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Sub-mm VLBI from the Arctic — Imaging Black Holes

Makoto Inoue[1]
and the Greenland Telescope team[1,2,3,4]

[1]Academia Sinica Institute of Astronomy and Astrophysics,
P.O. Box 23-141, Taipei, 10617 Taiwan, R.O.C.
email: inoue@asiaa.sinica.edu.tw

[2]Smithsonian Astrophysical Observatory,
60 Garden Street, Cambridge, MA 02138, USA
[3]MIT Haystack Observatory,
Off Route 40, Westford, MA 01886-1299, USA
[4]National Radio Astronomy Observatory,
520 Edgemont Road, Charlottesville, VA 22903-4608, USA

Abstract. We are deploying a new station for sub-millimeter Very Long Baseline Interferometry (VLBI) to obtain shadow images of Supermassive Black Hole (SMBH). Sub-mm VLBI is thought to be the only way so far to get the direct image of SMBH by its shadow, thanks to the superb angular resolution and high transparency against dense plasma around SMBH. At the Summit Station on Greenland, we have started monitoring the opacity at sub-mm region. The Summit Station subtends long baselines with the Atacama Large Milimeter/submillimeter Array (ALMA) in Chile and Submillimeter Array (SMA) in Hawaii. In parallel, we started retrofitting the ALMA North America prototype telescope (renamed as Greenland Telescope: GLT) for the cold environment.

Keywords. Supermassive Black Hole (SMBH), Sub-millimeter telescope, Very Long Baseline Interferometry (VLBI)

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1. Introduction

An experiment in the sub-millimeter (submm) Very Long Baseline Interferometry (VLBI) has shown the capability for direct imaging of Sumermassive Black Hole (SMBH) (Doelaman *et al.* 2007). The angular resolution reaches the expected size of several tens of micro arcsec (μas) for some of SMBHs. Submm observations also allow us to see the immediate vicinity of SMBH, penetrating into the dense plasma around it. Supported by imaging simulations (e.g., Luminet 1979, Falcke *et al.* 2000, and Dexter *et al.* 2012) and good mass estimations of SMBHs (Ghez *et al.* 2008, and Gebhardt *et al.* 2011), we are now confident to be able to observe and resolve the shadow image of SMBHs: Sgr A* and M87 being the best targets based on their apparent angular sizes.

The image of SMBH can be seen as a shadow against bright accreting materials, and the shadow size is expected to be about 5 times of the Schwarzschild radius for non rotating black hole, enlarged by a lensing effect of the strong gravity. The shadow size depends on the black hole spin (Luminet 1979). This means we could measure directly the key parameters of black hole, *i.e.*, the mass and spin of SMBH by its shadow image with submm VLBI, in addition to observing other physical conditions under strong gravity field, such as the energy transfer in the accretion flows and the launching mechanism of relativistic jets.

However, the number of the submm VLBI telescopes is very limited, and the distribution of baselines, or the *uv* coverage, is not well arranged. Under such circumstances, development of new submm VLBI sites is a key to promote the SMBH science. Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) has awarded a new submm telescope with CfA and started a site development for the telescope to establish a new submm VLBI station. We will describe below the science target and the siting situation.

2. Science Target

As the Schwarzschild radius r_s is proportional to the SMBH mass, the apparent size of the shadow depends on the mass and distance. Sgr A* at the center of our Galaxy shows the largest apparent diameter of 52 μas because of its distance. The second largest one is in M87, showing a comparable apparent diameter of 40 μas to Sgr A*. The apparent diameter of other galaxies is at most 10 μas or smaller.

For SMBHs of Sgr A* and M87, we are now able to resolve the black hole shadow with ground-based submm VLBI. In terms of the apparent size of the black hole shadow, Sgr A* would be the best target. However, it becomes clear that Sgr A* shows rapid time variations within a day even at mm and submm wavelengths (Miyazaki *et al.* 2004, and Fish *et al.* 2011). This is probably due to the small mass of the black hole. The rapid variations make it difficult to generate synthesized images of Sgr A*. On the other hand, the mass and size of the SMBH of M87 are 10^3 times larger than that of Sgr A*, and much longer time scale is expected for M87. The SMBH mass of M87 indicates a dynamical timescale of about 5 hours, and a typical orbital timescale at the Innermost Stable Circular Orbit (ISCO) is 2-18 days, depending on the SMBH spin. Therefore, unlike Sgr A*, the structure of M87 may not change during an entire day for the image synthesis. In this point, M87 is better candidate for the VLBI imaging synthesis technique by Earth rotation. It would be possible to produce a sequence of images of dynamical events in M87, occurring over many days. M87 is thus a promising target to image the black hole shadow and bright accreting materials rotating around it.

