Combining Radial Velocitity and Astrometric Data

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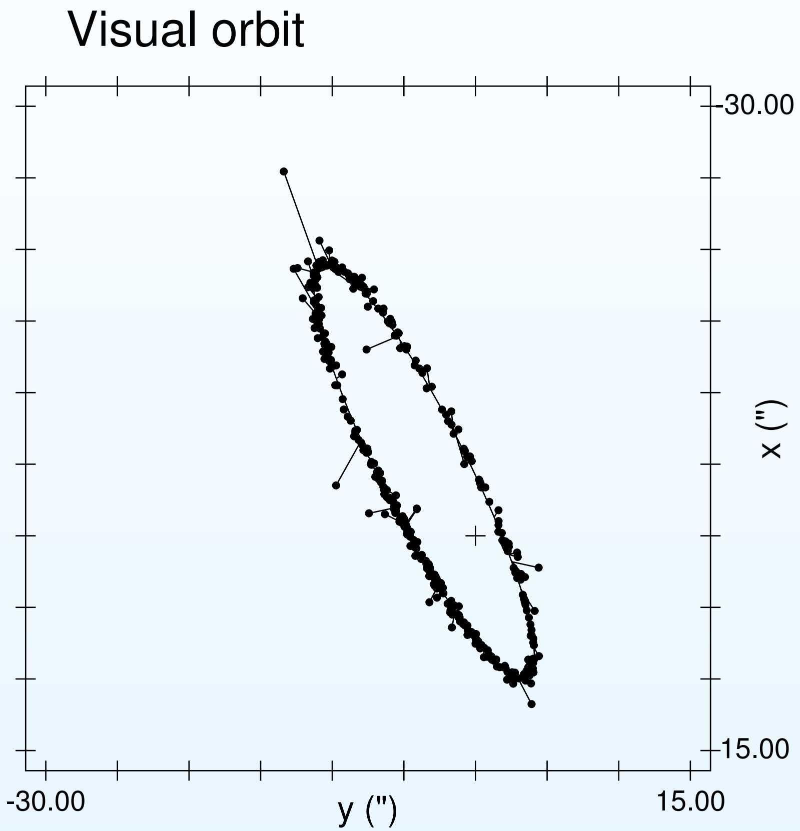
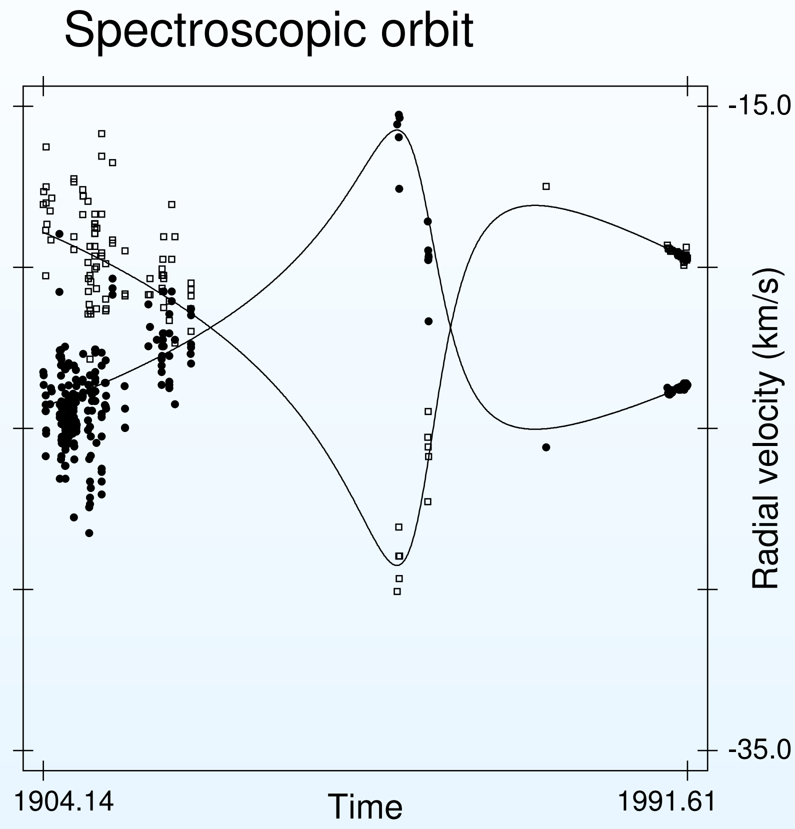
Overview

1. Visual, astrometric binaries and extrasolar planets astrometric orbit fitting
2. Spectroscopic watch dog
   - Benefit from combining
   - When distribution is not enough
   - Also for single-lined (inclination)
   - Use with caution (even if you get what you want)
   - Additional tests required
   - Preliminary conclusions
3. Blind fit

When 7 and 6 yield 10





$a, i, \omega, \Omega, e, P, T$ $\qquad$ $K_1, K_2, \omega, e, P, T, V_0$

$a, i, \omega, \Omega, e, P, T, \varpi, \kappa, V_0$

What you see is not what you need!

In KL#3, a is the semimajor axis of the true relative orbit.

