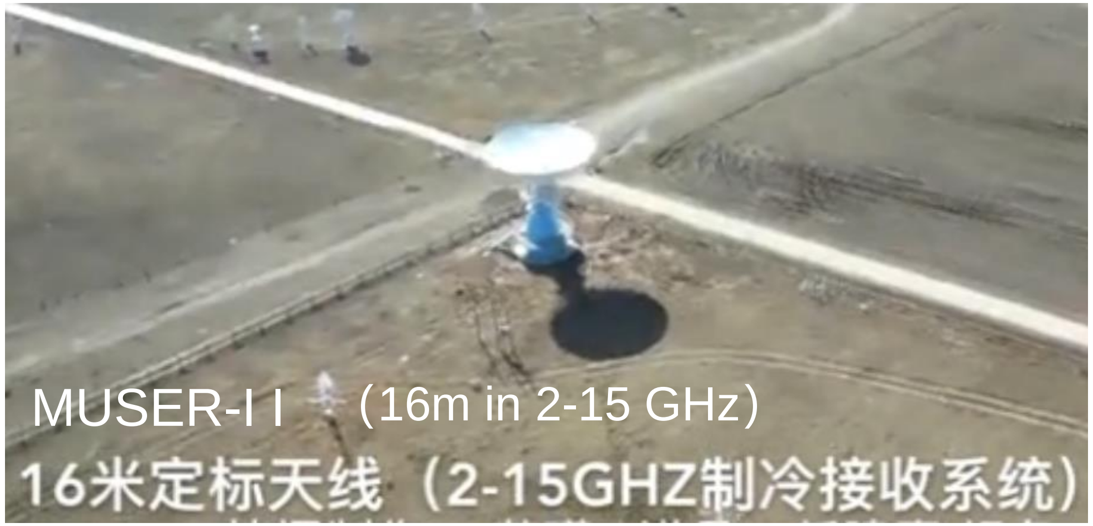
In Gary (2023, ARAA), it was pointed out: "MUSER has exactly the right specifications to perform high-quality imaging spectroscopy, but in practice it has struggled to produce useful images, and those only at a few frequencies (Zhang et al. 2021)." The reason is that MUSER "seems to be lack of a good calibration." "The MUSER ... is to add a large dish with a cryogenic receiver for calibration like that used by EOVSA."

A new calibration method is developed (Zhou et al., 2022) and the 16m and 20m calibration antennas for MUSER-I & II under the Meridian II project have been constructed so that MUSER will be fully functioning.

Construction of MUSER Calibration Antennas







A new formula for calibration

original sources

with MUSER array

with offset errors ~5 times of the angular resolution

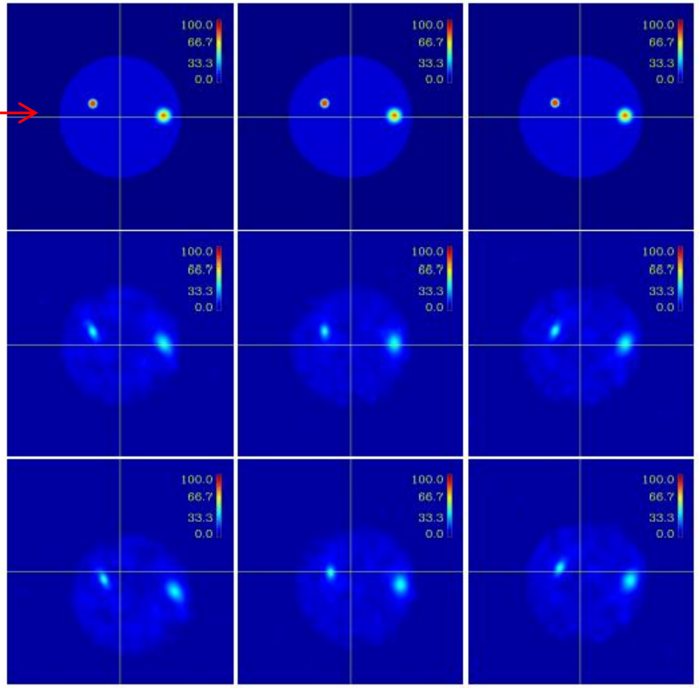


Figure 3. *Upper row*: the solar model at three instants in the morning, at noon and in the afternoon at 02:05:00, 04:05:00, and 06:05:00 UT respectively. *Middle row*: the corresponding dirty images of the model if they were observed by MUSER. *Bottom row*: the corresponding dirty images further affected by the calibrator position deviation.

（Zhou et al. 2022, RAA）

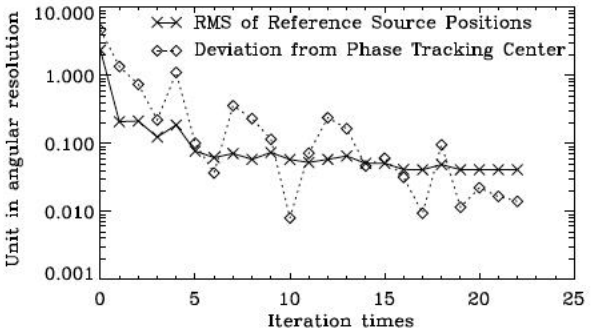
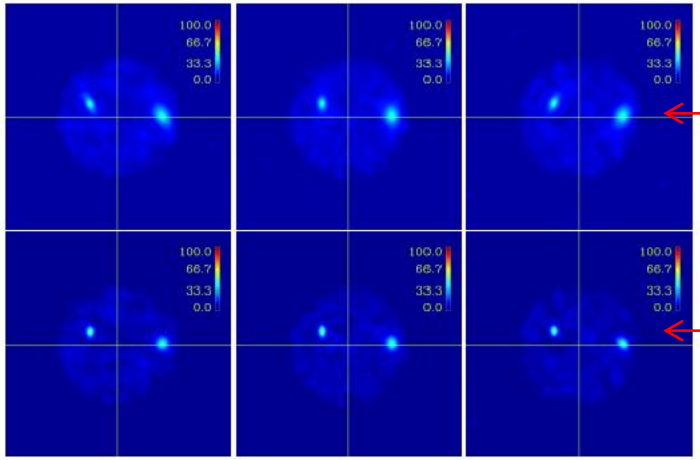


Figure 4. The iteration history *a posteriori* of the RMS values of the reference source positions (solid line and "cross" symbol) and the deviation from the phase tracking center (dotted line and "diamond" symbol) for the solar model simulation. These values are expressed in unit of the angular resolution at MUSER observing frequency.

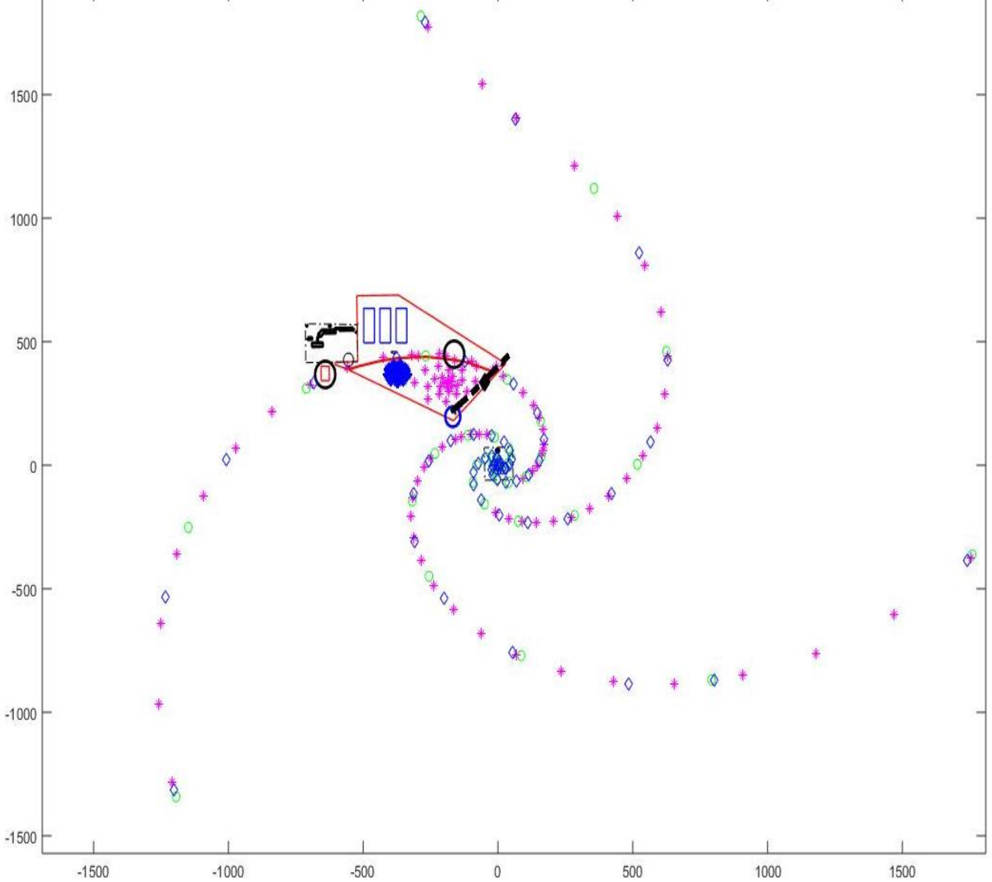
restored accuracy: <5% angular resolution

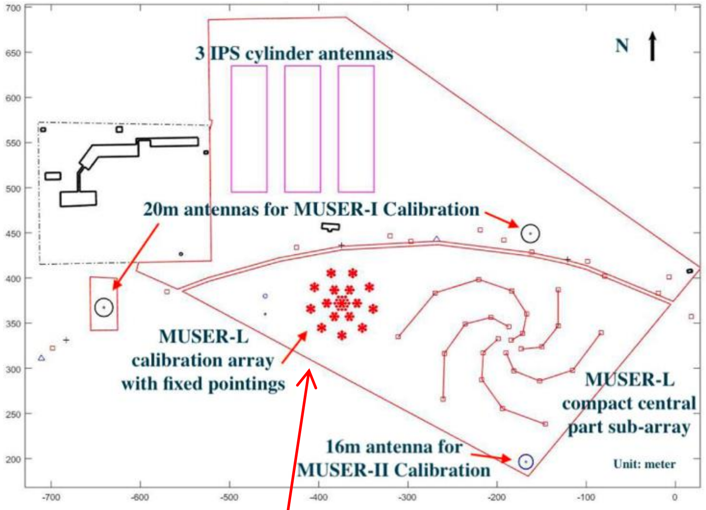


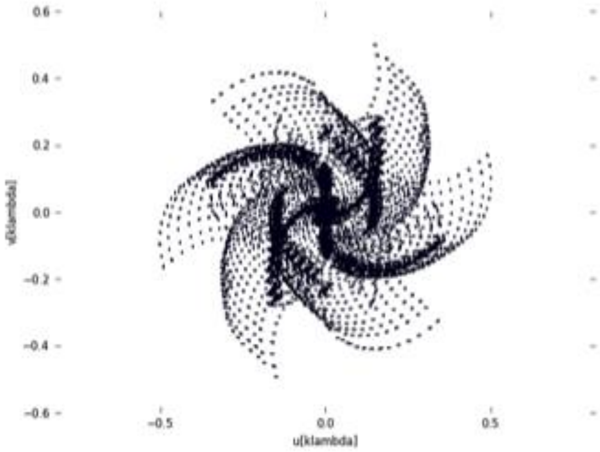
restored

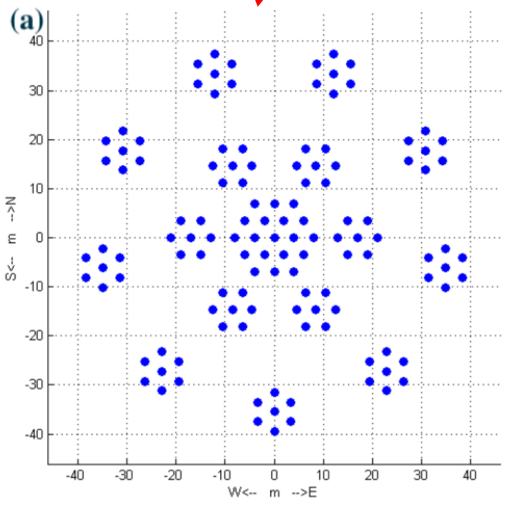
cleaned

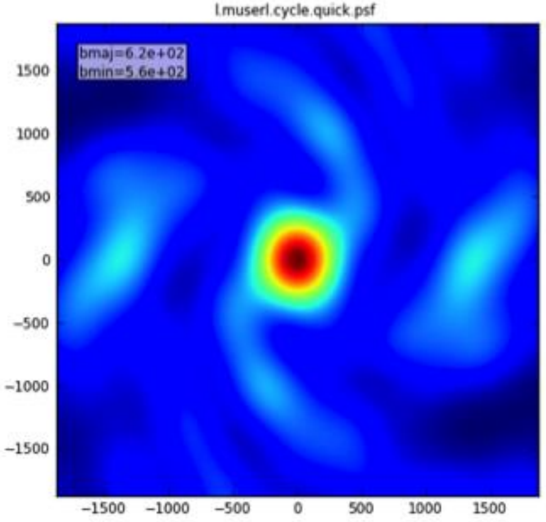
MUSER at metric & decametric wavelengths: MUSER-L











blue & green ------ MUSER-I/II

red: -------MUSER-L

MUSER-L

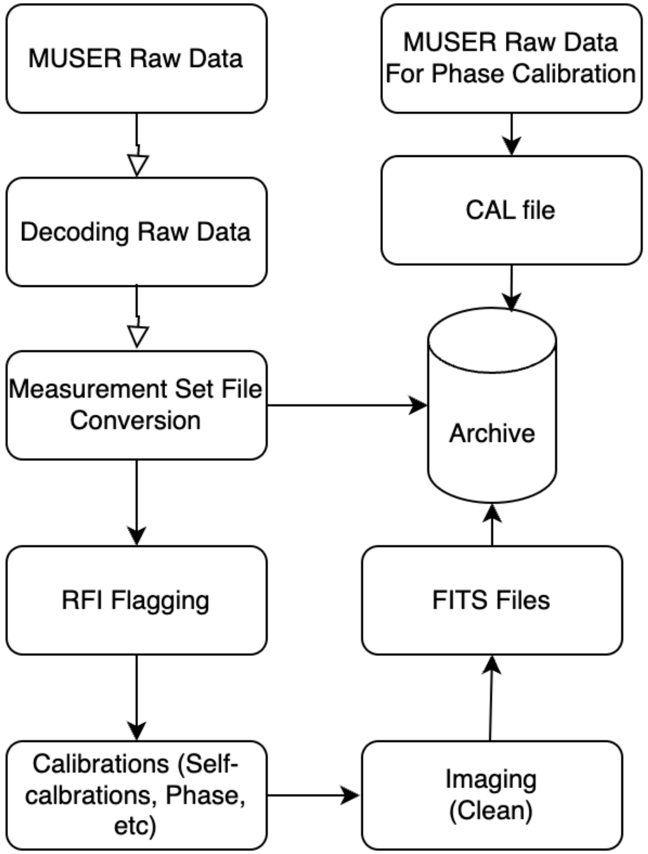
Table 1
Performance of MUSER-L.

