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Greenland Telescope (GLT) Project

"A Direct Confirmation of Black Hole with Submillimeter VLBI"

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Abstract. The GLT project is deploying a new submillimeter (submm) VLBI station in Greenland. Our primary scientific goal is to image a shadow of the supermassive black hole (SMBH) of six billion solar masses in M87 at the center of the Virgo cluster of galaxies. The expected SMBH shadow size of 40-50 μas requires superbly high angular resolution, suggesting that the submm VLBI would be the only way to obtain the shadow image. The Summit station in Greenland enables us to establish baselines longer than 9,000 km with ALMA in Chile and SMA in Hawaii as well as providing a unique u–v coverage for imaging M87. Our VLBI network will achieve a superior angular resolution of about 20 μas at 350 GHz, corresponding to $\sim$ 2.5 times of the Schwarzschild radius of the supermassive black hole in M87. We have been monitoring the atmospheric opacity at 230 GHz since August. 2011; we have confirmed the value on site during the winter season is comparable to the ALMA site thanks to high altitude of 3,200 m and low temperature of -50°C. We will report current status and future plan of the GLT project towards our expected first light on 2015–2016.

1 Introduction

A direct confirmation of the black hole (BH) in the universe, is one of the ultimate goal in the modern physics and astronomy. When it is achieved, we for the first time access matter and electromagnetic fields under the extremely strong gravity. A BH shadow is expected against the bright-enhanced annulus of an emission around the BH. The size of annulus, "Event Horizon" as defined by the Schwarzschild radius (r_s), is lensed and self-magnified by its strong gravity. Therefore, a detection of the BH shadow is the direct confirmation of the existence of BH, and provides a test for General Relativity under the strong gravity. In addition to the detection of the strong lensing, the BH spin can be also probed by a precise imaging of the shape and axis of the shadow, since it is expected that the BH shadow would be compressed perpendicular to the spinning axis of the BH. Furthermore, since we observe BHs as the silhouette against accretion disks and/or relativistic jets, BH shadow imaging will simultaneously bring us the images of innermost region of accretion disks and formation region of relativistic jets as well.

It has been a growing recognition that submillimeter (submm) VLBI technique could be a unique technique to attain an enough resolution to resolve nearby SMBHs at the center of AGN, and imaging a shadow of the BH in the coming decade [1]. Since apparent size of shadows is expected to be very small, practically at this moment, there are only two possible candidate sources even for submm VLBI: our galactic center Sgr A* and one of nearest AGNs M87. The BH mass $M_\bullet$ of Sgr A* has been estimated by monitoring stellar orbits around the BH as $M_\bullet \simeq 4.3\times 10^6$ $M_\odot$ [2]. With the current best estimate of the distance of 8.3 kpc [2] to the galactic center, the BH shadow has an angular diameter of $\theta = 3\sqrt{3}r_s \simeq 52\,\mu$as ($r_s \sim 10\,\mu$as). On the other hand, the BH mass is measured with a range $3.2\times 10^9 M_\odot$ [3] to $6.6\times 10^9 M_\odot$ [4] in M87; together with the distance of 16.7 Mpc to the source [5], the largest $M_\bullet$ gives the second largest angular diameter of $\theta \simeq 42\,\mu$as ($r_s \sim 8\,\mu$as).

Therefore, in order to image a shadow of these SMBHs, an angular resolution of at least 40–50 μas in submm VLBI observations would be required. Very recently, [6] conducted the Event Horizon Telescope (EHT) observation at a wavelength of 1.3 mm, deriving the size of 230 GHz VLBI core to be a FWHM of $40\pm 1.8\,\mu$as, corresponding to $5.5\pm 0.4\, r_s$. This is smaller than the diameter for the innermost stable circular orbit of a retrograde accretion disk, suggesting that the M87 jet may be powered by a prograde accretion disk around a spinning SMBH. Indeed, this work gives a promising insight that Earth-sized submm VLBI networks are functional to provide angular resolutions to unveil the SMBHs.

