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The following proposal has been submitted for consideration of an award by NASA:

Solicitation Number: NNH25ZTR001N-26NIAC_A1

Solicitation Title: NASA Innovative Advanced Concepts (NIAC) Phase I

Proposal Number: 25-NIAC26A-0288

Proposal Title: Multi-Wavelength VLBI Constellation for Black Hole Movies

Submitting Organization: BROWN UNIVERSITY

Authorized Organization Representative: Melissa Medeiros

Principal Investigator: Ref Bari

Date submitted: 07/15/2025 13:04:33

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Cover Page for Proposal Submitted to the National Aeronautics and Space Administration

NASA Proposal Number

25-NIAC26A-0288

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SECTION I - Proposal Information

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Proposal Title : **Multi-Wavelength VLBI Constellation for Black Hole Movies**

Proposed Start Date	Proposed End Date	Total Budget
03 / 16 / 2026	**12 / 15 / 2026**	**No budget required**

SECTION II - Application Information

NASA Program Announcement Number	NASA Program Announcement Title
NNH25ZTR001N-26NIAC_A1	**NASA Innovative Advanced Concepts (NIAC) Phase I**

For Consideration By NASA Organization *(the soliciting organization, or the organization to which an unsolicited proposal is submitted)*

NASA , Headquarters , Space Technology Mission Directorate , NIAC

Date Submitted	Submission Method	Grants.gov Application Identifier	Applicant Proposal Identifier
07 / 15 / 2025	**Electronic Submission Only**		

Type of Application	Predecessor Award Number	Other Federal Agencies to Which Proposal Has Been Submitted
New		

International Participation	Type of International Participation
No	

SECTION III - Submitting Organization Information

UEI	EFT	CAGE Code	Employer Identification Number (EIN or TIN)	Organization Type
E3FDXZ6TBHW3		**23242**		**8H**

Organization Name (Standard/Legal Name)	Company Division
Brown University	

Organization DBA Name	Division Number

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SECTION IV - Proposal Point of Contact Information

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SECTION V - Certification and Authorization

Certification of Compliance with Applicable Executive Orders and U.S. Code

By submitting the proposal identified in the Cover Sheet/Proposal Summary in response to this Research Announcement, the Authorizing Official of the proposing organization (or the individual proposer if there is no proposing organization) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of their knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in this solicitation.

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Authorized Organizational Representative (AOR) Name	AOR E-mail Address	Phone Number
Melissa Medeiros	**Melissa_Medeiros@brown.edu**	**401-863-6170**

AOR Signature *(Must have AOR's original signature. Do not sign "for" AOR.)*	Date
Digitally signed by Melissa Medeiros	**07/15/2025 13:04:33**

Multi-Wavelength VLBI Constellation for Black Hole Movies
(Quantum-Enabled Space-Space VLBI for Direct Imaging Black Holes)

Innovation

• **Multi-Wavelength VLBI Constellation**: A VLBI Constellation consisting of both radio and optical telescopes, enabling time-resolved multi-messenger astronomy of black hole and binary black hole targets.

