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The Scientific Rationale of Space-Borne Sub-Millimeter Interferometry and the Challenges

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Abstract

In astronomy, ultra-high angular resolution has always been a crucial tool for fundamental discovery. New momentum in high angular resolution astrophysics was provided by the millimeter VLBI system's Event Horizon Telescope's direct imaging of the vicinity of the supermassive black hole in the nucleus of the radio galaxy M87 and a number of pioneering results from the Space VLBI mission RadioAstron. The angular resolution was approximately 10–20 microarcseconds (0.05–0.1 nanoradians) in both of these instances. The requirements of advanced astrophysical research necessitate further progress toward "sharper" values of at least one order of magnitude at the level of one microarcsecond. The paper emphasizes that placing millimeter and submillimeter wavelength interferometric systems in space is the only way to achieve these higher values. In the context of the ESA Call for White Papers for the Voyage 2050 long-term plan in 2019, a concept of this kind of system has been proposed. It is called Terahertz Exploration and Zooming-in for Astrophysics. Based on recent research on active galactic nuclei and supermassive black holes, we present new science objectives for this concept in the current paper. In addition, we go over a number of strategies for overcoming the technological obstacles that arise when building a space-based interferometric system at millimeter or submillimeter wavelengths. We focus on a novel space-borne millimeter/submillimeter antenna configuration that has the potential to overcome a number of obstacles to the creation of large, precise mechanical structures. In addition, a summary of potential space-qualified technologies for low-noise analog front-end instrumentation for millimeter and submillimeter telescopes is provided in this paper. Instrumentation for data handling and processing is another important technological part of a sub-millimeter Space VLBI system. This instrumentation's requirements and potential implementation options are extrapolated from the most recent, cutting-edge Earth-based VLBI data transport and processing equipment. The interferometric baseline state vector determination, synchronization, and heterodyning systems are also briefly discussed in this paper. The paper's technology-focused sections do not aim to present a comprehensive set of technological solutions for space-borne interferometers operating at terahertz (sub-millimeter) frequencies. Instead, when used in conjunction with the original ESA Voyage 2050 White Paper, it makes a stronger case for the next generation of microarcsecond-level imaging instruments and serves as a foundation for more in-depth studies of technology trade-offs.

Keywords: Radio interferometry • VLBI • Millimeter astronomy • sub-millimeter astronomy • Space-borne astrophysics

Introduction

An astronomical observing instrument's efficiency is largely determined by its angular resolution. The Very Long Baseline Interferometry (VLBI) method has held the angular resolution record for half a century. The global Event Horizon Telescope (EHT) team was able to image the black hole shadow in M87* and probe the innermost regions of Active Galactic Nuclei (AGN) jets at a wavelength of 1.3 mm with an angular resolution of approximately 20 as in recent years thanks to advancements in VLBI technologies and new data processing algorithms. With baselines up to 30 Earth diameters and wavelengths down to 1.3 cm, the Space VLBI mission RadioAstron was able to achieve angular resolution of 10 as. However, the scientific drives toward even sharper radio astronomy "vision" on the ground and in space are not satisfied by these observing capabilities at the angular resolution of tens of microarcseconds. In point of fact, over the course of the past four decades, a number of studies have attempted to attain even higher angular resolution, including several design studies of Space VLBI missions [1].

Literature Review

The electromagnetic spectrum's range of hundreds of gigahertz to several terahertz (for simplicity's sake, hereafter referred to as the terahertz range); It has wavelengths ranging from one millimeter all the way down to submillimeters, and it is utilized in numerous scientific and technological contexts. For the purpose of comprehending the astrochemistry of various constituents of galactic matter and the evolution of galaxies, stars, and planets, spectroscopic studies in the THz range provide information on the spectral lines of molecules and atoms. As recently demonstrated by the EHT, the millimeter domain offers the highest angular resolution of any Earth-based telescope for the VLBI method. However, water vapor in the Earth's atmosphere absorbs THz radiation. As a result, stratospheric aircraft and balloon observations at frequencies up to 350 GHz are practically possible in very special locations, such as extremely cold and dry regions like Antarctica or high altitudes. Therefore, deploying THz telescopes into outer space would represent a radical solution to the issue of atmosphere opacity.One component of this global initiative is the idea of TeraHertz Exploration and Zooming-in for Astrophysics (THEZA). In response to the ESA's Call for White Papers for the long-term plan Voyage 2050, it was developed in 2019. A space-borne mm/sub-mm interferometric system that can image celestial radio sources with an angular resolution of a few microarcseconds is the idea. The THEZA White Paper presents the science case as well as a brief description of the engineering difficulties associated with such a mission and possible solutions to them. The primary goals of the THEZA concept are bolstered by the new scientific topics we discuss in this paper. In addition, we offer a number of novel engineering strategies that have the potential to bring the THEZA mission to life [2].

