Impact of RVS instrument on the GAIA science case

Resulting requirements on the design of the instrument

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In this note, we examine (i) the scientific impact and goals of the RVS instrument and the resulting requirements in terms of radial velocities accuracy, signal to noise ratios and resolution, (ii) the adequation of the study report design and the new Astrium designs (propositions made before the 20/02/2002) with the RVS scientific requirements.

This note is meant as a starting point to discuss and define the RVS scientific case. All the aspects presented in Table 1 and 2 can and must be commented. In particular, the RVS scientific priorities must be revised by the GAIA Science Team, while the requirements (σ_{Vr}, S/N, R) must be confirmed or modified by detailed studies.

By lack of time, neither the crowding, nor the telemetry are discussed in the present note. Nonetheless, both may have a **very** large impact on the scientific capabilities of the instrument in dense area. It is most likely that the increase by a factor of three of the pixel size (from 1×1 to 1×3 arcsec^2), in the new Astrium design, will have a large effect on the crowding. Both crowding and telemetry will be discussed in a coming note.

1 - Introduction

The GAIA mission has been designed as a Galaxy explorer, measuring simultaneously, in a survey mode, the six parameters of the phase space of all stars brighter than the 20th magnitude, along with a description of their astrophysical characteristics. These capabilities are obtained by combining an astrometric instrument, aiming at micro-arcsecond accuracies, a photometric system providing magnitudes and colours in 10 or more bands, and the Radial Velocity Spectrometer (RVS).

Thanks to the simultaneous use of the these three parts of the GAIA instrument, the expected scientific outcome of the mission covers various fields of astronomy and astrophysics: besides the main motivation of the GAIA mission, i.e. to unravel the composition, formation scenario and subsequent evolution of our Galaxy, many other applications are extremely promising. They range from stellar astrophysics, with detailed observation of all types of stars in every evolutionary stages, to fundamental physics, with stringent new tests of general relativity, through a comprehensive survey of a variety of objects (tens of thousands of extra-solar planetary systems, minor bodies in our solar System, galaxies in the nearby Universe, some 10 million distant quasars). However, the respective impacts of astrometry, photometry and spectroscopy may be very different from one scientific target to another one.

2 - RVS scientific case

The aim of this note is to disentangle the specific impact of the Radial Velocity Spectrometer on these various aspects of the GAIA mission science case, to pinpoint the applications where the RVS has a unique or essential contribution, and to subsequently examine the relative influences of each of the characteristics of the instrument (mainly radial velocity accuracy, resolution and signal to noise) on the expected scientific outcome. More simulations and studies will be needed to refine the contents of the RVS science goals (Table 1 and 2).

Table 1 presents the expected scientific impact of radial velocity, and the resulting requirement on the radial velocity accuracy. It is constructed in a similar mind, and using similar entries, as the Table

1.1 of the GAIA Concept and Technology Study Report (called ref. table in the following).

Explanation of the columns

- scientific targets: few modifications with respect to the ref. table
- scientific rate: splitted in four columns
  - GAIA as a whole: scientific importance of the target for the mission. From **** = primary target of the global GAIA science case, decreasing to *
  - contribution of astrometric measurement to that subject
  - contribution of photometric measurement to that subject. 'Indirect' means that photometry brings the information necessary to obtain the absolute magnitude and the type of the object
  - additional impact of the RVS instrument: from **** = primary target in the RVS science case, decreasing to *
- limiting distance: splitted in two columns
  - best = englobes nearly all objects of the category
  - acceptable = provides large enough samples in each category to allow a deep investigation of that population
- limiting apparent magnitude: splitted in two columns
  - best = englobes nearly all objects of the category. Identical to V_1 in the ref. table
  - acceptable = provides large enough samples in each category to allow a deep investigation of that population. Intermediate V_1 and V_2 of the ref. table
- 'velocity dispersion': velocity dispersion for lines 1 and 2; mean velocity for line 3; amplitude for line 5.
- radial velocity accuracy required to tackle the topic: over the mission for lines 1 to 3; par transit for lines 4 and 5.

