

# Space VLBI 2020: Science and Technology Futures Conference Summary<sup>†</sup>

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## 1 Introduction

The “Space VLBI 2020: Science and Technology Futures” meeting was the second in The Future of High-Resolution Radio Interferometry in Space series. The first meeting (2018 September 5–6; Noordwijk, the Netherlands) focused on the full range of science applications possible for very long baseline interferometry (VLBI) with space-based antennas. Accordingly, the observing frequencies (wavelengths) considered ranged from below 1 MHz ( $> 300$  m) to above 300 GHz ( $< 1$  mm). For this second meeting, the focus was narrowed to mission concepts and the supporting technologies to enable the highest angular resolution observations at frequencies of 30 GHz and higher ( $< 1$  cm).

This narrowing of focus was driven by both scientific and technical considerations. First, results from the RadioAstron mission and the Event Horizon Telescope (EHT) have generated considerable excitement for studying the inner portions of black hole (BH) accretion disks and jets and testing elements of the General Theory of Relativity (GR). Second, the technologies and requirements involved in space-based VLBI differ considerably between 100 MHz and 100 GHz; a related consideration is that there are a number of existing instruments or mission concepts for frequencies of approximately 100 MHz and below, while it has been some time since attention has been devoted to space VLBI at frequencies above 10 GHz.

This conference summary attempts to capture elements of presentations and discussions that occurred.<sup>1</sup> While every effort has been made to summarize material from the formal presentations,

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<sup>1</sup> Presentations are available at

<http://www.cvent.com/events/space-vlbi-2020/agenda-c7b30de0068e454591a66e5639f86668.aspx>.



the structure of the meeting included a number of discussion sessions and a poster session, and not all discussions or material from those sessions may be included here. (Appendix A shows the workshop schedule.)

For reference, standard nomenclature is used for orbits, namely low-Earth orbit (LEO) having altitudes of no more than about 2000 km and orbital periods of approximately 90 min., medium-Earth orbit (MEO) having altitudes of order 10 000 km and orbital periods ranging from a few hours to more than 10 hr, and geosynchronous orbit (GEO) having altitudes of approximately 35 000 km and orbital periods of just under 24 hr. Unless otherwise noted, L2 refers to the Earth-Sun Lagrange 2 point, exterior to the Earth’s orbit.

## 2 Science Motivations

This meeting began with a review of the topics covered at the first meeting. Historically, one of the strong drivers for VLBI has been a “cosmic conspiracy.” In order to reach the limiting brightness temperature for an incoherent synchrotron source ( $10^{12}$  K), an interferometric baseline of order the Earth diameter ( $\sim 10^4$  km) is required (assuming a source flux density  $S \sim 0.5$  Jy at a redshift  $z \sim 1$ ). A notable result from RadioAstron, referenced by multiple speakers, is the detection of a number of sources with brightness temperatures (well) above the  $10^{12}$  K value expected for an incoherent synchrotron source (e.g., Kovalev et al., 2016). The presence of such compact sub-components within sources suggests additional physics is needed, such as coherent emission or highly relativistic beamed emission.

Subsequently, though, a number of drivers for long baselines, including extending to space, have emerged. Broadly, these drivers have three classes, “classical” drivers (e.g., study of jets, extragalactic masers, astrometry), “emerging” drivers (e.g., localization of fast radio bursts [FRBs] or electromagnetic counterparts to gravitational wave events), and “discovery science” (of sources yet to be identified).

The focus of this workshop was motivated by recent successes in imaging a BH’s event horizon and the subsequent questions that it has raised: The role of magnetic fields in launching and collimating relativistic jets remains uncertain; increasing the sample of targets beyond Sgr A\* and M87\* potentially would allow for population studies; and it may be possible to test theories of gravity beyond GR by high-fidelity imaging of a BH’s “photon ring.”

