The Event Horizon Explorer mission concept

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Abstract. The Event Horizon Explorer (EHE) is a mission concept to extend the Event Horizon Telescope via an additional space-based node. We provide highlights and overview of a concept study to explore the feasibility of such a mission. We present science goals and objectives, which include studying the immediate environment around supermassive black holes, and focus on critical enabling technologies and engineering challenges. We provide an assessment of their technological readiness and overall suitability for a NASA Medium Explorer (MIDEX) class mission.

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1 Introduction

The Event Horizon Telescope is an intercontinental Very Long Baseline Interferometry (VLBI) array of radio telescopes that successfully imaged radio emission in close vicinity of a black hole.[1,2] While this array will continue to increase in capability by deploying new ground-based stations, and increasing bandwidth and frequency range,[3] adding a space-based radio dish to the array would enable transformative science. Extension to space improves angular resolution by creating longer interferometric baselines than are possible on the Earth. Spacecraft can also enable better time resolution by rapidly sampling a wide range of Fourier spatial frequencies as orbital motions sweep out space-ground and even space-space baselines. Combined, these improvements can deliver unique improvements in ultra-high resolution VLBI imaging. There is precedent for such high scientific impact issuing from specific interferometric array enhancements. Establishing long VLBI baselines at 1.3 mm wavelength from the continental United States to Hawaii led to the discovery of structure on the scale of the black hole event horizon in both Sgr A* and M87,[4,5] and to the detection of ordered magnetic fields close to the horizon.[6]

The NASA Explorers program may provide a suitable funding opportunity for a dedicated space VLBI mission within the next decade. The Event Horizon Explorer (EHE) mission concept study seeks to ascertain whether a Medium-class Explorer (MIDEX) proposal may be feasible in the next cycle (2025-2026). Here we present the organization and structure of the mission concept study, and a broad overview of the science and technical issues under consideration.

The EHE mission concept study has three phases: (1) a Science Study which articulates plausible goals and objectives (2) an Engineering Study which articulates overall feasibility and technological readiness and (3) a Mission Architecture Study which combines the results of the previous studies to match achievable science goals and objectives with feasible engineering to yield a plausible mission architecture. Impetus for this study included initial work by the concept team members, which indicated that a MIDEX-scoped mission could deliver a major scientific advance.

In Section 2 we discuss the process of determining the science goals of an EHE mission. In Section 3 we highlight some of the technical challenges, as identified in our ongoing engineering study, in order to make such a mission feasible. In Section 4 we summarize the current status of this ongoing investigation

2 Science Goals and Objectives

The mission concept study conducted a week-long intensive study to explore potential science objectives. This workshop was attended by 51 scientists and engineers from nine institutions. They had expertise ranging from general relativity and theoretical astrophysics to radio astronomy and very long baseline interferometry, as well as applied physics and/or engineering disciplines that were deemed important, such as precision timing and optical communications.

The science study included plenary sessions and numerous breakout sessions for discussion. External presenters gave talks on subjects such as crafting a science case, the science traceability matrix, the MIDEX proposal review process, as well as technical topics such as precision timing technologies, antennas and optical communications.

The science study aimed to articulate plausible goals and objectives for the mission. Goals were defined to be overarching and qualitative in nature. Objectives were defined to be more specific and quantitative, from which spacecraft mission requirements may ultimately be defined. Not all of the goals and objectives considered were intended to be realized in a single mission, due to competing requirements. Not all of these objectives may be feasible, due to constraints on cost and/or technological readiness.

Potential science goals and objectives were grouped into four categories: (1) Precision black hole measurements, which focused on detecting and studying the photon ring around a supermassive black hole (2) Black hole accretion and jets, which focused on how black holes interact with accreting matter to produce jets of radiation, i.e how black holes shine, and (3) Black hole formation and demographics, which aimed to study how supermassive black holes have affected the evolution of galaxies. (4) Finally, a variety of potential ancillary science topics were explored including the processes driving and inhibiting star formation, galactic foregrounds for understanding cosmological inflation, and the role of water in planet formation.

