Radial Velocity Spectrometer

Status report

RVS-CoCo-007
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Abstract: This status report summarises the discussions of the 5th RVS workshop (November 28-29, Paris), which was mainly dedicated to the choice of the spectrograph resolution and number of CCD and to the assessment of the scientific merits and drawbacks of the tilt mechanism. The recommendations of the RVS working group (validated mid-December by the GAIA Science Team) are: resolution R = 11 500, implement a tilt mechanism and 3 CCD. This status report also reviews the new RVS baseline and presents the work breakdown of the RVS preparation for the 2003-2004 period.

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1 Introduction

The RVS working group started its activity mid-2001 with the initial aim of defining/optimising the Radial Velocity Spectrometer characteristics (i.e. spectral resolution, spectral dispersion direction, tilt mechanism, CCD number and size, CCD read-out mode, pixel size, wavelength range) with respect to its scientific objectives and environmental constraints (e.g. antenna power). This first phase (hereafter referred to as the definition phase) lasted 18 months. During this year and a half, studies have been conducted to: (i) define/refine the RVS scientific priorities and specifications, (ii) assess and compare the performances of the different spectrograph configurations, (iii) assess the telemetry budget and define the data compression strategy. Several of the RVS characteristics have been defined or adjusted at intermediate stages of the definition phase: i.e. spectral dispersion direction: along scan, pixel size: $10 \times 15\ \mu m^2$ (see RVS-CoCo-004), CCD read-out mode: whole CCD read (see RVS-CoCo-005), wavelength range: [8480, 8740] A (see RVS-CoCo-006). Concluding this first phase, the 5th RVS workshop (28-29 November – Paris) has been devoted to the choice of the RVS characteristics that remained to be defined (i.e. resolution, tilt mechanism, CCD number and size) and to the definition of the next RVS preparation phase (January 2003 – December 2004) work breakdown.
The review and synthesis of the RVS scientific case, performances and telemetry constraints led the RVS working group to unanimously express the following recommendations:

- Resolution: $R = \lambda / \Delta\lambda = 11\ 500$
- Implementation[1] of a tilt mechanism to compensate the spectra periodic transverse motion, induced by the satellite precession motion.
- Number of CCD: 3 (size: 2020 × 3930 pixels)

Those recommendations have then been fully approved by the Gaia Science Team during the 6th GST meeting (9-10 December – Nice) and adopted as the RVS baseline configuration.

The goal of the present note is threefold: (i) summarise the discussions of the 5th RVS workshop that led to the choice of the resolution, tilt mechanism and number of CCD (Sect. 2), (ii) review the RVS baseline characteristics (Sect. 3) and (ii) present the work breakdown of the next RVS preparation phase: the consolidation phase (Sect. 4).

2 5th RVS workshop summary

The main goal of the 5th RVS workshop was to review the merits and drawbacks of the different configurations of the RVS that have been studied all along the 18 months of the definition phase and to recommend to the GAIA Science Team a single and "optimal" baseline for the spectrograph. The convergence towards a single configuration was driven by the start of several industrial studies (end 2002), which require "frozen" and well defined RVS characteristics to proceed. Three industrial contracts are concerned: the "RVS design optimisation" (optimisation of the RVS optics, mechanics, thermal accommodation, focal plane assembly, proximity

[1] This recommendation will be reviewed from the technical side (technical solutions, mechanical performances, impact on the environment, failure mode) by the RVS consortium, by May 2003.

electronics and Video Processing Units (VPU), conducted by the RVS consortium – see RVS-CoCo-006 and MSSL/GAIA-RVS/AD/002.03 available on Livelink), the "Payload and data-handling electronics" (evaluation and modelling of the electronics required for the on-board data handling) and the "CCD & focal plane assembly demonstrator".
The dispersion orientation, pixel size, CCD read-out mode, wavelength range having already been considered and defined during earlier workshops, the 5th RVS meeting discussions were focused on the spectral resolution on one side, and on the tilt mechanism and the focal plane assembly, on the other side. The two issues are reviewed respectively in Sec. 2.1 and 2.2 below.

The studies conducted over the past 18 months led to define in more details the RVS scientific objectives, priorities and specifications, to assess the first order relative performances of the different configurations proposed for the instrument and to quantify its telemetric flow. All these information were necessary, but not sufficient, to determine the "optimal" configuration of the spectrograph. Therefore, the definition of the RVS characteristics has also been based on preliminary results (e.g. impact of the crowding on the RV performances) and on hypotheses that appear reasonable (e.g. the successive CCD observations may be summed over a transit before sending the composite spectra to the earth).
The second objective of the 5th RVS workshop was to identify the issues that have to be investigated in detail during the next RVS preparation phase, in order to check that all the assumptions, which have led to adopt the new baseline, are valid.
After investigation, one or several of the hypotheses may reveal themselves to be wrong. If this happens, the RVS characteristics will be reconsidered to take into account the new results.
The studies and hypothesis that need to be consolidated are briefly discussed in the paragraphs below and presented in more details in the RVS consolidation phase work breakdown section (Sect. 4).

The third objective of the 5th RVS workshop was to define the work breakdown of the next preparation phase (e.g. consolidation of the choice of the RVS characteristics, implementation of the RVS in GDAAS and in the GAIA simulator). The consolidation phase work breakdown is presented in Sect. 4.

2.1 Choice of the resolution

The recommendation of the RVS working group concerning the resolution is based on two criteria: the adequation of the performances with respect to the scientific objectives (Sect. 2.1.3) and the constraints set by the telemetry (Sect. 2.1.4). The issue of the observation of the "faint" objects (for which less than 1 photon is collected per pixel, per CCD and per transit) was also considered. Yet, the faint stars error budget was in a too early stage of assessment, to be taken into account in the choice of the resolution (Sect. 2.1.5).

2.1.1 Scientific case

The RVS scientific priorities and specifications have been slightly reviewed and updated since the Monte-Rosa 4th RVS workshop to take into account the comments about RVS-CoCo-006, the new developments of the collective work of M. Wilkinson,

A. Vallenari, M. Haywood, A. Helmi, K. Kuijken, A. Robin, H.S. Zhao, J. Kleyna and G. Nelemenans (see RVS-MW-001), on the Galactic structure scientific case and the recommendations expressed by G. Bono concerning the Bulge and the Local Group Galaxies.

2.1.1.1 Scientific priorities

The role and priorities of the RVS instrument have been reviewed step by step: firstly in term of stellar/astrophysical parameters and diagnostics (e.g. radial and rotational velocities, source classification and parameterization), secondly in term of the Galactic populations and stellar topics (e.g. Milky Way disk and halo, stellar structure) and finally by merging the two points of view.

The RVS stellar/astrophysical parameters and diagnostics have been sorted by priority levels (i.e. 2 levels: high or intermediate priority) according to two criteria: (i) their significance for the study of the Milky Way structure, formation and evolution (ii) their complementarities with the astrometric and photometric information.

The first (i.e. high level) priority of the RVS instrument is to provide the radial velocities. Indeed, this information can be determined only by the spectrograph (with the exception of the nearby stars and open clusters for which radial velocities can be derived from the astrometric data) and is crucial: (i) to correct the astrometric observations from the perspective acceleration, (ii) for the kinematical and dynamical study of the Milky-way and (iii) to detect and characterize multiple systems.

The classification (e.g. as star or non-star, normal or peculiar) has been placed as intermediate level priority. The spectra will be quite efficient in spotting and classifying stars with uncommon features (e.g. emission lines, peculiar line intensities or profiles). On the other hand, the astrometric and photometric data (11 medium band and 5 broad band filters) will also provide efficient diagnostics.
The determination of the atmospheric parameters (effective temperature, surface gravity, metallicity) and alpha elements has been classified as intermediate level priority, because the astrometric (absolute magnitudes) and photometric (atmospheric parameters plus one or two alpha elements) data will already give estimate of those parameters. The RVS will nonetheless complement efficiently the other instruments in the parameterization of the stars (in particular in absorbed area of the sky).
The determination of the individual abundances (other than those of the iron and of the alpha elements, which are accessible via the photometry) has been classified as intermediate level priority. This information is very interesting for the study of the chemical history of the Galaxy and can be extracted (by equivalent width measurement) only from the spectroscopic data (provided that the resolution is high enough, see Sect. 2.1.2.3). On the other hand, the measurement of the equivalent width of (weak) lines requires a much higher signal to noise ratio than the derivation of the radial velocities. The detailed chemical analysis of the stars might be performed up to magnitude $V \sim 14$ (TBC): i.e. about 15 millions sources, mainly relatively nearby thin disk stars, are concerned.
The interstellar reddening (accessible via the 8620 A Diffuse Interstellar Band) and the rotational velocities have been classified as intermediate level priorities.

