A Potential Use of AGN Single-Dish Monitoring for Optimization of Geo-VLBI Scheduling

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Abstract Source structure is an important characteristic of extragalactic radio sources that are used to keep the celestial reference frame(ICRF2 defining sources). Their structure is variable with time, and its changes are connected to the total flux variations. Observations of total flux variatopns with a single radio telescope is much cheaper time- and laborwise than VLBI imaging. We consider a possibility to use single dish AGN monitoring results as precursor of approaching activity in ICRF2 defining sources that are prone to be unstable in the active state. This information could be used for scheduling of geo-VLBI sessions, when active sources could be temporarily replaced by the currently stable ones.

Keywords source structure, total flux, single-dish, monitoring

1 Introduction

The second realization of the International Celestial Reference Frame (ICRF2) is defined by accurate positions of 295 bright active galactic nuclei (AGN) that are distributed nearly evenly over the sky (Fey et al. , 2009). Extended structure of many ICRF sources introduce additional delays of up to several hundreds ps (Charlot , 1990; Fey & Charlot , 1997, 2000) that limits the accuracy of ICRF axis stability and coordinate determination (e.g., Charlot , 2008). Fey & Charlot (1997) introduced a quantitative measure of the correction needed to compensate for these structure-induces delays: a structure index that runs from 0 (small corrections – compact source) to 4 (large corrections – extended source). One of the selection criteria for the sample of defining sources for ICRF2 was a limit on maximum average continuous structure index of 3.0 (Fey et al. , 2009), that ensured relative compactness of ICRF2 defining sources. This threshold was calculated based on images obtained at S (2 GHz) and X (8 GHz) bands during 1994–2007, with number of observational epochs ranging from 1 to ≈30 (e.g., Charlot , 2008). The resulting noise floor of ICRF2 is 0.04 mas with individual measurements errors up to ≈0.2 mas, and axis stability is 0.01 mas (Fey et al. , 2009).

However, there are two aspects of the AGN physics that should not be neglected: nuclear opacity and connection of the structure changes to the total flux variability. AGN are compact bright cores of massive galaxies, where disc accretion on a central black hole causes a formation of two collimated conical relativistic jets of magnetized plasma, that propagate perpendicularly to the plane of an accretion disc. Jets emit synchrotron radiation in vawebands from radio to far infrared. The compact extragalactic radio sources that are observed at VLBI scale and associated with AGN are in fact optically thick (where synchrotron self-absorption optical depth $\tau = 1$ at a given frequency) unresolved inner regions of the jet at a distance of $r_{core} \approx 10^4 R_g \approx 1pc$ ($R_g = GM_{BH}/c^2$ is gravitational radius of a central black hole) from the center (Blandford & Königl , 1978; **?**). Thus, the observed position of a defining source, measured via VLBI observations, is actually a position of such a VLBI "core" that may change with frequence and time. The location of $\tau = 1$-surface changes with frequency as $r_{core} \propto \nu^{-1/k_r}$, with $k_r = 1$ for a conical jet with the particle and magnetic field energy density equipartition and with domination of synchrotron self-absorption (Blandford & Königl , 1978; Königl , 1981; Lobanov , 1998). Thus, the core shifts upstream at higher frequencies and downstream at lower fre-