Further, as shown in Figure 1, the tracing back of the jet radius is one of the crucial tests to identify the launching point of the jet, and put constrains on the formation mechanism. If the parabolic shape of the jet extends towards the innermost region, *i.e.*, up to $2r_s$, the jet must originate within the ISCO of the accretion disk around the SMBH or the SMBH itself. Submm VLBI could make observations of the jet radius to reveal the launching point of the relativistic jet (Asada & Nakamura 2012).

3. Submm VLBI Network

As seen in Figure 2, the baselines between Greenland, Hawaii, and Atacama in Chile form a big triangle for M87, extending 9,000 km long, which achieves the angular resolution of 20 μas at 350 GHz. At 230 GHz, other submm telescopes like IRAM 30-m (Pico Veleta, Spain), PdBI (France), SMT (Arizona, USA), LMT (Mexico), CARMA (California, USA), etc., will provide a good *uv* coverage to make plausible quality images of M87. The Summit Station on Greenland has good baselines between both European and American submm telescopes. The North-South baselines subtended by the Summit Station and other telescopes provide good opportunity to investigate the structure of M87 jet which is running toward almost West (see Figure 1).

ASIAA is the only Institute which has close relations to both the SMA and ALMA. The project for phase-up ALMA is in progress with international collaboration, and the phased array of the SMA, JCMT and CSO is already under development by the Haystack

Observatory and the SAO. This triangle is then expected to provide high sensitivity and high angular resolution at 350 GHz and even higher frequencies. At 230 GHz, many other submm telescopes will collaborate with this big triangle to form a good submm VLBI network.

4. Retrofitting Telescope

Since April 2011, the ALMA-North America (NA) prototype telescope has been re-tested and studied to retrofit for the cold environment on Greenland. After retrofitting, the telescope, renamed Greenland Telescope (GLT), will be shipped to Greenland in 2014. In parallel, construction works for the foundation and infrastructures have started, collaborating with a company who operates the summit facilities.

For the submm VLBI receivers, 230, 350 and 650-GHz receivers are planned. The GLT is also expected to be a forerunner of Cerro Chajnantor Atacama Telescope (CCAT) in science and as a test bench of receiver developments for single-dish observations. Heterodyne multi-feed receivers and multi-pixel bolometers up to 1.5 THz have been discussed.

