Surveys of compact extragalactic radio sources

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Several recent global and Space VLBI surveys of quasars, AGN of other types and star-burst galaxies provide a wealth of material on milli- and sub-milliarcsecond radio structures in hundreds of sources. Results of these projects are presented with an emphasis on the statistics of redshift- and angular-scale-dependent properties of the milli- and sub-milliarcsecond radio structures. These studies make possible disentanglement of intrinsic (possibly, evolutionary) phenomena of parsec-scale radio structures and the imprints of the cosmological model.The studies indicate a very promising potential of high-resolution applications of the Square Kilometre Array. Based on our pilot projects we estimate that a sample containing of the order of 10^4 faint radio sources in the luminosity range $10^{22} - 10^{26}$ W/Hz can be surveyed by a high-resolution SKA with the milliarcsecond resolution at cm wavelengths. Such the high resolution radio survey, including those conducted jointly by SKA and Space VLBI missions, in conjunction with data from other domains, will provide a new ground for extragalactic studies.

1. Introduction

It has been repeated more than once in the course of preparation of this volume that major scientific impacts of a new telescope which improves observational characteristics by at least an order of magnitude are hard to predict. High-resolution configurations of SKA with baselines of the planetary scale (several to ten thousand kilometres) as well as its extension into Space with Earth-Space baselines (Space VLBI) are precisely in this “unpredictable” category. Bearing this in mind I dare to state that high resolution applications will feature prominently among highlights once the Square Kilometre Array is operational.

The radio sky at metre to centimetre wavelengths is dominated by extragalactic sources. At higher flux densities (Jy to tens of mJy) most of them are Active Galactic Nuclei (AGN). At lower flux densities radio sources associated with star-burst galaxies begin to dominate the source count statistics (Condon 2004, Garrett 2004). Both categories of these sources constitute a very considerable fraction of all targets of present-day VLBI studies.

As any other astronomical technique, VLBI began by observing just a few “famous” sources. However, its rapid progress since the first observations in the late 1960s has resulted in the conduct of VLBI surveys of thousands of extragalactic sources. VLBI surveys of extragalactic radio sources provide a wealth of information on the nature of physical phenomena in the close vicinity of AGNs (see the review and the list of completed and ongoing VLBI surveys in Gurvits 2002).

At present, VLBI surveys are de-facto flux-density limited regardless of the particular set of criteria used in one or another observing project. This is illustrated by Fig. 1 which, as an example, shows luminosity versus redshift for 330 sources analysed in the cosmological context by Gurvits et al. (1999). The sample has a flux density limit of ~ 300 mJy. The total number of sources in the Universe with that high flux density is limited, and the only way to increase the size of the sample dramatically is to include sources at $z \geq 1$. This requires VLBI study of high-redshift sources with luminosities as low as $10^{23} - 10^{25}$ W/Hz, which corresponds to mJy-level and lower flux densities.

2. Toward understanding the AGN power plant design

As pointed out by Zensus (1997), the de-facto paradigm of the AGN phenomenon, the relativistic jet model (Blandford & Königl, 1979; see also Falcke, Körding & Nagar, this volume), is based on three pillars: (*i*) accretion on the massive central object, (*ii*) relativistic ejection from nuclei, and (*iii*) relativistic beaming. The accre-

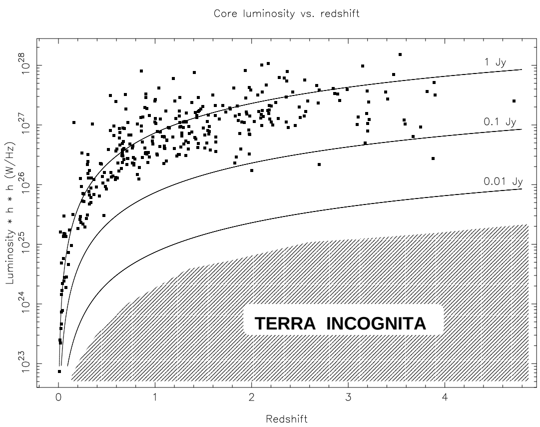

Figure 1. Luminosity of compact cores versus redshift for the sample of 330 quasars and radio galaxies for which VLBI images at 5 GHz are available with a dynamic range of at least 100 ($q_o = 0.5$, $H_0 = 100h$ km/s/Mpc). This ad-hoc sample is effectively flux-density-limited at ~ 300 mJy at 5 GHz. Until recently, the shadowed area was not accessible to VLBI studies due to sensitivity limitations. Adopted from Gurvits et al. (1999).