You see	you derive
One set of RVs (SB1)	$a_1 \sin i$, $f(M) = \frac{(M_2 \sin i)^3}{(M_1+M_2)^2}$
Two sets of RVs (SB2)	$a \sin i$ and $\frac{M_2}{M_1}$
Eclipses (EB)	inclination
Relative positions (VB)	angular size of a, inclination
Absolute motion (AB1, AB2)	a_1 [a_2], inclination

No single type but AB2 yields the individual masses but these types overlap partially.

Benefit from combining: additional derived quantities

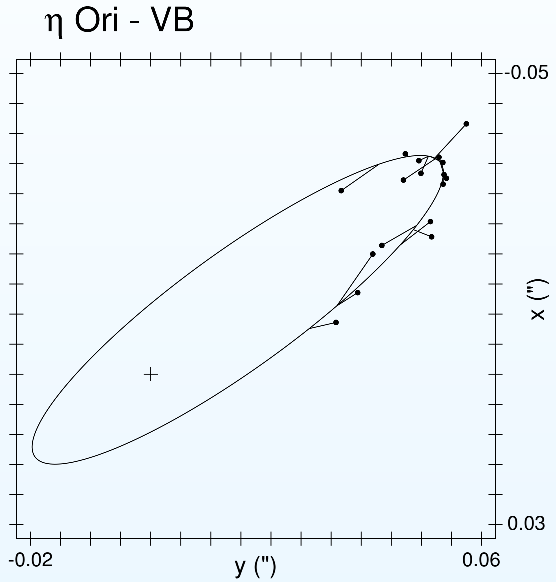
With no ad hoc hypothesis,

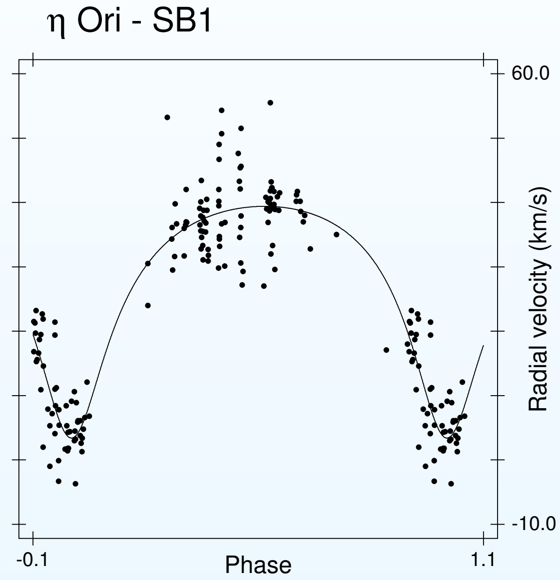
	SB1	SB2	EB	AB1	AB2
VB	-	M_1, M_2	-	M_1, M_2	M_1, M_2
SB1			-	-	M_1, M_2
SB2			M_1, M_2	M_1, M_2	M_1, M_2
EB					M_1, M_2

- EB-SB2 is by far the most numerous combination and, still, accounts for a few hundred systems only.
- Thanks to ground-based interferometry (VLTI, Keck, PTI, Array), the number of VB-SB2 is increasing.
- SIM and Gaia will substantially increase the number of AB.

VB-SB1 & ϖ

Example: η Orionis ($\equiv$HIP 25281)





$$\left.\begin{array}{c}\text{VB}\\ \text{SB1}\end{array}\right\} \Rightarrow \frac{\kappa}{\varpi}$$

