Parametrization of the source coordinates and its astrophysical interpretation

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Motivation

The International Celestial Reference Frame ICRF3, released in August 2018, is the newest realization of the Celestial Reference System (CRS). In this catalog the positions of the radio sources are given as time invariant coordinate pairs. Nevertheless, systematics within the astrometric positions are present, which led to the alienation of a small number of conspicuous sources in the ICRF2 catalog. Recently new evidence was presented for a generalization of such systematics, showing that a majority of the sources is subjected to positional variations; albeit at different levels and time scales. Such systematics, if neglected, may affect the quality of the CRF, and consequently impair depending parameters such as the Earth orientation parameters (EOP). A proven approach to overcome these shortcomings is to extend the parameterization of the source positions within the VLBI data analysis: the multivariate adaptive regression splines (MARS) allow complete automation by combining recursive partitioning and spline fitting in an optimal way.
In this study, we investigate source coordinate time series and their residuals after the application of said parameterization. We aim to identify the effect of the parameterization on the noise content and level within the residual source position time series. To this end we investigate the Allan standard deviation functions from the uncorrected and residual time series exemplary for three different sources.

Spline Determination

Our study is based on more than 4500 sessions with global station networks spanning the time frame 1980-2018. The geodetic data analysis is performed using the VLBI software package VieVS [2], and following the conventions of the International Earth Rotation and Reference Systems Service (IERS,[6]). The modeling settings are chosen with respect to the routine single-session data analysis strategies of the International VLBI Service for Geodesy and Astrometry (IVS,[5]). The resulting source position time-series are used to determine the splines based on the multivariate adaptive regression splines (MARS) algorithm as discussed in [4]. Here we present exemplarily the results for the ICRF3 defining source 0048-097 and the ICRF2 special handling sources 4C39.25 and 2234+282. The resulting splines as seen in Fig. 1 are then used to correct the a-priori source positions which enter the VLBI analysis.