tion theory descends from the work done in the 1950s-1970s and has received its present form in direct application for AGN by Begelman et al. (1984; also references therein). The relativistic ejection from galactic nuclei has been suggested by Rees (1966) as a mechanism of powering extended (kpc-scale) radio structures in extragalactic sources. Relativistic beaming was proposed by Shklovsky (1963) as an explanation of the apparent high brightness of some extragalactic radio sources.

Since the formulation of the relativistic jet model more than quarter of a century ago, considerable progress has been achieved in its fine tuning, not the least owing to the data supplied by VLBI studies of particular AGN or their limited samples. Understanding of the physics of the central engine of AGN requires, in particular, a better knowledge of the "design" of its emitting region with adequate linear resolution. The need for further improvement in resolution at all wavelengths has been reviewed recently by Rees (2001).

One of the opportunities to address this question is being offered by VLBI surveys of AGN. They allow us to determine the characteristic scales of the central engine, or at least of its appearance at radio waves. Recent examples of such the studies include analysis of about 100 AGN observed at 5 GHz in the framework of the VLBI Space Observatory Programme (VSOP, Hirabayashi et al. 1998), specifically the VSOP Survey Project (Horiuchi et al. 2004 and references therein) and several hundred sources observed at 15 GHz with the VLBA (Yu.Yu. Kovalev et al. 2004, in preparation). Fig. 2 represents the mean value of the normalised correlated flux density versus projected baseline for about 100 radio-loud AGN from the VSOP Survey sample. The value can be considered as a measure of compactness of a source. Both plots on Fig. 2 indicate that on average the sources are resolved significantly on baselines up to ~ 500 Mλ at both frequencies. A small "kink" visible at about ~ 120 Mλ at 5 GHz and ~ 340 Mλ at 15 GHz is most likely caused by a sampling effect of the Very Long Baseline Array used in both cases: the array seems to have a peculiar geometrical

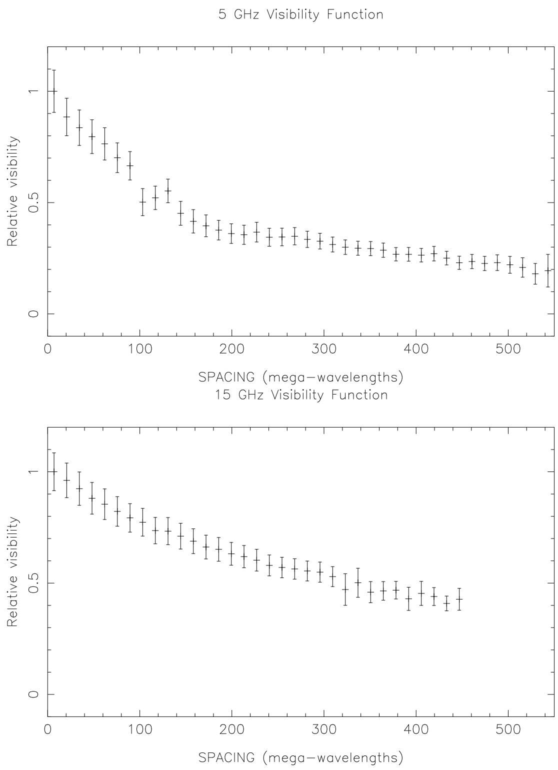

Figure 2. The mean value of correlated flux density versus projected baseline for a combined sample of VLBApls and VSOP Survey sources observed at (*top*) 5 GHz and (*bottom*) 15 GHz. The 5 GHz data used are from Hirabayashi et al. (2000) and Fomalont et al. (2000), 15 GHz data are from Kellermann et al. (1998) and Gurvits et al. (2001). Courtesy E.B.Fomalont.

configuration on the scale of about 6600 km corresponding to ~ 120 Mλ and ~ 340 Mλ at 5 and 15 GHz, respectively.

