PASJ: Publ. Astron. Soc. Japan **55**, L57–L60, 2003 August 25

LETTER

First Fringe Detection with VERA's Dual-Beam System and Its Phase-Referencing Capability

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(Received 2002 December 17; accepted 2003 May 30)

Abstract

We present the results of the first dual-beam observations with VERA (VLBI Exploration of Radio Astrometry). The observations of a pair of H_2O maser sources, W 49N and OH 43.8−0.1, were carried out on 2002 May 29 and July 23, and fringes of the H_2O maser lines at 22 GHz were successfully detected. While the residual fringe phases of both sources showed rapid variations over 360° due to the atmospheric fluctuation, the differential phase between the two sources remained constant for 1 hour with an r.m.s. of 8°, demonstrating that the atmospheric phase fluctuation was effectively removed by dual-beam phase referencing. An analysis based on the Allan standard deviation reveals that the differential phase is mostly dominated by white phase noise, and the coherence function calculated from the differential phase shows that after phase referencing the fringe visibility can be integrated for an arbitrarily long time. These results demonstrate VERA's high capability of phase referencing, indicating that it is a promising tool for phase-referencing VLBI astrometry at 10 μas-level accuracy.

Key words: astrometry — masers — techniques: interferometric — technique: phase-referencing — VERA — VLBI

1. Introduction

VERA (VLBI Exploration of Radio Astrometry: Sasao 1996; Honma et al. 2000 and references therein) is a new VLBI array dedicated to phase-referencing astrometry. Referring to distant radio galaxies and QSOs, VERA measures the proper motions and parallaxes of galactic H_2O and SiO maser sources (mainly star-forming regions and Mira variables) with 10 μas-level accuracy. With that high accuracy, VERA can measure the parallax of masers located at D kpc away with an accuracy of D% and the proper motion with an accuracy of $0.05 \times D\,\mathrm{km\,s^{-1}}$ for a monitoring time span of one year. Hence, VERA will be able to establish the 3-D structure and dynamics of the Milky Way with unprecedentedly high accuracy (for detailed scientific targets, see Honma et al. 2000).

The key to precise VLBI astrometry at 22 GHz and 43 GHz is how to remove the atmospheric phase fluctuation based on phase referencing. Previously, phase referencing has been done based on various methods, including fast switching, paired/clustered antennas, and water vapor radiometer (e.g., Beasley, Conway 1995; Asaki et al. 1996, 1998; Rioja et al. 1997; Carilli, Holdaway 1999; Thompson et al. 2001). Among them, the most popular one is fast switching, in which two adjacent sources are observed in turn in a short cycle (typically $\sim$1 min). There have already been some examples of switching VLBI observations at 22 GHz and 43 GHz, such as QSO–QSO astrometry by Guirado et al. (2000) and a proper motion measurement of Sgr A* by Reid et al. (1999), but the achieved astrometric accuracy remained at around 100 μas.

In order to achieve higher performance in phase referencing and also in astrometric measurements, VERA utilizes a rather unique system, a so-called dual-beam antenna, in which two steerable receivers located at the focal plane simultaneously observe two sources (target and reference sources) with the separation ranging from 0.°3 to 2.°2 (Kawaguchi et al. 2000). With dual-beam observation, the phase fluctuations of two sources can be measured at the same time, and thus one can expect a higher performance in phase referencing.

In order to investigate how effectively VERA's dual-beam system works for phase referencing, we have been conducting test observations since the completion of all four stations in early 2002. Here, we report on the results of the first fringe observations with the dual-beam system, and demonstrate its high capability of phase referencing.

