BHEX Mini Proposal

Directly Imaging Black Holes from LEO via VLBI

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In 2019, the Event Horizon Telescope (EHT) captured the first direct image of a black hole. The Black Hole Explorer Satellite (BHEX) is an ambitious successor to EHT which hopes to directly image the photon ring of a black hole. Brown University is leading the development of BHEX Mini, a SmallSat LEO partner to BHEX. BHEX Mini will operate at $f_{obs} \sim 86$ GHz ($\lambda \sim 3.5mm$) with a $d \sim 2m$ antenna operating at a primary receiver temperature of $\sim 20°$ K, with a frequency bandwidth $\Delta f_{BW} = 32$ GHz and coherence time $\Delta t \sim 100s$. By co-observing with BHEX, BHEX Mini will enable horizon-scale and extended jet-structure imaging of Sgr A^* and M87 for the first time. BHEX Mini's primary science objective is to conduct an all-sky survey of ~ 25 secondary science targets which include binary black hole systems, quasars, and black hole accretion disks. If successful, BHEX Mini would be the first demonstration of Space-Space VLBI.

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1 Introduction to BHEX Mission

In 2019, the Event Horizon Telescope (EHT) directly imaged the black hole M87 with an angular resolution of $\sim 23\mu as$ at 230 GHz [1]. This image ushered a new revolution in black hole spectroscopy, enabling the first observational constraints on the mass and radius of black holes [2]. The Event Horizon Telescope (EHT) collaboration is now planning a successor mission: the Black Hole Explorer Satellite (BHEX). BHEX is a 175 kg, ~ 170 million planned NASA Small Explorer Mission (SMEX). The primary scientific objective of BHEX is to directly image the photon ring of a black hole for the first time [3]. This would constrain the spin of $M87$ and Sgr A^* down to 10% of the ground truth. The secondary science objective of BHEX is to conduct a population survey of several black hole targets which include binary black holes, quasars, and blazars [4]. This would enable a deeper understanding of how the spin of supermassive black holes power relativistic blazar jets. BHEX will operate at an orbital altitude of $\sim 20,200$ km (Medium Earth Orbit) and operate at a dual-band observing frequency of $86-120$ GHz and $230-345$ GHz. BHEX will have a combined frequency bandwidth of $\Delta f = 32$ GHz across its low and high frequency bands, and a coherence time of $\Delta t = 100s$ [5].

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2 BHEX Mini Primary Scientific Objective

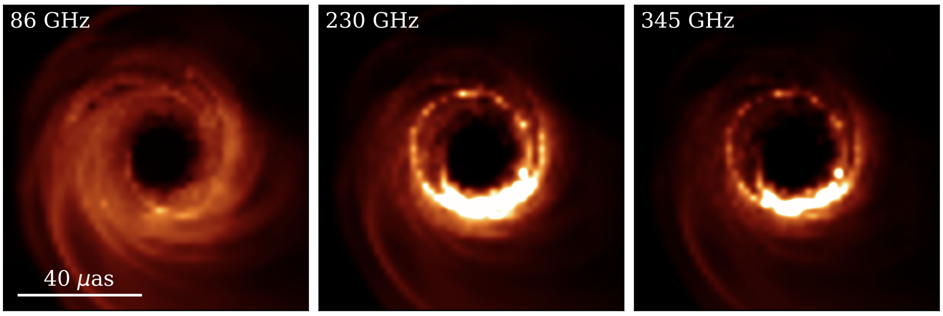

Figure 1: GRMHD Simulations of M87: BHEX Mini will observe at 86 GHz (left) whilst BHEX observes at 345 GHz (right). BHEX Mini will thus resolve extended accretion disk structure whilst BHEX resolves the photon ring. (Figure Credit: Issaoun et. al., 2023 [6])

As a VLBI satellite in low-earth orbit observing at 86 GHz, BHEX Mini will have four primary science objectives:

1. BHEX Mini will assist direct imaging of the photon ring by supplementing interferometric (u, v) coverage of Sgr A^* and M87 at 86 GHz.
2. By conducting an all-sky survey of ~ 25 Secondary Science Targets (SSTs) at 86 GHz, BHEX Mini will enable population modeling for supermassive black hole mass, spin, luminosity, and inclination distributions.
3. If successful, BHEX Mini would be the first demonstration of Space-Space VLBI (between BHEX in MEO and BHEX Mini in LEO).
4. Despite orbiting only at LEO, BHEX Mini can exploit the existing infrastructure of BHEX at MEO and EHT on Earth to leverage both long (Space-Space) and short (Space-Ground) baselines [7]. This enables BHEX Mini to probe both small and large-scale morphology in SSTs.