Frequency range:	30 ~ 400 MHz
Antennas:	100 steerable LPDA + calibration element (124 fixed pointing LPDA)
Max baseline:	~3000 m
Frequency resolution:	1–5 MHz
Time resolution:	~100 ms
Angular resolution:	14.0′-1.0′
Polarization:	I, Q, U, V
Dynamic range:	⩾25 dB

100 LPDA + Calibration (124 LPDA)

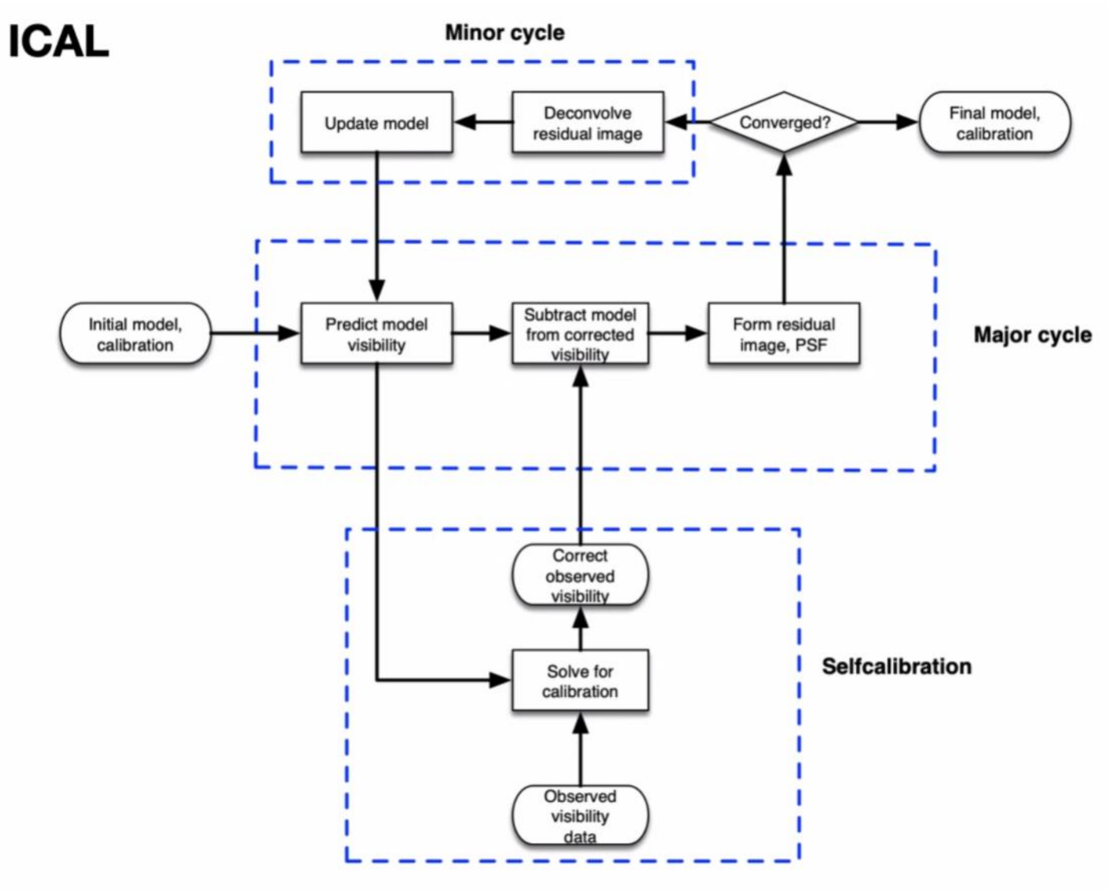
Data Processing Workflow

- MUSER-L SDHP System
  - Python + C/C++
  - GPU Support
  - WebUI
- Functions
  - Raw Data Decoding
  - Measurement/UVFITS
  - Calibrations (Self-calibrations)
  - RFI Flagging
  - Imaging And Clean (MS, MSMFS)

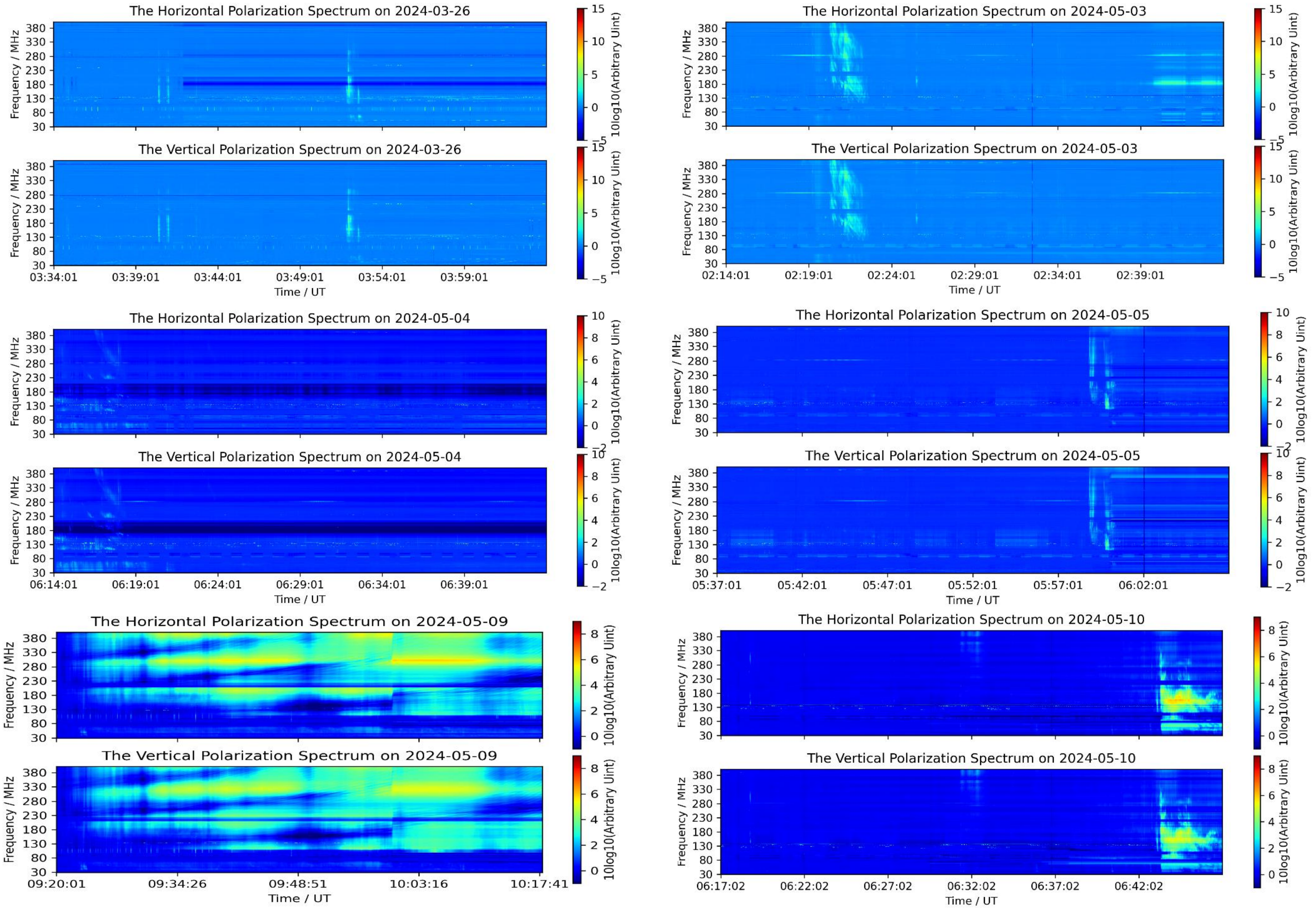


CLEAN

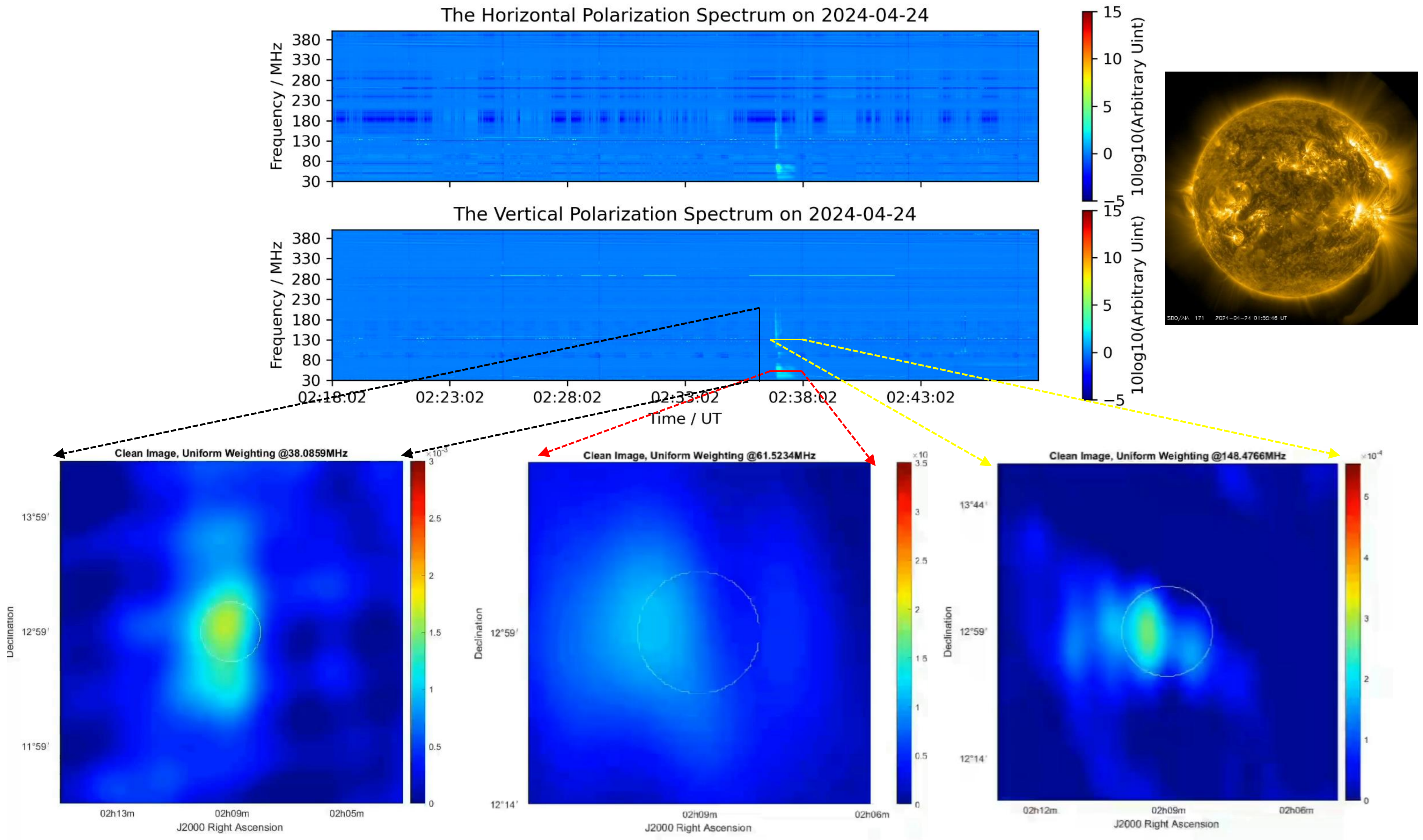
- IMAGING Function
  - Antenna Flagging
  - Baseline Flagging
  - Self-calibration
  - Imaging (supports Natural, Robust and Uniform)
- Scientific Production
  - FITS file



Solar radio observations



Solar radio observations (2024-4-24)



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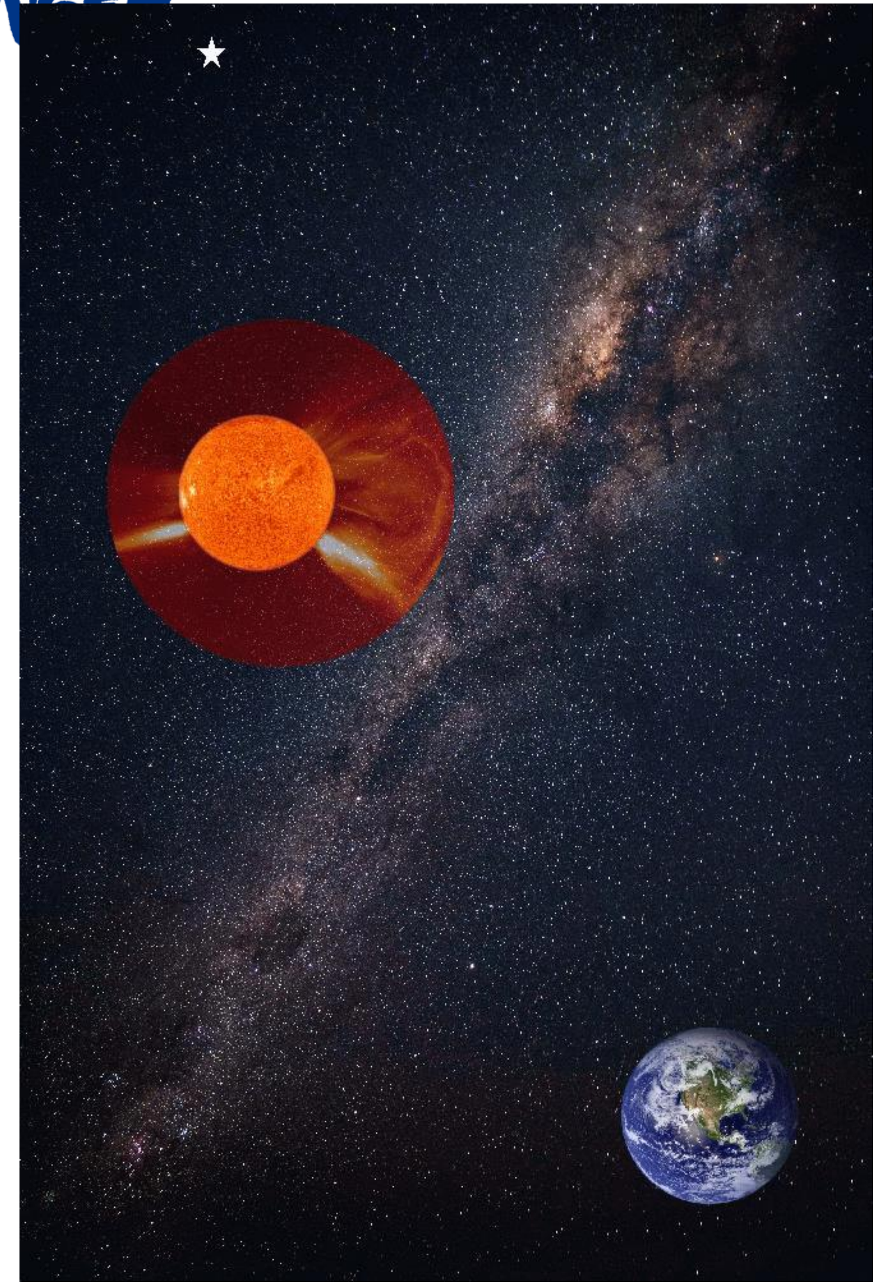
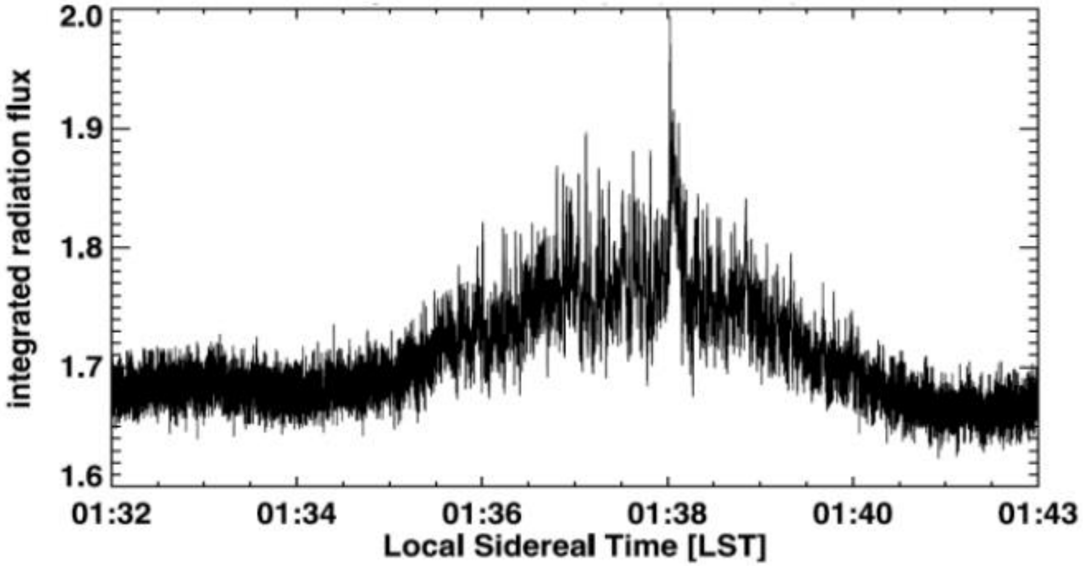
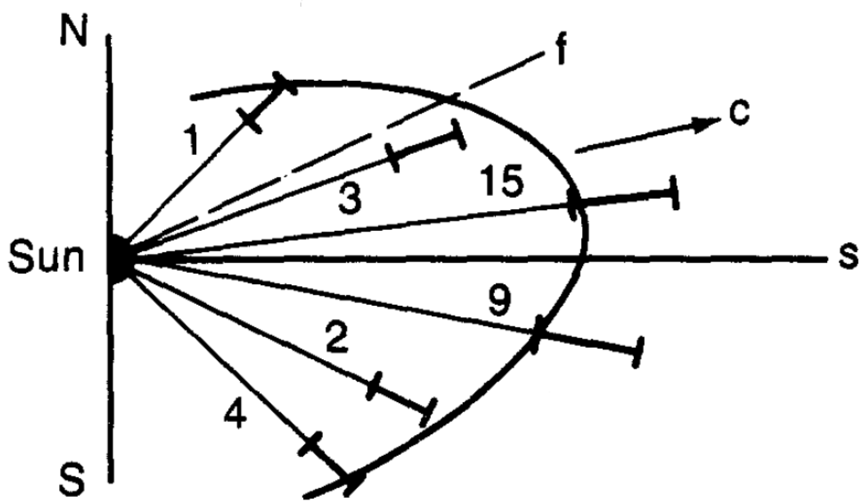