Precision black hole measurements: The EHE will provide an unprecedented view into the spacetime properties near a black hole. The curvature of spacetime in the black hole event horizon vicinity is strong enough to pull photons into orbits.[7,8] These strongly lensed photon trajectories produce a telltale signature on images seen by a distant observer: a sharp "photon ring," the appearance of which is only weakly affected by the surrounding matter.

The precision measurement component of the EHE mission has three key objectives, all related to the photon ring, with increasingly challenging requirements: (1) Establish the existence of the photon ring, confirming a striking and untested prediction of general relativity.[9] (2) Precisely measure the size and shape of the photon ring in M87* to determine the spin of the black hole.[10] (3) Compare the relative sizes and shapes of photon subrings in M87* to the universal predictions of General Relativity, as a sensitive new test of the "no hair" theorem.[11]

Black hole accretion and jets: Black holes do not emit electromagnetic radiation themselves. However, the interaction of matter with a strong gravitational field created by the black hole produces the most powerful sources in the Universe. Although a significant progress in our understanding has been achieved from a study of active galactic nuclei (AGN) for last 60 years at all wavelengths from low frequency radio through hard γ-rays, the details of the process of generating enormous energy are not yet clear.[12] The innermost region surrounding a black hole is not seen with ground-based instruments because of insufficient resolution and self-absorption at frequencies below 80–230 GHz. The unprecedented angular resolution of the EHE will extend our understanding of the interplay between black holes, as compact astrophysical objects, and the high-energy astrophysical jets that they power.

Black hole formation and demographics: There is strong observational evidence that most galaxies harbor massive, compact, and dark objects at their centers,[13] and efforts over many years to constrain the masses of these objects to smaller and smaller volumes supports their interpretation as supermassive black holes (SMBHs).[14] However, the current evidence for the SMBH nature of these objects is fundamentally indirect, typically relying on the orbital motion of gas or stars on spatial scales that are many orders of magnitude larger than the expected size of the SMBH itself. The SMBHs whose mass has been determined to live within the smallest region (relative to its expected Schwarzschild radius) are those in Sgr A* and M87, where EHT observations of the "shadow" confine the size of the SMBH to be $\lesssim$5 Schwarzschild radii.[2,15,16]

Such SMBH "shadows" are predicted to be generic features of accreting black holes.[17] When the emitting material is sufficiently optically thin, the strong lensing of light in the vicinity of an accreting black hole generically produces a characteristic ring-like emission structure.[18] The identification of such a structure on event horizon scales is thus a compelling piece of evidence in favor of the black hole nature of the central compact object. In particular, the ability to determine that the emitting structure is ring-like at the exclusion of other possible morphologies (e.g., disk-like, Gaussian, double source, etc.) is strong evidence that the observed object is indeed a black hole. The EHE can unambiguously identify SMBHs in a large sample of galaxies by looking for signatures of their shadows, then it will directly establish the expected ubiquity of these objects in the Universe.

Science Report and External Review: The principal findings of the science study were summarized in a science report and a Science Traceability Matrix (STM). The STM is a standard reporting tool used in NASA mission design; its specific format was taken from the MIDEX 2001 Announcement of Opportunity. The science report provided an explanation of the goals and objectives, and justification for the instrument requirements and top-level mission requirements.

An external review panel was assembled to provide an independent assessment of the results of the science study, and to help refine goals and objectives. Panelists were selected to have scientific backgrounds relevant to black holes, NASA astrophysics mission formulation as well as non-black hole astrophysics to provide a non-specialist perspective. Factors influencing panelist recruitment included subject matter expertise, as well as diversity. The resulting panel consisted of seven scientists and showed diversity in gender, geography and institutional affiliation, and it included both theorists and observers.

The review panel was charged with evaluating the science report and the STM similar to an actual MIDEX proposal review. Panelists were instructed to consider the first two factors in the scientific merit review according to the 2021 Astrophysics Medium Explorers (MIDEX) Evaluation Plan: Factor A-1, compelling nature and scientific priority of the goals and objectives and Factor A-2, programmatic value of the proposed investigation. Other factors in a MIDEX evaluation were not possible to review due to the early stage of development of this mission concept. The panel reviewed documents individually and then met in a single meeting for a group discussion. Subsequently, they reported their findings to the project team. Specific results and recommendations of the panel will be forthcoming.