Unlike BHEX which has only long baselines ($> 20G\lambda$) which can reveal horizon-scale structure of Sgr A^*/M87 (but which may not be as adept at observing larger-scale structure like jets), BHEX Mini will benefit from both a long Space-Space Baseline (BHEX to BHEX Mini) and a shorter, Space-Ground Baseline (BHEX Mini to EHT). **BHEX Mini is thus uniquely positioned to access both horizon-scale and extended jet-structure morphology of low-accretion state black hole targets.**

3 BHEX Mini Scientific Objectives

BHEX Mini seeks to conduct an all sky survey of ~ 25 supermassive black hole (SMBH) targets at an observing frequency of $f_{obs} = 86$ GHz. These targets include binary black hole systems (i.e., OJ 287), quasars (i.e., 3C 279), and AGNs (i.e., 3C84). This would enable population modeling for the mass, spin, and luminosity distributions of black holes across the SMBH trade space. BHEX Mini also seeks to supplement interferometric coverage of the primary BHEX targets M87 and Sgr A^*. By leveraging frequency phase transfer techniques, BHEX Mini can complement BHEX's observations at 345 GHz with lower-frequency observations at 86 GHz.

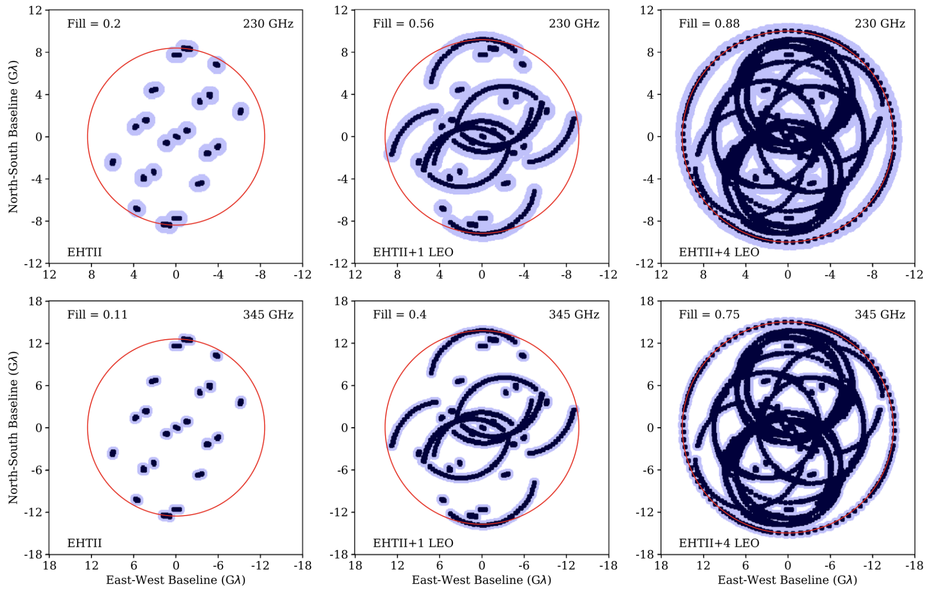

Figure 2: Extended (u, v) coverage from multiple satellites, as opposed to a single orbiter (Figure Credit: Palumbo et al., *ApJ* 2019 [8])

This proposal discusses the systems design study for BHEX Mini's antenna diameter and receiver temperature. The proposal is being continually updated by the BHEX Mini team to include cryocooler requirements, solar panel dimensions, orbital parameters, duty cycle calculations, and data downlink requirements. Section 3 discusses BHEX Mini's primary challenges and the need for a second satellite. Section 4 discusses the methodology for constraining BHEX Mini's Antenna Diameter. Section 5 discusses preliminary results on BHEX Mini's interferometric coverage at 86 GHz. Section 6 discusses potential funding sources for BHEX Mini. Finally, Section 7 discusses the prospective timeline for BHEX Mini.

4 BHEX Mini Antenna

BHEX Mini has an antenna diameter $d \sim 2m$ and a primary antenna receiver temperature of $T \sim 20°K$. BHEX Mini has compiled a non-exhaustive list of 25 secondary science targets (SSTs), which consist of a diverse range of sources, from binary black hole systems to quasars. To estimate the minimum antenna diameter required to resolve these targets with an $SNR > 5$, we estimated all targets as gaussian sources given by the visibility amplitude:

$$V(b) = S \cdot \exp(-\pi^2 b^2 \theta^2 / 4 \ln 2) \quad (1)$$

A detailed calculation of visibility amplitudes based on individual source morphology will be conducted once BHEX Mini's satellite component dimensions are constrained. We modeled the visibility amplitudes $|V|$ of each source as a function of baseline length b. Observe that the visibility of the radio targets becomes resolved out at longer baselines, so that bright features are more accessible on shorter baselines.

