Astrophysical Phenomena Revealed by Space VLBI
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Phase-Reference Observations with VSOP

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Abstract

We discuss problems associated with VLBI phase-referencing observations made with an orbiting antenna in space. Although HALCA cannot switch rapidly between sources, relative phase measurements between two close sources are possible if both are within the primary beam. We review VLBI Space Observatory Program (VSOP) observations of such pairs, and present a preliminary analysis for the source pair 1308+326 and 1308+328. For these observations the HALCA orbit was sufficiently well determined that it was possible to make a phase-reference map of 1308+326 and to perform the first ever Ground-Space VLBI relative astrometry between physically unrelated sources.

1 Introduction

Phase-reference mode observing has proved to be a useful technique for ground-based VLBI. The basic idea is that unwanted contributions to the visibility phase (e.g. from tropospheric and ionospheric path fluctuations) are nearly the same for two closely-spaced sources observed simultaneously or in rapid succession. For strong sources the visibility phase difference can be used directly for precision relative astrometry, whilst phase-reference mapping (Alef 1988, 1989; Beasley & Conway, 1995) can be used to image sources too weak for self-calibration. Prerequisites for success are a sufficiently strong, compact reference source, instrumental phase coherence between the sites and an accurate correlator model for the path delay difference between antennas; any uncompensated path differences arising in the propagation medium or from imperfect interferometer geometry appear in the relative phase, diluted by the source separation measured in radians.

2 Space VLBI and VSOP Phase-Referencing

In principle the phase-referencing technique can be extended to Space VLBI (e.g. Bartel, 1993). Problems include the possibilities that nearby reference sources are more likely to be resolved out at higher resolution, and that instrumental coherence may be limited by the space-ground link. Although there is no troposphere or ionosphere above the orbiting element, there may be large geometric delay errors due to a poor spacecraft position, and the position may be perturbed by source changes.

VSOP phase-reference observations are further restricted by the limited sensitivity of HALCA (hence fewer suitable reference sources) and the inability to change pointing sufficiently rapidly between sources. A special source-switching mode of HALCA was tested in August 1999 (VT759) on the strong source pair 0423–013/0424+006 (separation 2°) but the time between switching (30 min) was relatively long. Other investigations have been confined to observations of close pairs of sources, both of which are within the HALCA primary beam. These include 1038+528A/B (sep. 33 arcsec, V046 reported by Porcas & Rioja, 2000), 1342+662/3 (sep. 4.4 arcmin, V039 Guirado et al; Morabito, 1985), the nucleus of M81 and SN1993j (sep. 3 arcmin, W056a Bartel) and 1308+326/8 (V049), which we report on here.

3 VSOP Observations of 1308+326/1308+328

The two strong, flat-spectrum sources 1308+326 and 1308+328 are separated by 14.3 arcmin in PA 27°, about half of the HALCA primary beam at 5 GHz (FWHM 26 arcmin). They thus provide an ideal case for investigating the limits of phase-reference observing with VSOP. 1308+326 (z=0.996) is highly variable (S = 2–4 Jy) and has been studied by Gabuzda et al. (1993). Geodetic VLBI observations show that its structure is also variable. 1308+328 (z=1.65; Machalski & Engels, 1994) is variable but weaker (S = 0.3–0.6 Jy). Rioja et al. (1996) showed that it is essentially unresolved on ground baselines at 8.4 GHz, and measured the separation between the two sources to sub-mas accuracy.

VSOP observations of this pair were made from UT 1630–2230 on 29th June 1998 at 5 GHz. The ground array telescopes (VLBA and Effelsberg), which have smaller primary beams, were switched between the sources every 3 or 4 minutes. The HALCA data (2.5 h) were relayed via the Tidbinbilla tracking station. Correlation was done at the VLBA correlator and calibration and further analysis was made using AIPS.

