RVS radial velocity accuracy budget

RVS-ACC-001

D. Katz, M. David, U. Munari, F. Arenou, T. Zwitter, M. Cropper, F. Crifo, D. Walton, F. Chemla, D. Horville, F. Royer, A. Blazit, Y. Viala, M. Haywood, S. Mignot, H. Hensberge, A. Jorissen, A. Holland

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1 Introduction

During the phase of definition and selection of the Radial Velocity Spectrometer (RVS) characteristics, several studies have been conducted to assess the first order performances of the spectrograph in the determination of the radial velocities (RV). In the continuity of those works, the objective for the second part of the phase A (2003-2004) is to establish the RVS RV detailed accuracy budget. This activity has started early 2003, via mail discussion, with the aim of defining: (i) the list of error sources that may impact on the RV performances, (ii) the error sources whose impact should be assessed in priority, (iii) the people who were interested to address the different issues, and (iv) the protocols and agenda of the different studies.

The aim of the present note is to review the status of the evaluation of the RVS RV performances at the end of the first part of phase A (Sect. 2), as well as to summarise the recent discussions and present the work breakdown and agenda of the accuracy budget activities for the second part of phase A (Sect. 3).
Comments are of course most welcome as are the people interested by the accuracy budget issues. If you want to participate to one of the study described below, or to any other study related to the RVS RV performances, please contact D. Katz (david.katz@obspm.fr) and U. Munari (munari@pd.astro.it).

2 Status of the assessment of the RV precisions

From the initial proposal to implement a spectrograph on-board GAIA until the choice of the characteristics of the instrument, studies have been conducted to assess (to the first order) the RV performances of the different configurations of the RVS : e.g. Zwitter, 2002; Munari et al., 2003. Those studies have taken into account the following effects:

- Different spectral types
- Mean number of transits
- General characteristics of the instrument
  - Optics: pupil area, focal length, spectral resolution, FoV size, simplified transverse profile (i.e. average energy integrated over 2 pixels across scan)
  - CCD and focal plane layout: number and size of the CCD, number and size of the pixels

  - System overall efficiency
- Main sources of noise
  - Sampling: along scan position of the spectrum with respect to the pixel
  - Photon noise
  - Readout noise
  - Zodiacal light (assumed uniform on the length of a spectrum)
- Quantization of the output signal
- Mismatch between the source and the reference template

In parallel to the assessment of the impact of the parameters and error sources listed above (which mainly generate random errors), M. David has conducted several studies focused on some key sources of systematic errors:

- Review of key systematic error sources (David, 2001)
- Sampling error (David, 2001; David, 2002a)
- Boundary error (David, 2001; David, 2002a)
- Star line curvature mismatch (David, 2001; David, 2002a)
- Spectrum slope mismatch (David, 2002b)

Note: The RVS consortium is currently defining the spectrograph detailed optical design (number of lenses, curvatures, glass indices, ...). Four different configurations are compared. The selection of the baseline will be performed by the end of August 2003. Once the baseline is adopted it will be possible to assess or re-assess (see Sect. 3.2.1) the impact of the optical characteristics on the RV performances (see David, 2001): e.g. PSF shape, along and across scan distortions.

The RVS is a slitless/fiberless integral field spectrograph, dispersing the light of the whole field of view. As a consequence, on a large part of the celestial sphere, the spectra of neighbouring sources will overlap. Two studies devoted to the evaluation of the impact of the crowding on the RV performances have started mid-2002 (Zwitter, 2003; Cropper, 2003). They both rely on similar approaches to recover/separate the spectral information contained in the composite/stacked spectra. The sources are analysed from the brightest one to the faintest one. Source by source, the "background", i.e. the "neighbouring/contaminating" sources, is modelled (using the photometric and astrometric information as well as the spectroscopic information available at that stage) and subtracted. If necessary the procedure could be iterated (to re-inject the estimation of the RV of the faintest sources in the analysis of the brightest ones). The first results are encouraging (Zwitter, 2003). The RV performances appears to be little affected by the crowding up to stellar densities of ~ 20000 stars/degrees^2 (at $V = 17$). It is planed to continue this activity during the second part of phase A, in the form of a double blind test (see Sect. 3.2.5).

