Site Selection and Evaluation of Submillimeter-Wave Telescopes for the Next-Generation Event Horizon Telescope Postprint

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Date: 2024-07-03T00:00:00+00:00

Abstract

In 2019, the EHT captured the first image of a black hole using VLBI technology. To meet the demands of dynamic black hole imaging, the next-generation EHT array will incorporate additional stations located in the Eastern Hemisphere. The Tibetan Plateau in China, being the region with the highest average elevation in the world, possesses unique meteorological conditions that render it a potential site selection area. Using three years (2019-2021) of MERRA-2 data, a preliminary assessment of high-frequency radio observation conditions in the Tibetan Plateau region was conducted, encompassing a total of 759 data grid points. Based on the opacity performance of these grid points across different seasons, the optimal grid point for each of the four seasons was selected. These four grid points were evaluated in conjunction with the meteorological conditions of currently established stations, with the assessment primarily considering three meteorological factors: precipitable water vapor, liquid water path, and wind speed. Additionally, using the meteorological conditions of the ALMA telescope array as a benchmark, a preliminary range for new station site selection was delineated.

Full Text

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Abstract: In 2019, the Event Horizon Telescope (EHT) captured the first-ever image of a black hole using very long baseline interferometry (VLBI) technology. To meet the demand for dynamic imaging of black holes, the next-generation EHT array will incorporate additional stations located in the eastern hemisphere. The Tibetan Plateau in China represents the highest average elevation region in the world, and its unique meteorological conditions make it a promising candidate for site selection. This study conducts a preliminary evaluation of high-frequency radio observation conditions across the Tibetan Plateau using three years (2019–2021) of MERRA-2 data, encompassing 759 grid points. Based on the opacity performance of these grid points across different seasons, we identified the optimal grid point for each season. We then evaluated these four grid points against three key meteorological factors: precipitable water vapor (PWV), liquid water path (LWP), and wind speed, while also considering the meteorological conditions of existing stations. Furthermore, using the meteorological conditions of the Atacama Large Millimeter/submillimeter Array (ALMA) as a benchmark, we delineated a preliminary range for new station site selection.

Key words: EHT; opacity; precipitable water vapor (PWV); liquid water path (LWP)

1 Introduction

The Event Horizon Telescope (EHT) is a very long baseline interferometry array operating at 230 GHz [1]. In 2017, the EHT observed the M87 galaxy using eight telescopes at six locations, releasing in 2019 the first image of the supermassive black hole at the center of M87 [2–6]. In 2022, the EHT published an image of the Sgr A* black hole at the center of our Milky Way [7–11].

The next phase of observations will expand the array with additional telescopes in the eastern hemisphere to enable 24-hour continuous monitoring of black holes, constituting the next-generation Event Horizon Telescope (ngEHT) [12]. The EHT considers numerous factors when selecting new sites [13], primarily: (1) the location must provide good uv-plane coverage, and (2) the meteorological conditions must satisfy the requirements for high-frequency radio observations above 230 GHz. This paper focuses on meteorological conditions in the Tibetan Plateau region, as it represents the highest average elevation area globally. Its high-altitude, low-humidity environment makes it an important region for astronomical site selection [14, 15]. We utilize the Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) dataset from the National Aeronautics and Space Administration (NASA) [16] to conduct a comprehensive assessment of meteorological conditions across the Tibetan Plateau.

MERRA-2 data grids the entire globe with a spatial resolution of 0.625° × 0.5° (latitude × longitude). Our analysis covers 759 grid points in the Tibetan Plateau region. Using meteorological data from 2019, 2020, and 2021, we employ the atmospheric model (am) script [17] to calculate atmospheric opacity at 230 GHz for each data point. For each season, we select the geographic location with the minimum opacity as a target site, yielding four sites named MAMMin (spring minimum), JJAMin (summer minimum), SONMin (autumn minimum), and DJFMin (winter minimum). In addition to these four locations, we select four other grid points as evaluation references: Yangbajing (YBG) in Tibet, Ali in Tibet, the Atacama Large Millimeter/submillimeter Array (ALMA), and Dome A in Antarctica. These locations were chosen because YBG has been designated as a candidate site in global EHT site evaluations; Ali, located in western Tibet, hosts a permanent observatory established by the National Astronomical Observatories of the Chinese Academy of Sciences in Shiquanhe Town and represents an excellent site; ALMA in Chile' s Atacama Desert comprises 66 radio telescopes at 5,058 m elevation with climate conditions similar to the Tibetan Plateau; and Dome A, the highest point in Antarctica, is currently considered the most suitable site for high-frequency observations [18].