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quencies, so that the actual positions of the source at S and X bands may differ at a given time. In addition, random variations in the jet electron density, magnetic field strength and jet inclination to the line of sight (jet bending), as well as regular jet rotation (precession), and their combinations may cause erratic changes of the nuclear opacity and of a $\tau = 1$-surface position with time. A substantial brightening of the VLBI core that is defined at "nuclear flare" causes time variations in the core shift. Kovalev et al. (2008) and Sokolovsky et al. (2011) studied S/X-band core shifts of a number of geodetic sources from ICRF1 catalog, aligning self-calibrated source images comparing relative position of a common optically thin jet component. Unfortunately, this method naturally limits possible targets to the subset of most extended ones. Kovalev et al. (2008), based on imaging of RDV sessions data from 2002 to 2003, found that the median value of core shifts between S and X bands for 29 sources is 0.44 mas with the maximum value as high as 1.4 mas (for 0850+581). A further dedicated VLBA multi-frequency delay study by Sokolovsky et al. (2011) was performed on 20 sources, 15 of which were included also in the sample of Kovalev et al. (2008). It found median value of core shift between S and X bands to be 0.69 mas with the maximum value of 1.34 mas (for 0610+260). These values greatly exceed formal accuracy of the individual source position estimations. Kovalev et al. (2008) estimates a theoretical core shift between X and optical bands to be 0.1 mas that should be taken into account for the alignment between radio and optical ICRFs. They also report that for the sources that have multiple measurements of a core shift, its magnitude was proportional to the X-band VLBI core flux. The magnitude of this effect also suggests that during the nuclear flare physical parameters of the jet plasma change. Another example was reported by Fomalont et al. (2011). They compared relative core positions of four ICRF2 defining sources at 8, 23 and 43 GHz obtained via phase-referenced VLBA and VERA imaging to their nominal ICRF2 positions. The catalog positions are displaced by up to 0.5 mas from the actual core. The direction of the shift was towards the extended structure, and this displacement varied. This effect was attributed to the source structure in three cases, and to the core opacity in one.

Nuclear flare is an indication of a disturbance in the base of the jet. It also leads to the excitation of a shock wave that propagates along the jet away from the core. Propagation of a shock wave manifest itself as an emergence of a bright moving "knot" in the jet that can be traced on series of subsequent VLBI images (e.g., Marscher , 1996). Savolainen et al. (2006) investigated connection between emergence of new jet components in the VLBI images of the blazar jets at 22 and 43 GHz and total flux flares occuring at 22 and 37 GHz (Metsähovi Radio Observatory AGN monitoring). They argue that it is likely that every nuclear flare in a blazar leads to a formation of a shock wave, that is triggered at the moment of an onset of a flare (local minimum before the peak of the total flux light curve). However, in some cases these shock wave has faded out before they reach as far in the jet as to becomes visible at VLBI images. In this case, model-fitting of a source structure and direct inspection of closure phases and their residuals help to reveal the presence of a new component. In other cases, a newly born component becomes resolved approximately at the moment of time when the total flux flare reaches its maximum. Since resolution of geodetic VLBI network at 8 GHz is ≈ 0.6 mas, a displacement of the core within this radius may lead to an error of the position estimation since formal errors of coordinates are ≤ 0.2 mas. The magnitude of an effect of the resolved source structure on geodetic VLBI performance is comparable to the noise introduced by the imperfection of ionospheric corrections.

During the flare, flux density of a source may increase by the order of magnitude within the time period of several months. Hovatta et al. (2008) reports that for a sample of 55 blazars the duration of flares (from minimum to minimum of a light curve) in radio varies from four month to 13 years, with median value of 2.5 years. Kudryavtseva et al. (2011) determines an activity cycle of AGN as a time period from one nuclear flare to the other. Nuclear flares are characterized, in particular, by frequency-dependent time delays between maxima of the flare at different frequencies. This effect is being attributed to increase in nuclear opacity during the flare. Shabala et al. (2012) argues that such flares cause a substantial degradation of the quality of geodetic data.

Thus, a total-flux flare of an ICRF2 defining source in mm-cm domain is an indicator of intrinsic processes that lead to a substantial reduction of the geodetic data quality. AGN tend to have long recurrent activity cycles (Kudryavtseva et al. , 2011; Hovatta et al. , 2008), thus, at any given moment of time some fraction of the ICRF2 defining sources are flaring, hence, displaying two effects discussed above, nuclear opacity and ejection of a new jet component. Study of 22 and 37 GHz AGN total flux light curves from Metsähovi Radio Telescope shows that behavior of sources differ: some stay most of their time in the quiescent state and some are almost constantly flaring. Such trend is preserved over long time periods. Thus, knowing individual behaviorial patterns of each source, and being supplied

