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Long-term Variations of the EOP and ICRF2

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Abstract

We analyzed the time series of the coordinates of the ICRF radio sources. We show that part of the radio sources, including the "defining" sources, shows a significant apparent motion. The stability of the celestial reference frame is provided by a no-net-rotation condition applied to the defining sources. In our case this condition leads to a rotation of the frame axes with time. We calculated the effect of this rotation on the Earth orientation parameters (EOP). In order to improve the stability of the celestial reference frame we suggest a new method for the selection of the defining sources. The method consists of two criteria: the first one we call "cosmological" and the second one "kinematical". It is shown that a subset of the ICRF sources selected according to cosmological criteria provides the most stable reference frame for the next decade.

1. Introduction

The first realization of the International Celestial Reference Frame (ICRF) was based on the positions of 608 compact extragalactic radio sources (quasars, active galactic nuclei (AGN), and blazars) [6]. The stability of the system axes is guaranteed by the precise positions of the "defining" radio sources. One assumes that the coordinates of these sources are known as precisely as possible. These sources are unresolved on VLBI baselines comparable to the Earth diameter, and it was assumed that variations of their coordinates are negligible.

The second realization of the International Celestial Reference Frame (ICRF2) was established in 2009. The ICRF2 contains five times more radio sources, and the noise floor is of the order of 40 μas which leads to an axis stability of approximately 10 μas [5]. Regardless of these values we

- show that many of the new defining sources show significant apparent motion;
- show that a small rotation of the CRF is transformed into long-term variations of the EOP; and
- suggest a new source selection method to improve the stability of the reference frame.

To obtain the time series of the ICRF source coordinates we used the ARIADNA software. Solution "sai2009a.eops" was based on accepted positions of ICRF2 sources and precession-nutation model IAU2000. The terrestrial reference frame was fixed to the VTRF2008 coordinates and velocities of stations. Solution "sai2009b.eops" differs from the previous one by adding velocities for the sources. To calculate them we used the approximation of time series of coordinates by a polynomial model. The linear model with respect to regression polynomial coefficients β_i $(i = 0, 1, 2)$ is

$$y(t) = \beta_0 + \beta_1 t + \beta_2 t^2 + \varepsilon(t), \tag{1}$$

where t is time, $y(t)$ are corrections $(\Delta\alpha\cos\delta,\ \Delta\delta)$ to the ICRF coordinates (right ascension or declination) of a source, and $\varepsilon(t)$ are residuals. The coefficients of polynomials were found by regression analysis. The power of the polynomial was determined by R^2 statistics, where

$$R^2 = \frac{\sum(\hat{y}_j - \bar{y})^2}{\sum(y_j - \bar{y})^2} = 1 - \frac{\sum(y_j - \hat{y}_j)^2}{\sum(y_j - \bar{y})^2}. \tag{2}$$

Here y_j is the correction of right ascension or declination at the moment $t = t_j, j = 1, 2, \ldots, N$, and $\hat{y}_j$ is the estimation of the polynomial function at t_j, and $\bar{y}$ is the average value of the series over whole interval. The value R depends on the correlation between y and $\hat{y}$ [4]. Obviously, if the polynomial model is correct, that is values $\hat{y}_j$ are equal to y_j, the coefficient $R = 1$. Actually, $\hat{y}_j \neq y_j$ and $R < 1$, but the maximal value of R corresponds to the best fitting model.

Below we show several examples of our data analyses. These figures represent a variation of the celestial coordinates as polynomial function of time. One can see that all of these sources, which are defining sources in the ICRF2 catalog, have significant apparent motion.

The motion of the source 0106+013, which was an “other” source in the ICRF, is shown in Fig. 1. The total number of observations is more than 1500. The motion is modeled by the linear function 41.6 ± 1.6 for α and 13.3 ± 2.0 for δ (in μas/year). The total number of observations of the former “candidate” source 0229+131 was more than 2500. The motion of it is quadratic along right ascension 2.1 ± 0.1 μas/year^2 and linear 1.8 ± 1.5 μas/year along declination. And in the bottom part of Fig. 1 the motion of the “other” source 0536+145, which was observed ~ 50 times, is shown. The motion is linear with -8.9 ± 13.6 for α and -38.1 ± 19.8 for δ (in μas/year). The defining source 0556+238 of both the ICRF and ICRF2 has a significant linear motion along α (-19.8 ± 3.1) and δ (-15.2 ± 4.8 in μas/year). As we can see the values of velocities of the defining sources can reach a few tens of microarcseconds per year.

