Space VLBI Astronomy: Current Status and Future Prospects

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Abstract

Space VLBI (Very Long Baseline Interferometry) is an earth-space radio interferometry that consists of ground-based radio telescopes and one or multiple spacecrafts with a radio telescope orbiting around our Earth, which would provide high spatial resolution enabled by ground-space baselines extended to several times the diameter of the Earth. Given the extremely high spatial resolution down on scales of ~ 1-100 microarcseconds, space VLBI will enable us to study details of astronomical objects, such as relativistic jets from active galactic nuclei (AGN), environments of massive black holes, gravitational lenses, cosmology, star-forming sites, and high-precision astrometry. In this article, after a brief description of the early days of space VLBI, I focus on the two Japanese space VLBI projects of VSOP and VSOP-2 and comment on future prospects of space VLBI from my own view points.

Keywords：Radio astronomy, VLBI, active galaxies, active galactic nuclei (AGN)

1 Introduction

Space VLBI (Very Long Baseline Interferometry) is a radio interferometry that combines ground-based radio telescopes and one or multiple spacecrafts with a radio telescope in orbit around our earth, which would provide higher angular resolution that cannot be obtained from ground-based VLBI having solely intercontinental baselines. Ideas of space VLBI were first discussed at the IAU symposium in 1984 [2] in order to realize VLBI having baselines in excess of the diameter of the earth with a main purpose of resolving structures of compact radio sources with high brightness temperature. Since VLBI sensitivity, resolution, and image quality have been greatly improved after the first VLBI experiments in 1967, astronomers discussed about interpretation of images of Galactic and extragalactic compact sources like pulsars, nuclei and jets of quasars, and cosmic masers, obtained by VLBI. A concern about quasars with brightness tem-

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perature (T_b) of the 10^{12} kelvins (K) inverse Compton limit [9] was one of the key issues to be resolved by longer baselines, which had motivated a successful space VLBI experiment.

2 Early days of Space VLBI

Past and current space VLBI projects, including those which were not realized, are listed in Table 1, in which three projects have been realized while others have never been realized to date and one of them was terminated in the middle of its development phase. An original concept of QUASAT was studied at JPL, and proposed to an ESA-NASA joint mission in 1982. In the project, a spacecraft with a 15 m class radio telescope operational at 0.3, 1.6, 5, and 22 GHz was based, aiming at the highest angular resolution of 40 microarcseconds at 22 GHz [12]. The project competed with the ESA planetary mission, Cassini project with the Huygens probe, and the QUASAT lost in the competition and faded out.

Space VLBI experiments were first curried out in July and August 1986 by use of TDRSS (Transfer and Data Relay Satellite System) without launching a new radio telescope in orbit. The successful fringes using a 4.9 m diameter antenna of TDRSS and 64 m ground radio telescopes at Usuda in Japan and Tidbinbilla in Australia were detected both at 2.29 GHz (1986) and 15 GHz (1988). The results of the successful observations of quasars were reported in literature [10]. The maximum baseline lengths for observing each source were dependent to source declination, resulted in from 0.94 to 2.15 earth diameters [7]. The observation of a quasar PKS 1519-273 indicated the brightness temperature of $\sim 9 \times 10^{12}$ K in excess of the Inverse-Compton limit. The success of the TDRSS operations demonstrated the feasibility of space VLBI and phase transfer techniques. RadioAstron was proposed by the Astro Space Center in the former Soviet Union in mid-1980s. The initial idea of Radioastron was that an orbiting telescope has a 10 m diameter reflector with apogee height of 8,000 km and it was being planned to be launched in 1990s. RadioAstron is described in later section.

It should be remarked that there were two other plans of space VLBI projects that are not included to Table 1: they are IVS (International VLBI Satellite) and ARISE (Advanced Radio Interferometry between Space and Earth) by JPL and NRAO (National Radio Astronomical Observatory, USA) [13], both of them have not reached to the stage of realization. It is interesting to note that four space VLBI missions in Table 1 have been approved, however one of which, VSOP-2 was terminated in its halfway and QUASAT was cancelled. That may imply the difficulties of carrying out a space VLBI project over a decade.