The priority levels of the stellar/astrophysical parameters and diagnostics are summarized below:

High level priorities

- Radial velocities

Intermediate level priorities

- Classification (star, non-star, …)
- Atmospheric parameters
  (Effective temperature, surface gravity, metallicity)
- Alpha elements
- Individual elements abundances
- Interstellar reddening
- Rotational velocities

The Galactic and stellar issues have been sorted out by priority levels (i.e. high, intermediate and low): (i) according to their significance to decipher the structure and origin of the Milky Way and (ii) taking into account the foreseen status of the Galactic structure understanding in ~2017 (~GAIA catalogue release date).
The determination of the perspective acceleration is a high level priority for the RVS, because it is required to obtain accurate and unbiased astrometric parameters for the nearby, high velocity stars.
The thin disk, thick disk and halo have been classified as high level priorities. They are of course key components of the Galaxy and cover large fractions of the sky that are unlikely to be surveyed from the ground up to magnitude 17-18 (expected RVS limiting magnitude) in the next 15 years. The Galactic potential has also been classified as high level priority.
Binary systems, interstellar matter, spiral arms, stellar clusters and stellar structure remain classified as second level (renamed since RVS-CoCo-006 intermediate level) priorities.
The bulge and local group galaxies have been re-examined and remain classified as low level priorities (for the RVS instrument). The study of the bulge is extremely important to understand the formation and evolution of the Milky Way. Yet, the bulge displays a very high stellar density. The RVS observations in its direction will therefore be heavily crowded. The performances of the spectrograph will be significantly degraded in the direction of the bulge. Furthermore, the bulge covers a small surface of the celestial sphere and will intensively be observed, over the next decade, by the ground multi-fiber and integral field spectrographs. The local group galaxies are too faint targets for the RVS instrument.
The RVS Galactic/stellar issues are summarized (sorted by level of priorities) below:

High level priorities

- Perspective acceleration
- Thick disk
- Halo
- Thin disk
- Gravitational potential

Intermediate level priorities

- Binary systems
- Interstellar matter
- Spiral arms
- Stellar clusters
- Stellar structure

Low level priorities

- Bulge
- Local group dynamics

The two approaches, stellar/astrophysical parameters on one side and Galactic/stellar issues on the other one, have been merged into a single list of objectives divided in three levels of priority:

High level priorities

- Perspective acceleration
- Thick disk kinematics
- Halo kinematics
- Gravitational potential
- Thin disk kinematics

Intermediate level priorities

- Thick disk chemistry
- Halo chemistry
- Binarity detection/characterisation
- Classification (star, non-star, …)
- Reddening map
- Thin disk chemistry
- Spiral arms kinematics
- Stellar clusters
- Stellar structure (rotation, variability, …)

Low level priorities

- Bulge kinematics
- Bulge chemistry
- Local group dynamics

2.1.1.2 Scientific specifications

The scientific specifications are globally unchanged since RVS-CoCo-006 and are recalled below:

High level priorities

- Perspective acceleration : $\sigma Vr = 10$ km/s at V = 17
- Thick disk kinematics : $\sigma Vr = 15$ km/s at $V \geq 17.5$
- Halo kinematics : $\sigma Vr = 15\text{-}20$ km/s at $V \geq 17.5$
- Gravitational potential : $\sigma Vr = 5\text{-}10$ km/s down to $|b|\sim10$ deg.
- Thin disk kinematics : $\sigma Vr = 2\text{-}4$ km/s at $V \geq 16$

Intermediate level priorities

- Thick disk chemistry : $\sigma[Fe/H] = 0.1$ dex, $\sigma[\alpha/Fe] = 0.1$ dex
- Halo chemistry : $\sigma[Fe/H] = 0.1$ dex, $\sigma[\alpha/Fe] = 0.1$ dex
- Binarity detection/characterisation : R > 10 000
- Classification : TBD
- Reddening map : $\sigma EW = 35$ mA (eq. $\sigma E(B-V) = 0.1$)
- Thin disk chemistry : $\sigma[Fe/H] = 0.1$ dex, $\sigma[\alpha/Fe] = 0.1$ dex
- Spiral arms kinematics : $\sigma Vr = 1\text{-}2$ km/s at $V \geq 15$

- Stellar clusters : σVr = 1-3 km/s per transit at V ≥ 14
- Stellar structure : R = 10 000 to 20 000

Low level priorities

- Bulge kinematics : σVr = 10-20 km/s at V ≥ 17
- Bulge chemistry : TBD
- Local group dynamic : TBD

2.1.2 Performances

The RVS performances, in term of S/N ratios (Sect. 2.1.2.1) and radial velocities (Sect. 2.1.2.2), have been re-calculated with the post-4th RVS workshop spectrograph characteristics: wavelength range [8480, 8740] A, 6 CCD, 99 seconds integration time per transit, 35% overall efficiency of the spectrograph, 2 pixels wide spectra, 4 e- read-out noise per pixel, zodiacal light surface brightness V=22.5 magnitude per arcsec^2. Four resolutions have been considered: R = 5 000, 10 000, 15 000 and 20 000.

The spectrograph performances in the evaluation of the atmospheric parameters as well as the requirements associated with the determination of the detailed chemical composition are reviewed in Sect. 2.1.2.3.

2.1.2.1 Signal to noise ratios

Table 1 presents the signal to noise ratios (as a function of magnitude and resolution) calculated for a solar metallicity K1V type star (Teff=5000, logg=4.5, [Fe/H]=0.0).

Table 1: Signal to noise ratios as a function of magnitude and resolution derived for a single transit (99 s exposure time) and at the end of the mission (100 transits).

	Single transit				Mission (100 transits)			
V	R=5000	R=10000	R=15000	R=20000	R=5000	R=10000	R=15000	R=20000
10	78	54	44	37	783	544	436	372
11	48	33	26	21	481	326	256	214
12	29	18	14	11	285	185	140	114
13	16	10	7	5	158	96	69	54
14	8	4	3	2	80	45	31	24
15	4	2	1	1	36	19	13	10
16	2	1	1		16	8	5	4
17	1				6	3	2	2
18					3	1	1	1

2.1.2.2 Radial velocities

Table 2 and Table 3 present the radial velocity precisions obtained for a single transit and at the end of the mission respectively, for an isolated (not contaminated by neighbouring sources) solar metallicity K1V type star. Table 4 summarizes the "limiting magnitudes" (chosen as the magnitudes corresponding to a radial velocity precision of 15 km/s) derived for the 4 different resolutions.
At the "bright" and "intermediate" magnitudes the RV precisions increase with the resolution (e.g. at V = 16, the radial velocities are about 70% more accurate at

R = 20 000 than at R = 5 000). At the faint end, configurations with R = 5 000 to 15 000 lead to equivalent "limiting magnitudes", about 0.25 magnitude fainter than the R = 20 000 configuration.

The performances presented in Table 2, 3 and 4 have been derived from simple Monte-Carlo simulations, relying on the cross-correlation of a synthetic object with a synthetic template. The simulations take into account the sampling, photon, zodiacal and read-out noises. They were appropriate to establish the relative performances of the different spectrograph configurations (in particular the different resolutions) and to assess the first order precision of the instrument. One of the main objectives of the consolidation phase is to assess the full RVS accuracy budget (see Sect. 4.2): i.e. identify the sources of error that will affect the RVS data, quantify their impacts on the instrument performances and derive/refine the instrument overall precision as a function of magnitude and source type.

Table 2: Radial velocity precisions (single transit) as a function of magnitude and resolution.

V	σVr (km/s) R = 5 000	σVr (km/s) R = 10 000	σVr (km/s) R = 15 000	σVr (km/s) R = 20 000
13	2.4	1.4	1.2	1.0
14	4.9	3.5	2.6	2.1
15	11.7	8.2	7.7	7.2
15.5	18.0	19.1	37.5	>40.0

Table 3: Radial velocity precisions (whole mission = 100 transits) as a function of magnitude and resolution.

	σVr (km/s) R = 5 000	σVr (km/s) R = 10 000	σVr (km/s) R = 15 000	σVr (km/s) R = 20 000
16	2.4	1.8	1.5	1.4
17	5.9	4.9	3.9	3.5
17.5	9.6	7.9	7.2	7.5
18	16.3	16.3	29.7	58.2

Table 4: Limiting magnitude as a function of resolution.

	R = 5 000	R = 10 000	R = 15 000	R = 20 000
V (σVr=15 km/s)	17.95	17.95	17.90	17.70

The RVS instrument is an integral field spectrograph, implying that in dense area the spectra of neighbouring sources will overlap. The study performed by T. Zwitter (see the Monte-Rosa conference proceedings) predict that with a proper reconstruction (using the information provided by the astrometric and photometric instruments) and subtraction of the "background" sources, it will be possible to recover the radial velocity information will little degradation up to 20 000 stars/degrees^2 at V = 17 (equivalent to ~160 000 stars/degrees^2 at V = 20). Eighty five percents of the Galactic disk (defined as the area located between plus and minus 30 degrees of Galactic latitude) display a density lower or equal to 20 000 stars/degrees^2 at F = 17 (from star count performed with the GSC-II 2.2 catalogue) and therefore would be accessible to the RVS. The complexity of the modelling of the "background" increases with the resolution. At R = 5 000 and 20 000 stars/degrees^2 (at F = 17), the surface of a spectrum contains on average 2.5 stars of magnitude $F \leq 18$, while at R = 20 000 it contains 10 stars.

The Galactic thin and thick disks are key targets for the spectrograph. Therefore, the assessment/refinement of the performances of the RVS as a function of the stellar density of the observed field of view is one of the priorities of the consolidation phase (see Sect. 4.3).

