RVS WAVELENGTH CALIBRATION: SIMULATION OF REFERENCE STARS

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ABSTRACT

The Radial Velocity Spectrometer (RVS) has no internal wavelength calibration source. It is a self-calibrating instrument relying on many self-selected reference stars. Therefore, only the zero-point of the radial velocities has to be fixed from ground-measured standard stars with accurately known radial velocities. Here we examine the recovery of the wavelength scale as a function of spectral type and magnitude, with a frequently-used software, IRAF. The number of possible reference stars is evaluated from the Tycho-2 Catalogue.

Key words: Gaia; Radial Velocity Spectrometer; Radial velocities; Simulated spectra.

1. INTRODUCTION

The Gaia RVS (Radial Velocity Spectrometer) is a slitless spectrograph with *no* wavelength calibration source on-board. Like the astrometric and photometric instruments, it is a self-calibrating instrument (see Katz 2005; Katz et al. 2004). The calibration is made in two steps:

1. A consistent but relative system is built from many "good" (i.e., bright, stable, single...) reference stars found among the observed stars. These stars will be progressively selected according to their behavior.

2. The system zero-point is then fixed with the use of a much smaller list of regular RV standard stars measured with high accuracy from the ground, e.g., the list established by the IAU Commission 30, and extended with the many new ground-based measurements expected within the coming years.

Here we discuss only step 1:

- which stars should be adopted as reference stars (magnitude range, spectral type...);

- how accurately their RV can be retrieved, from a widely used software like IRAF.

2. SIMULATED REFERENCE STARS

- Synthetic spectra (Kurucz models) for various atmospheric parameters were used. From the ground-based experience we selected in a first time only main sequence stars corresponding to three $T_{\rm eff}$: 4500K (K5), 5500K (G5) and 6500K (F5), each in three magnitudes: 8, 10, 12. Each spectrum is given as a file (lambda, flux) with a spectral resolving power of 250 000, much higher than the RVS one.

- We then used the package *rvs_simu_V1.0* (available on the RVS web site[1]) to simulate the transit of a synthetic spectrum through the RVS: this simulator convolves the initial synthetic spectra to the RVS resolving power $R = \lambda/\Delta\lambda = 11\,500$, samples the spectrum to 0.375 Å /pixel, normalizes the flux according to the source and instrument characteristics (spectral type, apparent magnitude, telescope collecting area, optics throughput, CCD quantum efficiency...), generates the photon background and detector noises, and simulates the co-addition of the 10 elementary observations by the individual CCDs.

  It produces a file (pixel-number, flux, lambda) corresponding to the 694 RVS pixels. For "real" stars the RVS will give only pixel-number and flux, and the values of lambda will have to be recovered.

Each of the 9 initial spectra is processed 100 times through the simulator, with 100 different realizations of noise, giving 900 different spectra of 694 pixels.

3. WAVELENGTH RECOVERY WITH IRAF TASKS

For each couple ($T_{\rm eff}$, magnitude) the 100 resulting spectra are wavelength-calibrated with IRAF: our aim is to recover a calculated wavelength $\lambda_{\rm calc}$ for each pixel, to compare it to the initial theoretical wavelength $\lambda_{\rm th}$ given by the simulator, and to compare these 100 recoveries. Examples of initial spectra 'processed' through the RVS simulator are given in Figure 1.

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[1] http://wwwhip.obspm.fr/gaia/rvs

GAIA synthetic spectrum for Teff = 6500K (F5)
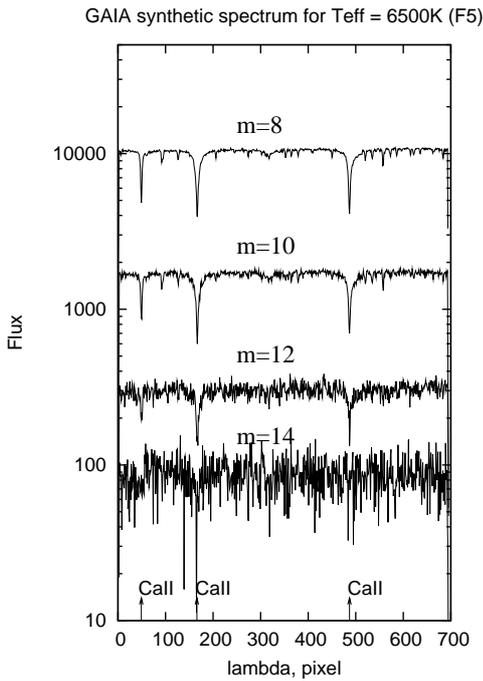
Figure 1. Examples of simulated RVS spectra, for various magnitudes, all for $T_{\mathrm{eff}} = 6500K$.

IRAF tasks *Identify* and *Dispcor* from the *noao.onedspec* package were used.

