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The ICRF: 2010 and Beyond

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Abstract

This paper considers future directions for improving the International Celestial Reference Frame (ICRF) over the next 10 years. The current ICRF includes a total of 717 extragalactic objects, most of which have position accuracies of 250–1000 microarcseconds (μas). Beyond 2010, the radio realization of the ICRF may be disputed by new instruments like the GAIA optical astrometric satellite which will observe 500 000 extragalactic objects with astrometric precision of 10–100 μas. The IVS should prepare for this challenge by improving as far as possible the present ICRF accuracy and source density. Position accuracies better than 100 μas may soon be achievable considering possible modeling refinements (troposphere, source structure) and improved instrumentation. Recent initiatives to densify the ICRF as well as future possibilities to massively increase the number of sources are discussed. Over 10+ years, the realization of an ultra-accurate extragalactic reference frame at both optical and radio wavelengths is an exciting perspective not only for astrometry but also for studying physics of active galactic nuclei.

1. Introduction

The International Celestial Reference Frame (ICRF) is a unique VLBI product because no other astrometric technique has been able to derive a similar highly-accurate extragalactic frame. The ICRF became effective as the fundamental celestial reference frame on 1 January 1998, following a resolution adopted at the XVIII General Assembly of the International Astronomical Union held on 1997 August 20 in Kyoto, Japan [1].

The ICRF differs from the previous realization of the celestial frame, the FK5 stellar catalog, in two important ways: (i) it relies on extragalactic objects (quasars and active galactic nuclei), and (ii) its axes are no longer related to the equator and ecliptic planes. Instead, the ICRF axes are specified through quasi-inertial coordinates of 212 *defining* extragalactic sources observed by VLBI between August 1979 and July 1995 [1]. The accuracy of the individual source positions is as small as 250 microarcseconds (μas) while the orientation of the ICRF axes is good to the 20 μas level. Positions for 294 less-observed *candidate* sources and 102 *other* sources with less-stable coordinates were also reported, primarily to densify the frame. Continued VLBI observations through May 2002 have provided positions for an additional 109 *new* sources along with refined coordinates for candidate and "other" sources [2]. The sky distribution and position accuracy of the current 717 ICRF sources are shown in Fig 1.

While there is presently no competition for the realization of the fundamental extragalactic frame, the situation may evolve within the next decade because new instruments will come on line, which may dispute the realization of the frame to VLBI. In the radio band, the e-MERLIN instrument (a development of the present MERLIN array using fiber-optics cables to transmit wide-band signals from telescopes)[1] will conduct geodetic-mode observations to measure absolute

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[1] See the e-MERLIN science case and technical specification at http://www.jb.man.ac.uk/e-merlin.

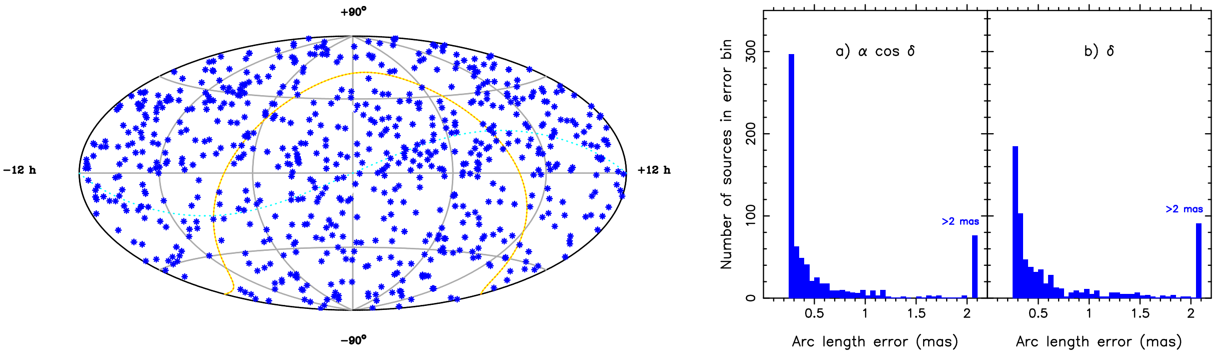

Figure 1. *Left panel:* Distribution of the current 717 ICRF sources on an Aitoff equal-area projection of the celestial sphere. *Right panel:* Histogram of source position errors in *(a)* right ascension and *(b)* declination.

positions to within a few milliarcsecond (mas) for milliJansky (mJy) sources. Plans are prepared for a survey of up to 100 000 such sources with observing starting by 2008 [3]. Though not up to the ICRF accuracy, this survey will be 100 times denser than the ICRF and will constitute a natural extension of the frame towards weaker objects north of approximately $-20°$ declination.

