Proposal of Photon Counting Terahertz Interferometry

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ABSTRACT

Future possibility of far-infrared and terahertz intensity interferometry in space is discussed. Fast photon counting detectors with 1 ns time resolution and NEP less than 10^{-17} W/$\sqrt{\mathrm{Hz}}$ can resolve all photon arrivals from bright far-infrared sources cataloged by *AKARI*. Intensity correlation due to photon bunches enable delay time measurements, and complex visibility is obtained for aperture synthesis imaging. Precise timing measurements on independent cryogenic telescopes and formation flights enable a long baseline intensity interferometer in space. In this paper, we discuss on a simulation based study to compare the intensity interferometry with heterodyne (amplitude) interferometry. Although the intensity interferometry requires longer integration time for the delay time measurements, the intensity cross correlation is stable against atmospheric phase fluctuation, which enables long baseline observations from ground. From space, sensitivity gain of direct detectors and photon counting detectors over heterodyne technologies can be several orders of magnitude under low background condition. The THz intensity interferometers can resolve many compact *AKARI* sources with angular resolution better than ALMA, and resolve inner region of protoplanetary disks and active galactic nuclei.

Keywords: Far-Infrared, Terahertz, Intensity Interferometry, Photon Counting Detectors

1. INTRODUCTION

In terahertz frequency region, there is a large gap in angular resolution, between ground-based submillimeter interferometers and space-borne far-infrared telescopes. Especially, since ALMA started observations with angular resolution approaching 10 milli-arcsecond, the gap had become even larger. Future space-borne telescopes, such as *Origin Space Telescope (OST*; Meixner et al. 2017), will have better angular resolution, but not comparable to the ground-based instruments. Far-infrared interferometry in space is the solution to close the gap of angular resolution. However, heterodyne interferometry, such as ESPRIT (Wild et al. 2008), is limited in sensitivity and bolometric interferometry, such as SPIRIT (Leisawitz 2007) and FIRI (Helmich and Ivison 2009), is limited in baseline length. Here, we discuss another possibility using intensity interferometry in terahertz frequencies, originally known by Hanbury-Brown and Twiss interferometers (Hanbury-Brown and Twiss 1956).

2. PHOTON STATISTICS AND REQUIREMENTS TO DETECTORS

Statistics of thermal photons is not Poisson, but Bose-Einstein, and photons are often bunched, especially in Rayleigh-Jeans region. Fluctuation of thermal radiation is given by the two terms, $h\nu$ and kT_{B}, in the following equation:

$$\mathrm{NEP} = \sqrt{2P(h\nu + kT_B)} \quad [\mathrm{W}/\sqrt{\mathrm{Hz}}], \tag{1}$$

where, P is total power, $h\nu$ is a photon energy, T_{B} is a source brightness temperature, and throughput of λ^2 is assumed. The thermal fluctuation (kT_{B}) can be explained by photon bunching, which dominates at lower frequencies and at higher temperatures. In terahertz frequencies, photons from most astronomical sources are expected to be highly bunched, when the source temperature is higher than 100 K (Matsuo 2012). Intensity interferometry is based on observations of these photon bunches. This is the reason, the correlation efficiency of intensity is expected to be high in terahertz frequencies.

Under low background observing condition, background limited detector performance is required for high sensitivity observations. When fast photon counting detectors are introduced, background limited sensitivity can be achieved, and photon statistics could be measured. Typical photon rates from bright astronomical sources cataloged by *AKARI* are about