IPS time series data



- IPS refers to random fluctuations in radio intensity of distant small-diameter celestial objects. The scattering and scintillation of emergent radio waves are ascribed to turbulent density irregularities transported by the solar wind streams.
- In 1960, Hewish at the University of Cambridge built the world's first IPS telescope, detected IPS signals for the first time (Nature, 1964) and discovered pulsars for the first time (Nature, 1967), the Nobel Prize in Physics in 1974.

Early Concept and Scientific Research of IPS in China



- Wang S.G., regarding the use of the Miyun meter-wave radio telescope for IPS observation research, 1990.
- By adding the signals from 28 9m antennas in adding mode, an effective aperture equivalent to a 47-meter telescope is obtained, while simultaneously achieving the resolution equivalent to a 1200-meter aperture telescope.

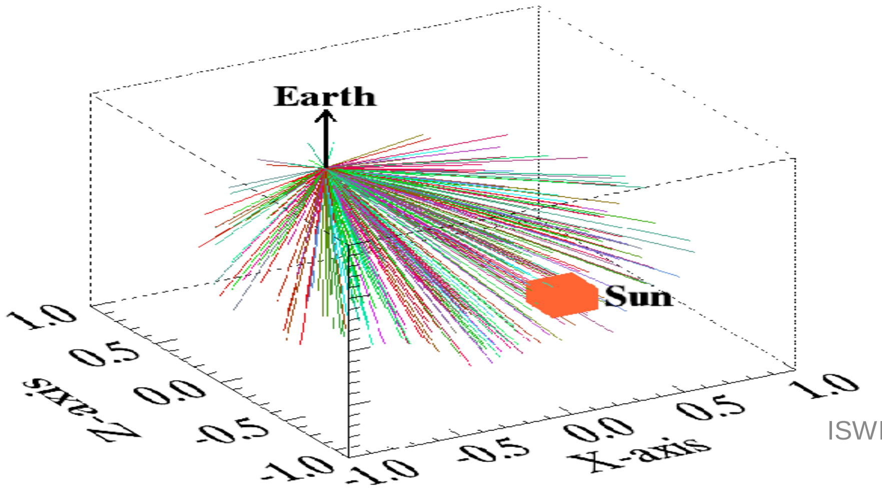
- Wei F.S., Revealing the Anisotropic Propagation of Interplanetary Shocks Based on IPS Observations (Wei & Murray, Solar Phys 1991)
- The current sheet impedes the transverse propagation of shocks, resulting in effects on the near-Earth space environment on both the same side and the opposite side of the current sheet.

Interplanetary scintillation (IPS)

Current facilities: (ORT, MEXART) 1 station with larger collecting areas
(ISEE) multiple-stations with intermediate size

Single Station IPS	Multiple Station IPS
ORT: one 530*30 m antenna	ISEE: 3 100*20 + 74*27 m antennas
~1000 radio sources	~100 radio sources
Vsw deduced from model	Vsw deduced from measurement

Lines of sight – typically observed in a day
By Ooty telescope (2-AU cube)---Manoharan

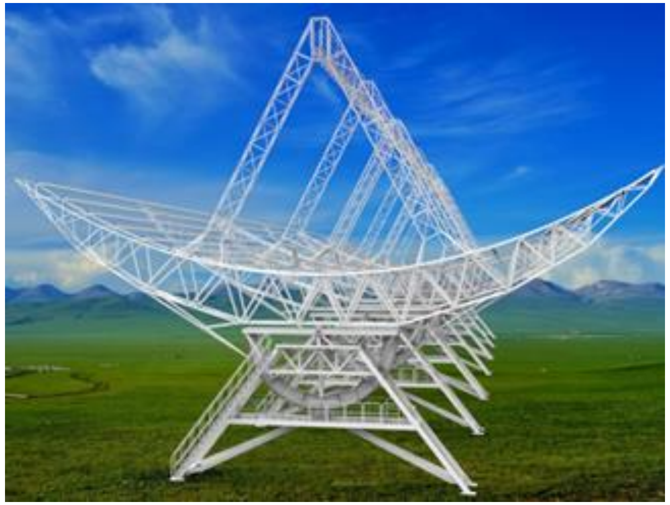


IPS technique applies "CT" to reconstruct 3-d solar wind structure. It would desire to achieve direct measurements from observing more radio sources!

A new Telescope Concept

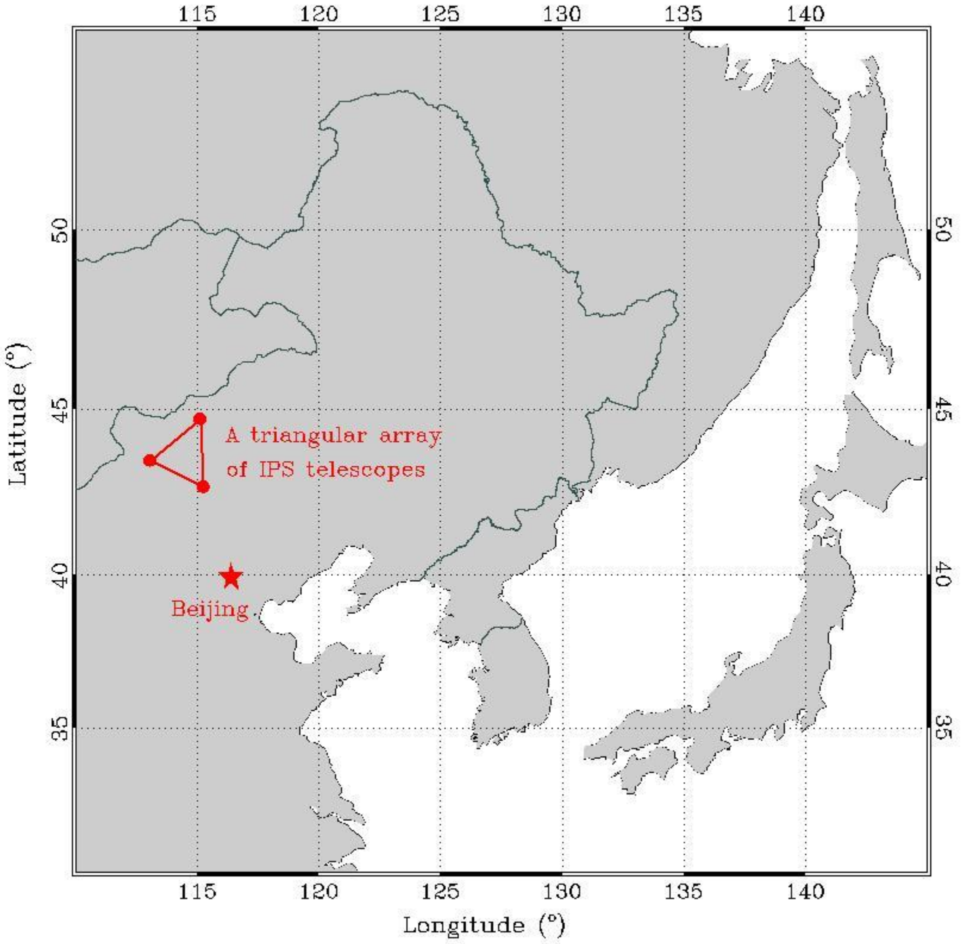
A new solution is proposed (Yan, Wang et al. 2018):

- The whole IPS telescope consists of 3 sites, one main site and 2 sub-site.
- Main site: 3 cylinder antennas placed side by side, and size of each antenna is 140m in N-S direction and 40m in E-W direction;.
- Sub site: 1 30m parabolic antenna with cryogenically cooled receiver.

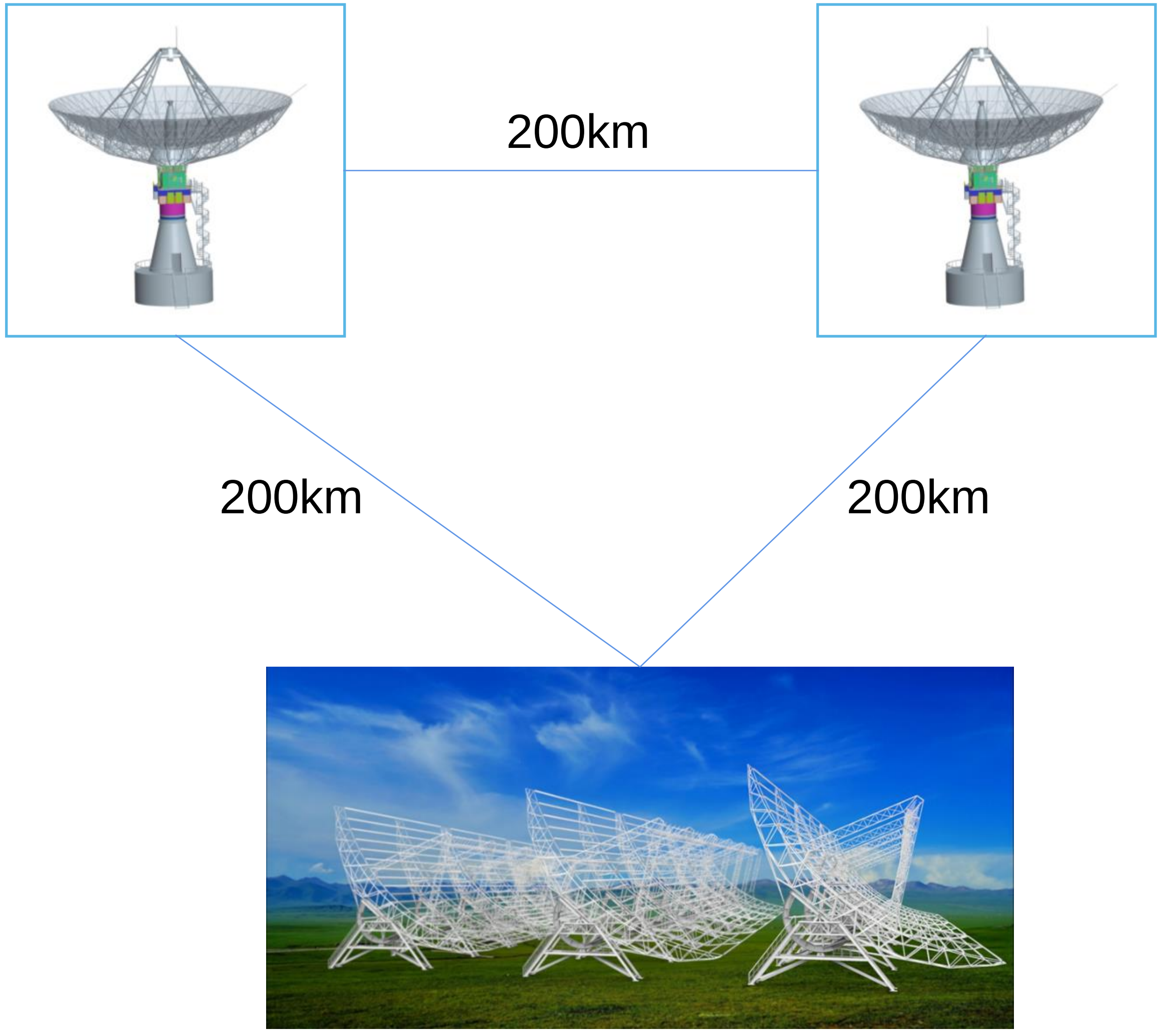


(Profs. Ramesh and Manoharan are gratefully acknowledged for comments and suggestions to improve the design for Chinese IPS telescope)