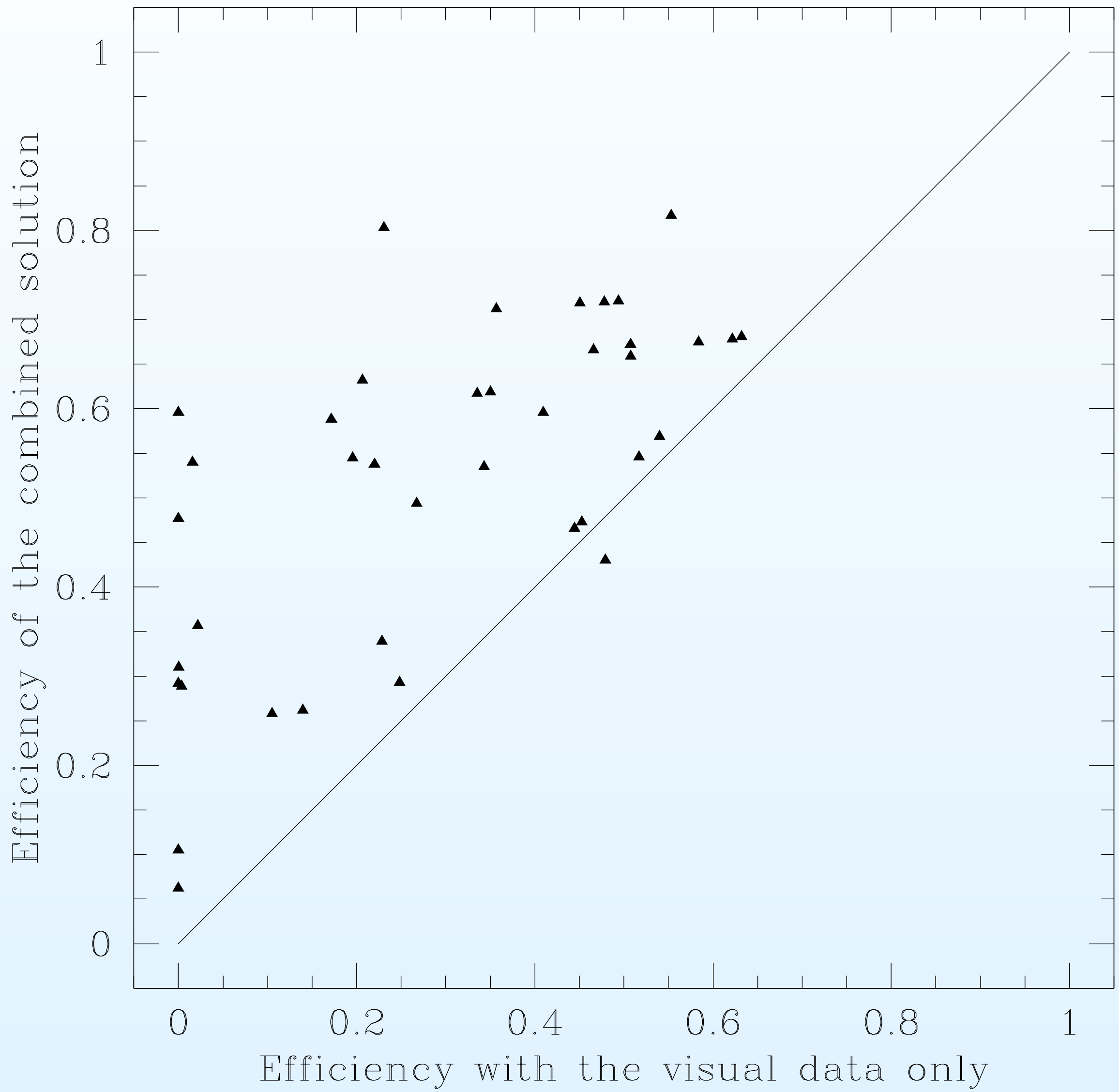
$$\left.\begin{array}{r}\kappa = 7.9(-1) \pm 7.0(+5)\\ \varpi = 6.2(-3) \pm 5.5(+3)''\end{array}\right\} \Rightarrow \frac{\kappa}{\varpi} = 127.8 \pm 7.\text{arcsec}^{-1}$$

Warning

- $\varpi_{HIP} = 3.62 \pm 0.88$ mas
  - $M_1 = 9.20 \pm 7.13 M_\odot$
  - $M_2 = 7.91 \pm 6.22 M_\odot$
- $\varpi_{Photom.} = 3.05 \pm 0.05$ mas (Waelkens & Lampens 1988)
  - $M_1 = 27.46 \pm 2.85 M_\odot$
  - $M_2 = 11.15 \pm 1.88 M_\odot$

The deduced individual masses are very sensitive to the adopted parallax.
One should therefore refrain from jumping on the Hipparcos parallaxes (or any other programme) to apply that method to all VB-SB1 systems.