More significant for the physics of the sources is a clear flattening (change of the slope) of the dependence at around ~ 200 Mλ at 5 GHz (Fig. 2, top; see also Fig. 2 in Horiuchi et al. 2004) which corresponds to the angular scale of about 1 mas. Indeed, as known from hundreds of available VLBI images at 5 GHz, AGN radio structures on the scale of several milliarcseconds (baselines shorter than ~ 200 Mλ) typically represent a combination of core and extended jet (e.g. Fomalont et al. 2000). Not surprisingly, at these baselines the slope is steep. The flatter slope at baselines ≥ 200 Mλ seems to indicate that on the sub-mas scale the core becomes resolved, and its inner structure is not self-similar to the large-scale "core-jet" morphology.

The change of slope described above is almost absent at 15 GHz (Fig. 2, bottom). This comes as no surprise if the change of morphology from "core-jet" to "core only" indeed takes place around the angular scale of ~ 1 mas. As the extended mas-scale jets have significantly steeper radio spectra than the cores, the contribution of jets to the correlated flux density at 15 GHz is smaller than that at 5 GHz. Thus, the "disappearance" of jets on sub-mas scales at 15 GHz is less prominent than at 5 GHz.

I note that the result at 5 GHz shown in Fig. 2 (top) is a combination of ground-based VLBA observations (up to a baseline length of ~ 150 Mλ, Fomalont et al. 2000) and the VSOP Survey (from ~ 50 Mλ to ~ 550 Mλ, Hirabayashi et al. 2000, Lovell et al. 2004, Scott et al. 2004). The significance of the VSOP results is obvious, because the change in structural regime takes place at baselines exceeding those available for ground-based VLBI systems at 5 GHz.

It has to be noted also that the change of structural regime described here is purely qualitative and is based on a sample of sources at different redshifts (thus, observed at different rest frame frequencies). Further detailed investigation must account for redshift-dependent effects. Importantly, future studies will require to go to lower flux densities. This necessitates higher sensitivity

VLBI observations.

3. Millijansky radio sources at the milliarcsecond scale: pushing the limits of today's VLBI

In order to get a "first-hand" impression on statistical properties of milliarcsecond-scale radio structures in mJy-level extragalactic radio sources, a pilot Deep Extragalactic VLBI-Optical Survey (DEVOS) using the MERLIN and Global VLBI network has been conducted (Gurvits et al. 2004, L. Mosoni et al. 2004, in preparation). The DEVOS study is centered around VLBI observations of a large sample of optically identified extragalactic radio sources. They are selected from the combination of radio surveys (primarily, the VLA Faint Images of the Radio Sky at Twenty-centimeters, FIRST, White et al. 1997) and deep optical surveys (e.g. the Sloan Digital Sky Survey, SDSS, Richards et al. 2002). The primary goal of the DEVOS project is to study the radio-faint (few to few tens of mJy) population of compact extragalactic radio sources at angular resolution ranging from arcseconds (kiloparsecs) down to milliarcseconds (parsecs).

The multi-step process of sample selection, which involves "filtering" observations with MERLIN described by Gurvits et al. (2004) would make it possible to create a large (several thousand objects) sample of VLBI-imaged extragalactic radio sources with known redshifts. The efficiency of the "filtering" and phase-referencing procedures has been established originally by MERLIN and global VLBI observations by Garrington et al. (1999). Optical counterparts of about 50–80 % of all FIRST radio sources are expected to be identified by SDSS (e.g. Ivezic et al. 2002). The identification rate is likely to be close to the upper edge of the above range for the DEVOS sample because of selection of bright and compact FIRST sources.

Pilot observations for the DEVOS project were conducted on 47 sources, located in the North Galactic Pole area within 2° from the bright compact calibrator source J1257+3229, and called NGP01 to NGP47 in the order of decreasing FIRST flux density. Fig. 3 shows an example of four global VLBI images of DEVOS NGP sources with the peak brightnesses at 5 GHz in the range of $2 - 13$ mJy/beam obtained in that pilot DEVOS NGP project.

