

## 4-6 Development of the Compact VLBI System for Calibrating GNSS and EDM Devices

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We are developing a compact VLBI (Very Long Baseline Interferometry) system with 1.6 m diameter aperture dish in order to provide reference baseline lengths for calibration. The reference baselines are used to validate surveying instruments such as GPS (Global Positioning System) and EDM (Electro-Optical Distance Measurement) and maintained by the Geospatial Information Authority (GSI) of Japan. The compact VLBI system is designed to be assembled with muscle power simply in order to perform short-term (about one week) measurements at several reference baselines in Japan islands. First, we have evaluated a front-end system with a wide-band quad-ridged horn antenna by installing it on the 2.4 m diameter antenna at Kashima as a feasibility study. We have successfully carried out five geodetic VLBI experiments using it during September 2006 to July 2008. In addition we have concluded the new analysis concept to obtain indirectly the group delays on the baseline between two compact dishes is available. Next, we have carried out the VLBI experiments on the Kashima-Tsukuba baseline (about 54 km) using the two compact VLBI system during December 2009 to October 2010. The averaged baseline length and repeatability of the experiments is  $54184875.1 \pm 2.5$  mm.

### **Keywords**

Very Long Baseline Interferometry, Global Positioning System, Electro-Optical Distance Measurement, Geodetic survey

### **1 Introduction**

The National Institute of Information and Communications Technology (Hereinafter abbreviated as “NICT”) has been working on the development of compact VLBI (Very Long Baseline Interferometry) systems and analysis technologies in the framework for the second medium-term plan which began in fiscal 2006. At NICT a system which combines all these components is called MARBLE (MARBLE: Multiple Antenna Radio-interferometer for

Baseline Length Evaluation). NICT is carrying out the development of the MARBLE system based on a research collaboration with the Geospatial Information Authority (GSI) of Japan. The GSI has the responsibility to calibrate and maintain a 10 km reference baseline for validating surveying instruments such as GPS (Global Positioning System) and EDM (electro-optical distance measurement)[1]–[3]. We are developing a compact VLBI system with a 1.6 m diameter aperture dish to certificate the length of that reference baseline.

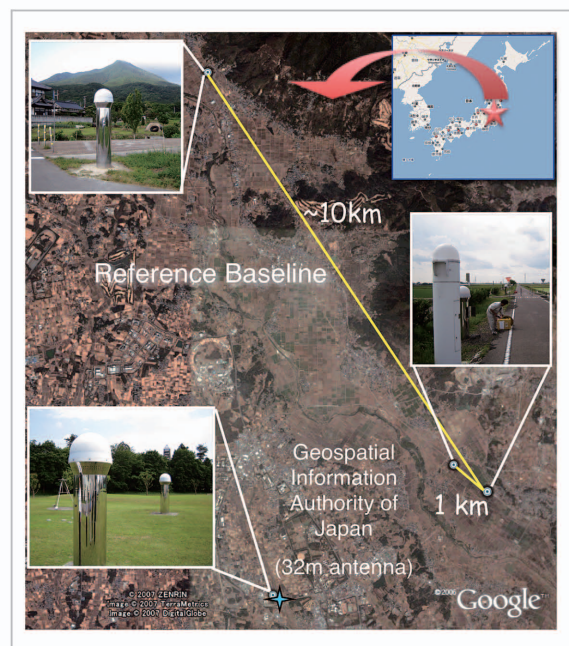
The validation procedure is performed by the usage of high performance EDM at present. However this procedure is not traceable to the national standards of length. We expect that the compact VLBI systems will be available to the traceable validation in the future. The scope of applying this system is not only limited to the reference baseline lengths for calibration validation, but enables also geodetic VLBI at locations where conventional VLBI system have not been deployed so far. In addition, NICT has considered the MARBLE system as a technology for realizing time and frequency (T&F) transfer for maintaining the precision of standard time systems by taking advantage of its portability and high precision characteristics.

The development of compact VLBI systems, which are the core of the MARBLE system, began with a feasibility study based on an existing 2.4 m diameter antenna. We have named this antenna system CARAVAN2400 (CARAVAN: Compact Antenna of Radio Astronomy VLBI Adapted for Network), and have carried out evaluations of pointing calibration/quasar tracking performance/signal strength, etc. in order to obtain the knowledge necessary for implementing geodetic observation using compact antennas[4][5]. The first geodetic experiment was successfully carried out on September 21, 2006[6].

Thereafter in fiscal year 2007 the first MARBLE compact VLBI system equipped with a broad-band front-end system was completed, and the 2<sup>nd</sup> system could be deployed in the fiscal year 2008. Each of the systems underwent performance evaluations before geodetic experiments were successfully carried out several times in fiscal year 2009. Evaluations were carried out using data from past geodetic experiments and effective methods were developed for actual geodetic VLBI experiments as well. This paper provides a summary of the details and results of MARBLE system development up until now, as well as future development based on the “VLBI2010[7]” concept which is proposed by the International VLBI Service for Geodesy and Astrometry (IVS) as the next generation VLBI technology.

## 2 Validation of reference baseline lengths for calibration and VLBI measurement technologies

The GSI has the responsibility to calibrate and validate survey instruments such as GPS receivers and EDM used by surveying companies. The facility which carries out this validation is called a “reference baseline lengths for calibration” and is located along a cycling road (built on leftover tracks of the former Tsukuba Tetsudo Tsukuba Line) of about 10 km length located approximately 4 km east of the GSI headquarters in Tsukuba City, Ibaraki Prefecture (see Fig. 1). This validation is regulated in accordance with the Performance Standards for Surveying Instruments of the Survey Act, and for GPS surveying instruments. Thereby, in particular “a precision of  $5 \text{ mm} + 1 \text{ ppm} \times \text{distance}$  (dual frequency static receiver/15 mm over a distance of 10 km)” is required. The reference baseline itself is measured at a precision of 2 mm, which is nearly an order of magnitude above the required precision for the GPS surveying instruments subject to validation, which means that it is necessary to measure a 10 km baseline vector length to within RMS 2 mm re-



**Fig. 1** Reference baseline of the Geospatial Information Authority of Japan (GSI)



peatability[1]. Further, performance standards based on national measurement standards (international standards), so called traceability, should also be considered for measurements using surveying instruments[2].