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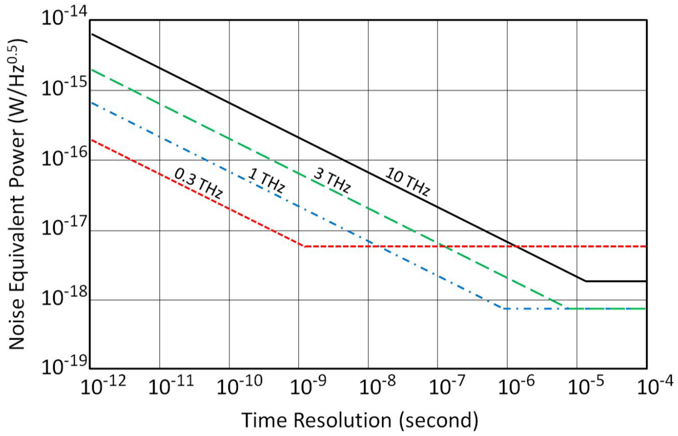

Figure 1. Requirements to NEP for photon counting as a function of detector time resolution at 0.3 THz, 1 THz, 3 THz and 10 THz. Spectral resolutions are $\nu/\Delta\nu = 3$ for all frequencies. The horizontal levels at low time resolution side indicate the background limited NEPs (Matsuo and Ezawa 2016).

100 M photons/sec, which can be measured by photon counting detectors with time resolution of 1 nsec and NEP of less than 10^{-17} W/$\sqrt{\mathrm{Hz}}$ at terahertz frequencies. The requirements to the detector sensitivity is presented in Figure 1 which is discussed in Matsuo and Ezawa (2016). Developments of such detectors using superconducting tunnel junctions are presented in (Ezawa et al. 2016).

3. INTENSITY INTERFEROMETRY FOR TERAHERTZ IMAGING

Intensity interferometry is known by Hanbury-Brown and Twiss interferometers (Hanbury-Brown and Twiss 1956), which were demonstrated first in radio, and then in optical wavelengths. Since correlations are obtained from intensity measurements, correlation analysis can be made separately from the detection process. Hanbury-Brown used analog correlators, but nowadays we can record the signal and the correlation analysis can be made afterwards on computers. Moreover, the intensity correlations are stable against phase fluctuation, since the coherence time is inverse of the frequency bandwidth, and the coherence length is much longer than the wavelength.

The difficulty of intensity interferometry was their correlation efficiency and imaging capability. In optical wavelengths, only bright early type stars were successfully observed because of the low correlation efficiency (Hanbury-Brown et al. 1974). Larger collecting area is needed for optical intensity interferometry; such as the usage of Cherenkov Telescope Array (Dravins et al. 2013). In radio frequencies, requirements of large dynamic range measurements limited their usage. In terahertz frequencies, these difficulties could be solved, because high correlation efficiency is expected and fast photon counting detectors could realize large dynamic range measurements.

Since intensity interferometry do not measure electromagnetic phase, application to imaging was quite limited, such as measuring diameter of stars (Hanbury-Brown et al. 1974). We have been proposing to used intensity fluctuation, or photon bunches, to measure the delay time directly (Matsuo 2012). In terahertz frequencies, high photon rate of 100 M photons/sec enables good statistical accuracy for the delay time measurements, which can be estimated by the following equation:

$$\Delta t = \frac{1}{N\sqrt{N \cdot \tau}}, \tag{2}$$

where N is the photon rate and τ is integration time. With the photon rate of 100 M photons/sec, an integration time of 100 sec correspond to the delay time accuracy of 10^{-13} sec, which is 1/10 of time 1 THz wave passing.

There is another limitation for the delay time accuracy from receiver noise and coherence time, which can be estimated by the following equation:

$$\Delta t = \frac{T_{\mathrm{sys}}}{T_{\mathrm{A}}} \cdot \frac{1}{\sqrt{\Delta\nu \cdot \tau}} \cdot \frac{1}{\Delta\nu}, \tag{3}$$

where T_{sys} is system noise temperature, T_{A} is antenna temperature, $\Delta\nu$ is the bandwidth. From the delay time accuracy, phase error can be defined as: $\Delta\phi = 2\pi\nu\Delta t$.

Figure 2 is an example using Nobeyama Radioheliograph (NoRH), which shows a comparison between amplitude and intensity cross-correlation in microwave (Ezawa et al. 2015). NoRH observed solar radiation at 17 GHz, which was down-converted to 200 MHz with a bandwidth of 80 MHz. The intensity correlation shows single positive peak with a coherence time of $1/\Delta\nu$.