The statistics of the DEVOS NGP sample and its detection by MERLIN and Global VLBI is shown on Fig. 3 (vertical axis in logarithmic scale). The overall distribution of FIRST flux densities at 1.4 GHz ranging from $\sim$ 480 mJy to $\sim$ 30 mJy is shown as diamonds, while MERLIN and Global VLBI brightnesses (mJy/beam in logarithmic scale) are shown as squares and triangles, respectively. The observations resulted in about one third of the DEVOS NGP sources originally selected from FIRST (or 80% of the preselected MERLIN sources) have shown brightness exceeding $\sim$ 2 mJy/beam thus enabling imaging with acceptable dynamic range.

The DEVOS pilot project should be considered as a proof of feasibility of milliarscecond-scale studies of millijansky-level sources. However, it also indicates that en-mass DEVOS-style surveying will require a much higher sensitivity. Similar and even deeper surveys will be a noble task for the SKA in its high-resolution configuration!

4. AGN pc-scale radio structures and cosmology

VLBI data on radio loud AGN provide measurable parameters which could be looked at in a cosmological perspective. These parameters are the source's characteristic angular size, apparent proper motion of its structural components and the source count statistics.

The radio emission from the AGN cores on the milliarcsecond scale ought to be controlled by a limited number of parameters (such, as, e.g., the mass of central black hole, the ambient and intrinsic magnetic fields in the base of jet, the accretion rate and the angular momentum of the black hole). Kellermann (1993b) argued that the milliarcsecond-scale radio structures in AGN are much less dependent on the source evolution and properties of interstellar/intergalactic medium comparing to the arcsecond (kiloparsec) scale structures. Thus, mas-scale radio "cores" could be considered as non-ideal cosmological standard

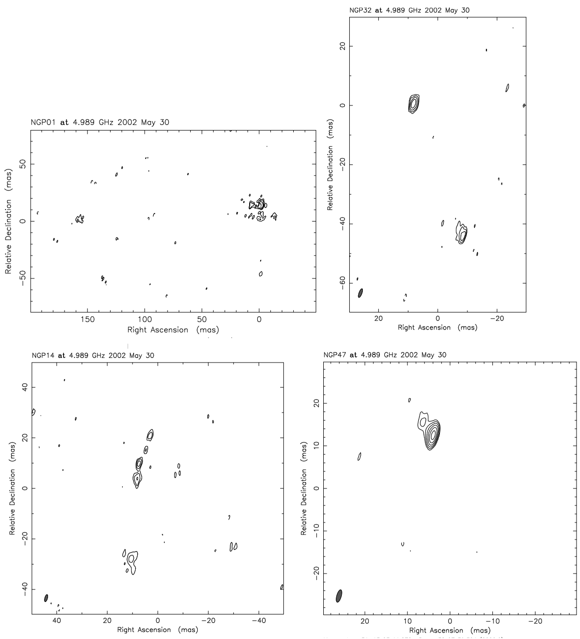

Figure 3. Examples of VLBI images of mJy-level DEVOS NGP sources at 5 GHz obtained in the pilot project. Peak brightnesses of the images are (from top left clockwise) 4.4, 7.9, 2.1 and 13.4 mJy/beam for the sources NGP01, NGP32, NGP14 and NGP47, respectively. Note that the brightest source of these four, NGP47, is the weakest FIRST source in the DEVOS NGP sample, with the total flux density at 1.4 GHz of 30 mJy.

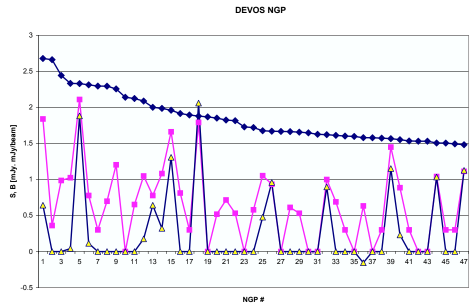

Figure 4. Statistics of 47 DEVOS NGP sources and their detections at 5 GHz. The horizontal axis shows the number of a source in the NGP sample. The vertical axis shows the logarithm flux density (diamonds, mJy) or logarithm peak brightness of MERLIN (squares) and VLBI (triangles), mJy/beam.