The scientific benefit of being able to measure precisely the diameter of a BH’s “photon ring” was discussed by multiple speakers. The photon ring marks the region where photons circle the BH one or more times before escaping to the observer; in actuality, there are a series of photon rings, progressively thinner and dimmer approaching the event horizon marking where photons circle once, twice, thrice, and so on. For a non-spinning BH of mass  $M$ , the photon ring radius is

$$r_p = \frac{3GM}{c^2} = \frac{3}{2}r_g, \quad (1)$$

where  $G$  is the Newtonian constant of gravitation,  $c$  is the speed of light, and  $r_g$  is the gravitational or Schwarzschild radius. For a spinning BH, the intensity of the photon ring becomes highly asymmetrical, raising the possibility that the BH spin could be measured from the shape of its photon ring.

Speakers described how photon rings could be used as cosmic rulers and potentially would enable precision tests of GR. A potential confounding aspect of these measurements is that one would need to be able to distinguish effects due to the astrophysics of the accretion flow and effects due to the theory of gravity. Discriminating between these effects might be difficult because the assumed theory of gravity could affect the accretion flow in turn affecting the appearance of the photon ring.

The current EHT results achieved approximately 10% precision on the measurement of the M87\* photon ring. Obtaining much higher angular resolution than did the EHT (e.g.,  $10\times$  improvement) would increase dramatically the population of BHs for which photon rings might be measurable, both by increasing the volume and by being able to measure much lower masses (e.g., M31\*).

A topic noted, though not discussed at length, is how to present photon ring measurements. While photon rings have a distinctive signature in the visibility domain (Fourier or  $u$ - $v$  plane), neither the larger astronomical community nor the general public is accustomed to thinking in the visibility domain.

Jets are ubiquitous structures, observed from pre-main sequence stars to supermassive BHs (SMBHs). A continuing question is whether the jets launched from the immediate environments of BHs are powered by the Blandford-Znajek or the Blandford-Payne mechanism and what aspect of the accretion flow or the BH itself determines the mechanism.

Numerous speakers referred to the advances made possible by the high angular resolution obtained by RadioAstron for probing the inner structures of jets. Some RadioAstron observations are consistent with a frequency-dependent jet structure (limb-brightened at 1.6 GHz, centrally brightened “spine” at 5 GHz). However, it is also clear that the innermost structures remain optically thick, even at frequencies as high as 22 GHz and higher frequency observations are required to probe closer to the central engine.

Various speakers discussed how to probe GR by imaging the innermost portion of the accretion flow, near the innermost stable circular orbit (ISCO). The time domain behavior of an image could be a powerful means of determining properties of the inner accretion flow or the BH or both, particularly if material plunging into the BH can be identified, from which tests of GR could be conducted.

The importance of fully polarized observations (Stokes I, Q, U, V) for characterizing the inner portions of the accretion flow and the magnetic field in the disc was stressed by multiple speakers. General Relativistic-magnetohydrodynamic (GRMHD) simulations are being developed by multiple groups, with radiative transfer then used to predict what an observer at infinity would observe. One potential complication of interpretation is that the GRMHD simulations are typically only for protons (ions), whereas the radio emission is generated by electrons. Differences in temperature

between the electrons and protons, and how to include those differences in the modeling, likely introduces ambiguities in the predictions.

These various drivers may lead to two different sets of requirements for any future mission concept. Some of these science questions would favor (much) higher angular resolution, requiring longer interferometric baselines, while others would require higher imaging fidelity, which could be achieved by exploiting orbital dynamics to obtain rapid filling of the (Fourier) visibility plane.

There was limited discussion of multi-wavelength and multi-messenger astronomy opportunities from BH imaging, but one exciting possibility involves nanohertz gravitational waves, such as being sought by the North American Nanohertz Observatory for Gravitational Wave Astronomy (NANOGrav). A direct example of multi-messenger astronomy would be to image a SMBH binary that had been identified by NANOGrav as a gravitational wave emitter. Alternate possibilities include discriminating between potential candidate gravitational wave emitters and providing potential targets for NANOGrav. More generally, the formation of a binary SMBH requires some amount of interaction with its environment to “harden” the binary to the point at which gravitational waves begin to extract sufficient energy from the system that a future merger is inevitable. While the binary SMBHs that NANOGrav detects are too far from merger to be relevant for the planned Laser Interferometer Space Antenna (LISA) mission, the detection of binary SMBHs will provide information about merger rates and potential constraints on the nature of their interactions with their environments (e.g., stars vs. gas).