Array layout of IPS telescope



Main site: Mingantu
Sub site: Abaga and Sonit You

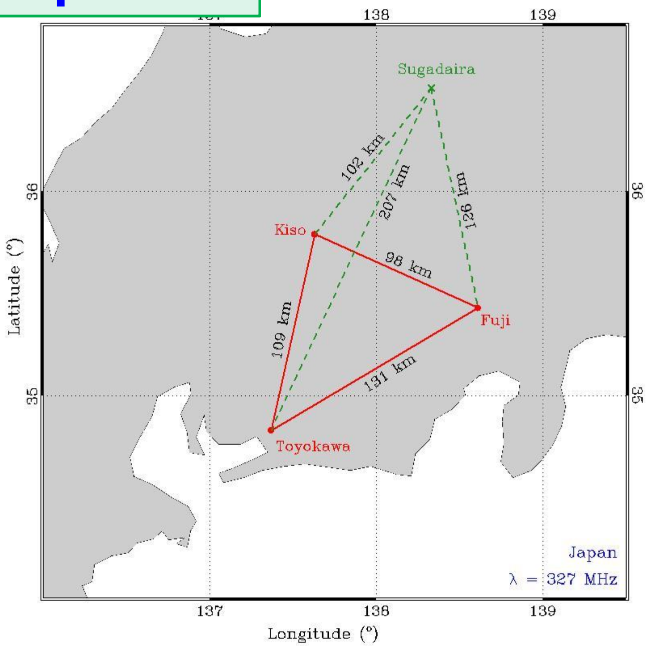


Specifications of IPS telescope

Antenna	**Cylinder: 3 × 140m×40m**
	Dish: 2 × Ø30m
Frequency	327 MHz, 654 MHz, 1420 MHz(*)
Bandwidth	1-40 MHz
Beam size	Main site Cylinder: 1.6°× 27’ @ 327 MHz 0.8°× 13.7’ @ 654 MHz
	Sub sites 30m Dishes: 2.1° @ 327MHz 1.1° @ 654MHz 0.5° @ 1420MHz
System Temperature	Cylinder: ~110K
	Dish: ~ 120K
Polarization	Horizontal and Vertical polarization
ADC	14bits @ 200 Msps
Sensitivity	Main-site: ~4.4 mJy@1s with 65% efficiency
	Sub sites: ~75mJy@1s with 70% efficiency

Comparison with other IPS telescope

ISEE Nagoya in Japan

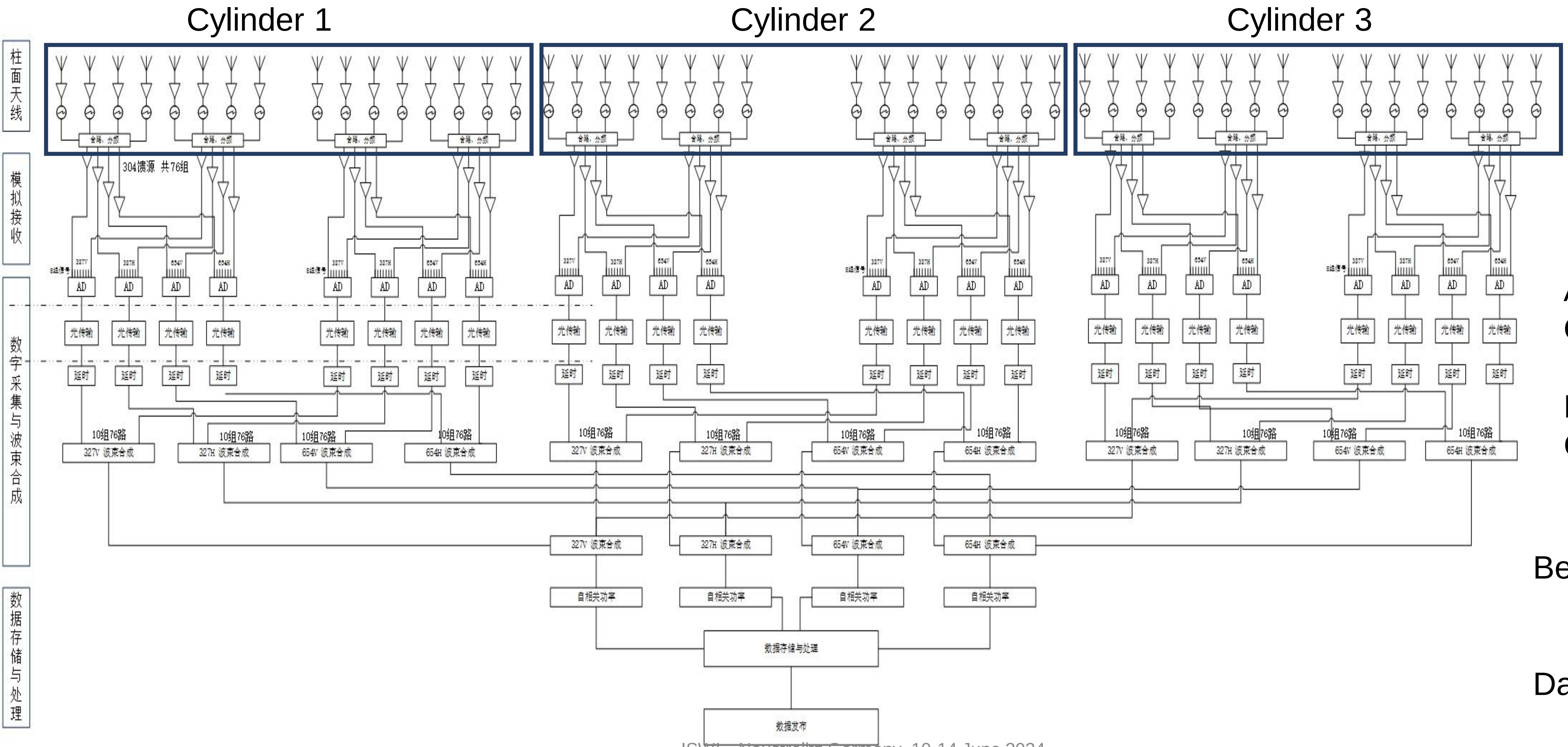


Ooty in India

- ISEE Antenna: Toyokawa 4000m^2,
  others 2000m^2
- Ooty Antenna: 15900 m^2
- IPS antenna: cylinder 16800m^2,
  dish 700m^2

Frequency ISEE and Ooty: 327M   IPS telescope: 327 / 654 / 1400 M

Signal Flow Diagram



Feed
LNA
BF 1

ADC
Opt-trans.

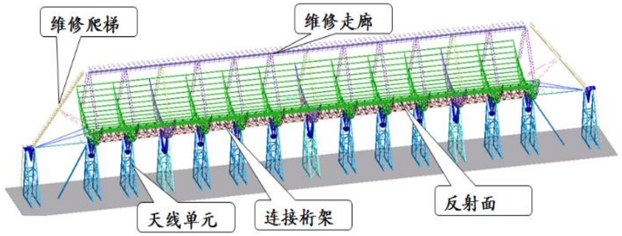
Delay phas
Comp.

Beamforming

Data storage

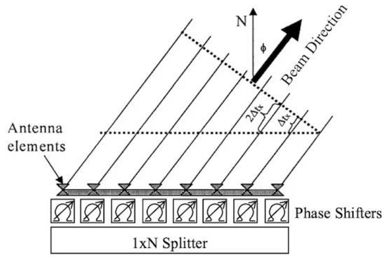
Key technologies of IPS telescope

High-precision synchronous control of large steerable parabolic cylindrical antennas 140-meter mechanical drive, Rotation range: ±45 degrees



Measurement and correction of the tight coupling effects of feeds Three cylindrical antenna with 1800 feeds

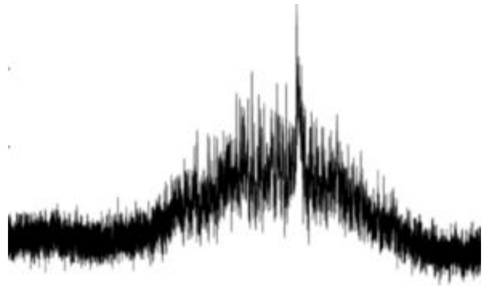
High-stability amplitude-phase reception with a mixed analog-digital beamforming architecture; North-south phased array electronic scanning with 16 beams



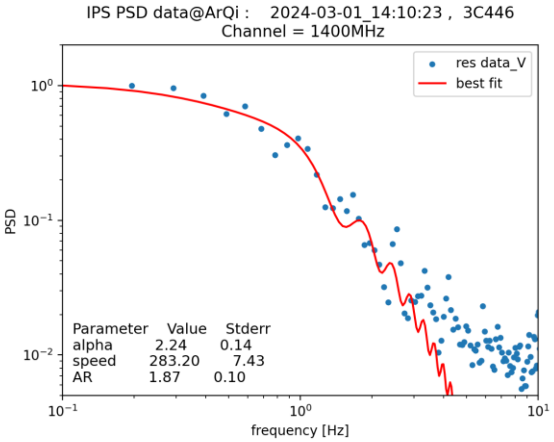
To observe weak IPS signals in a strong background

- the scintillation is only at the level of 1% of the source flux
- capture the entire flicker power spectrum.

Time series data



Power Spectral Density



Timeline of IPS telescope

- **June 2018:** Completed the **proposal and the technical specifications**.
- **March 2021:** Completed **detailed design**.
- **Nov. 2021:** Completed foundation construction for the main station antenna.
- **June 2022:** Completed foundation construction for the sub station antenna.
- **July 2022:** Conducted joint testing of **the feed prototype and receiver** in a microwave anechoic chamber, finalized the design of the receiving equipment.
- **Sept. 2022:** Completed installation and commissioning of the 30-m sub station antenna, and completed the installation of the receiver.
- **April 2023:** Completed installation of digital acquisition at the sub station.
- **June 2023:** Completed mounting of the A-frame of the main station antenna.
- **Nov. 2023:** Completed 1/9 of the whole system.
- **May 2024:** Completed the entire system, and **testing and assessment**.

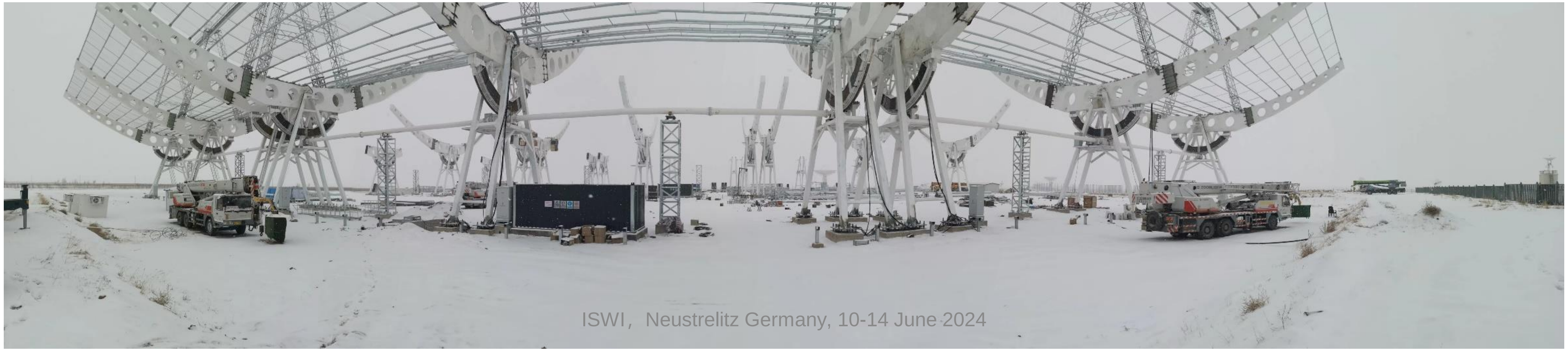

23-9-19 mount sector gear


23-10-3： mount feed leg and feed


23-10-30 finish 1/9 mesh surface


23-11-16： First light observation （3C84）

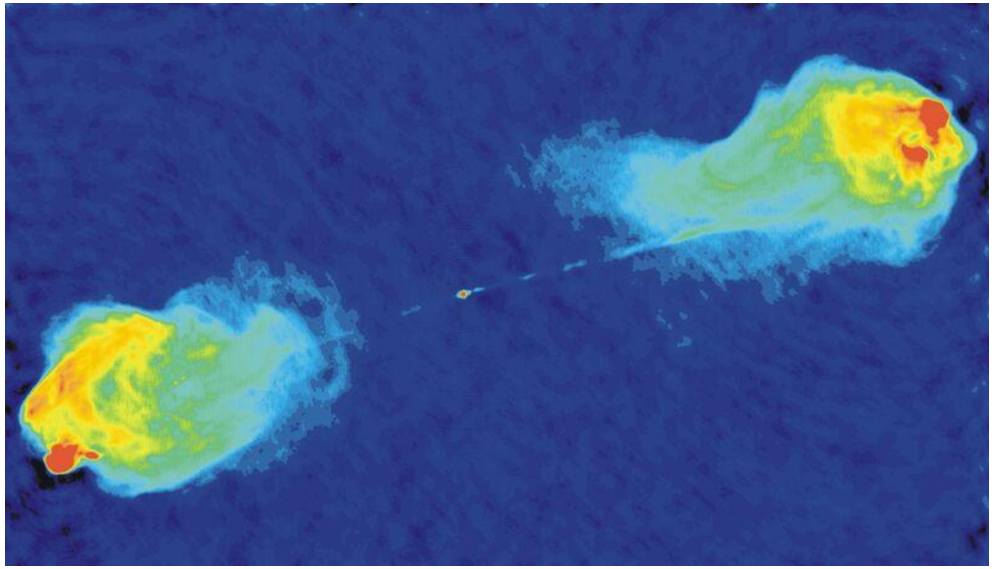

24-5-10: Complete construction , testing and assessment



IPS telescope's cylinder antenna （Fan's photo）

Calibration

- It is important and necessary;
- Many methods have been considered, including loop measurement, calibrators(man-made emitter or radio sources)
- Cygnus A is very suitable radio source for its declination and density

