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2.7 GALAXY—Real-time VLBI for Radio Astronomy Observations

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ABSTRACT

GALAXY is a research project on advanced VLBI technology, jointly conducted by CRL, NAO, and NTT. The testbed of the project is a 2.5-Gb/s ultra-high speed network using Asynchronous Transfer Mode (ATM). One of the aims of this project is to achieve high-sensitivity VLBI observation with this gigabit class network. GALAXY network consists of KSP and OLIVE networks provided by NTT and spans 200 km range. The sensitivity achieved in our current observation system is comparable to the world-highest class (~10mJy) using conventional VLBI samplers. This short baseline and high-sensitivity make GALAXY a unique VLBI network for astronomy in the world. Here we describe the properties of GALAXY network and observations focusing on some unique results that can be achieved with the capability of GALAXY. Developments of new networking technology such as Internet Protocol (IP) with GALAXY network are also presented.

Keywords: GALAXY, Real-time VLBI, ATM network

1. Introduction

The Giga-bit Astronomical Large Array Xross-connect (GALAXY) network combines the Key Stone Project (KSP)[1], a geodetic VLBI network of the Communications Research Laboratory (CRL), and the Optically LInked VLBI Experiment (OLIVE)[2], an experimental network operated by the National Astronomical Observatory of Japan (NAO) and Institute of Space and Astronautical Science (ISAS) for joint experiments (Fig. 1). These networks have been interconnected by optical fiber through a joint-research program with Nippon Telegraph and Telephone Corporation (NTT). This enables VLBI observation data to be transmitted for processing to the CRL Koganei KSP correlator or the NAO Mitaka Correlator Station over a digital optical line on an asynchronous transfer mode (ATM) network in real time.

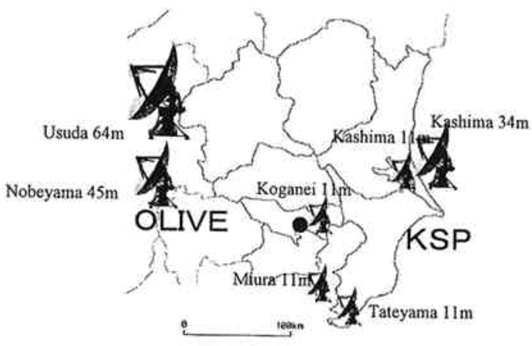

Fig. 1 The GALAXY network; NTT Musashino R&D Center lies on a point connecting the KSP and OLIVE networks.

One of the aim of GALAXY is to achieve high-sensitive astronomical VLBI observations by expanding the observation bandwidth. Detection sensitivity of an astronomical object by VLBI can be given by the following equation.

$$S_{lim} = 7 \cdot \frac{2k}{\eta_s} \sqrt{\frac{T_1 T_2}{\eta_1 A_1 \eta_2 A_2}} \frac{1}{\sqrt{2B\tau}} \quad \cdots\cdots (1)$$

Here, S_{lim} is the minimum flux density that can be detected, k is Boltzmann's constant, η_s is the loss coefficient (about 0.5) due, for example, to digitization and correlation processing, T_1 and T_2 are system noise temperatures of antennas 1 and 2, η_1 and η_2 and A_1 and A_2 are aperture efficiencies and physical aperture areas, respectively, of antennas 1 and 2, B is observation bandwidth, and τ is integration time. In addition, the coefficient "7" on the right side of the equation is the criterion for detecting correlation. In other words, correlation detection is assumed to have occurred when a peak at least seven times the noise level in the fringe-search window appears. This equation tells us that lower system noise, larger apertures, longer integration time, and wider observation bandwidth raise detection sensitivity (to lower S_{lim}).

At present, magnetic recording equipment is generally used for VLBI observations as the last step in collecting data. For 1-bit sampling, observation bandwidth B with respect to sampling rate f_s is given by $B = f_s/2$ [Hz]. In this regard, minimum flux density S_{lim} that acts as the detection boundary for astronomical objects is inversely proportional to $\sqrt{B}$. In the case of the DIR1000 VLBI recorder that is commonly used in Japan, maximum recording speed is 256-Mb/s, and observation bandwidth is consequently 128 MHz in the case of 1-bit sampling and 64 MHz for 2-bit sampling.

