Solar Eruptive Events as Observed by Radio Imaging-Spectroscopic Facilities

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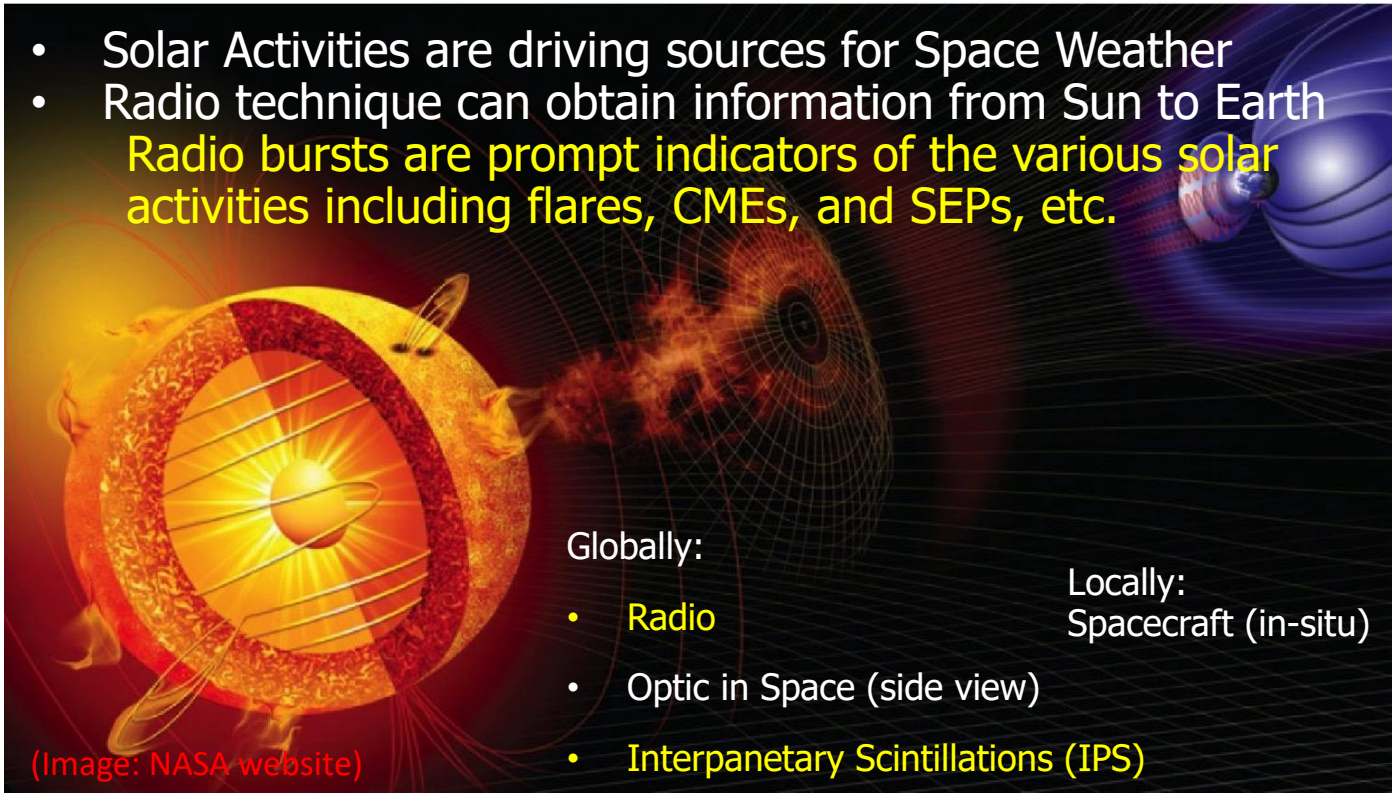
Outline

1. Introduction
2. Observations of 21-June-2015 Event with Radio FSs
3. Imaging-Spectroscopy of the Event
4. Discussions & Summary

Introduction

- Solar Activities are driving sources for Space Weather
- Radio technique can obtain information from Sun to Earth
  Radio bursts are prompt indicators of the various solar activities including flares, CMEs, and SEPs, etc.



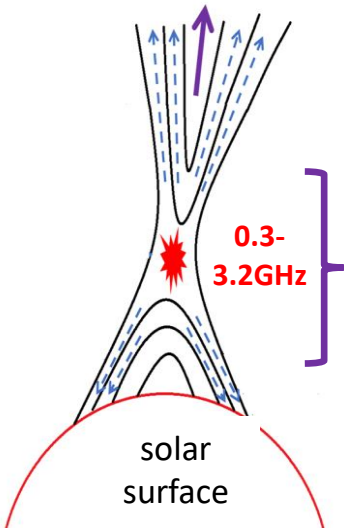
(Image: NASA website)

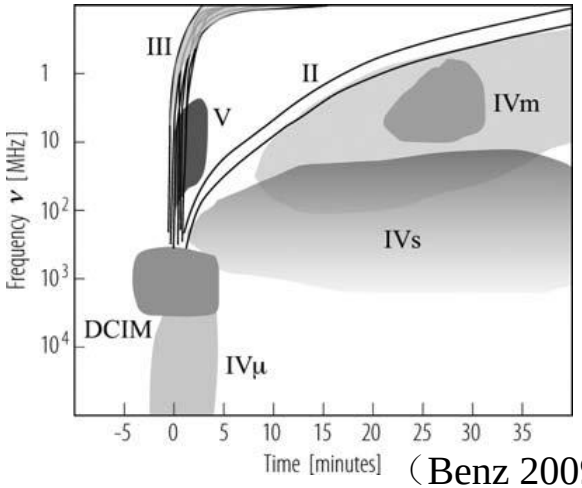
Globally:

- Radio
- Optic in Space (side view)
- Interpanetary Scintillations (IPS)

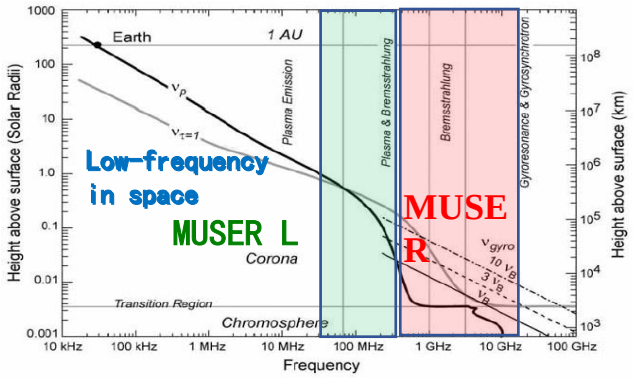
Locally:
Spacecraft (in-situ)

Developing Imaging-Spectroscopy Capacity





（Benz 2009）



(Gary & Hurford, 1999)

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

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

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

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

- to diagnose coronal magnetic fields - key factor for solar activities
- to understand the primary energy release process, particle accelerations and propagations
- to connect the solar atmospheres to interplanetary space (e.g., recent review by Gary 2023).

Progress with Solar-/Non-Solar Dedicated Facilities:

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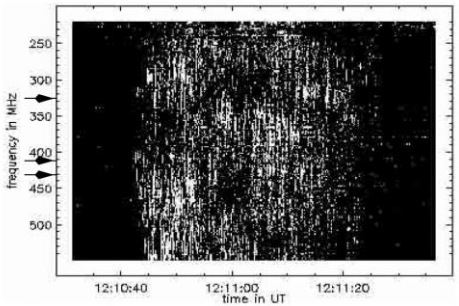
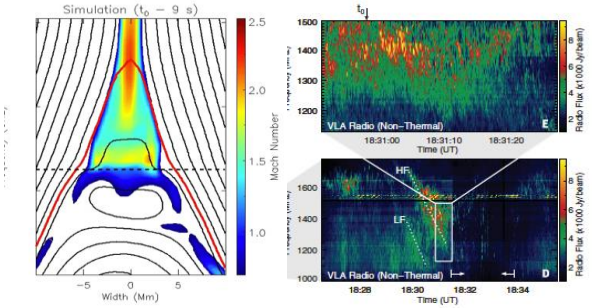
- Radio Bursts and Flares/CMEs (Kansabanik et al. 2023, Chen et al. 2023, Zhang et al. 2022, Liu et al. 2022, Armatas et al. 2022, Mohan 2022, Chen et al. 2021, Yan et al. 2021, Chhabra et al. 2021, Reid, 2020, Carley et al. 2020, Gary et al. 2018, …)
- Fine structures in Radio Bursts (Luo et al. 2022, Altyntsev, et al. 2022, Clarkson et al. 2021, Zhang et al. 2021, Chen et al. 2020, Kuznetsov et al. 2019,Alissandrakis et al. 2019, Chen et al. 2019, Yu et al. 2019, Kontar, et al. 2017, Wang et al. 2017, Reid & Kontar, 2017,Chen et al. 2015, Morosan et al. 2015, Chen et al. 2013, ...)
- Coronal Magnetic fields (Fleshiman et al. 2022, Tan 2022, Silva et al. 2020, Mahrous 2018, Casini et al 2017, …)

Recently, Kontar et al (2023) found that the number density of non-T (>=20 keV) electrons is ~2 orders lower than previously inferred from microwave observations of the same event (Fleishmann et al., 2022). The highlights of recent advances from imaging spectroscopy of solar radio emission were presented in Gary (2023, ARAA).