2. Observation and Reduction

After detecting a single-beam first fringe of the Orion-KL H_2O maser with the Mizusawa–Iriki baseline on 2002 February 20, we made the first dual-beam VLBI observation with VERA on 2002 May 29 at 22 GHz. A pair of strong H_2O maser sources, W 49N and OH 43.8−0.1, separated by 0.°65 on the sky plane, was observed with the Mizusawa and Iriki stations from 13:15 UT for about 40 minutes. The sky conditions at two stations were moderate, with the system noise temperatures (at the zenith) between 300 and 400 K at both stations. Only left-handed circular polarization was received and sampled with 2-bit quantization, and filtered with a bandwidth of 16 MHz for each source using the VERA Digital Filter before being recorded onto magnetic tapes at a rate of 128 Megabit s^{-1} (16 MHz band × 2 beams). Correlation process was carried out on Mitaka FX correlator located at the NAO Mitaka campus with a spectral resolution of 31.25 kHz (512 channels per 16 MHz band). Fringes were successfully detected for both W 49N and OH 43.8−0.1. In order to confirm the system reliability, we also made dual-beam observations of the same sources on 2000 July 23 for a longer period with the same system configuration. The dual-beam fringes were successfully detected again for the second observation.

Due to the error in the tracking-center positions of the maser sources as well as an error in the station positions, the residual fringe rates of raw correlator outputs were fairly large for both sources and for both observational sessions in May and July. To correct for the effect of the residual fringe rate and fringe phase, we fitted the fringe phase (and also the fringe rate) based on the relation $\phi = U\Delta X + V\Delta Y$ (ϕ is the fringe phase, U and V are the projected baseline components in the UV plane, and ΔX and ΔY are the position offsets of the tracking center), assuming that the residual fringe phase totally comes from the position error of the tracking center. This procedure can be regarded as 'high-pass filtering', in which the rapid phase variation due to atmospheric fluctuation is conserved while slowly varying phase error due to a position offset is corrected for. In the following sections we present the residual fringe phase after a correction of the position offset.

For both observations, no calibration was made to correct for the variation of the instrumental delay difference in the dual-beam system. Recent results of a dual-beam phase calibration based on the horn-on-dish method (Kawaguchi et al. 2000) revealed that the instrumental delay in the dual-beam system was quite stable, with a phase drift of less than 3° hr^{-1} at 22 GHz. Therefore, the result presented in this paper would hardly be changed by including the dual-beam phase calibration.

3. Results

3.1. Dual-Beam Phase Referencing

Figure 1 shows the residual fringe phase of the intensity peak channel for two maser sources observed on 2002 July 23. Here, the visibilities for W 49N and OH 43.8−0.1 were integrated for 5 s, and the constant bias of the phase, which is of no interest here, was corrected for so that the residual fringe phase becomes 0 at the time origin (11:30 UT). In figure 1

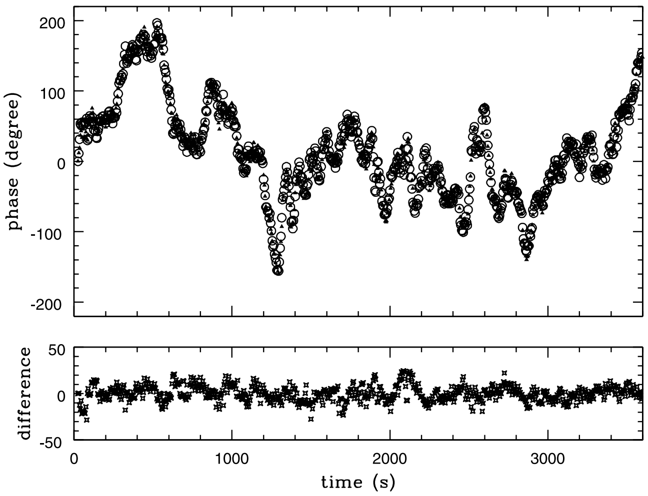

Fig. 1. (Top): Residual fringe phases for W 49N (open circle) and OH 43.8−0.1 (triangle) intensity peak channel. (Bottom): Differential fringe phase (phase difference of the two sources). The time origin was 11:30 UT on 2002 July 23.

the residual fringe phases show a strong time-variation due to atmospheric fluctuations. During the observed period (3600 s), the residual phase ranges from −180° to +200°. In particular, from 1300 s to 1330 s, the phase varies by 114° from −149° to −35°. For fast switching observation, a phase jump of ∼ 180° is critical because of a 360° ambiguity in the phase, and hence a rapid phase variation like this could cause a systematic error in a fast-switching VLBI unless the switching cycle is sufficiently shorter than the time scale of the phase variation.

