

Radio imaging-spectroscopy observations of the Sun in decimetric and centimetric wavelengths

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Abstract. To address fundamental processes in the solar eruptive phenomena it is important to have imaging-spectroscopy over centimetric-decimetric wave range. The Chinese Spectral Radioheliograph (CSRH) in 0.4-15 GHz range with high time, space and frequency resolutions is being constructed to achieve this goal. The perspectives to open new observational windows on solar flares and CMEs will be achieved by mapping the radio emission from unstable electron populations during the basic processes of energy release. CSRH is located in a radio quiet region in Inner Mongolia of China. The array of CSRH-I in 0.4-2.0 GHz with 40 4.5m antennas has been established and starts test observations. The 60 2m antennas for array of CSRH-II in 2-15 GHz have been mounted and assembled. The progress and current status of CSRH are introduced.

Keywords. Radioheliograph, solar radio bursts, flares, CMEs, coronal magnetic field

1. Motivation

Radio bursts are prompt indicators of the various solar activities including flares and CMEs, etc. RHESSI observations indicate that non-thermal particles may account for a significant fraction of flare energy released during initial phase (Lin *et al.* 2008). Imaging spectroscopy over centimeter and decimetric wavelengths is important for addressing the problems of primary energy release, particle acceleration, and transportation processes (Bastian, *et al.* 1998, Gary & Keller 2004, Aschwanden 2004, Pick & Vilmer 2008)

From statistical study of radio dynamic spectral observations it was inferred that the acceleration site is located in a low-density region with a density of $n_e^{acc} \sim 3 \times 10^9 \text{ cm}^{-3}$, corresponding to a plasma frequency of $\nu_p \sim 500 \text{ MHz}$, from where electron beams are accelerated in upward (type III) and downward (RS bursts) directions (Aschwanden & Benz 1997). However, the available radio imaging observations are presently only at a few discrete frequencies in the range 40 - 150 MHz from Gauribidanur Radioheliograph (Ramesh *et al.* 1998), in the range 150 - 450 MHz from Nancay Radioheliograph (Radioheliograph Group, 1989), at 5.7 GHz from Siberian Solar Radio Telescope (Grechnev *et al.* 2004), and at 17/34 GHz from Nobeyama Radioheliograph (Nakajima *et al.* 1994).

A flare event on 20 February 2002 at 11:07 UT was studied by Vilmer *et al.* (2002). They compared the hard X-ray images observed with RHESSI and of the radio emission sites observed by the NRH between 450 and 150 MHz. They found that variations in the HXR and decimetric emitting sources showed that both emissions were closely related to the energy release sites and to their variations during the flare. Thus they confirmed the previous suggestion of common acceleration/injection sites for HXR and

Table 1. CSRH specifications

Frequency range	400 MHz~15 GHz (λ : 75 ~2 cm)
Frequency resolution	64 channels for CSRH-I in 400 MHz ~ 2 GHz
	> 500 channels for CSRH-II in 2 ~ 15 GHz
Spatial resolution:	I: 10'' ~ 50''
	II: 1.3'' ~ 10''
Temporal resolution:	I: 25 ms
	II: ~ 200 ms
Dynamic Range	25 db (snapshot)
Polarizations	Dual circular L, R
Array	I: 40 \times ϕ 4.5m parabolic antennas
	II: 60 \times ϕ 2m parabolic antennas
Maximum baseline	3 km
Single dish beam (Field of view)	0.6° ~ 7°

decimetric/metric emitting electrons. However, as the lack of the knowledge of the magnetic connections between the emitting sites, it was not easy to understand in detail the link between the X-ray and radio sources and their evolution. So it is desired to image radio emissions from non-thermal electrons at even higher frequencies to better image the acceleration sites of the electrons which are responsible for HXR emission.

Trottet *et al.* (2006) carried out a detailed analysis of spectral and imaging observations of the November 5, 1998 flare obtained from hard X-rays and NRH radio images at 410, 327, 236 and 164 MHz. They found evidence that hard X-ray and decimetric/metric radio-emitting electrons were produced by the same accelerator. However, the available observations and analysis did not allow them to establish a clear and direct magnetic connection between the hard X-ray emitting region and the radio-emitting sources in the middle corona. Therefore the multi-frequency image observations in decimetric and centimetric wave range higher than 400 MHz are needed.