The fact that the ICRF sources have apparent motion was observed by several authors [7, 8, 11, 12], and special methods were developed for ranking of sources [5]. They are based on statistical properties of the position time series.

To increase the stability of the celestial reference frame we propose the following method for source selection. First of all, we consider kinematical characteristics of sources. We can predict the value of y_{N+1} and its confidence intervals outside the observed data span when we have a well-fit polynomial model of motion. We call a source stable if it has a small apparent motion, i.e., the confidence intervals of predicted corrections to right ascension and declination include zero value. Otherwise, if the model shows a significant difference of the correction to α or δ from zero, we can call this source unstable (at corresponding confidence level).

The analysis of data shows that many of the ICRF sources reveal significant apparent linear motion—their confidence intervals increase rapidly and do not include zero. Therefore we must consider them as unstable. Actually, one can subtract a well-predicted linear trend, and afterwards the confidence intervals include zero and this source can be considered as “stable”. To substantiate this possibility we consider the physical model of an ICRF source.

2. Blandford–Rees Model of Extragalactic Radio Sources

The apparent motion of extragalactic sources is a very intriguing fact. There are two reasons for such motion. The first one is that there are some real kinds of motion inside the source. The second one is that the light (radio waves) is refracted in a stochastic extragalactic media propagating from source to observer, which originates apparent motion of the source image.

From our point of view, the more realistic possibility is that there are motions inside the sources. The more appropriate model of the ICRF source is the unified AGN model [1, 2]. The main idea

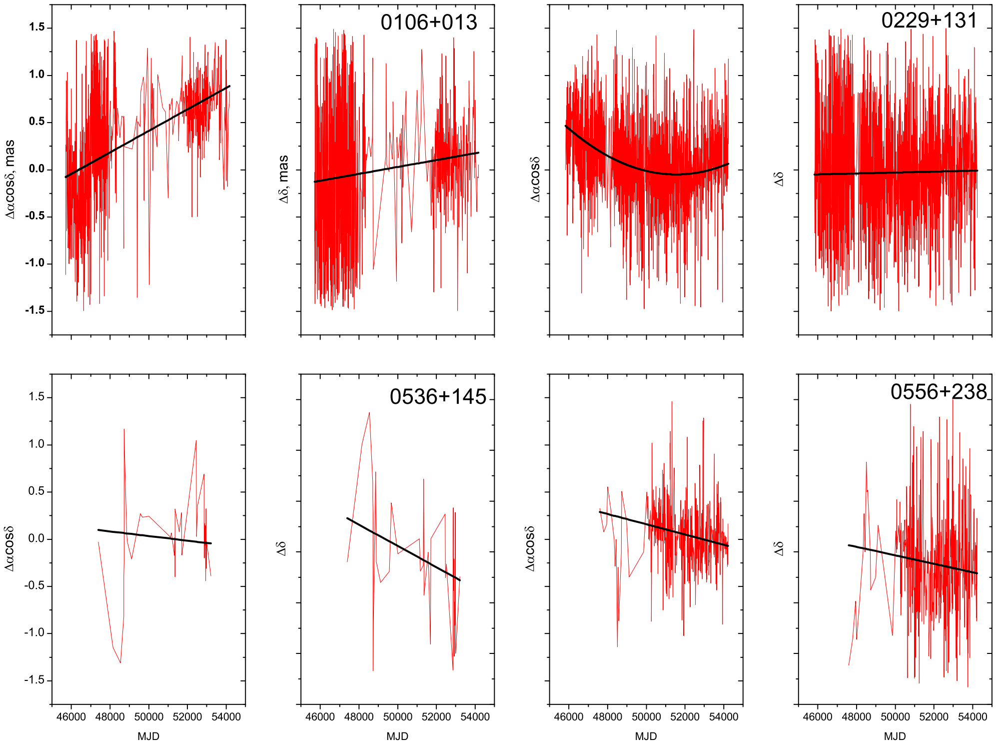

Figure 1. Right ascension (left) and declination (right) variations of the defining sources 0106+013, 0229+131, 0536+145, 0556+238 as function of time (MJD 46000 through 54000).