The International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF) are critical infrastructure for both astronomy and larger society, e.g., global navigation satellite systems (GNSS) such as the Global Positioning System (GPS) depend upon precise reference frames in order to obtain accurate and precise locations on the Earth. Structures of astronomical sources used to define reference frames is a recognized potential systematic, particularly if they change with time. As such, merely increasing the number of sources  $N$  used in defining a reference frame may not improve its precision as  $\sqrt{N}$  because systematic errors would increasingly limit the reference frame. Multiple speakers noted that sub-structure was found by RadioAstron and that a future space VLBI mission could provide information about source structure that in turn could be used to improve modeling of sources used for defining reference frames.

For reference the two prior space VLBI missions, the VLBI Space Observatory Programme (VSOP)/Highly Advanced Laboratory for Communications and Astronomy (HALCA) and RadioAstron, were reviewed (Figure 1). The intent was to provide a summary of both the scientific results and the “lessons learned” from these missions. Not covered during the meeting, but of importance for the initial demonstrations of the feasibility of space VLBI, were a series of observations using a Tracking and Data Relay Satellite System (TDRSS) antenna as the orbiting component of a VLBI array (Levy et al., 1986, 1989; Linfield et al., 1989, 1990).

The VSOP/HALCA mission (1997–2005) was formally an engineering demonstration mission designed to conduct a number of tests (Hirabayashi, 1991), including the deployment and use of an antenna, demonstrating pointing accuracy, and the supply of frequency signal with sufficient precision to the spacecraft. The spacecraft carried an 8 m-diameter deployable antenna, on an orbit that took it to an apogee of 22 500 km, obtaining angular resolutions of 0.75 mas at 1.6 GHz and 0.25 mas at 5 GHz. Initial results from HALCA have confirmed the presence of multiple AGN having brightness temperatures in excess of the  $10^{12}$  K limit, and re-analysis of the data have shown that AGN jets can be traced to as close as  $300 r_g$  of the SMBH. Further, there are continuing efforts to make the data more accessible. One cautionary aspect of the discussion was that, while HALCA had many notable results, there was concern about the relatively small number of refereed journal publications that were produced and that the angular resolution obtained were lower than what

