ORBIT DETERMINATION FOR GAIA SPECTROSCOPIC BINARIES

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ABSTRACT

Synthetic radial velocities for a population of 2300+ known spectroscopic binaries are generated according to the present scanning law. The effect of the distribution of the observations and of the noise on the orbit fitting is investigated. According to our preliminary results short periods, below one day, will be hard to identify among the many aliases, even in the absence of noise. Requirements in terms of computing power for this shell task are estimated in conjunction with the adopted algorithm for the period search part of the orbit reconstruction. These results are for binaries detected in the Radial Velocity Spectrometer only.

Key words: Gaia; Radial Velocity Spectrometer; Spectroscopic binaries; Period search.

1. A BIT OF RANDOMNESS WOULD BE NICE!

The number of Radial Velocity Spectrometer observations at the end of the mission according to the Nominal Scanning Law (NSL, Lindegren 2001) is plotted in Figure 1. On average, each area will be observed 66±19 times. Even at the lower-end, the number of data exceeds the number of orbital parameters by a factor 5.

Due to the NSL, even in the absence of noise, the spectral window (Figure 2, top panel) exhibits a peak at 6 hours causing a comb-like structure in the power spectrum (Figure 2, central panel). There is no guarantee that the leftmost or highest peak of the power spectrum matches the right period. The great regularity of the NSL is responsible for lots of aliases and the orbit determination of very short period binaries will be difficult. There is no way to know whether we are identifying the genuine period or one of its aliases.

We thus study the effects of the NSL and the precision of radial velocities on the spectroscopic orbit determination problem using synthetic data of real binary systems. We first guess the period of the orbit and then, for true recovered period, we derive the other parameters. The situations of radial velocity variables and photometric variables are quite different. Indeed, the temporal distribution of the two sets of data will be different because of the number and location of the detectors.

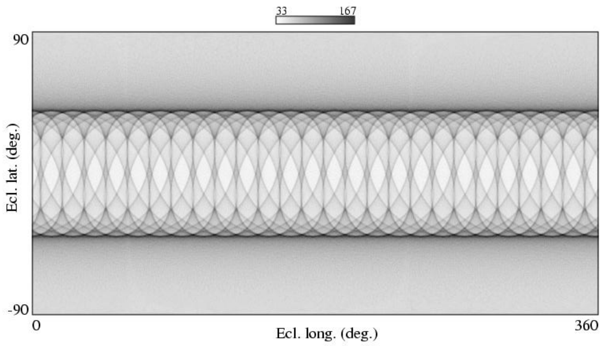

Figure 1. Number of RV observations according to the Nomimal Scanning Law described in Lindegren (2001).

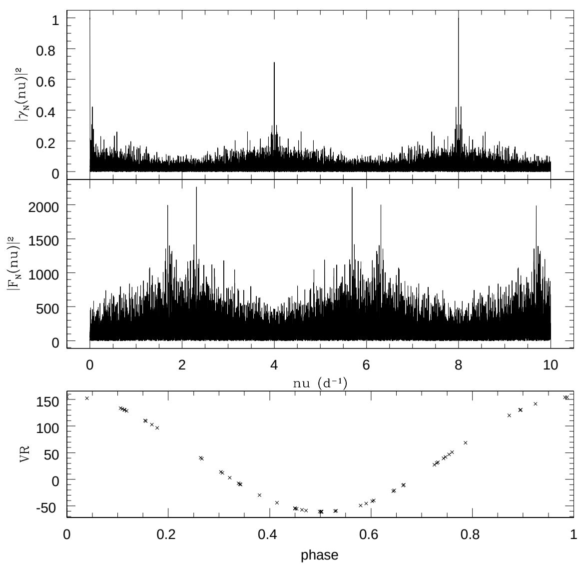

Figure 2. Spectral window (top) and power spectrum (central panel) for given radial velocities.

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2. SIMULATIONS WITH KNOWN SPECTROSCOPIC BINARIES

The real binaries were retrieved from the *9th Catalogue of Spectroscopic Binary Orbits* (Pourbaix et al. 2004). Their distribution with respect to the period is given in Figure 3.