2.1.2.3 Atmospheric parameters and chemical composition

C. Soubiran (RVS-CS-001) has used the "low" resolution (R = 5500) 706 observed spectra of Cenarro et al. 2001 (MNRAS, 326, 959 and MNRAS, 326, 981), to evaluate the performances of the "minimum distance methods" (MDM), applied to the RVS data, to determine the atmospheric parameters (effective temperature, surface gravity and metallicity). The principle of MDM is to compare (in the least square sense) an object spectrum to a library of standard spectra of known parameters, looking for the most similar ones. The parameters of the object are obtained by averaging those of its "twin" standard. The 706 stars were matched, one by one, against the 705 other "reference" spectra. Their parameters were recovered with precisions of: σTeff = 207 K, σlog g = 0.34 , σ[Fe/H] = 0.18 dex (not adding noises to the object spectra) and σTeff = 275 K, σlog g = 0.36 , σ[Fe/H] = 0.22 dex (degrading the object spectra to S/N = 20).

The RVS wavelength range contains spectral lines of several chemical elements (e.g. Mg, Ti, Si). Those transitions could be used to derive individual abundances, provided that the spectrograph resolution is "high enough": i.e. the lines are neither diluted in the spectral continuum, nor too blended with other lines. F. Thevenin et al. have studied the evolution of the contrast between lines and continuum as well as the separation between the lines, as a function of spectral resolution (see RVS-CoCo-005 and the Monte-Rosa conference proceedings). They concluded that a detailed chemical analysis, based on the measurement of the equivalent widths of the "weak" lines contained in the RVS spectral range, required a spectral resolution of R = 11 000 or more.

2.1.3 Scientific case versus resolution

The RVS scientific specifications have been confronted to the instrument performances, in order to establish, for each of the scientific objectives: (i) the range of spectral resolution "compatible" with its study and (ii) the resolution the best adapted to its study. "Compatible" intervals (Col. 2) and "optimal" resolutions (Col. 3) are summarized in Table 5.

The determination of the perspective acceleration, the studies of the Galactic disk kinematics and of the gravitational potential present similar requirements. They aim to probe the largest possible volume and rely (in part or in totality) on observations of dense areas. The resolution R = 10 000 appears the best adapted to fulfil those specifications. It provides the same limiting magnitude as the R = 5 000 and 15 000 resolutions (0.25 magnitude fainter than R = 20 000) and generates a lower spectra overlapping rate in dense area than R = 15 000 and 20 000 resolutions. It has been

preferred to the resolution R = 5 000, because of its better performances in the determination of the radial velocities of the “bright” and “intermediate” stars.
The main requirement of the study of the Galactic Halo kinematics is to observe stars as faint as possible. This motivated the adoption of R = 10 000 to 15 000 as the “optimal range” of resolution, because it displays the better performances in term of RV limiting magnitude: i.e. 0.25 magnitude fainter than R = 20 000.

The resolution R = 12 500 has been considered as the best trade-off between the maximisation of the information contained in the spectra and the minimisation of the field of view crowding and therefore the best adapted to study the chemistry of the thin and thick disks. The Halo being little concerned (only in the directions located behind the disk) by the issue of the crowding, the resolution R = 15 000 has been adopted as “optimal” to investigate its chemistry. It was preferred to R = 20 000, because of its better performances in terms of S/N ratio.
The resolution R = 15 000 appeared to be the most appropriate for the study of the kinematics of the spiral arms, which requires to derive the radial velocities of “intermediate” brightness ($V \geq 15$) tracers, located in dense regions, with a precision of 1 or 2 km/s.
The detection of binary stars requires a good separation of the lines in SB2 systems and an accurate determination of the epoch radial velocity in SB1 systems, thus advocating for a high RVS resolution. Yet, the double stars should be identified in low as well as in dense regions. The resolution R = 15 000 was chosen as the one offering the best balance between the two specifications.
The main requirement for the characterisation of binary systems as well as for the study of the stellar structure is to obtain spectral information as detailed as possible. As a consequence, the resolution R = 20 000 appeared the best adapted to investigate those issues.

Because of its very high surface density, the RVS observations of the Bulge will be heavily crowded. This was the main driver of the choice of the “optimal” resolutions for its study: R = 5 000 to 10 000 for the kinematics and R = 11 000 for the chemistry.

Table 5:”Compatible” resolution intervals (Col. 2) and “optimal” resolutions (Col. 3) for the study of the RVS scientific objectives.

High level priorities		
Perspective acceleration	[5 000 – 20 000]	10 000
Thick disk kinematics	[5 000 – 20 000]	10 000
Halo kinematics	[5 000 – 20 000]	10 000 – 15 000
Gravitational potential	[5 000 – 20 000]	10 000
Thin disk kinematics	[5 000 – 20 000]	10 000
Intermediate level priorities		
Thick disk chemistry	[11 000 – 20 000]	12 500
Halo chemistry	[11 000 – 20 000]	15 000
Binarity detection	[10 000 – 20 000]	15 000
Binarity characterisation	[10 000 – 20 000]	20 000
Classification	[5 000 – 20 000]	TBD
Reddening map	[10 000 – 20 000]	TBD
Thin disk chemistry	[11 000 – 20 000]	12 500
Spiral arms kinematics	[5 000 – 20 000]	15 000

Stellar clusters	TBD	TBD
Stellar structure	[10 000 – 20 000]	20 000
Low level priorities		
Bulge kinematics	[5 000 – 20 000]	5 000 – 10 000
Bulge chemistry	[11 000 – 20 000]	11 000
Local group dynamic	[5 000 – 20 000]	TBD

2.1.4 Selection & compression strategy vs. telemetry budget

The RVS raw data flow will largely exceed the satellite antenna power and the 0.25 Mbit/s allocated to the RVS instrument. Therefore, it will be necessary to select the "relevant" data and pre-process/compress on-board the spectra before transmitting them to the Earth. Four stages are foreseen:

- Extract numerically the central row or the two central rows of the spectra (according to its position with respect to the CCD lines) and discard the outer rows which are only illuminated by some few percents of the total flux.
- Sum the 2 to 6 (according to the number of CCD filling the RVS focal plane) successive observations of the same object in order to transmit a single spectra per object and per transit.
- For stars fainter than V = 16: extract numerically and transmit only 2 intervals (e.g. [8480, 8568] and [8642, 8689] A, about half of the RVS wavelength range) containing the 3 Calcium lines, which are assumed to concentrate most of the relevant information in faint/noisy stars.
- Apply "classical" numerical compression algorithm(s).

Y. Viala and D. Morin have used the GSC-II 2.2 catalogue to simulate the RVS telemetry stream, taking into account the above pre-processing/compression scenario and assuming an RVS limiting magnitude F = 18 (F is the GSC-II 2.2 red photographic filter). According to the stellar density of the fields scanned by the spectrograph (it could happens that the RVS instrument scan the Galactic plane for several days on a row), the compressed telemetry flow may exceed the antenna power and saturate the on-board storage capacity (~173 Gbits to be divided between the astro/photo/spectro instruments), resulting in data loss. Table 6 presents the fraction of the observations (up to magnitude F = 18) that could be transmitted to the ground as a function of resolution: from 90% at R = 5 000 to 54% at R = 20 000.

Table 6: Fraction of the RVS observation up to magnitude F = 18, that could be transmitted to the Earth, as a function of resolution.

	R = 5 000	R = 10 000	R = 15 000	R = 20 000
Percentage of data transmitted	90%	75%	61%	54%

The selection/pre-processing/compression strategy presented above should be simulated, tested and validated during the consolidation phase. In particular, the impact on the performances of the instrument, of the summation of CCD and of the extraction of the Calcium lines regions, should be assessed.

2.1.5 Observation of the "faint" stars

The signal recorded during a single transit of a V~16 or fainter star is too weak to be used to derive its radial velocity. Yet, each source will be observed on average 100 times (times the number of CCD in the focal plane). It is planned to sum the several hundred individual observations[2], in order to reach a signal to noise ratio high enough to extract the radial velocity. This approach will work only if no uncalibrated systematic error dominates the stellar signal (which is very weak) at each observation. Otherwise, the signal to noise ratio will not increase with the number of observations.
Table 7 presents the average number of photo-electrons collected per transit of a V = 17 K1V type star, per CCD and per pixel (assuming 2 pixels wide spectra) as a function of resolution: it varies from 0.89 at R = 5 000 to 0.22 at R = 20 000. In all cases the mean flux collected is very weak (smaller than 1 photo-electron). This emphasizes the importance of the problem, since even very small errors may have a significant impact on the instrument performances. The identification and quantification of the errors which may affect the determination of the radial velocities of the faint stars (and the assessment of the RV accuracy budget in general) are key objectives of the consolidation phase (Sect. 4.2). Yet, the faint stars error budget was in a too early definition/quantification stage to be considered when choosing the resolution. If it appears, during the course of the accuracy budget assessment, that there are errors depending upon the resolution, that affect significantly the RVS performances, the RVS resolution will be reconsidered.

Table 7: Spectral sampling, spectrum area (assuming a 2 pixels spectrum width) and number of photo-electrons collected per pixel during one CCD crossing (for a V = 17 K1V star and assuming 16.5 s per CCD crossing) as a function of resolution.

