Wavelength calibration

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(D. Katz and M. David contributed heavily with discussions and suggestions)

Many papers, documents and talks are already dedicated to the problem or errors in RV measurements.

The wavelength calibration is one of the error sources.

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I- Brief list/review (incomplete) of already mentionned errors sources (no order) :

1- Effect of PSFand optical design:

- Initial shape
- Propagation of the already detected photons with TDI mode, and of new photons along a somewhat different path

=> progressive widening or smearing , partly corrected by optical improvements and tilt mechanism

No details here (see papers by M. Cropper, F. Chemla)

2- Effects due to resolution and atmospheric parameters of the star.

Probably the most sudied effects in this group:

Resolution, noise, magnitude, vsini, Teff, abundances...

No details here.

3- Sources for systematic errors

3 nice papers from Marc DAVID (available on Live Link), with various numerical simulations.

Main recommendations and effects to be checked carefully:

- CCD: make bias frames before launch! Detailed map of each CCD.
- Data Reduction Software: careful in selecting the right algorithm for data extraction!
- Doppler-shift measurement procedure:

. Choice of the template spectrum is IMPORTANT => the spectral type will first have to be determined from photometry BEFORE reduction.
From what photometry??? Not obvious, as the star is not observed photometrically at the same time.

. Need for a good centroiding of the correlation peak, after the correlation is made with the template. Remember that 1km/s is only 0.0765 pixel.

. Watch for discretization effects and possible asymmetry in the lines (calculations will have to be readapted to the new design with tilt mechanism). The blue end of the wavelength range has already been moved from 849 to 848 nm in order to minimize the effects due to the ends of the interval.

. Possible "rectification" of the spectra for the slope of the continuum, if different from that of the template.

. Paper in A&A suppl 136,591 (1999): "Random error minimization during cross-correlation of early-type spectra" (wide peak).

4- Accuracy of the on-board clock

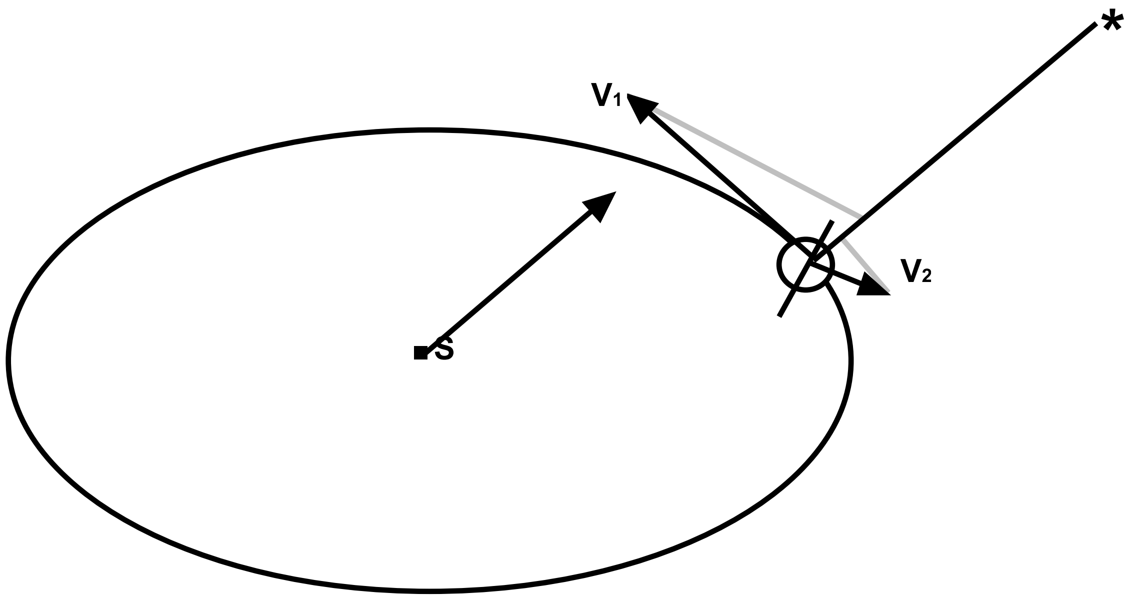
1km/s = 0.0765 pixel = 1.25 ms transit time.