rods. The dependence of their apparent angular sizes on redshift (the so called "$\theta - z$" test, Fig. 5) contains an imprint of the cosmological model. Attempts by Gurvits (1993, 1994) and Kellermann (1993a, 1993b) to extract the cosmological information from independent ad hoc VLBI samples favoured a value of the cosmological deceleration parameter $q_0 \leq 0.5$ (under assumption that the cosmological term $\Lambda = 0$). Further work on the milliarcsecond scale "$\theta - z$" test by several authors (reviewed by Gurvits, Kellermann & Frey 1999) addressed various "pros" and "cons" of the approach. In particular, Dabrowski et al. (1995) pointed out the difficulty in obtaining a meaningful constraint on the average density Ω due to the effects of relativistic beaming in limited (let alone ad hoc) source samples. They estimated that cosmologically conclusive results could be obtained with VLBI samples containing several thousand sources.

Recently Vishwakarma (2001) used the data set by Gurvits et al. (1999) for considering models

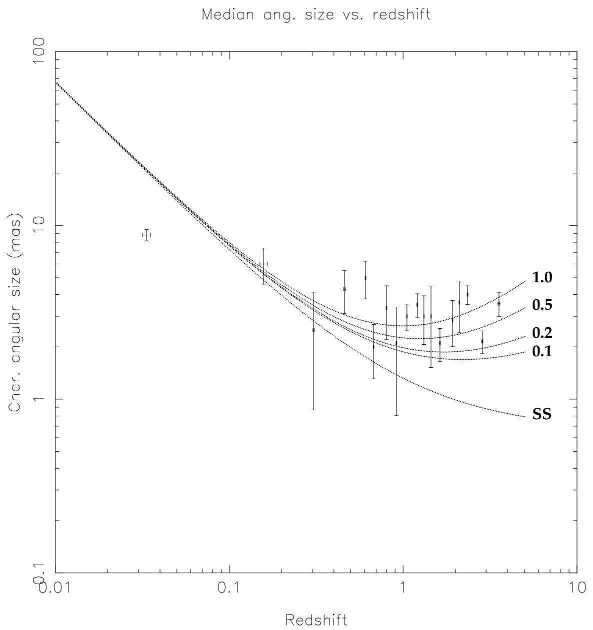

Figure 5. An example of the "$\theta - z$" test: median angular size of the sample of 330 AGN versus redshift (Gurvits, Kellermann & Frey 1999). The full length of error bars corresponds to 1σ. The solid lines correspond to the assumed linear size of 9.6 pc, the Steady-state model (SS) and models of a homogeneous, isotropic Universe with $\Lambda = 0$ and values of $q_{\circ}$ = 1.0, 0.5, 0.2, 0.1 (as marked on the plot). Data are binned into 18 bins nearly equally populated (18–19 sources per bin). The curves are shown as examples only. none of them represents the best fit.

with $\Lambda \neq 0$ and concluded that for realistic values of the matter density parameter, Ω_m, the best-fitting models are those with $\Lambda \propto H^2$, $\Lambda \propto \rho$ or flat models with $\Lambda = \text{const}$.

The same data set was analyzed by Lima and Alcaniz (2002) as a test-bed for the models containing the dark energy ("quintessence") which is characterised by the equation of state $p_x = \omega \rho_x$, where $\omega \geq -1$. Under this formalism, the parameter ω becomes a cosmological model parameter alongside the various density parameters Ω. The test was based on the earlier work by the same authors on the behaviour of angular sizes in the "quintessence" cosmology (Lima and Alcaniz, 2000). Their result favoured two sets of best fit parameters, $\Omega_m \leq 0.62$, $\omega \leq -0.2$ and $\Omega_m \leq 0.17$, $\omega \leq -0.65$. These estimates depend strongly on a fixed value of the source linear size, lh, which in this context is a certain liability.

Yet another cosmological formalism, the so called "Cardassian expansion" was confronted with the same $\theta - z$ data set by Zhu and Fujimoto (2002). They found (not surprisingly) that the best fit parameters of that model depend heavily on the value of the mean projected liner size of the sources, lh. However, they claim that the data favour the ΛCDM model and make it unnecessary to invoke the Cardassian expansion approach.