Table 2 presents the expected scientific impact of detailed spectral information, and the resulting requirement on the signal to noise ratio and on the resolution.

Explanation of the columns

- scientific targets: parameter to be measured
- scientific rate: same columns as in Table 1
- considered spectral type range
- limiting apparent magnitude: same columns as in Table 1
- required from RVS , splitted in two columns: signal to noise ratio and on the resolution

3 - Note on the RVS scientific priorities

Columns 5 of Tables 1 and 2, named Impact of RVS, give the levels of priority of the scientific targets. The aim of this classification, is to help choosing between instrumental options with conflicting impact on different scientific targets.
In the actual version, the classification is (TO BE DISCUSSED/REVISED) :
Priority $\star\star\star\star$: Perspective acceleration, thin disk, thick disk, halo, gravity K_z, spectral peculiarities.
Priority $\star\star\star$: Spiral arms, clusters, binary systems, pulsating stars, individual elements, early type stars rotational velocity.
Priority $\star\star$: Bulge, extinction, temperature, gravity, metallicity, late type stars rotational velocity.
Priority $\star$: Local group dynamics.

Table 1 : Scientific requirements over the mission. a= from A.Helmi simulations

Scientific Target	**Scientific rate**				**d_{lim}**		**V_{lim}**			**Required**
	GAIA as a whole	**Contribution of**		**Impact of RVS**	**best** [kpc]	**accep-table** [kpc]	**best** [mag]	**accep-table** [mag]	**Velocity dispersion**	**from RVS (1)** σ_{RV}
		astrom.	**photom.**							
									km/s	km/s
1- Perspective acceleration	****	yes	no	****			20			1-2
2- Galactic tracers	****	yes	indirect	****						
2.1- Bulge	****	yes	indirect	**	**9**	**8**	**20**	**17**	**100**	**10-15**
red giants					9	8	20	17		
bulge-bar					8	7	20	17		
MS turnoff					9	8	21	19		
2.2- Spiral arms	****	yes	indirect	***	**10**	**8**	**18**	**15**	**10**	**1-2**
Cepheids					10	8	18	15		
Supergiants					10	8	17	14		
Perseus arm					2	2	16	13		
2.3- Thin disk	****	yes	indirect	****	**10**	**8**	**19**	**17**	**20**	**2-4**
center, gK					8	8	18	16	40	
center, turnoff					8	7	20	19	40	
anticenter, gK					10	8	19	17	10	
2.4- Thick disk	****	yes	indirect	****	**20**	**18**	**21**	**17**	**40**	**4-8**
center					8	8	19	17	50	
anticenter					20	8	21	17	30	
2.5- Halo	****	yes	indirect	****	**30**	**18**	**21**	**16**	**100**	**10-15**
red giants					30	10	21	15		
HB					30	10	21	15		
streams					30	15	21	18.3 (2)	150	15-20
2.6- Gravity, Kz	****	yes	indirect	****	**2**	**2**	**20**	**15**	**20**	**2-3**
3- Local Group dynamics	**	yes	indirect	*	**850**	**800**	**21**	**15**	**<RV> 100-300**	**30-40**
4- Clusters	***	yes	indirect	***	**8**	**3**	**18**	**14**		**1-3 per transit**
5- Binary systems	***	yes	yes	***	**8**	**$\geq$ 1**	**18**	**14**		**1-3 per transit**
6- Pulsating stars	****	yes	yes	***	**50**	**10**	**15**	**12**	**amplitude 2-40**	**1-3 per transit**

Table 2 : Scientific requirements (2)