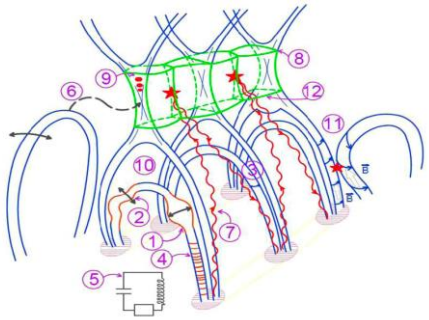
Radio Fine Structures



Spikes (Benz et al. 2002)



Spikes due to Termination shock (Chen et al. 2015)



Explanations of QPPs (Kupriyanova et al. 2020)

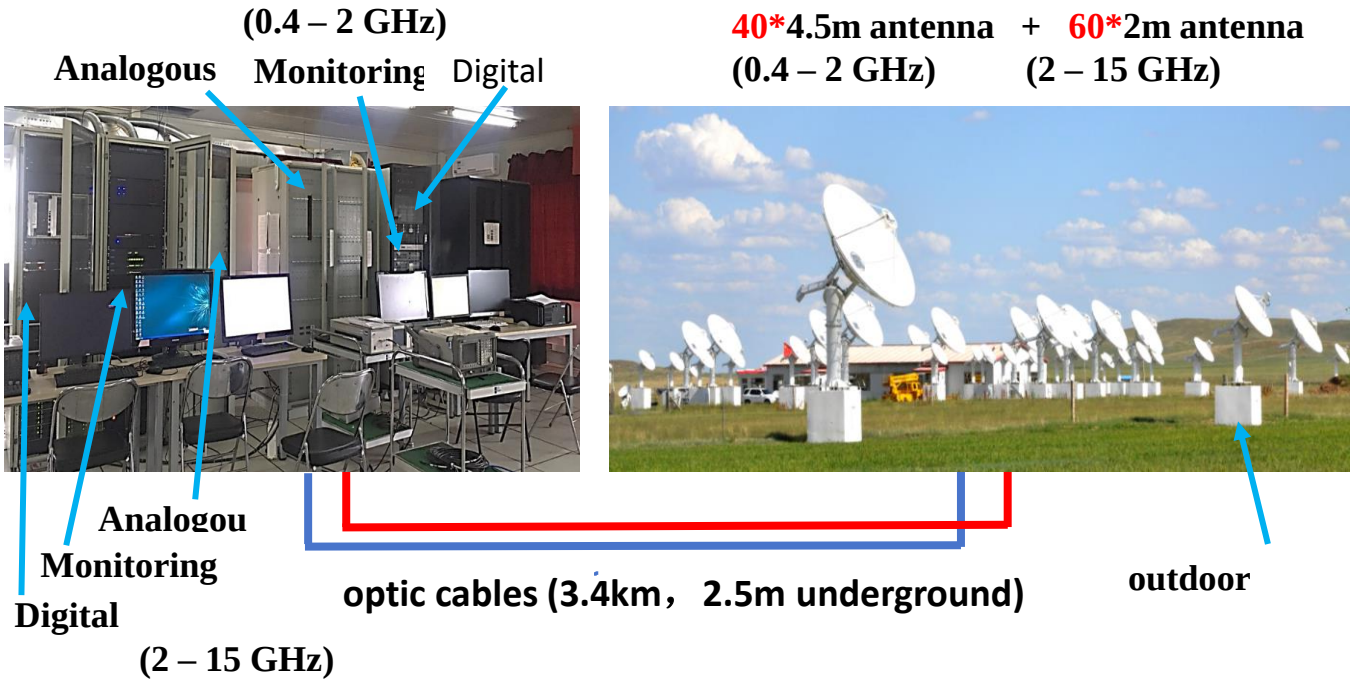
- **Solar radio spikes associated with solar flares: narrow band, very short and bright structures in the dynamic spectrum**
- **Quasi-periodic pulsations (QPPs): broadband, very short and high drifting features**

  Both FSs are considered as manifestations of energy release processes in the solar corona.
- **The spikes and QPPs in the decimetric wave range are of high interest because the understanding of them can provide detailed information about plasma processes in solar flares on kinetic scales.**

A MUSER event with groups of spikes co-occurred on QPPs?

Brief introduction
Mingantu Spectral Radioheliograph — MUSER

- MUSER constructed in 2009-2013 by National Major Scientific Research Facility Program
- MUSER upgrated to add MUSER-L and IPS telescope in 2019-2023 by Meridian II project.

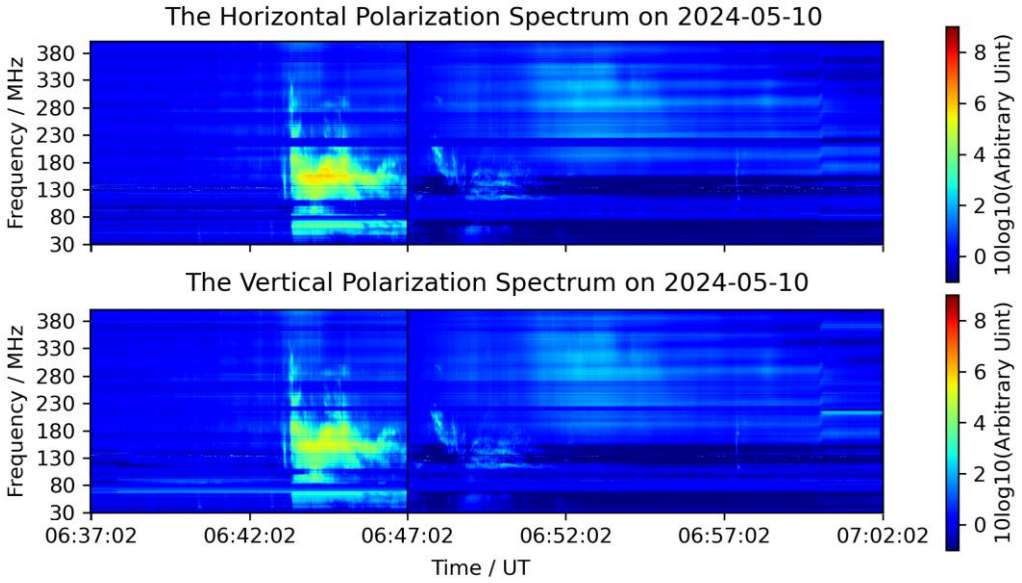


MUSER-L: operated for observations

Table 1
Performance of MUSER-L.