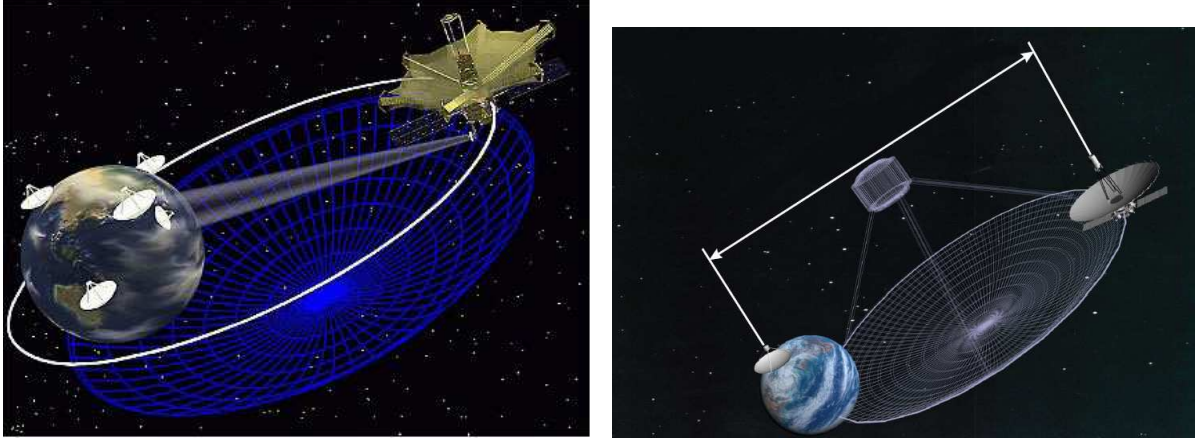


Figure 1: (*left*) VLBI Space Observatory Programme (VSOP)/Highly Advanced Laboratory for Communications and Astronomy (HALCA) (Courtesy of JAXA); (*right*) RadioAstron (Courtesy of Roscosmos).

has been obtained in subsequent millimeter-wavelength VLBI.

Following HALCA was to be the ASTRO-G mission, also known as VSOP2. Its objectives were to obtain a factor of 10 improvement in sensitivity, angular resolution, and highest frequency of observation. It would have consisted of a spacecraft carrying a 10 m-diameter antenna and cryogenic ally-cooled receivers on an orbit with an apogee of 30 000 km. It would have observed at frequencies of 8 GHz, 22 GHz, and 43 GHz, obtaining resolutions of  $260 \mu\text{as}$ ,  $9 \mu\text{as}$ , and  $5 \mu\text{as}$ , respectively. However, the level of technology development required resulted in schedule delays and cost growth, and the eventual termination of the project.

The RadioAstron mission (Kardashev et al., 2013) consisted of a space-borne 10 m diameter antenna equipped with receiving systems at 0.3 GHz, 1.6 GHz, and 22 GHz (as well as a non-operational 5 GHz system). In conjunction with ground-based antennas, it obtained angular resolutions as high as  $8 \mu\text{as}$ , due to its high apogee of 350,000 km. The science mission consisted of observations of active galactic nuclei (AGN), masers, and pulsars, with multiple speakers presenting results from different projects.<sup>2</sup> One of its prime objectives was to test for the presence of AGN having brightness temperatures in excess of the incoherent synchrotron limit, as discussed above. The distribution of AGN brightness temperatures does extend above this limit, with some sources having brightness temperatures up to  $10^{14}$  K.

Among other results from RadioAstron are that linear polarization observations could be conducted when the satellite was close to periastron. As noted above, polarization measurements are essential to characterizing the magnetic field, and the detection of and subsequent study of polarized emission on the sub-milliarcsecond scales was an expected result from RadioAstron. Observations of pulsars revealed complex sub-structure in images, consistent with interstellar scattering along the line of sight. Finally, with the deployment of km-scale neutrino detectors, it was discovered that AGN that are particularly bright to RadioAstron are also potential neutrino sources.

<sup>2</sup>A comprehensive list of publications from the RadioAstron mission is at <http://www.asc.rssi.ru/radioastron/publications/publ.html>.



### 3 Technology Drivers and Readiness

The meeting surveyed the state of technology development and readiness for future space VLBI missions. This survey was wide ranging, from the receiving antenna to the data reception on the ground, and a conclusion of the meeting was that advancing some technologies would be of general use to any future mission while the advancement of other technologies would only be relevant for a limited set of mission concepts (Table 1).

Table 1: Space VLBI Technology Classification

Likely Mission Agnostic	Likely Mission Specific
Sampling & Digital Processing	Antenna (size, frequency)
Data Transmission	Receiver (bands, cooling)
Time & Frequency References	Orbit Design & Orbit Determination (precision)
	Data Analysis (imaging, modeling, polarization)

Various speakers noted that the likely time scale for the development and qualification of a new component is plausibly a decade. However, a tentative consensus from the workshop is that, while there are likely to be challenges with some aspects of technology, many technologies needed for at least some kinds of space VLBI missions are reasonably mature or will be matured in various technology demonstration missions over the next few years. (“No unobtainium appears required.”)