One method of improving VLBI observation sensitivity is to raise the recording speed of magnetic recording equipment. At CRL, magnetic recording equipment having a world's top recording speed of 1 Gbps has already been developed (GBR equipment) and has begun to be applied to VLBI observations[3].

Another method for broadening the bandwidth is to transmit observation data over an optical fiber network without using magnetic recording equipment. In recent years, the spread of information-sharing networks like the Internet has been explosive and information transfer speeds on the gigabit level, faster than recording speed, are being achieved. The way that these networks are currently expanding also suggests great possibilities for the future.

Since a detailed report on KSP can be found in the Journal of the Communications Research Laboratory (volume 46, number 1), we do not describe it here. We do, however, provide a brief description of OLIVE, which is operated jointly by NAO, ISAS, and NTT. With this network, experimental VLBI observations have been performed between the HALCA, space VLBI satellite in conjunction with the Nobeyama 45-m antenna (NAO), Usuda 64-m antenna (ISAS), and Usuda 10-m link antenna. These experiments are of two types: space OLIVE that achieves real-time correlation processing through HALCA and ground antennas, and high-sensitivity OLIVE that achieves ultra-broadband, high-sensitivity VLBI observations between ground antennas[4][2].

Various engineering feats like the development of real-time VLBI observation technology have also been accomplished through OLIVE experiments[5]. The baseline distance between Usuda and Nobeyama, however, is short at 20 km, and the fringe spacing is 100 milli-arc-second (mas) or greater even at 22 GHz. Thus, while high-sensitivity observations can be performed, this resolution is insufficient for radio astronomy observations.

With the aim, therefore, of constructing an observation network having both high sensitivity and sufficient resolution for radio astronomy observations, GALAXY experiments were started in December 1998. Section 2 of this article overviews the GALAXY network and describes the current state of the observation system and experimental observations. Section 3 describes achievements in radio astronomy observations, Section 4 discusses the prospects for future expansion of VLBI using GALAXY and optical networks, and Section 5 summarizes the article.

2. GALAXY Network

2.1 GALAXY network overview

The antennas participating in the GALAXY network are shown in Figs. 2(a) to (e) and antenna specifications (antenna name, aperture efficiency, system noise temperature Tsys, and system equivalent flux density SEFD) are listed in Table 1. The Nobeyama 45-m antenna, whose receivable frequency bands are 22-GHz and higher, does not normally participate in GALAXY observations. The Kashima 34-m and 11-m antennas cannot participate in GALAXY at the same time (due to only one set of ATM transmission equipment). The following describes standard GALAXY experiments, that is, observations performed with the Usuda 64-m, Kashima 34-m, Koganei 11-m, and Tateyama 11-m antennas.

The geocentric coordinates of each observation station and the baseline lengths between the antennas are given in Tables 2 and 3, respectively. The longest baseline is about 208km between the Usuda 64-m and Kashima 34-m antennas. At present, observations by GALAXY are conducted in the observation mode using KSP terminals. Observation frequency bands are S and X (2 and 8 GHz) and observations in these bands are performed simultaneously. The KSP type sampling mode, video bandwidth of 8 MHz, 16 channels, and 1-bit sampling is used. One to ten channels are allocated to X-band and 11 to 16 to S-band with all observed simultaneously. The maximum number of participating stations is four. Detection sensitivity and observation frequency at each baseline are given in Tables 4 and 5, respectively.

The observation stations making up GALAXY are interconnected by STM-16 (2.5-Gb/s) ATM network. Each observation station is equipped with a VLBI-ATM interface (ATM transmission terminal) that converts VLBI data output from the sampler at 256-Mb/s to ATM cells for transmission over the network. Since the KSP observation system is simply being applied at this time, the terminal equipment has been designed to match the system, and its maximum data speed is therefore 256-Mb/s. The relationship between the VLBI observation system in KSP and the ATM network is described in detail by Kiuchi[6][7][8]. The ATM interfaces at the Usuda and Nobeyama stations are the same that of KSP.

Observation data from each observation station are sent to NTT Musashino R&D Center and, via cross-connect equipment or an ATM switch, to the Koganei KSP correlator. At Koganei, data received in the form of ATM cells are converted to VLBI data in an ATM receiving terminal. These transmission/receiving terminals make the network transparent with respect to VLBI observations, which means that the KSP correlator can perform correlation processing in the same way as done by playing back a magnetically recorded signal. Cross-correlation in real-time, and bandwidth-synthesis processing at off-line are performed in the correlation site (Koganei). Correlation amplitude after bandwidth synthesis becomes observational data.