Fig1 shows the visibility amplitude vs. resolution for the two sources; both showed strong fringes on ground-space baselines. The weaker, but highly compact nature of 1308+328 is also evident. Maps using ground baselines only (CLEAN beam 1×1 mas) are shown in Fig. 2. At this epoch, 1308+326 consists of two, nearly equal components, separated by 1 mas. 1308+328 is almost point-like, apart from a faint (10 mJy/beam) extension of 2 mas in PA –45 (reported for the first time here). For simplicity we chose this as the reference source in our analysis.

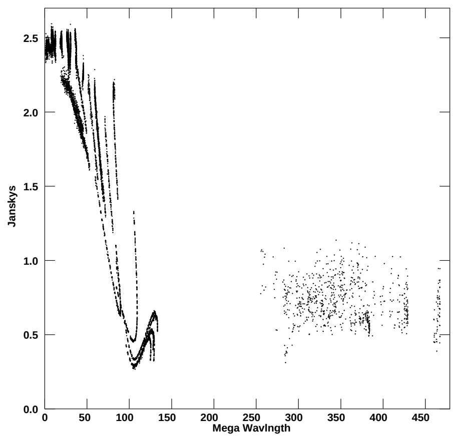

Figure 1: Amplitude of visibility function vs (u, v)-distance for **a** (left) 1308+326 and **b** (right) 1308+328

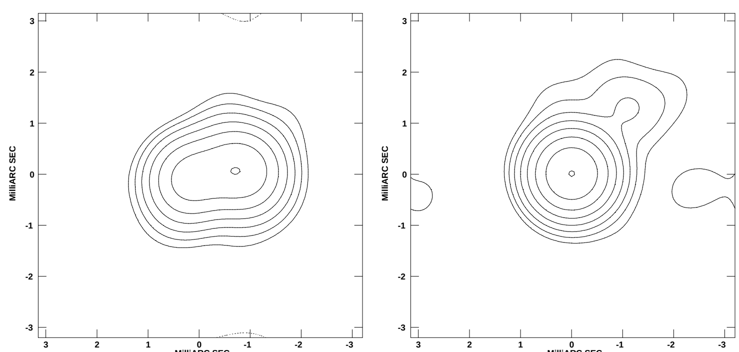

Figure 2: GRT-only maps: **a** (left) 1308+326: peak 1294, base contour 20 (mJy/beam); **b** (right) 1308+328: peak 258, base contour 2 (mJy/beam)

We started our phase-reference analysis by making VSOP hybrid maps of 1308+328 (using only the single phase self-calibration step in FRING). Maps with uniform weighting and equal data weights for all baselines are shown in Fig. 3 (CLEAN beam 0.35×0.35 mas). As expec-

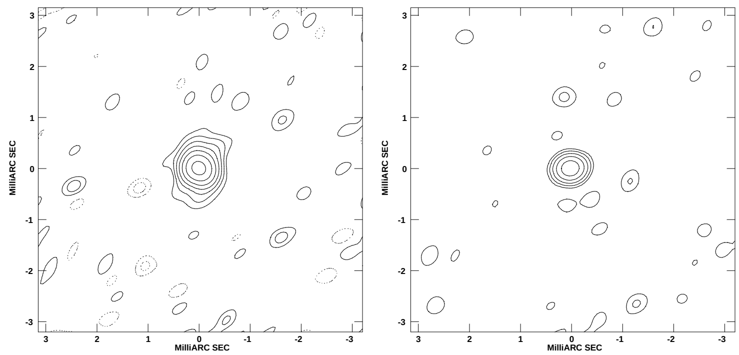

Figure 3: VSOP maps of reference source 1308+328: **a** (left) Using data from all baselines: peak 171, base contour 2 (mJy/beam); **b** (right) Using only baselines to HALCA: peak 105, base contour 4 (mJy/beam)

ted, these show a single, compact component, with 100 mJy still visible in a map made with baselines to HALCA alone (Fig. 3b).

