PROCEEDINGS OF SCIENCE

The VSOP-2 (ASTRO-G) project

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Following the success of the first space VLBI mission, VSOP-1 (HALCA), with the contributions from European VLBI commnunity, Japanese group started the next project VSOP-2 (ASTRO-G). The ASTRO-G satellite can observe at 8, 22 and 43 GHz bands, and has the orbit of 25,000km apogee, 1,000km perigee, and the inclination of 31 degree, which can make image with about 40 micro arcsecond resolution at 43 GHz. Observational targets of ASTRO-G are the root of the jet in AGN, accretion disks around the black hole, astronomical jet, and masers in galaxies and starts. Current planned launch period is the begining of 2013 (within the Japanese fiscal year of 2012) with the H-IIA rocket.

Now the development of ASTRO-G is in phase-B, so-called the basic design phase, when we develop the rough design of each components on the satellite, and checking ASTRO-G will work as we expected, in the very special environment on the orbit. We can also get the system capability of ASTRO-G more precisely than that we expected in the initial phase of the project.

We also started the international activities such as the starting the VISC-2 (VSOP-2 International Science Council), and other international collaborations.

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1. introduction

Space VLBI was realized in 1997 as the first space VLBI project, VSOP (VLBI Space Observatory Program; we call VSOP-1)[1,2], after some preceding experiments and vast amounts of effort with the international colleages. The spacecraft for VSOP-1 is known as the first dedicated space VLBI satellite, HALCA. The angular resolution of VSOP-1 is 3 times better than that of ground-based VLBI at 1.6 and 5 GHz. About seven hundred observations were carried out in the mission lifetime of 7 years, and had the scientific outputs with its high resolution of Jets and lobe of AGN, high brightness temperature sources with survey observations, and so on.

Japanese group started the next project VSOP-2 (ASTRO-G). The ASTRO-G satellite has the observing bands of 8, 22 and 43 GHz. It has the orbit of 25,000km apogee, 1,000km perigee, and the inclination of 31 degree, which can make image with about 40 micro arcsecond resolution at 43 GHz. It is planned to be launched in the begining of 2013 with the Japanese H-IIA rocket. Figure 1 shows a schematic display of the ASTRO-G satellite observing with the ground VLBI network to support ASTRO-G and the ground tracking station to send the signal from the hydrogen maser and to receive the 1 Gbps VLBI data.

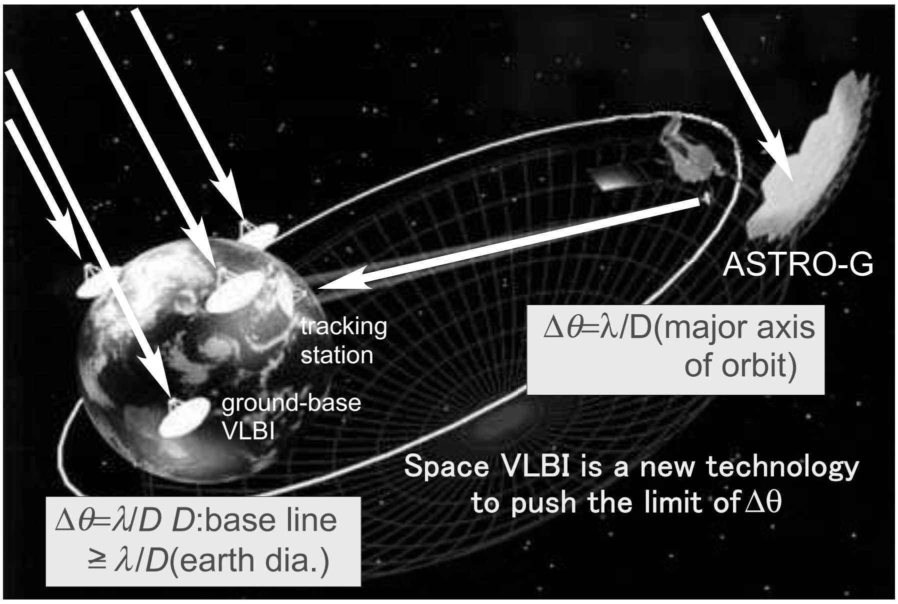

Figure 1: Schematic display of the comparison between space VLBI and ground-based VLBI.

2. The ASTRO-G satellite

The space radio telescope of ASTRO-G satellite is an offset Cassegrain-type telescope. Figure 2 shows an artist's drawing of the ASTRO-G satellite.[3,4] The observing frequency bands of the ASTRO-G satellite are 8(8.0 -8.8), 22 (20.6 -22.6), and 43 (41 - 45)GHz. The antenna consists of a 9.3-m paraboloid main reflector (Large Deployable Reflector, hereafter LDR), a hyperboloid sub-reflector, and three feed horns at 8, 22, 43 GHz. LDR has 7 hexagonal metal mesh-surface modules, which are deployed on the orbit. Each band has LHC and RHC polarizations, and has wider bandwidth to get the effective data for rotation measure observation. ASTRO-G has cooled mm-wave receivers by Stirling cycle refrigerator for 22 and 43 GHz bands, to get the better performance of the higher frequency bands. There are many large radio telescopes at 8 GHz in the world, being this frequency band used for down-link satellite communication from space research service, and geodesy VLBI observation, though this band is not allocated for the radio astronomy service. The 22 and 43 GHz bands involve H_2O ($\nu = 22.235$ GHz) and SiO ($\nu = 43.122$ and 42.820 GHz) masers, respectively.