Searching for an Optimal Strategy to Intensify Observations of the Southern ICRF sources in the framework of the regular IVS observing programs

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Abstract The quality of the VLBI-derived ICRF in the southern hemisphere is much worse than in the northern hemisphere. The main reason is that only about 3% of the observations have been made of the sources at declinations below –30 deg due to the relatively small number of VLBI stations located in the southern countries. In this paper, we investigated a possibility to increase the number of observations of the existing and prospective southern ICRF radio sources by inclusion of more such sources in the regular IVS sessions like R1 and R4. We tested the influence of adding supplementary southern sources to the IVS R1541 (12JUL09XA) session on EOP and baseline length repeatability with Monte Carlo simulations. We found that adding more observations of southern sources to the standard schedule causes a slight degradation of some geodetic products and a slight improvement of others, depending on the number of added southern sources. Similar results were obtained for the IVS R1591 (13JUN24XA) session. Generally, it has been shown that it is possible to increase the number of observations of southern sources without loss of the overall accuracy of geodetic products. So, the task is to find an optimal trade-off between the maximum increasing of the number of observations of southern sources and the degradation of geodetic results.

Keywords VLBI, IVS, ICRF, scheduling

1 Introduction

The quality of the ICRF in the southern hemisphere is much worse than in the northern hemisphere. The main reason is that the number of southern VLBI stations participating in the astrometric observing programs is much smaller than that in the northern hemisphere. As a consequence, the number of observations of the southern sources is very small. Only about 3% of the observations have been made of the sources at declinations below -30 deg (see Fig. 1). The situation improves with time, but very slowly despite new southern stations and new CRF-dedicated observing programs (see Fig. 2). The relative number of observations of most southern sources does not improve with time at all.

Deficiency of observations of southern sources leads to the following well recognized consequences:

- the number of the southern ICRF sources is much smaller than the northern;
- the number of the southern ICRF sources with reliable position and stability estimate, herein reliable core/defining sources, is much smaller than the northern;
- the position accuracy of the southern sources is generally worse than the northern.

Special CRF programs for the southern hemisphere are rare, and are often conducted on poor networks of 2-3 stations, which can deteriorate the source position accuracy because of the source structure effect. Two possible ways were proposed by (Malkin et al., 2012) to increase the number of observations of poorly observed and new prospective ICRF sources on the southern sky: inclusion of more such sources in the regular IVS sessions like R1 and R4, and implementing new scheduling strategies not requiring sky coverage for the stations. In this paper, we investigate possible strategies to force an improvement in the ICRF sources observation distribution over the sky by:

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- including prospective ICRF sources in the regular IVS observing programs, such as R1 and R4;
- finding a trade-off between a slight degradation of the EOP precision and the long-term ICRF improvement.

We made use of the VieVS scheduling and simulation tools (Böhm et al., 2012) for our study.

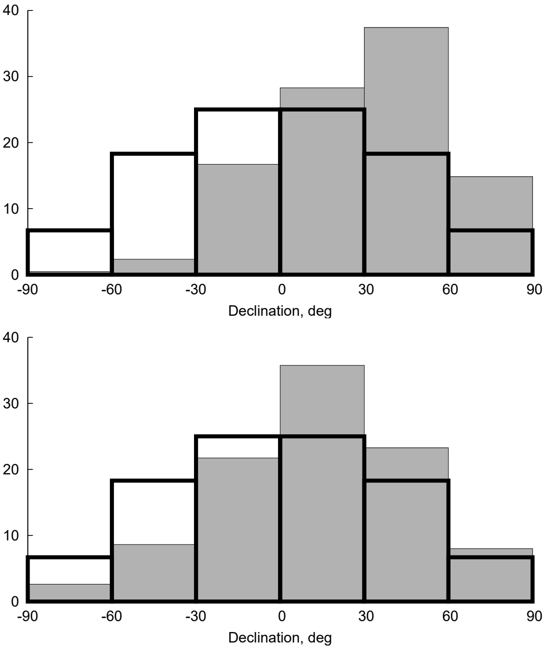

Fig. 1 Percentage of observations by DE bands (top) and percentage of the well observed sources with Nsess $\geq$ 10, Nobs $\geq$ 200 (bottom). Actual numbers of observations are shown by grey boxes, numbers of observations expected for a uniform distribution are shown by thick lines).