Chen and Ratra (2003) described a method which makes the linear size parameter lh a "nuisance" rather than a "liability". Their method was demonstrated by fitting the "maximum use" data set into two low-density CDM models: the first was parameterised by two density parameters, Ω_0 and Ω_Λ, the other was spatially flat with a dark energy scalar field, which could be formalised as a time-variable Λ-term. Their conclusion was that the $\theta - z$ test, applied to the "maximum use" data set was consistent with ΛCDM models but less constraining than the test based on the redshift-magnitude Type Ia supernova data.

The statistics of apparent velocity of VLBI components in AGN jets as a function of redshift (the "$\mu - z$" test) has been analysed by Vermuelen & Cohen (1994) and refined later by Vermeulen (1995) as a promising tool for studying the beaming model under various unification scenarios as well as a means of measurements of the Hubble constant H_0 and the deceleration parameter q_0. This method is based on the assumption of a "standard velocity" of moving features in milliarcsecond scale jets translated into observed apparent, sometimes superluminal, velocities (Pelletier & Roland 1989). An effort to exploit the "$\mu - z$" test with multi-epoch VLBI data for the CJF sample of AGN (several hundred sources) is underway (S. Britzen, 2004, in preparation).

Yet another potentially efficient application of large VLBI surveys for cosmological tests might be based on the studies of gravitationally lensed images of extragalactic sources (Koopmans, this volume and references therein).

This brief review of cosmological tests with milliarcsecond radio structures in extragalactic radio sources should be viewed as an indication on the usefulness of the approach. Its further development will require deeper and larger VLBI surveys. Their impact is likely to cover the following topics:
(i) The *cosmological evolution* of the radio-loud active galaxy population could be studied with the large database in the light of orientation-dependent unification models of powerful radio sources (cf. Wall & Jackson 1997).
(ii) The morphological classification of low-luminosity sources could be compared with that of their high-luminosity counterparts.
(iii) The dependence of source *compactness* on luminosity could be verified on milliarcsecond angular scales.
(iv) A large database of mas-scale radio images would be useful to study *gravitational lensing* since the survey of weak compact radio sources probes the parent population of lensed objects being found in e.g. the VLA CLASS survey of $\sim 10^4$ weak flat-spectrum sources (Browne et al. 2003).
(v) As shown by Dabrowski et al. (1995), several thousand milliarcsecond-scale images of optically identified extragalactic sources with known redshifts are needed to determine conclusive estimates of fundamental *cosmological parameters*, such as the density parameters $\Omega_{\rm m}$ and Ω_Λ.
(vi) Obtaining VLBI images of $\sim 10^4$ extragalactic sources will be an essential supplement to, and basis for, future development of the *astrometric* VLBI data bases (e.g. Johnston et al. 1995; Fomalont & Reid, this volume) and the next generation space-borne optical astrometry missions (e.g. GAIA).

5. High-resolution radio astronomy and SKA configurations

The issue of SKA configuration is of special concern when it comes to inevitable involvement of this ultrasensitive instrument in VLBI and Space VLBI studies. The most important quality which SKA brings into VLBI and SVLBI is an increase of baseline sensitivity by a factor proportional to "$\sqrt{\text{square kilometer}}$". However, the distribution of the SKA components (stations) over the Earth surface has serious impact on the imaging capability of the (S)VLBI system which contains SKA (see the materials of the workshop "High Resolution Options for SKA", Bonn, December 2001, www.EUSKA.org/workshops/hr_ws_mpifr_bonn.html). Therefore, at the present early stage of the SKA development it is expedient to include (S)VLBI in the algorithm of optimization of the "geographical" configuration of SKA.

5.1. Nominal specification of SKA and VLBI

In its nominal configuration, SKA could be considered as a "single dish" addition to the existing network of ground-based radio telescopes. Assuming its sensitivity at 5 GHz $T_{\rm sys}/A_{\rm eff} = 5 \times 10^{-5}$ K/m^2, the integration time $\tau = 120$ s, and the signal bandwidth of 512 MHz (corresponding to the data rate of 1024 Mbit/s for one-bit sampling), the baseline sensitivity (7σ) on the baseline to SKA will be

- 15 μJy detection threshold to a 70-m telescope ($T_{\rm sys}/A_{\rm eff} = 10^{-2}$ K/m^2);
- 40 μJy detection threshold to a 25-m telescope ($T_{\rm sys}/A_{\rm eff} = 10^{-1}$ K/m^2).