Scientific Target	**Scientific rate**				**Spectral type**	**V_{lim}**		**Required from RVS (1)**	
	GAIA as a whole	**Contribution of**		**Impact of RVS**	**range**	**best** [mag]	**accep-table** [mag]	**S/N**	**resolution**
		astrom.	**photom.**						
1- Extinction	********	**yes**	*******	******	**O-A**	**20**	**14-15**	**$\geq$ 20**	**$\geq$ 10000**
2- Stellar parameters									
2.1- temperature	****	no	****	**	all	20	14-15	$\geq$ 20	$\geq$ 5000
2.2- gravity	****	yes	****	**	all	20	14-15	$\geq$ 20	$\geq$ 10000
2.3- metallicity	***	no	****	**	F-M	20	14-15	$\geq$ 20	$\geq$ 10000
2.4- individual elements	**	no	**	***	F-M	20	13-14	$\geq$ 50	$\geq$ 10000
3- Rotational velocity									
3.1- early-type stars	**	no	no	***	O-F	18	14	$\geq$ 20	$\geq$ 5000
3.2- late-type stars	**	no	no	**	G-M	19	14	$\geq$ 20	$\geq$ 20000
4- Spectral peculiarities	*	no	no	****	any	19	14-15	$\geq$ 20	$\geq$ 10000

4 - Design

The objective of the present exercise, is to provide tables which could make explicit if a given design is compatible with the GAIA science goals and, in the case of a trade-off between several options, could identify the most satisfactory. It is of course impossible to test all the combinations (of collecting area, FoV along and across scan, spin rate, ...). Instead, 3 different designs are considered, each one with 3 different resolutions $R = 5\ 000$, 10 000, 20 000 : (A) the design presented in the study report and which has been considered as the baseline in the last year studies, (B) the redesign proposed by Astrium in order to accommodate the instrument with a smaller diameter satellite and (C) the same redesign as B, assuming a decrease of a factor of 2 on the satellite spin rate. The characteristics of the three designs are presented in Table 3. Their appropriateness with respect to the RVS science goals is presented in Tables 4 and 5.

Annexes A and B contain tables of signal to noise ratios and radial velocity accuracies as function of magnitude and design (for a single transit and over the mission). They have been used to establish the compatibility (or incompatibility) of the different designs with the GAIA science goals (Tables 4 and 5).

In addition to the specification of the RVS science goals, the objective of this document is to give a quick way to estimate the relevance of a new design with respect to the GAIA science case. Annex C describes a program, design.c, that allow to compute S/N ratios and RV accuracies (similar to those of Annex A and B) for any design. Those data can then be easily compared to the science goals tables, Tables 1 and 2.

Table 3: Characteristics of the three considered design : (A) study report design, (B) Astrium proposition with a satellite spin rate of 120 $''$/s and (C) Astrium proposition with a spin rate of 60 $''$/s. Each design will be examined for three resolutions $R = 5\ 000$ (0.862 Å/pix), $R = 10\ 000$ (0.431 Å/pix) and $R = 20\ 000$ (0.215 Å/pix).

	Design A	Design B	Design C
Collecting area (m2)	0.49	0.25	0.25
FoV along scan (°)	2	2.46	2.46
Exposure time (s)	60	74	148
Spin rate ($''$/s)	120	120	60
FoV across scan (°)	1	1.3	1.3
Mission duration (year)	4	5	5
Nb transit / mission	100	163	81.5
Spectrum width (pix)	2	2	2
Nb CCDs (along scan)	2	3	3
Pixel surf (arcsec^2)	1	3	3

5 - Note on the resolution

A resolution of $R = 10\ 000$ is needed to study the kinamtics (per transit) of clusters and binary systems (priority $\star\star\star$) up to $V = 14$, to identify spectral peculiarities (priority $\star\star\star\star$), to derive stellar individual elements (priority $\star\star\star$), extinction and stellar gravities and metallicities (priority $\star\star$). The resolution $R = 20\ 000$ is needed to study the late type stars rotational velocity (priority $\star\star$).