At optical wavelengths, the GAIA space mission, a second-generation astrometric satellite to be launched by 2010–2012, will survey all stars and quasars down to an apparent magnitude of 20 [4]. Position accuracies will range from 10–40 μas at magnitude 15–18 to 100–200 μas at magnitude 20. Based on current estimates from local surveys, it is expected that 500 000 such quasars should be detected. Hence, there will be plenty of material to construct the extragalactic frame from *direct* observations of defining sources in the visible wavebands. Simulations show that with a sample of 10 000 defining sources the residual spin of the GAIA reference frame could be determined to 0.5 μas/yr [5]. In practice, the ultimate accuracy of the frame may be limited by random instability of the sources which may show extended and variable structure on these spatial scales, similar to that observed at radio wavelengths [6, 7]. Despite this limitation, the GAIA reference frame will clearly surpass the current ICRF, both in accuracy and in source density. Hence, the realization of the fundamental celestial frame is likely to be brought back to visible wavebands in about 10 years.

This perspective should be regarded as a strong motivation to further improve the current ICRF, design ambitious VLBI programs, and possibly invent new VLBI instruments that will challenge the future optical realization of the extragalactic frame by GAIA. Sections 2 and 3 below consider possible future directions for improving the accuracy and source density of the ICRF with the GAIA perspective in mind. In Sect. 4, I will give my own view on how such improvements may be accomplished and propose a time frame for the work to be done from now to beyond 2010.

2. Improving the Accuracy of the ICRF

Improving the accuracy of VLBI astrometric results require improving the entire VLBI observing, calibration and analysis system. This includes modeling capabilities, data acquisition technology, and astrometric target selection. Overall, the largest contributor to ICRF inaccuracy is the propagation in the troposphere (150–250 μas error), followed by the data acquisition technology (50–100 μas error), and source structure (widely-variable error) [8]. Recent or foreseeable improvements for each of these three major error components are discussed below.

2.1. Troposphere Modeling

While the charged particle propagation media effects (ionosphere) have been effectively calibrated using two observing frequencies, the modeling of the troposphere has improved in discrete steps associated with consideration of asymmetry and variability [9] and development of new troposphere mapping algorithms [10]. Current research is directed toward the use of global weather data in computing the mapping function through ray tracing or a proxy. However, computational limits as well as temporal and spatial resolution of the weather models preclude direct ray tracing for every observation in place of estimating troposphere variations.

Another approach would be to install advanced water vapor radiometers at each VLBI site to calibrate the atmospheric path delay along the line of sight for every observation [11]. This technology, developed for the Cassini gravitational wave experiment, has been very successful. However, it is very expensive and there are no plans to replicate such instruments at the moment. Further engineering studies should be carried out to determine whether the cost for these instruments could be lowered so that a wider use may be considered.

Reducing the impact of tropospheric mismodeling also implies devising optimum observing strategies for improving the estimation of troposphere variations. Such strategies may be facilitated by future increased baseline sensitivities (see below) which will permit integration over shorter scans and hence observation of more sources over a given period of time for improving the local sky coverage around each VLBI station.

2.2. Data Acquisition Technology

This category covers a wide range of instrumental errors, among which atomic clock instabilities, phase-calibration errors, and recording-media deficiencies. When taken altogether, these errors may be the second largest contributor to inaccuracy in astrometric VLBI results.

While fiber optics have greatly reduced the errors in distributing the frequency standard to the antennas, atomic clocks (hydrogen masers) still wander at a level VLBI is sensitive to. There is ongoing research with mercury-ion clocks that shows promise especially on the long time scales (many hours to days) but this technology is not yet operational for VLBI [12]. The pulse generation and process of injecting phase-calibration tones into the signal chain are imperfect and do not calibrate the antenna optics (primary dish, subreflector, feed). Additionally, there is usually no polarization calibration while it is known that polarization leakage may be a potentially significant error. Overall, imperfect calibration produces phase instabilities in both time and frequency which affect the measurements at some level. While certainly a long process, scrutinization of all such errors appears to be a necessary step to further improve data quality.