Two or 3 easy-to-recognize spectral lines (here, the CaII lines) are designated with the pointer (in the future Gaia-RVS calibration pipeline, this task will be fully automated). Then *Identify* recognizes a list of good spectral lines of known wavelength given aside and carefully selected. In ground observations this list contains the lines of the calibration lamp; here we have to take the lines contained in the spectrum itself. We used in this first step a list of 27 lines well distributed over the spectral interval (848 – 874 nm), deep enough on a synthetic spectrum corresponding to $T_{\mathrm{eff}} = 5500K$, and not blended, or blended with a much weaker line. This list is very important for a good recognition; in fact a list adapted to each spectral type should be used. *Identify* then calculates the coefficients of the selected representation for the dispersion law. Here we adopted a second-order Chebychev polynomial.

From these coefficients, *Dispcor* calculates the corresponding wavelength of each pixel λ_{calc}. The efficiency of the recovery is measured for each pixel by:

$$\Delta\lambda = \lambda_{\mathrm{th}} - \lambda_{\mathrm{calc}}, \quad \text{and}$$
$$\Delta RV = c.\Delta\lambda / \lambda_{\mathrm{th}}$$

4. RESULTS

Figure 2 shows the 100 dispersion solutions corresponding to the 100 simulated transits for one given star, plotted versus pixel number. In ordinate the quantity ΔRV is plotted, rather than $\Delta\lambda$. The positions of the 3 CaII lines
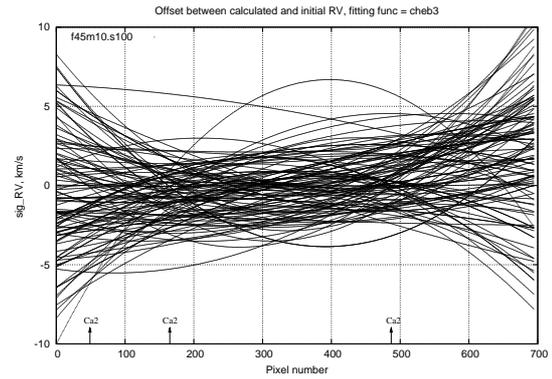
Figure 2. The 100 realizations and dispersion solutions for ($T_{\mathrm{eff}} = 4500K$, mag=10): individual solutions.
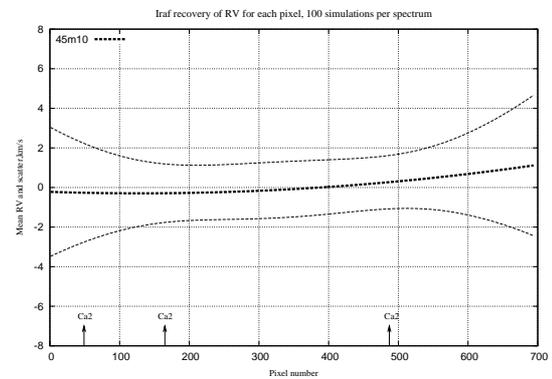
Figure 3. The 100 realizations and dispersion solutions for ($T_{\mathrm{eff}} = 4500K$, mag=10): mean value and 1σ scatter for each pixel.

are indicated at the bottom. The wavelength recovery is quite good *between* the lines, and less good outside.

From this figure it appears that the parameters of interest are the mean value and the dispersion *for each pixel* resulting from the 100 "observations" of the star: they are shown in Figure 3.

Curves similar to Figure 3 may be drawn for the 9 combinations (T_{eff}, magnitude), each with its 100 realizations, and are plotted in Figure 4 and Figure 5.

4.1. Effect of T_{eff}

Figure 4 shows, for the magnitudes 8, 10 and 12, the results obtained for the 3 temperatures: the K and G stars give good results; the F star is less good. This result is already known from ground-based measurements. However in the reduction process the basic list of spectral lines is the same for the 3 types of stars: it is similar to keeping the same mask for the cross-correlation on the ground-based spectrometers; whereas big progress on the recent ground-based RV spectrometers was obtained precisely by replacing the old permanent mask by a numerical mask adapted to each spectral type. Our basic list of spectral lines should be adapted to each temperature and optimized.
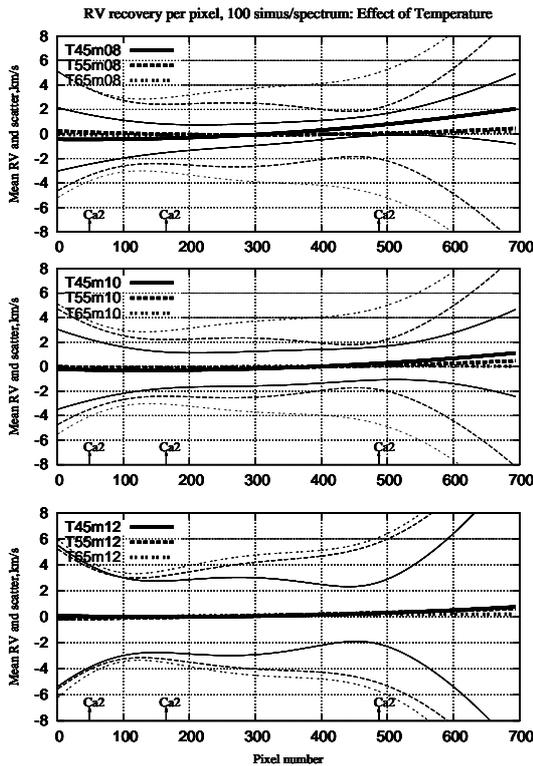
Figure 4. Effect of temperature: each graph corresponds to a given magnitude, each for the 3 temperatures. Magnitude 8 (top); 10 (center); 12 (bottom).

