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Scientific perspectives of VLBI operations in the frequency phase transfer mode

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Abstract. The technique of frequency phase transfer (FPT), pioneered at the Korean VLBI Network, is now gaining strong momentum with a number of telescopes and VLBI arrays considering it as a backbone of future operations. These include, most notably, the Global Millimeter VLBI Array (GMVA) and the upgrade of the Event Horizon Telescope. Implementation of FPT at these instruments would increase the sensitivity and dynamic range of imaging by factors of 10-70 and reaching an unprecedented ~ 1 microarcsecond accuracy of relative astrometric measurements, opening up a range of new scientific areas for investigation with FPT VLBI observations.

1. Introduction

Frequency phase transfer (FPT) is a VLBI technique for applying measurements at a lower (reference) frequency to improve phase coherence in simultaneous measurements made at a higher (target) frequency. Enabled by novel multiband receivers with shared optical path (Han et al., 2013, 2017), FPT allows for calibration of non-dispersive phase effects, using phase measurements at a lower (reference) frequency (Rioja & Dodson, 2011) and thereby extending the phase coherence at a higher (target) frequency by more than an order of magnitude (Algaba et al., 2015). Further improvements of phase coherence and positional accuracy can be achieved with applications of additional calibration steps such as source frequency phase referencing (SFPR, Rioja et al., 2015) and second order phase transfer (Zhao et al., 2018).

FPT has been successfully implemented at the Korean VLBI Network (Jung et al., 2012; Rioja et al., 2015) operating at 22/43/86/130 GHz. In the coming years, it may become the backbone operational mode for the Global Millimeter VLBI Array (GMVA) at 86 GHz (Dodson et al., 2023; Ros et al., 2025) and provide a crucial sensitivity improvement for the Event Horizon Telescope (EHT) at 230 GHz (Issaoun et al., 2023). A number of scientific areas would benefit from wide scale application of FPT for VLBI (Dodson et al., 2017), including in particular high precision astrometric measurements (Rioja & Dodson, 2020). This paper briefly summarizes the main performance improvements expected from VLBI observations made in the FPT mode and describes some of the science areas that can be addressed by these observations.

2. VLBI observations in the frequency phase transfer mode

Systematic tests and studies carried out at the KVN have successfully demonstrated potentials of FPT for increasing the time intervals for fringe fitting (Jung et al., 2012) and coherent averaging of visibility data (Rioja et al., 2015), improving the sensitivity and positional accuracy of VLBI observations. These studies can be used to obtain an estimate of phase errors that can be achieved in FPT VLBI measurements,

$$\sigma_\mathrm{p}(\nu) \approx 5^\circ(\nu/22\,\mathrm{GHz})(\mathcal{S}_{22\,\mathrm{GHz}}/10)^{-1/2}\,,$$

where $\mathcal{S}_{22\,\mathrm{GHz}}$ is the signal-to-noise ratio of detection at the reference frequency of 22 GHz. The resulting signal-to-noise of visibility measurements at a target frequency can be improved by more than and order of magnitude (Dodson et al., 2017) as the maximum integration time is then effectively limited only by the acceptable losses due to time averaging smearing and phase variations due to source structure. Some of the impacts of these improvements on fidelity of VLBI measurements are outlined below.

2.1. Dynamic range

Considering the effect that signal-to-noise ratios, $\mathcal{S}_\mathrm{a}$ and $\mathcal{S}_\mathrm{p}$, of amplitude and phase detections in the visibility measurements (Perley, 1999) have on fidelity of image reconstruction, the expected image dynamic range can be estimated as

$$D_\mathrm{img} = \frac{N_\mathrm{bas}}{\sqrt{N_\mathrm{bas}+t_\mathrm{obs}/\tau_\mathrm{coh}}}\,\frac{\mathcal{S}_\mathrm{a}\,\mathcal{S}_\mathrm{p}}{\sqrt{\mathcal{S}_\mathrm{a}^2+\mathcal{S}_\mathrm{p}^2}}\,, \qquad (1)$$

where N_bas is the number of baselines, τ_coh is the coherence time, and t_obs is the total observing time. The improvement of dynamic range expected from application of FPT is quantified by the ratio $t_\mathrm{obs}/\tau_\mathrm{coh}$ which becomes smaller with increasing coherence time. Deriving from the coherence times achieved at the KVN (Jung et al., 2012; Rioja et al., 2015), Figure 1 presents the expected effect of FPT on dynamic range of VLBI observations and shows that factors of $\sim$ 10–50 improvements should be expected for the existing VLBI arrays at 86 GHz and 230 GHz.
The other two important effects of employing the FPT technique to increase $\mathcal{S}_\mathrm{a}$ and $\mathcal{S}_\mathrm{p}$ are the respective im-