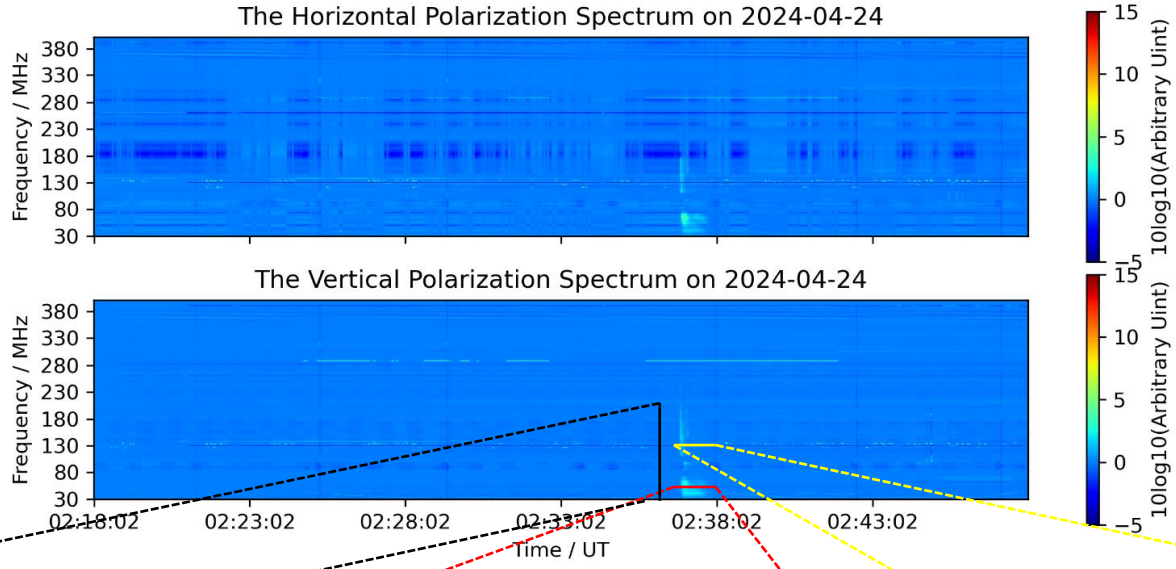
Frequency range:	30 ~ 400 MHz
Antennas:	100 steerable LPDA + calibration element (124 fixed pointing LPDA)
Max baseline:	~3000 m
Frequency resolution:	1–5 MHz
Time resolution:	~100 ms
Angular resolution:	14.0′-1.0′
Polarization:	I, Q, U, V
Dynamic range:	⩾25 dB

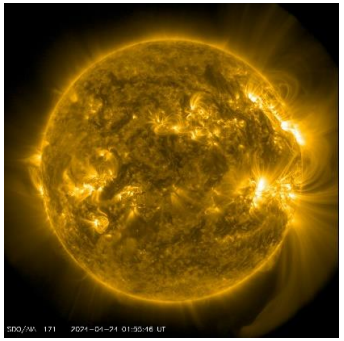
100 LPDA + Calibration (124 LPDA)

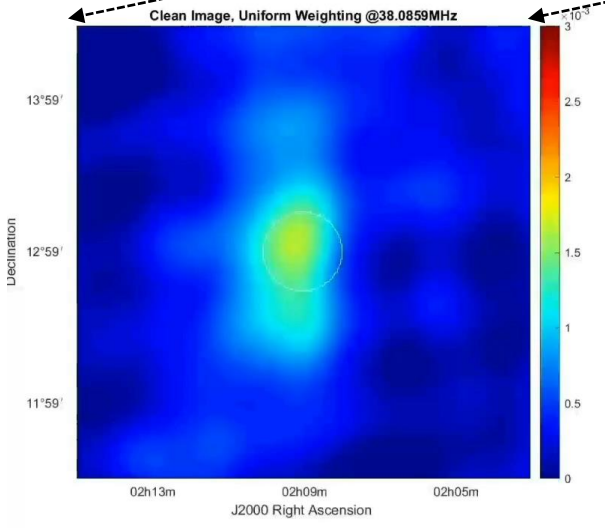


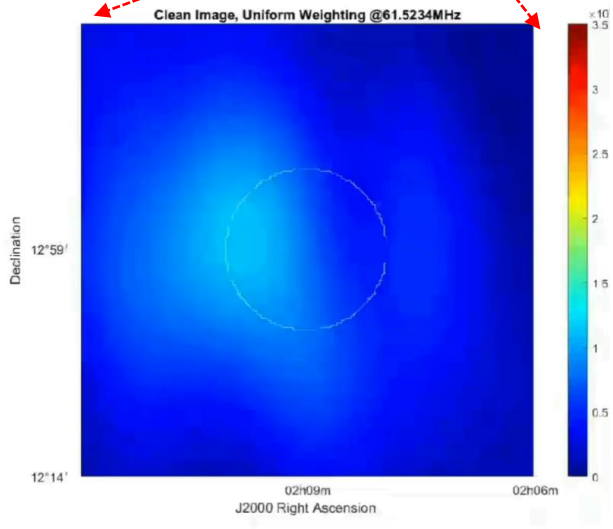
Spectrum on 10 May 2024

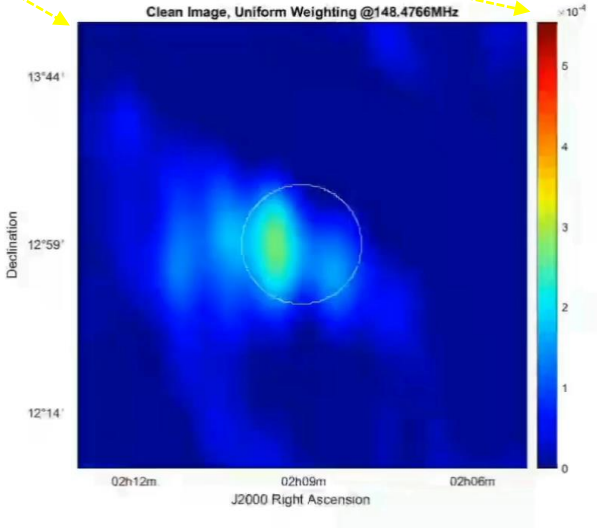
A MUSER-L observation (2024-4-24)





