Calibration and Data Processing for a Chinese Spectral Radioheliograph in the Decimeter Wave Range

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Abstract

The Chinese Spectral Radioheliograph (CSRH) is a solar-dedicated interferometric array with a frequency range from 400 MHz to 15 GHz. There are 40 4.5 m antennas with 400 MHz to 2 GHz, and 60 2 m antennas with 2 GHz to 15 GHz in this telescope. CSRH is under construction at Mingantu station, which is about 400 km away from Beijing in China. Now, CSRH-I, which includes an antenna, a receiver, and a correlator in the decimetric wave range, has already been established. CSRH-II is under construction and will be completed by the end of this year. This paper introduces the whole system of CSRH-I briefly, and presents delay measurements, polarization calibration, and some other results of calibration and data processing for CSRH-I.

Key words: Methods: observational — Sun: radio radiation

1. Introduction

Imaging spectroscopy over the centimeter and decimeter wavelength range is important for addressing fundamental problems of energy release, particle acceleration, and particle transport (Bastian et al. 1998). However, the running solar-dedicated telescope only observes the Sun at several low or high point frequencies in the world. The Nancay Radioheliograph in France images the Sun only at several point frequencies from 150 MHz to 450 MHz (Kerdraon & Delouis 1997). The Siberian Solar Radio Telescope in Russia observes the Sun at 5.7 GHz (Grechnev et al. 2003), and the Nobeyama Radioheliograph in Japan observes it at 17 GHz and 34 GHz (Nakajima et al. 1994). Therefore, there is an urgent need for a new instrument capable of true imaging spectroscopy, along with high temporal, spatial, and spectral resolutions to meet this end (Gary & Keller 2004). Depending on proposals and some pre-studies during the past 30 years, it was suggested to build a Chinese Spectral Radioheliograph (CSRH) in the decimeter to centimeter-wave range in recent years (Yan et al. 2004, 2009). The CSRH being developed will be a solar-dedicated radio interferometric array that will observe spectroscopic imaging of the Sun, with high spatial resolution, high time resolution, and high frequency resolution images of the Sun simultaneously in the decimeter to centimeter wave range (Yan et al. 2009).

2. Description of CSRH-I

CSRH is located at Mingantu station of NAOC, which is about 400 km away from Beijing in China. CSRH consists of two arrays, CHRH-I and CSRH-II. CSRH-I is composed of 40 equatorial mounted parabolic 4.5 m antennas. The frequency is from 400 MHz to 2 GHz. CSRH-II is composed of 60 equatorial mounted parabolic 2.0 m antennas, and the frequency is from 2 GHz to 15 GHz. The center of these arrays is 115°15′1.8′′ east longitude, 42°12′42.6′′ north latitude, altitude 1365 m. All of these antennas are installed according to a three-arm spiral arrangement. The antenna arrangement is shown in figures 1 and 2. Now, CSRH-I, which includes an antenna, a receiver, and a correlator, has already been established. CSRH-II is under construction, and will be completed by the end of this year. Some technical specifications of CSRH-I and CSRH-II, as driven by scientific requirements, are given in table 1.

Left and right-handed circular polarization signals from a radio source are received by feed in the 0.4–2.0 GHz range mounted at the prime focus of each dish. LNA (Low Noise Amplifier) is connected to left and right-handed circular polarization ports of the feed. The optical transmitter and LNA are...
Fig. 2. Antenna arrangement of the CSRH central part. The rectangle, 105 m × 130 m, indicates the observation area.

Table 1. CSRH specifications.

<table>
<thead>
<tr>
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<th>CSRH-I</th>
<th>CSRH-II</th>
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<tbody>
<tr>
<td>Frequency range</td>
<td>0.4–2 GHz</td>
<td>2–15 GHz</td>
</tr>
<tr>
<td>Number of antennas</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Antenna size</td>
<td>4.5 m</td>
<td>2 m</td>
</tr>
<tr>
<td>Maximum baseline</td>
<td>~3000 m</td>
<td>~3000 m</td>
</tr>
<tr>
<td>Minimum baseline</td>
<td>~8 m</td>
<td>~4 m</td>
</tr>
<tr>
<td>Frequency channels</td>
<td>64 channels</td>
<td>528 channels</td>
</tr>
<tr>
<td>Time resolution</td>
<td>25 ms</td>
<td>206.25 ms</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>10′.3–51′.6</td>
<td>10′.3–1′.4</td>
</tr>
<tr>
<td>Polarization</td>
<td>Left, Right</td>
<td>Left, Right</td>
</tr>
</tbody>
</table>