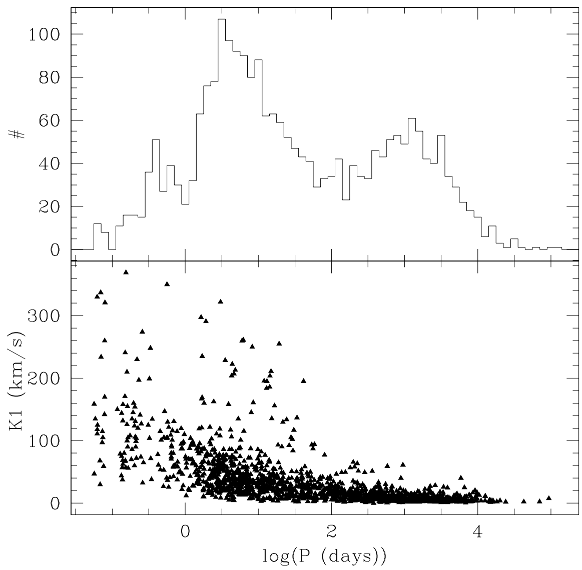

Figure 3. Top panel: Distribution of the period. Bottom panel: Period-amplitude diagram.

Owing to the repetitive patterns of the NSL, we can limit the analysis to the [0,15°] × [0,60°] grid. Radial velocities are generated for all binaries assuming a Gaussian noise of 1, 5 and 10 km s^{-1}. To obtain a periodogram and thus derive a first guess of period, we used the algorithm by Scargle (1982). The percentage and the distribution of recovered periods as a function of noise are plotted in Figures 4 and 5. The period is assumed to be recovered if it is off by less than 10% with respect to the period used for the simulations.

In the absence of noise, 25% of the right periods are missed owing to aliases. The effects of the scanning law are completely washed out. Thus, the number of observations does not compensate for the increase in noise. The percentage of periods recovered within 10% from the true value continuously vanishes as the noise increases.

What about the RV amplitude determination once the period is accurately guessed?

As illustrated in Figure 6, the longest accessible period decreases as the noise increases and there is almost no effect on amplitude determination for short period orbits. Since the long periods correspond to small K, the effect noticed is essentially S/N-driven (Figure 3, bottom panel).

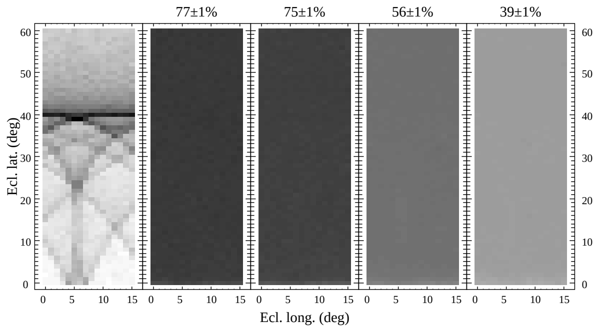

Figure 4. . Map of the percentage of recovered periods. At the noise level, 0, 1, 5 and 10 km s^{-1}. The quoted percentages do not account for systems discarded for S/N below 3.

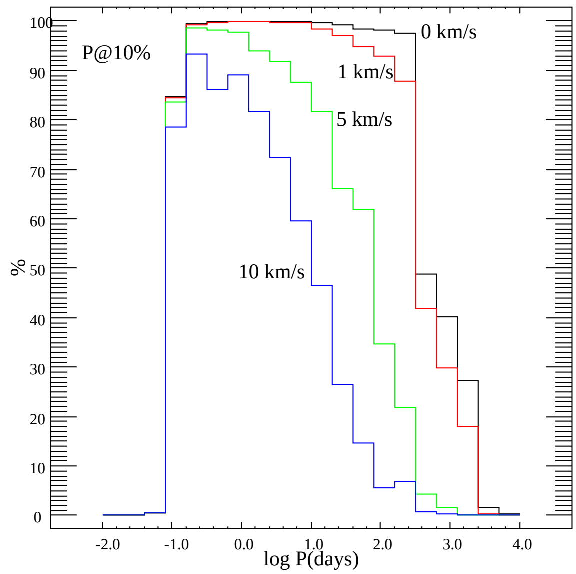

Figure 5. Effect of a noise on period determination. The quoted percentages do not account for systems discarded for S/N below 3.