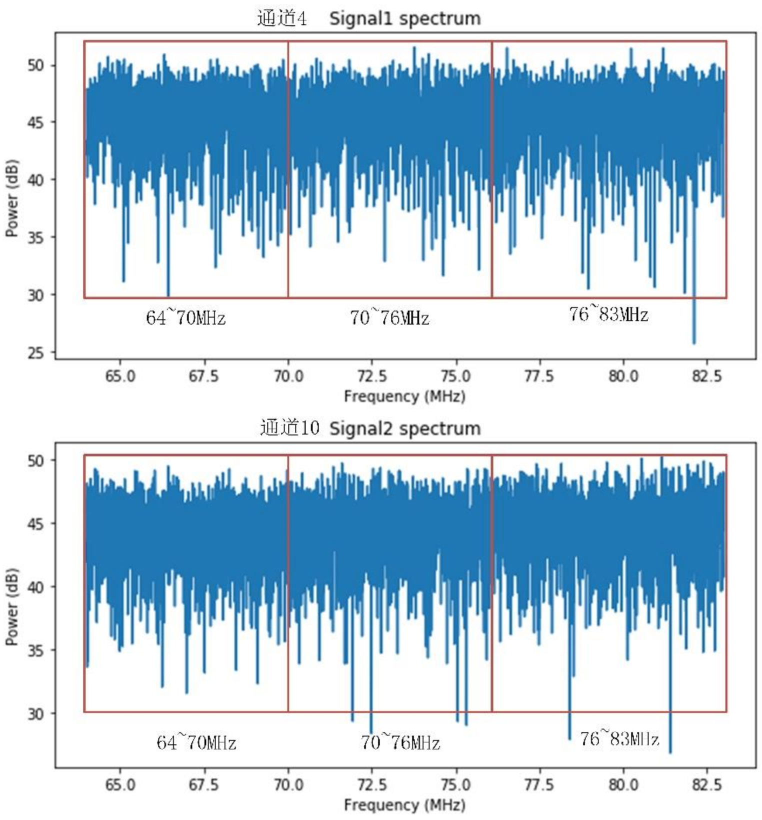


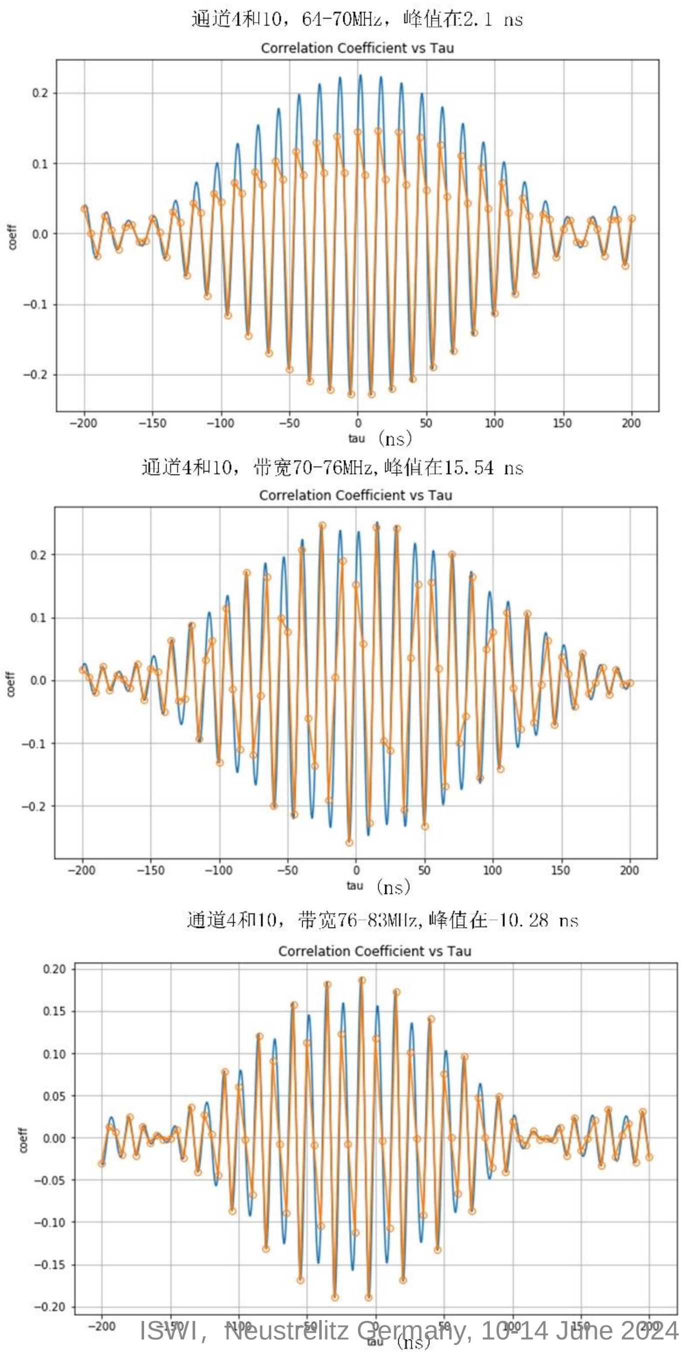
https://www.nrao.edu/archives/items/show/33385

Method 1:

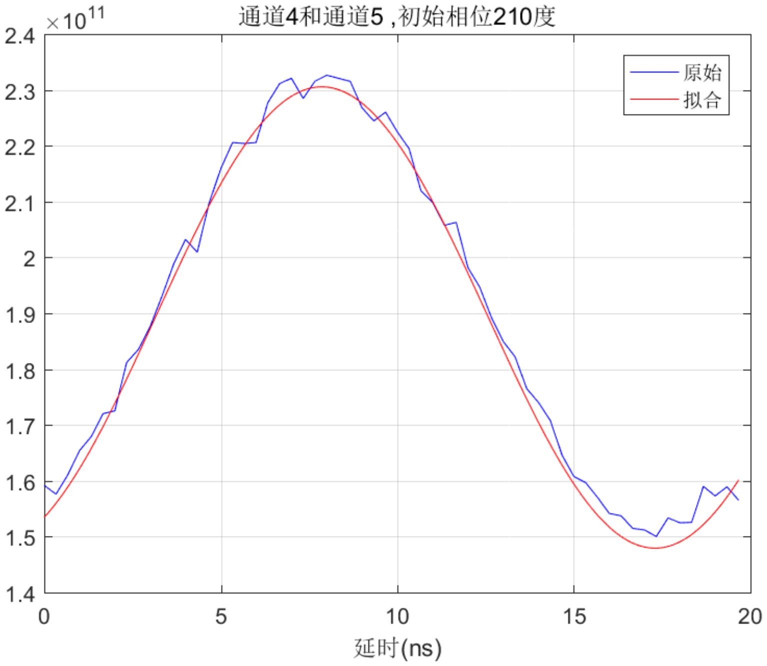
1、Before performing beamforming, a small amount of raw digitized data is stored for analyzing delay and phase.

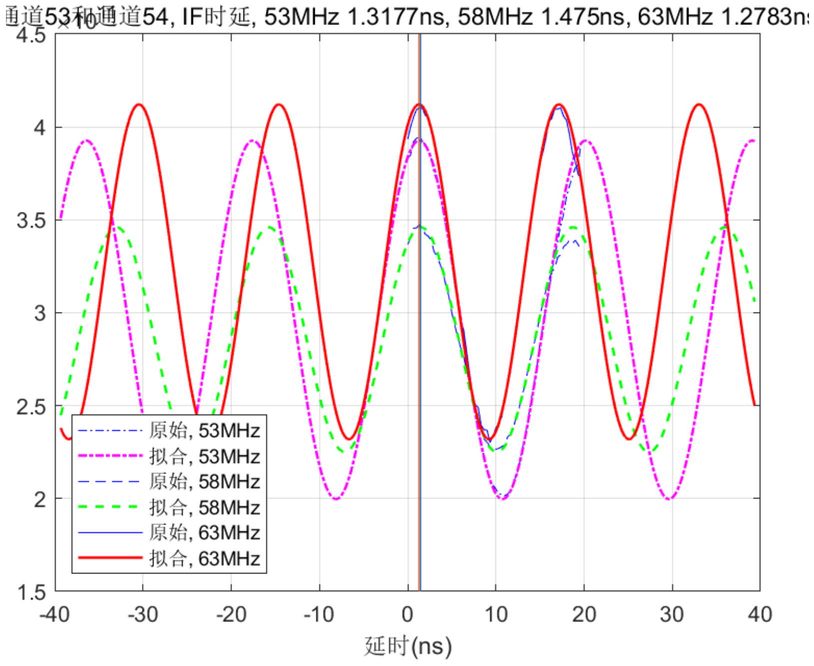
2、Perform cross-correlation on the two signals to sequentially analyze the amplitude difference and phase difference between the two receiving units.

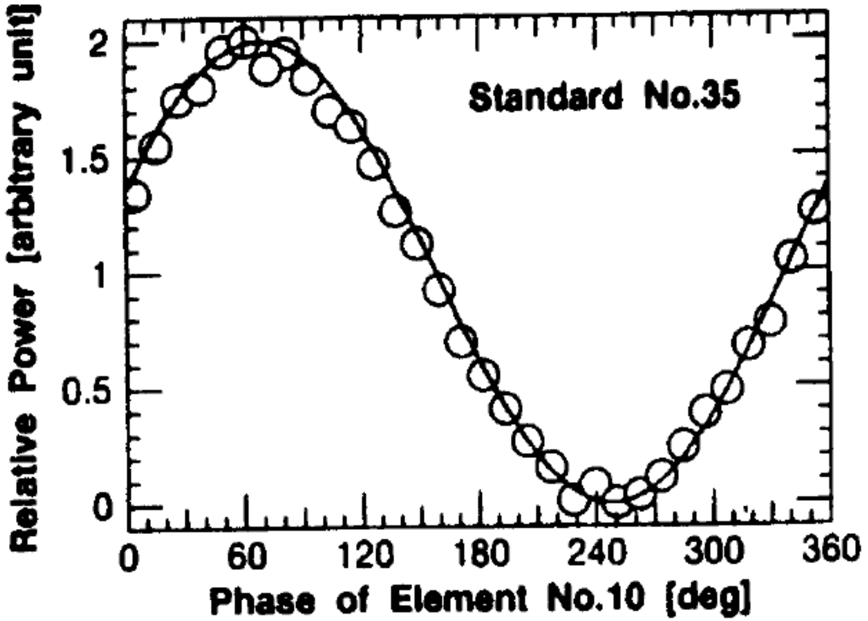




Method 2:





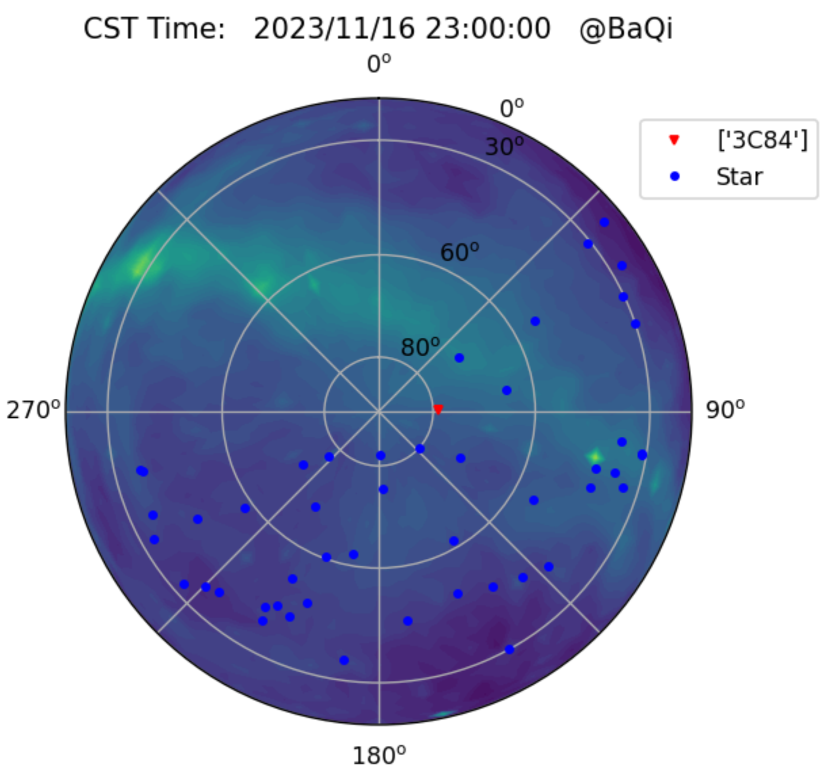


Kikuo Asai, 1997

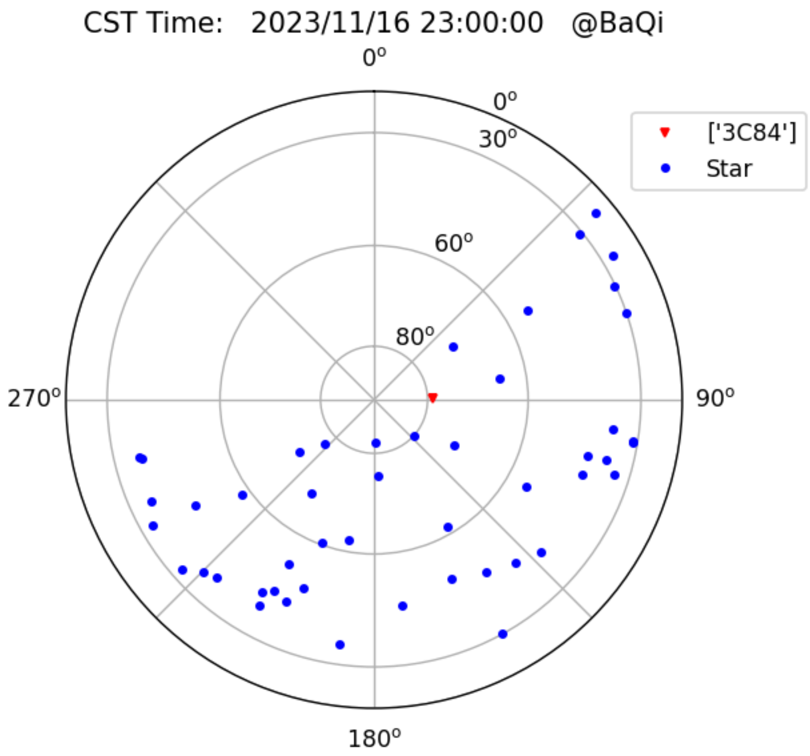
By adjusting the amplitude and phase of the two receiving units, the beamforming system output is maximized.

First light observation： 3C84 on 16th and 17th Nov. 2023

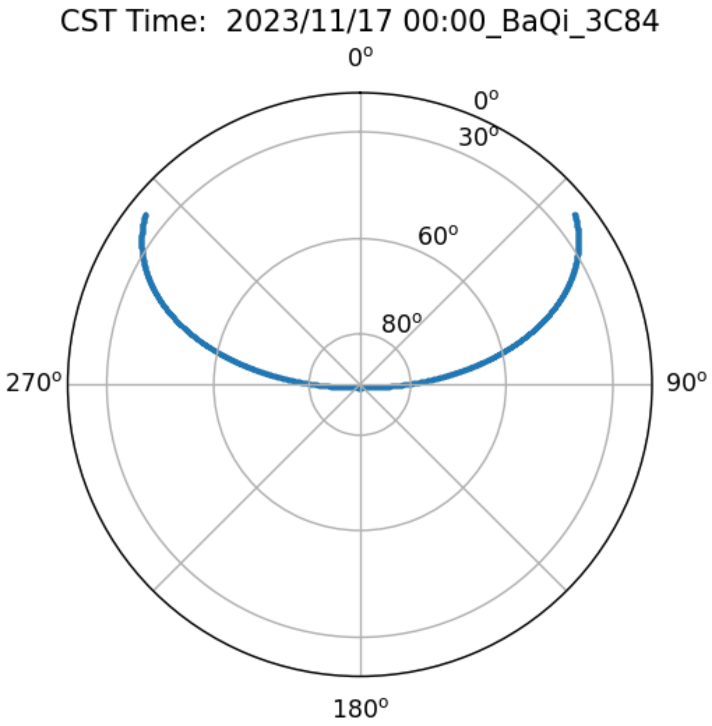
IPS source on the galactic background radiation