	R = 5 000	R = 10 000	R = 15 000	R = 20 000
Sampling (A/pixel)	0.84	0.42	0.28	0.21
Spec. area (pixel)	620	1240	1858	2478
Photo-electrons/pixel	0.89	0.44	0.30	0.22

2.1.6 Synthesis and choice of the resolution

Most of the RVS high level scientific priorities will be "optimally" addressed with the resolution R = 10 000. The intermediate level priorities favour higher resolutions: from R = 12 500 (thin and thick disks chemistry) to R = 20 000 (binary systems characterization, stellar structure study). Furthermore about 2/3 of them can not be addressed with resolutions lower than 10 000/11 000. From the telemetry point of view (with the current compression scenario), the resolution R = 10 000 allows to transmit about 75% of the data collected up to magnitude F = 18 (or equivalently all observations up to magnitude F ~ 17.6). With the resolutions R = 15 000 and 20 000 this percentage decrease to 61% and 54% respectively.
Taking all above considerations into account, the RVS working group has unanimously recommended to adopt a resolution in the interval R = 11 000/12 000. It is close to the high level priorities "optimal" resolution, it allows to address all the

[2] U. Munari has proposed that in high density regions, the radial velocities be derived by multi-dimensional fitting of whole area of the celestial sphere. In this approach, the successive observations of a given object are not summed in the way described above. Yet, the "global" information collected on successive transits are combined and the general problematic of the derivation of the radial velocities of the "faint" stars (as discussed above) remains valid.

intermediate level priority topics and it generates a data stream compatible with the transmission of all the data up to F ~ 17.5 (or a partial transmission to fainter magnitude).
The Astrium optical architecture was designed for the resolution R = 11 500. This resolution is in perfect agreement with the range of resolutions recommended. Therefore, the RVS working group has proposed to the GAIA Science Team to adopt it as the baseline RVS resolution. This proposal was approved by the GST during its 6th meeting (9 – 10 December – Nice).

2.2 Tilt mechanism and number of CCD

The precession motion of the satellite spin axis around the Sun/Earth direction induces a sine transverse motion of the spectra with respect to the CCD. The spectra are periodically widened, with the consequences of a decrease of the signal to noise ratio and of an increase of the spectra overlapping in dense areas.
A solution, to reduce the impact of the transverse motion, consists in dividing the focal plane with several CCD. The shorter is the exposure time (per CCD), the smaller is the spectra blurring (per CCD). On the other hand, the total contribution of the read-out noise increases with the square root of the number of CCD and the telemetry stream increases linearly with the number of CCD.
Another solution to the transverse motion problem is to implement a mechanism, which aligns the CCD lines with the motion of the stars (either by rotating the CCD plane or the grism or the field of view). A mechanism would cancel the across scan blurring of the spectra, and therefore improve the signal to noise ratio and reduce the spectra overlapping rate. In addition, with a mechanism, it would no longer be necessary/mandatory to divide the transverse motion with a large number of CCD. Nonetheless, configurations having both a tilt mechanism and "many" CCD, will present the advantage to be less affected by the failure of a CCD or of the tilt mechanism, than the configurations with a tilt mechanism and few CCD.

Ten configurations, with or without a tilt mechanism and having from 2 to 6 CCD, have been compared. Five criteria have been used to quantify their respective merits and drawbacks. A simple model of Gaussian PSF (FWHM = 15 μm), convolved by the appropriate transverse motion (averaged over the time), has been used to derive for each configuration: (i) its limiting magnitude (assuming that the 2 central rows will be extracted and transmitted to the Earth for each spectrum), (ii) the average number of photo-electron collected per pixel and per CCD on the spectra central row, (iii) the telemetry stream, (iv) the average width of the spectra (chosen as the width containing 95% or more of the energy) and (v) the average percentages of energy that fall outside the two central rows. The respective performances of the 10 configurations are listed in Table 8. Limiting magnitudes, numbers of photo-electrons on the central row and telemetry streams are expressed with respect to the configuration without tilt mechanism and 6 CCD.

The 5 configurations without tilt mechanism exhibit similar limiting magnitudes (as the number of CCD decreases, the energy lost because of the widening of the PSF is compensated by the reduction of the total read-out noise) and similar numbers of photo-electrons per pixel and per CCD (the energy lost in the wings of the PSF is compensated by the longer integration time). The telemetry stream decreases with the

number of CCD, but the spectra width and the percentage of energy collected outside of the two central rows increase very significantly between 6 and 2 CCD.
The limiting magnitudes, the numbers of photo-electrons per pixel on the spectra central row and the telemetry streams, of the configurations with tilt mechanism, improve with the number of CCD, while the spectra average widths and the percentages of energy falling outside of the two central rows remain constant.

Comparing the performances of the 10 configurations, the RVS members recommended (from the scientific point of view) the adoption of the configuration with tilt mechanism and 3 CCD, as baseline. This configuration brings significant improvement in term of limiting magnitudes, number of photo-electrons and crowding of the field of view with respect to the configurations without tilt mechanism as well as with respect to the configurations with tilt mechanism and only 6 or 5 CCD. It also exhibits "good" performances in term of telemetry stream. This configuration has been preferred to the one with tilt mechanism and 2 CCD (which exhibit better performances), because it would be less affected by a possible failure of one of the CCD. The recommendation of the RVS working group was approved by the GAIA Science Team during the 6^{th} GST meeting.

Table 8: Limiting magnitudes (Col. 3), numbers of photo-electrons on the central row (Col. 4) and telemetry streams (Col .5) of the 10 considered configurations, expressed with respect to the configuration without tilt mechanism and 6 CCD. Col. 6 and 7 lists respectively the spectra average widths and the average percentages of energy collected outside of the 2 central rows.

Tilt	CCD	Limiting magnitude	Photo-electrons /pixel/CCD	Telemetry Stream	Spectra <width> (pixels)	<Energy> outside 2 central rows
No	6	+0.00	×1	×1	3	12%
No	5	+0.05	×1.1	×5/6	3	15%
No	4	+0.10	×1.1	×2/3	3	19%
No	3	+0.10	×1.2	×1/2	4	28%
No	2	-0.05	×1.2	×1/3	5	42%
Yes	6	+0.10	×1.3	×1	2	5%
Yes	5	+0.15	×1.5	×5/6	2	5%
Yes	4	+0.25	×1.9	×2/3	2	5%
Yes	**3**	**+0.35**	**×2.6**	**×1/2**	**2**	**5%**
Yes	2	+0.50	×3.8	×1/3	2	5%

Studies in progress in the RVS consortium

The technical performances, the failure risk and the failure mode of the tilt mechanism are currently assessed by the RVS consortium. The consortium is also investigating the feasibility, merits and drawbacks of other technologies: i.e. the "Low Light Level CCD" (L3CCD) and the 2D clocking CCD.
As discussed above, an alternative to the tilt mechanism consists in splitting the FoV, and therefore the across scan blurring of the spectra, by a large number of CCD. With "classical" CCD, this approach presents two drawbacks: (i) it increases the total RoN integrated over the transit and (ii) it increases the raw telemetry rate. The use of Low Light Level CCD, which display very small RoN, would cancel the first disadvantage. Several studies are and will be conducted to assess the technical case of the L3CCD in the context of the RVS: e.g. radiation testing, assessment of the possible impact on the

saturation limits, minimisation of the total width of the dead-zones, estimation of the impact of the summation of the successive observations on the required processing power and on the instrument performances.
The 2D clocking CCD are detectors in which the charges can be transferred in both dimensions. A. Holland has proposed to use this technology to propagate the electrons in a parallel direction to the star motion (without mechanically rotating the CCD). The study of the 2D clocking CCD characteristics and performances is in progress.
The RVS consortium will express a recommendation about the most appropriate approach/technology to solve the transverse motion problem by May 2003.

3 RVS instrument baseline

This section presents the characteristics, the processing and calibration strategies and the performances of the new Radial Velocity Spectrometer baseline.

3.1 RVS characteristics

3.1.1 Overview

Tables below summarize the satellite and mission (Table 9a), optics (Table 9b), sky-mappers (Table 9c) and detectors (Table 9d) characteristics.

Table 9a: GAIA satellite and mission characteristics.

General characteristics	
Mission duration	5 years
Satellite spin rate	60 arcsec/s
Mean Number of transits	100

Table 9b: Characteristics of the RVS optical design and status of the tilt mechanism

Optics & mechanism	
Entrance pupil	0.5 × 0.5 m^2
Focal length	2.1 m
Angular to linear scale	1 arcsec = 10.18 µm
Resolution	11 500
Sampling	0.375 A/pixel
Spectrum length	694 pixels
Spectrum width (downloaded)	1 or 2 pixels
Dispersion	Along scan
Wavelength range	[8480, 8740] A
Total field of view (incl. dead-zones)	74 × 58.95 mm^2
Total field of view (incl. dead-zones)	2.02 × 1.61 deg^2
Total transit time (incl. dead-zones)	121.2 s
Tilt mechanism	Yes
Total efficiency	35 %

Table 9c: Characteristics of the RVS sky mappers.

Sky mappers (RVSM)	
Number	6 out of 8 are used by the RVS
Tasks	Detection/confirmation/photometry
Incident light	Undispersed light
Size (/CCD)	3.36×58.95 mm^2
Size (/CCD)	336×3930 pixels
Size (/CCD)	0.09×1.61 deg^2
Exposure time (/CCD)	5.5 s
Pixel size	10×15 µm^2
Pixel size	0.98×1.47 arcsec^2
RON	4.6 e-
Dark current	TBD
Saturation	140 000 (e-/pixel)
Gain	TBD
Operating mode	Time Delay Integration (TDI)
Number of phases /pixel	TBD
Read-out mode	Whole CCD read

Table 9d: Characteristics of the RVS detectors.