The most critical meteorological factors affecting high-frequency observations are precipitable water vapor (PWV) and liquid water path (LWP). We conduct a comprehensive comparison of PWV and LWP across these eight sites. Additionally, we consider wind speed, as high-frequency stations have strict requirements regarding site wind conditions—excessive wind speeds can affect telescope pointing accuracy. Beyond the overall three-year assessment, we also evaluate the observational conditions at these sites for each season.

2 Data and Analysis

MERRA-2 is NASA' s latest modern satellite meteorological reanalysis product, utilizing a series of instruments from near-infrared to microwave wavelengths to provide meteorological data for any region worldwide. It offers reliable measurements of basic meteorological parameters such as temperature, pressure, and wind speed, as well as data on water vapor, clouds, and ozone that affect astronomical observations.

Numerous meteorological factors influence high-frequency radio observations. Previous site selection efforts have primarily focused on PWV, but this approach cannot accurately measure site quality, and PWV data mostly originate from ground meteorological stations, which cannot comprehensively assess observation conditions across a large region. The MERRA-2 dataset we employ includes meteorological data for all global regions, gridded at a spatial resolution of 0.625° × 0.5°. Using these data, we can comprehensively evaluate meteorological conditions across large areas and identify optimal sites.

We utilize two types of MERRA-2 products: (1) MERRA-2 inst3_{{{3d}}*{{asm}}*}{Np}, three-dimensional 3-hour instantaneous data with 42 pressure levels; and (2) MERRA-2 inst1_{{{2d}}*{{asm}}*}{Nx}, two-dimensional 1-hour instantaneous data with a single pressure level.

Our analysis region spans 76.25°E–96.25°E and 28°N–39°N, encompassing 759 locations across Tibet, southern Xinjiang, and western Qinghai. We use the am (atmospheric model) software to calculate radiative parameters such as opacity and background temperature. The am software can model the atmosphere and compute electromagnetic wave propagation properties at different frequencies by reading atmospheric data. We use data from 2019–2021, divided into four seasons: spring (MAM), summer (JJA), autumn (SON), and winter (DJF). Opacity at each data point is calculated using median values of absolute humidity and ozone for each season.

This processing pipeline involves substantial data reading, writing, and computation. To improve efficiency, we write all three years of raw data into a local database to facilitate subsequent unified processing of each grid point.

2.1 Opacity Distribution

The am program is a tool for calculating optical depth, radiative transfer, and other parameters, applicable to any narrow-beam propagation problem that can be modeled under local thermodynamic equilibrium conditions. Using am with the appropriate radiative model and MERRA-2 data, we calculate the 230 GHz zenith opacity for each grid point in our selected region for each season. Figure 1 [Figure 1: see original paper] shows the winter 230 GHz opacity distribution, with the location of minimum opacity marked as DJFMin. When calculating opacity at each site using the am software, the amc configuration file employs median values of absolute humidity, ozone, and temperature from the three-year dataset for each season. In Figure 1, the grid points with minimum opacity in spring, summer, and autumn are marked as MAMMin, JJAMin, and SONMin, respectively. For convenient comparison, we also mark four important locations in Tibet: Lhasa, Yangbajing (YBG), Shigatse, and Ali, plus one Indian station, HAN.

In addition to the four grid points corresponding to seasonal opacity minima, we select four other sites as references: Dome A in Antarctica, the highest point on the continent and currently the best site for high-frequency radio observations; the ALMA telescope in Chile' s Atacama Desert, the premier high-frequency interferometric array; the Ali region in Tibet, known as the "Atacama of Asia," where the National Astronomical Observatories of the Chinese Academy of Sciences has established a permanent station in Shiquanhe Town; and Yangbajing in Tibet, the only domestic candidate site in EHT site evaluations. This paper studies eight sites total, with location information provided in Table 1 . The coordinates listed represent the grid points where each site is located in the MERRA-2 data grid. Due to the limited spatial resolution of satellite data, each grid point represents a region rather than a precise geographic location; our reference sites lie within these grid points, so we use the grid point coordinates to represent each site.

Figure 2 [Figure 2: see original paper] shows how opacity varies seasonally at each site, with colored lines representing the six domestic sites, black dashed lines for ALMA, and black dot-dashed lines for Dome A. Since ALMA and Dome A are in the southern hemisphere, we swap their winter and summer data and spring and autumn data for easier comparison; Dome A' s seasonal differences are minimal, so no swapping was applied. Dome A exhibits the lowest opacity in every season, confirming its status as the world' s premier site. Our four selected locations show opacity comparable to ALMA in autumn and winter, slightly worse in spring, and significantly worse in summer. Overall, JJAMin and SONMin can achieve observational conditions similar to ALMA. The figure also reveals that Yangbajing is not an ideal site. Except for summer, the opacity differences between our four selected locations and ALMA are minor. Data corresponding to Figure 2 are presented in Table 2 .