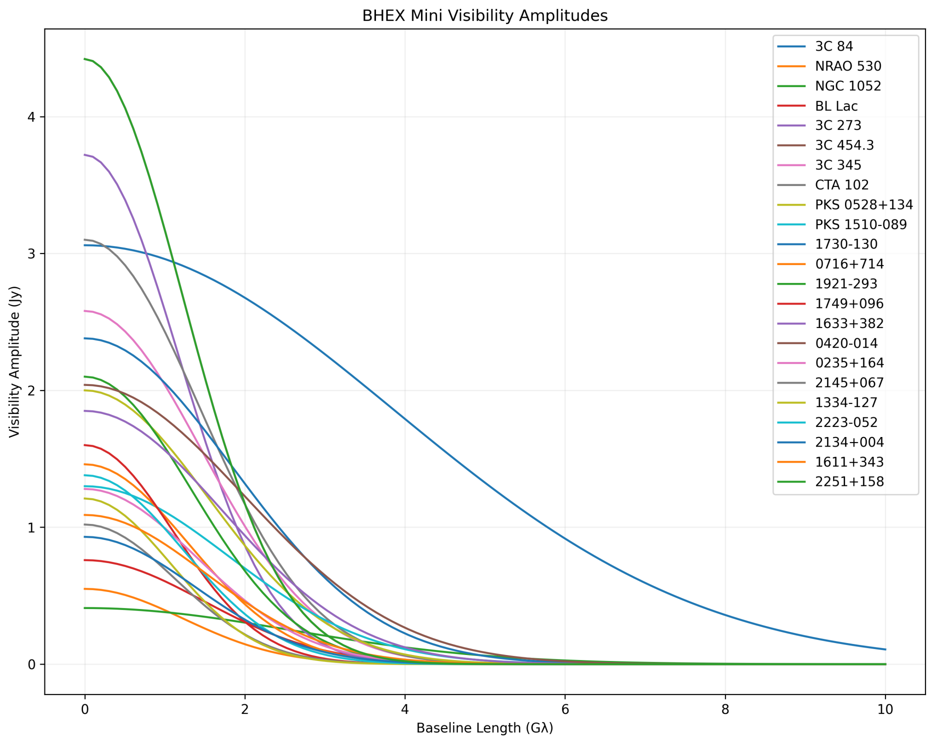

Figure 3: Visibility Amplitude of 25 SSTs modeled as Gaussian Sources

This enables constraints on the thermal noise σ on a given baseline (either Space-Space baseline or Space-Ground baseline), via

$$\sigma_{SS} < \frac{|V_{SS}|}{SNR}, \sigma_{SG} < \frac{|V_{SG}|}{SNR} \tag{2}$$

Since the Visibility Amplitude $|V_{ss}|$ will be smaller on BHEX Mini's space-space baseline, the thermal noise constraint is more stringent on the space-space baseline than the space-ground baseline: $\sigma_{SS} < \sigma_{SG}$.