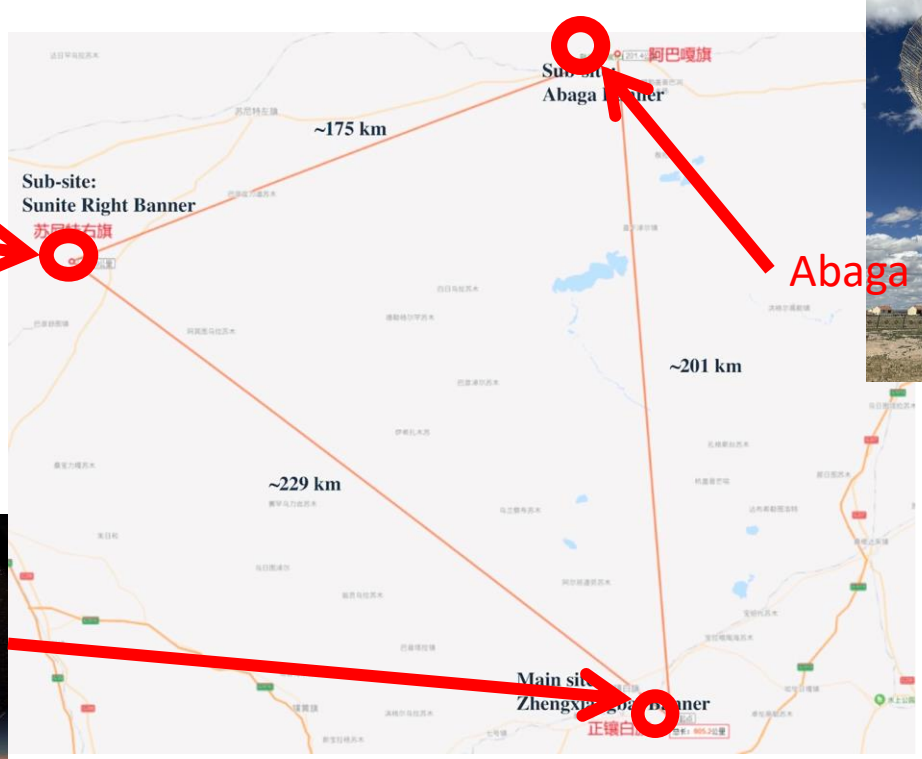






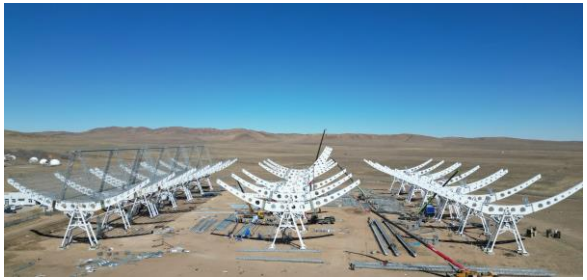
IPS Telescope Array

Sunite



Abaga

Construction of IPS telescopes





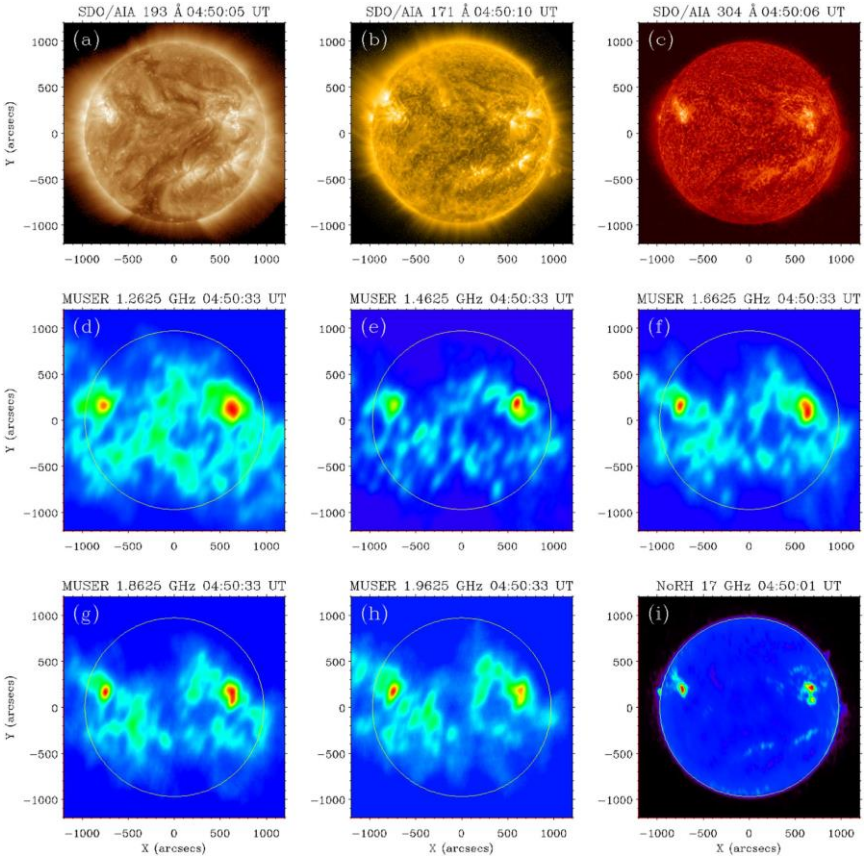
Passed CAS test process on 10 May 2024.
(Movie Courtesy of Jin Fan)

Auroral photo taken on 11 May 2024.

MUSER Data Processing with a New Caliration Method

- **Obtained a new formula for point-source calibrator deviating from its nominal position.**
- **Radio interferometry and aperture synthesis theory becomes a complete framework theoretically**

  --- calibration and imaging within the framework of radio interferometry and aperture synthesis.



（Zhou et al 2022，*Res. Astron. Astrophys*）

The statistical work on MUSER observations provides a database for further in-depth research (Zhang et al. 2021)

Table 2 Observational Results of Solar Radio Bursts

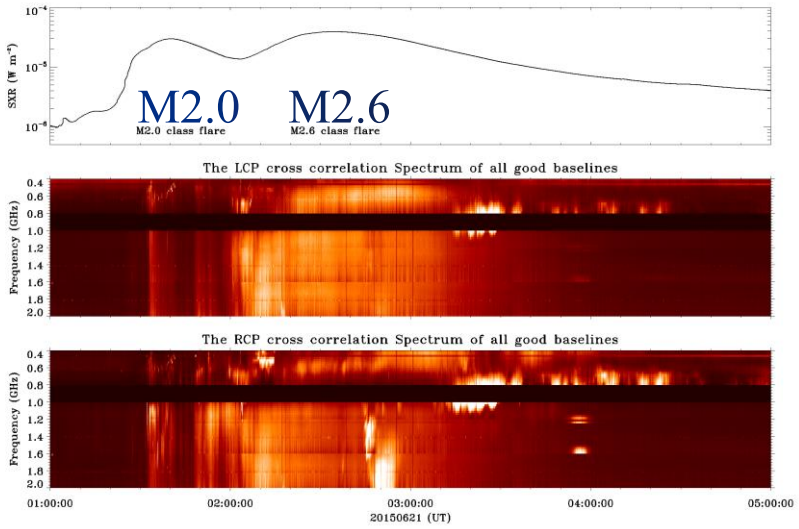
Event	Start	Stop	III-like	QPP	IV	Dif	Spi	Lac	Fib	Unu	Class/Level
2014 Nov 11	3:59(3:28)	4:00(4:32)	✓								C1.1
	4:16(4:11)	5:05(5:26)	✓	✓		✓					C3.4
	5:32(5:02)	5:53(6:04)	✓	✓							C2.1
	6:13(6:02)	6:30(7:14)	✓	✓							C3.1
	7:59(7:27)	8:00(8:41)	✓								C2.3
2014 Dec 17	1:46(1:11)	2:27(2:27)			✓				✓		M1.1
	4:22(3:55)	5:22(5:50)	✓	✓	✓	✓	✓	✓	✓		M8.7
2015 May 21	5:55(4:52)	5:57(6:23)	✓								B6.3
2015 Jun 20	1:13(0:51)	1:25(2:00)			✓			✓			B6.9
	2:08(2:06)	2:42(3:14)	✓	✓		✓					C2.3
2015 Jun 21	1:17(0:32)	6:13(3:32)	✓	✓	✓		✓	✓	✓	✓	M2.0 M2.6
2015 Nov 4	3:57(3:23)	4:04(4:35)	✓								C1.4
	4:52(4:20)	4:56(5:29)	✓								C1.0
2015 Nov 22	4:51(4:21)	4:53(5:30)	✓								C1.1
	5:35(5:01)	5:38(6:11)	✓								C5.6

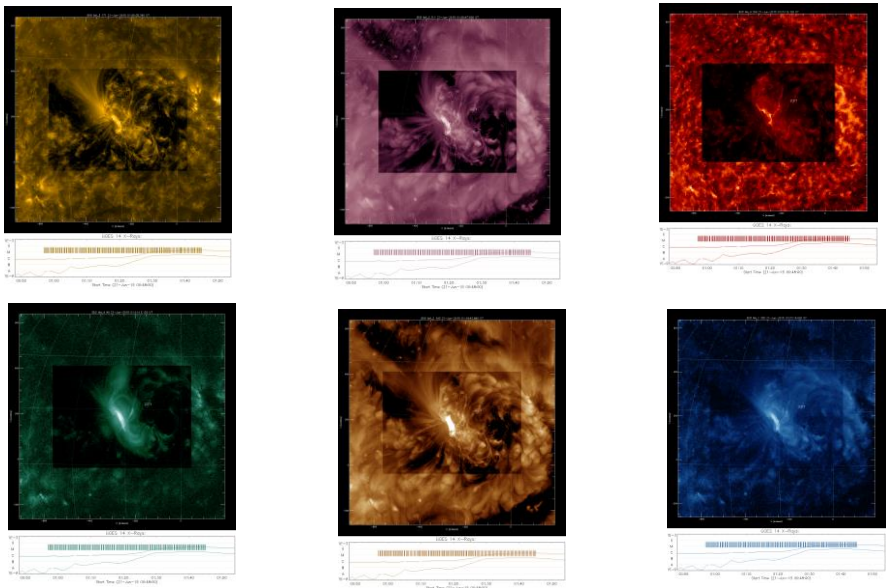
- **On 21 June 2015, many radio FSs such as QPPs, lace, spikes, fibers and slow drifting bursts etc., were observed when two successive M-class flares occurred.**
- **Among these fine structures, groups of spikes in 0.6–2 GHz range showed very interesting features, i.e., each group of spikes were co-occurred on QPPs (Huang et al. 2022).**

Observations

Flare Event on 21 June 2015

- Two GOES M-class flares occurred in active region NOAA 12371. The M2.0 flare occurred during 01:02 UT-01:42 UT followed by the M2.6 flare from 02:06 UT to 03:02 UT.
- The GOES SXR flux at 1–8 Å and the cross-correlation dynamic spectra in LCP and RCP of MUSER-I are shown in the left and SDO/AIA images in the right.