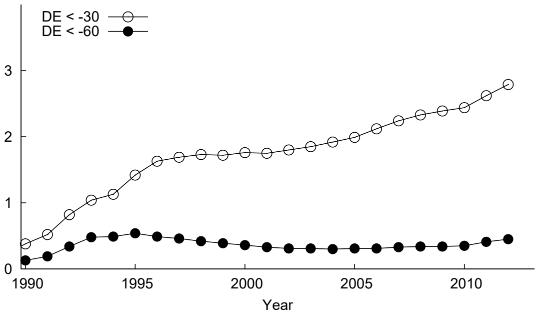

Fig. 2 Percentage of the observations of southern sources (cumulative by date).

2 Monte Carlo Simulation

The IVS R1541 (12JUL09XA) session was used for the Monte Carlo simulations in this paper. The R1541 session network includes 11 stations, 5 of them are located in the southern hemisphere (see Fig. 3). As expected, the Auscope (Australian VLBI Network), station Hartrao, station Tigo, and station Fortleza participated. The southern network size ensures large common view, and the multi-baseline observations are important to mitigate the source structure effects.

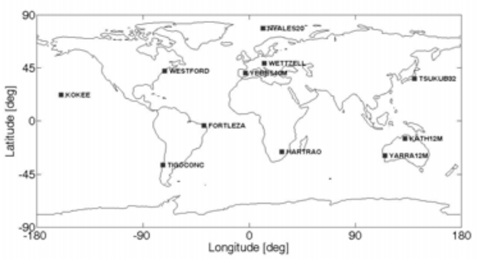

Fig. 3 11 stations network of IVS R1541 session, 5 out of 11 stations are located in the southern hemisphere.

2.1 Scheduling

The original schedule for the R1541 IVS session was generated making use of the SKED software (Gipson, 2010). There are 60 sources observed, 7 southern sources having declination less than -40 degrees. For comparisons, the supplementary southern sources are added to the original source list and experimental schedules are obtained to evaluate the trade-off between the number of southern sources and the accuracy of geodetic products.

Considering all the ICRF2 sources having the declination less than -40 degrees, they are sorted by some generalized criteria involving number of sessions, number of observations, and position uncertainty. “The worst end” of the list shows which sources we should consider first. The strong southern sources have preference in this study.

Schedule ’R1’ is achieved with the original source list. Schedule ’R1+’ includes three more southern sources and schedule ’R1++’ includes six more southern sources as compared with the original R1541 schedule. The three schedules for 24-hour continuous observations are generated with VieVS scheduling package (Sun et al., 2011). The distribution of observed sources is shown in Fig. 4, and detailed information on southern sources is given in Table 1.