3 Engineering Challenges

As the mission pushes the envelope in a range of areas, developing a viable concept that fits within the MIDEX class poses significant engineering challenges. We outline below the key areas which exemplify the challenges and assess the status in each. The parameter space that determines the sensitivity and viability of a prospective mission encompasses multiple subsystems and needs careful exploration. For this purpose, relevant expressions have been developed and a basic tool has been implemented, incorporating parameters spanning the subsystems.

3.1 Antennas

The antenna of the orbiting VLBI station collects signals from the astrophysical targets of observation. It is the first element in the signal path and is part of the sensor that measures and records the electric field at the location of the spacecraft for off-line correlation with similar records from other stations. Its main requirements are the ability to collect the incident energy efficiently onto the downstream coherent heterodyne receiver system, a stable phase center and an effective collecting area or aperture size that satisfies the science goals. As part of the EHE mission concept study, we have surveyed the status of the field to assess the technology landscape and readiness levels (TRLs), which are summarized below.

Besides cost, the geometric (physical) aperture size is limited by the fairing size of the launcher unless an unfurled antenna is used. The central Ruze component of the aperture efficiency is determined by the surface smoothness as a fraction of the wavelength of operation. The combination of surface smoothness and geometric aperture size is a key characteristic of the antenna that determines the effective aperture, and therefore, the sensitivity.

The largest non-unfurled aperture launched thus far (TRL 9) with adequate surface smoothness for 230/345 GHz operation is the 3.5 meter diameter silicon carbide mirror of the Herschel Space Observatory. However, being a FIR/THz instrument, its performance far exceeds the EHE requirements and at 300 kg, it may be too heavy for a MIDEX class mission.

There is significant heritage in the meteorological and Earth observation area with more relevant wavelength coverage. In this category, the largest antennas flown or under development (TRL 8-9) are lighter and have apertures of up to $\sim$ 2-m (e.g. Weather Systems Follow-on Microwave: Ball Aerospace/Advanced Aerospace Structures).

The largest unfurled antenna for X band operation is the recently delivered Airbus SDR five meter antenna.[19,20] Made of thin carbon fiber reinforced polymer (CFRP) panels, it is very light, with a surface tolerance that should allow performance up to $\sim$ 50 GHz. However, significant additional development would be needed to realize any conceivable 230 GHz operation.

CFRP and machined aluminium antennas for sub-orbital balloon borne platforms, previously flown (BLAST) or delivered/being developed (e.g. ASTHROS, TIM), provide adequate surface tolerance for the EHE. The current aperture sizes are 2-2.5 meter and their space qualification and development of larger apertures presents a viable path.

Inflatable antenna concepts are also being explored which hold the potential for large, extremely light weight apertures, but require substantial further development and understanding.[21]

The parameter space that determines the sensitivity is still being explored and understood and further work is needed to gain better clarity on the optimum combination of physical aperture, surface smoothness and technology path.

3.2 Flight Dynamics

The spacecraft orbit greatly affects the science that can be accomplished by the EHE mission. There are many important factors to consider including the potential data downlink rate, visibility to science targets, lengths of contact times to ground stations on Earth for downlinking science data, exposure to radiation, and the angular resolution for VLBI imaging. Some of these factors are incompatible. For example, a higher altitude orbit would provide greater angular resolution and increased target visibility but would limit the potential downlink rate and could expose the spacecraft to radiation.