Stainless steel pillar monuments for GPS antennae and EDM equipment are installed along the baseline. To guarantee the quality of validation, the baseline length has to be evaluated operationally. GSI compares an operational EDM equipment and an iodine-stabilized He-Ne laser wavelength standard (From July 16, 2009 onward optical frequency comb equipment became the national standard) in order to keep its traceability for length to a national standard maintained by the National Metrology Institute of Japan (NMIJ) of the National Institute of Advanced Industrial Science and Technology (AIST).

However, because a line of sight range using the laser interferometer is limited, the present comparison between GPS surveying instruments and the laser interferometer is performed on only 1 km length of the reference baseline. The direct comparison on the whole 10 km length of the reference baseline using the independent method from GPS has not been carried out so far.

Therefore, the traceability on the validation procedure of the GPS surveying instruments has not been established and GSI need the desirable method which provides equivalent or superior accuracy to GPS surveys.

VLBI technology has been considered as an effective method for resolving these issues. VLBI is a space geodetic technique to measure the time difference between the arrival times at two Earth-based radio telescopes of a radio wavefront emitted by an extra-galactic radio source (quasar). In VLBI, the time difference is obtained by cross-correlation processing of the data from both radio telescopes. Using time difference measurements from many quasars, VLBI can determine the relative positions of the antennas with one millimeter precision.

However, the large radio telescopes with at least a 10 m diameter dish are indispensable for conventional geodetic VLBI measurements.

Accordingly, the permanent installation of large scale VLBI observation systems at all baseline validation sites throughout the country is not realistic from the point of cost effectiveness.

Thus, NICT started to develop a compact VLBI system based on a 1 m class diameter aperture antenna which can be transported using a full size van and can be installed at the both ends of each reference baseline site. We have already developed a similar compact VLBI system in the CARAVAN system which was developed for astronomy purposes[8]. We have successfully detected a fringe of water maser source (W49N) at 22 GHz between the first prototype of the CARAVAN with 65 cm diameter dish and the Kashima 34 m radio telescope[8]. The development of the MARBLE compact VLBI system is based on the foundation built during the development of CARAVAN.

### 3 MARBLE concept and compact VLBI system development

#### 3.1 MARBLE system

In the medium-term plan, we have started the development of compact VLBI systems specialized for geodetic purposes. Here, we need to resolve one major issue on data processing. The compact antenna is too insensitive to detect fringe between both stations. Thus, we have designed a new observation concept by including one large antenna station into observation network and we have evaluated an availability of the concept. We refer to this method as the MARBLE concept and the schematic image of the new concept is shown in Fig. 2[9].

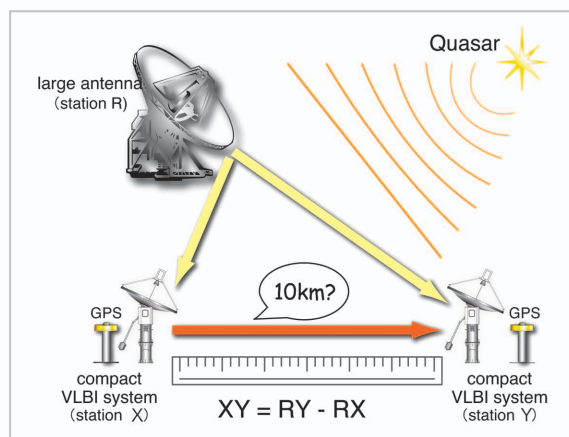
As shown in Fig. 2, compact VLBI systems are installed at both ends of the reference baseline lengths for calibration. Here, X and Y denote two compact VLBI stations at both ends of baseline. In addition, one large antenna such as NICT Kashima 34 m or GSI Tsukuba 32 m, is added into the observation network (station R). We can detect two group delays between each compact antenna and the large one based on conventional VLBI measurement. A group de-

lay XY between the two compact antennas can be indirectly calculated using a simple equation as shown in Fig. 2. RX and RY are two group delays obtained by a conventional way. Here, in order to obtain the baseline length with 2 mm accuracy each group delay of baseline RX and RY is determined within the comparable or superior accuracy. The MARBLE system mentioned earlier means the integrated system including the observation network composed of a large antenna and compact antennas and its new analysis concept.

### 3.2 Compact VLBI system

#### 3.2.1 Frequency

At the reference baseline various kinds of geodetic GPS receivers for the purpose of RTK (real-time kinematic) and static observations are evaluated. The dual frequency GPS receiver is a precise instrument for surveying. The dual frequency receiver effectively compensates errors due to the ionospheric propagation delay. In practice, it can be expected that the ionosphere effect is negligible on the 10 km reference baseline. However, taking into consideration the “reference baseline lengths for calibration validation,” compact VLBI system needs superior precision comparing with GPS surveying instruments. Thus, it is indispensable the compact VLBI system can compensate the ionospheric effect. For compact VLBI systems, a receiver capable of receiving signals in



**Fig.2** Schematic image of VLBI measurement for the reference baseline validation using the compact VLBI system

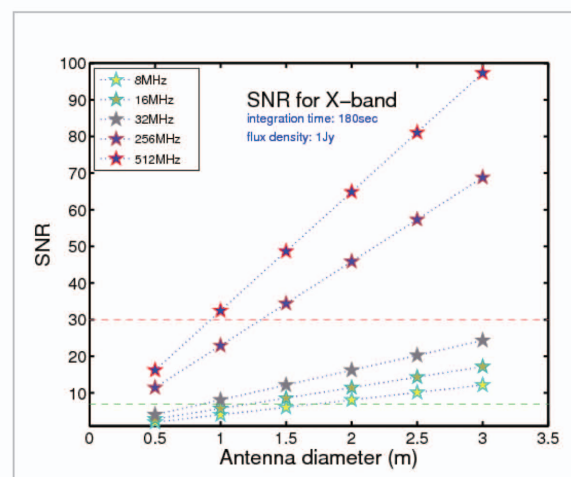
the S band (2 GHz band) and X band (8 GHz band), as with preexisting geodetic VLBI observation systems, was suggested.