3. PRACTICAL CONSIDERATIONS

Several period search algorithms were tested (Deeming 1975; Scargle 1982). Though the former provides both the spectral window and the power spectrum, thus making it possible to discard many aliases (Roberts et al. 1987), it does not perform significantly better than the latter in terms of identifying the true period.

Indeed, labeling ν_1 and ν_2 the significant lowest two peaks of the comb-like power spectrum, there is an integer N such that the orbital frequency ν_o satisfies either one:

$$\begin{aligned} \nu &= N\nu_2 + (N-1)\nu_1, \\ \nu &= N\nu_2 + (N+1)\nu_1, \end{aligned}$$

with $\nu_1 + \nu_2 = 4d^{-1}$. There is no guarantee that ν_o corresponds to either $N = 0$ or $N = 1$.

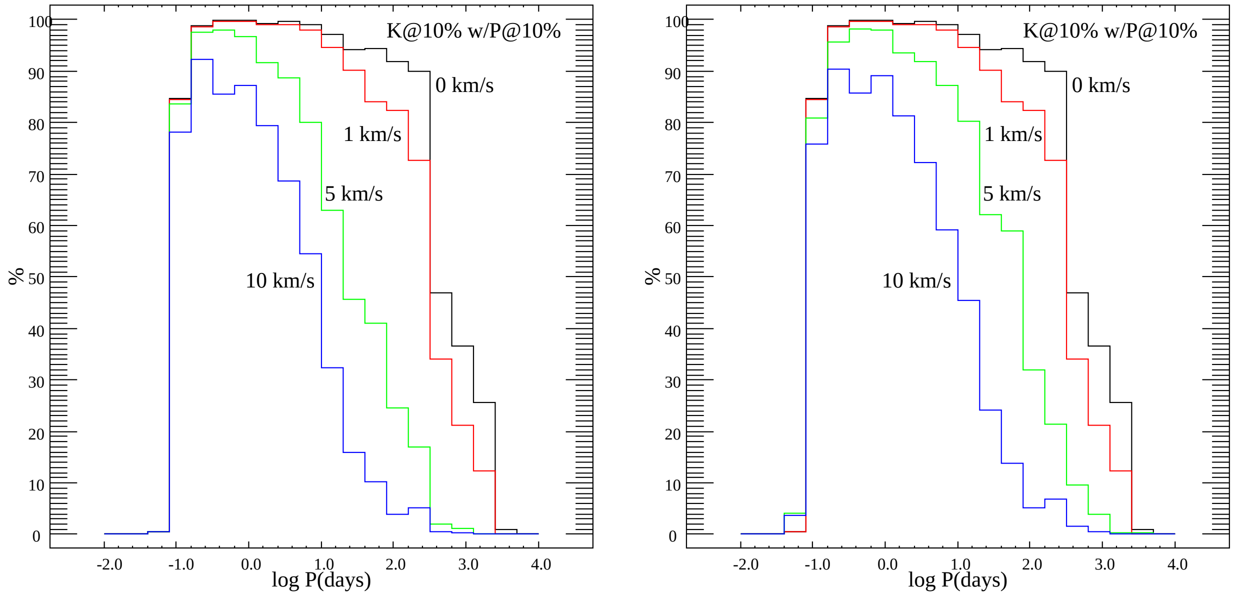

Figure 6. Effect of a noise of 0, 1, 5, and 10 km s^{-1} on amplitude using the method of Lehmann-Filhés (left) or a Fourier-like method (right) to derive a first guess of the orbital parameters in case of good periods. The quoted percentages do not account for systems discarded for S/N below 3.

