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RadioAstron Early Science Program Space-VLBI AGN survey: strategy and first results

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RadioAstron is a project to use the 10 m antenna on board the dedicated SPEKTR-R spacecraft launched on July 18, 2011, to perform very long baseline interferometry from space (Space-VLBI). We describe the strategy and highlight the first results of a P/L/C/K-band fringe survey of brightest radio-loud active galactic nuclei (AGN) at baselines up to 25 Earth diameters ($D_\oplus$). The survey goals include search for extreme brightness temperatures (with a hope to resolve the Doppler factor crisis and constrain possible mechanisms of AGN radio emission), study the observed size distribution of the most compact features in AGN radio jets (with implications to their intrinsic structure and properties of the scattering interstellar medium in our Galaxy), and select promising objects for detailed follow-up observations, including Space-VLBI imaging. Our survey target selection strategy is based on results of correlated visibility measurements at longest ground-ground baselines from previous VLBI surveys. The current long-baseline fringe detections include OJ 287 at 10 $D_\oplus$ (L-band), BL Lac at 10 $D_\oplus$ (C-band) and 0748+126 at 4.3 $D_\oplus$ (K-band). The L- and C-band fringe detections at 10 $D_\oplus$ imply brightness temperatures $T_b \sim 10^{13}$ K, about two orders of magnitude above the inverse Compton limit. This might indicate that often the jet flow speed is higher than the jet pattern speed.

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1. Space radio telescope

The 10 m space radio telescope of the RadioAstron project is installed on board the dedicated SPEKTR-R spacecraft. It was launched into a highly elliptical orbit on 2011 July 18 from the Baikonur Cosmodrome by a Zenit-3F rocket (Fig. 1). The orbit is selected so its parameters evolve under the gravitational pull of the Moon to provide a wide range of baseline projections for VLBI observations of various sky regions during the mission lifespan. As of October 2, 2012, SPEKTR-R orbital parameters were the following: 206-hour period, 73000 km perigee, 281000 km apogee, 79° inclination. Regular measurements of the spacecraft's distance and velocity using standard radiometric techniques supported by laser ranging, direct optical imaging and VLBI state vector measurements [1] allow one to reconstruct its position and velocity with accuracy, typically, no worse than ± 500 m. and ± 2 cm/s, respectively.

The space telescope is equipped with P (92 cm), L (18 cm), C (6 cm) and K-band (1.3 cm) receivers, an on-board hydrogen maser and a high-gain antenna system to downlink VLBI data to a ground station in real time. Currently, the 22 m antenna of the Pushchino radio astronomy observatory (near Moscow, Russia) serves as the ground data acquisition station. The second RadioAstron data acquisition station is under construction on the basis of the National Radio Astronomy Observatory's 43 m telescope at Green Bank, West Virginia, USA.

Figure 1: SPEKTR-R assembled at Lavochkin Association (left) and its launch from Baikonur (right).

2. AGN survey strategy

A fringe detection survey of radio-bright active galactic nuclei (AGN) is being conducted as part of the RadioAstron Early Science Program. The survey goals include search for extreme brightness temperatures (T_b), with a hope to resolve the Doppler factor crisis [2] and constrain possible mechanisms of AGN radio emission [3], study the observed size distribution of the most compact features in AGN radio jets (with implications to their intrinsic structure and properties of the scattering interstellar medium in our Galaxy), and select promising targets for detailed follow-up observations, including Space-VLBI imaging.

The survey target selection is based on the results of correlated visibility measurements on longest ground-ground baselines from the existing VLBI surveys including the S/X-band VLBA Calibrator Surveys (VCS) 1 to 6 [4, 5, 6, 7, 8, 9] and the Research and Development VLBA program (RDV) [10, 11, 12], K_u-band observations of the MOJAVE program[1], Q- and W-band results of the Boston University group[2] and [13], respectively. We also consulted the list of high–T_b sources observed at C-band by the VLBI Space Observatory Program (VSOP) [14, 15, 16].