#### 3.2.2 Observable radio sources and SNR evaluation

In the compact VLBI concept, the antenna diameter was provisionally set to at 1 m class for portability requirements. We evaluated whether this antenna size is suitable or not to obtain the required SNR level and sufficient precision of the group delay. First, the precision of the group delay determined through correlation processing is proportional to the inverse of the effective bandwidth and the SNR. The SNR can be found using the following equation[10].

$$\text{SNR} = \rho_{\text{eff}} \sqrt{2BT}$$

B is the observed bandwidth (Hz) and T is the integration time (sec). In addition,  $\rho_{\text{eff}}$  is the effective correlation coefficient when data is recorded with a 1-bit sampling. Figure 3 shows



**Fig.3** Signal to noise ratio of detected fringe as a function of antenna diameter of the compact VLBI system

The integration time and flux density of the radio source are assumed to be 180 seconds and 1 Jy, respectively. The diameter, system temperature, and aperture efficiency of the large antenna are assumed to be 34 m, 72 K, and 0.65, respectively. The system temperature and aperture efficiency of the compact VLBI system are assumed to be 120 K and 0.5, respectively.



the estimated results for SNR when VLBI observation is carried out through a combination of the Kashima 34 m antenna and compact antennas. Each SNR was calculated here based on the assumption of a conventional geodetic VLBI experiment with radio source signal strength at 1 Jy (Jansky/1 Jy= $10^{-26}$  W/m<sup>2</sup>·Hz), integral time at 180 seconds, and 5 bands from 8 MHz to 512 MHz.

The red and green horizontal lines in Fig. 3 are lines for SNR=7 and SNR=30 respectively, and are the lower limit for fringe detection in correlation processing and the lower limit considered valid as geodetic observation data. In order to obtain values for greater than SNR=30 in VLBI observation using 34 m antennas and compact antennas, it can be seen from this figure that a band of at least 256 MHz width and a minimum dish size of 1.5 m will be necessary. Even though the radio source signal strength were less than 1 Jy, we can include this radio source in a observation schedule without an extension of an integral time if a bandwidth of 512 MHz or wider would be used.

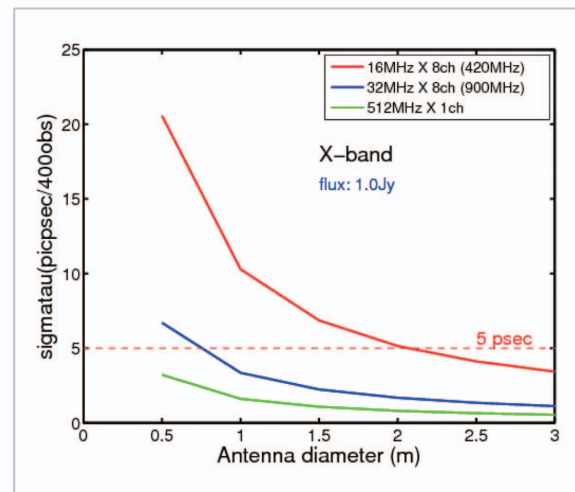
### 3.2.3 Delay accuracy evaluation

In order to determine the length of the baseline XY with 2 mm RMS, we have to obtain the baseline lengths of RX and RY with 1.4 mm formal error. As such, because the speed of light in vacuum is  $c \approx 3.0 \times 10^{11}$  (mm/sec), a delay precision of at least 5 psec will be necessary. In normal geodetic VLBI observation, for one experiment 300–500 observables (with observation of one radio source counted as one observable) are acquired in 24 hours, dependent on the observed band and the integral time per 1 obs. The delay time accuracy  $\sigma_{\text{tau}}$  required, for example, for acquisition of 400 data, is shown below.

$$\sigma_{\text{tau}} = 5(\text{psec}) \times \sqrt{400(\text{obs})} = 100(\text{psec})$$

Here, the group delay for the X band is simply discussed and its random errors are only considered (to be exact, it is necessary to examine both systematic and random errors due to several causes and carry out error evaluation). Based on this equation, we have investigated the accuracy of estimated group delay under various conditions such as antenna diameters, bandwidth, and channel numbers. These conditions are summarized in Table 1.

Here we evaluate the accuracy of group delay for each quasar (each observation) and a number of 400 observations, which is averaged over a 24 hours experiment, are assumed. In addition, the radio source strength is set to 1 Jy. The results of this calculation are shown in Fig. 4. As shown in the figure, we conclude that if the diameter is approximately 1.5 m, and data is acquired in a 32 MHz bandwidth with 16 channels or a 512 MHz bandwidth with a



**Fig.4** Estimated precision of a group delay at X-band as a function of antenna diameter

The flux density of 1 Jy is assumed.

**Table 1** Conditions for numerical simulation of group delay determination using the compact VLBI system

	Frequency	Band width and channels	Frequency setting for each channel (MHz)
CASE1	X-band	16 MHz × 8 ch	8180, 8237, 8294, 8351, 8408, 8465, 8522, 8579
CASE2	X-band	32 MHz × 8 ch	7700, 7824, 7948, 8072, 8196, 8320, 8440, 8568
CASE3	X-band		512 MHz × 1 ch

single channel, a 5 pico-second accuracy of group delay can be achieved. In order to achieve a specified accuracy in VLBI observation using compact VLBI systems, the following conditions are required,

- The signal strength of each radio source should be at least 1.0 Jy.
- An antenna of one end of baseline should be a 30 m diameter class.
- The lower limit of dish diameter for the compact VLBI system should be 1.5 m.
- If multi channel observation (at least 8 channels) is performed, at least 32 MHz per one channel bandwidth is required. A more wideband of 512 MHz per one channel is more desirable.
- If the above conditions are fulfilled, the maximum integral time per 1 observation can be set to approximately 150 seconds.

We have developed the compact VLBI systems based on these conditions.

### 3.3 CARAVAN2400

Before beginning the development of the compact VLBI system, we first conducted a variety of experiments using a VLBI system with the 2.4 m diameter, which is named CARAVAN2400, for feasibility studies. This 2.4 m antenna was originally operated by the GSI as a mobile VLBI station, and was received during the time of NICT's predecessor the Communications Research Laboratory (2002) as a testbed for compact VLBI stations. After renovation of the drive and control systems, it was

installed to the side of the former SLR observation building at the Kashima Space Research Center in February of 2005 (Fig. 5).