For the famous December 13, 2006 flare event many radio fine structures were observed by Chinese Radiospectrometer at microwave range and it was found that the scale height ratio of plasma density to magnetic field deduced from the zebra patterns decreased by a factor of about 2 before and after the flare peak (Yan *et al.* 2007). The later case was further confirmed by statistical results from 74 zebra pattern (Yu *et al.* 2012). However, what is the exact coronal magnetic field structure needs radio imaging-spectroscopy over wide frequency range in centimetric to decimetric wave range.

Therefore it is expected to have a new instrument that is capable of true imaging spectroscopy, with high temporal, spatial, and spectral resolution (Hudson & Vilmer 2007, Pick & Vilmer 2008). The Chinese Spectral Radioheliograph (CSRH, Yan *et al.* 2004) and Frequency-Agile Solar Radiotelescope (FASR, Bastian 2003, Gary 2003) have been proposed to reach this goal.

The project of the Chinese Spectral Radioheliograph (CSRH) has been supported as National Major Scientific Research Facility Program of China and is under construction now, which will open new observational windows on flares and CMEs at radio wavelengths. The whole budget for the instruments of CSRH project was approved in 2009. The site survey for the CSRH array was completed at Mingantu town in Inner Mongolia of China and the radio quiet zone protection with 10 km radius centered at CSRH site was setup in 2008. The construction also started in the autumn of 2008. The CSRH project is due to finish in 2013.

2. Description of CSRH

The Chinese Spectral Radioheliograph (CSRH) in centimetric-decimetric wave range is a solar-dedicated radio interferometric array that will be used to carry out imaging

Table 2. Current measured CSRH-I antenna locations in local coordinates (Unit: m)

Arm A	X	Y	Z	Arm B	X	Y	Z	Arm C	X	Y	Z
IA0	0	0	0								
IA1	-0.022	7.988	0	IB1	-6.884	-4.112	0	IC1	6.966	-3.990	0
IA2	-6.426	19.456	0	IB2	-13.559	-15.394	0	IC2	20.185	-4.093	0
IA3	-21.025	28.661	0	IB3	-14.214	-32.499	0	IC3	35.379	3.976	0
IA4	-44.371	31.799	0	IB4	-5.365	-54.364	0	IC4	50.088	26.883	0
IA5	-79.806	-0.535	0.1	IB5	40.334	-68.776	0	IC5	39.461	69.250	0
IA6	-92.243	-67.981	0	IB6	105.005	-45.994	0	IC6	-12.702	113.930	0
IA7	-49.823	-156.924	0	IB7	160.745	35.210	0	IC7	-110.987	121.621	2
IA8	75.111	-226.202	0	IB8	158.353	178.005	0	IC8	-233.431	47.856	2
IA9	283.605	-203.226	0	IB9	34.311	347.220	0	IC9	-317.836	-143.928	2
IA10	517.111	3.454	0	IB10	-261.386	446.416	5.5	IC10	-255.740	-449.563	2
IA11	624.882	459.903	0	IB11	-710.941	311.107	10	IC11	86.093	-771.081	0
IA12	356.229	1120.404	5.5	IB12	-1148.753	-251.691	10	IC12	792.346	-868.716	10
IA13	-286.460	1817.530	10	IB13	-1194.157	-1342.201	10	IC13	1759.184	-362.106	-0.1