Figure 5. Effect of magnitude. Each graph corresponds to a given T_{eff}, for 3 magnitudes (8, 10 and 12). T_{eff} from 4500 (top) to 5500 (center) and 6500 (bottom).

4.2. Effect of Magnitude

Figure 5 shows the 3 different stars, each seen at the magnitudes 8, 10 and 12. Magnitudes 8 and 10 give quite close results; magnitude 12 is less good.

5. HOW MANY REFERENCE STARS ARE AVAILABLE?

The use of reference stars not selected in advance, but selected afterwards on the basis of their general behaviour on successive transits, requires that a large number of such stars be available. A numerical estimation of the number of stars on the sky is made from counts in the Tycho-2 Catalogue (Høg et al. 2000): stars F8 to K8 (including giants) correspond roughly to:

$$0.5 \leq B - V \leq 1.5$$

Using the transformation equation:

B – V = 0.850(B_t – V_t) given in the Introduction and Guide to the Hipparcos and Tycho Catalogues (ESA 1997), Vol. 1 Page 57 we get: B_t – V_t = 1.177(B – V), or for the stars of interest:

$$0.6 \leq B_t - V_t \leq 1.76 : \text{F8 – GK stars}$$

The cumulative number of Tycho-2 stars within this interval and brighter than a given limiting magnitude V_t is counted versus V_t, and an exponential fit between magnitudes 6 and 11 (to avoid incompleteness effects) gives:

$$N_{\text{F8GK}} = 2.73 \times 10^{0.475 V_t} : \text{F8GK stars brighter than } V_t.$$

A similar count may be performed for only GK stars, as the F ones may be less convenient; the interval is now:

$$0.7 \leq B_t - V_t \leq 1.76$$

$$N_{\text{GK}} = 2.833 \times 10^{0.468 V_t} : \text{GK stars brighter than } V_t.$$

The counted number of stars and the corresponding fit are shown in Figure 6 ; the expected numbers (from the fits) are tabulated in Table 1 for several limiting magnitudes.

Table 1. Expected number of stars down to various limiting magnitudes, for several groups of spectral types. Unit = 10^3 stars.

V_t	8	9	10	11	12
N_{F8GK}, in 10^3 stars	17.3	52	155	462	1380
N_{GK}, in 10^3 stars	15.6	46	135	395	1160
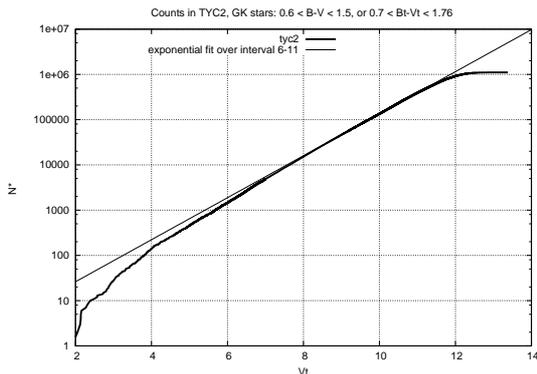
Figure 6. Cumulative number of stars brighter than V_t, GK stars, counted in the Tycho-2 Catalogue, and exponential fit for extrapolation. The fit is made over N*, while the plot is in log(N*).

Of these stars, not all will be usable as reference stars: almost half of them may be double; a much smaller fraction will be variable (according to the Hipparcos statistical results (ESA 1997)) this B – V interval contains only few variables, even among the giants); some more will have to be rejected for other various reasons. But even down to magnitude 10, some 50 000 to 60 000 objects may be available: at least one per square degree.

6.   CONCLUSION

A wavelength scale for the RVS may be recovered from many GK stars brighter than 10 and selected progressively during the mission according to their stability. More than 50 000 such objects are available. The basic list of spectral lines should be improved and adapted to the spectral type.

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