First, we installed an X band low noise amplifier (LNA) on ambient temperature in the CARAVAN2400<sup>[4][5]</sup>. Next, we started some developments to perform VLBI experiments at the beginning of 2005 and successfully carried out the first light experiment for solar radio on March 30, 2005. After the first light experiment we evaluated the receiver noise temperature, the system noise temperature, the antenna aperture efficiency, and the beam-width. In December 2005 a simple VLBI observation was successfully completed by simultaneously receiving solar radio waves together with the Kashima 11 m antenna. In the same month the CARAVAN2400 succeeded in independently receiving signals from Cas A (Cassiopeia A), and on March 15, 2006 the system's first fringe detection for extragalactic radio source was successfully performed. On March 29, 2006, though we performed the first geodetic VLBI experiment between the CARAVAN2400 and the Koganei 11 m, which was unsuccessful in obtaining a geodetic solution due to the low quality data.

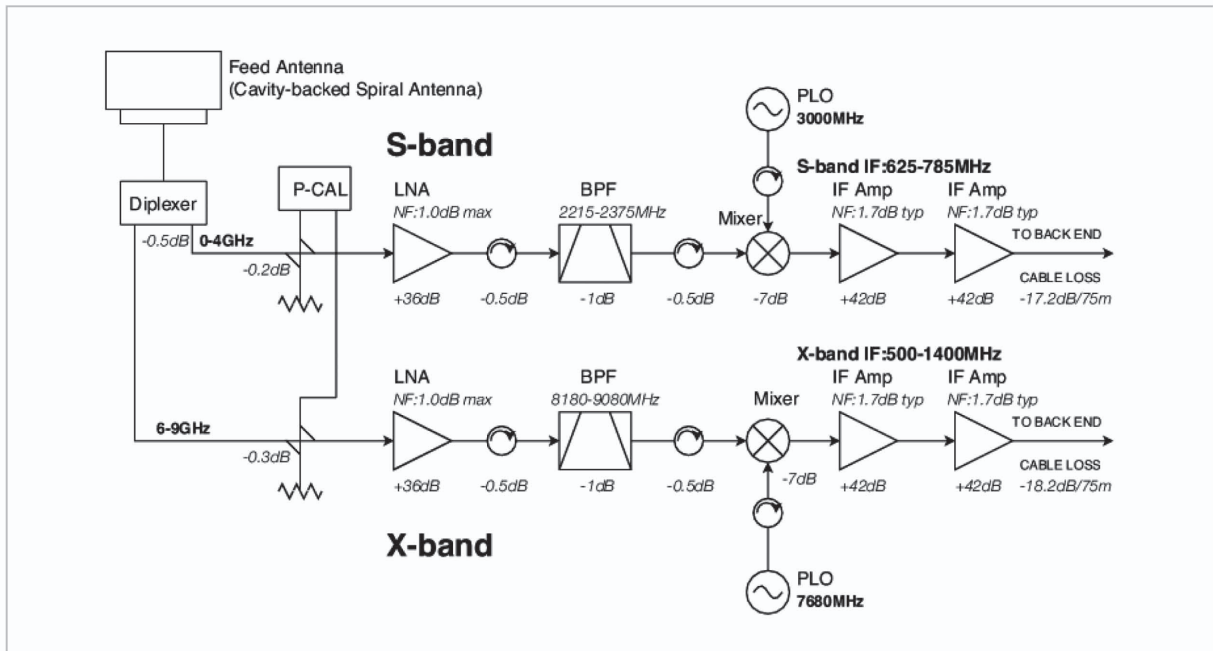
From the beginning of 2006, as a result of the continued establishment of operation through antenna control software "MAOS", it became possible to track radio sources based on conventional observation schedules. Moreover, axis calibration experiments were performed since the start of fiscal 2006 in order to



**Fig.5** Radio telescopes at the Kashima Space Technology Center, NICT

The big one on the left is the 34-m antenna. The next small one is the CARAVAN2400 system (see text). The right one is the 11-m antenna. The dome in the center is SLR station.



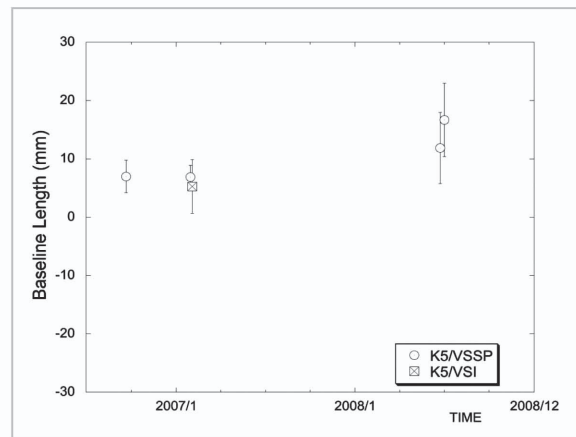


**Fig.6** The block diagram of the CARAVAN2400 system

improve an accuracy of radio source tracking. In September 2006 we finally succeeded to obtain the site position of the CARAVAN2400 through the analysis of the second geodetic VLBI experiment with the GSI 32 m station[6].

The third geodetic VLBI experiment was carried out in February 2007 using the K5/VSI system[11][12] which can acquire one gigabit data, and this experiment was also a success[13]. If we use the 1.5 m class antenna for the compact VLBI systems, the sensitivity of the system is insufficient for geodetic purpose. Thus, the broadband data acquisition system such as K5/VSI is indispensable. In this third experiment, simultaneous recording was carried out using two methods: (1) single channel recording using the K5/VSI in 512 MHz band width, and (2) multi-channel recording using the K5/VSSP32 in 128 MHz band width[14] and the baseline results by both methods were compared. As a result, both results were consistent with each other and the advantage of broadband observation was confirmed in term of smaller formal error (see Fig. 7).

Thereafter, we started the development of broadband frontend systems in 2007 in order to equip a simultaneous S/X band capability which is compatible with the conventional geo-



**Fig.7** Baseline length between CARAVAN2400 and Tsukuba 32-m antenna at the GSI in Tsukuba

detic VLBI observation. For large diameter antennas, there is a comparatively large margin for receiver arrangement in the antenna feed, however, in compact VLBI systems, it is necessary to bear in mind that there are severe spatial restrictions for receiver configurations of a simultaneous S/X band capability. Consequently, as a result of examining multiple comparisons of broadband primary radiators which are capable of receiving signals in bands which conjugate both S/X, we chose a broadband dual-polarized quadridge horn antenna (QRHA/type

Model 3164-05 made by ETS-Lindgren, see Fig. 11) ranging 2–18 GHz.