Cleaning algorithms such as the one by Roberts et al. (1987) help identifying ν_1 and ν_2 but that is clearly not enough since ν_o might not be one of them. However, once those two frequencies are identified, the quest for ν_o is significantly boosted and it no longer takes that many iterations to reach the Nyquist frequency.

Although the period plays an important role in the derivation of the other orbital parameters, one cannot overlook the other parameters. Here also, several methods have been proposed (Binnendijk 1960). Unfortunately, most of them rely upon the availability of the velocity curve to either measure some area or to pick up a few key values.

The method of Lehmann-Filhés (LF) essentially needs the velocity curve in order to compute a surface from which V_0 is derived. In the case of Gaia, the number of observations is large enough to assume that the area based on the polygonal contour of the data points is a good approximation of the curve-based area. When the noise is low, all the quantities required by LF can be derived thanks to that contour. The derivation of a first guess of the orbital parameters is then straightforward and they are close to the true values. The robustness of the method becomes more questionable as the uncertainty on the velocities increases.

In order to achieve a much higher robustness, a Fourier-based method similar to the one by Monet (1979) has been tested as well. The idea here is to fit the radial velocities with a second order Fourier series. The drawback of this approach comes from the difficulty to express the orbital parameters in terms of the coefficients of the series. That is especially true for the eccentricity. We investigated the effect of the degree of the expansion series and concluded that going any higher than the second order is not justified. The robustness of the method is way higher than with LF.

The better robustness of the Fourier approach with respect to LF is illustrated in Figure 6 for 5 and 10 km s^{-1} noise only (we did not run the simulations in case of very low noise and no noise at all). For instance, there are about 15% more amplitudes correctly estimated at $P = 10$ days with Fourier than with LF at the 10 km s^{-1} error level.

The final solution results from a nonlinear minimization of the χ^2 using a gradient-like method. At this stage, unlike at the previous one, the period is released and therefore fitted together with the other parameters. It is worth keeping in mind that the initial value of the period relies upon the assumption that it is a pure sine curve (circular orbit). Therefore, some tuning of the period might be needed if the orbit turned out not to be circular. Practically, the period based on the circular assumption is close enough to the truth for the other parameters not to be completely messed up.

It is nevertheless possible that an even better solution (i.e., a lower χ^2) could be achieved if the nonlinear χ^2 minimization was carried on for each individual tested frequency. The cost in terms of computation time would be likely prohibitive and does not seem to be justified so far.

The CPU time for the overall orbit determination essentially follows the number of data points (Figure 7). However, that figure reflects the time spent by the process at a given time of the mission, without accounting for the evolution of the temporal distribution of the observations during the mission. About 38% of the CPU time is expended in the period search (leading section of the code in terms of computing time). The time spent at that stage

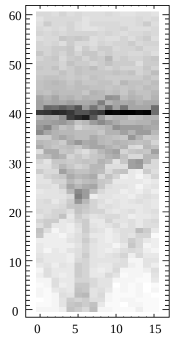

Figure 7. Evolution of the CPU time (the darker the longer).

depends much more on the time interval covered by the observations than on the actual number of observations. Hence, expanding the data set with just one observation 6 hours or 30 days later has very different consequences on the actual duration of the orbit fitting.

Even though the period search is the bottleneck in the orbit derivation, there are several possibilities to improve the situation. One relies upon some astrophysical considerations. As illustrated by Pourbaix et al. (2004), the Roche lobe filling case defines the shortest orbital period which can be fairly guessed from the position of the star on the Hertzsprung-Russell diagram. For instance, it does not make sense to look for orbital periods down to a few hours around giant stars. The main drawback of that approach is that the observed coloUrs can be misleading.

There are nevertheless reasons to be optimistic. Some short period spectroscopic binaries will be eclipsing as well thus making the period derivable from photometry too. In such cases, one can initially assume the photometric period in the spectroscopic fitting process and see what it leads to. Furthermore, the actual scanning law might not be as regular as the NSL which will also substantially reduce the number of aliases of the period present in the power spectrum.

ACKNOWLEDGMENTS

This research was supported in part by the ESA/PRODEX Research Grants 90078.

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