is that the quasars and AGN are objects that represent a system of a massive black hole and jets [15]. The optical radiation is formed in the black hole accretion disk while the radio emission is created in the jet, at some distance from the optical source (see also the recent discussion on the unification scheme of extragalactic radio sources in [3]). Below we refer to the radio source as "jet-core" instead of the optical core which coincides with the position of the massive black hole.

Taking into account the main properties of this model one can conclude that

- the ICRF radio source is the emission region (or jet-core) inside the jet;
- the position of the ICRF source is the position of the brightness center of the jet-core;
- the linear motion of the ICRF source can be explained by the jet precession mechanism [9, 13];
- the quadratic motion suggests some acting force and can be explained by acceleration of dense clouds inside the jet.

We assume that the linear apparent motion can be explained by the precession of the jet while quadratic apparent motion can be explained by the stochastic process of interaction of the jet particles with interstellar clouds. The period of jet precession is expected to be $10^3 \ldots 10^6$ years [13]. One can expect that the stability of the jet precession angular velocity in such an object would be as low as several percent [10]. As the precession periods of the jets are significantly larger than the time of observation, the source motions can be treated as linear, stable, and predictable with high accuracy for the time interval of VLBI observation of ~ 30 years, while the quadratic motion is stochastic and is unpredictable. As a result we restrict our consideration to two models

$$y(t) = \beta_0 + \beta_1 t + \varepsilon(t), \quad y(t) = \beta_0 + \beta_2 t^2 + \varepsilon(t),$$

and the decision of which model is valid is taken with the following criteria. We calculated R_1^2 (2) for the linear model and R_2^2 (2) for the quadratic model. If and only if $R_2^2/R_1^2 > 5$, we accept the quadratic model of apparent motion. Approximately two thirds of the sources show linear motion, and one third shows quadratic motion. As long as the linear motion is predictable and stationary for a long time, one can subtract the linear trend of the data and work with these "residual" data.

3. Cosmological Criterion for Choosing ICRF Sources

All other motions inside the radio source represent noise components of the astrometric observation. These motions occur inside some linear scale. The smaller the scale, the smaller the angular displacement seen by an observer. Hence, to decrease astrometric noise and to improve the coordinate system stability, we have to choose the most remote sources. It is correct in the Euclidean space: the more remote a source, the less the angular scale of its apparent motion. In the Friedman model of the expanding Universe it is not correct. Extragalactic objects have to be considered in expanding space-time and in the framework of the Standard Cosmological Model.

According to this model, the apparent angular size of the source has a minimum for redshift $z = 1.63$. An object located at this distance with a physical size of about 1 pc has an angular size of $\theta = 116$ μas. This is the minimal angular size of an object, and it will increase for $z < 1.63$ and for $z > 1.63$. It was shown that the redshift interval $0.8 \leq z \leq 3.0$ is the most favorable in terms of the physical shift inside such sources corresponding to the minimal apparent angular shift of a "jet-core". Details of these calculations can be found in [9]. After tagging sources as "unstable" and "stable" according to the "kinematical" and "cosmological" criteria, we obtained a final list of 137 sources (see Table 1 in [9]).

4. The ICRF System Instability

As was pointed out, the main purpose of selecting "stable" sources is the improvement of the stability of the celestial reference frame that is connected with the predictability of source motion. The variation of the ICRF source coordinates leads to a small rotation of the reference frame. To estimate the stability of the frame three small angles θ_1, θ_2, θ_3, which describe the small rotation, were calculated:

$$\mathbf{s}(t) = \begin{pmatrix} 1 & -\theta_3 & \theta_2 \\ \theta_3 & 1 & -\theta_1 \\ -\theta_2 & \theta_1 & 1 \end{pmatrix} \mathbf{s}(t_0)$$

where $\mathbf{s}(t)$, $\mathbf{s}(t_0)$ are unit vectors of a source at moments t and $t_0 = J2000.0$. As was shown in [14] the method of "cosmological" selection improves the stability of the ICRF over the next decade.