installed in a temperature-controlled box mounted at the back of the feed. The optical signal from each antenna is transmitted to the observation building, located at central part of this array by about 3400 m long optical fiber. The buried depth is about 3 m to maintain a constant temperature during the observation time. The outputs from the optical receiver come into a radio-frequency receiver in the observation room. The amplified RF signal is mixed with two local oscillator signals, and then down-converted to a single sideband IF signal. These signals are digitized, and passed through a polyphase filter bank with 16 channels. The bandwidth of each channel can be selected from 1.5625 MHz, 3.125 MHz, 6.25 MHz, 12.5 MHz, and 25 MHz before an observation. Then, signals are quantized with 2-bits and correlated with signals from other antennas. The correlated data are recorded on a hard disk for off-line processing. A basic system block diagram of CSRH-I is shown in figure 3.

3. Calibration

3.1. Delay Measurement

It is important that the amplitude and phase of the visibilities should be accurately measured to image the solar. We have measured the system noise and gain carefully by using the K-factor method. In order to obtain real visibilities of the radio source, precise delay measurements and compensation are required.

Firstly, a geodetic coordinate measuring system including 40 measuring points was established to measure the precise position of all antennas. Using a laser distance measuring method, the accuracy of the antenna position is about up to the mm level by laser total station. The other part that needs to be measured is any different length of the signal transmission line. In the CSRH case, the optical fiber from each antenna to the control building is of the nearly same length. The length of each fiber is about 3400 m. Because it is impossible to absolutely guarantee equal lengths, it is necessary for accurate measurements of the fiber length. For delay measurements,
the Sun and Cygnus A were chosen as calibrator sources to measure these length differences. The Sun can be used for short baselines, and Cygnus A for long baselines. The output amplitude of the correlator is equal to the maximal value by setting different delay compensation in the digital receiver for each antenna. The measured delay contains geometric delay and system delay; the geometric delay is determined by the position of the antenna. System delay involves differences in the length of the transmission line, especially any difference of each optic fiber. Furthermore, regarding the measured delay minus the corresponding geometric delay, we can calculate the system delay, which is due to any length differences. The rms of a delay error is less than 1 ns. Figure 4 is an example of a delay measurement, showing the measurement of delay between antennas IA0 and IB2. We carried out two similar measurements during the period of from 2011 July to 2013 March. The results of the two measurements are 36.87 ns and 36.62 ns, which are almost consistent.

3.2. Polarization Measurement

The feed of CSRH can receive left and right-circular polarization signals simultaneously in the 400 MHz to 2 GHz wave range. The polarizer in the feed is not ideal, so left circular polarizations are not perfectly isolated from the right circular polarization, and the right circular polarizations are not perfectly isolated from left circular polarization. To measure the performance of the polarizer, a mathematical model was introduced to correct this problem. The response of an interferometer can be factorized into antenna-based components, which can be further factorized into discrete contributions arising from a number of effects (Thompson et al. 2001). Two antennas, each with two differently polarized outputs, will produce four complex correlations. From these four outputs, four Stokes images can be obtained. Following these lines, a mathematical model describing the feed of CSRH was discussed and measured. Usually, the polarization degree is used to describe the performance of a receiver in solar physics, defined as:

\[ \text{polarization degree} = \frac{(P_l - P_r)}{(P_l + P_r)}. \]  

Here, \( P_l \) represents the power of left-circular polarization signals, and \( P_r \) represents the power of right-circular polarization signals. The polarization degree of a CSRH-I antenna element in the 400–2000 MHz range, measured on 2012 August 13, which is \( \leq 10\% \) over 96.9% of the whole frequency band, and, \( \leq 5\% \) over 89.4% of the whole frequency band (Yan et al. 2013).