See Note on Live Link by de Bruijne, GAIA-JdB-044, assuming clock accuracy requirement for RVS of 5*10^-6 over 34 sec (transit along 1 single CCD) : Probably underestimated; but fortunately astrometric requirements are much higher.

5- Orbit at L2

See Note on Live Link by F. Mignard, GAIA-FM-014

- Ground-based RV measurements

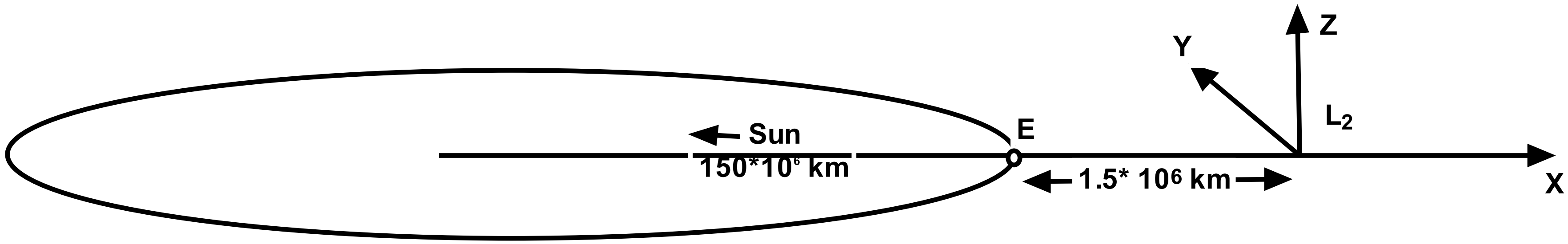


2 motions to be combined and projected on sun-star line of sight :

- V1 = velocity of Earth (earth-moon system) around Sun (Barycenter of solar system)
~30 km/s

- V2 = velocity of Earth rotation around its axis at observer's position, depending on observatory's coordinates and observing date
<= 0.5 km/s

- GAIA RV measurements from L2



3 motions:

- L2 around Sun:
~ 30 km/s (1% more than Earth)

- Spacecraft around L2 (Lissajous orbits), as recently proposed by F. Mignard, known to 10^{-3}
<= 60 m/s

- Spacecraft spin (same for all stars), depending on satellite's geometry:
<= 0.003 m/s

6- Strategy for error study and modelling:

See Note by L Lindegren on Live Link GAIA-LL-043

"Gaia astrometric error budget, proposed approach":

Progressive list of errors; error propagation;

Error analysis tree, a good part is convenient for RVS.

7- Possible check / comparison with ASTROMETRIC RV's?

Paper by Madsen, Dravins & Lindegren, A&A 381,446 (2002):

For open clusters and associations, stars sharing a common velocity vector, with application to HIP data (parallaxes and Proper Motions)

Comparison with ground data => systematic differences vs B-V and Vsini, see below figure on Hyades taken from Madsen et al (2002)

GAIA data will be much better, but one has to take into account the internal velocity dispersion (<3 km/s, often less: 0.49 km/s for Hyades)

The accuracy is strongly function of cluster's extension on the sky.

Systematic relativistic difference between astrometric and spectroscopic RV:

sig = v^2/c

RV, km/s	100	200	500	750
sig, km/s	0.033	0.133	0.833	1.88

=>There should be no problem for disk stars.

8- Other effects?

Please extend the list!