Tape-based recording has constantly suffered from varying amounts of data lost due to tape dropouts and tape synchronization up time, thus contributing to measurement errors. Fortunately, these problems are about to go away with the introduction of disk-based recording. This new system greatly improves data reliability and is a huge step forward in collecting uniformly-sampled data in time and frequency. Another practical effect of disk-based recording is that recording data rates are increasing (up to 1 Gb/s with the Mark 5 system), hence improving signal-to-noise-ratios. In the longer term, the introduction of modern digital video converters, replacing the present Mark IV analog video converters, will make it possible even higher data rates. According to [13], there is reasonable hope that a recording rate of 4 Gb/s be available by 2010. The astrometric consequence of such improved sensitivities will be examined in Sect. 3 below.

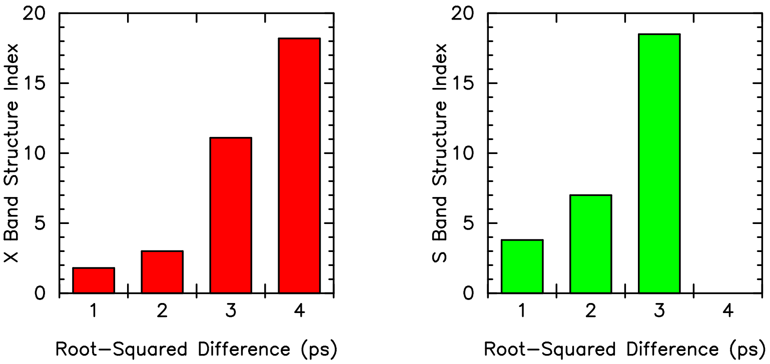

Figure 2. Delay residual improvements upon introducing source maps to model the structure delays. The improvement is given as a function of the structure index at 8 GHz (left panel) and 2 GHz (right panel). See [15] for further details on this analysis.

2.3. Source Structure

Various imaging programs have shown that extragalactic radio sources are generally not point-like on VLBI scales [6, 7]. While having a very compact core, they also often display extended jet emission and thus do not make perfect fiducial targets for building a reference frame. Source structure and changes in source structure put a floor on the stability of estimated source positions using VLBI astrometric data. A useful indicator of source quality is the "Structure Index" introduced in [6]. Values of the structure index range from 1 to 4 with increasing values indicating increasing average structural VLBI group-delay corrections on an approximately logarithmic scale. The current structure index distribution, available for 450 ICRF sources, shows that 57% of the sources for which a structure index is available, have a value of either 1 or 2 at the standard 8 GHz geodetic observing frequency, indicating compact or very compact structures for these sources, while the rest of the sources, with a value of either 3 or 4, show more extended structures [7, 14].

The impact of source structure effects on astrometric VLBI results has been tested on massive scales with a data set including 155 sources and a total of 800 maps to correct for such effects in multi-epoch observations [15]. Figure 2 shows the delay residual improvement as a function of structure index, indicating larger improvements for increased values of the structure index. These range from a few picoseconds (ps) for structure index 1 values to about 20 ps for structure index 4 values. Overall, the weighted rms delay residuals were found to decrease by 8 ps in quadrature upon introducing source maps to model the structure delays. The angular equivalent of this improvement is approximately 100 μas for typical VLBI baselines and amounts to a significant fraction of the 250 μas systematic error of the ICRF, thus confirming that source structure does affect VLBI analysis even though it is not currently the dominant error.

Such modeling, however, is very labor-intensive because of the many sources to be mapped at many epochs due to unpredictable evolution of source structure. An alternate approach, which would limit structural VLBI delay effects, would be to select only the most compact sources for the realization of the celestial frame. Structure index studies show that the more extended sources do have larger position uncertainties and are less positionally stable than the more compact sources [7]. The selection of targets could also be based on analyses of source position stability, as proposed in [16]. Interestingly, the vast majority (92%) of the 199 ICRF sources identified as stable in [16] have a value of the structure index of either 1 or 2, indicating compact or very compact structures.