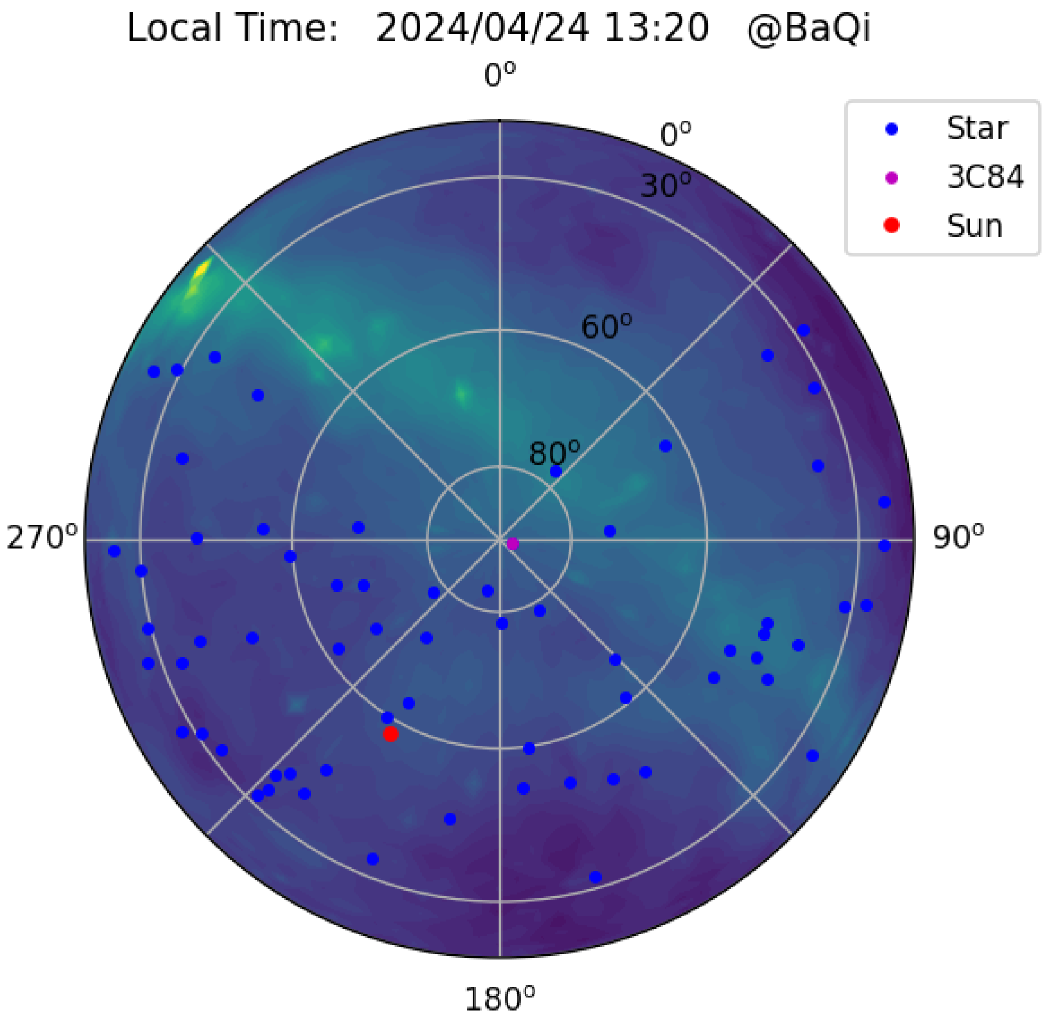
Position of IPS source at 23H

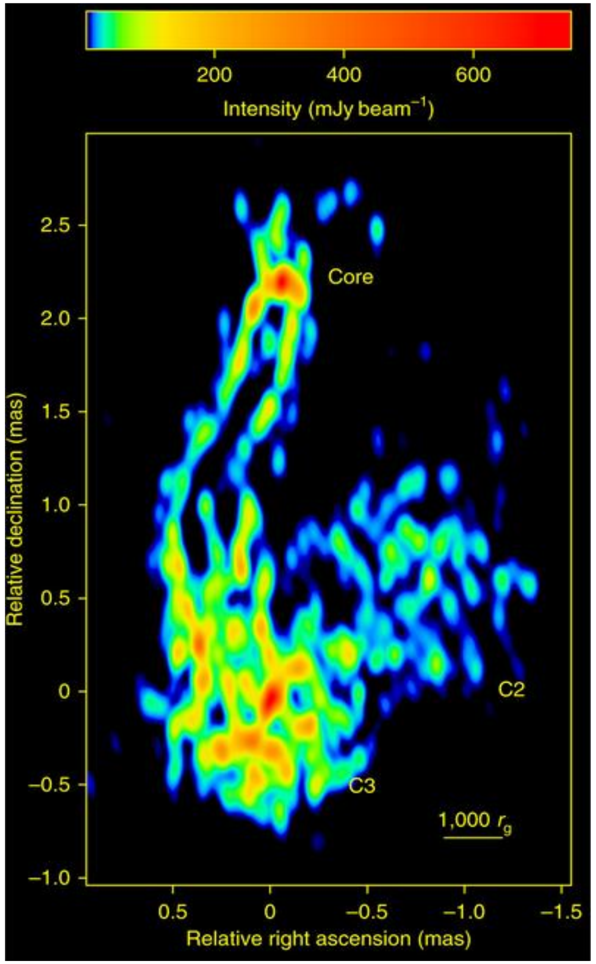


Trajectory map of 3C84



First IPS source: 3C84

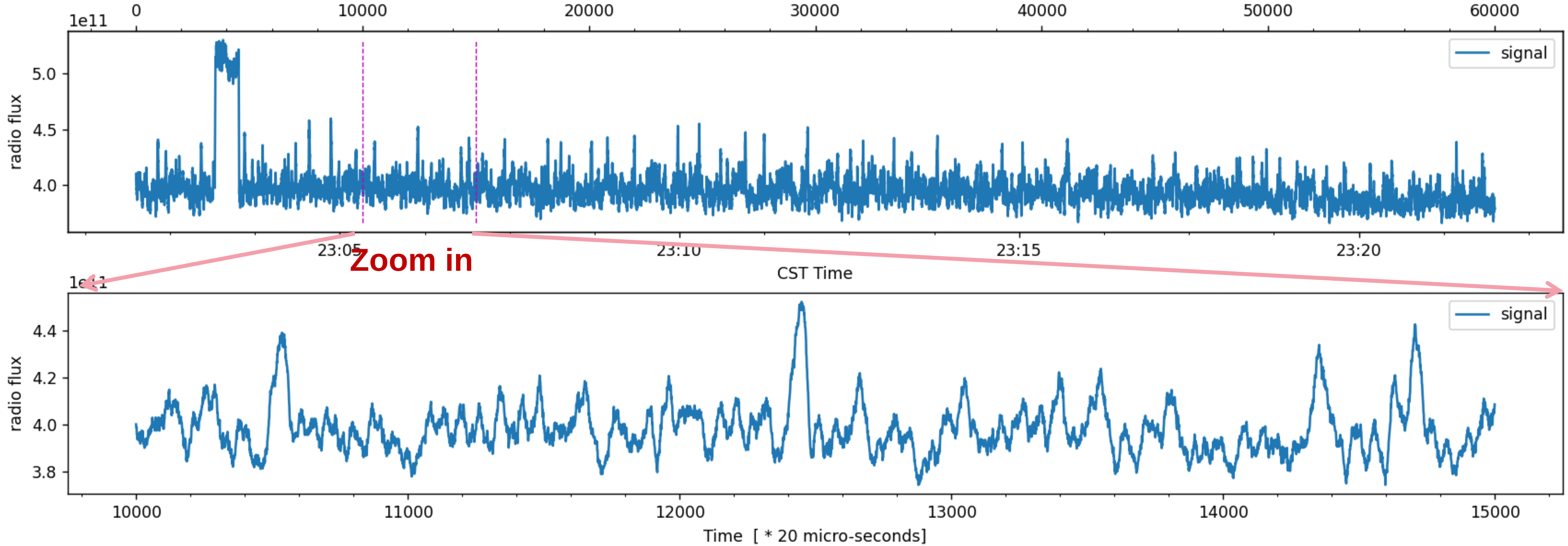


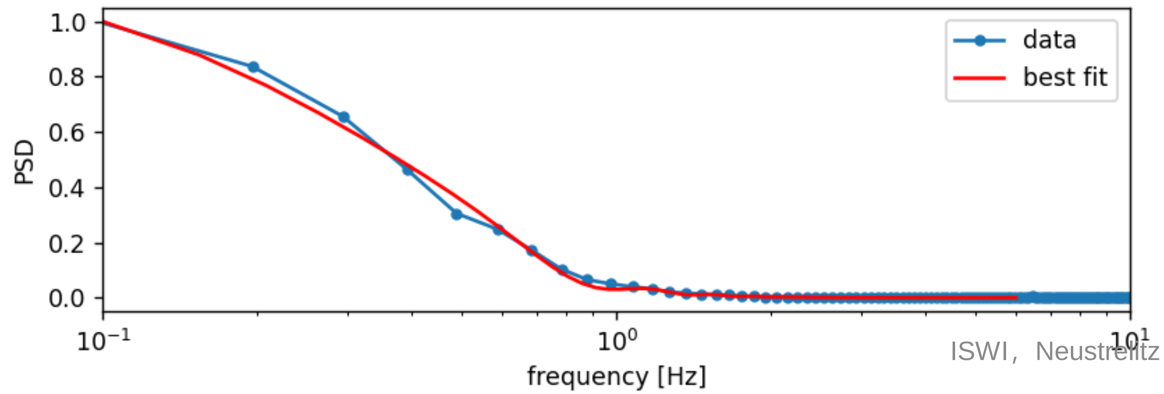


Radio image of 3C84 by VLBI

Beam width : 1.6 degree
3C84 as point source

IPS raw data of 3C84 observed by CHRISMA at 2023-11-17 23:02
L0 Level, 327MHz, sampling rate: 20 ms, Frequency Channel: 1

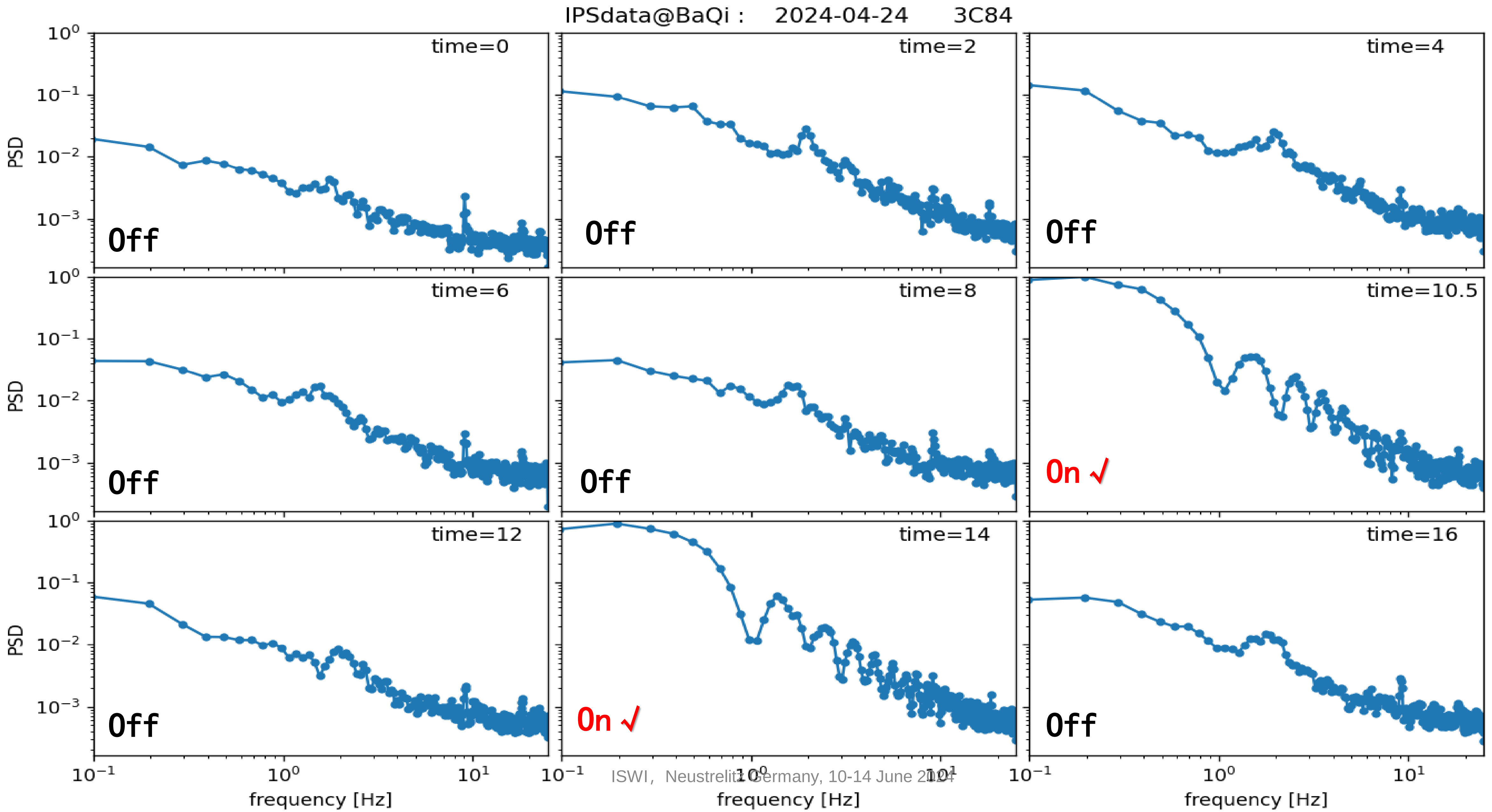




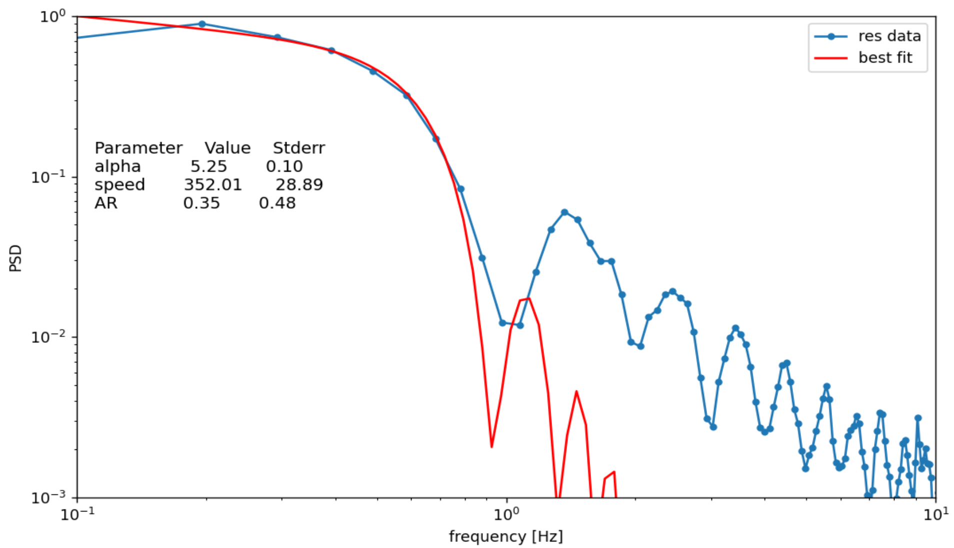
data points 60000:
mean value 397650029055.86, variance 18966457795.63 (4.8%)