Table 1 : Overview of space VLBI projects

Project	Period	PI Institute	Frequency [GHz]	Apogee [km]	Comment
QUASAT	1982-1995	ESA(EU), JPL(USA)	0.3,1.6,5,22	50,000	cancelled
TDRSS	1986-1988	JPL	2.3,15	12,000	
VSOP	1997-2005	ISAS(Japan)	1.6,5,22	21,500	
VSOP-2	2007-2010	ISAS/JAXA(Japan)	8,22,43	25,000	terminated
RadioAstron	2011-	ASC(Russia)	0.3,1.6,5,22	320,000	
Millimetron	–	ASC	17 - 0.02 mm	1,500,000	L2 orbit

3 VSOP

The success of the TDRSS experiments from 1986 to 1988 motivated VLBI astronomers in the world to proceed a next space VLBI as early as they could: The VSOP (VLBI Space Observatory Programme) mission was led by a Japanese space agency, ISAS (Institute of Space and Astronautical Science) in Japan, in collaboration with international partners. The VSOP spacecraft (HALCA: Highly Advanced Laboratory for Communications and Astronomy) was successfully launched in February 1997 and deployed an 8 m diameter radio telescope in orbit [6]. The 8 m telescope operating at 5, 1.6, and 22 GHz was positioned in an elliptical orbit with an apogee height of 21,400 km and perigee of 560 km. VSOP has made a variety of radio continuum and spectral-line observations with promising scientific returns [5]. However, the 22 GHz band receiver seemed to be severely damaged due to vibration at launch and was not capable of scientific observations, as the result of which observations were mostly conducted at 1.6 and 5 GHz.

After the detection of the first fringes between HALCA and ground radio telescopes, HALCA had participated in over 780 space VLBI observations, resulted in a number of radio images, particularly on relativistic jets from active galactic nuclei and hydroxyl (OH) masers in star-forming sites. It is interesting to note that HALCA was originally designed as an engineering satellite including demonstration of technology for space-ground communication, deployment of a large antenna in orbit, and stable data-link from an orbiting satellite to ground tracking stations. For the success of VSOP, the importance of international collaboration, along with cooperation across 11 institutions in Japan, USA, and Australia, should be remarked. About 25 ground radio telescopes joined to the HALCA observations with ground tracking station facilities. (For more details about HALCA, please see the web pages: http://www.vsop.isas.jaxa.jp)

4 VSOP-2

Nearly at the end of the VSOP, a next generation space VLBI mission was considered, and a working group was formed to investigate the possibilities of a new mission that follows to HALCA-VSOP. At that time the new mission was simply named to be VSOP-2, with an expected launch after 2006. The VSOP-2 is capable of observations at a factor of 10 times higher frequencies, 10 times better sensitivity, and 10 times higher angular resolution than VSOP (Fig. 1), with phase-referencing capability to enhance imaging sensitivities of space baselines. In this mission, a spacecraft was designed to have a 9.2 m deployable antenna and cryogenically cooled receivers operational at 8, 22, and 43 GHz all in dual-polarization reception with apogee height of 25,000 km, yielding the angular resolution of 38 microarcseconds at 43 GHz (Table 2).

The primary science goal of the mission is to study innermost regions of active galactic nuclei (AGN) where relativistic jets (streams of ionized gas, or plasma) are ejected at the near vicinity of super massive black hole (SMBH) with masses of more than 10^6 $M_\odot$ to ~10^9 $M_\odot$ [4]. The giant elliptical galaxy in the Virgo cluster, M 87 is known as a key source for studying a putative accretion disc around a SMBH. By observing M 87 with the highest resolution enabled by the mission, it is expected that accretion discs or a part of the discs around SMBHs would be spatially resolved at millimeter wavelength. The goal also involves understanding physical mechanism of acceleration and collimation of the jets in terms of VLBI observations with near-contemporaneous observations of gamma-ray emission and magnetohydrodynamics numerical simulation. The 22 GHz water vapor megamasers that trace molecular gas discs around SMBH were important targets of the mission. Thus, the mission scientific merits were designed for exploring the AGN nuclear regions closer to SMBH.

After the internal scientific and technical reviews for the science missions of ISAS/JAXA, the VSOP-2 had been formally approved given the developmental name "Astro-G" in 2007, with a planned launch of 2012. The VSOP-2 team in Japan continued development of the spacecraft and also began to formulate international collaboration schemes followed by the successful coordination with overseas partners executed during VSOP.