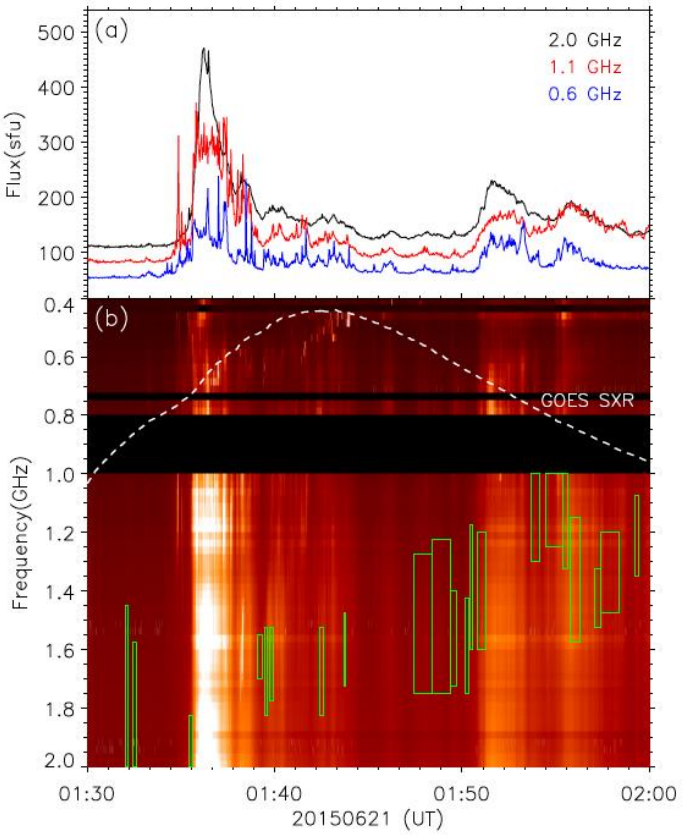




Solar Radio Burst Fine Structures

From these fine structures, 64 groups of spikes were found (Huang et al. 2022) with two different spectral features:

1. There were 21 groups of spikes in RCP spectra. Each group of spikes is divided into many quasi-periodic clusters and each cluster contains many individual spike bursts. These spikes were concurrent with the broadband QPPs.
2. There were other groups of spikes randomly scattered in a broader frequency band. These include 34 groups in the LCP spectrum, 3 groups in the RCP spectrum and 6 groups in both LCP and RCP spectrums.



The latter category has the common spectral feature as studied in many previous literatures.

For the first category, Huang et al. (2022) performed the spectral analysis of these 21 groups (in green boxes) of quasi-periodic clusters of spikes during the M2.0 flare.

Some Peculiar Examples of FSs

- It is interesting that these quasi-periodic clusters of spikes co-occurred on QPPs, some peculiar examples of FSs are shown in panels below (Huang et al. 2022).

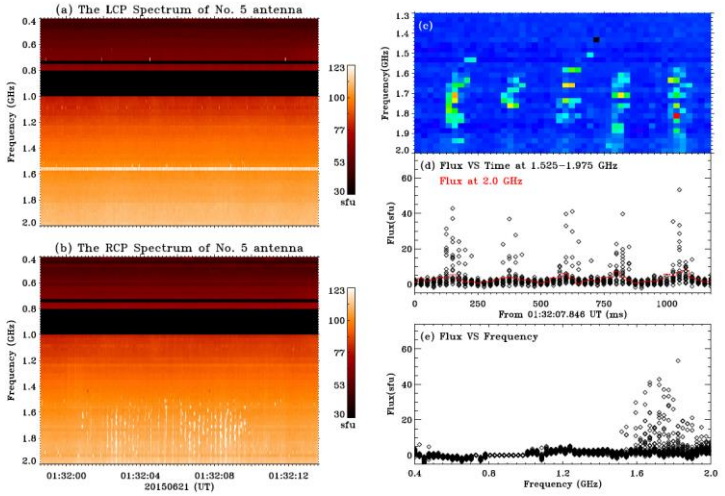


Figure 2. (**a**,**b**) The LCP and RCP spectrum from 01:31:58.597 UT to 01:32:13.597 UT observed by No.5 antenna of MUSER-I. (**c**) The zoomed-in spectral structure of QPSs from 01:32:07.846 UT. (**d**) The temporal evolution of the intensity of spikes by subtracting the continuum emission. (**e**) The frequency distribution of the intensity of spikes by subtracting the continuum emission.

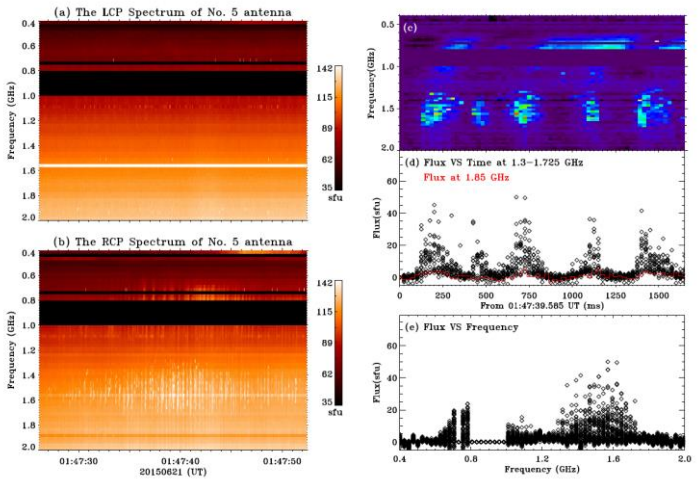
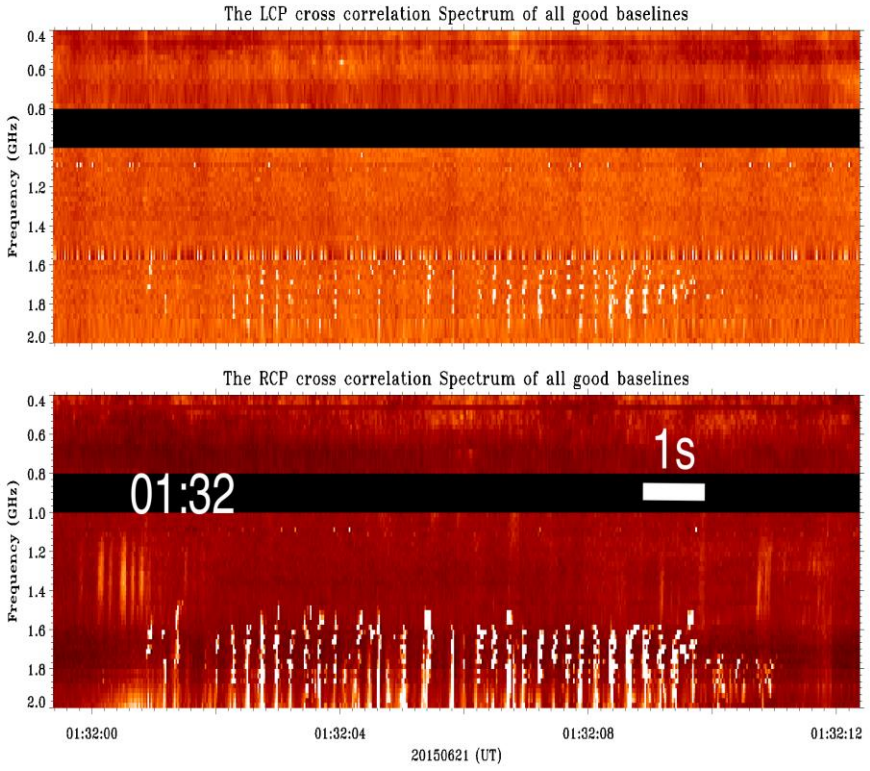