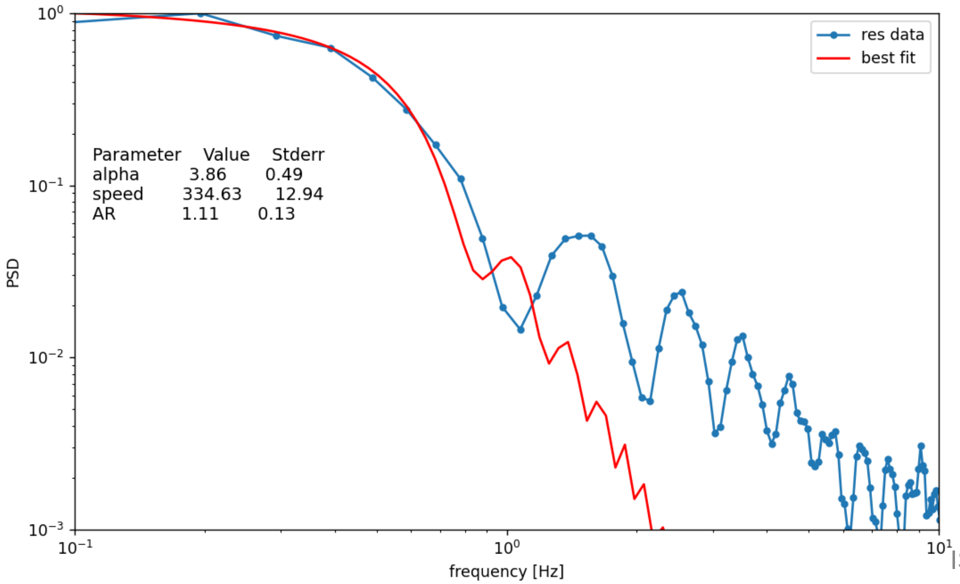
Parameter	Value	Stderr
alpha	3.35	0.15
speed	373.76	7.89
AR	1.57	0.06

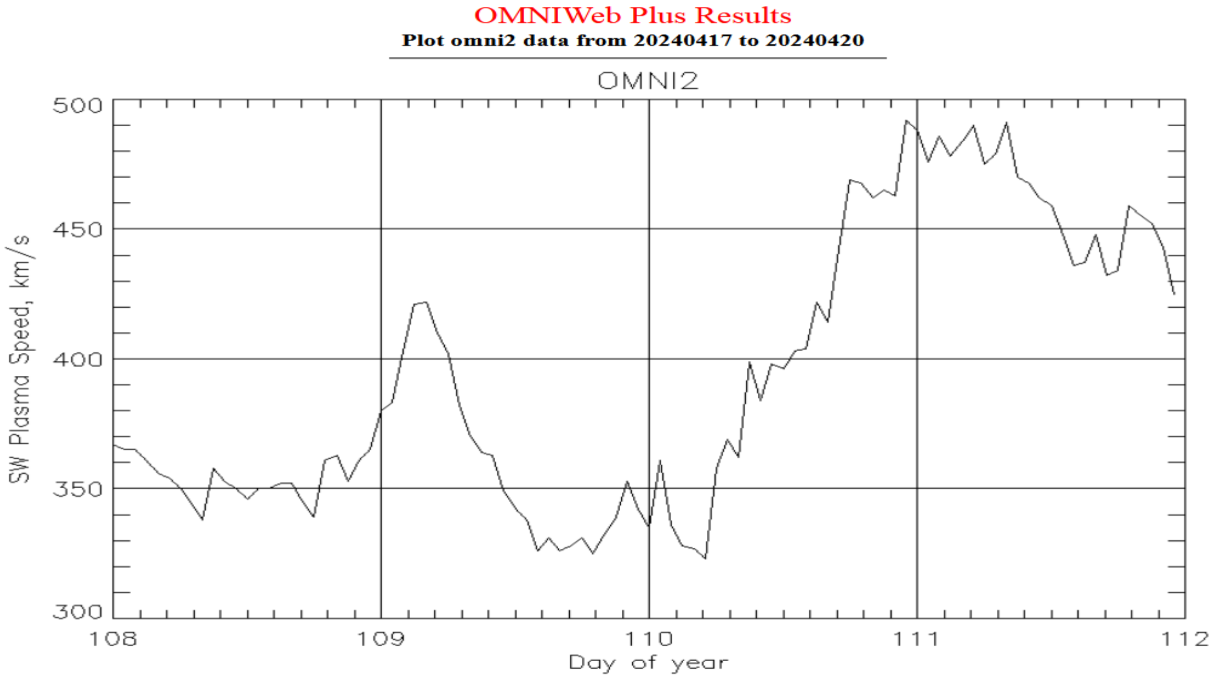
On-Off 3C84 to analyze PSD



Measurement of solar wind speed compared with in-situ observations from satellites on NASA's OMNI website.



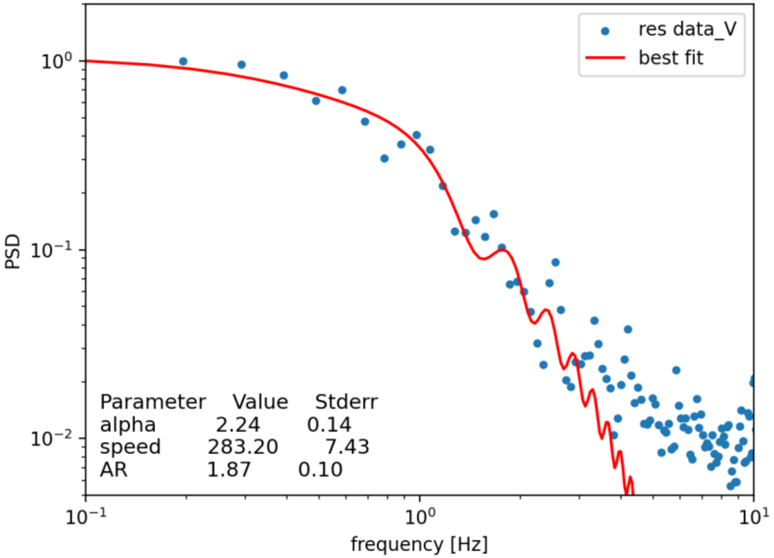




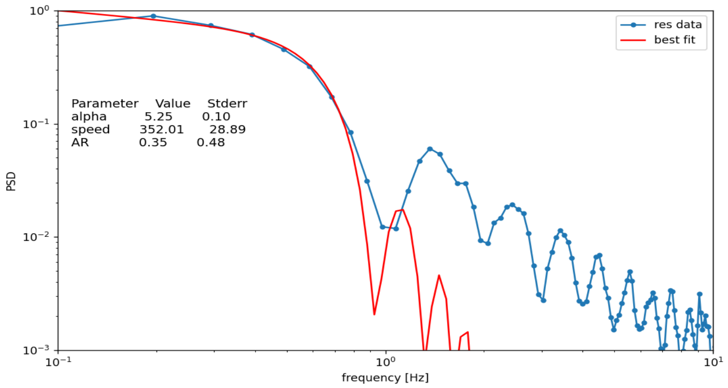
- IPS observations of 3C84 The power spectrum shape and amplitude remained consistent, the fitted solar wind speed was about 350 km/s.
- Comparing with in-situ observations at 1 AU, and considering comprehensive factors such as IPS observing near the solar limb, the solar wind source region's rotation with the Sun, and the radial propagation delay of the solar wind, we believe that the two measurement are consistent.

Comparison of the dynamic range between the IPS telescope and other similar equipment

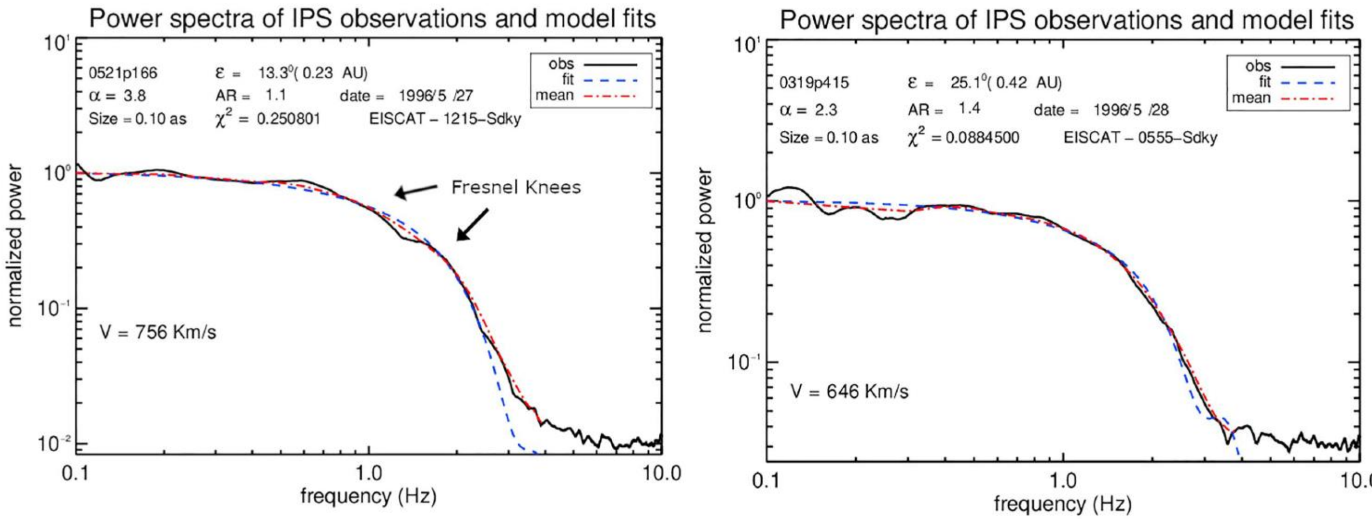
IPS PSD of 30m（DR ~ 20dB）



IPS PSD of cylinder（DR ~30dB）



Observation of EISCAT（DR，L: 20dB，R: 15 dB）



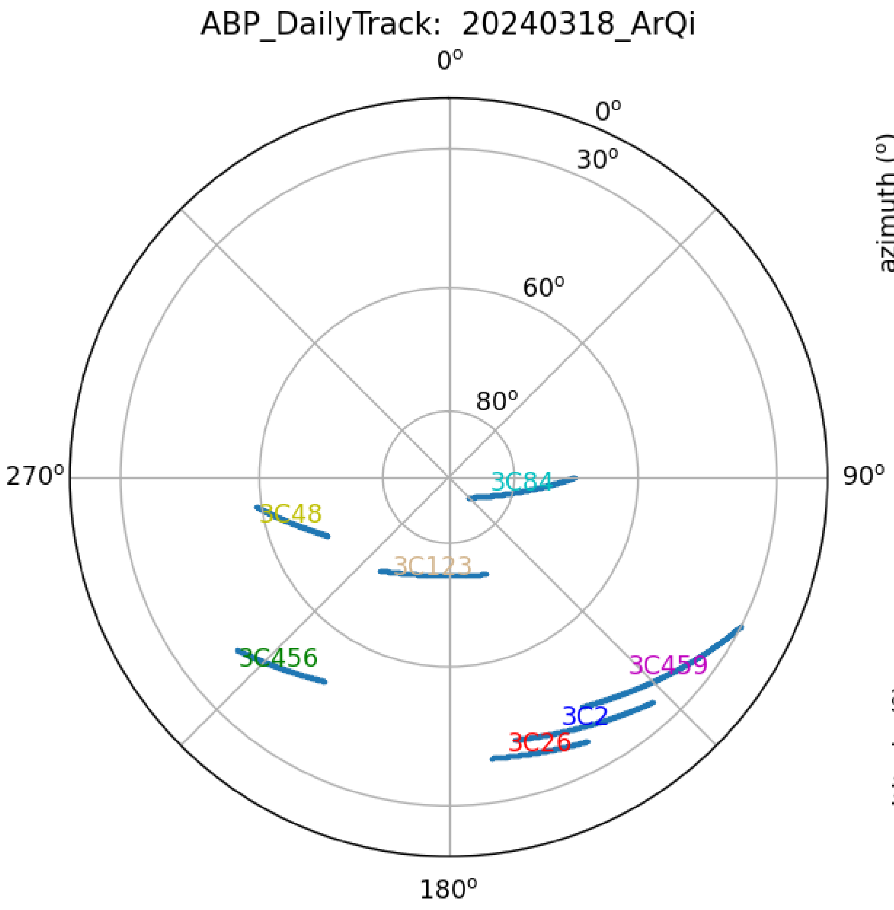
- Dr. Chang (Rutherford Appleton Laboratory)： the limit of what can and can't be used in terms of velocity results has been bound by the S/N ratio value. The results revealed that the minimum S/N ratio for a SSA reliable fit is ≥13.5 dB for these instruments. （《Space Weather》 2019）
- The min S/N ratio is about 15dB by Prof. Kojima(Uni. Nagoya)