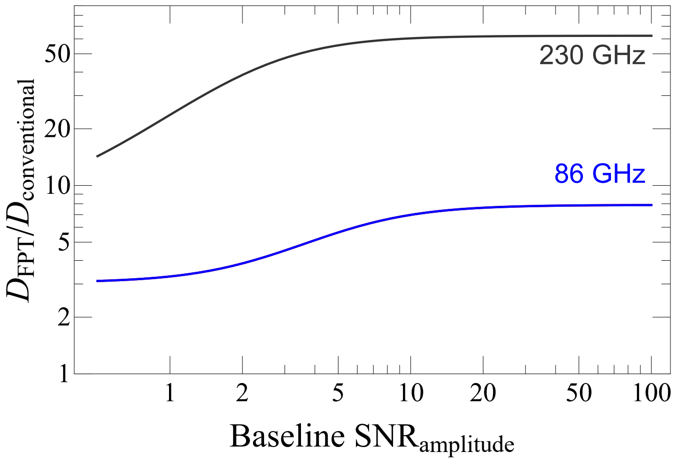

Fig. 1. Dynamic range improvement at 86 GHz (GMVA array, 16 telescopes) and 230 GHz (EHT-2017 array, 8 telescopes) expected to be achieved with FPT VLBI, plotted as a function of signal-to-noise detection at the reference frequency of 22 GHz. The improvement ratio calculated for a fiducial observing time of 18 hours, the conventional phase coherence times of 60 and 15 sec (at 86 and 230 GHz, respectively), and the expected factor of $\sim$ 100 improvement of the coherence time provided by implementation of FPT (Jung et al., 2012; Rioja et al., 2015).

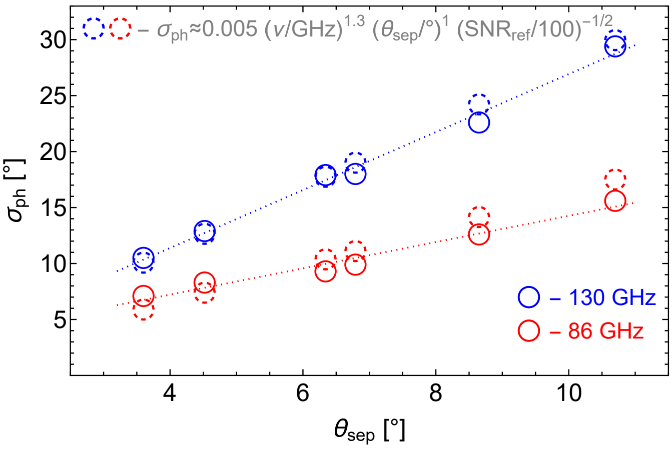

Fig. 2. Expected phase noise in SFPR observations, estimated from KVN measurements (Rioja et al., 2015, full circles), with the reference frequency of 22 GHz and target frequencies of 86 and 130 GHz. The phase noise increases linearly with increasing target separation from the calibrator (dashed lines show respective linear regressions), and can be jointly described by Equation 2, also reproduced in the top of the figure panel. Dashed circles represent estimates of the phase noise obtained using this expression.

provements of effective *image resolution* (Perley, 1999; Lobanov, 2005)

$$\theta_{\rm img} \propto {\rm FWHM}/\sqrt{\mathcal{S}_{\rm a}}$$

and positional accuracy of relative astrometric measurements

$$\sigma_{\rm pos} \propto {\rm FWHM}/\mathcal{S}_{\rm p}\,,$$

where FWHM signifies the full width at half maximum of the point spread function of an interferometric observation.

2.2. Astrometric accuracy

SFPR observations performed at the KVN achieve a positional accuracy of $\approx 50\,\mu$as (Rioja et al., 2015) for relative astrometric measuremnts. From these observations, an empirical dependence of rms phase noise, $\sigma_{\rm ph}$, at the target frequencies of 86 and 130 GHz can be obtained (see Figure 2)

$$\sigma_{\rm ph}(\nu) \approx 0\overset{\circ}{.}005\,(\nu/{\rm GHz})^{1.3}\,(\theta_{\rm sep}/1^{\circ})\,(\mathcal{S}_{\rm ref}/100)^{-1/2}\,, \qquad (2)$$

which depends on the angular separation, $\theta_{\rm sep}$, between the calibrator and target sources and on the signal-to-noise, $\mathcal{S}_{\rm ref}$ of detection of the calibrator source at the reference frequency. The resulting positional accuracy of relative astrometry measurements with FPT VLBI reaching a maximum baseline of $B_{\rm max}$ can then be expressed as

$$\sigma_{\rm pos} \approx 50\,\mu{\rm as}(B_{\rm max}/500\,{\rm km})^{-1}\,(\mathcal{S}_{\rm reference}/100)^{-1/2}\,. \qquad (3)$$

These dependence and he demonstrated feasibility of extending FTP measurements to intercontinental (10 000+ km) baselines (e.g., G.Y. Zhao et al., in prep; Issaoun et al., submitted to ApJ) indicate that accuracy of relative astrometric measurements using SFPR could soon reach the $\sim 1\,\mu$as, with a benchmark accuracy of $\approx 10\,\mu$as becoming firmly within the reach of FPT VLBI observations with the GMVA.