2.2 GALAXY features

The GALAXY has three main features: high sensitivity, short baselines, and real-time operation. Its Usuda 64-m and Kashima 34-m antennas are large by even world standards, and in the current observation system, the network's sensitivity for detecting astronomical objects is in the world's top class at about 10 mJy (1 Jy (jansky) = 10^{-26} W/m^{2}Hz). In comparison, the detection

(a) Usuda 64-m antenna

(b) Kashima 34-m antenna

(c) Koganei 11-m antenna

(d) Tateyama 11-m antenna

(e) Nobeyama 45-m antenna

Fig. 2

Table 1 Specifications of GALAXY antennas

Name	Aperture	Aperture Efficiency	Tsys[K]	SEFD[Jy]
Usuda	64m	0.53 (S-band) 0.25 (X-band)	63 50	102 172
Kashima 34	34m	0.60 (S-band) 0.60 (X-band)	70 54	355 274
Koganei	11m	0.81 (S-band) 0.67 (X-band)	76 95	2725 4118
Tateyama	11m	0.79 (S-band) 0.65 (X-band)	71 103	4602 2578
Kashima 11	11m	0.80 (S-band) 0.71 (X-band)	71 99	2578 4050
(Nobeyama)	45m	0.60 (22GHz) 0.60 (43 GHz)	150 150	478 478

Note: For Usuda, aperture efficiency and Tsys differ between observations in either S- or X-band and simultaneous observations in S/X. The above values are for the latter case.

Table 2 Geocentric coordinates of antennas

Name	Position [km]		
	X	Y	Z
Usuda	3855.355	3427.428	3740.971
Kashima 34	3997.649	3276.691	3724.279
Koganei	3941.938	3368.151	3702.235
Tateyama	4000.984	3375.276	3632.213
Kashima 11	3997.506	3276.878	3724.241
(Nobeyama)	3871.024	3428.107	3724.040

Table 3 Baseline lengths between antennas [km]

	Usuda	Kashima 34	Koganei	Tateyama	Kashima 11	(Nobeyama)
Usuda	—	208.0	111.9	189.1	207.7	23.1
Kashima 34	208.0	—	109.3	134.9	0.2	197.4
Koganei	111.9	109.3	—	91.9	109.1	95.4
Tateyama	189.1	134.9	91.9	—	134.8	167.7
Kashima 11	207.7	0.2	109.1	134.8	—	197.1
(Nobeyama)	23.1	197.4	95.4	167.7	197.1	—

Table 4 Detection sensitivity for each baseline [mJy]

	Usuda	Kashima 34	Koganei	Tateyama	Kashima 11
Usuda	—	11 8	31 31	30 33	30 31
Kashima 34	11 8	—	57 39	56 41	56 39
Koganei	31 31	57 39	—	156 161	155 151
Tateyama	30 33	56 41	156 161	—	151 159
Kashima 11	30 31	56 39	155 151	151 159	—

S-band bandwidth = 32 MHz; X-band bandwidth = 80 MHz(X); integration time = 900 sec; loss coefficient = 0.5, 7σ detection boundary

Table 5 Frequency settings for standard GALAXY observations

Band	Channel	Baseband Frequency
X-band	1	8284.99
	2	8294.99
	3	8304.99
	4	8324.99
	5	8354.99
	6	8414.99
	7	8444.99
	8	8464.99
	9	8474.99
	10	8484.99
S-band	11	2269.99
	12	2279.99
	13	2289.99
	14	2299.99
	15*	2309.99
	16*	2319.99

* Because channels 15 and 16 are not observed at Usuda, actual S-band bandwidth is 32 MHz.

sensitivity and fringe spacing of the Very Long Baseline Array (VLBA), the world's largest VLBI network for radio astronomy observations (operated by the National Radio Astronomy Observatory in the U.S.), is 14 mJy and 3 mas for the S-band, and 14 mJy and 0.9 mas for the X-band.

