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ON AN ALLAN VARIANCE APPROACH TO CLASSIFY VLBI RADIO-SOURCES ON THE BASIS OF THEIR ASTROMETRIC STABILITY

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Abstract. In the context of selecting sources defining the celestial reference frame, we compute astrometric time series of all VLBI radio-sources from observations in the International VLBI Service database. The time series are then analyzed with Allan variance in order to estimate the astrometric stability. From results, we establish a new classification that takes into account the whole multi-time scales information. The algorithm is flexible on the definition of "stable source" through an adjustable threshold.

Keywords: astrometry, VLBI, source stability, allan variance

1 Introduction

During the 90s, the celestial reference system leaves a stellar definition to an extragalactic definition. During the XXI$^{\text{st}}$ International Astronomical Union (IAU) general assembly (IAU 1991), it was recommended that a list of extragalactic radio-sources observed by the Very Long Baseline Interferometry (VLBI) technique is provided to realize the system, following International Earth Rotation Service (IERS) works (Arias et al. 1995). Those sources, mostly quasars, are called defining sources because they define the axis of the realized celestial reference frame. This new system, called the International Celestial Reference System (ICRS, Arias et al. 1995) and its first realization, the International Celestial Reference Frame (ICRF1, Ma et al. 1998) are approved by IAU (1997).

In principle, extragalactic sources should not present any variation of their position on the sky. In one way, this is the case because quasars are at such a distance that their proper motion and parallax are undetectable. But sources are not point-like and the apparent structure of their flux have an effect on their apparent position depending on the baseline orientation (Charlot 1990). This apparent structure for a given source is dependent of the frequency and evolves with time. This is the main reason why VLBI sources well-monitored present instabilities on their position records and one should be careful in its defining sources selection process. Precisely define the stability of the observed sources on the basis of the 37 years of VLBI observation is the goal of this paper. Since 1998, several methods were elaborated in this goal. Amongst other criteria, two variances has been used successively in order to estimate the source stability from time series: the classical variance was used by ICRF (Ma et al. 1998) and ICRF2 (Ma et al. 2009; Fey et al. 2015) working groups as well as other authors (Lambert & Gontier 2009; Liu et al. 2017) whereas the Allan variance (Allan 1966) was introduced by a group of researchers (Feissel et al. 2000; Gontier et al. 2001; Feissel-Vernier 2003; Feissel-Vernier et al. 2005) and taken up in more recent years (Le Bail & Gordon 2010; Le Bail et al. 2016; Liu et al. 2017). Chronologically, selected sources define celestial frames that proved to be more and more stable, from $\sim 20\mu$as to $\sim 5\mu$as, even if the selection process changes. This means that new observations have a dominant improvement of the axis stability. But Feissel-Vernier (2003) challenges both variances at the same epoch and shows best performance with the Allan variance. Nevertheless, authors restrict the Allan variance to a unique time-scale whereas it could provide multi-time scales information as revealed by Le Bail & Gordon (2010) without exploiting it in the selection process.

In our study, we propose a new method to determine the stability of VLBI radio-sources based on the multi-time scales Allan variance information. We begin with a short review of the current data available. Then we develop first the method used to build the astrometric time series and second the way to classify sources with respect to their stability. We conclude with the overview of our classification.

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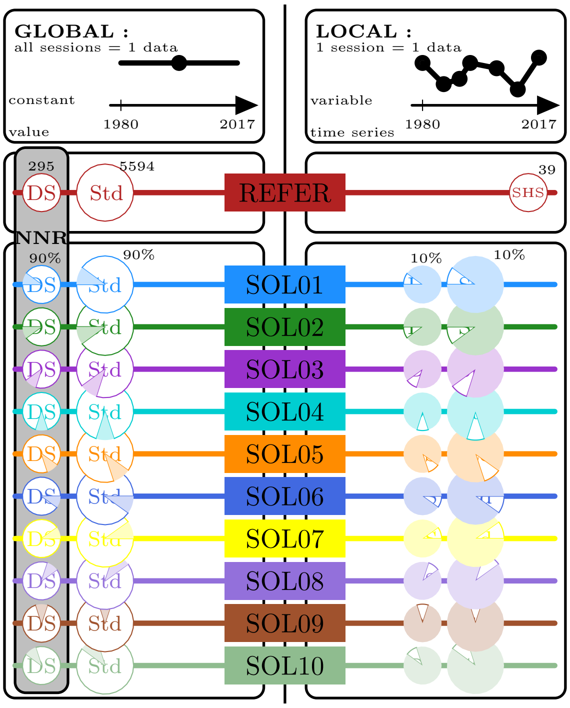

Figure 1: Illustration of the astrometric part in VLBI analysis strategy for each adjustment that determines sources astrometric time series. NNR = subset of sources on which a no-net rotation constraint is applied during the least squares adjustment.