However, the phase variations for W 49N and OH 43.8−0.1 observed with VERA coincides well with each other. In fact, the differential phase (difference of two fringe phases in figure 1) is nearly constant at ∼ 0° with a maximum deviation of less than ±30°. This result strongly demonstrates that the VERA's dual-beam system efficiently calibrates the atmospheric phase fluctuations. The r.m.s. noise level for the differential phase is 8°. In the differential phase plot there appear some structures with a time scale of 30 to 100 s (small bumps with peak-to-peak amplitude of 20°–30°). In fact, the power spectrum of the differential phase showed that while the power spectrum is almost flat in most frequency ranges, it has a gentle gradient with a power-law index of ∼ −1 in the range of 0.2 Hz to 0.02 Hz (5 to 50 s in the time domain), confirming the existence of some structures in that time range. These structures may be due to 1) small-scale structures of the atmosphere, which was not common to the two sources separated by 0.°65 and thus was not cancelled out, and 2) the structures of the maser sources themselves, which also introduce variation in the fringe phase. We note that the residual differential phase changes moderately when the phase of the different channel maser is used, and hence there is indeed some maser structure effect in the differential phase. In any case, we can smooth out that those structures in the differential phase based on averaging for a longer time scale, since the power spectrum of the differential phase is flat beyond a time scale of 100 s.

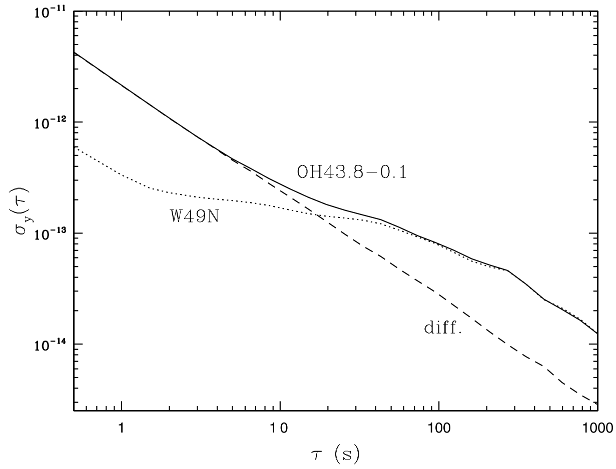

Fig. 2. Allan standard deviation for the fringe phase of W 49N (dotted line) and OH 43.8−0.1 (thin line), and the differential phase (dashed line).

3.2. *Allan Standard Deviation*

In order to investigate the characteristics of the phase variation, we calculated the Allan standard deviation for the residual fringe phases and the differential phase. The Allan standard deviation, $\sigma_y(\tau)$, can be calculated as follows (e.g., Thompson et al. 2001):

$$\sigma_y^2(\tau) = \frac{\langle [\phi(t+2\tau) - 2\phi(t+\tau) + \phi(t)]^2 \rangle}{8\pi^2 \nu_0^2 \tau^2}. \qquad (1)$$

Here, ν_0 is the observational frequency, ϕ is the observed phase, τ is time interval, and the brackets $\langle\rangle$ denote the average over all samples.