3 Site Evaluation

3.1 Basis for Site Evaluation

Meteorological conditions affect high-frequency radio observations in numerous ways, with precipitable water vapor (PWV) being the most direct influence and the most severe factor affecting far-infrared astronomy [19, 30]. PWV represents the vertical integration of atmospheric water vapor, expressed as:

$$PWV = \frac{1}{\rho_l} \int_{p_0}^{0} \frac{q}{g} dp$$

where ρ_l is liquid water density, g is gravitational acceleration, p_0 is surface pressure, and q is the specific humidity as a function of pressure.

PWV is a highly reliable reference quantity for weather forecasting. Existing PWV measurements in high-altitude, dry regions are relatively sparse, with measurement sites too far apart [20, 21]. Improving the spatial and temporal resolution of PWV measurements enables more effective weather prediction [22, 23]. Current PWV measurements are primarily obtained through satellite platforms using infrared radiation combined with ground stations, such as the GOES-R satellite instrument [21]. Insufficient ground stations can reduce spatial resolution, which is why experimental stations must still be established at candidate sites after preliminary selection. Increasing the number of ground stations to obtain more surface data makes site selection more reliable. Satellite data resolution remains insufficient for precise site selection. For example, MERRA-2 data has a spatial resolution corresponding to approximately 50 km on the ground—the size of one grid point. The final site location will certainly be much smaller than this scale, so our work can only define a broad region for future site selection; the exact telescope location must be determined using ground station data.

While PWV represents water in gaseous form, liquid water in the atmosphere —such as water in clouds—also strongly absorbs submillimeter waves. In meteorology, the physical quantity liquid water path (LWP) represents the liquid water content in clouds [24], defined as the integration of liquid water content between two points in the atmosphere. For an observation site, the LWP of the entire atmospheric column is:

$$LWP = \int_{p_0}^{0} r_L dp$$

where r_L is the liquid water mixing ratio as a function of pressure. LWP can be approximately retrieved through active or passive remote sensing using microwave radiometers [25, 26] and characterizes cloud cover. As LWP increases, the radiative absorption of clouds also increases. For high-frequency radio observations, LWP' s impact is less pronounced than PWV' s, but we still consider this factor. Figure 3 [Figure 3: see original paper] shows the effects of PWV and LWP on observations at different frequencies, illustrating how 10 µm and 100 µm LWP differentially affect observations: as frequency increases, LWP' s impact gradually increases.

In addition to water-related factors PWV and LWP, we also consider wind speed. While wind speed does not directly affect observations, it can interfere with telescope pointing. During observations, telescopes must track targets, and excessive wind can cause vibrations that lead to target loss, making wind speed an important consideration in site selection.

3.2 Impact of Water

Although water vapor constitutes a low proportion of the atmosphere, it strongly absorbs electromagnetic waves at millimeter and submillimeter wavelengths. PWV is the most important factor for evaluating high-frequency radio telescope sites. In addition to gaseous water, liquid water contained in clouds also significantly affects high-frequency observations, as liquid droplets produce strong scattering and influence background observation temperatures at millimeter and microwave wavelengths [19, 27].

We compared PWV and LWP across the eight sites using three years of data, with results shown in Figure 4 [Figure 4: see original paper]. Red lines represent median values of LWP and PWV, with LWP median values annotated in the upper right corner of each panel. Notably, ALMA has a median LWP of 0, indicating extremely scarce cloud cover. Our selected JJAMin site shows relatively high LWP, representing a significant disadvantage. Dome A has a median LWP of 0.104 µm, which has minimal impact on observations, while LWP at all other sites remains below 10 µm.

3.3 Wind Speed Evaluation

MERRA-2 provides various wind speed data; we use wind speeds at 50 m above ground level. Wind speed data are divided into east-west and north-south components, which are vectorially combined to obtain total wind speed. Figure

5 [Figure 5: see original paper] shows the cumulative distribution functions of three-year wind speed data for the eight sites. Dome A performs poorly in terms of wind speed due to Antarctica’ s special meteorological conditions. Our selected JJAMin site performs optimally, with only rare high-wind events. The Yangbajing site selected by EHT also shows good wind speed performance. Among our four selected locations, two have wind speed conditions superior to ALMA. Table 3 lists the percentage of time each site’ s wind speed exceeds 10 m/s, showing that except for SONMin, the other five domestic sites have better wind speed conditions than ALMA.

3.4 Seasonal Differences

To further characterize each location, we compared wind speed and LWP data across different seasons. Figure 6 [Figure 6: see original paper] shows seasonal distributions of wind speed and LWP for the eight sites, with values representing seasonal medians from the three-year dataset. For easier comparison, we swapped spring/summer and autumn/winter data for Dome A and ALMA. In Figure 6a, JJAMin shows the optimal wind speed conditions in every season. Dome A exhibits poor wind speed conditions in all seasons, reflecting general meteorological characteristics of Antarctica. The Ali, YBG, and DJFMin grid points all have better wind speed conditions than ALMA. SONMin also shows relatively poor wind speed conditions; while its opacity approximates ALMA’ s, its wind speed is much worse. Overall, these eight grid points show maximum wind speeds in winter and minimum in summer, with seasonal variations.