Central antenna IA0 location: E 115°15'1.8", N 42°12'42.6", Altitude 1365m

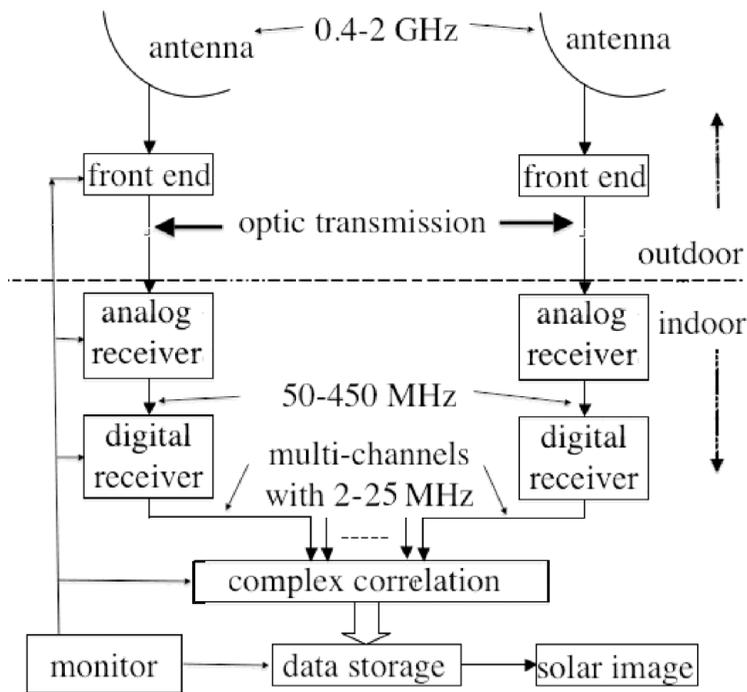


Figure 1. The system block diagram of CSRH-I. CSRH-II has a similar system structure except that the RF input is 2 – 15 GHz in place of 0.4 – 2 GHz.

spectroscopy of the Sun, to produce high spatial resolution, high time resolution and high frequency resolution images of the Sun simultaneously (Yan *et al.* 2004, Yan *et al.* 2009). The updated main specifications of CSRH are listed in Table 1.

The CSRH frequency range is 0.4-15GHz which is divided into CSRH-I covering 0.4-2GHz band and CSRH-II covering 2-15GHz band. The CSRH-I contains 40 antennas of 4.5m diameter, and the CSRH-II contains 60 antennas of 2m diameter. The complete system of CSRH-I array has been established and is in test observation now, whereas 60 antennas of CSRH-II have just been mounted in the field in 2012 and the whole system of CSRH-II is due to finish in 2013. The whole 100 antennas of both CSRH arrays are located

on 3 log-spiral arms, and the maximum baseline length is 3km. The currently measured antenna locations for CSRH-I array is listed in Table 2. The system block diagram for CSRH-I in dm-wave range is shown in Figure 1. CSRH-II system has a similar structure as in Figure 1 except that the RF input is 2–15 GHz instead of 0.4–2 GHz. Additionally two 20 m antennas for interferometry experimental in 400-1000 MHz were established in 2011 in CSRH site, which may be incorporated into CSRH-I calibrations later.

From Figure 1 it is seen that the solar radio emission in 0.4-2 GHz is detected by each CSRH-I antenna with the broadband feed and outdoor devices including LNA and optic transmitter. The signal with 400 MHz bandwidth, which covers the whole 1.6 GHz bandwidth by scanning 4 times, is then transmitted through optic fibers to indoor devices including optic receiver and analogous receivers with an output in 50-450 MHz range. It is then followed by digital receiver with 1 Gbps A/D converter to receive 400 MHz analogous signal and the digital receiver outputs 16 channels simultaneously for the complex correlations with ~ 2 -25 MHz bandwidth for each channel. The time delay compensation and fringe stopping are considered in the digital correlations. The whole correlation procedure is controlled by a monitoring subsystem. Similar procedure applies to CSRH-II except that the solar radio emission in 2-15 GHz is detected by each CSRH-II antenna with the broadband feed and the IF signal with 400 MHz bandwidth will need to scan the whole 13 GHz bandwidth by 33 times now.

3. Progress of CSRH Construction

Among the technical issues for CSRH system based on aperture synthesis technique (Taylor *et al.* 1999, Thompson *et al.* 2001), a key problem is that the high performance ultra-wide band feed is needed for reflector antennas. Such feed should be with wide impedance bandwidth, low profile, symmetrical radiation patterns, and fixed phase center over whole band. The Eleven feed (Olsson *et al.* 2006) has many advantages and is a good option. For its original version the return loss is less than -5 dB (or VSWR ≤ 3.53), which satisfies the requirements for observing other astrophysical objects. However, solar radio bursts and accordingly their polarizations may vary quickly. Therefore, the isolation is important for correct observations of the polarizations. So the return loss or VSWR should be further reduced in order to achieve this goal. We have successfully developed the feeds for CSRH-I with VSWR less than 1.5 over most the frequency range and exhibits low profile, 133% impedance bandwidth and good radiation characteristics. Figure 2 shows the polarization degree measurement of IC8 antenna element in 400 MHz–2 GHz range. It is seen that in nearly 90% frequency band the polarization degree, or $(P_L - P_R)/(P_L + P_R)$ is less than 5%, which indicates good isolation performance.