Suddenly, in the middle of the development phase, some technical problems with the 9 m antenna (LDA: Large Deployable Antenna) were found, which is relevant to the surface accuracy of the antenna, particularly at the highest frequency band. Since the telescope sensitivities required for achieving mission science goals significantly depend on the antenna surface accuracy, those problems found in that phase must have been sorted out, advancing the next development phase. Immediately after that, in September 2009 the intensive working group for tackling the technical problems including those which remain unidentified in the project was formed in the VSOP-2 team in Japan. The goal of the team was to demonstrate the feasibility of the mission by focusing on the

Table 2 : Mission Specifications : VSOP, VSOP-2, and RadioAstron

Specification	VSOP	VSOP-2	RadioAstron
Antenna Diameter (m)	8	9.2	10
Apogee hight (km)	21500	25000	320000
Orbit period	7.5 hours	6.3 hours	11 days
Polarization	LCP[a]	LCP/RCP[a]	LCP/RCP
Data downlink rate	128 Mbps	1 Gbps	144 Mbps
Frequency (GHz)	1.6, 5, (22[b])	8, 22, 43	0.3,1.6,5,22
Highest angular resolution (microarcsecond)	360	38	7

a) LRC: Left Circular Polarization, RCP: Right Circular Polarization

b) After launch, the 22 GHz band receiver was found severely degraded for observations.

surface accuracy of LDA, required for carrying out the science goals of the mission. The team members worked very intensively on the problems and a number of technical challenges to be solved out.

Despite of their enormous efforts nearly for a year, it was concluded at internal ISAS committee (and JAXA at a later time) that the mission does not fulfill the technical feasibility required for achieving the critical science goals, such as imaging AGN accretion discs, whereas it was promised to the community prior to the mission selection processes. As a result, the project was determined to be terminated in December 2011 with the advice of re-starting a project by returning to the working group formation process. However, the reality is that since after the mission termination there has been proposed no actual space VLBI plan. One may wonder if the Japanese VLBI community would lead a mission once again, however, no one could find an answer to it as there has seen no move for proposing a new mission in the VLBI community of Japan.

5 RadioAstron

As mentioned in earlier section, RadioAstron project led by the Russian Astro Space Center (ASC) was originally being planned in 1980s. After several postponements over two decades, the project has been finally realized. RadioAstron was successfully launched and reached to orbit in June 2011 and already produced many radio image of quasars, pulsars, and cosmic masers [11]. RadioAstron contains a solid-panel 10 m diameter telescope operating up to 22 GHz, with an apogee altitude of 320,000 km, the angular resolution of which will be 7 microarcseconds at 22 GHz. The resolution is two or-

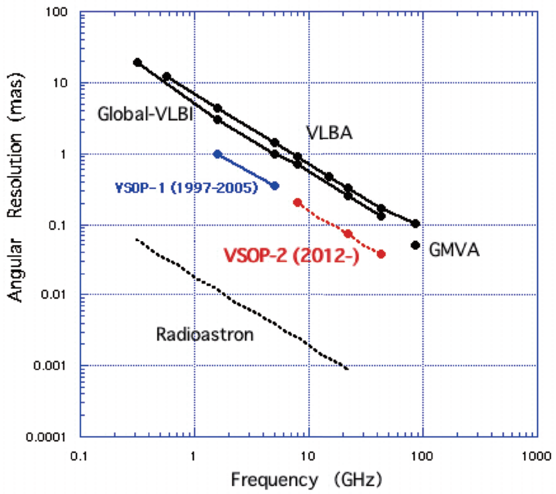

Fig. 1 : Angular resolution comparison of space VLBIs and existing ground-based VLBIs. VLBA stands for Very Long Baseline Array, operated by NRAO, and GMVA does for Global Millimeter VLBI Array, operated jointly by European VLBI Network (EVN) and NRAO. Horizontal axis denotes frequency in Gigahertz (GHz) and vertical axis is angular resolution in milliarcsecond (mas). Note that the GMVA observes only at 86 GHz (3 mm).

ders of magnitude better than VSOP achieved at 5 GHz (Fig. 1).

The mission is currently an only space VLBI project in orbit, and the mission has been supported by a number of international partners around the world. In Japan, the JAXA 64 m ground radio telescope at Usuda participates to RadioAstron observations. The main purpose of the mission is to resolve the ultra compact objects like quasars and pulsars for measuring source brightness temperatures and investigate the Inverse-Compton limit. Therefore, the mission is intended for measuring brightness temperatures of quasars and cosmic masers rather than "imaging" distant astronomical objects, which differentiates the mission purposes of VSOP-2. The observations of the quasar 3C 273 at 18 cm band resulted in measuring the brightness temperature of more than 10^{14} K, which cannot be explained only in terms of Doppler boosting [8]. So, they discuss possible interpretations by relativistic particle accelerations, coherent radiation from protons, and others [8]. More details can be found at the RadioAstron home page [11]. It is interesting to know that after the life time of RadioAstron the ASC plans Millimetron project aiming space VLBI observations at millimeter and sub-millimeter wavelength (Table 1).

