INVESTIGATION OF STABILITY OF RADIO SOURCES FROM ARC-LENGTH METHOD

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ABSTRACT. Obtained by various VLBI analysis centers time series of source positions contain two types of signal: changes in coordinates of sources and corrections to an orientation of the Celestial Reference Frame. Before to start an investigation of sources variability, one has to transform a CRF solution for each session to some reference celestial frame. On the other hand, the length of arc connecting two radio sources is invariant to the chosen CRF. In this talk we present results of study of variability of arc lengths derived from available time series of radio sources.

1. INTRODUCTION

New realization of International Celestial Reference Frame (ICRF) requires that many particular tasks should be solved. One of them is selecting a set of stable radio sources which are defining the orientation of a constructed celestial reference frame (usually called DEFINING sources). There are at least two approaches to accomplish this task: 1) a physical approach, based on analysis of source characteristics, such as a red shift, type of radio source, distribution of its brightness, and so on, and 2) statistical approach, based on analysis of variability of source positions from VLBI data processing. This work belongs to the second approach.

In the frame of IERS/IVS ICRF2 project in the mid of 2007 various VLBI analysis centers produced "time series" solutions – estimations of sources positions for each session of VLBI observations. A purpose of such solutions is aimed on studies of stability of sources positions and selection of stable radio sources for the ICRF2 implementation.

2. LENGTH OF ARCS FROM TIME-SERIES SOLUTIONS

Time series of sources positions usually are estimated simultaneously with the Earth orientation parameters for each session, therefore they are presented in its own, unique for each session, Celestial reference frame. Before to start an investigation of sources variability, one has to transform a CRF solution for each session to some reference celestial frame. On the other hand, the length of arc connecting two radio sources is invariant to the orientation of chosen CRF. Therefore, studying the variability of the arcs lengths, it is possible to infer about stability of radio sources.

In the frame of one session the length of arc, ℓ_{ij}, connecting i^{th} and j^{th} sources and its standard deviation, $\sigma^2_{\ell_{ij}}$, can be expressed as:

$$\ell_{ij} = \arccos\left[\sin\delta_i \sin\delta_j + \cos\delta_i \cos\delta_j \cos\left(\alpha_i - \alpha_j\right)\right],$$

$$\sigma^2_{\ell_{ij}} = (\frac{\partial \ell_{ij}}{\partial \delta_i})^2 \sigma^2_{\delta_i} + (\frac{\partial \ell_{ij}}{\partial \delta_j})^2 \sigma^2_{\delta_j} + (\frac{\partial \ell_{ij}}{\partial \alpha_i})^2 \sigma^2_{\alpha_i} + (\frac{\partial \ell_{ij}}{\partial \alpha_j})^2 \sigma^2_{\alpha_j} + 2\frac{\partial \ell_{ij}}{\partial \delta_i}\frac{\partial \ell_{ij}}{\partial \alpha_i}\rho_i \sigma_{\delta_i}\sigma_{\alpha_i} + 2\frac{\partial \ell_{ij}}{\partial \delta_j}\frac{\partial \ell_{ij}}{\partial \alpha_j}\rho_j \sigma_{\delta_j}\sigma_{\alpha_j},$$

where

α_i, α_j, δ_i, δ_j – right ascensions and declinations of i^{th} and j^{th} sources;

σ_{α_i}, σ_{α_j}, σ_{δ_i}, σ_{δ_j} – their standard deviations;

ρ_i and ρ_j – correlation coefficients between right ascension and declination of i^{th} and j^{th} sources.

In the expression of $\sigma^2_{\ell_{ij}}$, the terms which contain correlations between coordinates of i^{th} and j^{th} sources are omitted.

For each of the sessions, we evaluated lengths of arcs and their standard deviations. Then, for each arc we computed variability of the length, and, using least square method, made estimations of variabilities of sources positions.

Eight VLBI analysis centers submitted time series solutions of source positions. In Tab. 1 general characteristics of analyzed time series are presented.

Table 1: General characteristics of time series solutions

Sol.ID	Analysis Center	Software	Estimation of TRF	EOP	Number of Src	Sess	Arcs
aus003a	GA, Australia	OCCAM6.2	Session	Session	1089	3307	3768
bkg000c	BKG, Germany	CALC/SOLVE	Global	Session	1084	3468	13294
dgf000g	DGFI, Germany	OCCAM6.1e	Global	Session	801	3083	12426
gsf001a	GSFC NASA, USA	CALC/SOLVE	Fixed	Fixed	955	4319	14333
iaa000c	IAA RAS, Russia	QUASAR	Session	Session	583	3850	11730
mao000b	MAO NASU, Ukraine	SteelBreeze	Fixed	Fixed	2485	3907	12937
opa002a	OPAR, France	CALC/SOLVE	Session	Session	644	3741	11113
usn000a	USNO, USA	CALC/SOLVE	Fixed	Fixed	849	4061	13586

In the table for each solution identifier the following fields are shown: name of analysis center; applied software; how the coordinates and velocities of stations and Earth rotation parameters were treated: fixed, estimated as global or local parameters; number of sources in a time series; number of sessions; number of arcs with number of individual epochs more than ten.