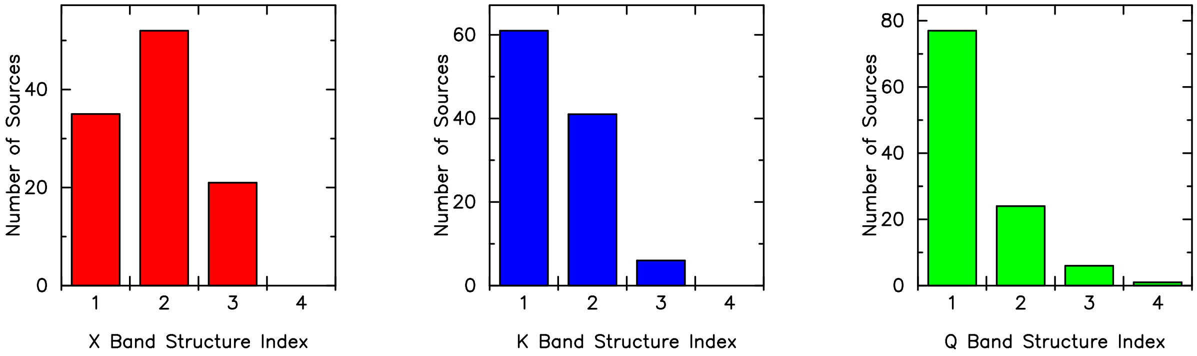

Figure 3. The structure index distribution at 8 GHz (X band), 24 GHz (K band) and 43 GHz (Q band) for 108 ICRF sources.

Such studies also revealed that the ICRF-defining sources are not as good as could be hoped for defining the celestial frame with the highest accuracy [7, 16]. This suggests that revision of source categories would be mandatory upon realization of a new ICRF.

Another approach to reduce structural VLBI effects would be to observe at higher radio frequencies. On average, active galactic nuclei are expected to be more compact at higher frequencies since extended jet emission has a steep spectrum and thus usually weakens (as regard to the core brightness) as observing frequency increases. Regular VLBI astrometric and imaging observations at 24 GHz and 43 GHz have been conducted since May 2002 to investigate this possibility [17, 18]. As shown in Fig. 3, the comparison of the structure index distribution at 8 GHz, 24 GHz, and 43 GHz for the first 108 sources observed in this survey is striking, indicating a larger proportion of structure index values of 1 as observing frequency increases (32% at 8 GHz, 56% at 24 GHz, and 71% at 43 GHz). Hence, these initial results already suggest that the sources make significantly better fiducial targets at 24 GHz and 43 GHz than at the standard 8 GHz observing frequency.

3. Increasing the ICRF Source Density

The current ICRF with a total of 717 sources has an average of one source per $8° \times 8°$ on the sky (Fig. 1). While this density is sufficient for geodetic purposes, it is clearly too sparse for differential-VLBI astrometric applications (phase-referencing of weak targets, spacecraft navigation), which require reference calibrators within a-few-degree angular separation. Additionally, the frame suffers from inhomogeneous distribution of the sources. For example, the angular separation to the nearest ICRF source for any randomly-selected location is up to 13° in the northern sky and 15° in the southern sky [19]. Another deficiency of the frame is the deficit of defining sources in the south and their less-accurate astrometric positions, as a result of the lack of well-established VLBI networks in the southern hemisphere.

The next subsection (3.1) reviews the current ICRF densification programs aimed at correcting these deficiencies. As the celestial frame fills up, increasing further the source density will require observing weaker and weaker targets. The number of sources that could be effectively observed in the future is thus closely connected to the evolution of the sensitivity of VLBI arrays. Future ICRF densification programs should also be devised with a long-term view, keeping in mind the GAIA perspective of an optical frame with 500 000 extragalactic objects in 10–15 years. This perspective raises the question (to be addressed in subsection 3.2 below) of the feasibility of massively increasing the ICRF source density (e.g. by one or two orders of magnitude) on this time scale.

3.1. Current Densification Programs

A specific observational effort is being devoted to the southern sky in order to attempt to correct the existing ICRF deficiency in the south. This effort is accomplished through dedicated astrometric and imaging observations using telescopes of the Australia Telescope National Facility plus other geodetic stations in the southern hemisphere [20]. The goals of this program are to image all southern ICRF sources at least twice for structure monitoring and to search for new astrometric sources for densification of the ICRF in the south. Astrometric positions for 22 new sources and first-epoch images for 69 ICRF sources have just been reported [21, 22]. Ultimately, the astrometric sessions should provide a strong tie between the northern and southern sky through the overlapping common sources at moderate southern declinations whose positions have already been measured with the northern VLBI networks.

