Black Hole Shadow Observations with Space-Ground Interferometers

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Abstract—The study explores black hole (BH) shadow images which can be restored by data processing and image recovery procedures during space Very Large Baseline Interferometry (VLBI) missions in the future. For Kerr BHs with masses and coordinates of SgrA*, M87*, and M31*, all illuminated by a light source behind them, three kinds of observation are considered: the ground-based interferometer (similar to the Event Horizon Telescope), space-ground interferometer with a satellite in geocentric orbit, and space-ground interferometer with a satellite located in Lagrange point \( L_2 \). The significant difference between the images produced by the ground-based telescope alone and one from the space VLBI with an added low-orbit satellite is caused by both the increased baseline and the improved \((u, v)\) coverage. The near-Earth configuration of the radio interferometer for BH shadow observations is the most preferable among the considered cases. As the orbit radius increases up to the Lagrange point \( L_2 \), the density of the \((u, v)\) filling decreases and the results appear less reliable. Model images for all the cases are presented.

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1. INTRODUCTION

The observation of black hole (BH) shadows is one of the current problems in astrophysics (see review [1–3]). The pioneer observations of the BH shadow in the innermost area of M87 by the Event Horizon Telescope (EHT)\(^1\) have recently been made ([4–9]). The resulting images clearly demonstrate the exceptional capabilities of modern instruments. At the same time, progress in the study of BHs and their nearby surroundings requires a continuation of research, i.e., the observation of BHs in other radio sources and at other (higher) frequencies.

At present, during the rapid development of BH interferometry, the terms used to designate the BH images are: “shadow”, “silhouette”, and “photon ring” (the last term was first used in [10]). Sometimes their meaning is shared, but is often mixed. Thus, the term “silhouette” is used in [11], which is understood as the image of the BH event horizon. In [12], the term “shadow” is used, which refers to the image of the so-called photon sphere \((r = 3GM/c^2)\) for a non-spinning BH. In English literature, the terms “shadow” and “silhouette” are often confused. The authors follow this practice and name the BH shadow as its image for the specific model, without detailing the shadow border. The BH image depends both on its mass and rotation, and on the properties of the source that illuminates the BH (disk, jet, bright spot, etc.). Some building aspects of the BH shadow in the General Relativity (GR) and extended theories of gravity have been discussed in [13] (see also references therein), as well as in [14–18].

However, regardless of the definition, the BH shadows have tiny angular sizes even for the closest BHs. This means that a VLBI technique should play a key role in shadow observations. Important parameters are also the magnitude of the baseline projection and the frequency at which the receiving equipment operates. The ground-based interferometers are limited by the Earth diameter, and their baselines cannot exceed 12800 km. However, the advantage of this construction is that it can be relatively easy controlled, repaired, developed, as well as big data array be collected. The ground-based VLBI array is realized in an EHT array, which has been carried out for the first observations of the BH shadow in the center of M87 at 230 GHz.

An angular resolution of interferometer can be improved by increasing the baseline or by drifting to higher frequency. Thus, it would be a more productive to build the array of space-based radiotelescopes, which could form an interferometer with huge base-

\(^1\)http://eventhorizontelescope.org
Nevertheless, the idea of a space-ground interferometer is very tempting and is now under heat consideration and discussion (see [22–24]). It can be realized in future space missions. One of them is the Millimetron space mission [25] with cooled 10-meter mirror operating in millimeter- and submillimeter bands, which is planned to be launched in the late 2020s. The angular resolution of this instrument in the interferometric mode is assumed to be so high that, in principle, the BH shadows can be clearly observed in many galaxies. However, there are disadvantages to this scenario. For example, there are limitations on the instrument sensitivity, the radiation scattering by plasma inhomogeneities may occur. In addition, all these effects depend drastically on the frequency. In this work, studies focus on the fundamental possibility of observing the BH shadow, as well as neglect the nuances associated with the characteristics of specific observational instruments and astronomical objects. The preliminary catalog of supermassive BHs can be found in [26], where the observational possibilities of the Millimetron mission were considered. The catalog is based on the extended catalog [27].