Another benefit: weaker correlation

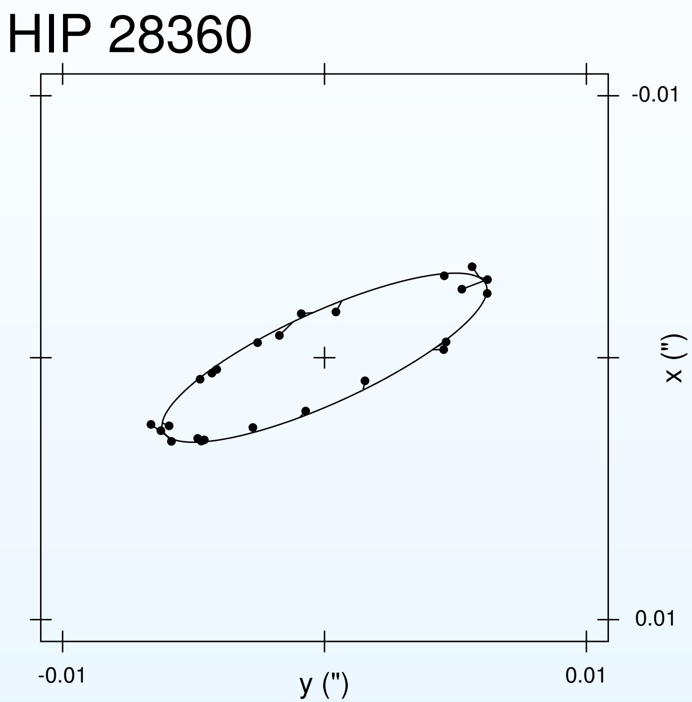


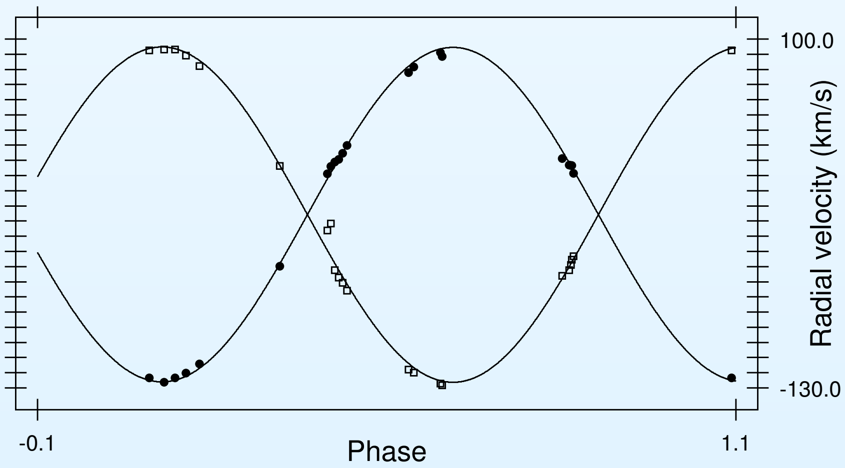
Efficiency (Eichhorn 1989, Pourbaix & Eichhorn 1999)

$$\epsilon = \sqrt[N]{\frac{\prod_{k=1}^{N} \lambda_k}{\prod_{k=1}^{N} q_{kk}}}$$

where N is the number of parameters, q_{kk} are the diagonal elements and λ_k are the eigenvalues of the covariance matrix of the parameters.

Yet another one: consistency of the error bars





Visual orbit: Hummel et al. (1995)
Spectroscopic orbit: Smith (1948)

$$\Rightarrow \begin{cases} M_A = 2.41 \pm 0.03 M_\odot \\ M_B = 2.32 \pm 0.03 M_\odot \end{cases}$$

Same data point but simultaneous solution (Pourbaix 2000):

$$M_A = 2.45 \pm 0.10 M_\odot$$
$$M_B = 2.44 \pm 0.10 M_\odot$$

Those uncertainties are consistent with those on the observations. Smith assumed the same uncertainties on both radial velocity sets (whereas the primary RV are 2.5 times better than the secondary ones).

Single $\longrightarrow$ double

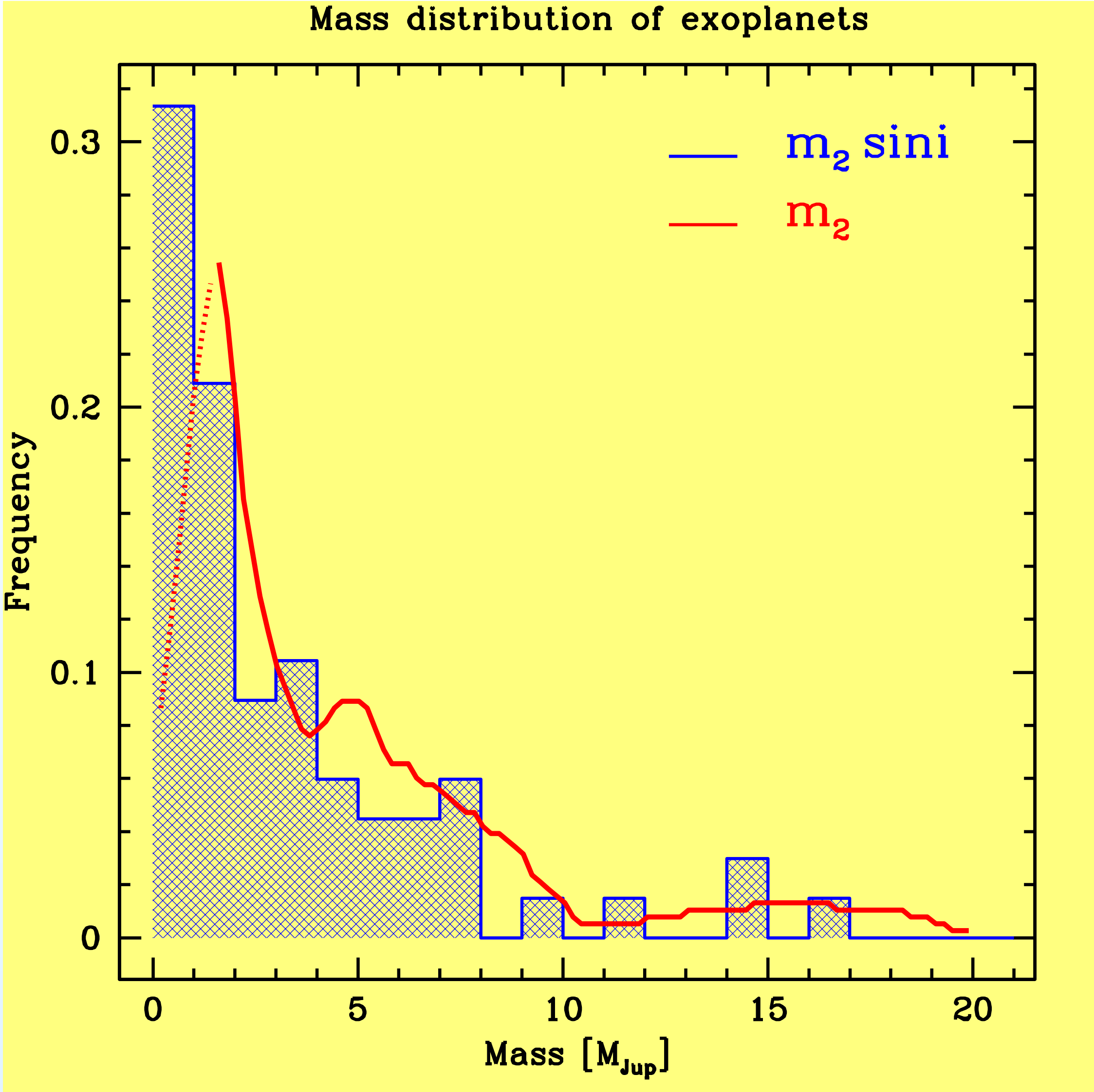
With the improvement of the precision of the radial velocity surveys, some stars thought to be single are discovered to host a companion!