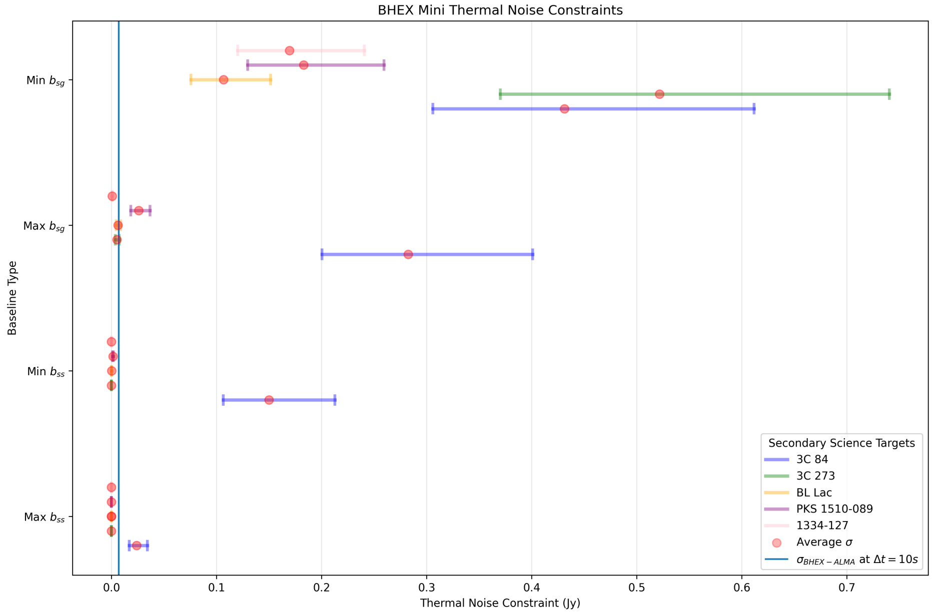

Figure 4: Thermal Noise Constraints for representative sample of SSTs, plotted for a range of $SNR \in [5, 10]$, for $5.6G\lambda < b_{ss} < 9.3G\lambda$ and $0.11G\lambda < b_{sg} < 3.5G\lambda$

This in turn constrains the System Equivalent Flux Density (SEFD), since the thermal noise is related to the sensitivity by:

$$\sigma_{SS} = \frac{1}{\eta_Q}\sqrt{\frac{SEFD_{\text{BHEX}}SEFD_{\text{BHEX Mini}}}{2\Delta\nu\Delta t}}, \sigma_{SG} = \frac{1}{\eta_Q}\sqrt{\frac{SEFD_{\text{BHEX Mini}}SEFD_{\text{EHT}}}{2\Delta\nu\Delta t}} \tag{3}$$

Solving for the required sensitivity of BHEX Mini on a given baseline, we find

$$\text{SEFD}_{\text{BHEX-Mini}} = (\sigma_{SS}\eta_Q)^2 \cdot \frac{2\Delta\nu\Delta t}{\text{SEFD}_{\text{BHEX}}} \tag{4}$$

This enables constraints on the antenna diameter and system temperature T_{sys} via

$$\text{SEFD}_{\text{BHEX Mini}} = \frac{2k_{\text{B}}T^*_{\text{sys}}}{\eta_{\text{A}}A} \rightarrow A = \frac{2kT_{sys}}{\eta_A \text{SEFD}_{\text{BHEX Mini}}} \tag{5}$$

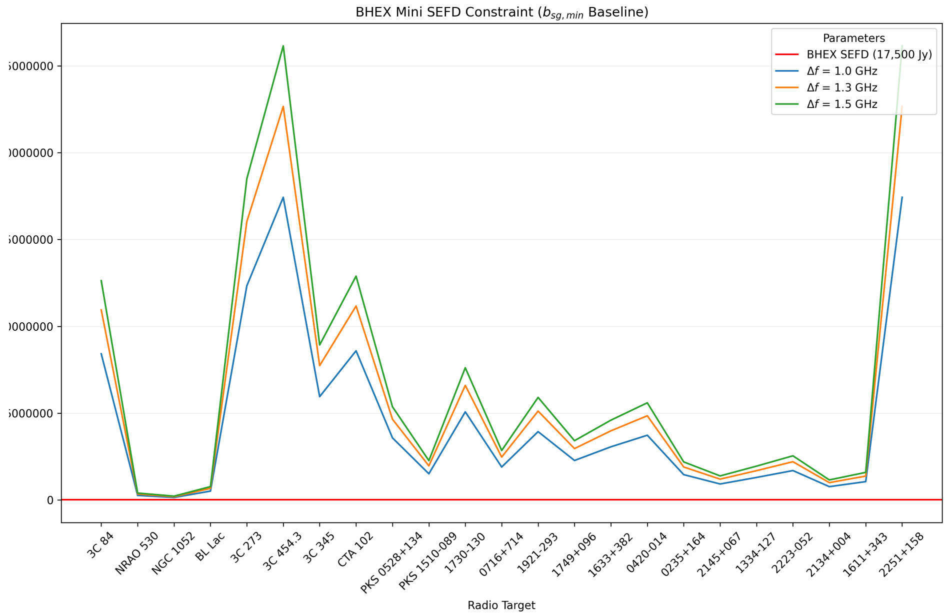

Figure 5: Constraints on BHEX Mini's SEFD

BHEX Mini's system temperature is given by

$$T_{sys} = [T_{rx} + \eta_{eff} T_{source}](1 + r) \tag{6}$$

where T_{rx} is the receiver temperature and T_{source} is the brightness temperature of the source, which is given by