3 Assessment of the detailed accuracy budget

3.1 Error sources

The list of parameters and effects that impact, or may impact, on the RVS RV performances is presented in Table 1. This list derives in large part from the "list of things to consider" in the assessment of the astrometric accuracy budget (Lindegren, 2002).

Table 1: List of parameters and error sources that may impact on the RVS performances

Sources	**Satellite and environment**
Source type and magnitude	Scanning law (number of transits)
Source type mismatch	Along and across scan velocity stability
Source multiplicity	Real time attitude determination
Source variability	On-ground attitude modelisation
Source confusion/overlapping	Thermal/mechanical stability
Sky background/interstellar extinction	
Cosmic rays	
Instrument	**Data processing and analysis**
Optics (transmission, PSF, aging, ...)	Source detec./selection/extraction
Mechanics (short term stability, ...)	CCD summation
Tilt mechanism	Spectra pre-processing
CCD (RON, QE, MTF, TDI, CTI, ...)	Data compression
Electronics (VPU, RPPU, PDHU, ...)	Calibrations (wavelengths, ...)
	Atomic data & reference spectra
	Background iterative modelling and subtraction
	RV determination algorithm(s)

3.2 "Short" term studies and coordination with the Accuracy WG

The list of effects entering the RV accuracy budget is quite large and the assessment of the impact of all of them will extend beyond the second part of phase A (2003-2004). As a consequence, issues which are likely to have a significant impact on the RV performances and which should be considered in priority (before the end of phase A) have been identified. Those key "error sources" are presented in the following section and are summarised below:

- Instrumental effects
- Conservation/recovery of faint signals
- On-board summation
- Spectroscopic Global Iterative solution: wavelength calibration
- Overlapping of the spectra in high stellar density areas
  - Iterative modelling and subtraction of the background
  - RV determination algorithm: determination of RV star by star from their background subtracted composite spectrum
  - RV determination algorithm: 2D cross-correlation of the whole field of view.
- RV determination algorithm

The assessment of the astrometric accuracy budget started several years ago and is in a more advanced state (see e.g. Lindegren 2002; de Bruijne, 2003a; de Bruijne, 2003b) than the radial velocity accuracy budget. Moreover, a significant part of the problematic is common to the astrometry, to the spectroscopy as well as to the photometry. In order to avoid as much as possible to duplicate the works and in order that all instruments benefit from the skills developed in the "Astrometry and Error Budget" WG it has been decided at the last GAIA Science Team (GST) meeting (25-26 June 2003, ESTEC) to transform the "Astrometry and Error Budget" working group into the "Accuracy" working group. The role of this new working group is to:

- Continue to refine the astrometric accuracy model.
- Adapt the accuracy model to include the radial velocities and the photometry.

- Include in the accuracy model the simulation tools developed in the RVS working group.
- Include in the accuracy model the results of the studies performed in the RVS working group.

The role of the RVS working group with respect to the assessment of the RV accuracy budget is as described in the present note:

- Define the errors which should be assessed in priority.
- Assess the key error sources.
- Provide simulation tools and studies output for inclusion in the accuracy model.

3.2.1 Instrumental effects

F. Chemla, D. Horville, D. Katz

The RVS optical (PSF shape, distortions, ...) and detectors (read-out noise, time delay integration mode, charge transfer inefficiency, ...) characteristics will induce random and systematic errors. It is foreseen to proceed in 4 steps to evaluate their amplitudes:

1. Compute, using an optical software (i.e. ZEMAX), the monochromatic point spread functions (PSF) and positions in the field of view as a function of wavelength and source position on the sky, taking into account the optical characteristics of the spectrograph: anamorphosis, star line curvature, variation of the dispersion across the FoV, dependence of the transmission on the polarisation, variation of the blaze profile across the FoV, ...
2. Compute the monochromatic PSF after a transit, taking into account the characteristics of the CCD: TDI rate, TDI inefficiency, MTF, RoN, structure in the dark current, fringes ....
3. Reconstruct the spectra from the "monochromatic PSF after transit", computed at step 2.
4. Assess the radial velocity performances via Monte-Carlo simulations.