The short baseline feature puts GALAXY in a special position compared to world VLBI networks that generally feature high resolution. Its fringe spacing is about 35 mas for the X-band, which provides enough sensitivity for detecting an astronomical object of about 10 mas in extent. Such an extended object could not be detected by networks like VLBA since resolving it down causes correlation flux to be low. In such a comparison, it is convenient to use brightness temperature (T_B), which is obtained by converting the brightness of the astronomical object to temperature. For blackbody radiation, brightness temperature agrees with physical temperature, which means that brightness temperature is also important as a physical parameter of an astronomical object. The minimum brightness temperature $(T_B)_{lim}$ that can be detected is given by the following expression in terms of the minimum flux density S_{lim} detectable by a single baseline and baseline-length D.

$$(T_B)_{lim} \cong \frac{2}{\pi k} D^2 S_{lim} \qquad (2)$$

Currently in GALAXY, detection sensitivity in terms of brightness temperature is high at about 2×10^5 K on the baseline between the Usuda 64-m and Kashima 34-m antennas. Compared to the brightness-temperature detection sensitivity of about 10^7 K for typical VLBI networks, we can see that GALAXY is quite strong in detecting astronomical objects of low brightness temperature.

The real-time properties of GALAXY means that results can be examined while observations are in progress and even fed back to the observation process. These functions are completely impossible in VLBI observations using magnetic recording equipment and are of particular significance when observing objects whose intensities fluctuate over short periods of time.

The purpose of VLBI radio-astronomy world networks is to achieve high-resolution images. The GALAXY network, however, is weak in observations made for imaging purposes, and is used instead to perform ambitious observations like detecting astronomical objects of low brightness temperature.

2.3 Experimental observations

The first successful experiment using the GALAXY network combining KSP and OLIVE were performed on December 9, 1998. This was followed by 23 observations in 1999 and six in 2000. One observation session lasts from five to seven hours in which the number of astronomical objects observed is typically ten. One object may be observed two or three times depending on the purpose of the observation.

3. Achievements in Radio Astronomy Observations

In this section, we present examples of astronomy-related achievements through experiments and observations performed on GALAXY.

3.1 Orion No.12

The Orion Nebula (M42) is an ionized region formed by ultraviolet radiation from young stars at the center, and is a strong radio source dominated by thermal emission (HII region). In a range of three arc minutes at the center of the nebula, more than 20 compact radio sources with apparent sizes under one arc-second have been discovered[9]. Most of these are condensed cloud of ionized gas irradiated by young stars like θ^1C Ori, and their radiation is thought to be thermal. However, an object called No.12 (hereafter Orion No.12) is known as a variable source. The flux density of the source changes by more than 40 times from 2 to 90 mJy. The size of the source is exceptionally small >1.3 mas = 0.6 AU (astronomical unit) as detected by intercontinental VLBI. High brightness temperature, $T_B < 5.2\times10^8$ K, indicates the radiation mechanism of the source is non-thermal. In the optical observation, it is known that this object corresponds to θ^1A Ori, the westernmost of the Trapezium stars, and is a binary of B0.5 and T Tauri types[10]. It has been suggested that orbital interaction in the binary system might relate to the flux fluctuation in Orion No.12.

Previous observations showed that Orion No.12 changes its flux density by ten times on a time scale of roughly ten days. Considering, however, that its size is about 1 AU or 10 light-minutes, there is also the possibility of flux variability on a time scale of one hour as seen in RS CVn-type stars. Such short-period flux variability would reflect the physical state of a radio-emission region, and for this reason, the search for such short-period variability is requested.

With the above background, we have performed observations of Orion No.12. These were conducted in normal GALAXY mode on March 16, 2000 (DOY076) and March 21, 2000 (DOY081). To avoid apparent variations caused by the fluctuation of system gain, we alternated observations between two reference objects (J0522+01, 0528+134) and Orion No.12. The sizes of these sources are enough small for GALAXY, and theie structures would not be resolved. Integration time was 900 seconds for Orion No.12, and 300 seconds for each of the reference objects. The observation period was from 10:50 to 12:40 (UT), during which five scans were performed.

Observed flux density for two reference sources are shown in Fig. 3. For J0522+01, flux density was 1.04±0.02 Jy for the S-band, and 0.40±0.03 Jy for the X-band. This object is known to exhibit no intensity fluctuation on a time scale of one hour, and observed fluctuation is attributed to the observation system. The fluctuation was under 2% for the S-band and under 7% for the X-band. The gain of the observing system was able to keep fluctuation within these bounds during the observation period. The same conclusion was reached with regard to the observation of 0528+134, the other reference object.