Importance of i

$$f(M) = \frac{(a_1 \sin i)^3}{P^2} = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2}$$

Known from spectroscopy, guessed from the spectral type.

Statistical mass distribution of exoplanets (early 2001)



(Jorissen et al. 2001, A&A, 379, 992)

Campbell's approach

Companions detected by spectroscopic surveys

$\Rightarrow a_l \sin i$ (or K_1), ω_1, e, P, and T.

If the parallax ϖ is known,

$$a_a\,(\mathrm{mas}) = 3.36\,10^{-5} K_1 P \sqrt{1-e^2}\varpi / \sin i$$

Two orbital parameters remain unknown: i and Ω

Together with the 5 astrometric parameters, a 7p model is required.

HIP 88848: Changing a mess into Science

Hipparcos:Known binary with a period $\sim$1.81d (1974)

$\Rightarrow$ No satisfactory solution: DMSA/X (stochastic sol.)

Jancart et al. (2005): no improvement of the fit with that 1.8d-SB1 solution.

Fekel et al. (2005):Third body with a period of 2092 days.

$\Rightarrow$Perfect astrometric orbit

- $\sigma_i = 2^\circ$
- Agreement w/Tycho-2: $30\sigma \rightarrow 2\sigma$

Both astrophysicists and dynamicists are happy!

The joke!

The result of Han, Black and Gatewood

(2001, ApJ, 548, L57)

Hipparcos data of 30 stars with sub-stellar companions ($P > 10$ d) fitted with an orbital model:

- 1 orbit with $i \sim 63°$;
- 29 orbits $i < 25°$.

Consequence:

- 9* with mass $\leq 10 - 15$ M_J;
- 11* with mass ranging from 15 M_J to 80 M_J;
- 4 companions are M dwarf stars;
- 6* for which the mass of the companion cannot be reliably guessed.

Explanation: bias toward small inclination angles (questioned by Pourbaix (2001, A&A, 369, L22)).

Thiele-Innes' approach

Fitting A, B, F and G, regardless of ω_1 and K_1:

$$\begin{aligned} x &= A(\cos E - e) + F\sqrt{1-e^2}\sin E, \\ y &= B(\cos E - e) + G\sqrt{1-e^2}\sin E \end{aligned}$$

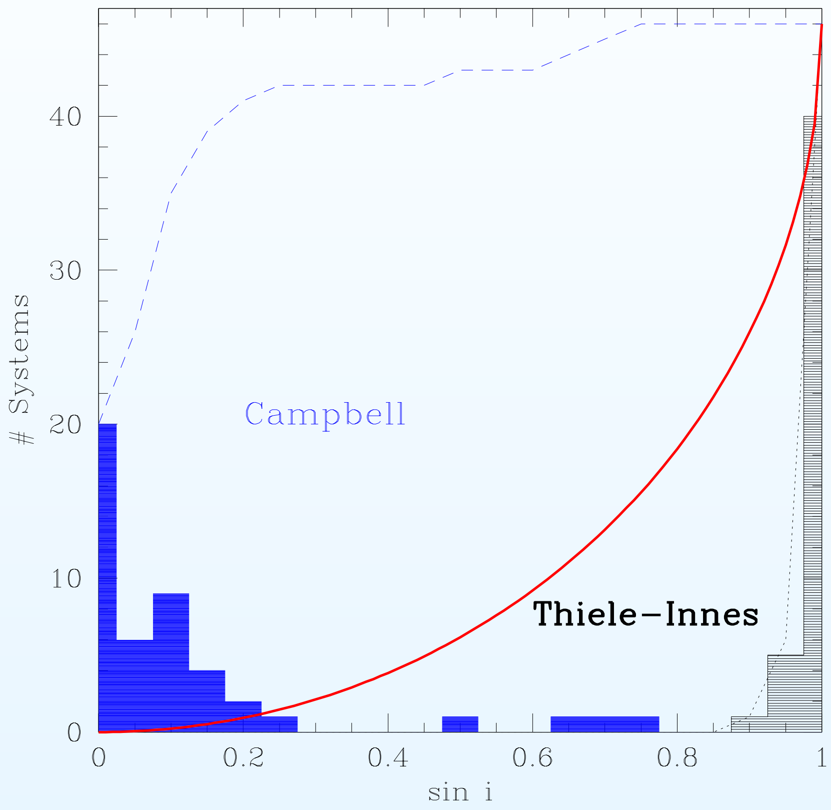
e, P and T are adopted from the spectroscopic orbit.