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A multipurpose astrophysical facility, THEZA, is a concept. The primary goals of its specifications are to enable investigation of the physics of space–time in the strong-field regime inaccessible by any other experimental method by supporting transformational studies of supermassive black holes (SMBH) with unprecedented angular resolution and sensitivity. However, as the THEZA White Paper demonstrates, the idea has numerous scientific applications, including population studies of active galactic nuclei, progenitors of gravitational wave events and other multi-messenger phenomena, stellar and planetary system formation, astrochemical studies, and the search for technosignatures. In this paper, we present a number of brand-new science cases that reflect the most recent developments and findings, while focusing on a few brand-new considerations for the mission architecture and necessary technologies. We note that many of THEZA's science goals are very similar to those of the Next Generation EHT or very similar to them [3].

Processing interferometric data necessitates precise knowledge of the THEZA telescopes' phase centers' velocities and accelerations, both absolute and relative. For terahertz frequencies, the baseline vector connecting the respective phase centers ought to be determined with a precision of the order of the wavelength. With the precise orbit determination methods and current tracking capabilities, this requirement is unattainable. However, as is well known from the practice of interferometry and VLBI in particular, processing of interferometric measurements makes it possible to alleviate this issue by searching for the interferometric response within wide enough windows of delay, delay rate, and occasionally delay acceleration. This makes it possible to relax the requirements for the precision of having an a priori knowledge of the baseline vector's velocity and acceleration, respectively. This processing is demanded more by the determination errors of larger baselines, and vice versa. In order to achieve precise orbit and baseline vector determination and subsequent time derivatives, a compromise must be made between advanced interferometric observation processing capabilities and methodologies [4].

Discussion

Using high-quality, dual-frequency Global Navigation Satellite Systems (GNSS) receivers allows for precise orbit determination of Low-Earth Orbiting (LEO) satellites (200–1500 km altitude) and Medium-Earth Orbiting (MEO) satellites (around km altitude). Using sophisticated dynamic force modeling and parameter estimation schemes, a precision level as good as 0.5 mm has been achieved post-facto for baselines around 200 km. Third-body perturbation (luni-solar and planetary ephemeris) and Earth's static and time-varying gravity field are typically included in the force modeling. Additionally, precise models or measurements of non-gravitational forces are required. Pressure from solar radiation and atmospheric drag at low altitude are the causes of these forces. They can be derived through precise modeling or directly from observations gathered by on-board accelerometers. The latter necessitates precise understanding of the satellite's geometry, surface properties (such as reflection), and attitude (such as can be derived from star camera observations). In addition, the precise location of the satellite's center of mass and the GNSS antenna's phase center must both be precisely characterized [5,6].

It is reasonable to assume that satellites in a THEZA constellation can also benefit from the current capabilities of precise orbit and baseline determination. However, careful consideration and investigation of a number of aspects is required. The tracking geometry is significantly different and less favorable for satellites flying above GNSS satellites than it is for LEO satellites. In addition, parameter estimation schemes typically include so-called integer phase cycle ambiguity fixing for the best possible baseline determination. This technique has proven to be effective for relatively short baselines up to a few hundreds of kilometres for the controlled GRACE tandem, but it is challenging for longer baselines as well as for more dynamic baselines, such as those between the lower and higher flying Swarm satellites [7-10].

Conclusion

The THEZA concept presented in this paper modifies the science objectives of the ESA Voyage 2050 White Paper [10] by addressing a diverse set of scientific goals. The creation of an interferometry facility that is capable of sharpening angular resolution in imaging observations by at least an order of magnitude compared to the best parameters achieved in Earth-based EHT and Space VLBI RadioAstron observations is the primary objective of the concept. The primary target specifications of the concept are defined by studies of photon rings around supermassive black holes, a specific science case: a 10–15 m-diameter interferometer with an angular resolution of approximately 1 as, observing frequencies between 220 GHz and 1.2 THz. Regardless of whether the angular resolution, VLBI baseline, or observing wavelength are increased or decreased, this paper argues that placing interferometer elements in space is the only way to achieve the concept's goal. We believe that a space-borne interferometry system like the one described in this paper is a necessary next step in the development of observational astrophysics for the following reasons: sooner or later, a system comparable to the THEZA conceptual three-element space-borne interferometer will come to pass. In creating an operational space-borne sub-millimetre interferometer, we also addressed some, if not all, engineering difficulties. We specifically argued in favor of large telescope assembly in orbit. In addition, we gave brief synopses of the current state of the receivers, heterodyning and synchronization subsystems, baseline vector estimates, and digital data handling and processing subsystems that make up the THEZA concept. All of the points made should be thought of as possible starting points for more in-depth engineering studies in the future.

Acknowledgement

None.

Conflict of Interest

None.

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