$$T_{source} = \frac{F_{tot} A_{eff}}{2k} \tag{7}$$

F_{tot} is the total flux density of the source and A_{eff} is the effective antenna collecting area. Observe that the visibility amplitude $V \propto \exp(-b^2)$, where b is the baseline length. Thus, most radio targets are resolved out when the baseline length exceeds $b > 5G\lambda$. Thus, BHEX Mini is able to resolve the extended-scale jet-like or accretion-disk structures on the smaller space-ground baselines b_{sg}. Figure 5 demonstrates that a $d \sim 2m$ is sufficient to resolve all secondary science targets with $SNR \geq 5$, regardless of the frequency bandwidth. We find that higher frequency bandwidths decrease the minimum required antenna diameter, with diminishing returns above $\Delta f \sim 9$ GHz. By virtue of having a longer space-space baseline b_{ss}, BHEX Mini also achieves a sub-30μas angular resolution:

$$\theta_{ss,max} \sim \lambda / b_{ss,max} < \theta < \theta_{sg,min} \sim \lambda / b_{sg,min} \tag{8}$$

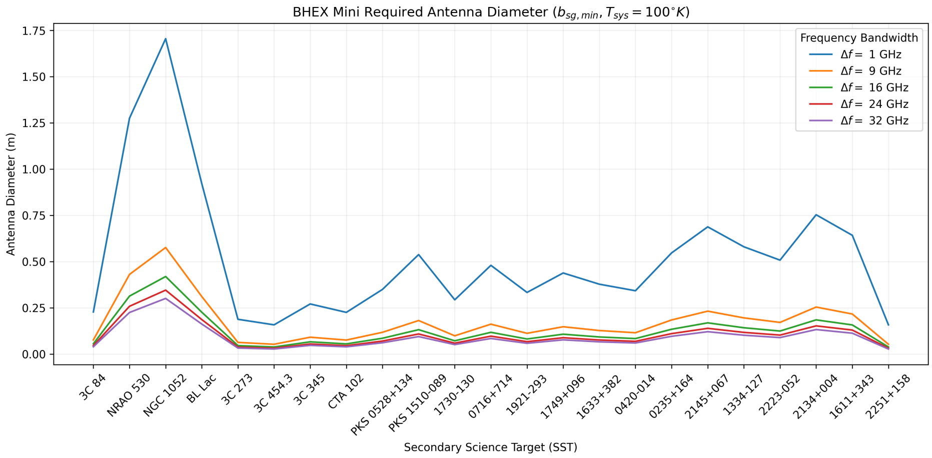

Figure 6: BHEX Mini Required Antenna Diameter

$$\frac{3.5 \cdot 10^{-3}\ \text{m}}{400 \cdot 10^{3}\ \text{m}} \cdot 2.06 \cdot 10^{11}\frac{\mu as}{\text{rad}} < \theta < \frac{1.3 \cdot 10^{-3}\ \text{m}}{33,400 \cdot 10^{3}\ \text{m}} \cdot 2.06 \cdot 10^{11}\frac{\mu as}{\text{rad}} \tag{9}$$

In 2019, the Event Horizon Telescope achieved a $\sim 23\mu as$ resolution, which would be the upper limit of BHEX Mini's angular resolution on its longest space-space baseline. Thus, although the visibility amplitude would be high on the space-ground baseline, the angular resolution would also be much greater, effectively adding a gaussian blur to the image.

$$\boxed{22\mu as < \theta < 1800\mu as} \tag{10}$$

5 Frequency Reference System

Very Long Baseline Interferometry (VLBI) involves the combination of multiple radio telescopes into a larger 'virtual' telescope with a smaller effective angular resolution given by $\theta \sim \lambda/D$. VLBI operates by combining radio signals from widely-separated telescopes. A highly accurate frequency reference system is required to coherently add radio signals from different telescopes and achieve higher SNR. The event horizon telescope uses highly precise atomic clocks such as hydrogen masers, which can achieve frequency stabilities on the order of ~ 1 in every 10^{-14} over $\Delta t = 10s$ of integration time. We now present constraints on BHEX Mini's Allan Deviation if it seeks to achieve a Coherence Loss $L \leq 10\%$ and phase error $\Delta\phi < 1$ radian. These constraints are required to resolve black hole and active galatic nuclei (AGN) targets at $SNR > 5$ and achieve phase coherence when combining radio signals between BHEX, BHEX Mini, and EHT.

