An Antennacluster-Antennacluster VLBI Project VERA

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Abstract. VERA (VLBI for the Earth Rotation study and Astrometry) is a project to construct an antennacluster-antennacluster VLBI system dedicated to precision geodesy and astrometry. The system will be composed of clusters of 4 identical medium-sized antennas at both ends of 2300 km baseline connecting Kitakami Ridge at north-east of Honshu and one of the South-West Islands. VERA will enable us to determine 3 spatial components of the baseline vector and the clock offset by just one simultaneous measurement of group delays for 4 radio sources with known celestial positions. Also, the system will realize highly precise phase delay astrometry and phase-tracking geodesy by means of multi-view differential VLBI observations of close radio-source pairs.

1. Introduction

Project VERA aims at high time resolution observations of the Earth rotation with millimeter level accuracy, for studying the angular momentum exchange between the atmosphere and the solid Earth, as well as the physics of the core-mantle coupling.

VERA will be used also for 10 μ arcsecond level differential astrometry between closely spaced radio sources. The accuracy goal is high enough to draw a precise 3-dimensional map of our Galaxy by measuring trigonometric parallaxes and proper motions of thousands of astronomical maser sources throughout the whole Galaxy (KAMEYA *et al.*, 1994).

The design adopted for the purposes is the antennacluster-antennacluster VLBI system, which consists of clusters of 4 medium-sized antennas using a common frequency standard at both ends of its baseline (SASAO and MORIMOTO, 1991). Site surveys are conducted in Kitakami Mountain Ridge and in Ishigaki Island where firm granite bedrocks are available. The baseline length will be about 2300 km.

We will use VERA basically in 2 observation modes.

One is "baseline determination mode", where group delays of 4 well separated radio sources with precisely known positions are simultaneously measured, yielding 3 spatial components of the baseline vector and a clock offset at once.

Another mode is "multi-view differential VLBI mode", where relative positions of closely spaced radio sources are measured by simultaneous differential VLBI observations avoiding degrading effects of the atomospheric fluctuations. Major application of this mode will be the maser astrometry. The mode is also applicable to the "phase-tracking geodesy" (KAWANO *et al.*, 1994).

Since geodetic applications of the new system have been discussed elsewhere (ex. SASAO *et al.*, 1993b), the present report will be focused on the possibility of the highly precise maser astrometry with VERA.

2. Maser Source Astromery

The astronomical masers are the most numerous VLBI objects in our Galaxy. Moreover, the maser spots are mostly pointlike and extremely bright. Therefore, they must be ideal targets for the astrometric measurements. In fact, statistical parallaxes have been successfully determined for a number of massive star forming regions by measuring relative proper motions of the H_2O maser spots (a concise summary is given in REID, 1993).

Nevertheless, it has been quite difficult to determine VLBI positions of the maser sources in the quasar-based radio reference frame, because (1) the line width of a maser spot is too narrow to yield any meaningful estimate of the group delay, (2) the fringe rate observable suffers from too large scatter due to the atmospheric fluctuations, and (3) therefore, there has been no way to remove the $2\pi n$ ambiguity in the fringe phase difference observable in conventional source-switching differential VLBI.

The multi-view differential VLBI will overcome the difficulties. The simultaneous observation will enable us to perform the long-time integration in terms of the phase referencing technique with almost complete cancellation of the atmospheric effects and then obtain an accurate estimate of the fringe rate difference. Using the position information derived from the fringe rate difference, we can resolve the $2\pi n$ ambiguity and get the highly precise fringe phase difference observable.

We have examined feasibilities of the above scenario.

a) Estimation of the atmospheric effects based on statistical models of the wet tropospheric turbulence by DRAVSKIKH and FINKELSTEIN (1979) and TREUHAFT and LANYI (1987) showed (1) the phase-referenced integration can be continued for several hours even at the frequency as high as 43 GHz if the target and reference sources, separated by no more than a few degrees, are simultaneously observed, (2) tropospheric limitation in the fringe rate difference determined from 1 hour integration is small enough to resolve the $2\pi n$ ambiguity, and (3) tropospheric limitation in the phase difference observable does not give rise to the position error larger than 10 μ arcsecond for a projected baseline of 2000 km length, as far as the sources are observed at moderately high elevation (SASAO *et al.*, 1993a; HARA *et al.*, 1994).

b) Instrumental phase at 43 GHz can be readly calibrated at a few degrees level for 1 hour time-scale if we use the phase calibration techniques adopted in modern connected element interferometer arrays.

c) A rough estimation based on existing VLBI radio source catalogues showed that 15 m × 15 m VLBI pair with modern receivers is capable of detecting at least 1 faint quasar within a few degrees around an object of interest after 1 hour integration.

Thus, everything seems encouraging so far, except for a problem: it has been required in the conventional phase referencing technique that at least one of the radio sources is strong enough to be detected within the ordinary coherence time. The requirement is rather too severe if one wishes to observe thousands of astronomical masers. In order to solve the problem, we propose a new method for obtaining the difference observables in the course of an integration procedure similar to the usual VLBI fringe search.