Detectors	
Number	3
Task	Record spectra
Incident light	Dispersed light
Size (/CCD)	20.2×58.95 mm^2
Size (/CCD)	2020×3930 pixels
Size (/CCD)	0.55×1.61 deg^2
Dead-zones (left and right edge)	3.5 mm
Dead-zones (between CCD)	3.2 mm
Exposure time (/CCD)	33.1 s
Pixel size	10×15 µm^2
Pixel size	0.98×1.47 arcsec^2
RON (/pixel)	4 e-
Dark current	TBD
Saturation	140 000 (e-/pixel)
Gain	1 ADU = 1 e-
Operating mode	Time Delay Integration (TDI)
Number of phases /pixel	4
Read-out mode	Whole CCD read

3.1.2 Optics and filters

The spectrograph is illuminated by a system of 3 off-axis mirrors. The telescope entrance pupil is 0.5×0.5 m^2. The telescope and the spectrograph have both a focal length of 2.1 m.

Two coatings are currently considered for the mirrors: Silver and Aluminium. The Silver coating has a reflective index of ~95% in the RVS wavelength range (leading to an overall reflective index of the 3 off-axis mirror system of ~86%), while the reflective index of the Aluminium coating is ~87% (~66% for the whole telescope). The drawback of the Silver coating is that its reflective index decreases very quickly below ~355 nm (e.g. reflective index: 83% at 380 nm, 76% at 355 nm, 34% at 330 nm and 17% at 300 nm), while the Aluminium reflective index is larger than 90% in the UV. This is a matter of concern for the photometric instrument who shares the 3 off-axis mirrors system with the RVS. Its performances would be significantly degraded without the UV bands located below 355 nm. Therefore, the use of Aluminium coating was strongly recommended during the 6th GST meeting. Yet, before a decision is taken, the RVS overall efficiency will be reassessed with the two options. The issue will be re-examined during the 7th GST meeting (March 12-13 2003).

3.1.3 Focal plane assembly

Photometric instrument and spectrometer focal planes

The sky-mappers, medium band photometric detectors and spectroscopic detectors share the same telescope but are not physically located in same plane. The sky-mappers and the photometric CCD are located at the telescope focal plane, while the RVS CCD are located at the spectrograph focal plane. Nonetheless, as Figure 1 shows, projected on the sky, the RVS detectors are preceded by the sky-mappers and are located across-scan between the two sets of medium band photometric CCD.

Radial Velocity Sky-Mappers

The Radial Velocity Sky-Mappers (RVSM) module is identical to the "red enhanced" medium band photometer chips and supports 8 CCD. The current definition of the role of the RVSM derived from a proposal made by members of the On-board detection, Photometric and RVS working groups (see GAIA-CUO-117). This proposal is fully open to discussion and will be revised according to the output of the relevant consolidation phase studies (e.g. characterisation/optimisation of the optical design, calibration of the background, assessment of the impact of the FoV crowding on the performances).

In the current scenario, the RVSM perform the following tasks:

- Detect / confirm / derive the positions of (i) the sources that the RVS should observe and (ii) of the fainter objects that contaminates the spectra. The positions and white light magnitudes (computed on-board to avoid transmitting a large stream of pixels) of all the detected sources up to G = 20 are send to the Earth. They complement the astrometric map by data measured at the same epoch as the RVS spectra. Three CCD (the first one without filter, the two others respectively coated with grey and red filters – see below) are devoted to the detection process. Each one is adapted (i.e. the source is neither saturated, nor too weak) to a different range of magnitude. The whole information provided by the 3 CCD will be combined (with the appropriate weight) to establish the "list" of detected sources. For the same reason, the confirmation is performed by 2 (or 3) CCD (one without filter and the other coated with a red filter).

- Derive the "RVS magnitudes" (over the band-pass [8480-8740] A) of all the detected sources and sample the surface brightness of the background (deriving the average surface brightness of the sky over areas of 32 × 32 pixels – see Sect. 3.3.3). Once again, only the magnitudes, and not the raw data, are transmitted. One of the aims of downloading those magnitudes is to help separating the stacked spectra (and the contribution of the background), in particular in crowded fields.

- Detect /confirm / follow Near Earth Objects (NEO).

The roles of the RVSM are distributed as follows:
The RVSM 1 and 2 are used to detect, confirm and derive the projected trajectory of Near Earth Objects (NEO). It is likely that RVSM 1 and 2 will be significantly vignetted and affected by optical distortions. Therefore, it is not foreseen to use them for the detection/confirmation of the RVS targets. This issue will be re-examined as soon as the optical performances of the telescope will be known.
RVSM 3 is dedicated to the detection of the sources. It is screened with a semi-transparent density in order to attenuate the source brightness and is well adapted to the magnitude range: (about) $4 \leq V \leq 10$.
RVSM 4 is also used to detect the sources. It exploits the whole range of sensibility of the CCD (no filter or optical density) and is most efficient over the magnitude range: $14 \leq V \leq 20$. RVSM 5 is a redundant CCD. In normal operating mode, it participates to the confirmation of the detections and to the rejection of the cosmic rays. It can replace either RVSM 4 or RVSM 8 in case of failure of one of the 2 CCD.
RVSM 6 and 7 are coated with the same filters as the spectrograph. They are respectively used to detect and confirm the presence of the sources (with an "optimal" efficiency over the range of magnitude: $10 \leq V \leq 14$). They also provide the magnitudes (over the RVS band-pass [8480-8740] A) of all detected sources up to magnitude G~20 and they sample the background surface brightness.
RVSM 8 is not coated with filters and participates to the confirmation process ("efficiency interval": $14 \leq V \leq 20$).
RVSM 4 and 8 are also used for NEO follow-up. The roles of the 8 RVSM are summarized in Table 10.

Note: According to their coating, the 6 CCD performing the detection/confirmation are optimized for different ranges of magnitude. Nonetheless, they will provide detection and confirmation diagnostics for saturated as well as for under-illuminated objects (all the diagnostics will be weighted according to their reliability and combined - see Sect. 3.2.1). In particular, the confirmation of the presence of the brightest sources will be based only on saturated data (in the scenario described here, it is not foreseen to coat one of the confirmation CCD with an attenuation filter).

Table 10: Coatings and roles of the Radial Velocity Sky-Mappers (RVSM).The ranges of magnitude indicate the intervals where the CCD are the most efficient.

CCD	Filters	Detection	Confirmation	Other role
#1	None	NEO		
#2	None		NEO	
#3	Grey filter: attenuation	RVS: $4 \leq V \leq 10$		
#4	None	RVS: $14 \leq V \leq 20$		NEO follow-up
#5	None		RVS: $14 \leq V \leq 20$	redundancy #4 or #8
#6	[8480 – 8740]	RVS: $10 \leq V \leq 14$		source/sky photometry
#7	[8480 – 8740]		RVS: $10 \leq V \leq 14$	source/sky photometry
#8	None		RVS: $14 \leq V \leq 20$	NEO follow-up

Detectors Layout

The spectrograph disperses the light along the scan direction. Therefore, if the edge of the first CCD coincides with the edge of the FoV (defined as the surface on the sky, whose light is dispersed), the first pixels of the first CCD are never illuminated by the "redder" wavelengths. This causes a difference of exposure time, over the crossing of the first CCD, between the red edge of a spectrum (27.9 s) and its central wavelength (33.7s). A similar situation happens when a source exits the FoV/third CCD: 27.9 s exposure time at the spectrum "blue" edge and 33.7 s at 8610 A. An exposure time constant at all wavelengths (over the first and third CCD crossings) requires gaps of half a spectrum length (3.47 mm) between the edges of the FoV and of the first and third CCD. The merits and drawbacks of an exposure time dependant, or not, upon the wavelength remain to assess. To be conservative, the option with two 3.5 mm gaps, located at each extremity of the FoV has been adopted as the current baseline. The question will be re-examined at the next RVS workshop (June 2003).