Four different orbits are currently being assessed. The first is a lower Earth orbit (LEO) which provides the highest downlink rates and avoids the Earth's radiation belts but provides less angular resolution and smaller visibility windows compared to higher altitude orbits. The next is a geostationary orbit whose orbital period matches the Earth's rotational period and appears stationary to an observer on the Earth. This orbit could enable continuous downlink to multiple stations and provides better angular resolution than the LEO but is always in a high-radiation environment. Additionally, the downlink rates from the geostationary altitude would be lower than in LEO. To avoid some of the radiation, an inclined geosynchronous orbit is also being considered. This orbit also has an orbital period equal to Earth's rotational period but does not appear stationary to an observer on Earth. It has many of the same advantages as the geostationary orbit but spends part of the orbit above the radiation belts. Finally, a highly elliptical orbit (HEO) is being investigated. The HEO can be designed to maximize orbital time above the radiation belts and to reach much higher altitudes than the geostationary and geosynchronous orbits, which provides outstanding angular resolution. Due to the high altitude though, achieving high downlink rates may be challenging for most of the orbit.

3.3 Precision Timing

A critical requirement for VLBI observations is a highly stable time reference to maintain coherence between data recorded independently at multiple stations. The instability of the reference impacts phase coherence which in turn lowers system efficiency. A stability of $\sim$ a few $\times 10^{-14}$ is required to limit coherence loss at 230 GHz to 5-20% for $\sim$ 10s of seconds of coherent integration time. The standard approach used by ground based arrays employs active hydrogen masers (AHM) for observations up to 230/345 GHz demonstrated by the EHT.[1] However, hydrogen masers have high space, weight and power (SWaP) - and alternatives are desirable, especially to fit into the MIDEX mission profile. As part of the EHE mission concept study, we have looked at the viability of potential alternative technologies for reference generation and evaluated their TRLs. We provide a brief summary below with more details to be presented elsewhere.

While AHMs have attained TRL 9 with successful operation as part of the Radioastron mission, in addition to high SWaP, it should be noted that one of the two identical AHM units flown on the same mission failed to function. The simplest option is presented by ultra-stable oven controlled crystal oscillators (USO/OCXOs), which offer the lowest SWaP and are TRL 8-9 (e.g. Accubeat). However, their main drawback is that they barely meet the requirements, needing further development work to improve margins, which may or may not be feasible.

In recent years, optical comb based techniques have become increasingly prominent as high precision time and frequency references and are replacing microwave technologies. There are two options possible in this technology path. In one route we would leverage low SWaP lasers being developed at NASA Goddard Space Flight Center as part of the Laser Interferometer Space Antenna mission,[22] of which a prototype that meets the requirements was recently delivered for testing. Transferring the stability of this laser by locking a mode-locked femtosecond pulsed laser comb to it allows the generation of the required microwave reference. The required subsystems are at different readiness levels, approximately in the range TRL 5-8. In a second approach, we seek to exploit optical two way time and frequency transfer (O-TWTFT) pioneered at the National Institute of Standards and Technology (NIST)[23,24] by mutually transmitting and synchronizing a highly stable ground based laser comb to one on-board. Stability levels exceeding the EHE requirements have been achieved in ground experiments by NIST. The current technology readiness is assessed to be approximately TRL 4-5 and is undergoing further development, including extension to $\sim$ 300 km path lengths. A notable advantage of O-TWTFT is the synergy with laser communication required to transfer data, central to the mission (section 3.4), thus allowing SWaP sharing. A drawback is the need for multiple ground stations with master reference combs which may pose a challenge to LEO mission concepts. For orbits with large link distances (e.g. HEO, cis-lunar), the impact of the time of flight on the TWTFT synchronization control may have to be considered. The overall SWaP for these technologies is assessed to be the best for the USO/OCXOs followed by O-TWTFT, laser comb and AHMs.

3.4 Optical Communications

Submillimeter VLBI generates enormous data volumes for which downlink to Earth becomes a significant engineering challenge. Recent advances in free-space optical communications capabilities can provide high-capacity laser communications from satellite and ground station(s) that can support VLBI downlink needs.