Table 4 : Design versus scientific requirements (1)

Scientific target	Vlim acceptable	Required from RVS $\sigma(RV)$ (km/s)	Design A 5000	Design A 10000	Design A 20000	Design B 5000	Design B 10000	Design B 20000	Design C 5000	Design C 10000	Design C 20000
1 - Perspective acceleration		**1-2**									
2 - Galactic tracers											
2.1 - Bulge	17	**10-15**									
red giants	17		●	●	●	●	●	●	●	●	●
bulge-bar	17		●	●	●	●	●	●	●	●	●
MS turnoff	19		×	×	×	×	×	×	×	×	×
2.2 - Spiral arms	15	**1-2**									
Cepheids	15		●	●	●	×	●	●	×	●	●
Supergiants	14		●	●	●	●	●	●	●	●	●
Perseus arm	13		●	●	●	●	●	●	●	●	●
2.3 - Thin disk	17	**2-4**									
center, gK	16		●	●	●	●	●	●	●	●	●
center, turnoff	19		×	×	×	×	×	×	×	×	×
anticenter, gK	17		●	●	●	●	●	●	●	●	●
2.4 - Thick disk	17	**4-8**									
center	17		●	●	●	×	●	●	×	●	●
anticenter	17		●	●	●	×	●	●	×	●	●
2.5 - Halo	16	**10-15**									
red giants	15		●	●	●	●	●	●	●	●	●
HB	15		●	●	●	●	●	●	●	●	●
streams	18.3	**15-20**	●	●	●	●	●	×	●	●	●
2.6 - Gravity, Kz	15	**2-3**	●	●	●	●	●	●	●	●	●
3 - Local Group dynamics	15	**30-40**	●	●	●	●	●	●	●	●	●
4 - Clusters	14	**1-3 p. tr.**	×	○	●	×	×	○	×	○	●
5 - Binary systems	14	**1-3 p. tr.**	×	○	●	×	○	×	×	○	●
6 - Pulsating stars	12	**1-3 p. tr.**	○	●	●	○	●	●	○	●	●

Table 5 : Design versus scientific requirements (2)

Scientific target	Vlim acceptable	**Required from RVS**		**Design**								
		S/N	Res.	**A**			**B**			**C**		
				5000	10000	20000	5000	10000	20000	5000	10000	20000
1 - Extinction	14	≥ 20	≥ 10000	×	•	•	×	•	•	×	•	•
	15	≥ 20	≥ 10000	×	•	×	×	•	×	×	•	×
2 - Stellar parameters												
2.1 - Temperature	14	≥ 20	≥ 5000	•	•	•	•	•	•	•	•	•
	15	≥ 20	≥ 5000	•	•	•	•	•	×	•	•	×
2.2 - Gravity	14	≥ 20	≥ 10000	×	•	•	×	•	•	×	•	•
	15	≥ 20	≥ 10000	×	•	•	×	•	×	×	•	×
2.3 - Metallicity	14	≥ 20	≥ 10000	×	•	•	×	•	•	×	•	•
	15	≥ 20	≥ 10000	×	•	•	×	•	×	×	•	×
2.4 - Individual elements	13	≥ 50	≥ 10000	×	•	•	×	•	•	×	•	•
	14	≥ 50	≥ 10000	×	•	×	×	•	×	×	•	×
3 - Rotational velocity												
3.1 - Early type stars	14	≥ 20	≥ 5000	•	•	•	•	•	•	•	•	•
3.2 - Late type stars	14	≥ 20	≥ 20000	×	×	•	×	×	•	×	×	•
4 - Spectral peculiarities	14	≥ 20	≥ 10000	×	•	•	×	•	•	×	•	•
	15	≥ 20	≥ 10000	×	•	•	×	•	×	×	•	×

Annex A : Signal to noise ratio versus design

Tables 6 and 7 present signal to noise ratios as function of magnitudes and designs. They have been computed for a star of atmospheric parameters : $T_{\mathrm{eff}} = 5500$ K, $\log g = 4.5$, [Fe/H] = 0.0. The S/N ratios are mostly insensitive to gravity and metallicity, and decrease with increasing effective temperatures. Table 8, gives mean multiplicative coefficients to extrapolate the S/N given in Tables 6 and 7 to other temperatures.