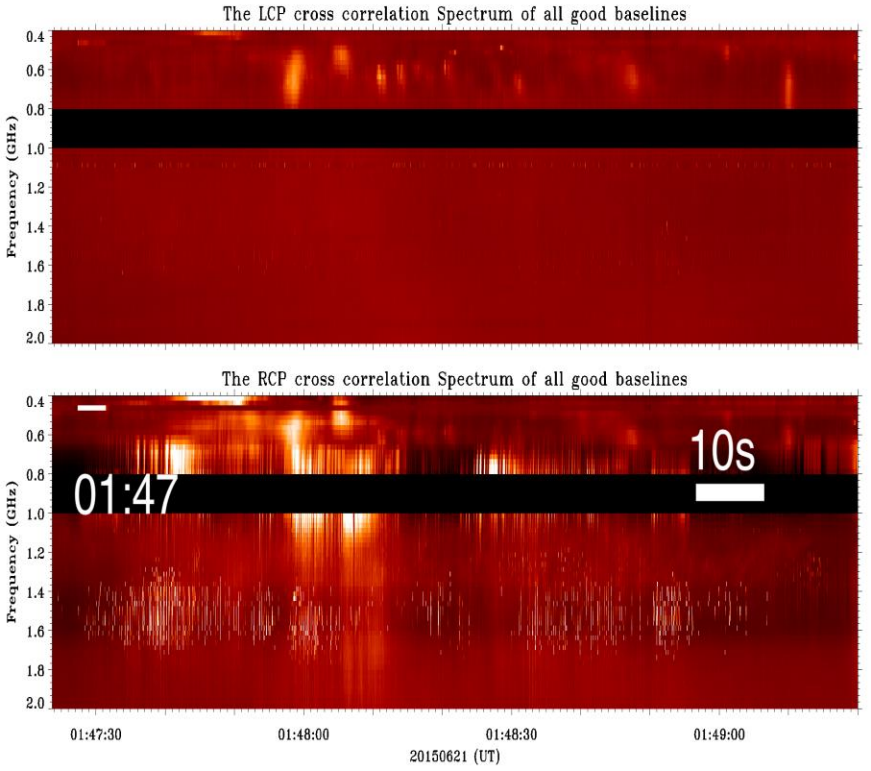
Figure 4. (**a**,**b**) The spectrum from 01:47:26.135 UT to 01:47:51.135 UT in LCP and RCP observed by the No.5 antenna of MUSER-I. (**c**) The zoomed-in spectral structure of QPSs from 01:47:39.585 UT. (**d**) The temporal evolution of the intensity of spikes by subtracting the continuum emission. (**e**) The frequency distribution of the intensity of spikes by subtracting the continuum emission.