The following provides a brief summary of various points discussed. It is intended to be illustrative of the range of topics, but there are undoubtedly other aspects of potential mission concepts that were not discussed at length. Most notably, there was little discussion of what ground data processing (including, but perhaps not limited to imaging) would be required.

**Antenna** Both HALCA and RadioAstron used deployable antennas, and Millimetron (§4) is planning to do so, while sub-millimeter wavelength missions have used monolithic antennas. None of the space VLBI deployable antennas have been required to operate above 25 GHz. Antennas with diameters up to 20 m and highest operating frequencies up to 30 GHz are feasible. Some capabilities for deployable antennas up to 50 GHz have been demonstrated, and there is initial testing of antennas operating up to 110 GHz.

**Receivers** Presentations and posters described technologies for receivers. New low-noise amplifier (LNA) technology, based on kinetic inductance detectors (KIDs), are being developed for millimeter-wave paramplifiers, for both ground- and space applications. New receiving systems are being developed and deployed to telescopes around the world, telescopes that could potentially serve as members of a ground telescope network to complement space-based antennas. These telescopes included the Atacama Pathfinder Experiment (APEX) and those in the Korean VLBI Network (KVN), among others.

**Frequency Standards and Clocks** Frequency stability and time transfer are critical elements of any VLBI array in order to ensure accurate correlation. For mission concepts involving a combination of space- and ground-based antennas, the space-based antennas will be moving at (much) higher velocities relative to the ground-based antennas and potentially through a varying gravitational potential. Maintaining the environmental stability (e.g., temperature) for a space-based clock is likely to be more resource demanding relative to a ground-based clock. Further, the requirements for VLBI may lead to requirements on space clock stability on time scales that are shorter than many other applications. The RadioAstron mission demonstrated the use of a space-based hydrogen maser, and there are a number of new clock

developments occurring, such as the Deep Space Atomic Clock (DSAC), and developments in sub-nanosecond time transfer accuracy that will likely be promising for future space VLBI.

**Orbit Determination** Just as for ground-based VLBI arrays, space-based antenna positions must be constrained prior to correlation so as to avoid excessive searching in phase delay or rate. For a space-based antenna, position determination becomes a problem in orbit determination because of the (high) orbital velocities involved. For instance, an antenna in LEO (velocity  $\approx 7 \text{ km s}^{-1}$ ) travels a distance of 1 mm (equivalent observing frequency = 300 GHz) in 140 ns. State-of-the-art orbit determination for single satellites located below GNSS constellations is at the centimeter level for absolute measurements and at the millimeter level for relative measurements between two spacecraft. The highest (relative) precision obtained is likely to be between the two GRACE-FO spacecraft (relative separation  $\approx 200 \text{ km}$ ), which can be of order  $1 \mu\text{m}$ . There is considerably less experience with spacecraft above the GNSS constellations, with the possible exception of the lunar-orbiting dual spacecraft Gravity Recovery And Interior Laboratory (GRAIL) mission. Judgments by workshop participants suggest that orbit determination above the GNSS constellations is likely to be at least an order of magnitude worse, at least in the near term, as compared to that below GNSS constellations.

**Data Transfer** Data rates for ground-based VLBI are routinely in the 2 Gbps regime and the EHT has achieved rates of 64 Gbps. Ground-based VLBI data rates are being achieved currently, by the European Data Relay Service (1.8 Gbps) and, soon, by NASA-India Space Research Organization (ISRO) Synthetic Aperture Radar (NISAR) mission (up to 4 Gbps). Over the next few years, technical demonstration missions are planned that should achieve as high as 100 Gbps from GEO, typically by using laser (optical) communications. All other things being equal, data rates scale as  $R^{-2}$  for a range  $R$ .

## 4 Mission Concepts

The Millimetron mission concept involves a 10 m deployable and cooled sub-mm and far-IR telescope. Placed into an orbit around the Earth-Sun L2 point, it will conduct VLBI observations at wavelengths of 0.8 mm to 3 mm (350 GHz to 100 GHz) and single dish observations to wavelengths as short as  $80 \mu\text{m}$ . The antenna will be cooled for the first three years of the expected 10 year science operations duration of the mission. The concept is in a Phase A study, funded by the Russian Space Agency.