Table 6: **Signal to noise ratios** (S/N) per wavelength bin, for a star of atmospheric parameters $T_{\mathrm{eff}} =$ 5500 K, $\log g = 4.5$, [Fe/H] = 0.0 and for a **single transit**, as a function of V magnitude, for the three different design (see table 1). For each designs, three resolutions are considered : $R = 5\ 000$, 10 000 and 20 000.

	Design A			Design B			Design C		
V	5000	10000	20000	5000	10000	20000	5000	10000	20000
12.0	33.18	22.78	15.23	25.00	16.48	10.36	35.93	23.97	15.32
14.0	11.47	7.14	4.18	7.42	4.24	2.30	11.11	6.48	3.57
15.0	6.03	3.47	1.89	3.49	1.87	0.97	5.36	2.91	1.53
15.5	4.20	2.33	1.24	2.32	1.22	0.62	3.59	1.90	0.98
16.0	2.86	1.54	0.80	1.51	0.78	0.40	2.37	1.23	0.63

Table 7: **Signal to noise ratios** (S/N) per wavelength bin, for a star of atmospheric parameters $T_{\mathrm{eff}} =$ 5500 K, $\log g = 4.5$, [Fe/H] = 0.0 and for the **mission**, as a function of V magnitude, for the three different designs (see table 1). For each design, three resolutions are considered : $R = 5\ 000$, 10 000 and 20 000.

	Design A			Design B			Design C		
V	5000	10000	20000	5000	10000	20000	5000	10000	20000
12.0	331.85	227.76	152.25	319.24	210.42	132.22	324.33	216.36	138.29
13.0	200.29	132.57	83.80	181.76	112.36	65.37	187.84	118.26	70.18
14.0	114.72	71.36	41.79	94.70	54.16	29.39	100.33	58.50	32.23
15.0	60.28	34.70	18.92	44.55	23.90	12.40	48.39	26.31	13.77
16.0	28.59	15.40	8.01	19.32	9.98	5.06	21.35	11.10	5.66
17.0	12.47	6.45	3.28	8.00	4.05	2.04	8.92	4.53	2.28
17.5	8.07	4.13	2.08	5.10	2.57	1.29	5.70	2.88	1.44
18.0	5.18	2.63	1.32	3.24	1.63	0.81	3.62	1.82	0.91
18.5	3.30	1.67	0.83	2.05	1.03	0.51	2.30	1.15	0.58

Table 8: Multiplicative coefficient k to apply to S/N ratios, as function of T_{eff}.

T_{eff}	k	T_{eff}	k	T_{eff}	k	T_{eff}	k
3500	1.8	4500	1.3	7500	0.8	12500	0.6

Annex B : Radial velocity accuracy versus design

Tables 9 and 10 present radial velocity accuracies as function of magnitudes and designs. They have been computed for a star of atmospheric parameters : $T_{\rm eff} = 5500$ K, $\log g = 4.5$, [Fe/H] $= 0.0$ (similar to the Sun). Table 11 gives the shift in magnitude, as a function of stellar type, to apply to Tables 9 and 10 in order to get the same limiting radial velocity accuracy ($\simeq$ 10-15 km/s). For example, from Table 10, at $V = 18.5$, design A and $R = 5\,000$ lead to $\sigma(RV) \simeq 15$ km/s. The same accuracy of 15 km/s will be obtained with a star of parameters $T_{\rm eff} = 5500$ K, $\log g = 4.5$ and [Fe/H] $= -2.0$ at $V = 18.5 - 1 = 17.5$.