Note: A detailed simulator of the CCD is currently developed at ESTEC by A. Short. When available, it will replace the simple CCD simulator that will be developed in the RVS WG.

The assessment of the instrumental effect should follow the agenda below:

2003 / 09 / 01	-	2003 / 10 / 31	Development of the simulator (steps 1 to 3).
2003 / 11 / 01	-	2004 / 01 / 31	First assessment of the instrumental errors (step 4).
2004 / 02 / 01	-	2004 / 12 / 31	Refined assessment of the instrumental errors.

3.2.2 Conservation/recovery of faint signals

D. Walton, A. Holland

A bit less than one photon will be collected per pixel, per CCD and per transit for a $V = 17$ K0V star. To reach a signal to noise ratio high enough to derive the radial velocity of the faint stars, it is planned to combine the signals recorded over the successive observations (3 CCD times one hundred transits on average). Because of the very small amplitude of the signal recorded at each observation, one can fear that some, presently unidentified, random or systematic error(s) make the summation useless and prevent the recovery of the radial velocities of the faintest RVS targets.

D. Walton has started laboratory tests, to check whether small signals could be combined and to quantify the possible loss of information. In a first series of tests, run during the first quarter 2003, an undamaged CCD operated in normal exposure mode, has been exposed 10 000 times with a signal very significantly smaller (1 e^- per pixel per frame) than the readout noise (20 e^- per pixel). The successive exposures have then been summed. The ratio of the combined signal (measured) over the expected signal is close to 1.

On short term, it is planned to repeat the tests above, but to operate the CCD in Time Delay Integration (TDI) mode (instead of exposure mode). On a longer term, it is planned to perform the tests with a damaged CCD (instead of an undamaged) and in TDI mode, in order to be as close as possible to the average mission conditions at L2.

The tests planned are summarised below:

Tests	Protocol	Status
First series	Repeated exposures, exposure mode, undamaged CCD	Completed
Second series	Repeated exposures, TDI mode, undamaged CCD	
Third series	Repeated exposures, TDI mode, damaged CCD	

3.2.3 On-board summation

M. David

If

1. the motion of a spectrum across the CCDs is perfectly uniform
2. the linear dispersion is constant over the area covered by the detectors
3. the CCD's are mounted so that their lines are strictly parallel
4. the clocks of the respective CCD's are synchronised so that they are all in phase with respect to the moving spectrum
5. the instant that e.g. the reddest wavelength bin is read from each CCD is known

then the spectra from the three CCD's can be summed directly without introducing systematic errors.

Conditions (4) and (5) can probably be satisfied with amply sufficient accuracy, and (4) becomes irrelevant anyway if either (1) or (2) is not satisfied. So we concentrate on (1-3).

Condition (3): since some of the applications listed in RVS-CoCo-007 (spiral arms kinematics, open clusters) require an accuracy of 0.1-0.2 pixel, ideally condition 3 should be satisfied with an accuracy of 0.01 pixel, i.e. the distance between the last column of one CCD and the first column of the next one should not change more than 0.1 micron over the length of the CCD's. If this cannot be realized technically, the sampling of spectra from different CCD's may exhibit a shift which is independent of the wavelength (if (1) and (2) are satisfied) and which can be eliminated by linear interpolation between successive pixels with coefficients which depend only on the orientation of the CCD's (supposed to be known accurately) and on the position of the spectrum in the Y-direction. This interpolation is unlikely to cause important systematic errors in the RV, but that will nonetheless be verified using simulations with sharp-lined spectra of both high S/N (possibly relevant for RV-standards) and low S/N (where noise-correlation may have some effect).