Figure 2 shows $\sigma_y(\tau)$ for the fringe phases of W 49N and OH 43.8−0.1 and for the differential phase (both for 0.5 s integration). For W 49N, $\sigma_y(\tau)$ is nearly constant at $\sim 2 \times 10^{-13}$ between $\tau = 2$ s and 30 s, indicating that the phase fluctuation is dominated by flicker-frequency noise. Beyond $\tau =$ 100 s, $\sigma_y(\tau)$ for W 49N (and also for OH 43.8−0.1) becomes almost white-phase noise, decreasing with τ^{-1}. This feature, a combination of the flicker-frequency noise for a shorter time scale and white-phase noise for a longer time scale, has been well-known as a typical behavior of the phase in VLBI (Rogers, Moran 1981; Rogers et al. 1984). In contrast, for OH 43.8−0.1 $\sigma_y(\tau)$ for short time scale (less than 10 s) is proportional to τ^{-1}. This is due to the S/N limit for OH 43.8−0.1, which is fainter than W 49N. In fact, the correlated flux density for the OH 43.8−0.1 peak channel was 1.8×10^2 Jy for the Mizusawa–Iriki baseline, and an estimate of the Allan standard deviation from the signal-to-noise ratio (*SNR*) gives 2.3×10^{-12} for $\tau = 1$ s, which is in good agreement with the observed value of 2.1×10^{-12}.

On the other hand, $\sigma_y(\tau)$ for the differential phase is inversely proportional to τ. This result indicates that the dual-beam phase referencing removed atmospheric fluctuation effectively, and that the differential phase is dominated by white phase noise. We note that in the time range of 5 to 50 s the differential phase is likely to be dominated by flicker-phase noise due to the phase structure shown in the figure 1, but that the flicker-phase noise also gives almost the same gradient to the white-phase noise in the Allan standard deviation plot (e.g., Thompson et al. 2001), and hence little feature is seen for the differential phase in figure 2. Since $\sigma_y(\tau)$ for OH 43.8−0.1 and $\sigma_y(\tau)$ for the differential phase become asymptotically equal toward a small time interval ($\tau \leq 5$ s), the differential phase is mainly due to *SNR* limit for OH 43.8−0.1.

For the data taken on 2002 May 29, we also calculated the Allan standard deviation and obtained similar results. We found that $\sigma_y(\tau)$ for $\tau = 100$ s was 3.7×10^{-14}, instead of 2.9×10^{-14} on 2002 July 23. This difference of factor of 1.3 is mainly due to the difference in the weather conditions. Nevertheless, $\sigma_y(\tau)$ for the differential phase taken on 2002 May 29 also shows a linear trend, like that in figure 2, proportional to τ^{-1}.

3.3. *Long-Term Integration*

As can be seen in figure 1, single-beam VLBI strongly suffers from atmospheric fluctuations. Due to the rapid phase variation, the complex visibility cannot be integrated beyond the so-called coherence time, which is around a few minutes at 22 GHz under typical atmospheric conditions. Phase referencing can be a powerful tool to overcome this coherence problem, enabling us to integrate the complex visibility beyond the coherence time. In order to see how the integration performance is improved based on the dual-beam phase referencing, we calculated the coherence function using the fringe phase and the differential phase in figure 1. The coherence function, $C(T)$, can be defined as follows (Rogers, Moran 1981; Thompson et al. 2001):

$$C(T) = \left| \frac{1}{T} \int_0^T \exp[i\phi(t)]\, dt \right|, \qquad (2)$$

where $\phi(t)$ is the observed visibility phase or the differential phase in figure 1, and T is the integration time.

As can be seen in figure 3, the integration using the fringe phase of W 49N is of course ineffective; the amplitude rapidly declines beyond the integration time of 250 s. We note that the constancy of the coherence function for W 49N beyond 1500 s is likely to be artificial, mainly due to 'high-pass filtering' of the fringe phase in which a slowly-varying long-term drift was corrected for; the real situation would be worse than what appears in figure 3. On the other hand, the integration using the differential phase gives an excellent result: the amplitude remains constant for any integration time t, and is still 0.98 after integration of 1 hr. This result indicates that, based on the phase referencing with VERA's dual-beam system, one can integrate the visibility for an arbitrarily long period, and hence one can improve *SNR* of the visibility as $t^{1/2}$. Thus, VERA's dual-beam phase referencing will provide a new and powerful tool to study faint objects that cannot be detected without long-term integration.