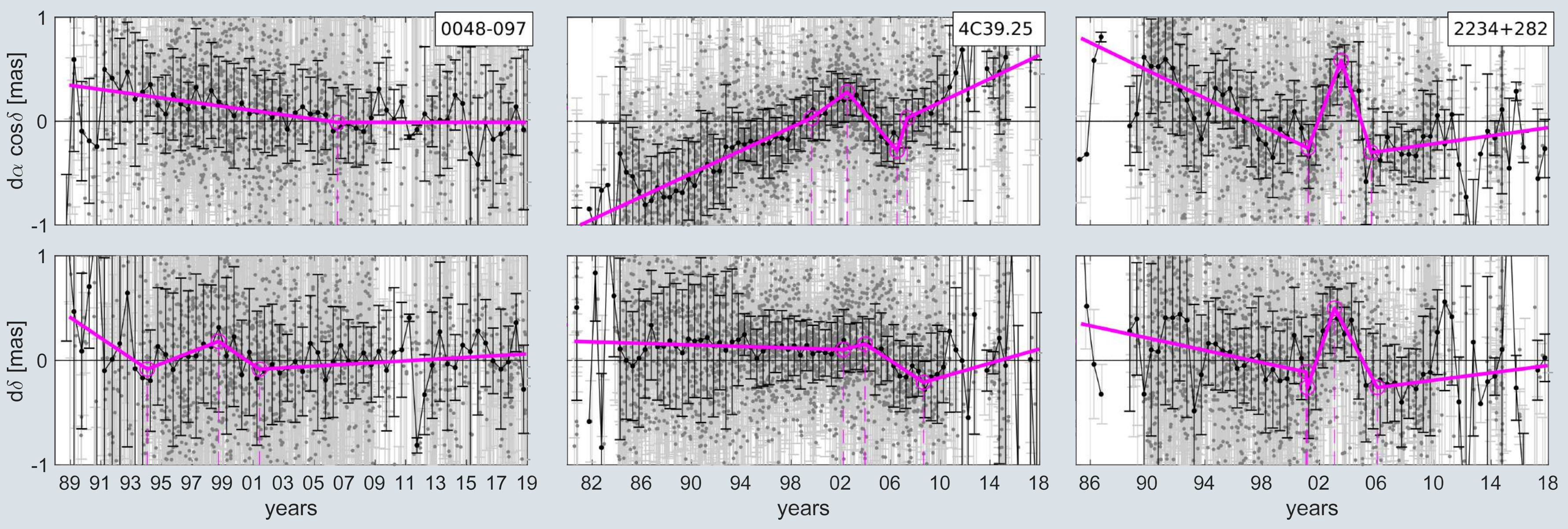

Figure 1: Time series of the residuals w.r.t. the ICRF3 a-priori coordinates of ICRF3 defining source 0048-097 and ICRF2 special handling sources 4C39.25 and 2234+282. The individual session-wise results in gray, half-year mean values in black, both with the corresponding error bars. In magenta, the splines as determined by MARS.

Allan Standard Deviation

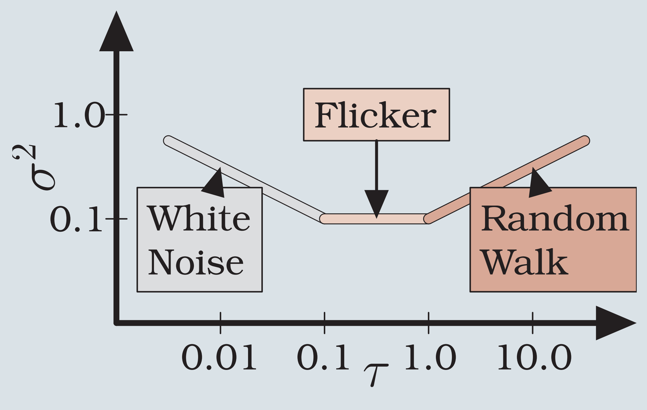

Figure 2: Scheme of the noise identification by the slope of the Allan standard deviation function represented in a log-log scale.

To asses the noise content of the source position time series, we used the Allan standard deviation function [1] that enables to identify in a data time series the different colours of the noise dominating at different time scales by the slope of the function represented in a log-log scale. The principle is illustrated in Fig. 2 and the practical method in the context of VLBI source position time series is discussed in [3]. A perfect source as fiducial mark on the sky, in the astrometric point of view, would have its two coordinate time series, represented as residuals with respect to the position given in ICRF3, returning only white noise at all time scales. On the opposite, a source affected by any position perturbation would present a colored noise at some time scales from one or both coordinates.