Condition (2): In principle the linear dispersion of a spectrograph may vary slightly with the direction of incidence and with the wavelength, through the angular dispersion relation (or grating equation) and the optics of the camera. Such a variation may change the size and the central wavelength of the wavelength bin corresponding to a given CCD pixel. Lacking an actual on-board wavelength calibration, this change could probably be described differentially with sufficient accuracy by assigning a small smooth change in position and size (on top of any other shift required) to the pixels from the first and third CCD's, with respect to corresponding pixels from the middle one. The importance of this variation can only be assessed when a detailed design of the spectrograph is known (this information should be available by early September 2003).

If indeed this change is important, again a rebinning will be necessary before summation to avoid degradation of the spectra. In this case the coefficients of interpolation will (in principle) be different for different pixels, but if condition (1) is satisfied they are still constant in time and may be determined from the optical lay-out (and checked experimentally both before commissioning and in-flight). Once the details of the interpolation are known, its effect on RV-accuracy will be studied by simulation. Since, in this case, some amount of degradation will already occur on each CCD separately, the simulations will have to take this into account as well.

Condition (1): If (1) is not satisfied this might require some further (probably very small) and "instantaneous" correction to the pixel boundaries before summation. Whether or not such a correction is necessary will be determined as soon as we have definitive information about the motion of a spectrum across the CCD's.

Error sources which may be reduced or eliminated in the summation: Since we have three independent spectra to start with, the actual "summation" had best be regarded as a weighted average, with weights which equal 1/3 in principle, but which can be adapted instantaneously to give less weight to (or eliminate completely) either of the three contributions. The weights could be adapted for an entire spectrum or for individual pixels therein, as necessity demands. Thus, if e.g. the motion of a spectrum near the upper or lower (in the Y direction) edge of a CCD is not strictly parallel to the lines owing to optical aberrations, so that part of the energy is lost from the spectrum, its weight can be reduced accordingly. Or if a spectrum has passed a known blemish on the CCD (hot/cold pixel, trap, ...) it can be eliminated from the sum. Comparing corresponding pixels from the three spectra should reveal most cosmic-ray events and the affected pixels can be given weight zero.

Agenda: The agenda to prepare for on-board summation of the three spectra could be as follows:

- gather detailed quantitative information about the extent to which conditions 1-5 are satisfied or otherwise;
- depending on the results of the previous step: produce a static map of the last row of CCD #2 on CCD's # 1 and 3, for all relevant wavelengths, showing which fraction of the signal from which pixels should be added to each of the last-row pixels of #2;
- if necessary, produce differential corrections to this map to take account of any variations of the speed with which a spectrum moves across the detectors;
- if necessary because of a serious violation of (2): use simulations to study the effect of single-spectrum degradation on the RV accuracy;
- study the effect of averaging three spectra which were differently sampled and subsequently interpolated linearly to common bins;

Additional notes:
The RVS consortium is working on the definition of the CCD layout. In particular, options to minimise the number of substrates supporting the CCDs are considered (large CCD with regions read independently would guarantee the parallelism of the lines between successive regions).

The interpolation of the spectra prior to summation might become somewhat simpler (TBC: the wavelength calibration could require more information than the estimation of a relative shift between CCD) and more consistent if reliable "instantaneous" on-board wavelength calibration were available. Below is a proposal of how this on-board wavelength calibration could be performed:

- From on-ground optical calibrations, obtain a "master" map relating (position in the FoV, wavelength) to (position on the CCD, wavelength).
- Convert the "master" map into a "reference" map relating (time of detection in the sky mapper, position across scan in the sky mapper, wavelength) to (RVS CCD, time of readout, position across scan on the CCD, wavelength).

- Monitor and correct the "reference" map at regular time-intervals, using RV-standard stars.
- Numerically (perhaps iteratively) inverting the "reference" map for the edges of each pixel which has been read, to derive the boundaries of the wavelength bin corresponding to this pixel.