In the DOY076 observation of Orion No.12 was detected at X-band only with Kashima-Usuda baseline (Fig. 4), while no fringe ($<7\sigma$) was detected at S-band at all baselines. In the DOY081 observation, it was not detected

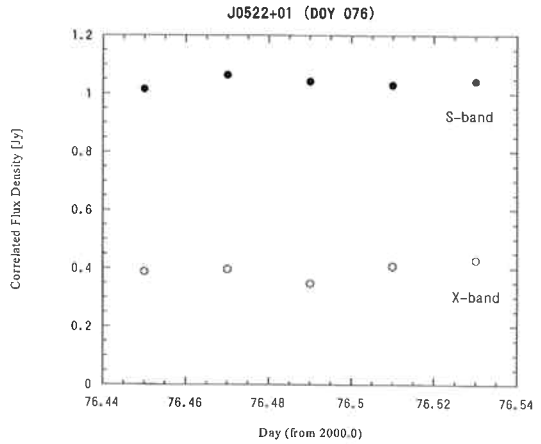

Fig. 3 Intensity fluctuation of reference radio source J0522+01

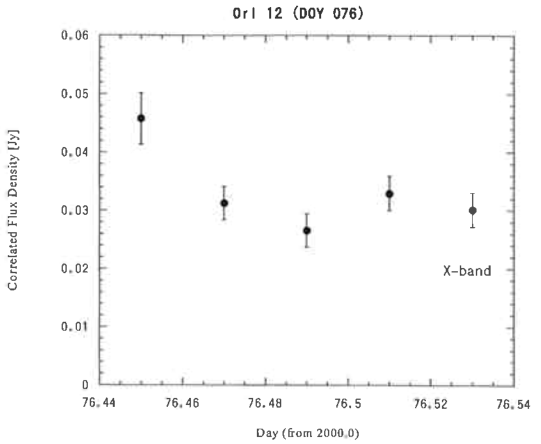

Fig. 4 Intensity fluctuation of Orion No.12, target of observation

both at S- and X-band. In the S-band, background radiation is strong due to the Orion Nebula, and the Usuda station in particular experienced a rise in system noise temperature of about four times. The 7σ-detection sensitivity for Orion No.12 was about 30 mJy at S-band. The following describes X-band, Kashima-Usuda observation results for DOY076 in which intensity fluctuation was detected.

The obtained correlation flux density was 22.9 mJy at the beginning of the observation, dropped down to 15.6 mJy 26 minutes later, and eventually became fixed at about 15 mJy. The change of this is much higher than that of fluctuation of system gain, hence the change of flux density of Orion No.12 is a real on occurred in the source. The size of an object can be estimated from the time scale of flux fluctuation. Here, the time required for light to cross the object (transversal time) should certainly be smaller than the time scale of flux fluctuation. From a fluctuation time scale τ=1500 seconds for Orion No.12, we get $c\tau=4.5\times10^8$ km=3 AU=6.5 mas at the distance of Orion Nebula of 460 kpc (c is the speed of light). This means that the size of the object as obtained from intensity fluctuation is less than 6.5 mas. Comparing with the result from direct observation by VLBI (>1.3 mas), we can say that object size θ_s lies in the range expressed by $1.3<\theta_s<6.5$ mas.

In 26 minutes, intensity fluctuation dropped from 22.9 to 15.6 [mJy] (68%=2/3). We see that object size obtained from flux fluctuation was only five times that of direct observation and that an amount of change equivalent to total flux exists. This means that either the speed of motion in the radiation region is equal to the speed of light or that severe fluctuation in radiation exists such that flux fluctuation occurs throughout the entire object all at once.

In addition, a fluctuation time scale on the order of 1500 seconds cannot be explained by synchrotron loss. We therefore consider that motion (or perhaps expansion) as fast as the speed of light exists, which is thought to be related to activity at the surface of a T Tauri type of star revealed also by X-ray observations.

The period of the binary star is P=65.4325 days. In past observations, the intensity of radio emissions became maximum at binary-star phase Φ=0.15, and after this, the system would tend to enter a low-activity state. In our observations, however, flux and fluctuation in excess of 20 [mJy] could be obtained even for Φ=0.5. A negative result was consequently obtained with regard to the relationship between the phase of a binary star and activity.