Results of many ground-based VLBI surveys are summarized in the Radio Fundamental Catalog[3]. The "unresolved X-band flux" parameter listed in this catalog is used to set scheduling priorities of sources. Among sources with comparable level of unresolved flux density that satisfy RadioAstron visibility constrains, the preference is given to sources for which *(i)* correlated visibility at S, X, K_u, and Q bands measured from the ground is not falling rapidly with increasing baseline, *(ii)* we can obtain both short ($< 5D_\oplus$) and long space–ground baselines within one or a few SPEKTR-R orbital revolutions. *(iv)* VSOP measured $T_b > 10^{12}$ K, *(v)* there is a W-band detection. We try to schedule the preferred sources first with a hope to maximize the detection rate at the early stages of the survey.

All four RadioAstron bands (P, L, C, and K) are employed in the survey, with the main focus on L, C, and K bands. Most observations are done in a dual-band mode: C+L or C+K. The space radio telescope is observing simultaneously at two bands while ground telescopes are divided in two sub-arrays or switching between two bands during experiment. A typical AGN survey observation consists of four 10 minute–long scans on a target source, separated from other series of scans by 40–60 minutes necessary to satisfy the spacecraft's thermal constraints and slew to a next target. The main factors affecting the scheduling include: Sun avoidance angle 90° (plus a limited solid angle centered on anti-solar direction), satellite visibility to the tracking station (TS), TS visibility to the satellite's high-gain antenna, target source visibility for ground telescopes, availability of ground telescopes during the time period when all the constrains are met. An example all-sky uv-coverage computed with the above

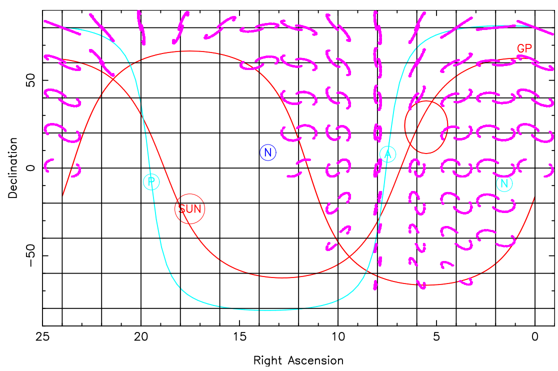

Figure 2: Possible space-ground uv-coverage for various sky positions computed for 206 hours (one orbital revolution) starting on December 15, 2012, 00:00 UT. Included telescopes: RadioAstron, EVN, LBA, Arecibo, GBT, Usuda. Also marked on the plot: Galactic plane, Sun avoidance regions, satellite's orbital plane, perigee, apogee, and perpendicular to the orbital plane directions.

[1] http://www.physics.purdue.edu/astro/MOJAVE/
[2] http://www.bu.edu/blazars/
[3] http://astrogeo.org/rfc

constraints (except the last one) is presented on Fig. 2 The plot represents a period of rather favorable observing conditions.

Ground telescopes participating in the AGN Early Science Program observations include Arecibo 300 m and NRAO GBT 100 m (USA), ATCA 6x22 m, Parkes 64 m, Mopra 22 m, Hobart 26 m, Tidbinbilla 70 m (Australia), Effelsberg 100 m (Germany), Evpatoria 70 m (Ukraine), Hartebeesthoek 26 m (South Africa), Jodrell Bank 70 m (UK), Medicina 32 m and Noto 32 m (Italy), Shanghai 25 m and Urumqi 25 m (China), Svetloe 32 m, Zelenchukskaya 32 m, Badary 32 m (Russia), Torun 32 m (Poland), Usuda 64 m (Japan), WSRT 14x25 m (Netherlands), Yebes 40 m and Robledo 70 m (Spain), as well as arrays: EVN, Kvazar-KVO, and LBA.