The implementation of an on-board wavelength calibration will depend on:

- The precision of the centroiding of the on-board source detection (note that for the on-ground wavelength calibration it is foreseen to rely on the astrometric information and not on the sky-mappers data - see Sect. 3.2.4) and the on-board knowledge of the satellite attitude and instrument geometry. The assessment of the on-board detection centroiding precision is in progress in the On-Board Detection WG.
- The processing power available on-board.

3.2.4 Spectroscopic Global Iterative Solution: wavelength calibration

F. Crifo, D. Katz, U. Munari, T. Zwitter

The GAIA instruments, among which the RVS, present several peculiarities with respect to classical ground based instruments: (i) they will observe continuously with (hopefully) no interruption during the 5 years of the mission, (ii) each source will be observed a large number of times, (iii) the number of objects observed will be very large and (iv) the instruments will be extremely stable. For all these reasons, it is thought that the instruments could be iteratively self calibrated. Therefore, it is foreseen to perform the wavelength calibration in the more general context of a "Spectroscopic Global Iterative Solution" (analog of the Astrometric "Global Iterative Solution", Lindegren, 2001a; Lindegren, 2001b).

The principle of the spectroscopic global iterative solution is to use an iteratively self-selected sample of "well-behaving" stars (which are bright enough, which appears "stable" on the successive transits, which are of a spectral type well adapted to the wavelength calibration, which are not significantly contaminated by other sources, ...) to iteratively:

- Derive the radial velocities of the iteratively-self selected sample.
- Calibrate the wavelengths.
- Calibrate the instrument response and geometry.

This procedure will use the astrometric parameters of the stars and the satellite attitude (known from the astrometric global iterative solution) together with the photometric data. Ground calibrations and ground radial velocity standards will help initialising the iterative process. The ground RV standard will be used to accelerate the convergence and will define the radial velocity zero point.

It is foresee to proceed in several steps to assess the precision of the Spectroscopic Global Iterative Solution:

- Evaluate the precision obtained in the calibration of the wavelength with a single "self-selected reference star" as a function of magnitude and spectral type. This issue will be addressed (by F. Crifo) using synthetic spectra together with classical wavelength calibration tools (i.e. IRAF or MIDAS).
- Evaluate the convergence/performances of the wavelength calibration iterative solution. This task will be performed in parallel with the development and implementation of the Spectroscopic Global Iterative Solution in GDAAS.
- In parallel with the studies above, T. Zwitter will investigate whether the sample of self selected reference stars could be complemented by reference asteroids. Observations, in collaboration with U. Munari and D. Hestroffer, are planned on the Asiago telescope to refine the knowledge of the characteristics of the spectra of the different family of asteroids in the RVS wavelength range.

3.2.5 Spectra overlapping

M. Cropper, M. Haywood, D. Katz, U. Munari, F. Royer, Y. Viala, T. Zwitter

The studies of the impact of the crowding (described in Sect. 2) will be carried-on in the form of a double blind test:

- A first team (M. Haywood, D. Katz, Y. Viala) will simulate:
  - One and two dimensional RVS observations for several stellar densities.
  - Data that will be provided by the on-ground calibration and analysis procedures (positions of the sources, magnitudes, atmospheric parameters, reddening) with the appropriate noises.
- Several teams (M. Cropper, U. Munari, F. Royer, T. Zwitter) will perform the analysis of the data.
  - Iterative modelling and subtraction of the background.
  - Iterative derivation of the radial velocities.
- The first team will compare the input and output radial velocities and derive the RVS RV performances.

Agenda:

2003 / 07 / 01	-	2003 / 08 / 31	Development of the 1D crowded spectra simulator.
2003 / 08 / 01	-	2004 / 12 / 31	Analysis of the 1D crowded spectra.
2003 / 09 / 01	-	2003 / 12 / 31	Development of the 2D images simulator.
2004 / 01 / 01	-	2004 / 12 / 31	Analysis of the 2D images.