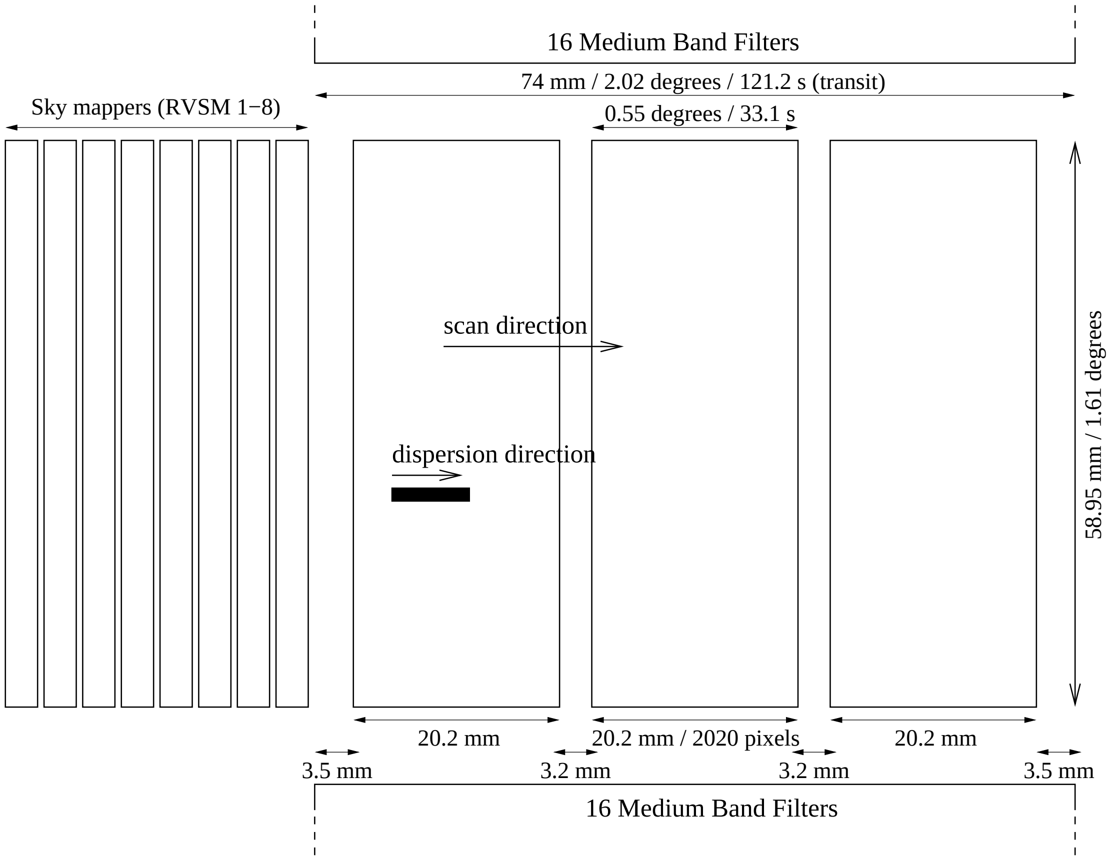

Fig 1: Sky-mappers/photometric and spectroscopic focal planes projected on the sky.

The CCD detectors are separated by dead-zones (linked to the CCD assembly process). The current baseline assumes gaps of 3.2 mm (considered as representative of the separation between 2 CCD). The "exact" width of the gaps will be provided by the RVS consortium during the optimisation of the spectrograph design. The size of the CCD will evolve in parallel with the size of the gaps.

3.1.4 Spectrum

Fig. 2 shows the synthetic spectrum (computed with the VALD atomic data and the V. Piskunov SYNTHE program) of a solar type star. It illustrates the level of spectral details contained in an RVS (R = 11 500) spectra.

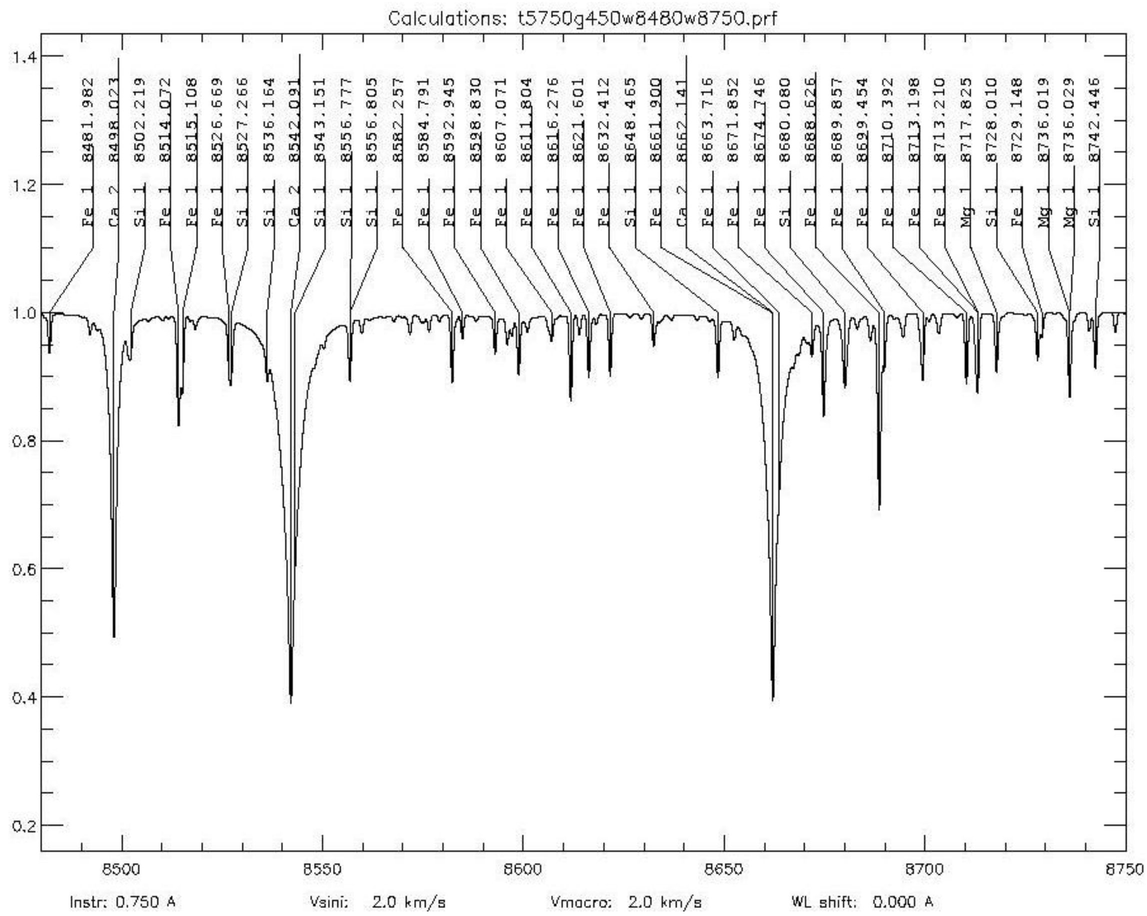

Fig. 2: Synthetic spectrum of a solar type star.

3.2 On-board processing

The RVS on-board processing could be divided in two groups:

- Detection of the sources and selection of the pixels containing relevant information, which will be transmitted to the ground (Sect. 3.2.1).
- Pre-processing and compression of the data, in order to fit in the 0.25 Mbit/s allocated to the transmission of the RVS spectra (Sect. 3.2.2).

3.2.1 Source detection, confirmation & selection

The RVS (as the other GAIA instruments) do not rely on a pre-defined input catalogue. It uses sky-mappers, illuminated by undispersed light, in order to: (i) detect the sources that will enter its field of view, (ii) confirm the validity of the detections and reject the false ones caused by cosmic rays or CCD/electronic defects and (iii) select the pixels that will be downloaded to the Earth.

Source detection

The development/testing/optimisation of the "source detection software" is in progress, in the On-board detection working group. The program, named GD (current version 1.4.1), is based on the APM algorithm (Irwin, 1985, MNRAS, 214, 575). It has been successively designed and coded by F. Chéreau (OBD-FC-01) and S. Mignot (OBD-SM-02). The detection is performed by successive steps: (i) all pixels above noise level are identified, (ii) the connex pixels (above noise level) are grouped by entity called "objects", (iii) each object is analysed to determine if it is made of a single or of several sources, (iv) type, position and magnitude of each source are derived. GD is described in more details in OBD-CoCo-03 and in OBD-FC-01.

It has been proposed to devote 3 RVSM (#3, #4 and #6) to the detection of the sources that will cross the RVS field of view. Two out of the three CCD would be coated with filters (grey/red – see sect. 3.1.3). The different opacities and band-widths of the filters should guarantee that for all magnitudes between V = 4 and 20, there is always at least one CCD that is neither saturated, nor under-illuminated.

One of the possibilities foreseen is to run 3 GD processes in parallel to analyse the 3 streams of pixels. The results of the 3 processes would be weighted according to the reliability of the detection (a detection will be more reliable if it is based on a bright but not saturated signal, than if it derives from the analysis of a faint or saturated spot) and combined to derive the positions and brightness of the sources entering the RVS field of view.

Detection confirmation

Cosmic rays or CCD/electronic defects could mimic sources. To save telemetry it is necessary to reject those false detections. In the current scenario two CCD, RVSM #7 and #8 (supported in normal operating mode by RVSM #5), are devoted to the confirmation of the detections. The principle of the confirmation is: (i) to run (in parallel) one GD process per CCD dedicated to the confirmation, (ii) to combine the results from the different processes to define a second "list" of detected object and (iii) to cross-identified the "lists" based on the information provided by the "detection RVSM CCD" and by the "confirmation RVSM CCD", in order to reject the false detections.

The objective is to detect all sources up to G = 20, in order to identify: (i) the objects that should be observed by the RVS (expected limiting magnitude V~17/18), but also (ii) the sources that will contaminate the downloaded spectra. It is currently foreseen to download the positions and magnitudes of all the detected objects.

Source and pixel selection

Unlike the astrometric and photometric instruments (which rely on patches) the three RVS detectors are read in totality. Nonetheless, in order to save telemetry, the Video Processing Units (VPU) perform the selection (among other tasks) of the "relevant pixels" (see below). Only those pixels are transmitted to the Payload and Data-Handling Units (PDHU) and then downloaded to the Earth.

The On-board detection working group has developed a preliminary version of the selection algorithms (OBD-CoCo-03). The software rely on the information provided by the detection program GD (type, position and magnitude of the sources), to identify and therefore select the "relevant pixels".

At the present stage, pixels are selected (considered relevant) if they belong to the central row or the two central rows (the number of rows extracted per spectrum depends upon the location of the spectrum with respect to the CCD lines) of the spectrum of a V = 18 or brighter star. Still in order to save telemetry, the outer rows of the spectra, which contain a small fraction of the total energy, are discarded. The selection strategy will be refined over the course of the consolidation phase.