The antenna phase calibrations determined from 1308+328 were then applied to the data of the "target" source, 1308+326, after interpolation across the observing gaps. Visibility phase plots on two baselines are shown in Fig. 4. Both are smoothly varying functions over the observing period, and represent the sum of target source structure phase, errors due to interpolation and correlator model errors (including the absence of an ionospheric path correction). It is clear that the position determination of HALCA is much better than the nominal 80 m requirement for the VSOP mission (from which one might expect phase changes up to 5 turns for the source separation of 0.004 radians).

We next made phase-reference maps of 1308+326 (Fig. 5; CLEAN beam 0.35×0.35 mas) using these calibrated visibilities, with no further phase self-calibration. The uniform-weighted map, using all baselines with equal weight (Fig. 5a) shows clearly the two compact source components, with the suggestion of an arching bridge between the two.

A map made using only baselines to HALCA (Fig. 5b) shows only one (the eastern) of these components, with a peak flux of 372 mJy/beam. A secondary component in PA –140 is clearly spurious, and can be at-

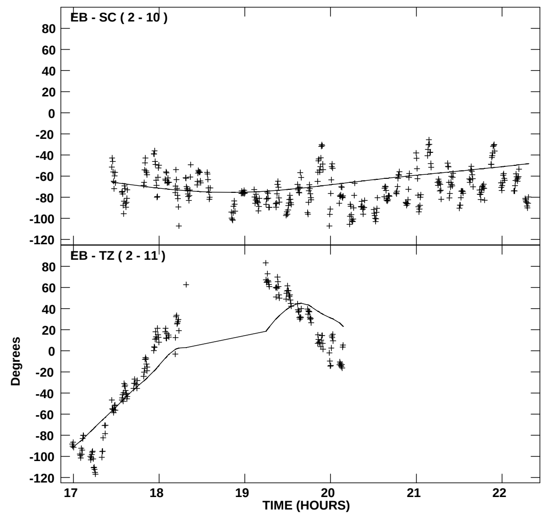

Figure 4: Phase of the 1308+326 visibility function on baselines from Effelsberg to (top) VLBA-SC and (bottom) HALCA, after applying instrumental phase corrections determined using the reference source 1308+328. Solid line is prediction from hybrid map in Fig. 6a.

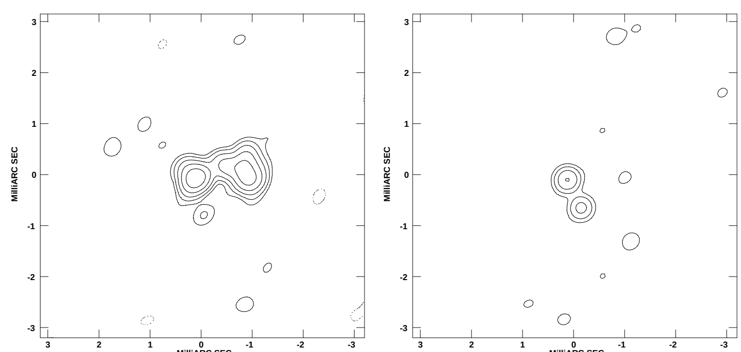

Figure 5: VSOP phase-reference maps of the target source 1308+326; **a** (left) Using data from all baselines: peak 579, base contour 20 (mJy/beam); **b** (right) Using only baselines to HALCA: peak 372, base contour 45 mJy/beam

tributed to phase errors. The difference in the positions of the peaks between Figs. 5 and 3 define astrometric corrections to the assumed source separation (δRA, δDec). Preliminary estimates give +100, –60 μas between Figs. 5a, 3a and +90, –100 μas between Figs. 5b, 3b.