3. Science with FPT VLBI

Strong improvements of dynamic range and astrometric accuracy expected from wide scale applications of the FPT technique should open up a whole range of new scientific areas and questions that could be addressed by VLBI observations (Dodson et al., 2017). Some particular examples of scientific advances that should be supported by FPT VLBI can be found in applications of precision astrometric measurements to cosmology and galactic dynamics, physics of black holes, and studies of binary systems of supermassive black holes (Dodson et al., 2023). These examples are outlined below in more detail.

3.1. Galactic dynamics and cosmology

Precision relative astrometry measurements reaching a $\approx 10\,\mu$as positional accuracy can be applied measuring proper motions and yearly and secular parallaxes throughout the Galaxy and in a number of nearby galaxies. For a conservative assumption of at least six observations required for a reliable parallax measurements, three-band (22/43/86 GHz) FPT VLBI observations with a maximum

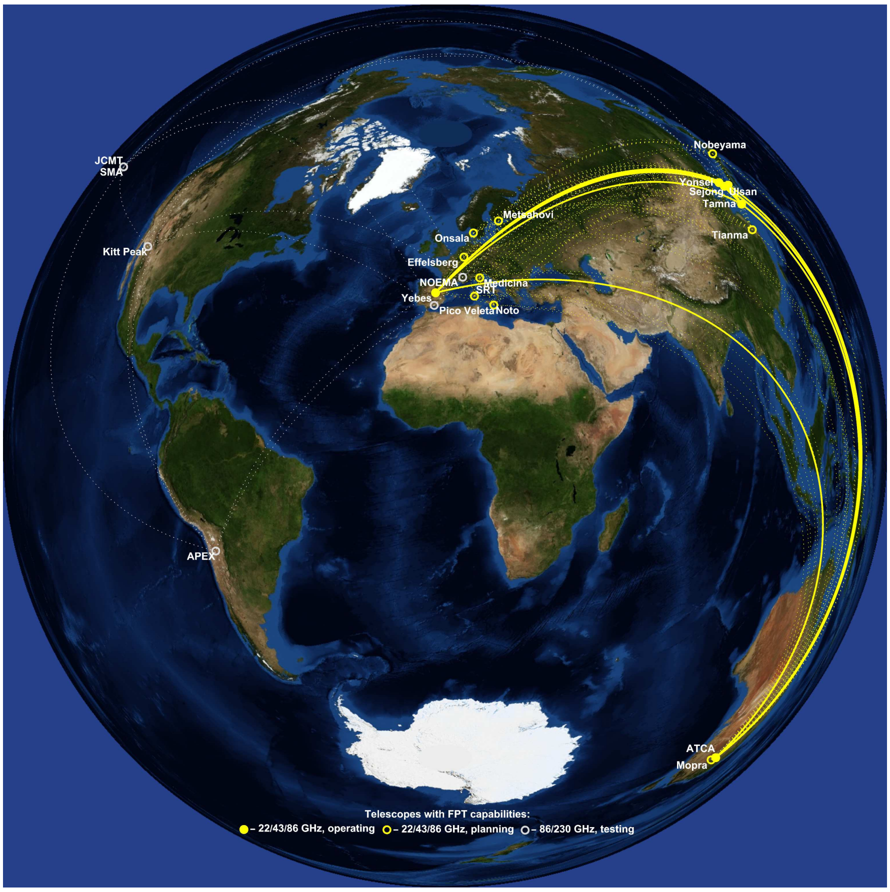

Fig. 3. Existing and potential *ad hoc* arrays that can carry out FPT VLBI observations at 22/43/86 GHz and 86/230 GHz.

baseline of $\approx 9000\,\mathrm{km}$ should be able to detect yearly parallaxes up the distance of

$$l_{\mathrm{yp}} \approx 100\,\mathrm{kpc}\sqrt{N_{\mathrm{obs}}/6}\,(10\,\mu\mathrm{as}/\sigma_{\mathrm{pos}})$$

and proper motions up to the distance of

$$l_{\mathrm{pm}} \approx 20\,\mathrm{kpc}\;v_{\mathrm{pm}}[\mathrm{km/s}]\;\Delta t[\mathrm{yr}]\;\sqrt{N_{\mathrm{obs}}/6}\,(10\,\mu\mathrm{as}/\sigma_{\mathrm{pos}})\,.$$

The yearly parallax and proper motion measurements made with FTP VLBI will yield accurate distance and kinematics measurements for objects throughout the entire Galaxy and reaching up to the Magellanic Clouds.

