Towards the Intensity Interferometry at Terahertz Wavelengths

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Abstract—**Results from the intensity interferometry experiment carried out with Nobeyama Radioheliograph (NoRH) is presented and discussed. Intensity interferometry is one of the key technologies to aim for future terahertz astronomy with high sensitivity and high image resolution. Proposed concept is to realize intensity interferometry by observing the photon bunches emitted from the thermal emission in terahertz region. This concept was proved by our experiment held with NoRH, which shows that complex visibility can be obtained even by intensity interferometry. This is the first step towards realizing intensity interferometers in terahertz wavelength. Future extension of this work includes to realize a prototype intensity interferometer with direct detectors and evaluate the performance with terahertz waves. Intensity interferometers well suits to space-borne telescopes, where each antennas can be built and operated individually, similar to VLBI systems. Direct detectors can be employed to achieve high sensitivity observations from space.**

I. INTRODUCTION

Numbers of astronomical telescopes are observing the universe through various wavelengths, either from the ground or from space. For optical and radio wavelengths, existing telescopes are capable to obtain astronomical images with angular resolution higher than 100 milli-arcseconds, by either large telescopes or interferometer techniques. Recently the Atacama Large Millimeter/Submillimeter Array (ALMA) has successfully imaged the protoplanetary disk surrounding a young star HL Tauri, with spatial resolution of 35 milli-arcseconds at 233 GHz [1].

Terahertz frequency region, namely 0.3 – 10 THz including far infrared and submillimeter wavelengths, is another important window for astronomy, which stands in between optical and radio wavelengths. Terahertz waves are suitable probes for various astronomical observations, such as to target high-mass star forming regions or to explore the formation of the universe. However, high resolution imaging is yet to be established for observation in terahertz frequency region. For ground based telescopes, the atmospheric transmission and its thermal emission becomes a big issue. Space-borne telescopes are free from atmospheric interference, while it is not easy to situate a large aperture telescope to gain the spatial resolution.

In the presentation, intensity interferometry will be introduced as a key technology to aim for future Terahertz astronomical observation with high sensitivity and high image resolution.

II. INTENSITY INTERFEROMETRY

The concept of intensity interferometry was presented and demonstrated by Hanbury-Brown et al. [2]. The major difference from the general interferometry technique is that the phase of electromagnetic waves are dropped by the detection process, therefore synthesis imaging is said to be impossible with intensity interferometers. On the other hand, the terahertz photons from thermal source is known to be governed by Bose-Einstein statistics, and the photons are bunched. We have proposed a method to obtain delay time measurements for aperture synthesis imaging by utilizing this photon bunches, which makes it possible to determine the complex visibility for synthesis imaging [3]. An experiment to prove this concept is discussed in the following section.

III. THE EXPERIMENT

A. Nobeyama Radioheliograph

In order to prove the concept of intensity interferometry utilizing photon bunches, we have carried out an experiment using Nobayema Radioheliograph (NoRH) [4]. NoRH is an aperture synthesis interferometer to monitor the solar activity in radio wavelengths, located in Nagano, Japan. The array consists of 84 antennas each with diameter of 80 cm, and with receivers sensitive to 17 GHz and 34 GHz [5]. The antennas are arranged in T-shape with redundant spacings, where the fundamental spacing (minimum baseline) is 1.528 m. The array has been monitoring the solar activity continuously for over 20 years. Observed data are processed in real time basis, and the image of the Sun is continuously made accessible to the public through the world-wide web [6].

B. Experimental Setup and Data Analysis

Our experiment was carried out on April 14th, 2014, during the normal operation of NoRH, by recording IF signals from the 17 GHz receivers. 16 antennas out of 84 were used, which are aligned in 1-dimention with fundamental spacing at the center of the array. The frequency of the IF signal is 200 MHz, with bandwidth of 80 MHz. The time stream data of 16 channels of IF signals were sampled simultaneously and recorded with the rate of 12.5 GS/s, utilizing two digital oscilloscopes, each with inputs of 8 channels (Yokogawa DLM-4058). The data were taken 3 times during the day, in the morning, around noon, and in the evening. Each time, 20 sets of data with 50 ms duration were recorded.

The acquired data were post-processed on the workstation of Astronomical Data Center of NAOJ. The time stream data were squared and smoothed, to emulate square law detection process, and cross-correlation was calculated between data from different antennas. Figure 1 shows an example of cross-correlation taken between the data from two neighbouring antennas for 50 ms duration. The plot shows that the delay time between the IF signals from two antennas were successfully measured, even without the phase information of the electromagnetic waves.

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Figure 1: Cross-correlation between two signals from neighbouring antennas.