Finally, we made hybrid maps of 1308+326 by performing five iterations of phase self-calibration using CALIB, starting with the phase-reference map of Fig. 5a. These are shown in Fig. 6, with the mapping parameters as for Fig. 5. Compared to the phase-referenced maps the

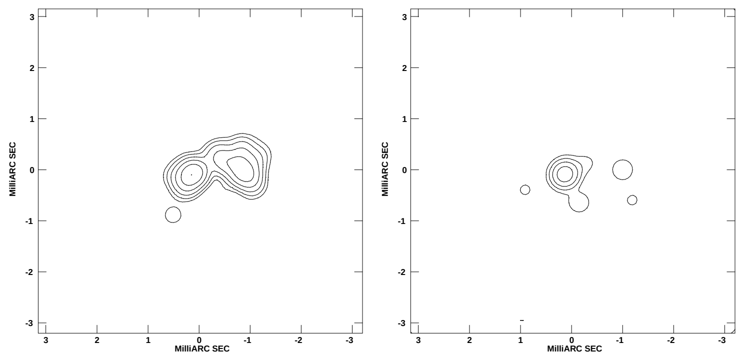

Figure 6: Hybrid maps of 1308+326: **a** (left) Using all baselines: peak 641, base contour 20 (mJy/beam); **b** (right) Using only baselines to HALCA: peak 578, base contour 45 (mJy/beam)

noise levels are much less; in particular the strong, spurious feature in Fig. 5b is considerably reduced in Fig. 6b. The peak brightness (on the eastern "core") is also increased in the hybrid maps — by 11 % in Fig. 6a and 55 % in Fig. 6b. The phase corrections derived in the CALIB phase self-calibration steps for the VLBA-SC and HALCA antennas are shown in Fig. 7. These represent the residual, differential path length errors between the two sources (with respect to the reference antenna Effelsberg), after removal of the 1308+326 source structure phase.

4 Conclusions

Our preliminary analysis of 5 GHz VSOP observations of the close pair of sources 1308+326/8 has shown that phase-reference observations are indeed feasible with Ground-Space VLBI.

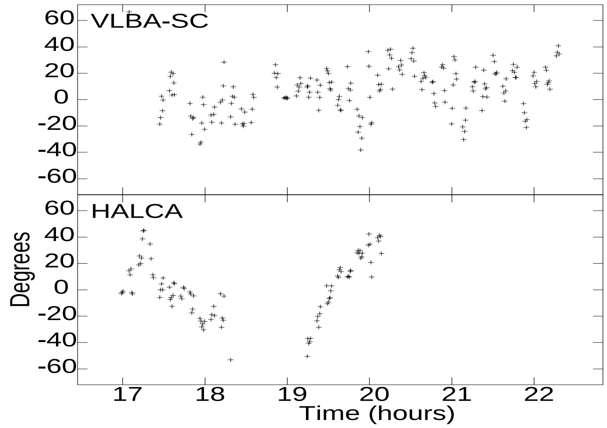

Figure 7: Antenna phase corrections for (top) VLBA-SC and (bottom) HALCA, determined using the referenced phase of 1308+326 and a hybrid map (Fig 6a)

1. The transfer of instrumental phases (determined on the reference source) to the target source was possible for ground-space baselines.

2. Phase interpolation using a 7 minute cycle worked (most of the time).

3. Phase-reference mapping, with limited dynamic range, was possible for 1308+326, using the reference source 1308+328 within the HALCA beam, 14.3 arcmin away .

4. The first ever Space VLBI relative astrometry between physically unrelated sources was achieved.

5. The orbit determination for HALCA is clearly much better than the 80 m mission requirement. The residual relative phase errors (up to 60°) imply HALCA position accuracies in the range 2–5 m. These are comparable to the uncompensated delay path differences introduced by the ionosphere at lower frequencies (e.g. 1.6 GHz) when using uncorrected residual phases from the VLBA correlator.

6. The residual relative phase errors for the source separation of 14.3 arcmin produce significant spurious features when using the ground-space baselines alone, and result in the loss of about 33 % of the expected flux.

7. One would expect the residual relative phase errors to scale proportionally with the target/reference source separation, and the observing frequency. Thus phase-referencing observations with closer source pairs should be possible with VSOP. However, a more general application of phase referencing to wider target/reference separations with future Space VLBI missions will need more precise orbit determinations. Note that Reid (1984) estimated a required baseline precision for QUASAT of 0.1 m for astrometric measurements of water-vapor masers.

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