3. Differential Fringe Search

A cross-power spectrum calculated from complex cross-correlations of k-th accumulation period obtained with a multi-lag VLBI correlator is expressed in the error-free limit as

$$S_k(\omega) = \begin{cases} \dfrac{2\pi A}{\Delta\omega} e^{-i\left[(\omega_0+\omega)(\Delta\tau_g+\tau_a+\tau_c)+\Phi_{\mathrm{inst}}\right]} & \text{for } \omega_I - \dfrac{\Delta\omega}{2} \le \omega \le \omega_I + \dfrac{\Delta\omega}{2} \\ 0 & \text{else} \end{cases} \tag{1}$$

where A is the fringe amplitude, $\Delta\omega$ is the bandwidth, ω_I is the IF band center, ω_0 is the LO frequency, $\Delta\tau_g$ is the time-dependent residual geometrical delay at the moment of the k-th accumulation period, τ_a is the atmospheric delay, τ_c is the clock offset, and Φ_{inst} means the instrumental phase (THOMPSON *et al*., 1986).

Let us calculate the cross-power spectra of a maser spot (M) and a quasar (Q), using respective correlator outputs of the simultaneous multiview observations, and combine the spectra at each accumulation period of equal moment to form the following "differential search function":

$$f\left(\delta F, \delta\tau_M, \delta\tau_Q\right) = \frac{1}{2\pi N}\sum_{k=1}^{N}\left\{\left[\int_0^\infty S_{Mk}(\omega)e^{i\delta\tau_M(\omega-\omega_I)}d\omega\right]^*\left[\int_0^\infty S_{Qk}(\omega)e^{i\delta\tau_Q(\omega-\omega_I)}d\omega\right]e^{i\delta F(t_k-t_0)}\right\} \tag{2}$$

where N is the number of accumulation periods in an observation, t_k is the central epoch of k-th accumulation period, t_0 is the central epoch of an observation, δF is the correction to the fringe rate difference, $\delta\tau_M$ and $\delta\tau_Q$ stand for corrections to the group delays for the maser and quasar sources, ()* means complex conjugation, and ω_I is adjusted to coincide with the line center of the maser spot.

Since the spectrum of a maser spot with the residual geometrical delay $\Delta\tau_{Mg}(t_k)$ can be approximated by a delta-function, Eq. (1) gives

$$\int_0^\infty S_{Mk}(\omega) e^{i\delta\tau_M(\omega-\omega_I)} d\omega \simeq A_M e^{-i\left[(\omega_0+\omega_I)(\Delta\tau_{Mg}+\tau_a+\tau_c)+\Phi_{\mathrm{inst1}}\right]}, \tag{3}$$

and, therefore, the $\delta\tau_M$-dependence disappears in the search function f. On the other hand, for a flat spectrum quasar source with the residual geometrical delay $\Delta\tau_{Qg}(t_k)$, we have

$$\int_0^\infty S_{Qk}(\omega) e^{i\delta\tau_Q(\omega-\omega_I)} d\omega$$
$$\simeq A_Q \frac{\sin\left[\Delta\omega\left(\Delta\tau_{Qg}+\tau_a+\tau_c-\delta\tau_Q\right)/2\right]}{\Delta\omega\left(\Delta\tau_{Qg}+\tau_a+\tau_c-\delta\tau_Q\right)/2} e^{-i\left[(\omega_0+\omega_I)(\Delta\tau_{Qg}+\tau_a+\tau_c)+\Phi_{\mathrm{inst2}}\right]}. \tag{4}$$

As the atmospheric effects and the clock offsets are mostly common for the two sources, terms τ_a and τ_c are cancelled out when we substitute Eqs. (3) and (4) into Eq. (2). Therefore, the amplitude of the differential search function $|f(\delta F, \delta\tau_Q)|$ takes its maximum when δF is equal to the fringe rate difference between the maser and quasar sources:

$$\delta F = (\omega_0+\omega_I)\left(\Delta\dot{\tau}_{Qg}-\Delta\dot{\tau}_{Mg}\right) \tag{5}$$

and $\delta\tau_Q$ is equal to the group delay for the quasar:

$$\delta\tau_Q = \Delta\tau_{Qg}+\tau_a+\tau_c, \tag{6}$$

provided that the instrumental phases are well calibrated. Thus, if we calculate the amplitude of the differential search function for a large set of trial values of the corrections, and find a peak at $\delta F = \delta F_m$ and $\delta\tau_Q = \delta\tau_m$, then the value of δF_m yields an estimate of the fringe rate difference. Also, the differential search function now gives an estimate for the fringe phase difference at the central epoch of the observation:

$$f(\delta F_m, \delta\tau_m) = A_M A_Q e^{-i(\omega_0+\omega_I)(\Delta\tau_{Qg}+\Delta\tau_{Mg})}. \tag{7}$$

The fringe phase difference can be found after integrating a large number of accumulation periods, even when the both maser and quasar sources are fairly weak. This implies that the high precision maser astrometry is really feasible by means of the multi-view differential VLBI technique.

We hope that the project will be funded in the later half of the 1990's.

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