The interpretation of the interferometric observations of BH shadows requires the simulation of the expected image. This problem, in turn, requires a lot of effort to develop the radiation source models. As is shown in many papers ([2, 28–36]), the BH image depends significantly on the BH surrounding such as on the accretion disk structure, the dependence of its temperature on the radial coordinate, on the existence of relativistic plasma jet, etc. It is also necessary to consider the corona radiation, the magnetic field geometry, the synchrotron radiation presence, and more. Besides, the image depends also on the interstellar scattering processes ([37], [38]). In our simulation, we do not consider all these effects and thus use the simplest model of the shadow image, which depends only on the mass and spin of a BH and the photon source—the bright plane behind the BH. Nevertheless, the characteristic feature results of ground-based observations and the observations in space-ground interferometer can be revealed. Rather than an image of the real source, SgrA* (or M87*, M31*), but a BH shadow model with the same angular size is considered.

The recent observation of the BH shadow was provided by the ground-based interferometer. Thus, the prospects for future BH research need to be studied, such as taking into account experience of the EHT and RadioAstron mission [39] for future space experiments. In the paper, we compare the BH shadow images which can be obtained by the interferometers with different configurations.

The main goal of the paper is to discuss the preferred satellite orbit, which can efficiently obtain a BH shadow with high resolution quickly. Such a high-quality image is able to deliver important data on physical processes in the very vicinity of supermassive BHs (structure of the inner disk and base of a plasma jet) inhabiting the innermost parts of massive galaxies. This also can be applied to test the GR in strong gravitational fields. Furthermore, the technical problems of interferometry are not discussed here and those issues shall be left for VLBI specialists.

2. MODEL OF BH SHADOW

The spinning BH and its shadow (or silhouette) with simple geometry of a photon source is considered. We assume that a BH is described by the Kerr metric and its spin is close to maximal, $a = 0.9981$ (dimensionless parameter describing the angular momentum ratio of the BH to its mass). The spin axis is perpendicular to the view line of the distant observer (see Fig. 1). Behind the BH and far away, there is a bright flat screen, which emits the quanta uniformly to a hemisphere (in solid angle $2\pi$). If the screen plane is perpendicular to the view line of the distant observer, then the BH silhouette looks like the one shown in Fig. 2. The similar image might appear if a BH of the stellar mass orbits a red giant star and passes in front of the star.

To build the photon trajectories, the motion equations under the GR assumptions for each quantum were solved. The system of six ordinary differential equations can be found in [40, 41]. Ordinary differential equation solvers are included in many packages and freely distributed on the Internet ([42, 43]). The simulated image counts the trajectories of approximately 10 million quanta.

This image has some characteristic details: it is asymmetric, its brightness is inhomogeneous, and a

\footnote{If the BH was irradiated from a solid angle $4\pi$, the shadow image would look different: a wide dark ring between narrow photonic arcs and a contrasting edge (the red ring in the color system Fig. 2) would be light.}

\footnote{https://www.mcs.anl.gov/petsc/}
thin annuli is included inside formed by the quanta, which became apparent to the observer after a few revolutions around the BH. The left-hand side of the annuli is presented, but cannot be adequately displayed because the width of all the annuli is much smaller than the pixel diameter. On the right-hand side, the annuli can be seen separately and their total width is only 17–18 times less than the shadow diameter. Thus, the image of a BH shadow has enough small-sized details to elaborate and discuss the data processing technique. Certainly, such minor details will be most likely blurred by the scattering processes, but this fact will be considered later (see conclusions).

Fig. 1. The location of the emitting surface, the BH and the observer. The view line of the observer is perpendicular to both the screen plane and the spin axis of the BH.

We presume that the spin axis of the BH in the Milky Way’s center is perpendicular to the galactic plane and coincides with the axis of the Milky Way rotation. Thus, its orientation on the celestial sphere is known. Regarding M87 and M31, their spin axes and the spin axes of their BHs are still uncertain, so it is assumed that their spins are oriented along the declination axis. Furthermore, it is assumed that our sources are time-independent.

3. IMAGES OF BH SHADOWS

To reconstruct the images of BH shadows, the well-established CLEAN procedure ([44, 45]) was used. This algorithm is widely used in astrophysics and allows to extract the image from the Fourier coefficients on a finite number of $(u, v)$ plane points (implying a smoothing procedure). Mathematically, an incorrect problem is dealt with due to the incomplete coverage of $(u, v)$ plane. As shown, i.e., in [7], the BH shadow images have some deviations between different image recovery methods and their different implementations. Nevertheless, the image morphology remains unchanged as it has been demonstrated there. In the paper, we also focus on image morphology and do not consider the features that may be associated with the use of a specific procedure for image recovery or with the source model. The CLEAN method does give a general idea about the shadow image.