The delay time accuracy can be estimated to be about 4 psec from the Equation (3) for antenna temperature of 550 K, receiver noise temperature of 360 K, bandwidth of 80 MHz and integration time of 50 msec. The measured accuracy of

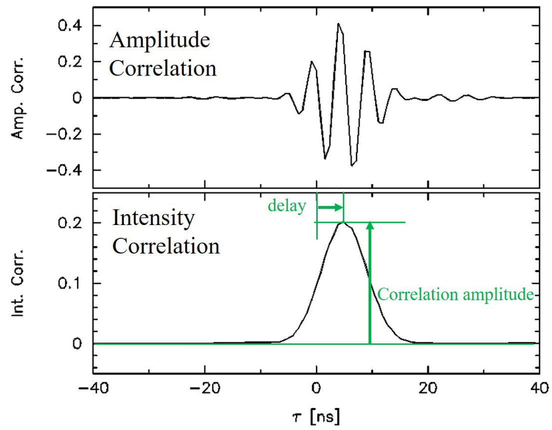

Figure 2. Amplitude and intensity correlation measured with NoRH at 17 GHz (Ezawa et al. 2015). The intensity correlation can be used to measure the delay time as given in Equation (3).

the delay time, 5–10 psec, is consistent with the estimate. We have demonstrated that the delay time was measured with enough accuracy to define the visibility phase from the intensity measurements. Limitation from the photon statistics defined by the Equation (2) have minor contribution to the delay time accuracy in microwave.

4. IMAGING SIMULATION OF AMPLITUDE AND INTENSITY INTERFEROMETRY

For feasibility study of the intensity interferometry in terahertz frequencies, we have performed a simulation to compare imaging capabilities of amplitude and intensity interferometry. The following two points are considered; one is an effect of the delay time accuracy for the intensity interferometry, another is an effect of phase fluctuation for amplitude and intensity interferometry.

Effect of phase fluctuation is modeled separately for amplitude and intensity interferometry. For amplitude interferometry, the phase fluctuation degrades the correlation efficiency as:

$$\eta = e^{-(2\pi\delta/\lambda)^2}, \tag{4}$$

where δ is path length fluctuation and λ is wavelength. The efficiency drops exponentially, when the path length fluctuation is larger than about $\lambda/10$. On the other hand, for intensity interferometry, efficiency drops like a low-pass filter as:

$$\eta = \frac{1}{\sqrt{(2\pi\Delta\nu \cdot \delta/c)^2 - 1}}. \tag{5}$$

Since the coherence length given by $c/\Delta\nu$ is much longer than the wavelength, intensity correlation is stable against phase fluctuation and degrades slowly compared to amplitude correlation.

Figure 3 shows the simulated results of aperture synthesis imaging for amplitude and intensity interferometry. The source structure is a double stars; the primary star is Betelgeuse-like star and a companion half in radius at a separation 10 times the primary star's radius. The antenna temperature of the source is assumed to be 0.13 K at 1 THz. With the system noise temperature of 500 K for both amplitude and intensity interferometry, whereas receiver bandwidths are 10 GHz and 100 GHz for amplitude and intensity interferometry, respectively. The top two images in Figure 3 are aperture synthesis images after integration of 60 sec and 600 sec for amplitude and intensity interferometry, respectively, which resulted in similar signal-to-noise ratios. Atmospheric phase fluctuation of 50 μm in path length error is introduces in these simulations, which have minor effects on the image quality. This simulation shows that intensity interferometry requires longer integration time for imaging, because the delay time accuracy is worse than the direct phase measurements. The bottom two images in Figure 3 show the same simulation except that the atmospheric phase fluctuation is increased to 100 μm in path length error. Due to the different dependence of the phase fluctuation given by Equations (4) and (5), amplitude correlation degrade exponentially, whereas intensity correlation is stable against the phase fluctuation. These results show that intensity interferometry is advantageous for long baseline interferometry in terahertz frequencies, where atmospheric phase fluctuation limit the baseline length of amplitude interferometry such as ALMA (ALMA Partnership et al. 2015).