In these observations, we were successful in detecting flux fluctuation on a short time scale of less than one hour by GALAXY network. In upcoming research, we aim to obtain more definite results by making more observations and plan to attempt detection on the S-band as well. Successful observations on both the S and X bands should make it possible to achieve important physical results for the astronomical object from fluctuation in the spectral index.

We would like to note here that the advantage of VLBI observations that cannot resolve structure is as follows. In the Orion region, the background HII region consists of strong radio sources, and weak objects of several tens of mJy cannot be observed by a single telescope. On the other extreme, observations by world-class high-sensitivity VLBI telescopes will resolve the object structure. Accordingly, high-sensitivity and low-resolution VLBI observations by GALAXY are optimal for observing weak objects of this type.

3.2 HR1099

HR1099 (V711Tau) is an extremely active, RS CVn-type close binary star. It is 36 pc (1 parsec = 3.26 light years) away and has a visual magnitude of 5.9. This binary consists of G5IV and KIV with orbital period of 2.837 days and an apparent orbit radius of 1.48 mas. HR1099 is a strong radio emitter. Its flux density changes from 10 to 300 mJy at X-band. Usually in a quiescent state, the flux density is about 30 mJy, while states of strong radiation called "flares" are known to occur frequently and the variation time scale of several hours at the flare. In optical observations, periodic intensity fluctuation accompanying the revolution of the binary star has been observed. To date, however, there has been no confirmation of periodicity in the flux fluctuation of radio waves, and a full explanation of intensity fluctuation in HR1099 has not yet been given. Likewise, the physical mechanism of flares has not been fully explained, although theories has been proposed.

GALAXY observation for HR1099 has two purposes; the first is to observe the intensity and spectrum of radio waves emitted from HR1099 in quiescent state, and the second to observe the flux and spectrum changes at the time of flares with the aim of setting limits on the physical state of radiation.

Observations of HR1099 by GALAXY are ongoing, and two flares have been detected so far. As astronomical results are being reported separately (Kawaguchi, in preparation), we will here describe the observation of June 8, 1999 that demonstrates the real-time characteristics of the GALAXY network.

On this day, there were actually plans to make other observations in addition to HR1099. However, in order to observe changes after a flare, it was decided to modify the observation schedule en route and to continue observing HR1099 up to the end of observation time, which meant five hours of continuous observation of HR1099. In the X-band, it was found that exceptionally strong radio emission at first, and that the flux dropped off in an almost linear fashion. In the S-band, though, the flux exhibited almost no significant change over time. Figure 5 shows a plot of the correlation-amplitude ratio of X to S-band (corresponding to the spectral index) versus time. As shown, the correlation-amplitude ratio decreases linearly over time indicating a sharp drop in radiation intensity in the X-band.

The discovery of a flare-up in HR1099 while the observation was in progress demonstrated the real-time characteristics of GALAXY. In ordinary VLBI observations, data is recorded only on magnetic tape and there is no way to understand what might be occurring at the astronomical object at that time. With GALAXY, however, the results of correlation processing are obtained during the observation making it possible to determine to a certain extent the state of the object. If this observation had been conducted with magnetic tape as usual, the flare would have been first discovered several days later

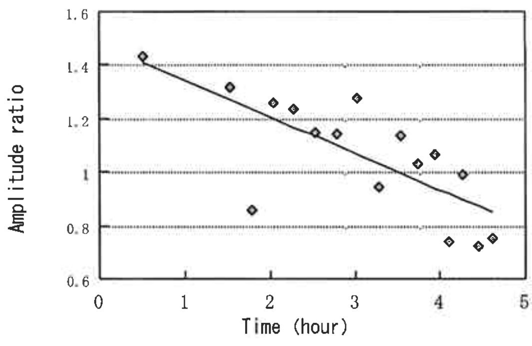

Fig. 5 Change in correlation amplitude ratio over time

in correlation processing, which of course would have been too late to change the schedule.

3.3 Search for unknown astronomical objects

GALAXY features detection sensitivity at world-class levels, and these features are being used in research that attempts to discover unknown astronomical objects. This research aims to detect astronomical objects that have never been observed by VLBI or astronomical objects considered undetectable by VLBI observations. It also aims to perform VLBI observations of radio sources whose properties are not well understood and to discover compact, high-temperature astronomical objects. This is ambitious research that, if successful, will open up a new field in astronomy. Astronomical objects that we have targeted so far include objects exhibiting gamma-ray bursts, radio sources in globular clusters, core of ordinary galaxies, HII regions, and planetary nebula. While no firm results have been obtained at the current stage, we expect major discoveries to be made by constructing an even more sensitive observation system.