4. Discussion and Conclusion

Here, we discuss whether the phase referencing capability of VERA is sufficient for 10 μas-level astrometry. In terms of

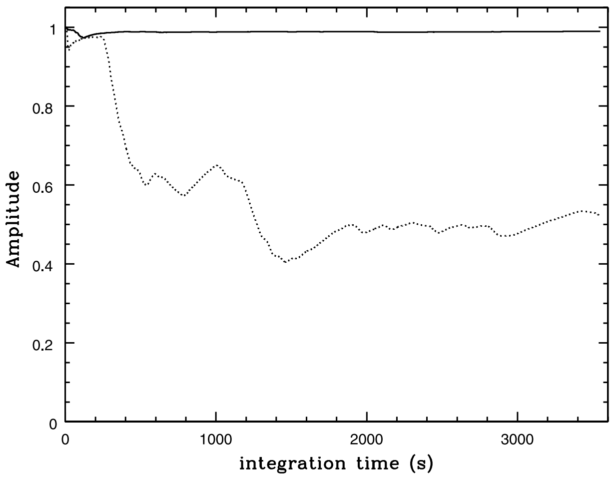

Fig. 3. Coherence function calculated for the fringe phase of W 49N (dotted line) and the differential phase (thin line).

the fringe phase, the target accuracy is $\sim 3^\circ$ for 22 GHz, which corresponds to 0.1 mm in path-length error. With a maximum baseline of 2300 km (between Mizusawa and Ishigaki-jima stations), one can obtain a rough estimate of VERA's astrometric accuracy as 0.1 mm/2300 km $\sim 10\,\mu$as. On the other hand, the differential phase residual in figure 1 has an r.m.s. error of $\sim 8^\circ$, which is still larger than the target accuracy of VERA by a factor of 3. However, we have also seen that the nature of the differential phase is mostly white phase noise that comes mainly from the *SNR* limit of the fainter source, OH 43.8−0.1. Hence, integrating the visibility for a longer period makes the residual phase error smaller, because the phase measurement error, $\Delta\phi$, and *SNR* is related to each other as $\Delta\phi \propto 1/SNR$. To obtain a smaller phase error by a factor of 3, increasing the integration time by an order of magnitude is sufficient, since *SNR* improves with the integration time t as $SNR \propto t^{1/2}$. This indicates that if we integrate the visibility for ~ 50 s, we can reach down to a differential phase error of 3°. Thus, the results presented here prove that as far as the calibration of atmospheric fluctuation is concerned, VERA's dual-beam system will allow us to obtain the phase accuracy required for $10\,\mu$as-level astrometry. We note, however, that the pair observed in the present paper had relatively good configurations, having a close separation on the sky plane ($0\overset{\circ}{.}65$) and a moderate declination ($\sim +09^\circ$ for both W 49N and OH 43.8−0.1). Also, the pair sources are sufficiently bright to be detected within the coherence time. For pairs with a larger separation and a lower declination, and/or for less-bright pairs, phase referencing by dual-beam system may not work as efficiently as for the pair in the present paper. For instance, the residual atmospheric phase fluctuation is expected to increase nearly proportionally to the pair separation, with a power law index of 5/6 in the case of a 'frozen screen' atmosphere with Kolmogorov turbulence (e.g., Carilli, Holdaway 1999). In order to study how the phase-referencing capability varies with the source configurations as well as the weather conditions, we have to observe several pairs under different conditions several times. These observations are the next targets of VERA's performance check in the near future. At this stage, however, we may conclude that VERA's dual-beam system can calibrate the atmospheric phase fluctuation with sufficient accuracy for $10\,\mu$as-level astrometry, at least for some bright sources with relatively good configurations.

We are grateful to the referee, Dr. James Moran, for reviewing and constructive suggestions. One of the authors (MH) acknowledges financial support from a grant-in-aid (No. 13740135) from the Ministry of Education, Culture, Sports, Science and Technology. Part of the data reduction was performed at the Astronomical Data Analysis Center of the National Astronomical Observatory, which is an inter-university research institute of astronomy operated by the Ministry of Education, Culture, Sports, Science and Technology.

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