Advantages:

- χ^2 is linear in terms of the 9 parameters;
- K_1 and ω_1 are used as check-points.

In case of a significant astrometric wobble, both approaches (Campbell's and this one) should yield consistent results.

Distribution of i



If the orbital planes are randomly oriented

$$P(\sin i < x) = 1 - \sqrt{1 - x^2}$$

Are these orbits really necessary?

Reduction of the residuals when there are $9 - 5$ additional parameters in the model: F-test

$$\hat{F} = \frac{N-P}{P-5} \frac{\chi_5^2 - \chi_P^2}{\chi_9^2}$$

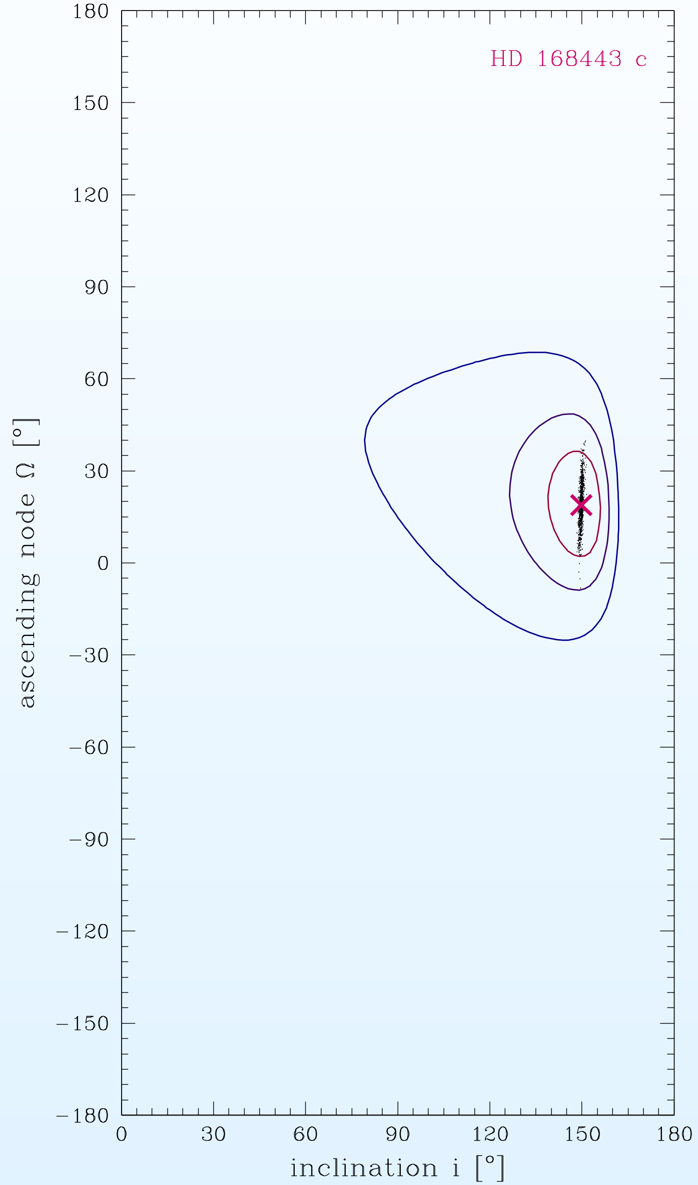
$$\alpha = Pr\left[\hat{F} < F(4, N-9) | \text{no wobble}\right]$$

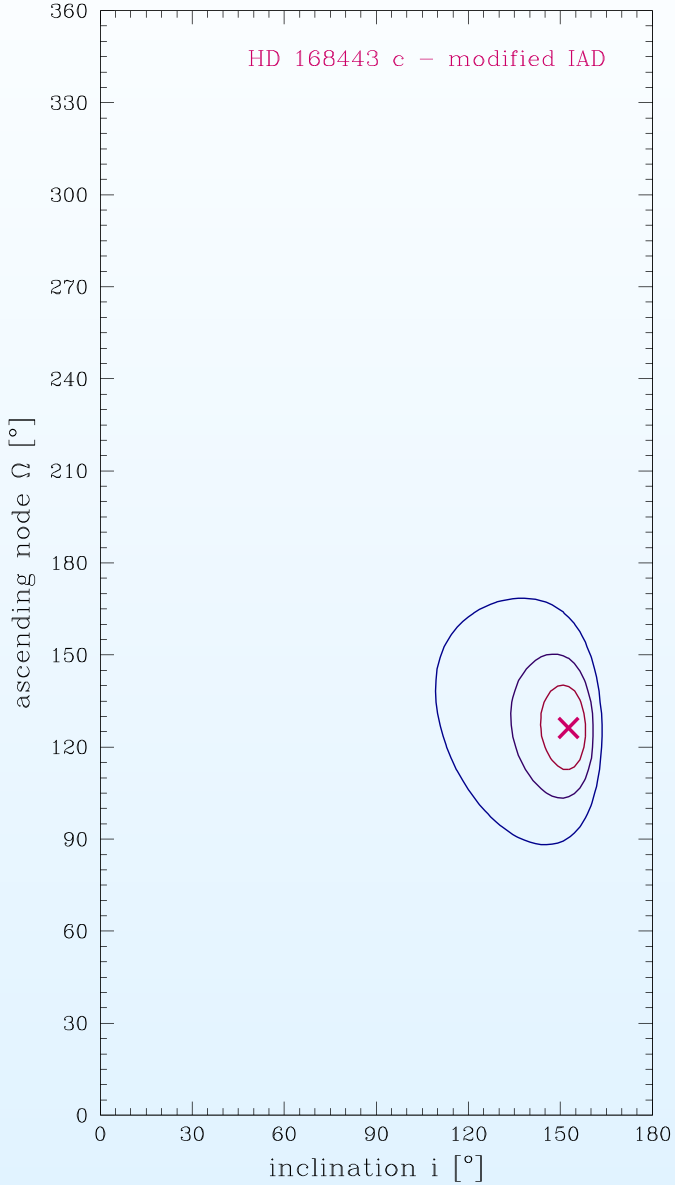
Warning: α is a function of the data **and** the orbit.