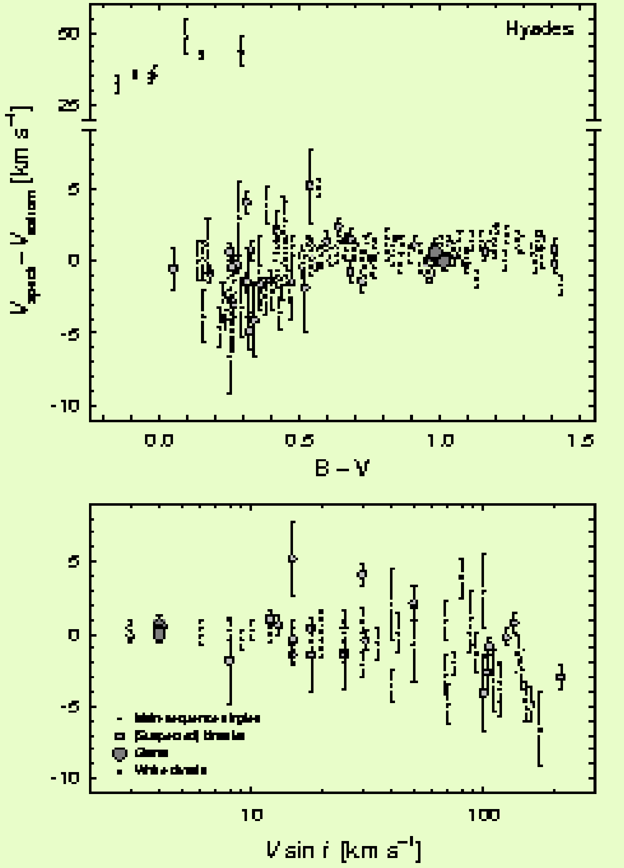


Fig. 4. The Hyades: Differences between spectroscopic radial-velocity values from the literature, and current astrometric determinations. Systematic differences depend on spectral type, and on the projected stellar rotational velocity $V \sin i$. (These dependences are correlated since rapid rotation dominates for early-type stars.) An increased blueshift of spectral lines in stars somewhat hotter than the Sun ($B - V \simeq 0.3$–0.5) is theoretically expected due to their more vigorous surface convection, causing greater convective blueshifts. Gravitational redshifts of white-dwarf spectra place them far off main-sequence stars. The error bars show the combined spectroscopic and astrometric errors; stars with errors >3 km s^{-1} are omitted (except for white dwarfs), as are stars that were not retained by kinematic solutions from both Hipparcos and Tycho-2 data.

II- Wavelength calibration using Standard Stars

The RVS is an instrument fully independant for the ASTROMETRIC telescope. It shares its telescope and focal plane with the MBP.
With the new design of the focal plane, with the MBP located above and below the RVS, the RVS stars are not the same ones as those observed at the same time in the MBP. So no other instrument is observing the same stars. This means that if we need data from the other instruments, they will have to be extracted from the general data bases of astrometry and MBP, obtained at different times.

1- The problem:

- For ground-based RV:

. A wavelength calibration in made in the dome, either by using an external laboratory source with many narrow and well-known spectral lines (lamps with Thorium, Argon, Neon, etc...), that can be fed easily in the telescope at any time; or by using *IN THE STELLAR BEAM* a vawelength reference , most usually an absorption cell containing gaseous I2 for today's very accurate measurements. The corrresponding spectral lines are "printed" on the stellar spectrum.

. Then a least-square fit is made trough the laboratory lines, and the stellar spectrum is regularly calibrated in wawelength; it becomes a function F(lambda), F being a flux.

. Then the correlation can be made.

- For GAIA:

NO on-board reference source.

Initial guess = to rely on RV standard stars to regularly calibrate the field.

This process is described NOWHERE and is not obvious.

Therefore some efforts are devoted to find also other methods, which may be complementary:

. Ulisse is investigating the possibility of having an absorption cell in the beam; main difficulties :

weight added; space needed; small wavelength range ; the instrument is VERY COLD and should not be heated, etc...

. Tomas is proposing other reliable sources with good narrow lines and known velocities (asteroids), to be used in complement to the standard stars.

2- Standard stars (SS):

Stars already well-studied from ground, with constant and stable RV.

The IAU commission 30 (RV) has on his web site a list of ~150 stars, with accuracy <300 m/s.

VERY SMALL LIST! Should be increased in the 5 coming years, with the results of the large programs on Planet search.

3- What we get on ground for all stars:

- For each star detected in the RVS StarMapper (SM):

t0 = time when is comes out of the SM => how precise???

- the beginning of the spectrum arrives at the end of the RVS-CCD1 a "known" time later (with some error);

- then the 694 pixels of the spectrum are counted and registered:

Pixel 1 arrives at time t1, ...pixel i arrives at time ti. Content of each pixel = flux Fi:

time	t1	t2....	ti.... t694	)	
flux	F1	F2...	Fi... F694	)	table 1, associated to time t0

Then the beam moves along CCD2 and CCD3.