Two current NASA programs can be considered pathfinders for this capability. The Laser Communications Relay Demonstration (LCRD) is operating at GEO with two available ground stations that can support multi-rate operation up to 1.2 Gbps.[25] Launched in Dec. 2021, LCRD is in a two-year operational experiment to gain a better understanding of how to leverage laser communication as a reliable, effective data delivery option for high bandwidth applications. The Terabyte Infrared Delivery (TBIRD) project is a cubesat class mission which demonstrates 200 Gbps data delivery from a LEO orbit.[26]

Current notional EHE data rate requirements are in the range 256 Gbps. To achieve such large data rates requires careful design trades between satellite-to-Earth link distances and the power-aperture product. Extending TBIRD technologies from LEO to GEO increases link distances by a factor of $\sim$40, which increases the power-aperture challenge by 32 decibels. In addition, the orbit of interest will drive a trade between the number of ground stations needed for coverage and the on-board storage requirements. For example, a LEO architecture will require either significant additional on-board storage or many ground stations to provide sufficient downlink coverage, while a GEO architecture can be supported by fewer ground stations (i.e., LCRD at GEO operates with only two ground stations).

Unlike radio frequency communications, laser communications can be blocked by clouds. The likelihood of such obstructions is reduced by having site diversity,[27,28] in which the presence of multiple ground stations with line-of-sight to the space terminal increases the probability of having a clear cloud-free line-of-sight to at least one ground terminal. By choosing ground terminal sites with uncorrelated weather, very high availability can be achieved.

The key technologies for high-capacity optical downlinks are currently between TRL 4–9, so it is likely that a technical solution to support VLBI needs for the EHE can be realized. The next step is to identify a design which minimizes the technology development and costs required for such a mission.

Numerous trades impact technology development needs for a given mission concept. For instance, preliminary link budgets indicate that a 256 Gbps link from GEO using a 10 cm diameter space terminal and a 70 cm diameter ground terminal aperture would require that the space terminal transmit at least 24 W of laser power to close the link. While high power amplifiers of this class exist for terrestrial applications, further technology development would be needed to increase the TRL for a space mission. Such high power requirements would also impact space-terminal SWaP and cost.

Alternatively, increasing the size of the space terminal aperture would provide a more collimated beam and allow the link to be closed with lower transmitted power. However, this would require costly development and tighter pointing and stability requirements for the space terminal.

In general, it is more practical for such trades to place the architectural burden on the ground side. Doubling the diameter of the ground terminal receive telescope (neglecting the effects of turbulence) allows the power transmitted by the spacecraft to be reduced by a factor of four. However, when turbulence is considered, increasing the diameter of the telescope will only help up to a point since larger apertures require more complex adaptive optics to correct the turbulence-aberrated wavefront. Furthermore, the cost of the ground terminal telescope and the adaptive optics grows non-linearly with aperture size.

Exploring the complex trades for high-capacity optical downlinks provides guidance for the targeted technology development and helps reduce costs for future missions of interest.

4 Conclusion

The EHE mission concept study seeks to explore science goals and objectives as well as engineering feasibility of a dedicated submillimeter wavelength VLBI spacecraft in the coming decade. Such a mission could enable dramatic new advances in resolved black hole studies. In general, spacecraft orbits can sample interferometric Fourier spacings that are inaccessible from the ground, providing unparalleled angular resolution for the most detailed spatial studies of accretion and photon orbits.

It should be noted that even as we propose space missions to sharpen our views of black holes, parallel ground-based work aimed at improving the capabilities of the current Event Horizon Telescope continues as well. The next-generation EHT (ngEHT) will, over the next decade, enable dynamical studies of black holes, connection of the black hole to relativistic jets, and more detailed study of the photon ring. These two approaches to advancing horizon scale studies of black holes share some science objectives, but are complementary in many ways and should both be pursued.

The EHE mission, also the subject of an Astro 2020 white paper,[29] will enable study of the fine photon ring structure, aiming to reveal the clear universal signatures of multiple photon orbits and true tests of general relativity, while also giving astronomers access to a much greater population of black hole shadows.

Some of the critical engineering areas associated with such a mission would include flight dynamics, precision timing, light weight antennas and optical communications. This mission concept study has explored several approaches in each of these areas. Concurrent technology development that is now underway in precision timing and optical communications may enable dramatic new capabilities in the coming years. This raises the exciting possibility of transformative science in the study of black holes to be enabled within a decade.

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