Quasi-periodic clusters of spikes

FS1

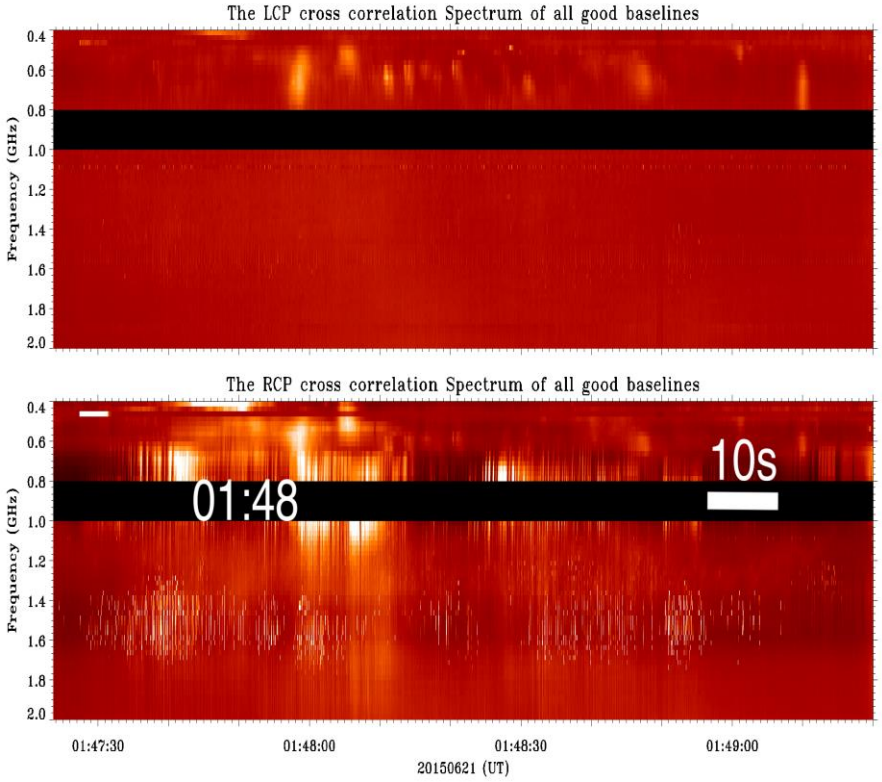


FS2

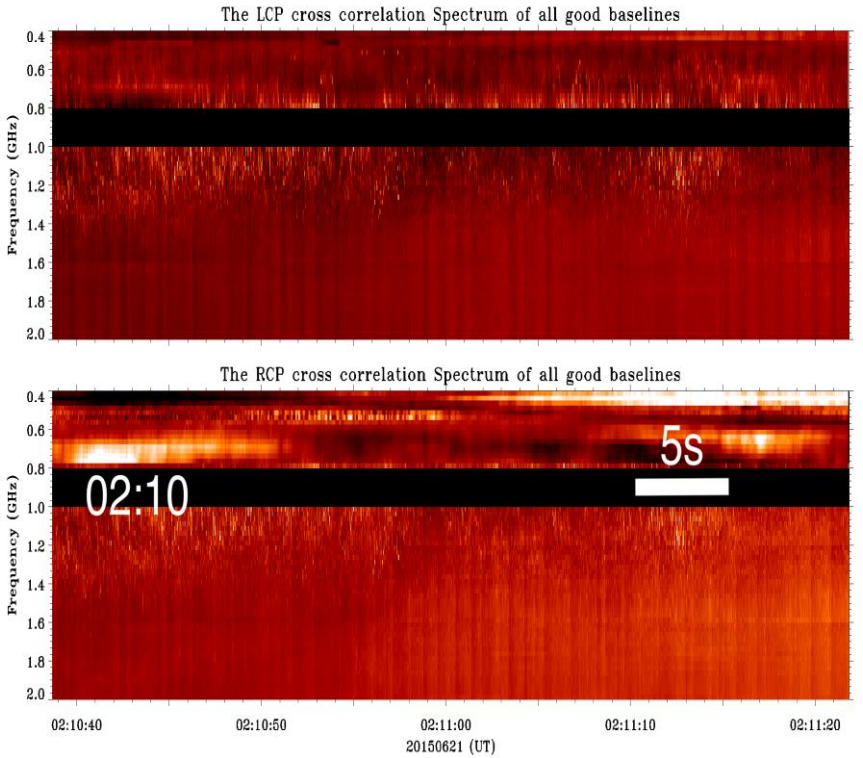


Quasi-periodic clusters of spikes

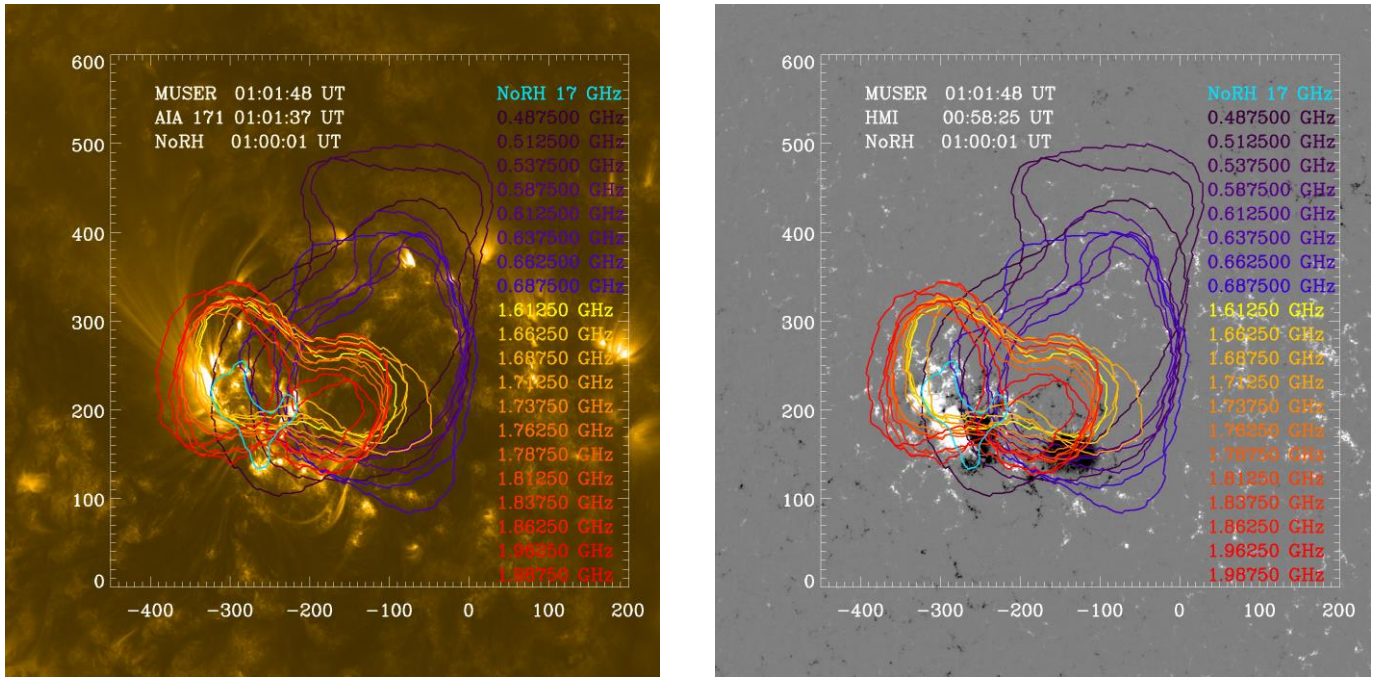
FS3



FS4

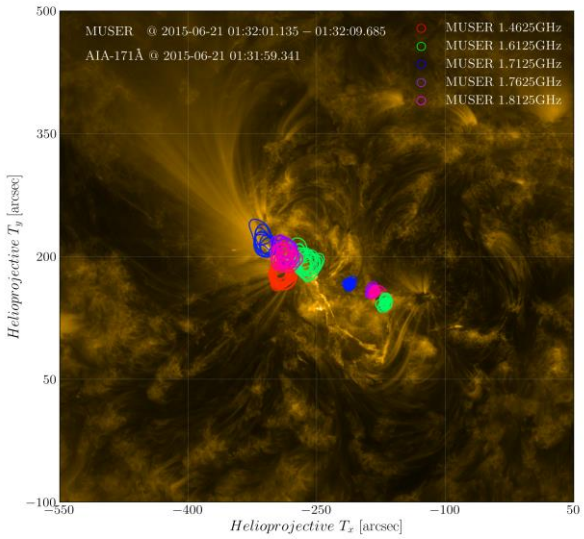


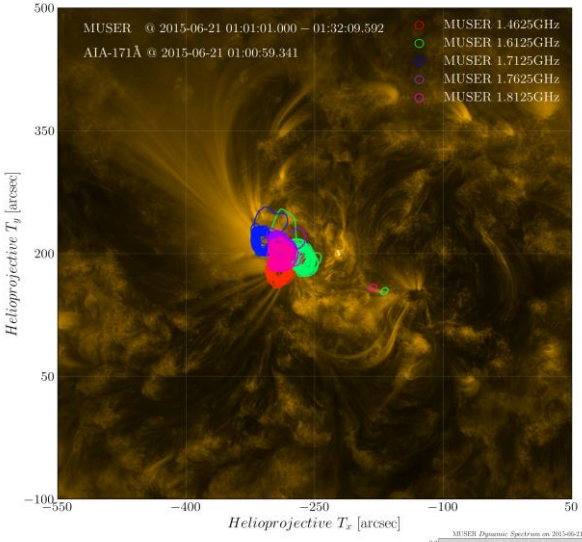
Imaging-Spectroscopy of the Event

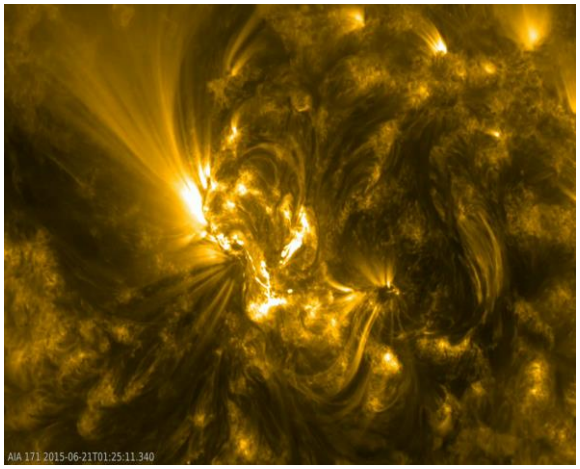


MUSER-I multiple frequency and the NoRH 17 GHz contours for the quiet Sun around 01:00 UT overlaid with AIA/SDO EUV image and HMI/ SDO magnetogram.