By the end of 2007, a front-end system using this QRHA was mounted on the CARAVAN2400. In December of 2007, fringe detection in S/X simultaneous reception between the CARAVAN2400 with the QRHA mounted and the Kashima 34 m antenna was successfully carried out, and it was verified that QRHA was effective as a primary radiator for compact VLBI systems[15]. Furthermore, on June 23–24 of 2008 and July 2–3 of the same year, we successfully carried out geodetic VLBI experiments with the GSI 32 m station using the same front-end[16]. A series of geodetic experiment results using CARAVAN2400 are shown in Fig. 7. The formal error for results using the new front-end is 6 mm. This large formal error is caused by the low antenna aperture efficiency less than 10%. The obtained baseline length analysis results were consistent with each other within the formal error. This result implies that the geodetic experiments can be carried out using the newly developed broadband front-end.

### 3.4 Laser-pumped Cs Gas-cell Frequency Standard for geodetic VLBI experiments

In geodetic VLBI observation using compact VLBI systems, transportability is required for the frequency standard as well as the antenna. However, a conventional hydrogen maser frequency standard is unsuitable for transportation. The Laser-pumped Cs Gas-cell frequency standard (hereafter, we call it ‘Cs gas-cell oscillator’) developed by Anritsu Corporation shows high stability of the order of  $10^{-13}$  for 1 – several tens seconds averaging

time and  $10^{-14}$  for 100 seconds averaging time, though its stability is a little inferior to that of the hydrogen masers[17]. In addition, compared to hydrogen masers, it is extremely compact and lightweight, and nearly the same size and weight (18 kg) as a single desktop PC.

In order to evaluate the effectiveness of this Cs gas cell oscillator, geodetic VLBI experiments were carried out on July 19, 2007 between the Kashima 34 m station and Koganei 11 m station baseline (Baseline length: approx. 110 km). Only the Kashima 34 m station used the Cs gas cell oscillator 10 MHz and 1PPS as a reference frequency signal, meanwhile the Koganei 11 m station used the conventional hydrogen maser reference frequency signal. The baseline length result obtained in this observation and the results from are shown in Table 2. Baseline length estimate values obtained from each observation are consistent with each other within a formal error of about 2 mm, and it was confirmed that the Cs gas cell oscillator was effective as a reference frequency signal source for geodetic VLBI experiments. However, as of November of 2010, development has stopped on this oscillator, and it is unclear whether or not it will be able to be used in the MARBLE system in the future. We refer to another article for more details on these experiments[18].

### 3.5 1.5 m class compact VLBI system

From fiscal 2007, the full-scale development of a compact VLBI system has begun in parallel with the development of the CARAVAN2400. From the concept design based on the earlier mentioned technological requirements and CARAVAN2400 development results, work was started on the first prototype

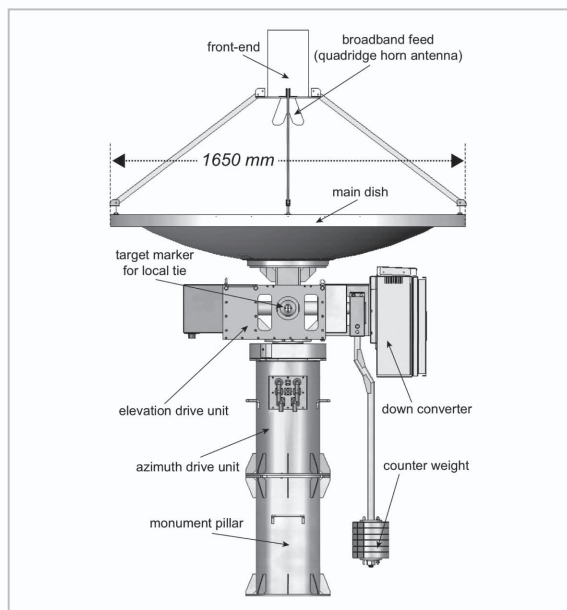
**Table 2** Summary of VLBI experiments

DATE	Duration (hour)	OBS No.	WRMS(※) residuals (psec)	Baseline length (mm)
2007.6.15	24.4	982	32	109337424.10±1.17
2007.6.17	37.6	1142	29	109337422.26±1.00
2007.6.20	71.2	2880	37	109337421.45±0.76
2007.7.19	25.9	1054	39	109337422.58±1.26

The laser-pumped Cs Gas-cell frequency standard is used in the last experiment on July 19<sup>th</sup> of 2007. (※WRMS: weighted root mean square)



and the development was able to be completed by the end of the fiscal year[19]. Figure 8 shows a conceptual diagram of the first prototype. Additionally, all the major components of the antenna are shown in Table 2. The system consists of a 1.65 m diameter aperture antenna with a broadband feed on ambient temperature, a drive unit of Az/El-mount type, an IF down-converter unit, an antenna control unit (ACU), a counterweight and a monument pillar. Each drive unit is equipped with a zero-backlash harmonic drive gearing component. The monument pillar is designed to install typical geodetic GNSS antennas easily and an offset between a GNSS antenna reference point and a location of the azimuth-elevation crossing point of the VLBI system is precisely measured



**Fig.8** Schematic image of the MARBLE compact VLBI system

and uncertainty of less than 0.2 mm.

Moreover, in fiscal 2008, we developed the second prototype of the system. By halfway through fiscal 2009, the first prototype was installed at NICT Kashima Space Research Center, and the second one was installed at the GSI, and both were set-up to carry out the first verification tests (Fig. 9). The antenna and mount can be disassembled into many parts avoiding the need for heavy machinery in approximately half a day using a tripod crane as shown in Fig. 10.

In compact VLBI systems, a QRHA is placed at the focal point of the reflector. At the back of the feed, there is a front-end receiver with wide-band LNAs which can amplify up to 11 GHz. The front-end receiver also plays the roles of a polarizer and frequency discriminator. At present, the receiver is only set-up for S and X bands. However, by replacing RF filters and other RF components, it will be able to receive arbitrary frequency bands between 2 and 11 GHz (see Fig. 11). This is to prevent degradation of the signal strength on both sides in the S/X band. As a test of this frontend system, on February 12, 2009, the first fringe detection was successfully completed using the first prototype and the Kashima 34 m antenna using the latest cutting edge “ADS3000+[22][23]” A/D sampler, operating at a sampling rate of 4096 Msps and equipped with a high speed FPGA function, confirming its functionality as a VLBI[24]. This allowed for the preparation of following full-scale geodetic experimentation.