In Figure 7, we plot the Coherence Loss as a function of Observing Frequency for three frequency reference systems: Ultra-Stable Oscillators (USO) for ESA's Jupiter Icy Moons Explorer (JUICE) mission and NASA's Laser Interferometer Space Antenna (LISA), as well as the Rakon RK409 Oven Controlled Crystal Oscillator (OCXO). RK409 OCXO has an Allan Deviation $\sigma_y = 10^{-12}$ for $\Delta t = 10s$; JUICE USO has $\sigma_y = 5 \cdot 10^{-13}$ for $\Delta t = 10s$. The USO being developed for LISA is projected to have $\sigma_y = 8 \cdot 10^{-15}$. From this limited trade space of frequency reference systems, it seems that only the LISA USO achieves the $L < 10\%$ coherence loss constraint required for BHEX Mini to resolve black hole targets at $SNR > 5$.

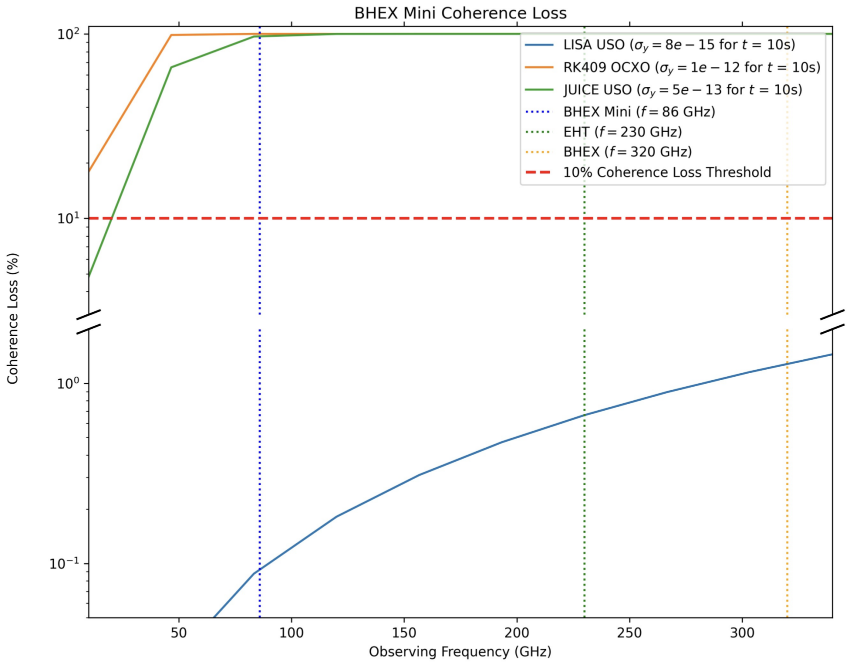

Figure 7: BHEX Mini Coherence Loss as function of Observing Frequency

In Figure 8, we plot the Phase Error $\Delta\phi$ for four frequency reference systems: O-CS41 OCXO, SMD OCXO, BHEX USO, and the RK409 USO. We compute the phase error by

$$\Delta\phi = 2\pi \cdot f_{obs} \cdot \sigma_t, \sigma_t = \sigma_y \cdot \Delta t \tag{11}$$

where f_{obs} is the observing frequency, σ_t is the timing jitter, which is proportional to the Allan Deviation σ_y and the integration time Δt. A phase error of $\Delta\phi < 1$ rad is required to achieve phase coherence and achieve $SNR > 5$. We find that for an integration time of $\Delta t = 1s$, Abracon's SMD OCXO far exceeds this phase error requirement at 86 GHz. However, the more precise O-CS41 OCXO seems to barely meet this constraint, whereas the BHEX USO and RK409 USO exceed the phase error requirement.