In the northern sky, an observing program is currently underway to densify the ICRF using the European VLBI Network and other geodetic antennas [19]. The approach used in this program has been designed to improve the overall source distribution in the ICRF. More specifically, the goal is to add 150 new sources at specific sky locations in order to fill the holes in the current frame. As shown in [19], this extension would reduce the angular separation to the nearest ICRF object from a maximum of 13° to a maximum of 6° for any location in the northern sky, and thus would largely contribute to homogenizing the source distribution. A secondary goal of this project is to identify new sources of high astrometric value which could potentially serve as defining sources in a future realization of the ICRF. This was accomplished by filtering out the potential targets using images from the VLBA Calibrator Survey (see below) in order to select only sources with no or limited extended structure for these observations.

The basis for current ICRF densification programs is the Very Long Baseline Array (VLBA) Calibrator Survey (VCS1). This survey reports previously-unmeasured VLBI astrometric positions for 1332 sources between $-30°$ and $+90°$ declination along with survey VLBI images at 2 GHz and 8 GHz for most of these sources [23]. This is the largest high-resolution radio survey ever undertaken and it triples the number of sources available for VLBI applications. The VCS2 extension reports positions for an additional 276 sources, most of which are in the declination range $-20°$ to $-45°$ and near the galactic plane [24]. Although not acquired in standard geodetic VLBI mode, these data may be useful for future ICRF extensions. Evaluation of the astrometric suitability of the VCS1 and VCS2 sources based on the available survey images would also be worthwhile to identify the most promising candidates for future inclusion in the ICRF.

3.2. How Many Sources in the ICRF by 2010?

As stated above, increasing further the ICRF source density will closely depend on how fast the sensitivity of VLBI arrays improves in the future. Disk-based recording with the Mark 5 system now permits data rates up to 1 Gb/s, a gain by a factor of 4 as compared to the standard 256 Mb/s data rate used so far on geodetic networks. A gain by an additional factor of two will be possible when Mark 5B units are available (two of these used in parallel will support up to 2 Gb/s), while the introduction of modern digital video converters opens up hope for recording data rates up to 4–8 Gb/s on the longer term. New large antennas that are being built, e.g. in Spain (40 m

Table 1. Present and future sensitivity of the baselines Algonquin–Medicina and Algonquin–Effelsberg. The sensitivity (in mJy) is given as a function of data rate and integration time for a signal-to-noise ratio of 20.

Epoch	Data rate	Algonquin–Medicina			Algonquin–Effelsberg		
	(Gb/s)	10 sec	60 sec	240 sec	10 sec	60 sec	240 sec
2004	1	140	60	30	36	14	7
2006	2	100	40	20	25	10	5
2010	4	70	30	15	18	7	3.5

telescope in Yebes to be inaugurated later this year), Italy (64 m telescope in Sardinia planned for 2006), or China (50 m telescope in Miyun and 40 m in Kunming planned for 2006) will also directly contribute to improving the sensitivity of VLBI arrays in the near future.

Table 1 compares the baseline sensitivity for recording data rates of 1 Gb/s (possible now), 2 Gb/s (likely available by 2006), and 4 Gb/s (foreseen by 2010). The sensitivity is given as a function of integration time (10 sec, 60 sec, and 240 sec) for the "standard" baseline Algonquin–Medicina and the highly-sensitive baseline Algonquin–Effelsberg. The results in Table 1 indicates that most ICRF sources should be detectable with 10-second long observations on standard baselines since the vast majority of these sources are stronger than 100 mJy. Use of such short scans will considerably increase the number of observations per day, hence permitting the monitoring of a larger portion of the frame within each session. Longer integration times will permit detection of sources as weak as 15 mJy on standard baselines, while inclusion of big antennas (e.g. Effelsberg) in the array will bring the detection threshold down to a few mJy.

This expected enhancement in sensitivity raises the question of how many of such weak sources do exist over the entire sky and whether they are compact enough for detection by VLBI arrays. Some insights into this questioning have recently been obtained from VLBI test experiments using the ultra-sensitive baseline Arecibo-Effelsberg [25]. The aim of these experiments was to explore the source compactness on a statistical basis by observing a sample of 1000 weak sources ($>$ 1 mJy) randomly-selected from the FIRST survey[2]. Each source was observed for 1 minute at a recording data rate of 512 Mb/s, which provides a 7σ detection threshold of about 1 mJy at 21 cm wavelength. Preliminary results based on a subset of the data show that roughly 20% of the targets have been detected [25], hence indicating the portion of the sources that are potentially useful for building a dense and precise reference frame at this sensitivity level.