**Table 3** Specifications of the compact VLBI system

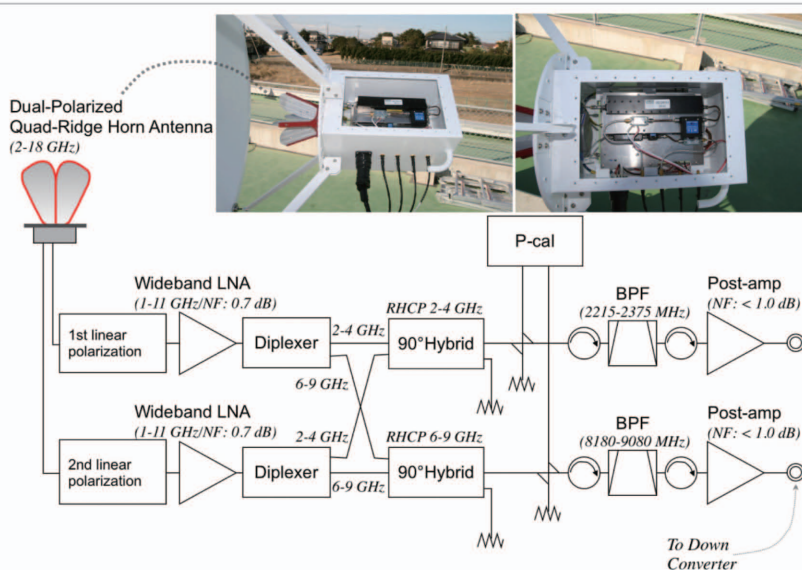
Antenna type	Prime-focus, paraboloidal
Antenna diameter	1.5–1.65 meter
Frequency	S/X band (dual-frequency), Operating frequency of the feed is ranging 2 to 18 GHz.
Mount type	Azimuth-elevation
Azimuth and Elevation slewing	5 degrees per second
Antenna control software	Field System 9 (FS9[20][21])
Weight	350 kg. The whole system is consistent with seven components and the maximum weight of the component is 100 kg.



**Fig.9** Left: The first prototype of the MARBLE compact VLBI system at Kashima Space Technology Center, NICT. Right: The second prototype at the GSI, Tsukuba



**Fig.10** Installation of a first prototype of the compact VLBI system on the top of the 34 m antenna building on December 9, 2008 at Kashima



**Fig.11** The new front-end system. A wideband LNA ranging 1-11 GHz and a broadband dual-polarized quad-ridge horn antenna ranging 2 – 18 GHz (type 3164-05) made by ETS-Lindgren™ are equipped in the system.



## 4 MARBLE system geodetic observation results

After various experiments using CARAVAN2400 and the fringe test using the first prototype, we carried out a 24 hour geodetic VLBI experiment using the Tsukuba 32 m antenna, the first prototype, and the Kashima 11 m antenna as the compact station on June 25, 2009. The purpose of this experiment was to verify the geodetic observation performance of the first prototype of the compact VLBI system in addition to evaluating the implementation of the MARBLE concept described above.

As a result of the experiment, we successfully obtained fringes over 24 hours and could estimate the baseline length between the Kashima 11-m station and the first prototype to about 200 m. The formal error of the measured baseline length was 2.3 mm. This result was the first obtained using the MARBLE concept<sup>[25]</sup>. After this, on December 24, 2009, a 24 hour VLBI test using 4 stations: two prototypes of the compact VLBI system, the Tsukuba 32 m station and the Kashima 34 m station, was carried out, and the formal error of the approximately 54 km baseline between the two prototypes at Kashima and Tsukuba was successfully able to be determined with the formal error of 2.7 mm<sup>[26]</sup>.

Reference baseline lengths for calibration validation require a short time repeatability (the same as the uncertainty of type A<sup>[27]</sup>) of  $\pm 2.0$  mm as a result of multiple baseline length analyses. As such, in order to further solidify the precision evaluation of the MARBLE system, the following verification experiments were vital:

- (1) In order to evaluate type A uncertainty, VLBI experiments to determine the baseline vector between compact stations should be implemented multiple times.
- (2) Carry out comparison with GPS baseline observation using compact VLBI support (Type B uncertainty evaluation).

However, in fiscal 2010, due to a short circuit of the directional drive motor of the second prototype caused by leaking water and time re-

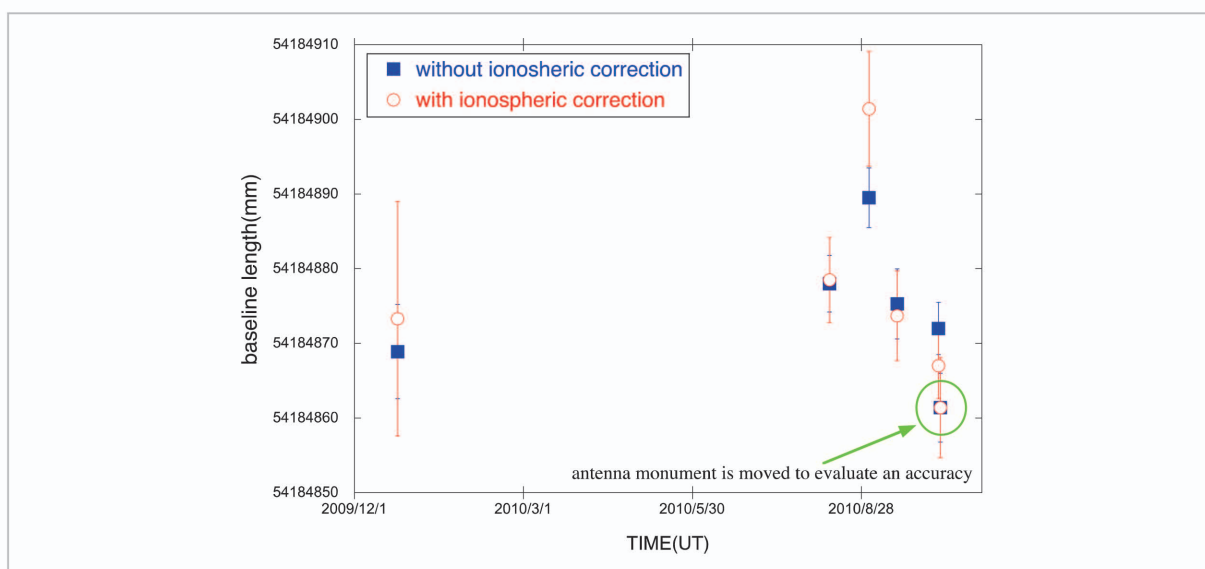
quired for improvement of the drive system controller software, the actual geodetic VLBI experiment was not started until the start of August. As of November 15, 2010, VLBI experiments have been carried out five times on the following dates:

- August 11–12, 2010
- September 1–2, 2010
- September 16–17, 2010
- October 8–10, 2010
- November 11–12, 2010

The final observation in November is still undergoing correlation processing, so the results up to October are shown in Fig. 12. In addition, the monument pillar for the second prototype, has a mechanism which allows for sliding of 20 mm in the horizontal direction. If this slider is intentionally displaced, the station position displacement detection can also be used as a precision evaluation item. In the final 24 hour experiment on October 9, 2010 in the figure, the monument was displaced using this slide mechanism, and this experiment is therefore discussed separately from the other analysis results.

First, unfortunately, for the two observations from the end of December 2009 and August 2010, the frequency arrangement optimization was insufficient, and there was a low rate of success with bandwidth synthesis due to trouble with the phase calibration signal generator, leading to a much larger formal error than other calibration analysis results. In particular the trouble in the latter experiment was caused by the ambiguity problem. When the bandwidth synthesis of data was performed, ambiguities were not resolved (occurrence of sub ambiguity problem). As a result only one portion of the total observation data was able to be used for analysis. RMS from the results of the three experiments for which conditions were favorable, the two experiments in September and the experiment of October 8, results in:

$$54184875.1 \pm 2.5 \text{ mm}$$



**Fig.12** Results of geodetic VLBI experiments

In fact, the dual-frequency (S/X bands) processing for ionospheric delay compensation has not yet been carried out in these analysis results. In the same manner, for the results in Fig. 12 for which ionosphere compensation has been carried out, the RMS value was nearly 50% rather worse yielding a precision of 4.7 mm. The cause of this is still unknown. Since the effect of ionospheric delay error is somewhat cancelled in the procedure of the MARBLE concept, it is possible to overestimate or to underestimate the effect. We need a further investigation about this issue.

Next, we will discuss the October 9 results wherein an artificial displacement was introduced using the slide mechanism. Using this slide mechanism, a maximum displacement of 18.7 mm can be introduced to the direction of the baseline between Kashima and Tsukuba. The displacement was set to 10.5 mm w.r.t. the results of October 8 and 13.7 mm when compared to the average value of the above three analyses, which is slightly too small. However these results were well within the formal errors. It is necessary to carry out similar experiments multiple times in the future to investigate the details.

For the MARBLE system precision goal of “measuring a 10 km baseline vector length to within RMS 2 mm,” these results are still insuf-

ficient when taking into consideration that the VLBI basics which do not depend on baseline length. In order to achieve this goal, increasing sensitivity by applying a broadband system and increasing observation frequencies by reducing integral time are both indispensable. Consequently, in the geodetic experiment of November, ADS3000+ was used for data acquisition with an A/D sampling method at 512 MHz bandwidth (260 MHz in reality for S band) per S/X band channel. In addition, in this experiment, nearly two times of observables were acquired by comparing with conventional VLBI experiments. At the time of writing this paper, correlation processing and analysis processing are still not complete, so we cannot report on the results, however we expect results which will demonstrate the high performance of the MARBLE system.

## 5 Conclusions and the future of compact VLBI systems

We developed the MARBLE system which integrates compact VLBI systems and the new analysis procedure for validation of reference baseline lengths for calibration in the medium-term plan framework together with the GSI since fiscal 2006. Through the broadband front-end using the testbed CARAVAN2400, trial



production of the compact VLBI system and evaluation of the MARBLE concept, we have demonstrated that the MARBLE system is capable to perform the geodetic VLBI experiments in the fiscal year of 2010. Meanwhile, accuracy of the system is still insufficient in maintaining traceability from national standards for length, and the current broadband data acquisition experiment is the key to achieving goals.

In addition, we are now planning to use the compact VLBI system into the precise time and frequency T&F transfer between separated locations. As one part of this, we plan to move the second prototype of the compact VLBI system to NICT Koganei headquarters in the near future and carry out T&F transfer experiments between Kashima and Koganei using the MARBLE system. T&F transfer VLBI experiments are essentially identical on the geodetic experiment and analysis method fronts, and we

also plan to test geodetic precision evaluation in these analyses as well.

In the medium-term plan for next term, planned to begin present fiscal year, the realization of more precision T&F transfer VLBI observation will be important. To this end, the further improvement of existing system will be indispensable. In addition to examining undertaking work on the next generation VLBI technology development concept “VLBI2010[7]” and the earlier introduced broadband data acquisition using ADS3000+, we also have plans for:

- Reexamination of antenna diameters and shapes
- A receiver system cooled to tens of K
- Digitalization of phase calibration signals
- Introduction of round trip systems for calibration of cable delay

We will discuss these items together with the results of the broadband VLBI experiments at our next opportunity.

## References

- 1 Kokudo-chiriin, Kisenba Kaisoku Yoryo, 2003. (in Japanese)
- 2 Nogami K., Hirai H., Tsuzuku M., Toyoda T., and Tanaka H., “About a System and Standardization of Traceability on Distance Standard Baseline,” Kokudo-chiriin Gijutsushiryo, A1-No. 312, pp. 11–12, 2006. (in Japanese)
- 3 Nogami K. and Tsuzuku M., “About a System and Standardization of Traceability on Distance Standard Baseline,” GSI journal, Vol. 112, pp. 7–15, 2007. (in Japanese)
- 4 Ichikawa R., Kuboki H., Kyama Y., Nakajima J., and Kondo T., “Development of the new VLBI facility with a 2.4-m dish antenna at NICT, NICT IVS TDC News,” No. 26, pp. 13, Sept. 2005.
- 5 Ishii A., Ichikawa R., Kuboki H., Koyama Y., Nakajima J., Takashima K., and Fujisaku J., “Development of the small dish VLBI system CARAVAN2400,” 2006 Japan Earth and Planetary Science Joint Meeting, D123-P007, 2006. (in Japanese)
- 6 Takiguchi H., Ishii A., Ichikawa R., Kuboki H., Nakajima J., Koyama Y., Fujisaku J., and Takashima K., “Development of Compact VLBI System with 1-m class Antenna for Validating 10 km Calibration Site — Geodetic observation using the CARAVAN2400 —,” Abstracts of 106th Meeting of the Geod. Soc. Japan, No. 7, 2006. (in Japanese)
- 7 Niell, A., A. Whitney, B. Petrachenko, W. W. Schluter, N. Vandenberg, H. Hase, Y. Koyama, C. Ma, H. Schuh, and G. Tuccari, “VLBI2010: Current and future requirements for geodetic VLBI systems,” IVS 2005 Annual Report, NASA/TP-2006-214136, pp. 13–20, 2006.
- 8 Yonezawa I., Nakajima J., Ohkubo H., Tsuboi M., and Kasuga T., “Development of compact VLBI system,” CRL IVS TDC news, No. 21, pp. 29–30, 2002.