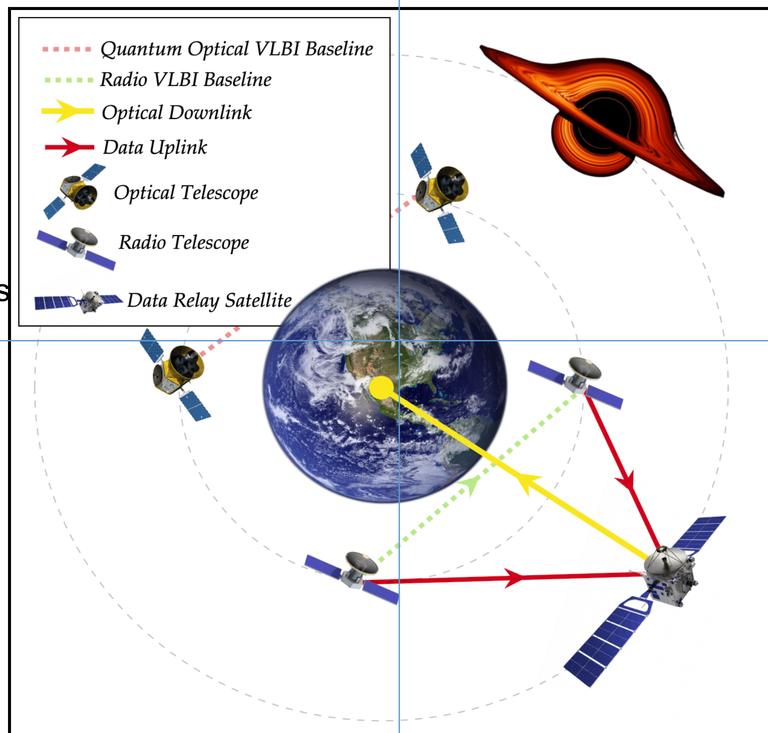
• **The Quantum Advantage**: Optical VLBI can achieve the same $23\mu as$ resolution as the Event Horizon Telescope with only a 2 km baseline.

• **Distinction**: Unlike VLBI Swarms such as GO-LoW, our constellation leverages quantum repeaters to enable multi-wavelength observations

Impact

• **Primary Science Objective**: Create the first video of a black hole and the first video of binary black holes.

• **Time-Resolve Accretion Disk of Sgr A***: The first image of a black hole was viewed by 4 billion people. The first video of a black hole will not only capture the public imagination, but also enable real-time confirmation of general relativity at an unprecedented timescale. It would also enable the first constraints on the spin of a black hole.



Mission

• **Dual Radio-Optical VLBI Constellation**: Enables imaging of Jets, Accretion Disks & Horizon.

• **Enable Multi-Messenger Black Hole Astronomy**: By co-observing binary black holes (BBH) with Pulsar Timing Arrays/LISA, our constellation would enable secondary posteriors for parameter estimation of Mass/Spins of BBH targets, such as OJ 287.

• **Orbital Architecture**: VLBI Sandwich Configuration enables both long and short baselines which probe both horizon-scale and extended-structure morphology of black holes. As shown in the figure above, the optical arm of the constellation will co-observe black holes with the radio arm. The optical arm will form quantum-enable baselines, whilst the radio arms also establish baselines with a data relay satellite in MEO.

Approach

• **Optical Telescope SWaPC**: Explore feasibility of integrating quantum repeater infrastructure which to enable spaceborne optical VLBI.

• **Optimal Constellation Configuration**: Implement AI-assisted determination of optimal orbital parameters to maximize radio coverage of targets

• **Feasibility of Dynamic Imaging of Sgr A***: Determine how to minimize integration time to enable time-resolved imaging of the accretion disk of Sgr A* and BBHs.

• **Quantum Data Compression**: We will determine feasibility of implementing Quantum Probability Image Encoding (QPIE) to rapidly accelerate the image reconstruction process whilst suppressing quantum errors.