2 Set of Data used

We use 6 327 diurnal geodetic VLBI sessions available on the IVS database in Mars 2017, in which 5 928 sources were observed. VLBI is a powerful astrometric technique in radio that takes advantage from interferometry on Earth-scaled baseline. It needs to process a complex data treatment involving several effects that need to be modelled and/or corrected: light deflection in the solar system, atmospheric corrections, Earth motion and deformation, thermal antenna and other instrumental corrections. The observation occurence for each sources is highly inhomogeneous. Most of the sources are observed a few times whereas less than 100 sources benefit from more than 1 000 observation sessions.

Only sources that have a large observational history can be characterized by means of studying their position time series. In our stability study, we reduce our set of data to 710 sources observed in 10 sessions or more with an observation history larger than 2 years.

3 Determine astrometric time series

Our first task is to determine astrometric time series for all VLBI sources. To this aim, we build a composite solution of 11 different adjustments inspired from Ma et al. (1998). The method is classical and used in several references cited in introduction. Here we only explain the astrometric part of the analysis strategy[1] illustrated on Fig. 1.

From a first adjustment, called `REFER`, we retrieve the astrometric time series for the 39 ICRF2 special handling sources (Ma et al. 1998) that are recommended to be adjusted locally (see Fig. 1) whereas the set of 295 ICRF2 defining sources is constrained during the least squares adjustment to not rotate, assuring the stability of the celestial frame. This is the important reason why defining sources should be stable, because any apparent motion due to, e.g., structure evolution will be transfered to other parameters such as the Earth orientation parameters because of this necessary constraint.

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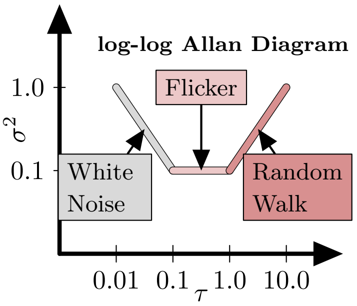
[1] The whole details of the analysis strategy not mentioned below can be found in the OPA technical file → `ftp://ivsopar.obspm.fr/vlbi/ivsproducts/eops/opa2017a.eops.txt`



	Drift in Allan diagram
Red noise also called Random walk	1
Pink noise also called Flicker noise	0
White noise	-1

Figure 2: Illustration of an Allan diagram for a perfect artificial noisy signal with three different types of noise, each one dominating at different time scales.

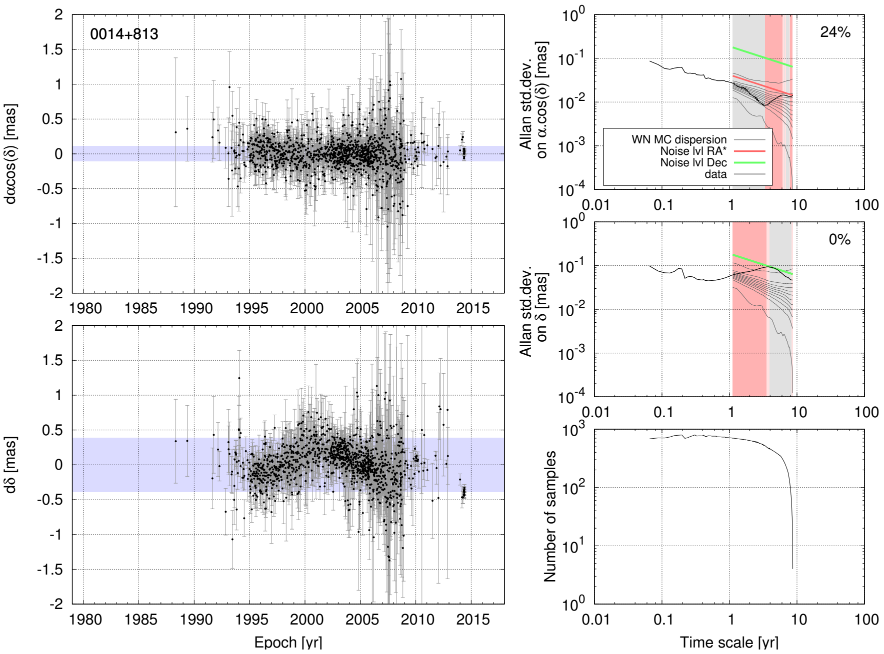


Figure 3: Example of 0014+813 astrometric instabilities and its corresponding Allan diagrams on $\Delta\alpha\cos\delta$ and $\Delta\delta$. Colored backgrounds indicate the type of noise respecting the Fig. 2 color scheme. Green and red straight lines show the minimum white noise level necessary too hide all other colored noise effects. The grey dispersion curves are a Monte-Carlo-based statistical validation test (see the text for more details).

Then, in each additional adjustment (`SOL01` to `10`), 10% of all the other sources adjusted globally in `REFER`, are adjusted locally (see Fig. 1). Consequently, the no-net rotation constraint is applied to 90% of the ICRF2 defining sources. By doing so, we reduce the noise level of the produced time series by a factor of two in mean with respect to time series obtained to a straightforward solution in independent mode in which all sources are estimated locally.