- 9 Ichikawa R., Ishii A., Takiguchi H., Kuboki H., Kimura M., Nakajima J., Koyama Y., Kondo T., Machida M., Kurihara S., Kokado K., and Matsuzaka S., "Development of a compact VLBI system for providing over 10-km baseline calibration," *Measuring The Future, Proc. of the Fifth IVS General Meeting*, 400–404, 2008.
- 10 Alan Robert Whitney, "Precision geodesy and astrometry via very-long-baseline interferometry," Massachusetts Institute of Technology, 355p. Ph. D. thesis, 1974.
- 11 Kimura M. and Nakajima J., "The implementation of the PC based Giga bit VLBI system," *IVS CRL-TDC News*, No. 21, pp. 31–33, 2002.
- 12 Nakajima J. and Kimura M., "VLBI de Gigabit Kansoku ga Kanoni," *Parity*, Vol. 17, No. 06, pp. 39–41, 2002. (in Japanese)
- 13 Ishii A., Ichikawa R., Takiguchi H., Kuboki H., Kimura M., Nakajima J., Koyama Y., Fujisaku J., and Takashima K., "Development of a compact VLBI system on a 10 km baseline with 1-m class antennas for calibration purposes," 2007 Japan Earth and Planetary Science Joint Meeting, D106-003, 2007. (in Japanese)
- 14 Kondo T., Koyama Y., Ichikawa R., Sekido M., Kawai E., and Kimura M., "Development of the K5/VSSP system," *Journal of the Geodetic Society of Japan*, 54, 4, 233–248, 2008.
- 15 Ishii A., Ichikawa R., Takiguchi H., Takefuji K., Koyama Y., Kurihara S., Kokado K., and Tanimoto D., "Geodetic VLBI experiments by a small VLBI antenna with a broad-band feed," *IVS NICT-TDC news*, No. 30, pp. 30–32, 2009.
- 16 Ishii A., Ichikawa R., Takiguchi H., Takefuji K., Koyama Y., Kurihara S., Kokado K., and Tanimoto D., "Evaluation of a Radio Telescope Using a Quadridge Horn Antenna on Geodetic VLBI," *Abstracts of 110th Meeting of the Geod. Soc. Japan*, No. 18, 2008. (in Japanese)
- 17 Ouchi Y., Sudo H., Soga T., Fujita M., Saito T., and Nagoya Y., "Practical use of a Laser-pumped Cs Gas-cell Type Atomic Clock with High Frequency Stability," *Papers of Technical Meeting on Instrumentation and Measurement*, IEE Japan, IM-06-29, pp. 25–32, 2006.
- 18 Ishii A., Ichikawa R., Takiguchi H., Kuboki H., Sekido M., Koyama Y., and Ohuchi Y., "Evaluation of a laser-pumped Cs gas-cell frequency standard on geodetic VLBI," *Journal of the Geodetic Society of Japan*, 54, 4, 259–268, 2008.
- 19 Ishii A., Ichikawa R., Takiguchi H., Kuboki H., Kondo T., Koyama Y., Machida M., and Kurihara S., "Current Status of Development of Compact VLBI System with 1-m class Antenna for Providing over 10 km Baseline Calibration," 2008 Japan Earth and Planetary Science Joint Meeting, D106-003, 2008. (in Japanese)
- 20 E. Himwich, in *Technical Workshop for APT and APSG* (Communication Research Lab., Kashima), 1996.
- 21 E. Himwich, in *IVS 2000 General Meeting*, Ed. by N. Vandenberg and K. Baver (NASA, Washington), 2000.
- 22 Koyama Y., Takeuchi H., Sekido M., Kondo T., Takefuji K., and Tsutsumi M., "Developments of Next-Generation A/D Sampler ADS3000+," *Abstracts of 110th Meeting of the Geod. Soc. Japan*, No. 8, pp. 185–186, 2008. (in Japanese)
- 23 Takefuji K., Koyama Y., Takeuchi H., Kondo T., Sekido M., and Tsutsumi M., "Performance of Next-Generation A/D Sampler ADS3000+," *Abstracts of 110th Meeting of the Geod. Soc. Japan*, No. 3, 2008. (in Japanese)
- 24 Ishii A., Ichikawa R., Takiguchi H., Koyama Y., Kurihara S., Takano T., Fukuzaki Y., Miura Y., and Tanimoto D., "Current Status of Development of Compact VLBI System with 1-m class Antenna for Providing over 10 km Baseline Calibration -Part 3-," *Abstracts of 112th Meeting of the Geod. Soc. Japan*, No. P. 6, 2009. (in Japanese)



- 25 Ishii A., Ichikawa R., Takiguchi H., Koyama Y., and Kurihara S., "Evaluation of the new approach to improving compact-compact antenna baseline in VLBI Part 2," Abstracts of 112th Meeting of the Geod. Soc. Japan, No. 56, 2009. (in Japanese)
- 26 Ishii A., Ichikawa R., Takiguchi H., Takefuji K., Ujihara H., Koyama Y., Kondo T., Kurihara S., Miura Y., and Tanimoto D., "Current Status of Development of Compact VLBI System with 1-m class Antenna for Providing over 10 km Baseline Calibration -Part 4-, " 2010 Japan Earth and Planetary Science Joint Meeting, SGD001-P07, 2010. (in Japanese)
- 27 Guide to the Expression of Uncertainty in Measurement, ISO/IEC Guide 98, 1995.

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