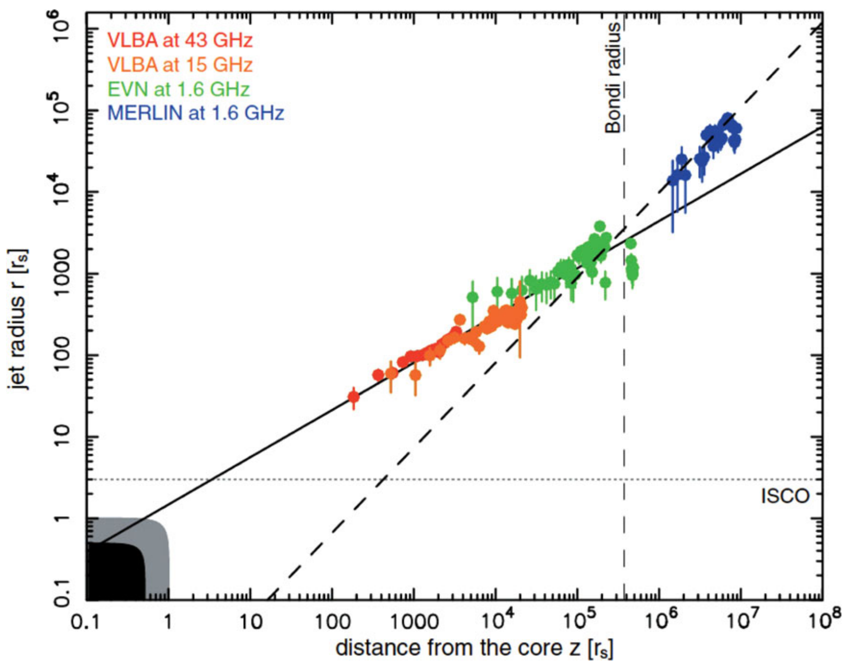

Figure 1. Distribution of the radius of the jet as a function of the deprojected distance r_s from the core. Images were obtained by previous VLBA measurements at 43 GHz (red circles) and at 15 GHz (orange circles), EVN measurements at 1.6 GHz (green circles), and MERLIN measurements at 1.6 GHz (blue circles). The jet is described by two different shapes. The solid line indicates a parabolic structure with a power-law index α ~1.7, while the dashed line indicates a conical structure with α ~1.0. HST-1 is located around 5×10^5 r_s, near the Bondi radius. The black area near the core shows the size of the minor axis of the event horizon of the spinning black hole with maximum spin. The gray area indicates the size of the major axis of the event horizon of the spinning black hole with maximum spin, which also corresponds to the size of the event horizon of the Schwarzschild black hole. The horizontal dotted line indicates the ISCO size of the accretion disk for the Schwarzschild black hole (Asada & Nakamura 2012).

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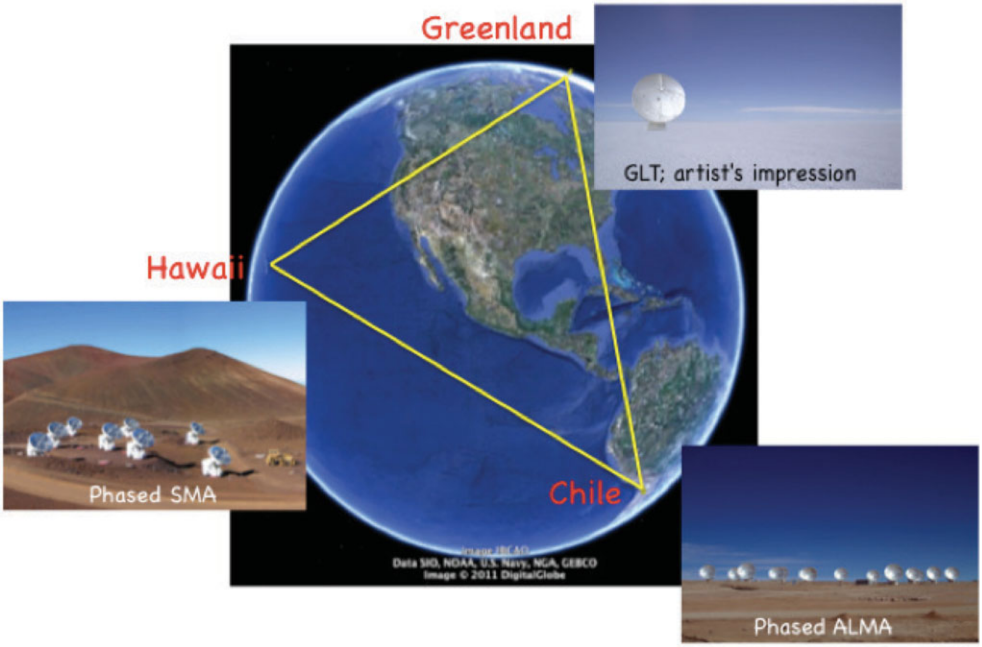

Figure 2. A big triangle formed by Summit Station on Greenland, the SMA in Hawaii and ALMA in Chile, as seen from the direction of M87. This network provides a 20-μas resolution at 350 GHz.

5. Summary

Direct imaging of SMBHs has been anticipated by the recent development of submm VLBI observatories. New sites for a submm VLBI network could provide good image quality, and a good site has been identified at the Summit Station of the ice cap on Greenland. ASIAA has been monitoring the sky opacity at the Summit Station, and the preliminary monitoring shows satisfactory opacity condition at submm region (see Matsushita *et al.* 2012). The ALMA-NA prototype telescope was awarded to ASIAA/CfA. Retrofitting the telescope, now called GLT, is under way for the Greenland Summit Station. The new submm VLBI network by the big triangle with GLT, ALMA, SMA and other submm telescopes, will be a powerful tool for imaging the SMBH shadows and related studies. Multi-feed and multi-pixel receivers are also planned at up to the THz region for single-dish observations.

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