3. First results

While the first months of the survey were marked by continuing development of correlation techniques, choosing optimal space telescope observing modes and debugging the satellite VLBI data downlink system, the observations provided some record-breaking results. Fringes to the space telescope at L- and C-band were detected on baseline projections of about 10 $D_\oplus$ for four blazars: 0748+126, OJ 287, 3C 273, and BL Lacertae. The Arecibo, GBT and Effelsberg telescopes were serving as a ground arm of the interferometer in these experiments. At K-band, fringes between the space telescope and the GBT were detected on 0748+126 at baselines up to 4.3 $D_\oplus$ (Fig. 3). Some of the current long-baseline fringe detections are presented in Table 1.

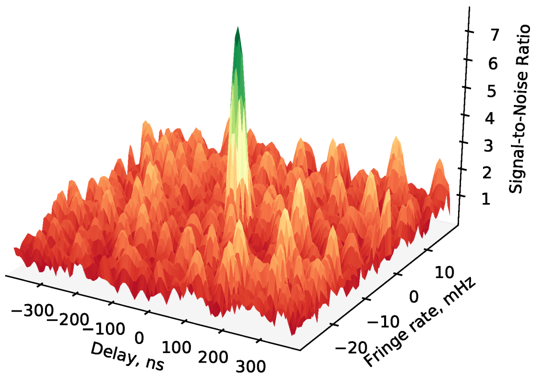

Figure 3: Interferometric signal from the quasar 0748+126 detected between RadioAstron and GBT (K-band) at the projected baseline of 4.3$D_\oplus$. The plot shows the signal to noise ratio as a function of residual delay and rate after delay-model subtraction and fringe fitting.

While the P-band is actively used for RadioAstron observations of pulsars, no P-band space–ground fringes on AGN were detected so far, most probably because of the limited number of attempts. This band was considered low-priority because of the interstellar scattering most prominent at longer wavelengths and the lower angular resolution compared to other RadioAstron bands. However, detection of L-band fringes at 10 $D_\oplus$ suggests, that interstellar scattering might not always prevent low-frequency fringe detections at long baselines and more P-band AGN observations should be attempted.

4. Summary

The RadioAstron space interferometer is exploring angular scales that were never accessible before at centimeter wavelengths. The L- and C-band fringe detections at 10 $D_\oplus$ imply brightness temperatures $T_b \sim 10^{13}$ K (about two orders of magnitude above the inverse Compton limit [17]).

Table 1: Some of RadioAstron long-baseline detections as of January 2013

Source	Ground telescope	B_{max} ($D_{\oplus}$)	B_{max}/λ (Mλ)	λ/B_{max} (mas)	z
		L-band ($\lambda = 18$ cm)			
OJ 287	Arecibo 300 m	10	708	0.29	0.306
		C-band ($\lambda = 6$ cm)			
BL Lac	Effelsberg 100 m	10	2124	0.10	0.0686
		K-band ($\lambda = 1.3$ cm)			
0748+126	GBT 100 m	4.3	4215	0.05	0.889

Column designation: (1) source name, (2) maximum baseline at which fringes were found, (3) ground telescope, (4) angular scale, (5) baseline (6) redshift (as listed in the MOJAVE database).

These brightness temperature values may be reconciled with the standard e^{-}/e^{+} incoherent synchrotron radiation model if the emission is Doppler–boosted by a factor of $\delta \equiv [\Gamma(1-\beta\cos\theta)]^{-1} \sim 100$. Here Γ and β are the bulk Lorentz factor and velocity (in the units of c) of the emitting plasma and θ is the angle between the plasma flow direction and the line of sight. Large values of δ derived from the RadioAstron T_b measurements combined with the inverse Compton limit argument are inconsistent with typical values of δ derived from ground-based VLBI kinematic data [18, 19]. This might indicate that often the jet flow speed is higher than the jet pattern speed. More observations at long baselines are planned to probe the range of $T_b \sim 10^{14-15}$ K. Surprisingly, interstellar scattering is not preventing fringe detection at long baselines even at L-band.

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