Note that the selection algorithm does not perform the packetisation of the data: i.e. define how to group the pixels, in which order those packets of data should be downloaded, what information should be added to the raw pixels to recover the spatial/temporal location of each pixel. As an example, a very frequent issue that the packetisation algorithm will have to tackle is: group/sort the pixels of the spectra collected in very dense area (where most of the pixels will be illuminated by several sources) and transmit a single time each pixel (to fit in the allocated telemetry budget). The packetisation strategy remains to be defined and to be implemented.

3.2.2 Data pre-processing & compression

As described in Sect. 2.1.4 three pre-processing/compression stages are currently foreseen to minimize as much as possible the volume of downloaded data:

- Interpolate (to avoid/minimize degrading the resolution) and sum the 3 spectra successively observed by the 3 RVS detectors and transmit a single spectrum per object and per transit.
- In stars fainter than V = 16: extract and download only parts of the spectrum. It has been proposed to select two windows, [8480, 8568] and [8642, 8689] A, which contains the 3 Calcium lines (whatever the radial velocity of the source, up to the Galactic escape velocity), which are assumed to concentrate most of the spectral information in V = 16 or fainter stars.
- Apply "classical" numerical compression algorithms.

In addition, it is necessary that the packetisation process, which could be coupled with the "classical compression", avoids any redundant transmission of pixels "belonging" to several sources.

The pre-processing/calibration strategy will be refined and tested during the consolidation phase (see Sect. 4.5).

3.3 Calibration strategy

3.3.1 Wavelength calibration

The current baseline for the wavelength calibration relies on radial velocity standards. Its principle is to measure, on "bright" (TBD) late type stars with constant radial velocities, the positions of well identified "laboratory standard" lines and to use this information to derive the spectral dispersion relation as a function of the position in the field of view and as a function of time. The initial list of stars, qualified as radial velocity standard from ground observations, will be iteratively complemented by stars which will display constant radial velocities over the 5 years of the mission.

It has been also proposed by U. Munari to use a calibration cell (an absorption cell, which superpose spectral line(s) of known wavelength(s) to the spectra of the object) to complement or (according to the respective merits and drawbacks of each approach) replace the baseline wavelength calibration.

Operating mode, technical solutions and performances of the baseline strategy as well as of the calibration cells will be assessed during the consolidation phase (see Sect. 4.2).

3.3.2 CCD/optics calibration

The RVS CCD (and more generally the GAIA CCD) operate in TDI mode. Therefore, offsets, transmission/responses will be calibrated line by line (instead of pixel by pixel as it is the case with CCD operating in "static" mode). The actual design of the spectrograph includes no calibration lamp. It is foreseen to rely on photometric and spectroscopic standard for the flight calibrations of the CCD. The exact CCD calibration strategy should be defined during the consolidation phase (see Sect. 4.2).

3.3.3 Background calibration

In ground spectroscopy, the "classical" approach to estimate the contribution of the background, is to record a spectrum of the sky close to the observed object. Yet, this procedure does not seem well adapted to the RVS instrument observing conditions. In crowded area, almost no pixel will be illuminated by the background alone. In low stellar density areas, it would be possible to download rows of sky, some pixels away from the sources (to avoid "contamination" by the wings of the PSF). But this would increase significantly, the already very large, volume of data to transmit.
It is foreseen to apply a different strategy for the calibration of the background in the RVS observations. It has been proposed to coat two RVSM CCD (#6 and #7) with red filters duplicating the band-pass of the RVS ([8480 – 8740] A). The detection algorithm GD would divide the sky in square of 32 by 32 pixels (exact dimensions to be refined) and compute the sky surface brightness (using a robust estimator rejecting the contribution of point sources) over those areas. Only the sky surface brightness would be downloaded (not the raw pixels), implying a modest increase of the telemetric flux: 3.69 kbit/s (before compression).
This approach presents two limitations with respect to the "classical" procedure: it exhibits a poor spatial resolution (32 by 32 $arcsec^2$) and it does provide no information about the spectral characteristics of the background. At the present time, those limitations are not considered critical, since it is assumed that the spatial and spectral dimensions will average. As a consequence, the contribution of the background should be close to a uniform white noise. The situation could be different in area exhibiting strong brightness contrast over small spatial scale (e.g. bright nebulae). The relevance and the performances of this calibration strategy will be assessed during the consolidation phase.

In addition to the sky surface brightness, it is also foreseen to download the RVS band width magnitudes of all detected sources up to V = 20, in order to help characterize and separate the stacked spectra (in particular in dense areas).

3.4 RVS performances

3.4.1 Signal to noise ratios

Table 11 presents the signal to noise ratios computed for magnitudes V = 10 to 18, with the new RVS baseline characteristics, for a solar metallicity K1V type star (Teff = 5000 K, log g = 4.5, [Fe/H] = 0.0).

Table 11: Single transit and mission averaged signal to noise ratios as a function of magnitude computed for a solar metallicity K1V type star.

V	10	11	12	13	14	15	16	17	18
Single Transit	52	32	18	10	5	2	1		
Mission	521	317	185	100	49	22	9	4	1

3.4.2 Radial velocities

Table 12 presents the radial velocity performances of the RVS instrument, for a solar metallicity K1V star, derived by Monte-Carlo simulation (relying on synthetic spectra).

Table 12: RVS radial velocity precisions (km/s) as a function of magnitude estimated in the case of a solar metallicity K1V star.

V	13	14	15	15.5	16	17	17.5	18	18.5
Single Transit	1.2	2.6	5.8	11.8	> 35	--	--	--	--
Mission	--	--	--	--	1.3	3.4	5.1	10.0	> 35

3.4.3 Atmospheric parameters

The assessment of the performances of the RVS instrument in determining the atmospheric parameters and individual abundances is one of the objectives of the consolidation phase.

4 RVS consolidation phase: work breakdown

Over the last 18 months, most of the RVS working group studies were oriented towards the definition of the RVS characteristics. This first phase was concluded by the adoption of the new RVS baseline. The objective of the RVS working group for the next phase is to consolidate the choices that have been made: i.e. define and optimize the detailed design of the instrument (activity mostly under the responsibility of the RVS consortium – see Sect. 4.1), prepare the future scientific analysis of the RVS/GAIA data, define the instrument calibration strategy, assess the RVS accuracy budget and check that the spectrograph performances are consistent with its scientific objectives, refine and test the selection, pre-processing and compression strategy and integrates the RVS instrument in the GAIA simulator and the GDAAS system. The consolidation phase work breakdown has been discussed and defined during the 5th RVS workshop. It is presented in Sect. 4.1 to 4.6.

A preliminary list of participants is associated to each task. If you want to add, move or remove your name, please send a mail to David Katz (david.katz@obspm.fr) and Ulisse Munari (munari@pd.astro.it).

The development of the RVS instrument is proceeding in parallel (and should remain in phase) with many specific industrial technology development efforts: e.g. CCD and Focal Plane Assembly, Payload and Data-Handling Electronics, data compression, GDAAS2 (see "GAIA in 2002", WG-STATUS-011 for more details).

4.1 Optimisation of the RVS design (RVS consortium)

The 15 months ESA contract, devoted to the definition/optimisation of the detailed design of the RVS instrument, started mid-December 2002. This study will be performed by a consortium of academic laboratories (hereafter referred to as the RVS consortium), lead by M. Cropper (MSSL) and made of Mullard Space Science Laboratory, Paris Observatory, Leicester University, Asiago Observatory and Ljubljana University.

The objectives of the RVS consortium are:

- Optimise the optical design and the filter system.
- Define and optimise the mechanical and thermal designs.
- Tilt mechanism
    - Identify technical solutions, assess performances, reliability and impact on the payload environment (mechanical, thermal and electromagnetic perturbations), define failure mode.
    - Recommend (based on the above criteria) tilt mechanism adoption or rejection.
- CCD and focal plane assembly:
    - Optical, radiation and ageing characterization.
    - Evaluation of the L3 CCD and 2D clocking CCD performances.
    - Recommendation/choice of a CCD technology.
    - Optimization of the CCD layout.
- Size, define and optimize the proximity electronics and the video processing units architectures.
- Refine the wavelength calibration strategy and assess its impact on the instrument performances.

4.2 Scientific analysis of the RVS/GAIA data

G. Bertelli, G. Bono, F. Boschi, A. Gomboc, A. Gomez, M. Haywood, A. Helmi, D. Katz, J. Kleyna, K. Kuijken, Y. Lebreton, P. Marrese, U. Munari, G. Nelemenans, D. Pourbaix, A. Prsa, A. Robin, R. Sordo, L. Tomasella, C. Turon, A.Vallenari, M. Wilkinson, H.S. Zhao, T. Zwitter

The RVS scientific objectives, priorities (Sect. 2.1.1.1) and specifications (Sect. 2.1.1.2) have been defined over the course of the past 18 months. The aim for the consolidation phase (and up to the exploitation of the GAIA data) is to assess and develop the methods, algorithms, models, data (…) required for the scientific reduction and analysis of the RVS/GAIA information.

4.3 Calibrations, accuracy budget & performances

F. Arenou, A. Blazit, F. Crifo, M. Cropper, M. David, H. Hensberge, A. Jorissen, D. Katz, U. Munari, F. Royer, C. Soubiran, F. Thevenin, T. Zwitter

Calibrations

The present status of the calibration strategies is presented in Sect. 3.3. The objectives for the next phase are to refine (define for the CCD/optics calibration) the calibration protocols, test/assess their performances/advantages/disadvantages and in the case where different approaches have been proposed, select the "optimal" one.