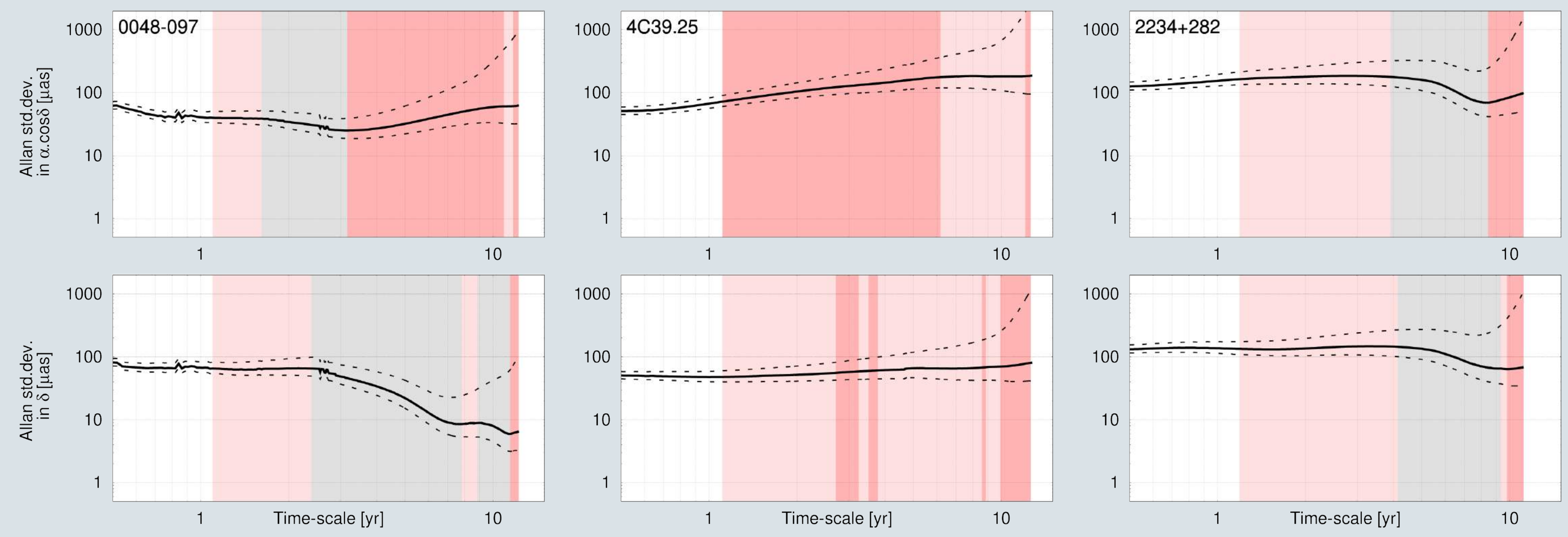

Figure 3: Allan st. dev. functions of the position residual time series w.r.t. the ICRF3 a-priori coordinates of 0048-097, 4C39.25 and 2234+282. The background colours indicates the noise colour identified at the corresponding time scale following the colour scheme of Fig. 2.

Results

0048-097 : Despite its ICRF3 defining status, we observed systematics for this source, revealed by the MARS algorithm (Fig. 1) and the Allan standard deviation functions of its two coordinates (Fig. 3). The right ascension is dominated by a random walk at time scales longer than 3 yr. The declination is affected by a flicker noise at time scale shorter than 3 yr and by a white noise at longer time scales. The correction from the splines (Fig. 4) slightly mitigates the noise level on the right ascension without changing significantly the noise content. On the declination, the flicker noise at shorter time scales was erased but the noise content at longer time-scales was degraded.

4C39.25 : this source is known to present exceptionally important systematics in its astrometric position as seen in Fig. 1. Its right ascension systematic is recognized as random walk like whereas its declination systematic is recognized as flicker noise like (Fig. 3). Taking into account the corrections from the splines improves the noise content. The right ascension becomes mostly dominated by flicker noise whereas the right ascension is in majority dominated by the white noise.

2234+282 : Its two coordinates are both dominated by flicker noise at time scales shorter than 4 yr and by white noise in majority at longer time scales. The linear spline corrections evince in majority the flicker noise and the noise level is diminished at all time scales even if the final residuals are not purely dominated by white noise.