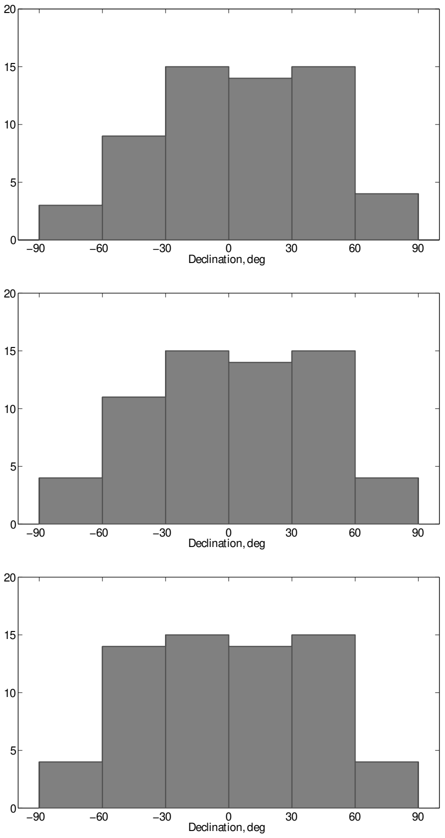

Fig. 4 Distribution of observed sources in the original R1541 schedule (top) and two experimental schedules: R1+ (middle) and R1++ (bottom).

Table 1 Number of scans/observations of southern sources in the IVS R1541 (R1) and two experimental schedules R1+ and R1++.

Source	R1	R1+	R1++
0637-752	39 / 39	42 / 48	37 / 39
0537-441	55 / 88	56 / 91	59 / 102
1104-445	16 / 18	25 / 27	19 / 23
2052-474	42 / 48	49 / 57	46 / 50
2300-683	3 / 3	1 / 1	1 / 1
0048-427	4 / 6	7 / 11	7 / 7
0308-611	4 / 4	6 / 6	2 / 2
2232-488		7 / 7	3 / 3
2204-540		9 / 9	6 / 6
2142-758		7 / 7	3 / 3
0208-512			18 / 18
0332-403			47 / 82
1424-418			42 / 67
Total	178 / 295	209 / 264	290 / 403

Except the different source list, the basic scheduling settings used in VieVS are in correspondence with the original R1541 schedule as summarized below. The optimization of source-based strategy is employed with VieVS for this study.

- frequency setup: R1 frequency setup (X/S band)
- SNR: 20/15 (15/12 for Tigo)
- recording data rate: 256 Mbps
- cut-off elevation angle: 5 degrees
- minimum scan length: 40 seconds
- extra time for settling down, calibration, correlator synchronizing

2.2 Simulating

For the Monte Carlo simulations, 50 sessions were simulated using the same 24-hour schedule but different realizations of noise delays, each time creating new values for wet zenith delay, clocks and white noise to simulate observations as realistic as possible. The random errors in delay measurement were modelled by white noise with given power spectral density (PSD). The clock rate instability was modelled using the Allan standard deviation (ASD). The turbulent troposphere was modelled using the site-dependent structure constant C_n, effective wet height H, and wind velocity V. The simulation parameters are summarized in Tables 2 and 3). See Sun et al., 2011 for details of the stochastic models used during simulation.

Table 2 Simulation parameters.

H [m]	2000
V_n [m/s]	0.00
V_e [m/s]	8.00
wzd_0 [mm]	250
$dhseg$ [h]	2
dh [m]	200
clock ASD	10^{-14}@50 min
WN PSD [ps]	32

Table 3 Site-dependent constant C_n, $m^{-1/3}$.

Sta name	$C_n \cdot 10^7$	Sta name	$C_n \cdot 10^7$
NYALES20	0.65	HARTRAO	1.34
ONSALA60	2.19	KATH12M	1.68
TSUKUB32	3.45	TIGOCONC	2.08
WESTFORD	2.30	WARK12M	1.94
WETTZELL	1.50	YARRA12M	1.76
YEBES40M	1.48	FORTLEZA	2.46
KOKEE	1.39		

3 Results

The simulated NGS data files are entered into the software package VieVS, which computes a classical least squares solution. All the source coordinates were fixed to the ICRF2 positions (Ma et al., 2009). The standard deviation of the 50 EOP estimates and mean formal uncertainties are listed in Table 4.

Table 4 Repeatability and standard deviation of EOP for the IVS R1541 and two experimental schedules R1+ and R1++.