As mentioned above, CSRH-I has been put into test observation and fixed time delays among CSRH-I array have been measured for calibration. The measured RMS variations are < 1 ns which is very robust, as similar results obtained after multiple measurements pursued 1 years apart (Liu *et al.* 2012). For the test observations, fringes of the satellite signals, the Sun, and Cygnus A have been obtained correctly for all baselines. The residuals of the phase closures for every tri-antenna composition were about 2 degrees for both geostationary and GPS satellites. Fringe stopping has been obtained for short and mid baselines when observing the quiet Sun. These experiments verify the system design and demonstrate the system performance. The two 20 m antennas in 400-1000 MHz will be incorporated into CSRH-I calibrations. It is expected to obtain CSRH-I first solar maps soon.

In October 2012, 60 CSRH-II antennas of 2m diameter were erected at the CSRH site whereas the analogous and digital receivers, digital correlators, and monitor subsystem,

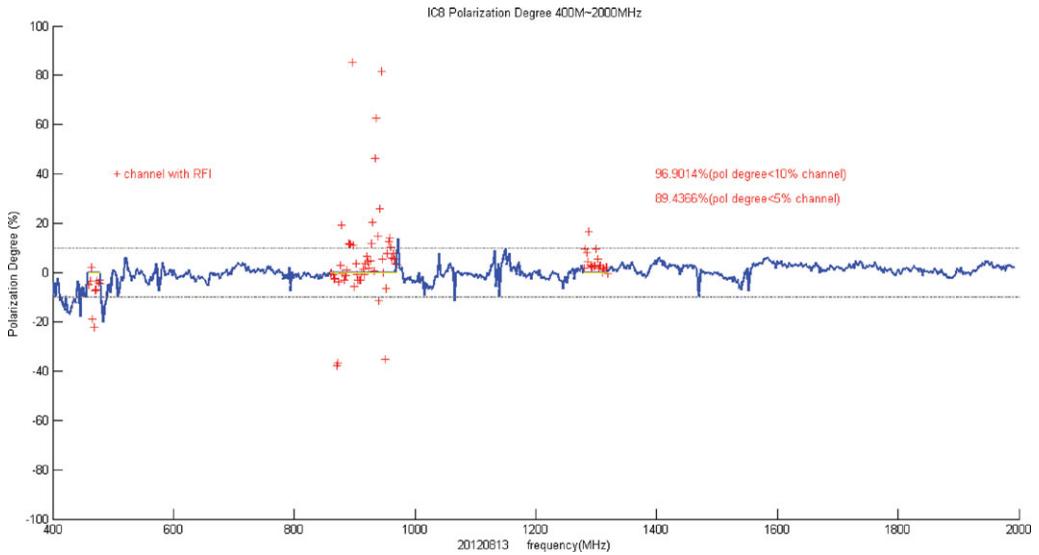


Figure 2. Polarization degree, or $(P_L - P_R)/(P_L + P_R)$ of a CSRH-I antenna element in 400 - 2000 MHz range measured on 13 Aug 2012, which is $\leq 10\%$ over 96.9% whole frequency band, and furthermore, $\leq 5\%$ over 89.4% whole frequency band. The red plus sign indicates frequency point where strong RFI occurred.



Figure 3. Central part antennas of CSRH-I array for test observation on 8 August 2012.

etc. are still under development and manufactures in laboratories and due to assemble and test in 2013. Figure 3 shows the central part antennas of CSRH-I array for test observation on 8 August 2012.

4. Conclusion

In summary, radio imaging spectroscopy is in its infancy and will open new observational windows on flares and CMEs, it will also provide coronal magnetograms. To reach this goal, CSRH project has been funded and will be fulfilled completely by the end of 2013. The radio quiet zone protection with 10 km radius for CSRH was established. The CSRH-I array in decimetric wave range has been established during 2008-2011. For the test observations, the phase fringes for all baselines have been obtained. The fringe stopping was obtained for short and mid baselines of the quiet Sun. It is still for calibration and verification now and it is expected to obtain first solar maps soon. The all 60 antennas for CSRH-II array have been mounted and the analogous and digital receivers, digital correlators, and monitor subsystem for CSRH-II will be assembled in 2013.

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