The deployable antenna is made of a series of panels. The panel production process has been qualified, with a substantial reduction in areal mass density having been achieved relative to many previous and current sub-mm and far-IR missions, and panel production is beginning. The antenna itself is considered to be in Phase B. Development of instruments is under discussion, including with international partners, but space VLBI receivers are planned to be part of the instrument package. The planned recording rate on-board the spacecraft is 2 Gbps for four channels, for a total rate up to 16 Gbps, but the downlink data rate is only 1.6 Gbps.

For future missions, two general architectures were discussed. In one architecture, one or more orbiting antennas have relatively low orbits (from LEO to MEO). The objective of such an architecture is to obtain higher imaging fidelity, potentially on more rapid time scales, in order to track dynamic changes in the inner accretion disk and jet. This approach would be most beneficial for lower-mass BHs (e.g., Sgr A\*), for which time scales are typically minutes to days. If there are two or more orbiting antennas, it may be possible to realize an entirely space-based array, with

no dependency on any ground-based telescopes. Such a space-based array could also operate at frequencies at which the atmosphere is largely or essentially opaque ( $> 600$  GHz).

In the second mission architecture, a single antenna is at a large distance from the Earth (e.g., Earth-Moon L2 or Earth-Sun L2). The objective of such an architecture is to obtain extreme angular resolutions, in combination with ground-based telescopes, in order to measure the characteristics of the “photon rings” for a large number of SMBHs. Some estimates for the number of SMBHs for which the “photon ring” characteristics could be measured were as high as  $10^4$  objects.

There was also discussion of a mixed architecture in which an orbiting antenna was placed on a highly eccentric orbit. During most of its orbit, it would be at a large distance from the Earth so as to obtain an extreme angular resolution while, for a short portion of the orbit, its rapid orbital motion covers the (Fourier) visibility plane rapidly in order to improve image fidelity.

Both HALCA and RadioAstron had significant international partnerships. The U.S. Space VLBI Project supported U.S. community engagement with both HALCA and RadioAstron, though RadioAstron launched after the termination of the project. Key “lessons learned” from the U.S. Space VLBI Project include

- A project can have non-scientific motivations. The U.S. Space VLBI Project was motivated partially by high-level U.S. Government desire to improve relations between the U.S. and the then Soviet Union.
- At least in the U.S., prior to a formal project, there is often a pre-project phase, and this series of meetings could be considered an example of a pre-project activity.
- The Project had a memorandum series, some of the analysis reported in those memoranda may be of value in developing future missions, and there was interest expressed in having those memoranda being available publicly.
- Over-optimism about technology maturity can lead to cost overruns, which can lead to severe stress or even mission cancellation.
- Debates about whether resolution or image quality are the most important factor can be acrimonious.
- It is important to have and adhere to a clear message regarding the science and technology in order to obtain high-level support, from both the science community and management (at institutes and within space agencies).
- It is important to discuss the distribution of science benefits among mission partners.
- The existence of an international science council (e.g., the RadioAstron International Science Council [RISC]) is important in obtaining long-term and broad engagement.
- Establishing an early agreement by ground-based radio telescopes, if they are to enable the mission’s science, is critical. There was some discussion that, prior to the establishment of the VLBA, the science case for space VLBI may have been perceived as weak.
- Next-generation missions need to have fewer constraints imposed by the spacecraft or operations in order to obtain better science.