4 Estimate sources astrometric stability

We use the Allan variance (Allan 1966; Rutman 1978) to quantify the stability of each sources. This statistical tool allows us to discriminate different natures of noise within the time series and estimate their levels at perceptible time scales through Allan diagrams (see Fig. 2). The Allan variance estimator is

$$\sigma^2(t,\tau) = \frac{\sum^{k} 1/2\left(\bar{y}_k - \bar{y}_{k+1}\right)^2}{N}$$

where t is the epoch of the first observation, τ is the measurements period and N their number. We compute both Allan diagrams on $\Delta\alpha\cos\delta$ and $\Delta\delta$ for the 710 sources observed in more than 10 sessions spread on more than 2 years (see Fig. 3 for an example). Then, we analyse the noise at each time scale.

Our classification is built on three categories. The first one, referred to as `AV0` are sources dominated by a white noise at most of the time scales or by flicker noise otherwise. The second one, referred to as `AV1`, are

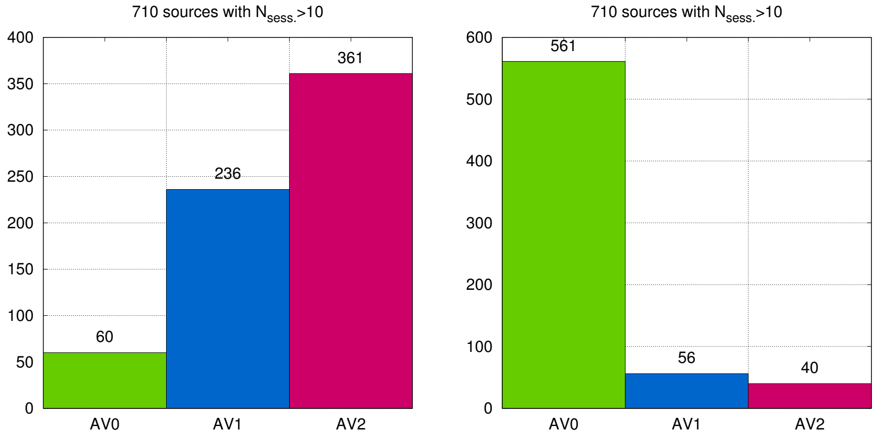


Figure 4: Classification overview in the most pessimistic scenario (left), where the statistical threshold was fixed at 100%, and the most optimistic scenario (right), where the statistical threshold was fixed at 0%.

sources that can present a red noise behaviour at intermediate time scale, but not at long time scale where it is dominated by white noise. Finally, the last class, referred to as `AV2`, are all others sources showing an unstable behaviour, i.e., red noise at long time scale.

Our estimation of sources stability includes the determination of the lowest white noise level that returns a pessimist limit on the source potential as defining sources (its corresponding Allan diagram maximizes the computed Allan diagrams built on the observations). It means that the potential of the considered source to define a stable axis direction will be better than this hypothetical purely white noise source on all perceptible time-scales. This information can be used to roughly resume the noise level of the source without consideration of the noises combination within the data.

Finally, and because our method appears to be too severe in determining stable sources (`AV0`), we implement a statistical validation test based on Monte Carlo analysis. The result of the test may rehabilitate `AV1` and `AV2` sources into the `AV0` class. For a given source, the test consists of simulating white noise on the data sampling and computing the corresponding Allan variance, repeating the operation over 1 000 random draws. Because of the irregular, finite sampling, a white noise can show false drifts from the expected -1-slope in its Allan diagram, especially at the longest time scales. Consequently, we computed a scatter plot of all the 1 000 Allan diagrams and superimposed it to the real Allan diagrams of the sources. Then we retrieve a percentage of white noises that drift more than the Allan diagrams of the source. The bigger the percentage, the better the chance than the observed drifts on the source Allan diagrams are not statistically significant.

Without the MC validation test, our method returns a very pessimistic overview of only 60 stable sources over the 710 well observed and 361 unstable. Nevertheless when we apply the validation test with the loosest threshold, the number of stable sources increases to 561. So, our classification established an adjustable hierarchy that can be used in the context of selecting defining sources. Within each category, the noise level enables to sort out the sources.

5 Conclusion

We establish a new classification of VLBI radio-sources on the basis of their astrometric time series analysed by Allan variance. Three classes are composing the solution : sources `AV0` with a stable behaviour, sources `AV2` with an unstable long-term behaviour and intermediate sources `AV1`. The distribution of the sources in this classification is user-dependent throught a threshold that can be modified in order to restrict or loosen a statistical constraint defining the border of stable/unstable behaviours.

This classification brings accurate additional information for the selection of defining sources in the realization of a celestial reference frame. For example, after fixing the threshold for the validation test, one can select only the `AV0` sources. A preferable strategy would be to combine the `AV` classes and the noise level information in order to select a set of candidates sources to define the celestial frame axis. Moreover the astrometric variability defined by the time series that we compute accurately is also rich on astrophysical information about active galactic nuclei (AGN) plasma jet. Their detailed study may answer some questions such as the origin of the instabilities or help to understand physical particularities of sources that are well-suited for geodetic observations and that should be preferred in the VLBI scheduling.

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