New statistical tests to assess the overall quality of such astrometric orbits (Pourbaix & Arenou, 2001, 372, 935)

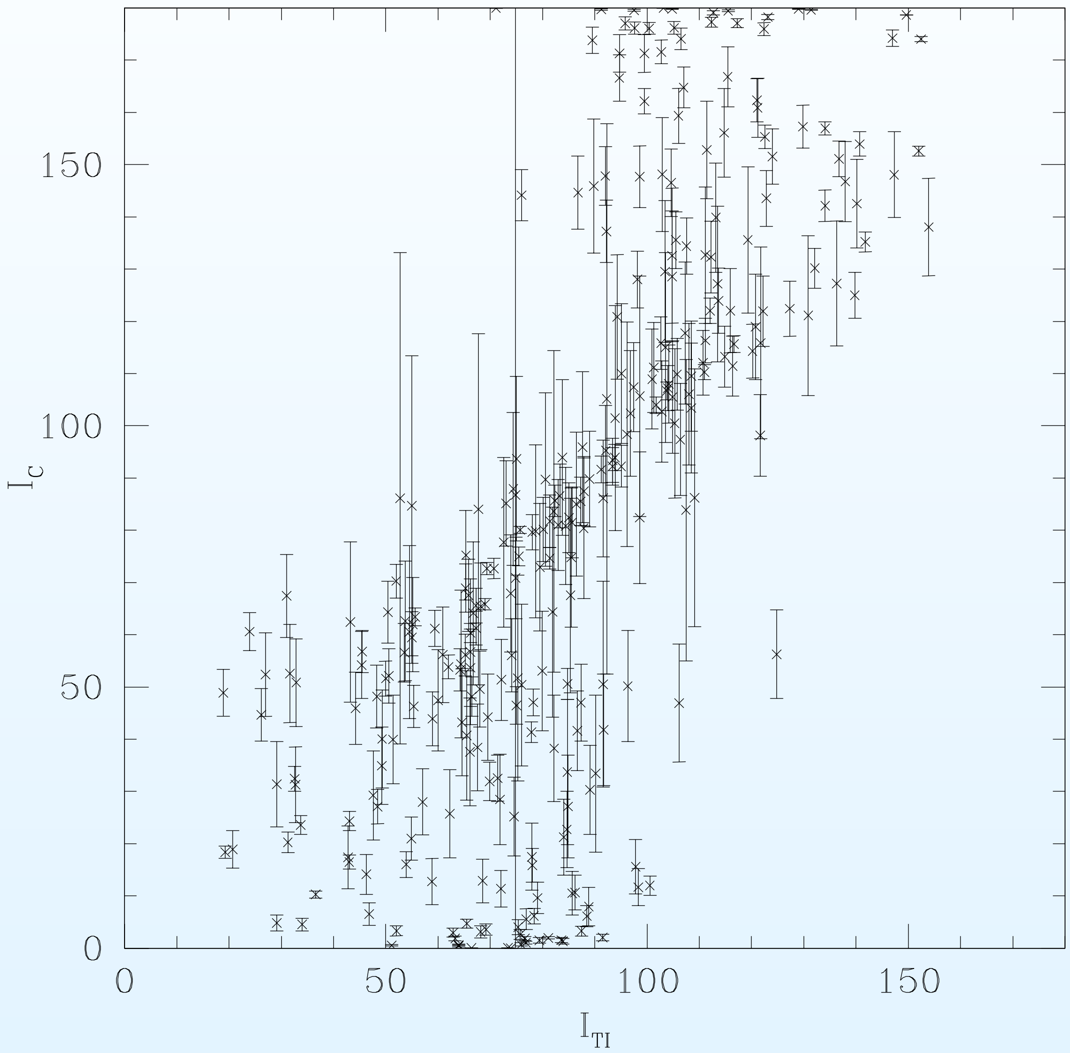
- F-test for Campbell's and Thiele-Innes' solutions (Pr1,2)
- χ^2 between Campbell's and Thiele-Innes' solutions (Pr3)

IntensiveCareUnit (2005)





Not-Not seeing not equivalent to seeing!