The secular parallaxes, arising from the motion of the Sun with respect to the CMB (Planck Collaboration et al., 2020), will be measurable up to the distance of

$$l_{\mathrm{sp}} \approx 80\,\mathrm{Mpc}\,\Delta t[\mathrm{yr}]\;\sqrt{N_{\mathrm{obs}}/6}\,(10\,\mu\mathrm{as}/\sigma_{\mathrm{pos}})\,,$$

thus opening up pretty much the entire local group of galaxies for precision astrometry measurements and providing exceptionally strong counterpart the best precision expected from similar measurements with Gaia (Paine et al., 2020).

Among the most exciting applications of these measurements would be aimed at resolving the current tension between Hubble constant measurements made at different cosmological distances (Verde et al., 2019) and attempting to detect *cosmic parallaxes* resulting from inhomogeneous expansion of the Universe that may be cause by dark energy (Quercellini et al., 2009).

3.2. Black hole physics

High resolution studies of black holes and their environment will benefit from both the improvements of dynamic range, D_{img}, and effective image resolution (Lobanov, 2005)

$$\theta_{\mathrm{img}} \approx 100\,\mu\mathrm{as}\,(86\,\mathrm{GHz}/\nu_{\mathrm{obs}})/\sqrt{D_{\mathrm{img}}}$$

and the superb positional accuracy of relative astrometry. These observations should provide viable testbeds for studying the disk-jet connection and probing close environment of supermassive black holes, as well as for attempting to distinguish between canonical black holes and some of their horizonless alternatives based on estimates of magnetic field strength on scales smaller than about 10^4 gravitational radii (Lobanov, 2017).

The latter measurements will benefit in particular from the combined improvements of the imaging sensitivity and astrometric precision which should allow for detecting the change of radial dependence of the opacity in the jet plasma in the presence of strong dipole or radial magnetic fields (Lobanov, 1998) that are expected to be found in the vicinity of the horizonless black hole mimickers (Mazur & Mottola, 2001; Kardashev et al., 2007).

3.3. Orbiting hotspot in Sgr A*

For the particular case of a hotspot orbiting the black hole in Sgr A* (GRAVITY Collaboration et al., 2018), FPT VLBI observations at 86 GHz or higher frequencies should be able to detect this motion at an N_σ sigma level, while beating the interstellar scattering, if the flaring spot is detected at a signal-to-noise of

$$\mathcal{S}_{\rm hs} \approx 40\, N_\sigma\, (\lambda/1\,{\rm cm})\, (B_{\rm max}/1000\,{\rm km})^{-1}\,.$$

This capability should enable making systematic studies of nuclear flares in Sgr A*, complementing and enhancing similar measurements made in the infrared band.

3.4. Binary SMBH

In a binary system of supermassive black holes (SMBH) located at an angular distance, $D_{\rm a}$, relative astrometry measurements reaching a $\approx 10\,\mu$as positional accuracy would enable detecting orbital motion over a half of the orbital period, $T_{\rm orb}$, at a significance level of

$$N_\sigma \approx \sqrt{\frac{N_{\rm obs}}{6}} \left(\frac{T_{\rm orb}}{10\,{\rm yr}}\right)^{2/3} \left(\frac{M_{\rm bh}}{10^9 {\rm M}_\odot}\right)^{1/3} \left(\frac{D_{\rm a}}{1\,{\rm Gpc}}\right)^{-1}\,,$$

assuming an equal mass binary and a face-on circular Keplerian orbit. This would allow to explore the binary SMBH scenario for a number of systems, even when only one of the two companions remain active and produces detectable radio emission.

4. Conclusions

Arguments and examples discussed above illustrate excellent scientific prospects that would arise from wide-scale implementation of FPT VLBI, with particular areas of improvement expected for VLBI measurements with the GMVA at 86 GHz (Dodson et al., 2023) and the EHT at 230 GHz (Issaoun et al., 2023). Present day FPT capabilities are illustrated in Figure 3 showing existing and planned *ad hoc* arrangements for FPT VLBI at 22/43/86 GHz and 86/230 GHz. Basic estimates presented here suggest that a global FPT VLBI array comprising ten or more antennas should make it possible to achieve a $\leq 10\,\mu$as astrometric accuracy at 86 GHz and increase image sensitivity by factors of 10 to 70, at 86 and 230 GHz respectively. This would enable reaching factors of ~ 3 to 8 improvements of image resolution and provide a firm foundation for carrying out pioneering astrometric measurements at a microarcsecond level precision. Combined together, these advancements would open up a whole range of areas of study in which FPT VLBI would start making critical contributions, including precision cosmology, galactic dynamics, and black hole physics.

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