Fig. 2. The shadow of a Kerr BH against the background of a flat luminous screen perpendicular to the line of sight of the distant observer. The BH spin axis is also perpendicular to the line of sight. The intensity is presented in logarithmic scale and normalized by the brightness of the background screen.
3.1. Ground-Based Interferometer

First, the image is considered, which can be reconstructed after the ground-based interferometric observations as the ones carried out by EHT. The daily coverage of \((u, v)\) plane for SgrA* is shown in Fig. 3 on the top left panel. The coverage of \((u, v)\) plane shown in the Figure is just one possible example and does not coincide with the real observational set of the objects by EHT. The maximal base projection here is about 0.8\(R_{\odot}\). For other objects, the look of \((u, v)\) plane coverage may vary due to the different celestial coordinates, but the general view remains approximately the same. As follows from the figure, the coverage is dense enough and looks relatively uniform.

Three other panels in Fig. 3 present the BH shadow images from Fig. 2 observed at the frequency of 240 GHz and then reconstructed by CLEAN technique for coordinates and masses of SgrA*, M87*, and M31*. As follows from the figure, the image resolution is not high, but we can identify some details of the characteristic image details, especially for SgrA*. For example, at the top right corner, there is bright detail that can be interpreted as a narrow crescent, which can also be found in the original model image. On the restored images of other BH models (bottom panels of Fig. 3), the shadow is not visible. Asymmetry and heterogeneity of the image are an artifact of the data processing procedure.

Fig. 3. Images of a sample BH shadow for SgrA* (the top right panel), M87* (bottom left), and M31* (bottom right) restored by data processing for ground-based interferometric observations. The appropriate coverage of \((u, v)\) plane is presented for SgrA*. The images are shown in conditional colors.
3.2. Low-Orbit Satellite Interferometer

The low-orbit interferometer implies that the satellite lays at the orbits at 200–300 km from the Earth to the geostationary orbit. Their mean value radius is approximately $2 - 3R_\oplus$. Depending on the radius, each satellite in the array makes 1 to 16 revolutions around the Earth per day. In our simulation, the orbit radius is close to $2R_\oplus$. The daily coverage of $(u, v)$ plane for SgrA* is shown on the top-left panel in Fig. 4. The tracks of ground-based telescopes are also presented in Fig. 4. They are the same as those shown in Fig. 3, but in a reduced scale. As mentioned above, the general view of the coverage is approximately the same for M87* and M31*.

The object images, restored by the CLEAN technique, are shown on three other panels in Fig. 4. The top-right panel presents the image of SgrA*. This image contains a lot of additional details in comparison with Fig. 3. Thus, in the top-right part of the inner dark area, one can see the bright crescent that corresponds to the appropriate detail in Fig. 2. Moreover, it is assumed that this image is rotated at some angle compared to Fig. 2 and can be immediately measured, which gives important data on the momentum of the BH and the direction of its axis. Thus, after image processing, the angular resolution in this case is so high that the parameters of a BH and its environment can be examined in great detail. The bright circle also has inhomogeneous intensity distribution, and the posi-
tion of its maximum agrees well with the one of the inner crescent.

The images of M87* and M31* on the bottom panels in Fig. 4 also have additional characteristic features. It is clearly seen that the intensity of the bright ring is inhomogeneous and this inhomogeneity carries important data about the orientation of the BH spin axis. Higher angular resolution leads to the fact that both the intensity range in the images and the intensity gradients are much higher than in Fig. 3.

The comparison of the images in Figs. 3 and 4 allows for the conclusion that the low orbital space-ground interferometer can accrue much more data about the nature of the BHs rather than the observations of the ground-based interferometers only.

### 3.3. High-Orbit Satellite Interferometer

The next step in increasing the baseline would be placing the satellite in the Lagrangian point $L_2$, such as for the forthcoming space observatory Millimetron. After the satellite reaches this point, it remains there during the whole experimental time. The interferometer base can be really huge, and its projection for some sources may exceed $100R_\odot$. However, the coverage of $(u,v)$ plane degenerates. During five years of experiments, one can only hope for a single observation of a specific object.