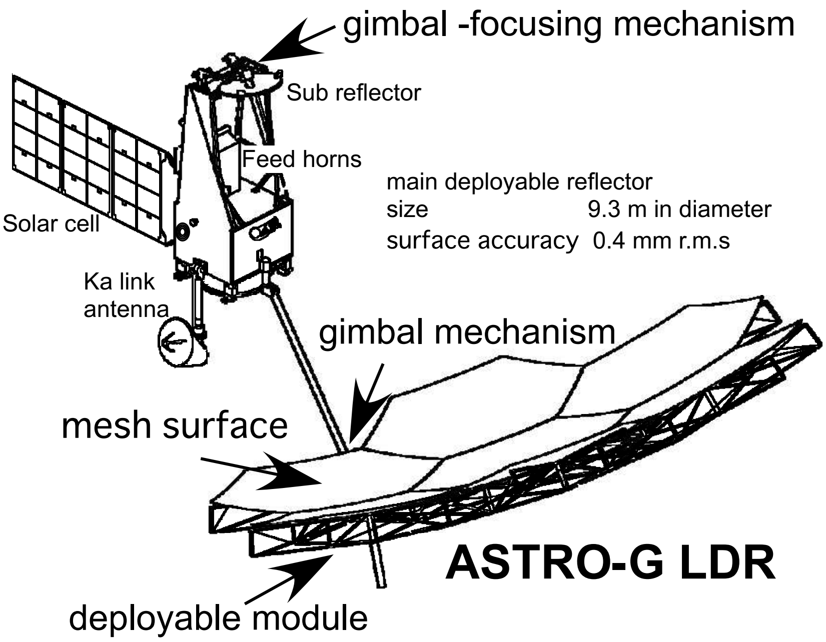

Figure 2: Schematic display of the space radio telescope of ASTRO-G satellite.

We can not observe two frequencies simultaneously, because different frequency bands use the different feed horns, but we can switch two frequencies at least within one minute. The bandwidth and the bit levels of the analog-to-digital converter (ADC) of ASTRO-G are "128 MHz and 2 bit", or "256 MHz and 1 bit". We will use 2-bit sampling mode in normal case. The 1-bit mode will be used in case ground radio telescopes can observe 2-bit, 2 channels, 256 MHz bandwidth (total 2 Gbps) mode to get better sensitivity for the continuum sources.

The data sampled onboard is sent through a broadband down link of $bandwidth \sim 900$ MHz at 37.5 GHz with a bit rate of 1 Gbps quadrature phase shift keying (QPSK) modulation. The phase transfer carrier signal to the local oscillators of observing system is sent with the up-link at 40 GHz. We hope to have at least 3 tracking stations in the world for obtaining sufficient observation time. They are expected to be in Japan, Spain, and one more.

Phase referencing VLBI is a method to improve the sensitivity and accuracy of the VLBI observation. ASTRO-G has the capability to do phase referencing. We need the function to change more than 2 sources (target and calibrators), and precise orbit accuracy. ASTRO-G will have 4 control moment gyro for fast-position switching capability for the separation of 3 degree within

1 minute. The antenna itself is very soft structure, we need the attitude control method without vibrating the soft antenna structure.[5]

We use both satellite laser ranging (SLR) and GPS systems for a high accuracy orbit determination. The target accuracy of the orbit determination is at least 10 cm to get any advantage against ground-base VLBI. The altitude of ASTRO-G around the apogee is higher than that of a GPS constellation. It is difficult to receive the signals when ASTRO-G is arround apogee over four satellites, which are required to determine the orbit of ASTRO-G directly. ASTRO-G also has a corner cube reflector for satellite laser ranging at the earth-pointing system of Ka-band link antenna, to get the orbit data around the higher altittude.

3. VSOP-2 Scientific Objectives

Targets of ASTRO-G are the root of the jet in AGN (ie accretion disks around the black hole), astronomical jet, and masers in galaxies and starts. The high angular resolution of 38 micro arcsecond at 43 GHz will make possible to study the neighborhood of an AGN black hole in unprecedented quality. The synthesized beam sizes of VSOP-2 corresponds to $13R_s$, which is smaller than the predicted accretion disk of M 87. Using VSOP-2, we will image the accretion disk of M87. The resolving an accretion disk will solve the following problems about the AGN jet formation. Blazars are also key sources for exploring the nature and physics of AGN jets. The high-resolution observations of VSOP-2 will resolve the gap between the emission region and core expected by the X-ray observation.