Figure 6b shows seasonal variations in LWP for each grid point. Except for JJAMin, all grid points have very low LWP in winter, with significant seasonal differences concentrated in summer. ALMA and Dome A maintain extremely low LWP in every season, making their dashed and dot-dashed lines difficult to see on the plot. This reveals a common disadvantage of Tibetan Plateau sites: relatively high LWP, though concentrated in summer, with lower values in spring and autumn and winter levels comparable to Dome A. Our selected JJAMin site shows the highest summer LWP but very low winter values, with spring and autumn also below 10 µm. The other four sites exhibit similar characteristics, suggesting that Tibet is generally unsuitable for high-frequency observations in summer.

3.5 Comprehensive Evaluation of the Tibetan Plateau

Beyond seasonal variations in PWV and LWP, we also examined monthly variations in their median values over three years, shown in Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper]. Dome A shows minimal monthly variation in both PWV and LWP, consistent with Figure 6b. ALMA’ s LWP only peaks during local summer, remaining at zero in other months. Among domestic sites, MAMMin, JJAMin, and SONMin achieve PWV standards comparable to ALMA, but all show large LWP differences.

Previous discussions and monthly PWV and LWP variations all demonstrate the excellent winter observation conditions in the Tibetan Plateau. Using ALMA' s winter median values of PWV, LWP, and wind speed as standards (PWV = 1.104 mm, LWP = 0 µm, wind speed = 6.634 m/s), we set the LWP standard to 0.001 µm and evaluated winter median values for each grid point in the Tibetan Plateau region, with results shown in Figure 9 [Figure 9: see original paper]. Yellow regions represent areas where winter PWV median values are below 1.104 mm, blue regions where winter LWP median values are below 0.001 µm, and areas outside red dot-dashed lines where winter wind speed median values are below 6.634 m/s. The figure reveals two small regions near Shigatse that meet all three standards, with our selected DJFMin point located on the edge of one such region, indicating that winter observation conditions comparable to ALMA exist in the Tibetan Plateau.

4 Conclusions and Outlook

Based on comprehensive evaluation of the eight grid points using MERRA-2 data, we conclude that the Tibetan Plateau is suitable for constructing high-frequency radio telescopes. The six domestic grid points (our four selected points plus Ali and YBG) generally represent climate characteristics of the Tibet region. JJAMin and SONMin, located at the border between northern Tibet and Xinjiang, show good opacity performance but suffer from high LWP at JJAMin and excessive wind speed at SONMin, which even exceeds Dome A in summer. Consequently, these two grid points are not ideal targets. Our other two selected grid points, DJFMin and MAMMin, are excellent candidate sites overall. MAMMin' s wind speed approximates ALMA' s, while DJFMin' s is superior to ALMA' s. Except in summer, median LWP values at both grid points remain below 10 µm—worse than ALMA but acceptable. In terms of opacity, these two grid points differ little from ALMA except in summer, even outperforming ALMA in winter, making them viable candidate sites.

Beyond our four selected grid points, Ali and YBG in Tibet have better wind speeds than ALMA and LWP below 10 µm except in summer, but their opacity performance is poorer. YBG is not an ideal target, while Ali performs relatively better. Ali, DJFMin, and MAMMin represent the optimal sites when considering all meteorological aspects.

The EHT's primary next observation target is the Galactic Center black hole [29], which lies in the southern sky, so site selection should favor southern locations as much as possible. MAMMin, located in northern Tibet, is therefore unsuitable as an EHT candidate site. DJFMin is an ideal target site. We considered potential obstruction by Mount Everest, which lies 57 km south of this site at elevations of 5,163 m and 8,848 m respectively, resulting in an elevation angle of approximately 3.7°—negligible obstruction. This grid point can serve as a candidate region for the EHT.

The MERRA-2 data used in this study are satellite reanalysis products. Although their accuracy has been validated in many studies, they still exhibit some deviation from ground-based data [28]. Before actual site construction, further analysis of ground data is required to identify precise telescope locations within MERRA-2 grid cells—this represents our next step. Additionally, since the 1990s, the Tibetan Plateau has gradually become more humid due to global warming [31-33], which will inevitably complicate our site selection efforts. Our work provides a preliminary assessment of the Tibetan Plateau using only three years of data (a relatively short time span). In future work, we plan to use 40 years of MERRA-2 data from 1980-2020 for more comprehensive evaluation and to characterize climate variations at specific sites.

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Note: Figure translations are in progress. See original paper for figures.