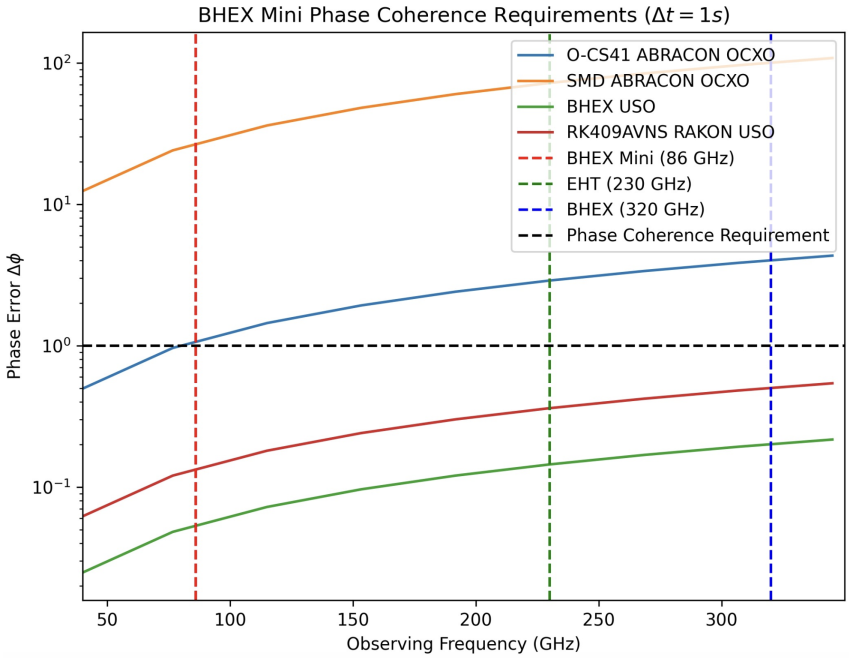

Figure 8: Phase Coherence $\Delta\phi$ against Observing Frequency f_{obs} for BHEX Mini

6 Future Challenges

To accomplish its goal of conducting an all-sky survey via 86 GHz VLBI observations, BHEX Mini must address four core challenges, which are currently being discussed by the team:

1. Achieve an angular resolution $\theta_{\text{BHEX-Mini}} < \theta_{\text{target}}$ 2-3 times smaller than the angular size of targets to enable probing of radio targets' morphology
2. Cool down primary antenna receiver temperature to sub-25°K temperatures to achieve the thermal noise $\sigma < \frac{|V|}{SNR}$ required to resolve targets at $SNR > 5$
3. Determine orbital parameters $(a, e, i, \Omega, \omega, v)$ required for BHEX Mini to maintain communication with EHT whilst maximizing observation time.
4. Manage potentially petabytes of data via a three-tiered approach: Physical Data Storage, On-board Data Processing, and Real-time Optical Downlink.

7 Appendix

7.1 Thermal Noise Calculations

Calculations were made separately for the BHEX-BHEX Mini and the Ground-BHEX Mini thermal noises. Assuming based on BHEX documents:

$$SEFD_{Ground} = \frac{2kT_G^*}{\eta_{A_G} A_G} = 5000Jy, \tag{12}$$

Additionally, utilizing a BHEX $T_{sys} = 50K$, $\eta_{BHEX} = 0.899$, $D_{BHEX} = 3.5$, we find the following for the BHEX satellite at 86GHz:

$$SEFD_{BHEX} = \frac{2k(50K)}{(0.899)(\pi)(\frac{3.5}{2})^2} = 15962.4Jy \tag{13}$$

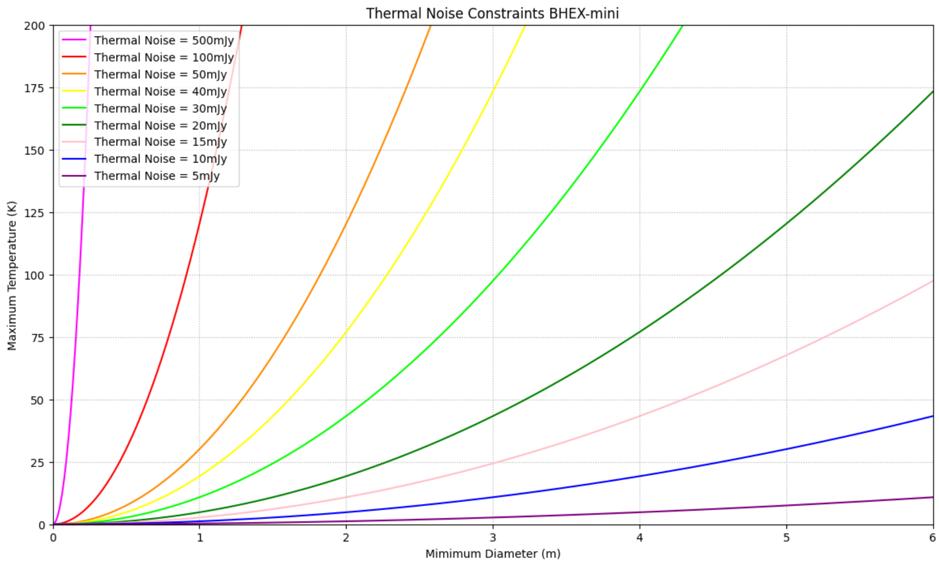

Figure 9: Trade Space of BHEX Mini σ_{SS} dependence on T_{sys}, d

The following derivation (based on BHEX-BHEXmini) is used to construct the graphs in this section. The Thermal noise is fixed, and the temperature is found as a function of the diameter (area). Note that T^* is the system temperature, not the antenna temperature.