Assuming that there are no systematic effects in variations of length of arcs and variations of different sources are uncorrelated we can write a system of equations for all arcs:

$$\sigma_i{}^2 + \sigma_j{}^2 = \sigma_{ij}{}^2, \quad i < j$$

where σ_{ij} is a variability of an arc between i^{th} and j^{th} sources, evaluated from time series of length of the arc, σ_i and σ_j are unknown variabilities of the sources.

3. RESULTS

From the solution of the equation system for each of time series we estimated variations of sources. In Tab. 2 the most stable and most unstable sources with corresponding variabilities are present. For some time series, where our assumptions are not met (primarily, due to outliers in time series), the solution of the equation system gives negative signs for particular $\sigma_i{}^2$. In such cases the sign is put before σ_i. The investigations have shown that negative sign of $\sigma_i{}^2$ usually means that variations of ith source position are small.

Evaluated values of variabilities of sources positions we have treated in the following way: sources from the upper third of the table (sorted by variability) we considered as stable sources in statistical sense (i.e., there are no systematic effects in their positions), while sources from the lower third of the table we considered as the unstable ones.

Based on obtained distribution of variations of sources positions we have created two lists: a list of stable radio sources (sources which have shown themselves as the stable ones in at least six of eight input time series), and a list of unstable sources (which are unstable in at least six time series). The results of such selections are summarized in Tab. 3 and Tab. 4. In the tables along with the names of sources are indicated their status and number of sessions.

As one can infer from the tables there are several radio sources with status CANDIDATE or OTHER which positions are stable enough that they could serve as the DEFINING ones in forthcoming ICRF2. On the other hand, we found that one of DEFINING sources, 1954–388, has variations which are remarkably larger than mean variations for time series. That is an indication of unstable coordinates of the source.

4. CONCLUSIONS

Investigation of time series of sources positions shows that arc lengths are independent from chosen orientation of reference frames, which in such solutions are unique for each VLBI session.

Table 2: Most stable and unstable sources per time series

aus003a		bkg000c		dgf000g		gsf001a	
Src	$\sigma, \mu as$	Src	$\sigma, \mu as$	Src	$\sigma, \mu as$	Src	$\sigma, \mu as$
1417 + 385	−278	1057 − 797	−234	1417 + 385	92	2209 + 236	−282
0917 + 624	−54	1101 + 384	−186	2209 + 236	187	0642 + 449	−82
2209 + 236	128	2209 + 236	−167	1652 + 398	224	1101 + 384	−56
2356 + 385	282	2223 − 052	−135	0642 + 449	245	2037 + 511	88
0955 + 476	292	0743 + 259	−71	0235 + 164	260	1606 + 106	114
0808 + 019	326	1606 + 106	149	0556 + 238	261	1417 + 385	163
2136 + 141	366	1417 + 385	154	2223 − 052	265	1057 − 797	177
1357 + 769	369	2136 + 141	199	2136 + 141	287	0917 + 624	184
1300 + 580	377	1652 + 398	199	1101 + 384	290	1807 + 698	186
0642 + 449	385	2113 + 293	217	0917 + 624	303	2113 + 293	192
1128 + 385	396	0917 + 624	217	2113 + 293	311	1749 + 096	196
1611 + 343	409	0642 + 449	221	1807 + 698	322	2223 − 052	269
0804 + 499	423	1749 + 096	230	0955 + 476	332	2356 + 385	293
⋮		⋮		⋮		⋮	
2243 − 123	988	1510 − 089	1026	1954 − 388	923	1954 − 388	1155
1124 − 186	1002	0212 + 735	1028	1958 − 179	945	2149 + 056	1187
0106 + 013	1014	1954 − 388	1112	1502 + 106	949	0106 + 013	1232
0212 + 735	1050	2128 − 123	1117	1144 − 379	952	1034 − 293	1233
0402 − 362	1067	1730 − 130	1118	2128 − 123	966	2251 + 158	1274
1502 + 106	1076	1622 − 253	1130	1730 − 130	979	1730 − 130	1289
0420 − 014	1096	0104 − 408	1274	1908 − 201	982	1921 − 293	1334
0742 + 103	1112	1921 − 293	1412	1622 − 253	996	2126 − 158	1352
0454 − 234	1116	0537 − 441	1429	1921 − 293	1046	1226 + 023	1379
0208 − 512	1140	1034 − 293	1434	2149 + 056	1054	1424 − 418	1379
1908 − 201	1163	2255 − 282	1557	1034 − 293	1076	2255 − 282	1382
2149 + 056	1208	1424 − 418	1879	0104 − 408	1115	2134 + 004	1434
1144 − 379	1243	0919 − 260	2305	2255 − 282	1233	0919 − 260	1796