As before, the coverage of $(u,v)$ plane for Sgr A* is shown on the top left panel in Fig. 5. The tracks of the ground-based antennas cannot be shown adequately due to the Fig. 5 scale. Although, they are present in the very center of this figure, as well as in the inset. It is also important to note that the low-orbit satellite is not included in here. The other panels in Fig. 5 demonstrate the reconstructed images of SgrA*, M87*, and M31*.

Even as the angular resolution of this configuration is extremely high, the result looks worse than in Fig. 4 due to very poor coverage of the $(u,v)$ plane. Thus, this coverage of the $(u,v)$ plane does not reliably restore the original image.

The bright photon ring can be easily distinguished in the image of SgrA*, but the narrow inner crescent detail is completely lost despite the very high angular resolution. Thus, any information about the axis orientation is lost too. The intensity distribution along the ring looks also uniform in contrast to Fig. 4.

Image analysis of the considered BH shadow model with M87* and M31* coordinates reveals the same features. We can conclude only that a certain ring-like structure is definitely observed. The edge of the shadow in M87* also does not reveal any characteristic details that would establish the angular momentum direction.

### 4. CONCLUSIONS

We found that the interferometer, including both the ground-based telescopes and a low-orbit satellite, has an advantage in comparison with other reviewed cases, in which it has the ability to fill the $(u,v)$ plane with high density during a relatively short time (a day or week). A low-orbit interferometer is able to successfully solve this problem because good coverage of the $(u,v)$ plane takes less than a week. Moreover, if the orbit lays at about $300–400$ km above the Earth, the revolution lasts 1.5 h. After 5–7 cycles, the coverage of the $(u,v)$ plane becomes dense enough. Here, the observation procedure may last only about 10 h and, in principle, the BH image can achieve satisfactory quality and resolution twice a day. A satellite in the orbit with $R \sim 2R_\odot$ has about a three-times longer orbital period. Thus, similar coverage of the $(u,v)$ plane will be achieved in about one day (see Fig. 4). The simultaneous use of two or three satellites can further reduce the timespan.

The ground-based arrays have enough $(u,v)$ coverage, but most objects cannot be observed all day long because they are below the horizon for some time period. During these periods, the coverage of the $(u,v)$ plane stops, and traces remain which look like a half of an ellipse (see Fig. 3). The great advantage of ground-based instruments is obviously their low cost.

The longer is a baseline of the interferometer, the more difficult is the correlation process. In particular, this is due to the difficulty in synchronizing of ground and on-board timers. Thus, the space-ground interferometer should have much more sophisticated equipment than a ground instrument.

A case of a high-orbit satellite differs from others. Indeed, its angular resolution is incredibly high. Theoretically, it is so high that the annuli inside the shadow area can be observed in Fig. 2 separately, i.e., the resolution could be even greater than its reproduction in the figure. However, a poor $(u,v)$ plane coverage is an issue. The information obtained in the interferometric observation is not the image of the object itself but rather it is a Fourier transform of the true image at limited number points of the $(u,v)$ plane. The reliable image reconstruction is possible only with a dense-enough coverage of $(u,v)$ plane. One satellite turn around the Earth in the Lagrangian point $L_2$ takes a full year. Even in the duration of observations will not have a radical effect on the coverage of the $(u,v)$ plane. A spacecraft moving in the orbit near point $L_2$ every year almost repeats its track on the $(u,v)$ plane. The spacecraft displacement up and down from the ecliptic plane only slightly increases the coverage of the $(u,v)$ plane.

Another interesting idea is to place the radiotelescope at the Lunar pole [21]. The orbital period of the natural Earth satellite lasts about a month. Thus, one...
third or a half of a year (a few turns around) is enough to cover the \((u, v)\) plane. In any case, this is much less than required for the satellite located at the Lagrange point \(L_2\). However, for the implementation of such a colossal project, there are still many technical problems to be resolved.

Currently, only two successful space VLBI missions have been implemented: the VLBI Space Observatory Programme (VSOP) [46] and RadioAstron [39]. Since both were equipped by receivers in centimeter wave bands, there is not enough experience compiled yet.

The long-awaited detections of the BH shadow by EHT is the first step to test the GR in strong gravitational fields. However, its quantitative features are not sufficient to distinguish between BHs using different gravity theories. Thus, attention is needed when interpreting the BH images as tests for GR [47]. Since the BH shadow can be measured more precisely by the space-ground interferometer than by the ground-based one, the space-ground VLBI mission can carry out stronger tests for GR and accretion models.

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