Multi-Wavelength VLBI Constellation for Black Hole Movies

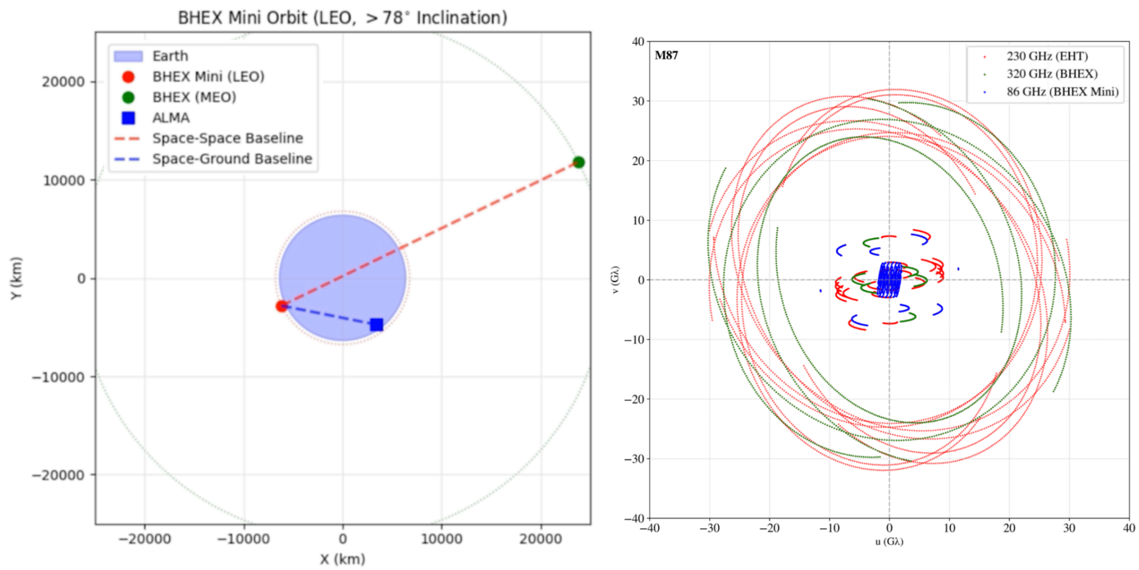
The first video of a black hole will enable breakthroughs in gravitational physics (Palumbo et. al., 2019). Resolving a binary black hole system would enable real-time confirmation of general relativity on an unprecedented timescale (Dittmann et. al., 2024). Time-resolving a black hole's accretion disk would enable definitive constraints on the spin of a black hole for the first time (Yfantis et. al., 2025). In 2019, the Event Horizon Telescope (EHT) captured the first direct image of a black hole using Very Long Baseline Interferometry (VLBI) (EHT Collaboration, 2019). However, VLBI struggles to create videos of black hole targets, due to the limited speed of Earth Rotation Aperture Synthesis (La Bella et. al., 2023). We propose a multi-wavelength VLBI satellite constellation to create the first black hole movie by co-observing targets in both the radio and optical regimes, exploiting two key innovations — a Quantum-Assisted VLBI Network & VLBI Sandwich architecture — to achieve the following goal:

Primary Science Objective: Create the first video of a black hole and a binary black hole system
Technical Objective: Time-resolve the accretion disk of Sgr A and resolve the temporal evolution of hotspots in the accretion disk; This would test the Blandford-Znajek mechanism, which predicts that relativistic jets are powered by black hole spin. The critical requirement to achieve a time-resolved movie of Sgr A* is to achieve* $> 50\%$ *interferometric coverage on* $t < \tau_{ISCO} = 30$ *minute timescales.*

The 2020 Decadal Survey established black holes as a key science priority for NASA in this decade. Our proposed satellite constellation is of direct relevance to NASA's "highest-priority sustaining activity, … [which] is the space-based time-domain and multi-messenger program," as it would enable the first time-resolved videos of black holes and binary black holes, in tandem with gravitational wave observatories (NASA, 2020). A spaceborne extension to the EHT is under development: the Black Hole Explorer Satellite (BHEX). Despite BHEX's innovations, space-ground VLBI faces four challenges:

1. Data Management: VLBI generates petabytes of data even after a few days of observation. It is difficult to downlink such significant amounts of data to ground stations on Earth (Gurvits, 2020).
2. Atmospheric Decoherence: Fluctuations in the Earth's atmosphere result in time-varying path delays, which result in loss of coherence and decrease SNR. (Pesce et. al., 2024)
3. Limited Imaging Capabilities: Long VLBI baselines can probe faint, horizon-scale structures surrounding a black hole, but are less effective for bright features. Short VLBI baselines can probe high flux-density targets such as synchrotron emission from relativistic jets launched by the black hole, but cannot probe fine-structure features. (Hudson et. al., 2024)
4. Static Imagery: VLBI has succeeded in enabling ultra-high angular resolution images of astrophysical phenomena. However, due to limited coherence time on the space-ground baseline and slow *(u,v)* coverage from ground arrays, it is difficult to leverage VLBI to generate time-resolved "videos" of dynamic astrophysical phenomena. (Blackburn et. al., 2019)