3.2.6 RV determination algorithm(s)

M. David

The algorithm(s) should not in itself be a source of error, but it may have a significant influence on the effect of many error sources (digitization, noise, spectrum mismatch, etc.). Therefore, this task should actually prepare an optimal choice for the "RV determination algorithm or algorithms". This task could be devided in several steps:

- Define (maybe iteratively) what accuracy and what fraction of successes the algorithm should deliver.
- Define the input data (e.g. a 1-D extracted and wavelength-calibrated object spectrum rebinned to a constant step in log(wavelength) and a single "best matching" template chosen from a library).
- Assuming the Doppler shift will be derived from the cross-correlation function, review the ways the CC-function can be calculated (direct summation or Fourier transform, with or without filtering) and the implications thereof for the kind of data we are dealing with.
- Review the ways the CC-peak can be centroided (e.g. first coarsely, then a refinement by fitting some model to the peak or using a gravity method).
- Perform extensive simulations to see, where necessary, with which choices or options the algorithm best meets the proposed level of accuracy and the proposed success rate (or shows the best performances).
- Devise some diagnostic(s) to indicate whether the measurement has probably failed and use the simulations above to verify that this works in, say, 95% of the cases.
- Implement a formal error model for the resulting RV and use the simulations above to verify it. This error model may involve sources which are systematic in principle but the effect of which depends on parameters that are themselves subject to predominantly random errors (like many cases of modest spectrum mismatch).

References

[1] de Bruijne, J., 2003a, GAIA-JdB-006, ESA report

[2] de Bruijne, J., 2003b, GAIA-JdB-008, ESA report

[3] Cropper, M., 2003, in GAIA Spectroscopy, Science and Technology, U. munari ed., ASP Conf. Ser. 298, 75

[4] David, M., 2001, RVS-MD-001, ESA report

[5] David, M., 2002a, RVS-MD-002, ESA report

[6] David, M., 2002b, RVS-MD-003, ESA report

[7] Lindegren, L., 2001a, GAIA-LL-34, ESA report

[8] Lindegren, L., 2001b, SAG-LL-37, ESA report

[9] Lindegren, L., 2002, GAIA-LL-043, ESA report

[10] Munari, U., Zwitter, T., Katz, D., Cropper, M., 2003, in GAIA Spectroscopy, Science and Technology, U. munari ed., ASP Conf. Ser. 298, 275

[11] Zwitter, T., 2002, A&A, 386, 748

[12] Zwitter, T., 2003, in GAIA Spectroscopy, Science and Technology, U. munari ed., ASP Conf. Ser. 298, 493

A Notes

In the course of the mail discussions, comments were made on some of the error sources. They are reported below:

Note 1: Object mismatch

The RV error due to spectrum mismatch is not necessarily a linear function of the error in the atmospheric parameters. In particular there may be spectral differences which are not quantified by the inevitably limited number of parameters we have to characterise a spectrum. Therefore it is important to use observed RV-standard spectra (on a grid as dense as possible) complementing synthetic spectra to study its influence on the RV accuracy. For the same reason it is hardly possible to make very accurate general predictions about the spectrum mismatch error as a as a function of spectral type, which could be applied to individual cases. This does not invalidate general assessments based on Monte-Carlo simulations (e.g. Zwitter, 2002) which gives a good idea of the first order impact of the mismatch.
In the final scientific analysis of the data, if a high degree of certainty is required, it could be suggested to follow e. g. the procedure below:

- Determine a confidence (hyper-)ellipsoid from the covariance matrix of the atmospheric parameters.
- Select all available templates (from a library of observed and synthetic spectra) which lie within that confidence region.
- Calculate the object's RV with respect to each of them and so obtain a sample of RV values which can then be analysed to obtain a likely value and an estimate of its uncertainty.

In the final analysis procedure, accuracy could be competing with computing time and a trade-off might be necessary.

Note 2: Cosmic rays

The availability of three independent spectra prior to on-board summation provides a good opportunity to detect them and to eliminate their effect.