Table 9: **Error on Radial Velocity (km/s)**, for a star of atmospheric parameters $T_{\rm eff} = 5500$ K, $\log g = 4.5$, [Fe/H] $= 0.0$ and for a **single transit**, as a function of V magnitude, for the three different designs (see table 1). For each design, three resolutions are considered : $R = 5\,000$, 10 000 and 20 000.

	Design A			Design B			Design C		
V	5000	10000	20000	5000	10000	20000	5000	10000	20000
12.0	1.49	1.00	0.64	2.00	1.10	0.74	1.45	0.98	0.64
14.0	4.30	2.52	1.69	7.24	5.09	3.72	4.56	2.64	1.84
15.0	8.25	5.95	4.49	14.30	11.70	19.70	8.74	6.57	5.17
15.5	12.00	8.75	8.83	26.15	>30.0	>30.0	13.97	11.49	19.31
16.0	19.95	22.12	>30.0	>30.0	>30.0	>30.0	25.59	>30.0	>30.0

Table 10: **Error on Radial Velocity (km/s)**, for a star of atmospheric parameters $T_{\rm eff} = 5500$ K, $\log g = 4.5$, [Fe/H] $= 0.0$ and for the **mission**, as a function of V magnitude, for the three different designs (see table 1). For each design, three resolutions are considered : $R = 5\,000$, 10 000 and 20 000.

	Design A			Design B			Design C		
V	5000	10000	20000	5000	10000	20000	5000	10000	20000
12.0	0.27	0.16	0.10	0.27	0.17	0.11	0.27	0.17	0.11
13.0	0.32	0.20	0.13	0.33	0.20	0.13	0.33	0.20	0.13
14.0	0.36	0.22	0.14	0.64	0.50	0.38	0.56	0.43	0.32
15.0	1.11	0.81	0.57	1.33	0.98	0.70	1.28	0.94	0.67
16.0	1.55	1.12	0.78	2.72	2.04	1.48	2.46	1.85	1.34
17.0	3.58	2.64	1.91	6.82	5.30	4.22	6.16	4.77	3.76
17.5	6.77	5.22	4.13	9.12	7.24	6.84	8.49	6.61	5.32
18.0	8.87	6.89	5.55	15.64	15.82	>30.0	13.87	12.00	22.07
18.5	14.91	13.01	25.24	>30.0	>30.0	>30.0	26.37	>30.0	>30.0

Table 11: Additive coefficient Δ V as a function of atmospheric parameters.

$T_{\rm eff}$	$\log g$	[Fe/H]	Δ V	$T_{\rm eff}$	$\log g$	[Fe/H]	Δ V
4750	4.5	0.0	0.5	5500	4.5	-1.0	-0.5
5500	1.0	0.0	0.5	5500	4.5	-2.0	-1.0
7500	4.5	0.0	-1.0				

Annex C : *design.c* program

The program design.c can be down-loaded from the RVS web page : *"http://wwwhip.obspm.fr/gaia/rvs"*, in the section *"Bibliography and data"*, in the subsection *"Data and software packages"*.
To compile : cc -o design.e design.c -lm

Input parameters :

- Mission duration (year)
- Satellite spin rate (arcsec/s)
- Mirror surface (m^2)
- Length of the FoV along scan (deg)
- Length of the FoV across scan (deg)
- Number of CCDs along scan
- Pixel surface ($arcsec^2$)
- Width of the spectra (pixel)

Output data :

- Table 1 : Design characteristics
- Table 2 : S/N ratios (per wavelength bin) as function of magnitude and resolution (for a single transit and over the mission)
- Table 3 : RV accuracies (km/s) as function of magnitude and resolution (for a single transit and over the mission)

Table 2 and Table 3 are computed for a star of atmospheric parameters :
$T_{\rm eff} = 5500$ K, $\log g = 4.5$, [Fe/H] = 0.0