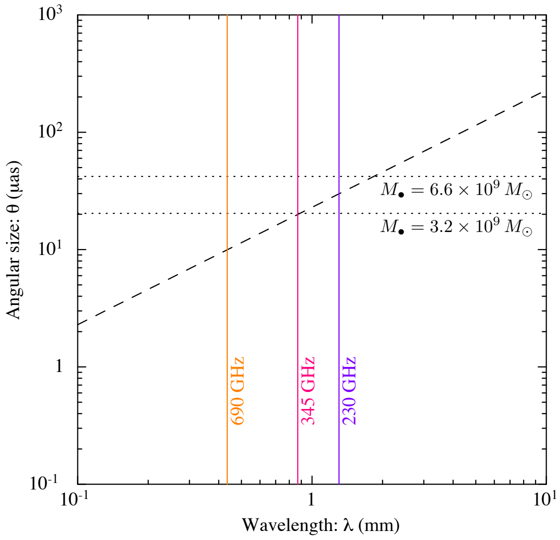

Figure 1. Required resolutions to image the black hole shadow in M87. Dashed line: estimated resolution of a radio interferometer, taken by $\theta_{\rm res} = k\lambda/d$ with $k = 1$ and $d = 9,000$ km. Dotted lines: angular diameter of the BH shadow $\theta = 3\sqrt{3}\, r_s$, corresponding the largest and smallest $M_\bullet$ cases. Imaging the BH shadow of M87 will be possible with submm VLBI $\lambda \lesssim 1$ mm, indicated as vertical solid lines of 230 GHz (purple), 345 GHz (magenta), and 690 GHz (orange), respectively.

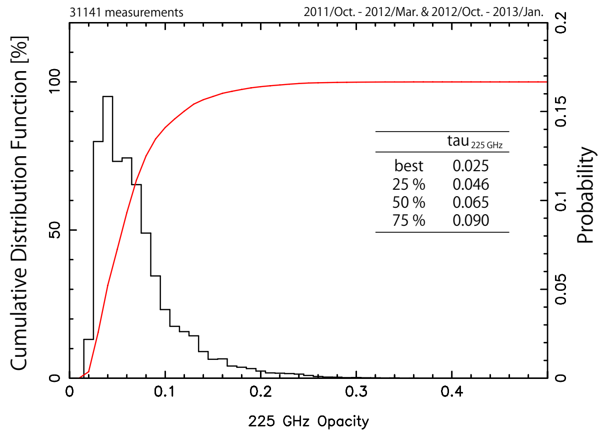

Figure 2. Histogram of the 225 GHz opacity at the Summit Camp, Greenland from 2011 Aug. to 2013 Jan. and its cumulative distribution function.

2 Site Selection

In July 2010, the US National Science Foundation (NSF) announced a call for expression of interests for a prototype ALMA 12m telescope, which is designed from mm to submm wavelength (or 30 to 950 GHz). CfA/ASIAA was awarded this telescope in April 2011, under collaborating with MIT Haystack observatory and NRAO to conduct a submm VLBI operation. We have examined suitable site for allocating a new submm telescope; our main requirements are (1) excellent atmospheric conditions to perform high quality observations at submm and even shorter wavelengths, and (2) a location which provide the longest baselines connecting with other key stations of submm operations.

Based on the precipitable water vapor (PWV) data mesured by the NASA satellites, as well as scientific merits and logistics, we have finally selected Summit Camp in Greenland as the best candidate. Then, M87 has become our primary target for imaging the BH shadow by the submm VLBI with other facilities, such as SMA in Hawai, LMT in Mexico, and ALMA in Chile (Sgr A* cannot be observed from Greenland, as it is on the southern sky). From here, we name our project as Greenland Telescope (GLT) project.

Figure 1 shows the resolution of a radio interferometer in order to resolve the BH shadow in M87 at a given baseline $d = 9,000$ km, which is a comparable length between the GLT and the ALMA. This yields $\theta_{\rm res} \simeq 23\lambda_{\rm mm}$, where $\theta_{\rm res}$ is the resolution in μas and $\lambda_{\rm mm}$ is the observed wavelength in millimeter. Fig. 1 indicates submm VLBI observations at $\lambda \lesssim 1$ mm can fairly resolve the BH shadow diameter in M87 [see also 7, for Sgr A*].

2.1 Atmospheric condition

We investigated the distribution of the monthly mean of the PWV in 2008 based on data taken by NASA Aqua and Terra/MODIS. It turns out that the PWV at the inland of the Greenland is less than 2mm though the year, indicating a promising candidate for submm VLBI observation.

We purchased a tipping radiometer from Radiometer Physics GmbH. After a test run at the summit of Mauna Kea, Hawaii, the radiometer was deployed to Summit Camp in August 2011. The atmospheric opacity has been monitored since August 2011 at Summit Camp. The median values of the measured opacity at Summit Camp varied in the range from 0.04 to 0.18 between August 2011 and Jan. 2013 (Fig. 2). Summit Camp on Greenland is expected to be an excellent site for submillimeter and Terahertz astronomy.

2.2 Expected u–v coverage

Figure 3 shows expected u–v coverage towards M87 including the GLT Baselines between the Summit Station and the other stations provide the longest and unique baselines. The longest baseline is provided by the combination between the Summit Station and the ALMA, giving the baseline length of 9,000 km. It provides us an angular resolution of 20 μas at 345 GHz, which corresponds to half of the expected size of the BH shadow with $6.6 \times 10^9 M_\odot$ [4] in M87.