4. Outlook for the Future

At present, existing equipment is being diverted to provide GALAXY with samplers and correlators, and as a result, higher levels of sensitivity though broadband techniques have not yet been achieved. Research and development of a broadband observation system is now under way with the goal of achieving 2-Gbps observations. At the same time, research in future observation systems is being performed using the GALAXY network as a test bed for developing technologies that combine radio telescopes through a high-speed network. These R&D efforts are summarized below.

4.1 Achieving ultra-high-sensitivity VLBI through 2-Gb/s observations

The experimental observations now being performed by GALAXY are in the 256-Mb/s (KSP) mode. Research is moving forward, however, on achieving observations at a data speed that makes best use of circuit capacity (meaning 2-Gb/s) by 2001 (Fig. 6).

Given observations at 2-Gb/s and the observation system of the Usuda 64-m antenna set for the X-band, a detection-sensitivity on the level of 1 mJy will be achieved (Table 5). The detection sensitivity of brightness temperature would also reach a level of about 2.7×10^4 K. This would be the highest detection sensitivity of VLBI networks in the world. Such improvement in detection sensitivity would enable observations of astronomical objects that have so far been impossible to perform. In particular, observations of astronomical objects with no past examples of VLBI observations have the potential of becoming a breakthrough in astronomical research. One goal here is VLBI observations of thermal objects such as fixed stars and HII regions that have a typical temperature of 10^4 K. In other words, if a brightness-temperature detection sensitivity of 10^4 K can be achieved, VLBI observations of thermal astronomical objects that up to now have been completely impossible may become a reality.

An important target in the observation of thermal

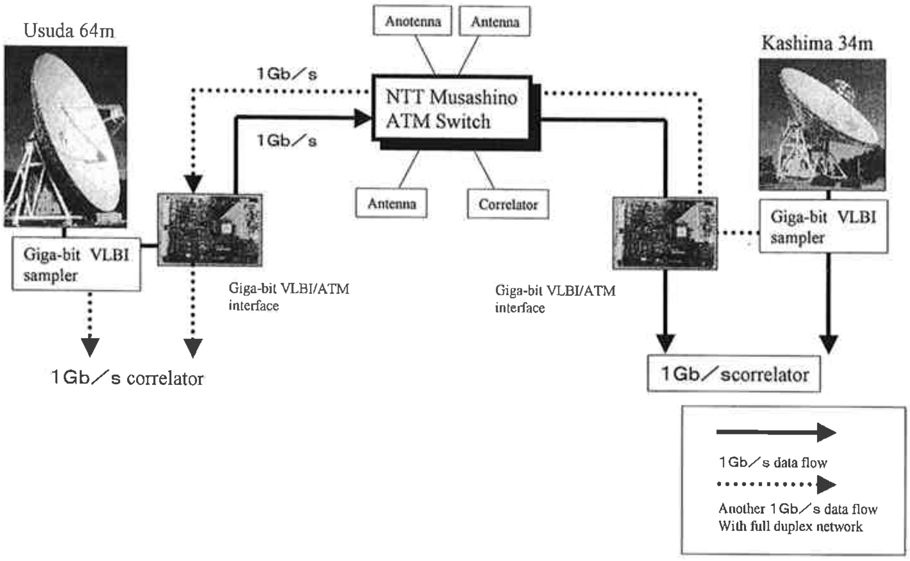

Fig. 6 Gigabit-class data-transmission experimental network

Table 6 Predicted detection sensitivity of each baseline for 2-Gbps observations (upper values: X-band detection sensitivity [mJy]; lower values: brightness-temperature detection sensitivity [K])

	Usuda	Kashima 34	Koganei	Tateyama	Kashima 11
Usuda	—	1.3 2.7×10^4	5.2 3.0×10^4	5.5 9.0×10^4	5.1 1.0×10^5
Kashima 34	1.3 2.7×10^4	—	11 6.10^4	12 9.5×10^4	11 0.2
Koganei	5.2 3.0×10^4	11 6.10^4	—	45 1.77×10^5	42 2.34×10^5
Tateyama	5.5 9.0×10^4	12 9.5×10^4	45 1.77×10^5	—	45 3.77×10^5
Kashima 11	5.1 1.0×10^5	11 0.2	42 2.34×10^5	45 1.77×10^5	—