Two ground-based telescopes of relevance for future space-based VLBI are the Atacama Large Millimeter/submillimeter Array (ALMA) and the next-generation Very Large Array (ngVLA). Due to the addition of phasing capabilities (Matthews et al., 2018), ALMA was already an integral part



of the initial EHT results on M87\*, and it is now part of the Global mm VLBI Network (GMVA) and the EHT. ALMA has developed a development roadmap to 2030 (Carpenter et al., 2020), and an on-going project to improve its capability involves improving the capabilities to include (i) Spectral line VLBI; (ii) Extending the frequency range of the current phasing mode to Bands 1–7; (iii) Improving the calibration to enable observations of weaker sources; and (iv) Single-dish mode and pulsar modes.

The ngVLA is a concept for a North American-based telescope operating between approximately 1 GHz and 120 GHz (Murphy et al., 2018), and it would be a clear complement to any future space-based VLBI system operating below 100 GHz. Its design includes antennas across North America for trans-continental VLBI and a phasing mode for pulsar observations.

## 5 Future Steps

Any future mission will require a compelling science case, and continued millimeter-wave VLBI on the ground will be an essential aspect of building that science case. Notably future EHT observations, particularly of Sgr A\*, could help motivate whether a mission to achieve high image fidelity or extreme angular resolution is more compelling.

A number of technology advances are likely to occur in the near term, with motivations separate from space VLBI, but from which a space VLBI mission would benefit. The DSAC technical demonstration mission was noted above, but there also are a number of technical demonstrations of laser (optical) communications to achieve higher data rates. Monitoring of these technical developments, potentially complemented by proposals for targeted technical developments in other areas relevant to a space VLBI mission, is warranted. There was also substantial discussion of potential pathfinder missions, in order to prove out technologies, and discussions about the extent to which (long-duration) balloons would be able to contribute either to the technology development or even science observations.

At various times during the meeting, the extent to which the participants adequately represented the diversity of the astronomical community was questioned. In some potential axes of diversity, there was broad representation, but other axes were quite narrow.

Finally, there was general agreement that a third meeting in the series should occur, likely in the latter half of 2021.<sup>3</sup> On that time scale, a number of events should occur including future maturation of the Millimetron concept, new results from the EHT including on Sgr A\*, and the U.S. Decadal Survey report. With those developments, it may be possible to identify a concrete next step for a future space VLBI mission.

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<sup>3</sup> This conclusion is likely to have to be revisited in light of the novel coronavirus pandemic.

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# A Workshop Schedule

Tuesday, January 28, 2020				
7:30 AM	9:00 AM	Registration		1:00
8:45 AM	9:00 AM	Welcome		0:15
		Science Motivation	Session Chair: Anton Zensus	
9:00 AM	9:40 AM	The Future of High-Resolution Radio Interferometry in Space	L. Gurvits & V. Fish	0:40
9:40 AM	10:00 AM	Mapping Spacetimes with Horizon-scale Imaging	A. Broderick	0:20
10:00 AM	10:20 AM	The Sharpest View of Blazar Jets with Space VLBI	J. Gomez	0:20
10:20 AM	10:50 AM	Break		0:30
10:50 AM	11:30 AM	Ergomagnetospheres, Ejection Disks and Relativistic Jets	R. Blandford	0:40
11:30 AM	11:50 AM	Black Hole Science with Extremely Long Baseline Interferometry	D. Pesce	0:20
11:50 AM	12:10 PM	Measuring Black Hole Spin with Time-domain VLBI Observations of Infalling Gas Clouds	K. Moriyama	0:20
12:10 PM	12:30 PM	Multi-messenger Astronomy with Space mm VLBI	V. Ravi	0:20
12:30 PM	2:00 PM	Lunch (90 min)		1:30
		Science Motivation con't	Session Chair: Shep Doeleman	
2:00 PM	2:20 PM	Simulations of VLBI Observations of Black Holes and Jets from Space	F. Roelofs	0:20
2:20 PM	2:40 PM	Polarization Imaging of M87 Jets by General Relativistic Radiative Transfer Calculation Based On GRMHD Simulations	Y. Tsunetoe	0:20
2:40 PM	3:00 PM	The Need of Space VLBI for the Space Geodesy Program	L. Petrov	0:20
3:00 PM	3:40 PM	Discussion Topic: Space vs. Ground		0:40
3:40 PM	4:10 PM	Break		0:30
4:10 PM	4:50 PM	VSOP-1 (HALCA) Project	Y. Murata	0:40
4:50 PM	5:30 PM	The Space VLBI Mission RadioAstron: Overview and Results	Y. Kovalev	0:40
5:30 PM	5:35 PM	Poster Flash (5 min)		0:05
5:35 PM	6:35 PM	Reception		1:00