The former value should be considered as a benchmark for SKA operating within the VLBI network of existing large ground-based radio telescopes. The latter value shows what should be expected on the baseline SKA–SVLBI. Such a baseline sensitivity will offer a chance to detect compact sources which are significantly below detection threshold of any other "Earth–Space" baseline. For some astrophysical applications this could be useful. Since the detection threshold on other than "SKA–Space" baseline will be at least ten times higher, this single ultrasensitive baseline will contribute very little in the reconstruction of an image with angular resolution defined by fringe spacing on this baseline. Therefore, the resulting image will be either significantly tapered thus making the image less sharp than would be expected from the simple $\lambda/B_{\rm max}$ estimate, or its dynamic range will be determined by much less sensitive "non-SKA–Space" baselines. To overcome this difficulty one should consider a "global VLBI" configuration of SKA.

The highest sensitivity of VLBI observations can be achieved by exploiting the phase-referencing technique in which a signal from a weak target is calibrated using measurements of a nearby strong reference source obtained in the same observation. Not surprisingly, this technique occupies a very prominent position in the wish-list for future astronomical VLBI systems. VLBI use of SKA will make phase referencing a default mode of observations, which will come in two flavours. First, the sensitivity of a single SKA station will make it possible to find a reference source virtually everywhere on the sky – something hardly available for the present day VLBI observations. In turn, this will enable the most efficient "in-beam" mode of phase referencing, with a weak target and stronger reference sources within the primary beam of a VLBI element. The second possible mode of phase referencing will use the Cluster-Cluster VLBI technique described by Porcas et al. (2003). This latter mode will benefit especially due to the ability of SKA to observe with more than one independent beam simultaneously. It has to be noted that Cluster-Cluster VLBI applications of SKA could be of interest for astrometric and geodetic applications as well (see e.g. Fomalont & Reid, this volume).

6. Concluding remarks

The experience of VLBI AGN surveys has shown convincingly that their astrophysical and cosmological applications are far from being exhausted. Further progress will require improvement of angular resolution and sensitivity. The former is needed to confirm and exploit in full the trend hinted by the dependences shown in Fig. 2. It is clear that a large volume of the "luminosity – redshift" space (dashed in Fig. 1) requires to include in all-sky VLBI imaging surveys objects with the flux densities in the range of 100 – 1 mJy (and perhaps less in specially selected deep fields), which correspond to luminosities $\leq 10^{25}$ W/Hz and lower. This will increase the size of VLBI imaging samples by 2–3 orders of magnitude. The role of the SKA in such studies is hard to overestimate.

A higher resolution will become possible with future Space VLBI missions to be in orbit after 2020. Comparing to the VSOP mission, their higher angular resolution will be achieved owing to a higher orbit and higher observing frequencies. The SKA-SVLBI interaction should be kept in the field of view at the design stage of the Square Kilometre Array.

The combination of SKA on the ground and SVLBI in orbit offers an unprecedented combination of angular resolution (milli- and sub-milliarcsecond) AND sub-millijansky (tens microjansky) baseline sensitivity. In order to exploit this opportunity, it is essential to have a sufficient frequency overlap between SVLBI (which tends to emphasize the higher frequency domain toward mm wavelengths) and SKA with its strong drive toward lower frequencies (below 5 GHz). A range of frequency overlap around 5 (possibly, 8) GHz should be preserved. Two highly desirable extensions toward 1.5 GHz (and, possibly, high UHF frequencies below 1 GHz) for SVLBI on one hand and 22 GHz for SKA on the other should be considered.

As a ground-based component of a Space VLBI system, the SKA in its "compact" configuration will provide the most sensitive baseline "Space – Earth", which would be useful for detecting interferometric fringes from compact ultraweak sources. However, as an effective component of an imaging system with sub-milliarcsecond resolution, the SKA should be distributed over global distances on the Earth's surface. Such a configuration will create a truly advanced VLBI system with superior angular resolution and imaging sensitivity at least 10–100 times higher than available at present. This "Global" SKA configuration could be implemented with minimal impact on low brightness sensitivity of the nominal "compact" configuration by distributing over global distances only up to 30% of the overall SKA collecting area. The "Global" SKA configuration is also in line with the de facto widely international character of the SKA endeavour.

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