X-band bandwidth = 1 GHz; integration time = 900 sec; loss coefficient = 0.5, 7σ detection boundary (For Usuda, when observing in X-band only, system noise temperature = 35K, aperture efficiency = 0.5, and SEFD = 60 Jy)

objects is the fixed stars. In contrast to a flare star like HR1099, radio waves from a fixed star are normally quite weak—there are no more than a few astronomical objects that have been detected at a sensitivity of about 1 mJy. If, however, direct observations at VLBI angular resolution can be made of the corona, that is, the outer atmosphere of the fixed star considered to be a region of radio-wave emission, great findings may be in store for research in the outer atmosphere of fixed stars. In this regard, observations would begin by measuring the size of the astronomical object since the image capability of GALAXY is low. For example, while Betelgeuse (α Ori) is the only star (except for the Sun) for which an image of a photosphere has been obtained by an optical interferometer, the state of its outer atmosphere could only be estimated from the structure of absorption lines. On the other hand, if the extent of high-temperature corona can be determined by radio-wave observations, limitations can then be assigned to the state of gas flowing out from the star. Such information should be useful in research of the evolutionary process from a supergiant star to a planetary nebula.

4.2 Basic research toward future network observations

4.2.1 Research of IP transmission systems

At present, GALAXY is using ATM for the network transmission system. The explosive spread of the Internet, however, is making Internet Protocol (IP) a major data transmission protocol. A research and development of IP transfer technique for ultra high-speed data, and improvement of connectivity with a number of other research organizations/observatories are undergoing using GALAXY network.

4.2.2 Research in distributed processing systems

We can consider two methods for correlation processing: the present method that uses a centralized correlator, and a distributed method that uses many compact correlators each with a limited set of functions. In the case of centralized processing, there is always the possibility of a network bottleneck at the input section of the correlator. Distributed correlation processing, however, has the potential of showing great affinity with the network. The 2-Gb/s observations scheduled for 2001 can be regarded as one form of distributed correlation processing, though quite simple at this time. More complex-distributed processing with IP transfer technique is under development.

4.2.3 Geographical expansion of the network

The GALAXY experiments connect large antennas in the Tokyo metropolitan area. Studies are now being performed, however, on applying the technical results achieved by GALAXY to the VLBI Exploration of Radio Astrometry (VERA) observation stations (Mizusawa in Iwate, Iriki in Kagoshima, Chichijima in Ogasawara, and Ishigaki in Okinawa) now being constructed by NAO. The VERA project aims to perform phase-compensation VLBI by the 2-beam method that enables astronomical objects to be observed by long-term integration so as to overcome atmospheric fluctuations. Connecting VERA with an optical fiber network will make it possible to improve both τ and B parameters associated with observation sensitivity. This development should have a profound effect on VERA observations.

Another feature of network-type VLBI is that the use of no magnetic tape makes observations extremely easy to perform. This, in turn, means more productive observations and the capability of generating useful feedback to VLBI observations in general. Real-time imaging may also become possible in the future.

Connecting the VLBI antennas in Japan in this way should inevitably lead to VLBI observations using overseas observation stations connected to the network.

5. Summary

GALAXY is a real-time VLBI network that combines the KSP and OLIVE VLBI observation networks operating in the Kanto and Koshin areas of Japan. Experiments began in December 1998. In GALAXY, observation data are transmitted to correlation stations in real time over an ATM network for processing. GALAXY features high sensitivity, short baselines, and real-time processing, as well as the world-class Usuda 64-m and Kashima 34-m antennas. At a data speed of 256-Mb/s, GALAXY has a detection sensitivity of about 10 mJy, which can be improved to the 1 mJy level in observations at 2-Gb/s, a data speed impossible for magnetic recording. Due to its short baseline feature, GALAXY is useful in observations of astronomical objects of low brightness temperature, and it also has the potential of making VLBI observations of thermal astronomical objects. Making use of these features, GALAXY has been used to perform astronomical observations and has been successful in observing objects with variable flux and unknown objects as well. GALAXY is also the only VLBI observation network in the world that uses a digital data transmission system, and is therefore being used to research and develop technologies that will serve as a foundation for future VLBI observation systems.

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