Despite Pr1,2,3<5%, 282 spectroscopic binaries from SB9 (1387) exhibit an astrometric signature in the Hipparcos data.

(Jancart et al., 2005, A&A, in press)

Additional tests

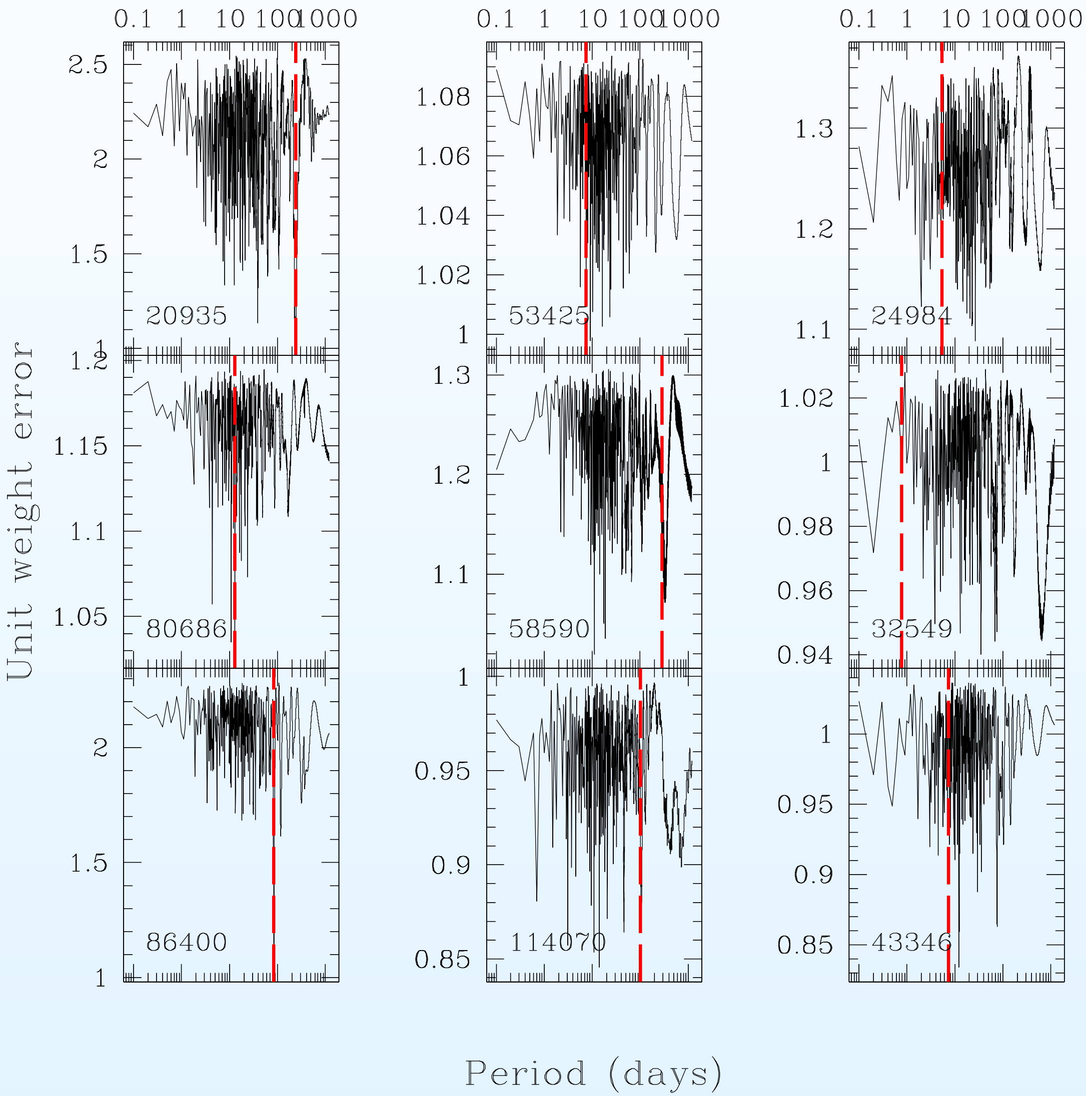
The tests so far assess the improvement of the orbital solution over the single star fit.
Complement them with:

- Goodness of fit (Kovalevsky & Seidelmann 2004)

$$F2 = \sqrt{\frac{9\nu}{2}}\left(\sqrt[3]{\frac{\chi^2}{\nu}} + \frac{2}{9\nu} - 1\right) \sim \mathcal{N}(0,1)$$

- Efficiency (e.g. > 0.4)
- S/N ratio
- Periodograms

Periodogram screening



(Pourbaix et al. 2004)

Conclusions

(Pourbaix et al. 2004)

- Adopting the spectroscopic orbit does make life easier!
- Even for objects known to be binaries, the assessment of the reliability of the orbit is difficult.
- About 70 SB9 with astrometric orbit.