C. Results from Preliminary Analysis

Figure 2 summarizes the “delay” between two IF signals calculated with the method described above. The upper panel shows the measured “delay”, together with the green over plotted line indicating the expected delay time, calculated from earth rotation. Lower panel shows the residual between measured and expected values. One can clearly see that the measured “delay” agrees with its expected value, with residuals within 10 ps rms. This value of 10 ps corresponds to approximately 1/6 of the wavelength of the RF signal at 17 GHz, where the result implies that the “phase” can be evaluated from photon bunches.

The cross-correlation amplitude as a function of projected baseline length is shown in Figure 3. Here, the cross-correlation between two antennas with spacing of 1 to 3 times the fundamental spacing (FS) are plotted together. Detailed data analysis is currently on-going, while this result indicates that the data is representing the diameter of the Sun as expected. On the other hand, the noise floor can be seen in this plot, which confirms that large dynamic range in the detector system is required for intensity interferometers.

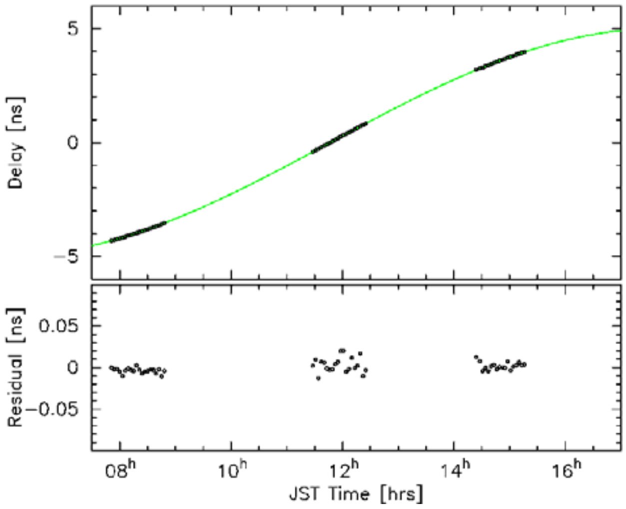

Figure 2: Measured “delay” between two neighbouring antennas versus time. Upper panel shows the measured delay (black) with expected delay time (green line), and the lower panel shows the residual between measured and expected values

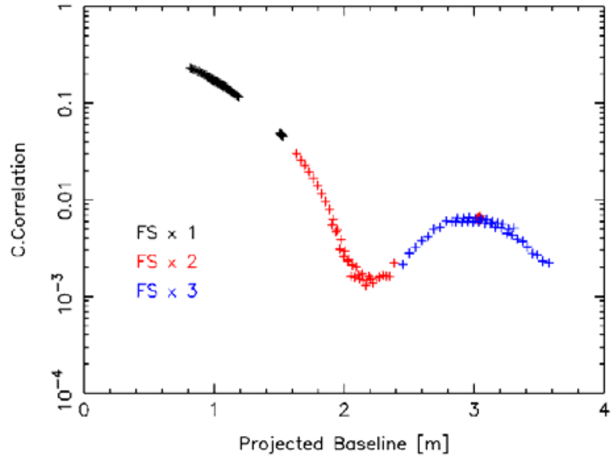

Figure 3: Cross-correlation amplitude versus projected baseline. Colors indicate different baselines, Black: FSx1 (neighbouring antennas), Red: FSx2, Blue: FSx3, where FS stands for fundamental spacing (minimum baseline) of NoRH.

IV. DISCUSSION AND FUTURE EXTENSION OF THIS WORK

The experiment with NoRH indicates the possibility of synthesis imaging with intensity interferometry by making use of photon bunches. The noise level is not low enough at this point. The receiver system of NoRH employs room temperature heterodyne mixers. Ultimately, the sensitivity of heterodyne system is limited by the quantum limit.

The next step is to carry out an experiment with terahertz waves and direct detectors, such as SIS photon detectors [7]. Intensity interferometers can employ direct detectors, since the phase of the induced electromagnetic waves does not need to be measured. An advantage of direct detectors over heterodyne systems is that their sensitivity is not limited by quantum limit.

It is also possible to extend the bandwidth far wider than that of heterodyne receivers to improve the signal to noise ratio. Several projects to plan for interferometers with direct detectors are proposed, such as multi-Fourier transform interferometers [8]. Intensity interferometer does not need to optically correlate the induced waves. This is similar to VLBI system, where each element antennas can be built and operated individually; baseline length and number of elements are not limited. This characteristic well suits to space-borne telescopes. Compared to ground based systems, cryogenic space telescopes are free from thermal radiation, and wide band high sensitivity detectors can be used. We plan to build a prototype system employing direct photon detectors and evaluate it with terahertz waves.

ACKNOWLEDGMENTS

We thank Nobeyama Radio Observatory of National Astronomical Observatory of Japan (NAOJ) for their various support to carry out the experiment. We would like to also thank Yokogawa Electric Cooperation for providing us the opportunity to use their oscilloscopes. Data analysis are in part carried out on open use data analysis computer system at the Astronomy Data Center (ADC) of NAOJ. This work is supported by research grant from Matsuo Academic Foundation, and Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA).

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