Large improvements in sensitivity are expected when background noise level is decreased and direct detectors or fast photon counting detectors are introduced. The low background observing condition is achieved with cryogenic telescopes in space, such as *SPICA* (Swinyard et al. 2009) and *OST*. The background limited observation will achieve noise equivalent power (NEP) of the order of 10^{-19} W/$\sqrt{\text{Hz}}$. Using the following equation, NEP can be converted to the receiver noise

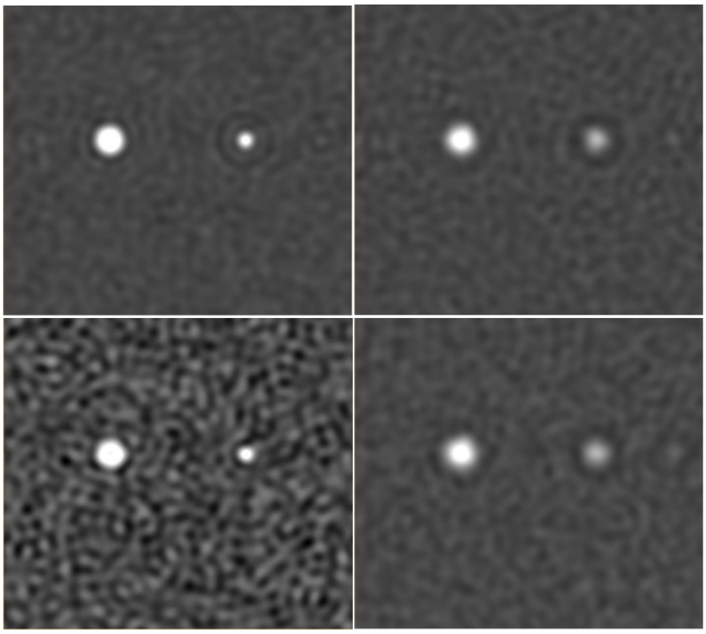

Figure 3. Simulated synthesized images of double stars for amplitude (left) and intensity (right) interferometry. amplitude interferometry is with 10 GHz bandwidth and 60 sec integration, and intensity interferometry is with 100 GHz bandwidth and 600 sec integration. Path length fluctuation of 50 μm and 100 μm are introduces in top two and bottom two images, respectively. Intensity interferometry have blurred image due to lower signal-to-noise ratio at longer baselines.

temperature:

$$T_{\rm rx} = {\rm NEP}\sqrt{\Delta\nu}, \tag{6}$$

which estimates the receiver noise temperature of about 10 mK; several orders of magnitude lower than the quantum limited temperature of heterodyne receivers. The above simulation for a source with antenna temperature of 0.13 K can be scaled to antenna temperature of 2.6 μK, when observed with background limited detectors; this sensitivity would enable imaging exo-planets.

5. FUTURE PROSPECTS

To conclude, future prospects of THz intensity interferometry is discussed. Since Hanbury-Brown and Twiss demonstrated in 1950's and 1960's, intensity interferometry has not been used for long. With new generation of advanced detectors and electronics technologies, intensity interferometry can be a powerful tool for aperture synthesis imaging. Based on our simulation study, there are two proposed applications with terahertz intensity interferometry. One is ground-based long baseline interferometry at high terahertz frequencies from high altitude sites in Atacama or in Antarctica. Another is space-borne interferometry using photon counting detectors in terahertz frequencies to achieve high sensitivity and high angular resolution. The space-borne intensity interferometry, or photon counting terahertz interferometry, will improve the sensitivity of very long baseline interferometry and will resolve many far-infrared sources cataloged by *AKARI* satellite.

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