For our NIAC study we propose BHEX Mini: A Multi-Wavelength VLBI constellation that leverages Quantum-Assisted VLBI Networks to time-resolve transient astrophysical phenomena. BHEX Mini will be a Low Earth orbit constellation of n radio telescopes and m optical telescopes, co-observing black hole targets. The key innovation of BHEX Mini is two-fold: (1) The optical telescopes will have spaceborne quantum-assisted baselines, completely eliminating the problem of atmospheric decoherence; The radio telescopes will directly image black hole targets at a high observing frequency $\sim$ 86 GHz. (2) We propose a VLBI Sandwich architecture which will exploit simultaneous short- and long-baseline lengths to dynamically image both horizon-scale and extended-structure morphology in black hole targets, resolving the latter two challenges faced by contemporary VLBI Space Systems. We now proceed to elaborate on these two innovations.



Left: BHEX Mini VLBI Sandwich Configuration. Right: Simulated (u,v) Coverage with 1 LEO Satellite

Our representative mission is as follows: We envision BHEX Mini as a dual-band radio-optical constellation consisting of both radio and optical telescopes, enabling multi-messenger observations of black holes for the first time. The radio (optical) satellites in the constellation will hereafter be referred to as “the radio (optical) arm of BHEX Mini.” Both arms will form an interferometer, but in two fundamentally different ways:

- The radio arm will time-tag radio signals using quantum synchronization between VLBI stations to reduce dependence on ultra-stable oscillators (Quan et. al., 2016). We will also explore the possibility of real-time correlation of VLBI data using quantum links between satellites, which may mitigate atmospheric decoherence effects. Additionally, we seek to explore the possibility of quantum data compression before optical downlinking (Brunet et. al., 2024). These nascent quantum technologies may enable a significant increase in coherence time and SNR.
- The optical arm leverages emerging quantum technologies to form baselines longer than ground optical telescopes (Gottesman et. al., 2012, Khabiboulline et. al. 2019). **This is the quantum advantage**: **While EHT requires an earth-sized baseline to achieve** $\theta = 23\mu as$**, optical VLBI (**$600\ nm$**) can achieve the same resolution with only a** $2.4\ km$ **baseline** (Huang et. al., 2025).
- The hybrid demography between radio and optical arms of the satellite constellation is essential to its success. The radio arm is crucial because targets such as Sgr A* are hidden behind optically-absorbing interstellar dust, gas, and plasma. The optical arm is critical for imaging binary black hole targets, many of which have variable optical emission.

The second key innovation lies in the orbital architecture itself, which is coined “the VLBI Sandwich”. This configuration implies placing the VLBI satellite constellation in LEO, whilst simultaneously placing another VLBI satellite in MEO. This infrastructure should be technically feasible in a decade, when BHEX launches in 2035. The VLBI Sandwich architecture addresses Problems 3 & 4 of Space VLBI. By sandwiching the constellation close to the Earth, between the Event Horizon Telescope on the ground and the BHEX satellite at MEO, BHEX Mini establishes both short and long baselines. The short Space-Ground baselines $0.11G\lambda < b_{SG} < 3.5G\lambda$ (BHEX Mini to EHT) enable probing of high flux-density targets such as accretion disks and jets. Simultaneously, the long Space-Space baseline $5.6G\lambda < b_{SS} < 9.3G\lambda$ (BHEX Mini to BHEX) probes faint fine-structure features of the black hole targets. BHEX Mini can thus probe both small and large-scale morphology in targets.