The total number of radio sources for a given flux threshold may be derived from the NRAO VLA Sky Survey [26]. This catalog contains 2 million radio sources, of which 50 000 are stronger than 50 mJy at 1.4 GHz, approximately equivalent to 15 mJy at 8 GHz, the expected threshold to be reached by 2010 (Table 1). As noted above, if 20% of these have at least one compact component on VLBI scales, this implies that 10 000 sources should be detectable with standard VLBI arrays by that time. Assuming 250–500 sources may be observed per 24 hours, a reasonable assumption if using large VLBI arrays, the observing load represents a total of 20–40 experiments, equivalent to observing once per month during 2–4 years. This observing load is only twice that of the current bi-monthly Research & Development VLBA program (RDV) and thus is not unrealistic.

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[2] The FIRST Survey is available at http://sundog.stsci.edu/

4. Proposed Plan and Timeframe

4.1. Build ICRF–2 (2004–2006)

The ICRF has accomplished its primary goal of providing an accurate and stable celestial reference frame conceptually independent of the motion of the Earth in space. However, it was recognized from the beginning that there were several intrinsic deficiencies in its realization, in particular the uneven distribution of defining sources and the weakness of the criteria for selecting these sources. Since the inception of the ICRF in 1995, a wealth of VLBI data (including those from the highly-accurate RDV experiments) has been acquired, modeling has been refined (e.g. for troposphere propagation effects), and improved criteria based on source structure and position stability have been devised to categorize the sources. With such additional data and analysis improvements, the source position error floor is now most probably at the 100 μas level or below [27], a significant gain as compared to the 250 μas systematic error of the ICRF. For this reason, I feel that it is now time to initiate a new realization of the celestial frame. Targeting the completion of this second realization, ICRF–2, by 2006 sounds like a reasonable objective.

4.2. Initiate a Massive Survey (2006–2010)

The next step I see once ICRF–2 is done is a massive increase in source density. As noted above, observing 10 000 sources will be feasible on a time scale of a few years when data rates of a few Gb/s are available. For higher efficiency, large networks of 15–20 telescopes should be used so that both imaging and astrometry could be carried out simultaneously (as currently done with the RDV experiments). Inclusion of sensitive telescopes (40–50 m class antennas) would also be desirable to pick up the weakest sources. Such a survey may be handled jointly with the astrophysical community which is considering similar surveys for studies of radio source population and cosmology. More generally, obtaining a large set of accurate radio positions would be invaluable for comparison with the future GAIA optical positions, not only for astrometric purposes but also for astrophysical goals. Pinpointing the relative positions of the optical and radio counterparts in active galactic nuclei is indeed especially useful for investigating emission processes in these objects. This massive survey is a long-term work with sustained observations over several years, therefore it should start as soon as the required sensitivity is available so that results could be obtained by the end of this decade or soon after, prior to the realization of the GAIA frame.

4.3. Get Involved in SKA (Beyond 2010)

On the longer term, the astrometric VLBI community should keep a close eye on the development of future radio instruments such as the Square Kilometer Array (SKA)[3]. This instrument, envisioned by 2015–2020, would have one square-kilometer collecting area (equivalent to 100 times that of the Effelsberg telescope), making the nanoJy sky accessible to radio observations. While the general SKA concept is agreed, there are many different designs still competing at this point. Will the collecting area consist of big antennas (e.g. 100 "Effelsberg" telescopes) or smaller antennas (e.g. 10 000 telescopes with a diameter of 10 m)? Will this instrument observe only at low frequencies or will the frequency coverage go up to 22 GHz? Will the baselines be limited to a few hundred kilometers or be intercontinental? High frequencies and long baselines would be of most

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[3] See http://www.skatelescope.org/

interest for building a future accurate and ultra-dense celestial frame down to the nanoJy level. Multi-beaming, a specific SKA feature considered for observing up to 100 sources simultaneously, is also highly interesting as it would permit the construction of a celestial frame free of terrestrial frame and Earth orientation errors by using measurements of the arc length between sources [28].

Overall, I feel the geodetic, astrometric but also astrophysical VLBI communities should express their views as regard to the design of the SKA instrument and should especially push towards higher-frequency and longer-baseline capabilities. A SKA-VLBI workshop[4] held in Bonn in 2001 could serve as a basis for future detailed studies and proposals regarding these issues. On the astrometric side, SKA is the only radio instrument that may be able to compete with GAIA for the realization of the celestial reference frame. Therefore, it is important that the astrometric VLBI community get involved in SKA if the decision to build this instrument is taken.

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[4] See http://www.euska.org/workshops/hr_ws_MPIfR_Bonn.html.

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