Young stellar objects (YSO) are as well promising targets of VSOP-2. Though VSOP-2 cannot observe thermal emission from gas in/around YSO, motions of H_2O and/or SiO maser spots can trace structure and kinematics of the gas. or position and transversal velocity, and acceleration of such gas (e.g., [6]). Then, VSOP-2 will make clear how such gas accretes into the YSO and how the angular momentum is exchanged. And we already knew that large flares occur around the surface of YSO. Direct imaging of these flares may be a fantastic target of VSOP-2.

The H_2O masers of NGC4258 is a famous example of disk masers resolved by VLBI. Cosmology using disk masers of galaxies may be another scientific target of VSOP-2.

Recently, we had a 2 scientific meetings for VSOP-2. One is the VSOP-2 symposium held in Sagamihara, Japan in 2007, and the other is the scientific workshop of VSOP-2 held in Bonn, Germany in May, 2008.

4. The current status

VSOP-2 project was proposed to ISAS/JAXA in October, 2005, and approved to move to phase-A (Concept design phase) in March 2006. After the concept design, we had a system definition review in March 2007, and the JAXA reviewed for approving as a project in JAXA in April 2007. The ASTRO-G project formally started from July, 2007, and it is now in phase-B (basic design phase).

We design each components and estimate the size, weight, power consumption, thermal interface, of the satellite and the endurance for radiation, vibration, and temperature environments.

Band	Freq. [GHz]	Gain [dB]	η_0	x-pol. [dB]	η_S	$\exp\{-(4\pi\varepsilon/\lambda)^2\}$	η_A	T_{sys} [K]	SEFD [Jy]
X	8.0-8.8	56.3	0.64	-27.8	1.00	0.98	0.60	90	6100
K	20.6-22.6	64.9	0.67	-32.9	1.00	0.88	0.58	52	3600
Q	41.0-45.0	70.8	0.68	-35.6	0.87	0.61	0.35	65	7550

Table 1: Expected antenna performances of ASTRO-G antenna and SEFD

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Purpose of the basic design is to confirm the satellite system works under the requirements of observations. The review of the basic design (PDR: preliminary design review) will be the middle of 2009, and the detailed design phase (phase-C) to produce the detailed design of each component will happen in 2010, following the basic design. Manufacture of the flight model will be 2010, then the test of the components ant final test will be 2011 - 2012.

Antenna is one of the important component to decide the ASTRO-G characteristics. We started the developments and experiments of the breadboard model (BBM) or engineering model (EM) for the basic design in 2008. The deployment mechanism of the antenna is same as that of ETS-VIII, which is JAXA's engineering satellite launched in December, 2006. To get higher surface accuracy of the antenna, ASTRO-G adopted newly developed radial rib-hoop cable structure in each module.[7] We made one-module engineering model (EM), and the thermal model test was carried our in August-September, 2008 to confirm the thermal mathematical model. We also made the radio wave test for the 1.5m size module with the compact range system. We measured the surface of the test module by the photogrammetry method, and measure the gain and beam pattern, to confirm the electro-magnetic mathematical model. Based on these test results we can estimate the characteristics of the antenna at the basic design phase.

The characteristics of the receiver is another part of the important component to decide the capability of the radio telescope. The ultra-low noise and un-conditionally stable amplifier (LNA), low loss feed and polarizer, are required to get enough capability of the receiver. The LNAs at 22 and 43 GHz are cooled to 30 K and the dual circular polarization feed horns are cooled to 100 K by a Stirling-cycle refrigerator. We developed GaAs monolithic microwave integrated circuits (GaAs MMIC) technology for these LNAs. The LNA at 8 GHz is located at the radiator panel of the receiver system. This is cooled passively. The noise temperatures of LNAs at the bread board model (BBM) phase are 60 K at 8 GHz, 20 K at 22 GHz, and 35 K at 43 GHz. We measured (estimated for some components) loss and noise of the receiver components and estimate system noise temperatures at the basic design phase. We will make receivers at the engineering model (EM) phase in autumn 2008.

The values of the antenna efficency (η_A) are also estimated based on the basic design. Current guess of the observing performance of ASTRO-G are summarized in table 1, which shows the estimated antenna efficiency, the system noise temperature, and the SEFDs of ASTRO-G for three bands. We will be able to achieve the performance at least at the begin of the life time. However, the radiation condition of ASTRO-G is very hard because it will pass radiation belt over 3000 times during the mission life time. The performances at the end of the life time are under investigation with the radiation test of the antenna components.

5. VSOP-2 International Collaborations

We need a world-wide collaboration for VSOP-2 both in space and ground telescopes to give a sufficient quantity of observation time for international astronomical community, as we did in the VSOP-1 project. However, nternational collaboration is a complicated issue. VSOP-1 formed the VSOP International Science Council (VISC-1) as an international body to provide guidance on scientific aspects related of the mission. We are acknowledging that VISC-1 functioned successfully in maximizing scientific result with VSOP-1. In a similar fashion for VSOP-2, we formed VISC-2. The primary function of VISC-2 will be to form an international consensus about issues relevant to science operation of the VSOP-2 mission. VISC-2 expects to have face-to-face meeting approximately twice per year and more frequently teleconferences.

Acknowledgments

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