Parameter		R1	R1+	R1++
Number of scans		1258	1351	1375
Number of observations		3905	3813	3997
EOP repeatability	Xp	143.2	125.5	98.2
[μas, μs]	Yp	98.2	79.1	96.8
	UT1	5.6	4.6	5.9
	dX	36.2	42.8	39.1
	dY	45.0	39.5	37.2
Mean EOP uncertainty	Xp	94.8	95.6	93.4
[μas, μs]	Yp	77.2	77.3	74.8
	UT1	4.4	4.6	4.7
	dX	29.8	30.9	29.5
	dY	29.1	29.6	28.1

Fig. 5 shows baseline length repeatability obtained from the simulations. For the baselines shorter than ~5,000 km the R1 schedule shows the best result, and R1+ and R1++ schedules yield worse repeatability, whereas for longer baselines the R1++ schedule is the best, and R1 is the worst. However, in fact, the results obtained with the three schedules are close to each other. The mean baseline length repeatability derived from R1, R1+, and R1++ schedules are 13.5 mm, 12.4 mm, and 11.9 mm, respectively.

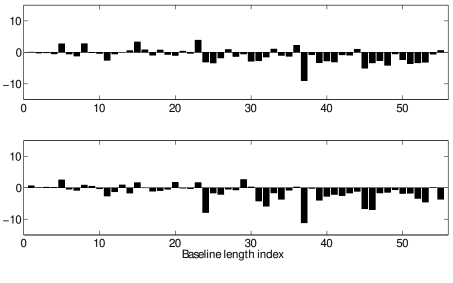

Fig. 5 Differences in baseline length repeatability [mm] between two schedules: R1+ minus R1 (top) and R1++ minus R1 (bottom). The horizontal axis represents the 55 baselines with the shortest one WETTZELL–YEBES40M (1575 km) on the left and the longest one TIGOCONC–TSUKUB32 (12401 km) on the right.

It has been found that further increasing of the number of southern sources (cf. R++ and R+ schedules) leads to a small degradation of baseline length repeatability for short baselines, and small improvement for long baselines. Errors in some EOP become smaller with inclusion of more southern sources, and some EOP show small degradation in the accuracy.

4 Summary

Including more southern sources in the regular IVS sessions may be a practical way to force an improvement of the VLBI-based ICRF in the southern hemisphere. In this paper, we studied a trade-off between the small degradation of the EOP precision and the ICRF improvement using the source-based scheduling algorithm (Sun et al., 2011). We found no degradation of the overall accuracy of main geodetic products, such as EOP and baseline length repeatability after the inclusion of several supplementary southern sources.

Although the number of southern sources added and the number of their observations are not large with respect to the standard scheduling algorithm, regular inclusion of selected sources needed for densification and accuracy improvement of the ICRF in the southern hemisphere will provide a valuable contribution to the next VLBI-based ICRF. Having quarterly observations during two years will give us a good preliminary estimate of both average source position and its stability. Rotating the list of supplementary sources between sessions, e.g., on the quarterly basis, we could substantially increase the number of reliably observed southern sources. The latter is, in particular, very important for selection of new ICRF core (defining) sources.

We tested a new approach to the scheduling using two IVS sessions R1541 (12JUL09XA) and R1591 (13JUN24XA). The results obtained with the first session are described in this paper in detail; the results obtained with the second session are very similar. However, a serious problem for schedule optimization is that southern stations are equipped with relatively small antennas, which makes it difficult to observe the weak sources. However, the much greater recording rate (as compared with the present R1/R4 operations) planned for the VLBI2010 observation mode (Behrend et al., 2008) can mitigate this problem.

The results of our work presented in this paper have shown that it's possible to add more observations of southern sources without degradation of the tested geodetic products, such as EOP and baseline length repeatability. Indeed, more study is needed to find an optimal trade-off between the quality of geodetic and astrometric (CRF) products. More detailed investigations are anticipated for different R1, R4, and other IVS network configurations and an extended list of southern sources. In particular, inclusion of non-ICRF sources shall be considered at the next stage, as well as sources near the southern polar cap. Also, testing with VLI2010 recording parameters would be useful for future scheduling.

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