iaa000c		mao000b		opa002a		usn000a	
Src	$\sigma, \mu as$	Src	$\sigma, \mu as$	Src	$\sigma, \mu as$	Src	$\sigma, \mu as$
1417 + 385	155	1652 + 398	253	0642 + 449	105	0642 + 449	128
2209 + 236	203	0642 + 449	306	1652 + 398	180	0917 + 624	188
0642 + 449	220	1101 + 384	310	2209 + 236	181	0743 + 259	297
1652 + 398	258	1128 + 385	382	1101 + 384	235	2223 − 052	320
2223 − 052	278	0602 + 673	384	2136 + 141	271	1101 + 384	342
1807 + 698	293	0955 + 476	386	0955 + 476	274	1652 + 398	346
1101 + 384	303	1417 + 385	402	2113 + 293	279	1745 + 624	369
0235 + 164	305	1807 + 698	420	1606 + 106	285	1807 + 698	403
2136 + 141	307	1726 + 455	421	1417 + 385	300	2136 + 141	413
1749 + 096	347	0014 + 813	426	1745 + 624	305	2113 + 293	413
0917 + 624	368	2356 + 385	427	2223 − 052	308	1057 − 797	438
0014 + 813	369	1745 + 624	428	0917 + 624	310	0955 + 476	442
0718 + 792	372	0808 + 019	434	1749 + 096	313	2356 + 385	457
⋮		⋮		⋮		⋮	
1144 − 379	961	0208 − 512	1057	1641 + 399	1051	1954 − 388	1172
2128 − 123	975	1633 + 382	1073	0106 + 013	1098	1641 + 399	1185
1954 − 388	976	1144 − 379	1099	2128 − 123	1120	0106 + 013	1193
0402 − 362	1009	1502 + 106	1104	1908 − 201	1182	1351 − 018	1212
1921 − 293	1010	1034 − 293	1120	1622 − 253	1230	1730 − 130	1215
2149 + 056	1032	2128 − 123	1134	2126 − 158	1258	2149 + 056	1253
0104 − 408	1046	1954 − 388	1212	1730 − 130	1265	1908 − 201	1257
1730 − 130	1054	0104 − 408	1215	1034 − 293	1309	1034 − 293	1264
1034 − 293	1056	1730 − 130	1262	1958 − 179	1322	1226 + 023	1373
2251 + 158	1185	1921 − 293	1284	2251 + 158	1364	1921 − 293	1408
1641 + 399	1231	2251 + 158	1373	1921 − 293	1521	2255 − 282	1547
2255 − 282	1266	1641 + 399	1406	1226 + 023	1530	1424 − 418	1822
1226 + 023	1345	2255 − 282	1509	2255 − 282	1568	0919 − 260	1952

From analysis of arcs variations it is possible to select sets of stable and unstable sources. The analysis reveals few stable sources, which have status CANDIDATE or OTHER and could be used as DEFINING sources in future. Also, one of DEFINING sources, 1954–388, shows large variation of coordinates and is

Table 3: A list of selected stable sources

Src	St	N Ses	Src	St	N Ses	Src	St	N Ses
0014 + 813	D	1007	0917 + 624	D	134	1652 + 398	C	209
0059 + 581	O	1738	0955 + 476	D	1717	1726 + 455	D	1156
0133 + 476	D	1128	1057 − 797	D	287	1745 + 624	D	597
0235 + 164	D	658	1101 + 384	C	323	1749 + 096	C	2238
0528 + 134	C	2865	1128 + 385	D	1014	1807 + 698	C	756
0552 + 398	C	3870	1156 + 295	D	1055	2037 + 511	D	877
0602 + 673	C	395	1300 + 580	O	735	2113 + 293	D	346
0642 + 449	D	1006	1357 + 769	C	1565	2136 + 141	D	843
0718 + 792	D	886	1417 + 385	C	193	2209 + 236	D	155
0743 + 259	D	476	1519 − 273	C	405	2223 − 052	C	821
0804 + 499	D	1177	1606 + 106	D	1991	2356 + 385	C	387
0851 + 202	C	3105	1638 + 398	O	1056			

Table 4: A list of selected definitely non-stable sources

Src	St	N Ses	Src	St	N Ses
0104 − 408	O	422	1641 + 399	O	1113
0106 + 013	O	1279	1730 − 130	O	458
0402 − 362	O	260	1908 − 201	C	422
0537 − 441	O	650	1921 − 293	O	1174
0919 − 260	O	217	1954 − 388	D	429
1034 − 293	O	872	1958 − 179	O	888
1144 − 379	C	385	2126 − 158	C	185
1226 + 023	O	953	2128 − 123	O	607
1424 − 418	O	424	2134 + 004	O	745
1502 + 106	O	488	2149 + 056	C	222
1510 − 089	O	222	2216 − 038	O	370
1622 − 253	O	1271	2251 + 158	O	1098
1633 + 382	O	373	2255 − 282	O	845

definitely unstable. It is interesting to note, that this source was never suspected in instability.

However, the number of detectable stable sources by this method (in this work it is 35) is small. Moreover, arcs length analysis of time series reveals systematic effects in variations of sources positions for almost all time series. Further investigations of the effects should be continued.

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5. REFERENCES

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