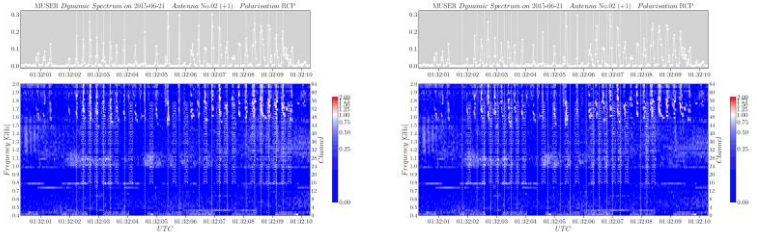
Multiple Frequency Images of Radio FS1



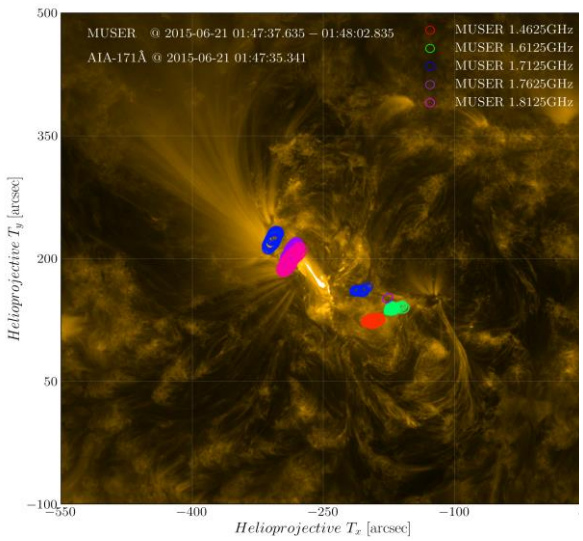


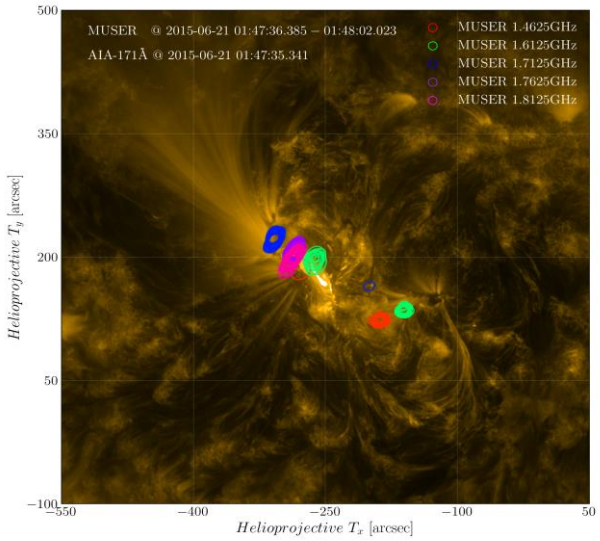


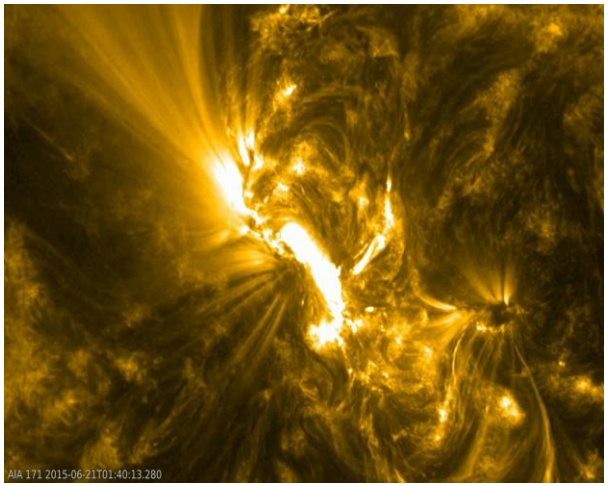
01:32:00 to 01:32:10 UT with (left) and without (right) the spike enhancement.



Multiple Frequency Images of Radio FS2

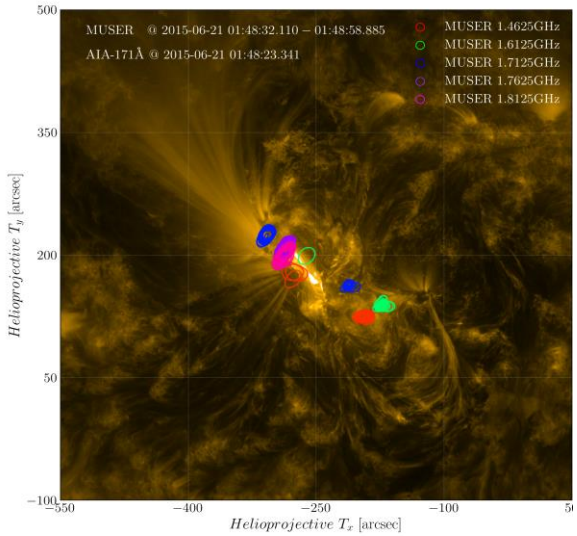


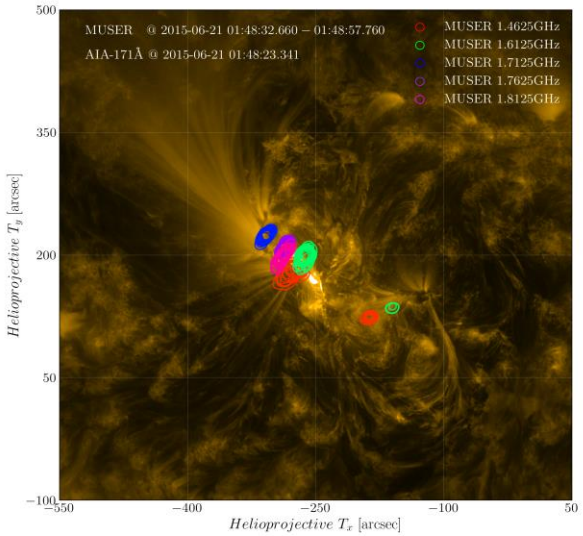


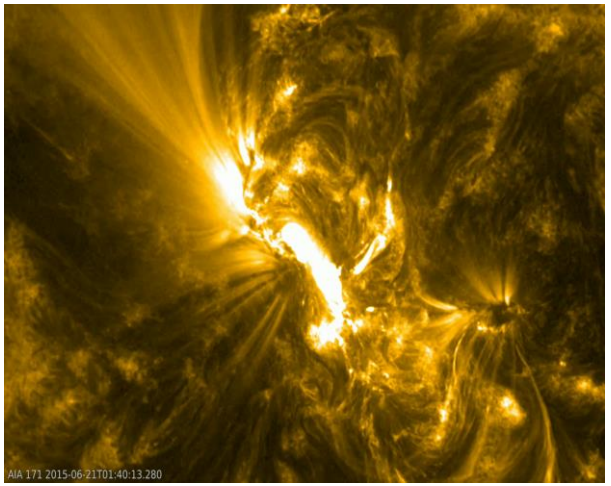


MUSER-I multiple frequency contours showing bursts from 01:47:37 to 01:48:02 UT with (left) and without (right) the spikes/QPPs enhancement.

Multiple Frequency Images of Radio FS3

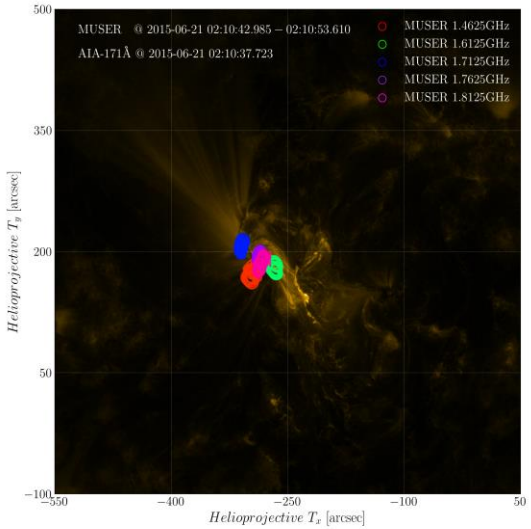


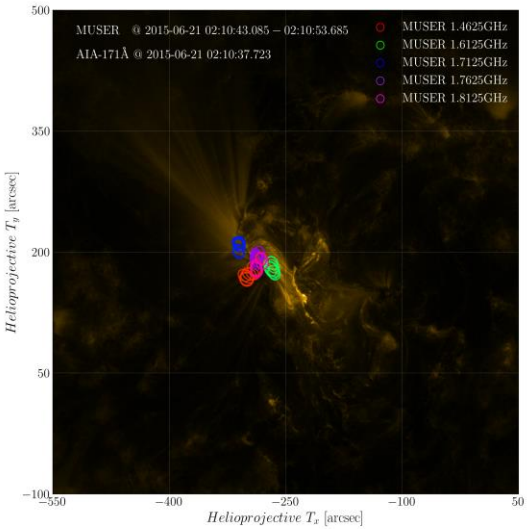


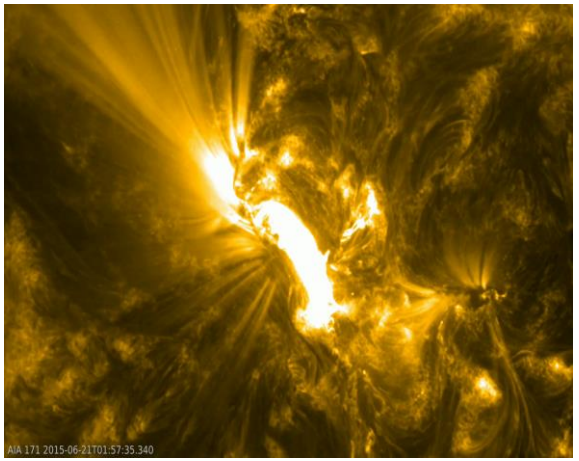


MUSER-I multiple frequency contours showing bursts from 01:48:32 to 01:48:58 UT with (left) and without (right) the spikes/QPPs enhancement.

Multiple Frequency Images of Radio FS4







MUSER-I multiple frequency contours showing bursts from 02:10:42 to 02:10:53 UT with (left) and without (right) the noisy burst enhancement.

Discussions & Summary

- MUSER multi-frequency images of these peculiar fine structures are presented
  - flare radio sources mainly located in the left bipolar region
  - FS1 radio sources located elsewhere in the right area
  - FS2 & FS3 radio sources were in both flare and burst sites,
  - FS4 radio sources mainly located in flare site

  These RCP burst FSs should be excited in X-mode (Further investigation is under way).
- The solar radio imaging-spectroscopy is very important in understanding the solar flares, energy release processes and particle accelerations. It is effective tool for space weather monitor and research.

Thank You !