$$\sigma_{SS} = \frac{1}{\eta_Q} \left(\frac{1}{2\delta\nu\delta t} [SEFD_{BHEX}] \left[\frac{2kT^*_{Mini}}{\eta_{A_{Mini}} A_{Mini}} \right] \right)^{1/2} \tag{14}$$

$$\sigma_{SS}^2 \eta_Q^2 \left[\frac{2\delta\nu\delta t}{[SEFD_{BHEX}} \right] = \frac{2kT_{Mini}^*}{\eta_{A_{Mini}} A_{Mini}} \tag{15}$$

$$T_{Mini}^* = \sigma_{SS}^2 \eta_Q^2 \left[\frac{2\delta\nu\delta t}{[SEFD_{BHEX}} \right] \left[\frac{\eta_{A_{Mini}} \left[\pi \frac{d}{2}^2 \right]}{2k} \right] \tag{16}$$

The following values were assumed: $\eta_Q = 0.75$ $\eta_{mini} = 0.75$ $\delta\nu = 8,000,000,000$

The following graphs were generated at fixed thermal noises values. There purpose was to determine the general effect of variations of the system temperature and antenna diameter on thermal noise constraints. Of note, 2.71mJy is the smallest thermal noise between BHEX and any ground-station (BHEX-ALMA), and 33.23 mJy is the thermal noise between BHEX-SMT.

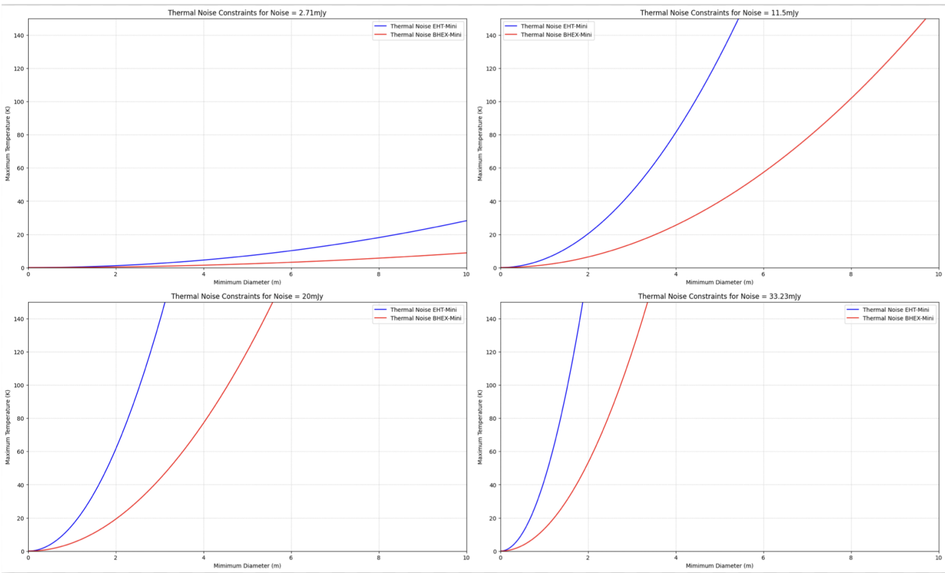

Figure 10: Four graphs of BHEX-BHEXmini and EHT-BHEXmini Thermal noise constraints; 2.71mJy, 11.5mJy, 20mJy, 33.23mJy

Note that the BHEX-BHEX Mini thermal noise will always be higher than the Ground-BHEX Mini thermal noise. Therefore, to achieve a set thermal noise, only the BHEX-BHEX Mini thermal noise needs to be considered. With this in mind, Figure 7 was constructed demonstrating the relationship between minimum required antenna diameter and maximum allowed system temperature for BHEX Mini, at set BHEX-BHEX Mini thermal noise values.

8 Secondary Science Targets

Parameters for Select Secondary Science Targets			
Secondary Science Target	Flux Density (Jy)	Angular Size (μas)	Visibility Amplitude (Jy)
OJ287	2.49	172.9	3.0
NRAO530	0.55	63	0.0083
3C84	3.06	20	2.0
3C279	13.0	80	0.015
N1052	0.41	30	0.16
J0319+4130	3.50	150.5	1.39e-10
J0013+4051	0.19 ± 0.061	34 ± 9	0.036-0.069
J0017+8135	0.099 ± 0.022	30 ± 5	0.033-0.040
J0030+7037	0.121 ± 0.026	26 ± 5	0.053-0.059

All values are for a frequency of 86 GHz and space-Earth maximum baseline.

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