The question of summing or not the 3 flux tables from the 3 CCDs on-board is still in question and will not be examined here in this 1st stage.

4- For a SS only: spectrum and RV already known.

. Theoretical wavelength are corrected for star's RV and known satellite motion.

. The lines are searched in table 1 and recognized. Tops are found.

A time tj, not necessarily an integer, can be associated with the top of each line, and a wavelength λj. => New table: (λj, tj) = table 2

A polynomial of convenient degree is fitted in (λj, tj), associated to the initial detection time t0, and the effects of RV and satellite motion have been removed.

If everything is perfectly stable (instrument, rotation rate...), this relation should hold indefinitely. Every new standard star entering the field should help to verify it and increase the accuracy.

. from fit in table 2 a wavelength λi may be associated to (t0, ti, Fi).

This can be done for each CCD prior to summation, or after . Differences in the 3 laws show immediately the degradation due to further summation.

This procedure also takes into account any permanent variation of the dispersion over the FOV, but not variations in the scanning rate.

5- For a "normal" star:

The above relation (t0, ti, Fi, λi) should be used, at least until the next SS is observed.

A template spectrum of known RV and "adapted" SpT is cross-correlated with (Fi,λi) and gives the RV of the star.

"Good" calibration if there are only very small drifts between 2 SS, and if ALL rows of the CCD are well calibrated.

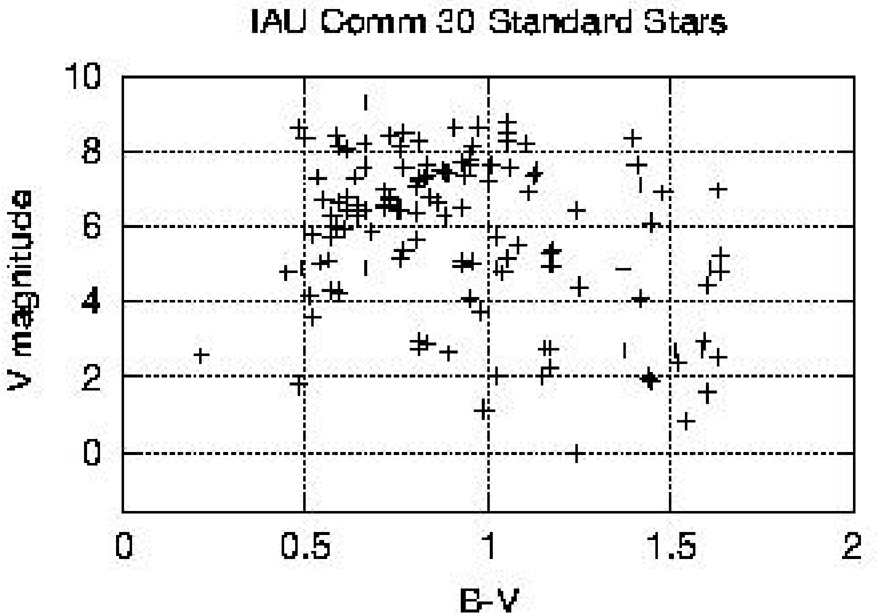
Therefore the SS should consitute a rather dense network, and allow often enough the calibration of all the rows in the CCD.

6- Questions, problems, remarks...

- How precisely is the time difference (t1- t0) known?

- How many standard stars are needed?

- Present SS are very bright (V<10) and should be detected correctly ONLY in SM3: is it enough?



- How to choose the best template for cross-correlation (see suggestion of M. David)
- How to constitute the library of templates? Real/ synthetic spectra? (The Asiago library will be of course the beginning)
- Multiplicity...

Problems and errors related to on-board summation of spectra

- Summation on pixels; or on wavelength? (if the calibration for the 3 CCDs are different)
- Suggestion of M David: in order to insure that the 3 CCDs are perfectly parallel, is it possible to produce them all on one substrate from a single print?
- Removal of fast-moving targets?
- Numbers in all that?