Accuracy/Error budget and performances

The RVS radial velocity precisions have been assessed to the first order (taking into account the object mismatch and the sampling, photon, zodiacal and readout noises). The objective is now to refine this first estimate and to establish the RVS error budget: i.e. (i) to identify "all" the sources of error that may affect the instrument performances, (ii) to quantify their impact and (iii) to combine the errors in order to assess the overall RVS accuracy.

The error sources may have very different impacts according to the astrophysical parameters considered: e.g. the residual of the wavelength calibration will affect the radial velocity accuracy, while it will, most likely, be of little consequence for the equivalent width measurement precision. The priority for the consolidation phase is to assess the effects of the errors affecting the determination of: the radial velocities, the atmospheric parameters and the individual element abundances.

Table 13 below presents a preliminary list (to be refined) of error sources and of parameters (magnitude, stellar type) that may impact on the RVS performances. This list is highly inspired by the description of the *"GAIA astrometric error budget"*, written by L. Lindegren (GAIA-LL-043).

Table 13: Parameters and error sources that may impact on the RVS performances.

Source	**Satellite and environment**
Object type and magnitude	Scanning law (number of transits)
Object type mismatch	Real time attitude determination
Source confusion/overlapping	On-ground attitude modelisation
Sky background & interstellar absorption	Thermal/mechanical stability
Data analysis	**Instrument**
Source detection/selection/extraction	Optics: transmission, PSF shape, ageing, …
CCD summation	Mechanics: short term stability, ageing
Spectra pre-processing	Tilt mechanism performances
Data compression	CCD: offset, response, CTI, saturation, …
Wavelength calibration	Proximity electronics, VPU, PDHU
Atomic data & reference spectra	
RV determination algorithms	
Atmospheric parameters det. algorithms	

Precision as function of spectral type

The RVS radial velocities, atmospheric parameters and individual abundances precisions are function of the source spectral type. The spectrograph performances should, therefore, be assessed for different spectral types, representative of the stellar components of the Milky Way. Table 14 presents a list (based on the GAIA CTSR (ESA-SCI(2000)4) and on RVS-MW-001) of "tracers" (chosen either because they represent the bulk of a population or because they allow to probe a structure over long distances) of the Galactic populations. This list will evolve in parallel with the progress of the preparation of the RVS/GAIA data analysis.

Table 14: Galactic populations "tracers".

Thin disk	Solar metallicity G5 MS/TO Teff = 5500 logg = 4.0 [Fe/H] = 0.0 [α/Fe] = 0.0
	Solar metallicity K0/1 giant Teff = 4500 logg = 2.0 [Fe/H] = 0.0 [α/Fe] = 0.0
Thick disk	Intermediate metallicity G0 MS/TO Teff = 6000 logg = 4.0 [Fe/H] = -0.7 [α/Fe] = +0.3
	Intermediate metallicity K0/1 giant Teff = 4500 logg = 2.0 [Fe/H] = -0.7 [α/Fe] = +0.3
Spiral structure	Solar metallicity Cepheids Teff = 7000 logg = 1.0 [Fe/H] = 0.0 [α/Fe] = 0.0
Internal Halo	Metal poor F5 MS/TO Teff = 6500 logg = 4.0 [Fe/H] = -1.5 [α/Fe] = +0.4
	Metal poor K0/1 giant Teff = 4500 logg = 2.0 [Fe/H] = -1.5 [α/Fe] = +0.4
External Halo (halo streams)	Metal poor K0/1 giant Teff = 4500 logg = 2.0 [Fe/H] = -1.5 [α/Fe] = +0.4

Source confusion/overlapping

Most of the RVS observations of "low" latitude (|b| < 30 degrees) stars will be blended with spectra of neighbouring sources. Therefore, the studies of the thin disk, the thick disk and the bulge will require the development of dedicated techniques, which could disentangle and/or analyse stacked spectra. T. Zwitter has developed (see its contributions in the Monte-Rosa conference proceedings) such a method. The overlapped spectra are iteratively modelled (thanks to the information provided by the astrometric and photometric instruments) and separated. This algorithm has been applied to synthetic data in order to derive a first estimate of the spectrograph RV performances as a function of stellar density. It appears that the radial velocity precisions are almost not degraded up to stellar densities of 20 000 stars per square degrees (at V=17).

The development/refinement of the "disentanglement" methods and the assessment of the impact of the crowding will be carried on during the consolidation phase. It has been proposed to develop a double blind test procedure. A first team will generate the RVS and GAIA data/information (e.g. spectra, sources positions, sources characteristics, satellite attitude) degraded by the appropriate errors. A second team will separate the spectra and derive the sources radial velocities. *In fine,* the input and output radial velocities will be compared to assess the RVS RV performances as a function of magnitude, stellar type, stellar density and number of transits.

4.4 Selection/compression strategy & telemetry budget

F. Arenou, M. Cropper, S. Mignot, D. Morin, Y. Viala

The status of the selection, pre-processing and compression strategy is reviewed in Sect. 3.2.1 and 3.2.2. The objectives for the consolidation phase are the following:

- Refine the selection, pre-processing and compression scenario.
- Investigate new/additional pre-processing/compression approaches.
- Assess the impact of the data pre-processing (currently: summation of the 3 CCD and selection of the Calcium lines intervals) on the RVS performances.
- Simulate the selection/pre-processing/compression procedure in order to estimate the degree of completeness of the data transmission (as a function of time/Galactic coordinates) and assess its impact on the RVS performances.
- Size and design the electronics required by the selection, pre-processing and compression algorithms (RVS consortium).

4.5 RVS simulator

M. Cropper, D. Katz, T. Zwitter

Several home made simulator have been developed over the course of the RVS definition phase in order to tackle specific problems: assess RV performances, quantify the impact of the crowding on the RVS performances or test/compare data compression strategies. The objective for the consolidation phase is to merge those programs into a single simulator and to integrate it into the global GAIA simulator (currently developed by the simulation working group). The RVS simulator will allow people to generate and use RVS like spectra without investing a huge amount of time in coding. It will also guarantee that all studies based on RVS (and other GAIA instrument) simulated data, rely on the same assumptions. It is intended as a tool to:

- Assess (part of) the RVS accuracy budget (e.g. design dependant effect, crowding)
- Define/optimise data analysis algorithms (e.g. cross-correlation in direct or Fourier space).
- Optimise the RVS design (e.g. compare different options).
- Study "GAIA global issues" (e.g. star parameterisation, which will rely on astrometric, photometric and spectroscopic data).

The full RVS simulator will be a complex program. Its design, implementation and integration will take about a year. To fill the gap until its integration into the GAIA simulator, it is foreseen to develop and distribute autonomous versions with precise and restricted objectives. Table 15 presents a preliminary agenda for the RVS simulator development.

Table 15: RVS simulator development plan.

Release date	Simulator versions/status
Q1/2003	Single spectra – Gaussian PSF
Q1/2003	Single spectra – Optical PSF
Q2/2003	Field of view image
Q3/2003	Full RVS simulator UML model
Q4/2003	Integration in the GAIA simulator

4.6 GDAAS algorithms

F. Arenou, D. Katz, T. Zwitter

The storage and processing/analysis of the 5 years of GAIA data will be a huge and complex task: i.e. about 1 Petabyte of data, 10^{20} to 10^{21} operations, complex data structure (astrometric information, 5 broad and 11 medium photometric bands, RVS spectra) and data highly correlated in time and space. The "GAIA Data Access and Analysis Study" (GDAAS) started mid-2000. During the first phase of the study, 2000-2002, a prototype of the database and of the data analysis system (integrating two key algorithms: the object matching and the global iterative solution) have been designed and developed. One of the objectives of GDAAS for the period 2003-2004 is to integrate, in the data analysis system, new algorithms, representative of the key steps of the future processing of the astrometric, photometric and spectroscopic data. It is not necessary to implement the final and optimized versions of those algorithms, but routines mimicking the complexity (input/output) and the processing power required by the future "optimal" methods. L. Lindegren (GAIA-LL-044) has established a list of algorithms that should be integrated in the data analysis system during the GDAAS phase 2. Three of them concern the RVS instrument. They are listed in Table 16.

Table 16: GDASS/RVS algorithms development plan

Algorithms	Delivery date
Radial velocity cross-correlation	July 2003
Wavelength calibration	April 2004
Source detection	September 2004

5 Web sites and workshop

Web address:

- RVS working group : http://wwwhip.obspm.fr/gaia/rvs
- RVS Consortium : http://www.mssl.ucl.ac.uk/gaia-rvs/
- Monte-Rosa conference : http://ulisse.pd.atro.it/GAIA2002/
- ICAP working group : http://www.mpia-hd.mpg.de/GAIA/icap.html
- On-board detection WG : http://wwwhip.obspm.fr/gaia/obd
- Simulation working group : http://gaia.am.ub.es/SWG/
- ESA Livelink : http://astro.estec.esa.nl/livelink

Workshop:

- 7th GST Meeting : 12-13 March – Heidelberg
- 6th RVS Workshop : mid-June 2003 – Mullard Space Science Laboratory
- 8th GST Meeting : 26-27 June – ESTEC