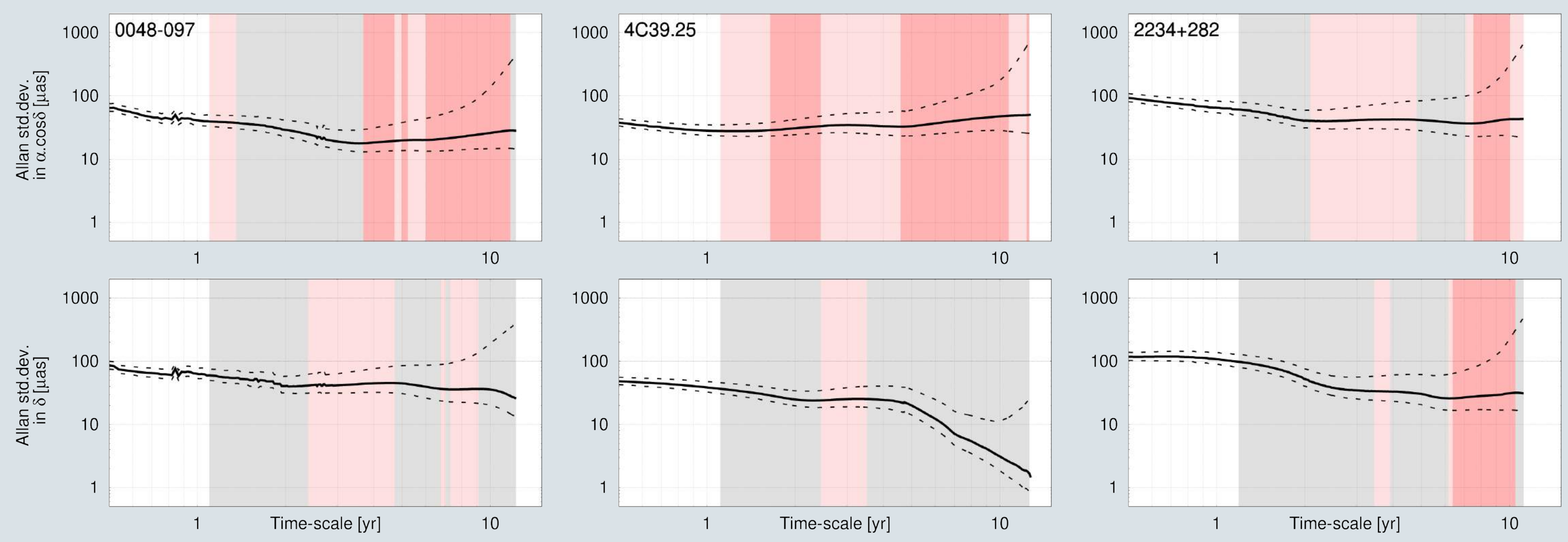

Figure 4: Allan st. dev. functions of the position residual time series w.r.t. the splines derived by the MARS algorithm for 0048-097, 4C39.25 and 2234+282. The splines represented in magenta in Fig. 1 take into account the systematics. The background colours indicates the noise colour identified at the corresponding time scale following the colour scheme of Fig. 2.

Interpretation Taking into the linear splines to correct the source coordinates from systematics improves the quality of the noise by mitigating the noise level, and sometimes even changing the noise content. Coloured noise (e.g. flicker noise, random walk) may be associated with source-dependent perturbation that affect the position estimate from VLBI. The most probable perturbation is a change of the source structure. For example, starting from a compact structure, the appearance of an extension may drift the position estimate in a peculiar direction on the plane of the sky. Such a noisy drift would appear as a random walk domination. Then, if the extent disappear, the position will drift in the opposite way. A succession of jumps in the position estimates is characterized by a flicker noise. Therefore, only the white noise process is an evidence of source stability in term of behaviour.

Concluions & Outlook

We present a new approach to model the astrometric position variations of radio sources within VLBI analysis and assess the quality and performance of it in terms of noise in the residuals. The method benefits from two statistical tools: the MARS algorithm enables to extract an empirical model of the source position variation with time; the Allan standard deviation analysis enables to characterize the noise content of data time series. The combination of these allowes the tuning of the paramtererization in order to retrieve purely white noise source position residuals.

This method will be applied to all sources which were observed within at least 100 geodetic VLBI sessions. For the determination of the MARS splines some options need to be investigated further, e.g. splines which allow more nodes (meaning higher computation times but more refined parameterization), or cubic instead of linear splines. Also the impact of gaps in the time series and/or sparse data coverage needs to be investigated in this context. The aim is to find a parameterization for each source so that the remaining noise is white. Last but not least further work need to be done on the interpretation of the splines as well as the resulting noises. Final goal is to pin down the astrophysical processes driving the source.

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