There are five key advantages to the VLBI Sandwich Configuration:

1. *Sub-milli arcsecond angular resolution*: $22\mu as < \theta_{BHEX-Mini} < 1800\ \mu as$.
2. *Dual short and long baseline lengths:* Enables both horizon- and extended-structure imaging
3. *Rapid, dense coverage of the (u,v) plane*: The orbital period in LEO is $T = 90$ mins
4. *Decreased signal loss:* Decreased loss in VLBI optical downlink favors LEO instead of MEO
5. *Decreased interstellar scattering from LEO*: Compared to BHEX at MEO, BHEX Mini will have an order of magnitude reduction in ISM scattering. From preliminary calculations, the visibility amplitude for a Gaussian source after scattering may be modeled by $V_{obs}(b) = S\exp(-\frac{\pi^2 b^2 \theta^2}{4\ln 2})\exp(-\frac{1}{2}C^2 b^{\alpha} r^{2-\alpha})$, where $1.38 \le \alpha \le 1.99$ represents the scattering coefficient. A minimum baseline ⅕ of BHEX and an observing wavelength results in $\lambda = 3.5\lambda_{BHEX}$, $V_{BHEX-Mini} \sim 10V_{BHEX}$ – the visibility amplitude of a gaussian source is ten times larger in LEO at 86 GHz.

The radio and optical satellites in the constellation may have different satellite components. However, the general systems design will remain similar. The tentative instrumentation breakdown for each satellite includes: Antenna/Telescope, Primary Receiver, Cryocooler, Ultra-Stable Oscillator, Digital Backend, and Quantum Infrastructure. Each satellite in the radio arm of the constellation will feature a $2.5m$ diameter antenna coupled to a primary receiver cooled down to cryogenic sub-20 K temperatures, operating at 86 GHz ($3.5mm$). According to preliminary SWaP constraints, each satellite in the constellation will be $100kg$ with $P \sim 500W$. Our Phase I NIAC study will further constrain the SWaP requirements for the optical arm of the satellite constellation and determine the quantum infrastructure to be placed onboard.

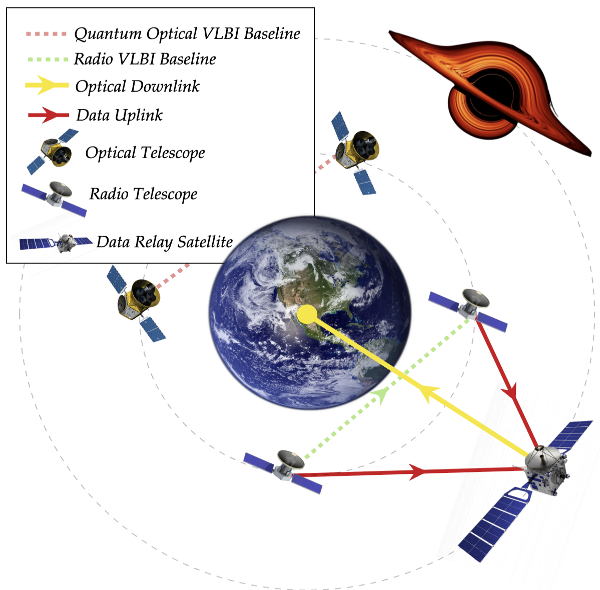


Diagram of Orbital Architecture

Using NIAC Phase I funding, the BHEX Mini team would address the following key challenges: (1) Determine quantum infrastructure for the optical arm of the constellation; (2) Implement AI-assisted determination of optimal orbital parameters to maximize radio coverage of black hole targets. (3) Determine how to maximize interferometric *(u,v)* coverage of Sgr A* under the dynamical timescale of the accretion disk; (4) Determine the feasibility of enabling multi-messenger black hole astrophysics with BHEX Mini. (5) Determine feasibility of Quantum Data Compression algorithms to manage data.

If successful, BHEX Mini will achieve several historical milestones: (1) Enabling the first multi-wavelength VLBI observations and (2) Enabling quantum-assisted VLBI observations for the first time – all in service of creating the first movie of a black hole. By leveraging state-of-the-art innovations in quantum technology, BHEX Mini has the potential to be the first Space-Space VLBI satellite mission and enable spaceborne Optical VLBI. By time-resolving black holes and binary black hole systems, BHEX Mini will also enable the first constraints on the spin of a black hole, as well as time-resolved parameter estimation of binary black hole systems. This is the decade of black hole spectroscopy and BHEX Mini is the vehicle of this audacious vision.

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