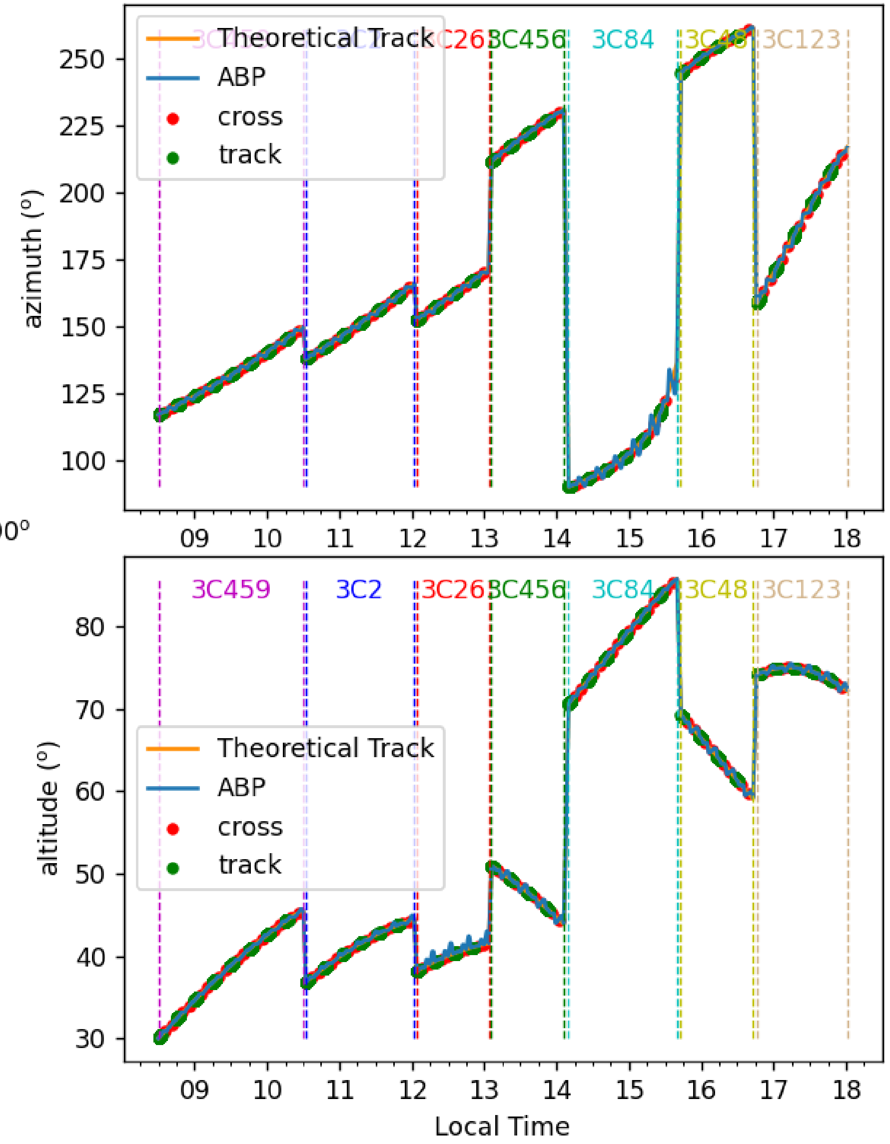
Daily observation schedule

20240318_AUX_AbpTrack_ArQi.txt - 记事本

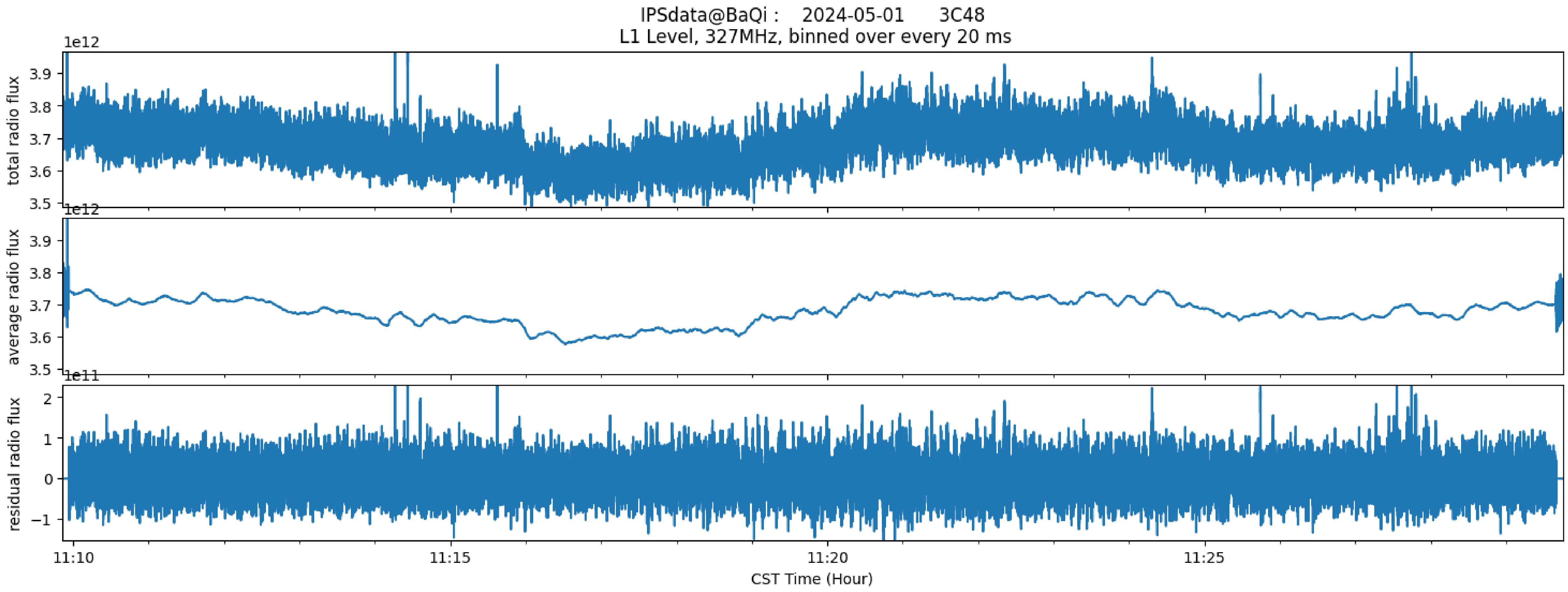
件(F) 编辑(E) 格式(O) 查看(V) 帮助(H)

	StarName	StartTime	EndTime
1	3C459	03-18 08:30:00	03-18 10:30:00
2	3C2	03-18 10:32:00	03-18 12:02:00
3	3C26	03-18 12:04:00	03-18 13:04:00
4	3C456	03-18 13:06:00	03-18 14:06:00
5	3C84	03-18 14:10:00	03-18 15:40:00
6	3C48	03-18 15:43:00	03-18 16:43:00
7	3C123	03-18 16:46:00	03-18 18:01:00

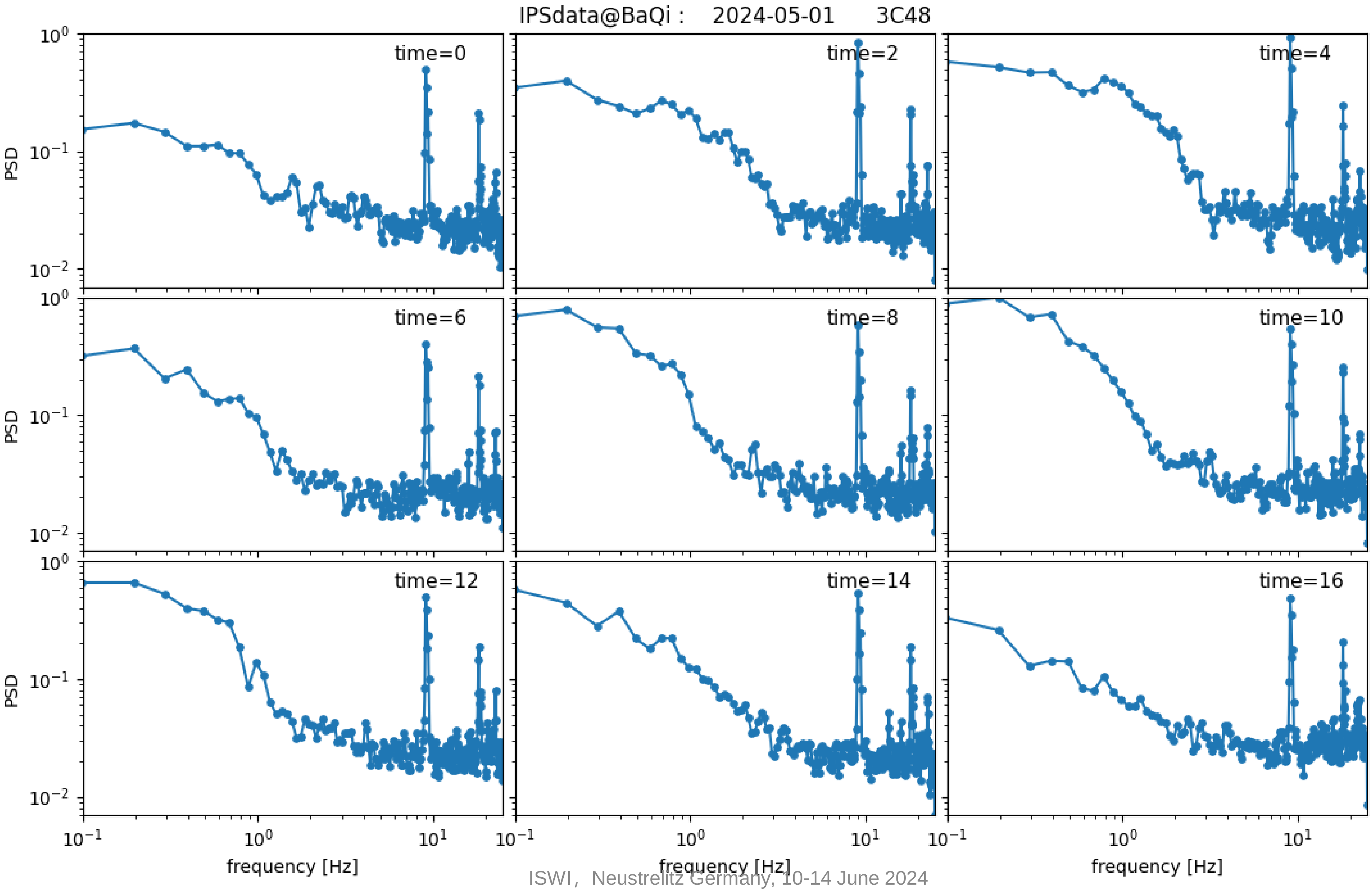




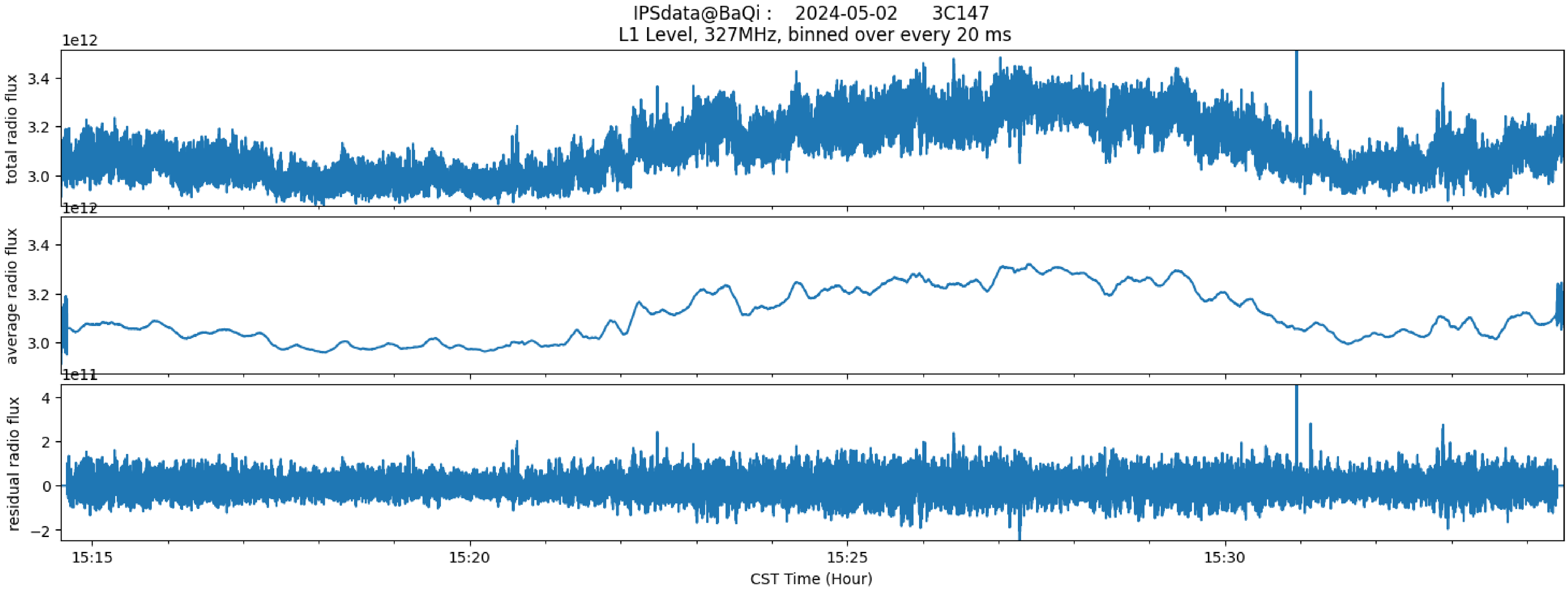
More observations： 3C48 by cylinder antenna on 1st May



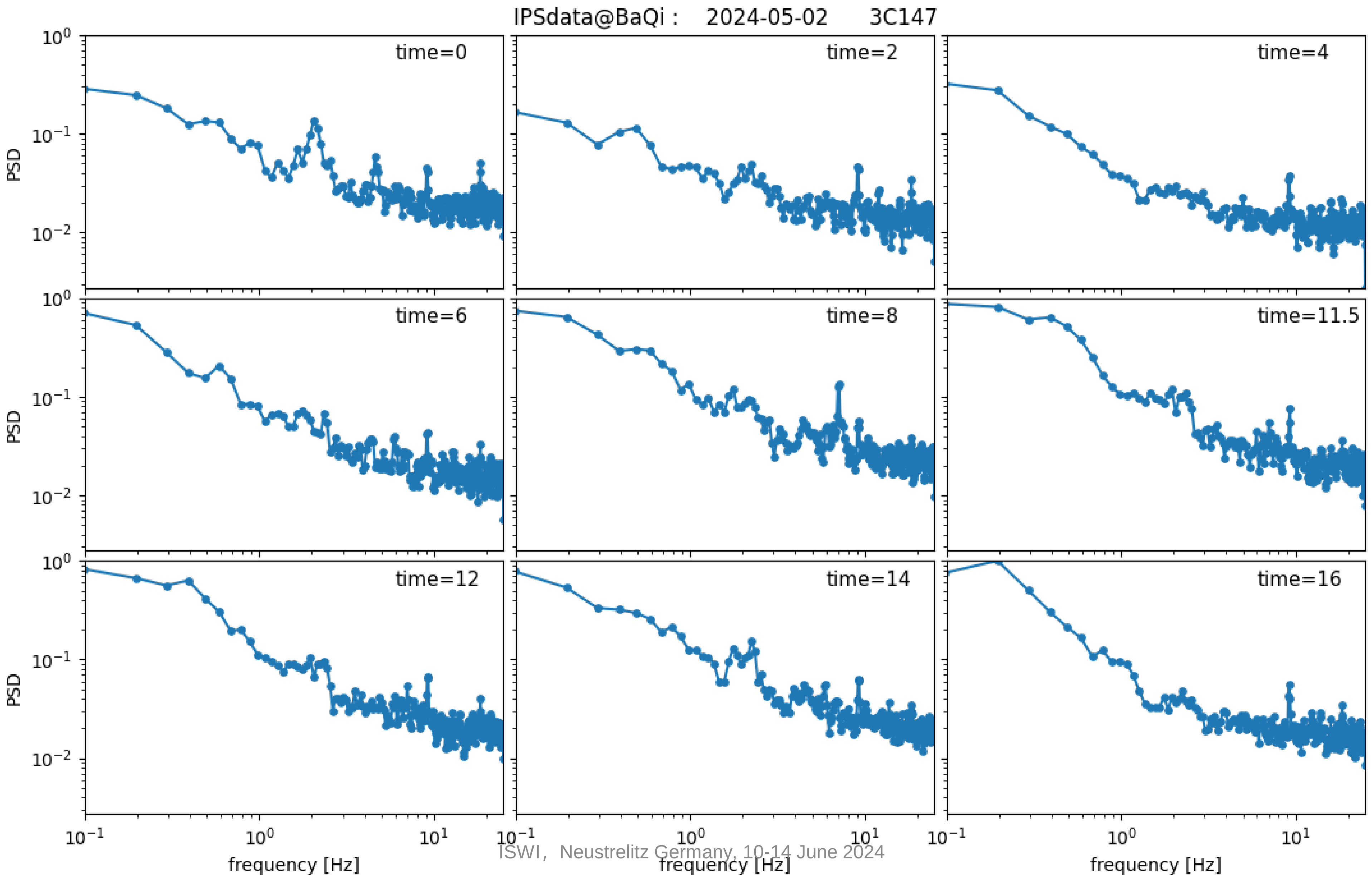
More observations： PSD of 3c48 signals



More observations： 3c147 by cylinder antenna on 2nd May



More observations： PSD of 3c48 signals



Summary

- **We have upgraded MUSER's calibration, built new calibration antennas, established new calibration methods, and expanded MUSER's observation frequencies.**
- **We have built a new telescope, which is the first radio telescope in China dedicated to IPS observations. It features the largest parabolic cylindrical antenna in China.**
- **The team is continuously optimizing the data calibration process, aiming to achieve daily imaging spectroscopy and interplanetary monitoring, and to provide observation data and forecast products for space weather.**


Thanks!