6 Lessons-learned from VSOP-2

It is being recognized that since the launch of RadioAstron in 2011, no new space VLBI project has been approved. The launch period of the Millimetron project is not still certain. Since the termination of VSOP-2 in Japan, there has been no plan of space VLBI at ISAS/JAXA, which is due to not only technical problems of satellite development but seems to be rooted on a more fundamental problem in the Japanese VLBI community. The VLBI community in Japan is not strong enough to propose a project competitive to other space or planetary missions. For instance, the total number of VLBI astronomers in Japan would be estimated to at most one hundred, while that of high-energy astronomers or planetary scientists is maybe, at least, a factor of 5 larger than that of VLBI. Moreover, it is felt that consensus on continuing astronomical VLBI activities is not sufficiently well established in the radio astronomy community. It may be true that the VLBI community should have thoughts on involving wider science areas in order to obtain wider support for space VLBI.

As mentioned above, the VSOP project was approved as a technical experiment but not as a science mission for astronomy. In a sense, Japanese VLBI astronomers might have not yet succeeded in the approval of a space VLBI as a genuine science mission. To my thought, this is because science areas covered by VLBI are relatively so narrow that we cannot expect broarder supports from astronomers or scientists in other fields, although the science merits of space VLBI are as competitive as other astronomical missions.

One might think that this point is wrong, but even so, I would tell that space VLBI has disadvantage in that it requires enormous amount of resources, while we obtain less scientific returns than other space missions. Nevertheless, I believe that there still remain a number of scientific issues to be addressed only by space VLBI.

7 Future prospects

There are several existing radio telescope arrays or planned arrays that can address the same or similar sciences like space VLBI. In order to obtain optimum (u,v) coverage from space-ground baselines, it would be ideal to have multiple radio telescopes in orbits, which would provide better quality of images. It is clear that launching and operating multiple telescopes is very expensive, and that would require enormous infrastructure necessary for technical development and testing in which these telescopes can be built all the same time. If the operations of two different space VLBI projects with the same frequency band happen to be carried out in overlapping periods, the (u,v) coverage of images produced by these should be greatly improved. In fact, this was likely to happen around 2011, if the VSOP-2 and RadioAstron were both in orbits at a time. However, that did not come true as the former was terminated on its halfway as mentioned in earlier section.

Lastly, we have to admit a current situation in that there will be no space VLBI observatory after the life time of RadioAstron and there is no solid plan of a new space VLBI which is likely to be approved. Presently, sub-millimeter VLBI experiments are being conducted at mm wavelength and begin to produce radio images of nuclear regions of quasars (e.g.,[1]), although the resolution of which will not yet be competitive to mas or microarcsec resolution enabled by space VLBI. It is thus being felt that it is worth considering the next generation VLBI observatory by extending its baselines into space. Moreover, the participation of ALMA (Atakama Large (sub)-Millimeter Array) to the sub-millimeter VLBI array is expected to enhance the performance of the sub-millimeter VLBI, which might solve poorer sensitivity of VLBI observations [3].

8 Summary

I overviewed astronomical space VLBI missions in the past and at present. There have been proposed several space VLBI missions to date, however only three of which have been realized, and the rests are being postponed or cancelled or terminated. This may indicate the difficulties in continuing a space VLBI mission with patience over a decade. After the RadioAstron mission operation is completed, there would be no approved space VLBI project although there are ideas or plans in the international VLBI community.

Clearly, it is felt that long baseline lengths exceeding the earth diameter would be necessary to resolve the highly compact object like pulsars or the innermost part of AGN nearer to SMBH, so new thoughts on initiating a next generation space VLBI mission with competitive scientific purposes should be invented in near future among the international VLBI community.

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和文摘要

スペースVLBI天文学 — 現状と将来

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要旨

スペースVLBI（Very Long Baseline Interferometry）とは、地球上の電波望遠鏡と地球を周回する軌道上の電波望遠鏡から構成される地球サイズを超えた電波干渉計である。地球直径の数倍の基線長を実現することにより、非常に高い空間分解能による天体の観測が可能になる。スペースVLBIにより実現されうる1-100 マイクロ秒角台の空間分解能により、天体の詳細な構造を空間的に分解することができるようになる。研究の対象としては、活動銀河核から噴出するジェット、巨大ブラックホールの周辺領域、宇宙論、重力レンズ天体、星形成領域、などがあげられ、また高精度アストロメトリ観測も含まれる。本論文では、スペースVLBIの簡単な歴史の記述に始まり、過去の日本のスペースVLBI プロジェクトであるVSOPとVSOP-2 について述べた後、スペースVLBIに関する将来の見通しについての意見を、筆者自身の観点から述べる。

Keywords：電波天文学, VLBI, 活動銀河, 活動銀河核

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