3.3. Phase Closure

The closure relationships have proved to be very important in synthesis mapping (Thompson et al. 2001). When applied to unresolved point sources, the phase closure should be zero. Thus, the closure relationships are useful for us to check the accuracy of calibration and to examine instrumental effects. Observations of a meteorological satellite, whose name is Fengyun-2E, which was launched in 2004 and is stationed along the equator at 105° east longitude, and a GPS satellite were carried out with 40 antennas since 2010 May. The cosine and sine fringes variation that we observed are good agreement with theoretical values, which depended on the orbit prediction. The average values of the phase closure of geostationary satellites observation are less than 3°, and the rms of phase closure are less than 2° during the 20 hours observation period, as shown in figure 5. The average values are less than 1°, and the rms values are less than 1° during 20 minutes. Thus, these results showed that the receivers and correlator worked well. Furthermore, the phase closure relationship can be used to improve the calibration accuracy for observations, especially for the high dynamic-range requirement.
4. Observations

4.1. Solar Burst Observation

The first burst, associated with C1.5 class X-rays and observed by a 5-element system, was recorded at 07:59–08:20 UT on 2010 November 12. Figure 6 shows the fringe observed by antenna IB7 and IC1. The total flux and spectrum from 1.2–1.6 GHz are also shown in panels (b), (c), and (d).

4.2. Image of a Geostationary Satellite

CSRH-I consists of 40 antennas, and its maximal baseline is about 3 km. Therefore, how to measure the whole system and to correct observations in data processing is a very difficult problem. Usually, there are several methods to measure the complex gain of the receiver, such as a round-trip phase measuring system, a Swarup and Yang system, a frequency-offset round-trip system, and others (Thompson et al. 2001). Unfortunately, these methods cannot measure the antenna directly. Thus, calibrator sources in the sky are the best choice. Satellites are the strongest radio sources in the sky for CSRH-I. In the 400 MHz–2 GHz frequency band, some geosynchronous orbit satellites and GPS satellites are available. The Fengyun-2E satellite was observed on 2013 June 4.

CASA, the Common Astronomy Software Applications package, is being developed with the primary goal of supporting the data post-processing needs of the next generation of radio astronomical telescopes. We took advantage of CASA to process this observation, in order to ensure that the data processing of this observation can be trusted. Figure 7 shows an image of the FengYun-2E satellite processed by using CASA on 2013 June 4. The frequency is 1.7025 GHz. The ellipse in the lower left corner is the synthesized beam.

For CSRH-I, because its size is much smaller than the synthesis beam at a corresponding frequency, the satellite can be seen as a point source. This orbit of a meteorological satellite is about 35600 km above the equator. This distance is not so far that the signals coming from satellite to separate antennas are not assumed to be a plane wave for long baselines. These errors due to spherical waves would be more than 360° for the longest baseline, and they are not consistent, but vary with any changing of the satellite position. Thus, these errors need to be corrected by data processing. However, this satellite was observed two times. Such errors existed in two observations. We used the second observation to calibrate the data of the first observation. If the satellite is absolutely stationary, these errors would be eliminated. The declination of the satellite changed from 6.910° at 0:25UT to 7.488° at 18:25 UT on 2013 June 4. The phase error caused by the changing of the satellite position during these observations was about 2.796° for the maximal baseline.

4.3. Observed Fringes of Cygnus A

Because CSRH is a solar-dedicated radio telescope, the receiver was designed for solar observations. The linear dynamic range of its receiver should be considered when CSRH observes a relatively weak source, such as Cygnus A and other compact radio sources. Therefore, the basic idea of the calibration for CSRH is as follows. Firstly, the satellites are observed as calibrator sources to calibrate at several point frequencies. Then, Cygnus A as is used as a calibrator source at the full frequency band. The spatial resolution of CSRH-I at 2 GHz is about 10′. When Cygnus A was treated as the calibrator source its structure had to be considered. Certainly, their structures needed to be considered when other compact radio sources were observed as calibrator sources, and their sizes were not much smaller than the synthesis beam.

Observations of Cygnus A were carried out with the CSRH-I in 2012. Fringes of the observation were obtained for both

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short baselines and long baselines. The observed fringes of short, middle, and long baselines are shown in figure 8. The fringe frequency changes with the baseline length.

5. Conclusion

CSRH is a solar-dedicated interferometric array in the decimetric to centimeter-wave range, and will play an important role in solar physics and space weather studies. All instruments of CSRH-I have already been established. CSRH-II will be completed by the end of this year.

Some measurements and experiments have been carried out to test and calibrate the whole system. The precise location of each antenna and the delay of each baseline have been measured. The circular-polarization degree was measured for polarization calibration. Satellites, Cygnus A, and the Sun are treated as calibrator sources to observe. The phase closure relationship showed a good design of the whole system. Calibration and data processing have been carried out for images of satellite observation. It is expected that the first scientific image of the Sun will be obtained soon.

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