2.3 Logistics

The Summit Camp is a geophysical and atmospheric research station, established and maintained by the U.S. NSF, cooperating with the Government of Greenland. The Summit Station is located roughly 72.5° N, 38.5° W (north

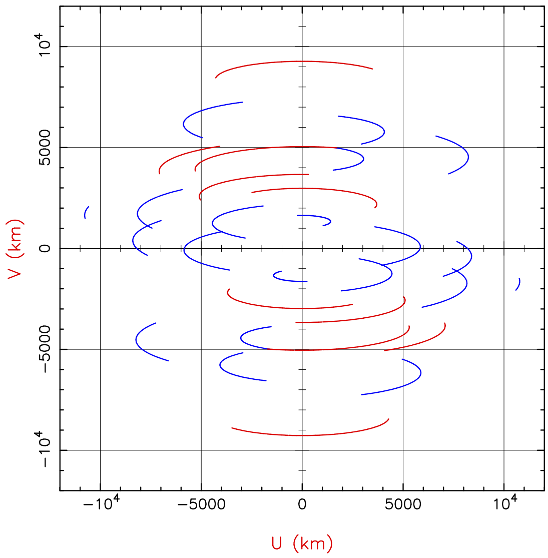

Figure 3. Expected *u*–*v* coverage towards M87. We assume the frequency at 350 GHz with telescopes of large aperture size, the ALMA, the SMA, the SMTO in Arizona, the Large Millimeter Telescope (LMT) in Mexico, and the IRAM 30-m telescope at Pico Veleta in Spain, together with GLT at Summit Camp. Red lines indicate baselines with the GLT.

of the Arctic Circle) with a 3,200 m altitude, and is on top of the Greenland ice cap. Main purpose of this station is logistic supports for researchers to conduct year-round, long-term measurements for monitoring and investigations of the Arctic environment. However, NSF funded researchers in any field can have access to this facility. The station can be physically reached by C-130 and small aircrafts. So far, diesel power and a network of 64 kbps VSAT satellite link are available upon request.

3 Science Case: Imaging Simulation of the SMBH Shadow

It is thought that (uncharged) SMBHs can be completely specified by two parameters, their mass and their spin or angular momentum. Although current methods are able to provide an estimate for both of these, their extraction is very coarse and typically only very rough limits are discussed for the spin and very large errors are found for the mass. The detection of a shadow of nearby SMBHs can provide us with an alternative, more direct way, to extract their mass and spin. Furthermore, efforts in order to understand the submm emission on M87 are currently undergoing and is still unclear if dominant emission at these wavelengths arises from disk, jet, or a combination of these [8, 9].

A number of simulations is currently undergoing in order to understand and estimate how these parameters will affect the silhouette of the SMBH shadow. Inversely, once we are able to obtain an image, we will be able to constraint the parameters space. Our current models are based on steady solutions of the radiatively inefficient