The rotation of the reference frame is transformed to the secular variations of the EOP. From the difference of solutions "sai2009a.eops" and "sai2009b.eops" a linear trend in the x-coordinate of the pole equal to $-2.77 \pm 0.22\mu$as/year was found. The variations of the y-coordinate of the pole and the nutation in longitude and obliquity are $1.60 \pm 0.15\mu$as/year, $0.47 \pm 0.46\mu$as/year, and $-0.54 \pm 0.15\mu$as/year, respectively; and UT is $0.144 \pm 0.007\mu$s/year.

5. Conclusions

The physical basis of the "cosmological" and "kinematical" criteria is the assumption that the apparent motion of the ICRF radio sources is connected with real motion inside quasars. Therefore apparent angular motion corresponds to a real physical shift of the "jet-core" inside a radio source. The motion of the defining sources is transformed to secular variations of the EOP.

The red-shift interval $0.8 \leq z \leq 3.0$ is the most favorable in terms of the physical shift inside such sources corresponding to a minimal apparent angular shift of a "jet-core". The method of "cosmological" selection improves the stability of the ICRF over the next decade.

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References

[1] Begelman M.C., Blandford R.D., Rees M.J., 1984, *Rev. Mod. Phys*, **56**, 255

[2] Blandford R.D., Königl A., 1979, *AJ*, **232**, 34

[3] Browne, I.W.A. The Role of VLBI in Astrophysics, Astrometry and Geodesy. Proc. of the NATO Advanced Study Institute, held September 17-29, 2001, in Bologna, Italy. Series II, mathematics, physics and chemistry, Vol. 135. Edited by Franco Mantovani and Andrzej Kus. Published by Kluwer Academic Publishers, Dordrecht, The Netherlands, 2004, p.175

[4] Draper N.R., Smith H. Applied Regression Analysis. 3-rd edition. John Wiley & Sons, Inc. 1998.

[5] The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry Presented on behalf of the IERS. Alan L. Fey, David Gordon, and Christopher S. Jacobs (eds.) IERS Technical Note No. 35. Verlag des Bundesamts für Kartographie und Geodäsie. Frankfurt am Main 2009.

[6] Ma C., Arias E.F., Eubanks T.M., et al., *AJ*, **116**, 516, 1998.

[7] MacMillan D.C., 2003, in Romney J.D., Reid M.J., eds, Future Directions in High Resolution Astronomy, (The 10th Anniversary of the VLBA ASP Conference series). astro-ph/0309826

[8] MacMillan D.S., & Ma C. 2007, J. of Geodesy, **81**, 443

[9] Sazhin M.V., Sementsov V.N., Zharov V.E., Kuimov K.V., Ashimbaeva N.T., Sazhina O.S., 2009, arXiv:0904.2146v1

[10] Davydov V.V., Esipov V.F., Cherepashchuk A.M., Astronomy Reports, **52**, p. 487, 2008.

[11] Titov O., 2008, Proper motion of reference radio sources, arXiv:0804.1403

[12] Titov O., 2008, Systematic effects in apparent proper motion of radio sources, arXiv:0805.1099

[13] Zharov V.E., Sazhin M.V., Sementsov V.N., Kuimov K.V., Sazhina O.S., *Astron. Rep.*, **53**, 579, 2009.

[14] Zharov V.E., Sazhin M.V., Sementsov V.N., Kuimov K.V., Sazhina O.S., and Ashimbaeva N. T., 2009, The celestial reference frame stability and apparent motions of the radio sources. In Proc. IAU Symposium No. 261, S. A. Klioner, P. K. Seidelman & M. H. Soffel, eds. p.50–55.

[15] Zensus J. Anton. Annu.Rev.Astron.Astrophys. 1997, v.**35**, p.607-636.