Wednesday, January 29, 2020				
		Session: Technology Drivers	Session Chair: Katie Bouman	
9:00 AM	9:40 AM	Technical Developments for Millimetron Space Observatory	A. Baryshev	0:40
9:40 AM	10:20 AM	Instrumentation Status for Space VLBI with the Event Horizon Telescope	K. Haworth & A. Raymond	0:40
10:20 AM	10:50 AM	Break		0:30
10:50 AM	11:10 AM	Recent Results in Millimeter (mmW) Performance of Mesh for Space Reflectors	S. Ortiz	0:20
11:10 AM	11:30 AM	Wideband Superconducting Parametric Amplifiers for Microwave and Millimeter Wavelengths	P. Day	0:20
11:30 AM	11:50 AM	APEX SEPIA345: a New Generation Receiver for EHT	V. Belitsky	0:20
11:50 AM	12:10 PM	Interferometric Imaging at Extreme Baselines and Spatial Frequencies	A. Zensus	0:20
12:10 PM	12:20 PM	Conference Photo		0:10
12:20 PM	1:50 PM	Lunch (90 min)		1:30
		Session: Technology Drivers con't	Session Chair: Walter Briskin	
1:50 PM	2:20 PM	Fundamental Physics of Moving Clock Time Synchronization in a Weak Gravitational Field	S. Wilkinson	0:30
2:20 PM	3:00 PM	Precise Satellite Orbit and Baseline Determination: Status and Outlook	P. Visser	0:40
3:00 PM	3:30 PM	Break		0:30
3:30 PM	3:50 PM	Mission Optimization: From Science Goals to Orbit Selection	D. Palumbo	0:20
3:50 PM	4:10 PM	Incoherent Clocking and Potential Applicability to Space VLBI	B. Carlson	0:20
4:10 PM	5:10 PM	Discussion Topic: Common Requirements and Technology Developments?		1:00
6:00 PM	9:00 PM	Conference Dinner		3:00

Thursday, January 30, 2020				
		Session: Technology Drivers and Mission Concepts	Session Chair: Joseph Lazio	
9:00 AM	9:40 AM	The Future of ALMA	I. Cleeves	0:40
9:40 AM	10:00 AM	Progress in the Event Horizon Imager Mission Concept	M. Martin-Neira	0:20
10:00 AM	10:20 AM	MicroArc Second Astrometry with Multi-Beam Space VLBI	M. Eubanks	0:20
10:20 AM	10:50 AM	Break		0:30
10:50 AM	11:10 AM	The U.S. Space VLBI Program	D. Murphy	0:20
11:10 AM	11:30 AM	Expanding the Event Horizon Telescope into a MEO/GEO-sized Imaging Array	K. Akiyama	0:20
11:30 AM	11:50 AM	Two Options for Space VLBI Telescope Orbit: LEO and GEO	Y. Asaki	0:20
11:50 AM	12:10 PM	A Proposal of Space Terahertz Intensity Interferometry	H. Matsuo	0:20
12:10 PM	1:40 PM	Lunch (90 min)		1:40
		Session: Technology Drivers and Mission Concepts, con't	Session Chair: Tony Beasley	
1:40 PM	2:20 PM	Space VLBI in the ngVLA Era	E. Murphy	0:40
2:20 PM	3:20 PM	Discussion Topic: Mission Architecture - One Big Space Antenna vs. Many Small Antennas?		1:00
3:20 PM	3:30 PM	Concluding Remarks		0:10