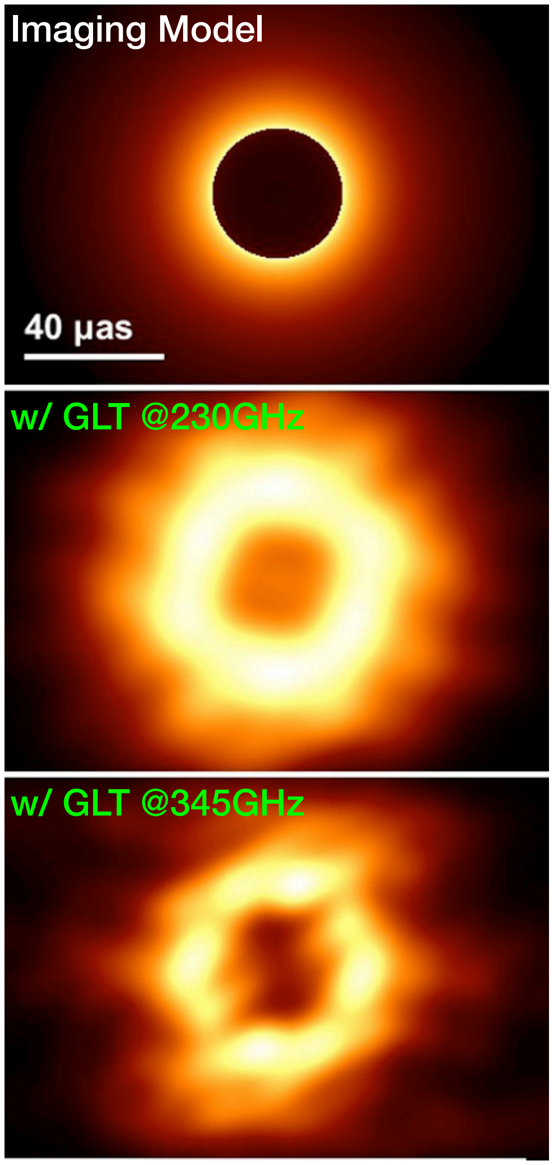

Figure 4. Simulated images of SMBH shadow of M 87. By using the ray-tracing method, we model the shadow image for the case of a non-rotating, six billion solar masses SMBH enclosed by optically thin, free-falling materials. The panel shows the model image (top), and the image obtained by CLEAN deconvolution algorithm with simulated submm VLBI array including GLT, of 230 GHz (middle) and 345 GHz (bottom), which are affected by finite resolution, instrumental thermal noise, and CLEAN error that deconvolution process introduces.

accretion flows and ergosphere/disk-driven general relativistic magnetohydrodynamic (GRMHD) jets by (semi-)analytical formulations. These key ingredients are then used for the ray-tracing and general relativistic radiative transfer (GRRT) around the SMBH to obtain a "theoretical" (infinite resolution) image. We then input this model into a simulated submm VLBI array including the GLT to understand how the real observation image is affected by finite resolution, *u*–*v* coverage, sensitivity and antenna performances [10]. Figure 4 shows one of our imaging samples, suggesting the future submm observations includ-

Figure 5. Disassemble one of the ALMA prototype antennas for retrofitting and ready to operate in the extremely cold environment on the Greenland ice sheet. This picture shows the disassembly process in November 2012, at the site of the Very Large Array near Socorro, New Mexico. This effort is led by ASIAA personnel, Philippe Raffin, Ted Huang, and George Nystrom, in collaboration with the engineers from Aeronautical Research Laboratory.

ing the GLT will be capable of resolving the BH shadow in M87. Note dynamical effects will be taken into account by implementing the GRMHD simulation and time-dependent GRRT in the future to examine observed time variability.

4 Current Status and Future Prospects of the GLT Project

4.1 Antenna

We plan to use the ALMA-NA prototype antenna (see Fig. 5) originally designed as a prototype for the ALMA. The antenna needs to be retrofitted to adapt to the new environment condition, since the environment condition at the Summit Camp is significantly different from that at the ALMA site. We have already started to work with Vertex on it. We note that Vertex is the original vender of the antenna and has extensive experience with similar telescope working in similar environment, the South Pole Telescope. We have started initial inspection and functional test from 2011. We also conducted surface measurement by photometography and installed a new antenna control software and an optical pointing telescope before it had been disassembled for the retrofitting at the NRAO VLA site in New Mexico (see also Fig. 5). In November 2012, the antenna was disassembled and shipped to many sites for retrofitting.

4.2 Receiver plan

For the submm VLBI purpose, we are considering to have 86, 230, 345, and possibly 690 GHz receivers. For the single dish observation, we are considering to have heterodyne multi feed receivers and a multi-pixel imaging array at THz and sub-THz frequency.

4.3 Future Prospects

After retrofitting, the antenna will be shipped to Greenland in 2014. In the meantime, we will work on construction for the foundation and infrastructures with help of NSF US and CH2MHILL Polar Services. We hope to have the first light in 2015/16.

5 VLBI Data Acquision

5.1 ALMA Phase-up project

The introduction of ALMA antennas will be a key in the submm VLBI network, as it will be able to increase the sensitivity by a factor of ten due to its large collecting area. ASIAA has a very active participation in an international collaboration led by MIT Haystack Observatory aiming towards the ALMA phase-up project. An international consortium is presently constructing a beamformer for the ALMA in Chile that will be available as a facility instrument. The ALMA beamformer will have impact on a variety of scientific topics, including accretion and outflow processes around black holes in active galactic nuclei (AGN), tests of general relativity near black holes, jet launch and collimation from AGN and microquasars, pulsar and magnetar emission processes, the chemical history of the universe and the evolution of fundamental constants across cosmic time, maser science, and astrometry [11].

5.2 DiFX correlator

ASIAA has acquired a CPU cluster with broadband interconnect network connection (infini-band) capabilities and started the development of a DiFX software correlator, which is easy to maintain and upgrade and will be able to handle the massive data rate from submm VLBI observations. We have correlated test data and obtain fringes using 1.3 mm VLBI data from the EHT observation in 2012. We aim to solve discrepant sampling schemes between ALMA and other VLBI stations, including GLT, by DiFX enhancements.

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