Telemetric flows for the RVS computed by using star counts from the GSC-2.2 catalogue

RVS-YV-001

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June 3, 2003

Abstract

The GAIA Nominal Scanning Law and star counts from the GSC-II (version 2.2) catalogue have been combined to estimate telemetric flows expected from the Radial Velocity Spectrometer (RVS) all along an assumed 5 years (1800 days) GAIA mission. Mean telemetric flows integrated over one day are determined for the set of parameters of the spectrometer recently adopted by the Gaia Science Team on recommendations from the RVS Working Group. The telemetry budget is computed for two pre-processing scenarios and two magnitude limits. The impact of compression factors on the amount of data that can be downloaded is also studied. Future works planned to refine the determination of the RVS telemetry budget are summarized at the end of this note.

1 Introduction

During the last two years, a working group was in charge of specifying the main characteristics of the Radial Velocity Spectrometer (RVS), one of the instruments implemented on the GAIA satellite. The main instrument parameters to be defined were : the spectral resolution, the magnitude limit of objects to be observed according to the scientific purposes, the number and characteristics of CCD detectors covering the field of view (FoV), the number of CCD rows perpendicular to dispersion extracted per spectrum. The telemetry budget currently assumed to be allocated to RVS, 0.25 Mbits/s, is a severe constraint impacting on the instrument design. Combining the Nominal Scanning Law (NSL) of GAIA, which provides the RVS-FoV position on the sky as a function of time, and the distribution of star density throughout the sky versus magnitude, obtained from star counts from the GSC-II catalogue (version 2.2), we computed telemetric flows expected for RVS all along the mission for various sets of the instrument parameters mentioned above. The results were presented at the Monte Rosa Conference [1]. In its last meeting held in Paris in november 2002, the RWS-WG agreed upon the instrument specifications which were finally adopted by the GAIA Science Team. We present in this note telemetric flows computed for RVS by using these parameters and star counts from the GSC-2.2 catalogue. As a conclusion we list a series of studies that should be undertaken to refine the estimations of the telemetric flows expected from RVS. All suggestions from inside and outside the RVS-WG are of course most welcome.

2 Adopted procedure to compute telemetric flows from RVS

The way the RVS telemetric flows have been computed is described with some details in [1]. The computational procedure, which combines star counts from a catalogue covering the whole sky, the GAIA NSL, and the RVS specifications including CCD parameters, is summarized hereafter.

2.1 Distribution of star density versus galactic coordinate from the GSC-II (version 2.2) catalogue

Counting the number of stars observed by GAIA requires first to determine the distribution of star density throughout the whole sky and this can be obtained from star catalogues. We choose to use the second generation Guide Star Catalog GSC-II because it was, as we started this study, the most complete catalogue covering the entire sky. More information on the GSC-II project can be found in e.g. [2].

We used the 2.2 public release which is set up in the Centre de Donnees Stellaires in Strasbourg. This release contains positions, classifications and magnitudes for 455 851 237 objects. These data were obtained through 1" resolution scans of the photographic sky survey plates from the Palomar and UK Schmidt telescopes in photographic F and J bandpasses. This spatial resolution is very close to the one with which the RVS will work. The GSC-2.2 release is complete up to magnitude 18.5 in F-band ($\lambda \sim 0.71\mu$) and 19.5 in J-band ($\lambda \sim 0.44\mu$). Magnitudes in V-band ($\lambda \sim 0.55\mu$) are also given, but for a much smaller number of objects. For the moment, the GSC-2.2 release contains only two classes of objects : star and non-star. Apart from extended objects, most of non-star objects consists of unresolved multiple systems.

A recent analysis [3] of the GSC-II up to $m_F = 18.5$ has shown that, in crowded areas of the sky, the density of objects derived through scanning Schmidt plates with a 1 arcsec resolution underestimates the true stellar density because of blending : several point source objects overlap to appear as an extended single one. Correction factors depending on positions on the sky are provided by [3]. We do not apply these correction factors since the spatial resolution of RVS is close to the one used to build the GSC-2.2 release.

We have performed star counts within boxes of 1x1 deg centered every degree in galactic coordinates ($0\,\mathrm{deg} \leq l \leq 359\,\mathrm{deg}$ and $-90\,\mathrm{deg} \leq b \leq 90\,\mathrm{deg}$). Within each box, we performed counts in the three (F, J and V) bands, and, in each band, for the three class of objects : stars, non-star objects, and total. Nine ASCII files have hence been produced : each file gives, as a function of galactic coordinates (for each integer value of the galactic latitude and longitude for the entire sky), the number of objects per square degree and by 0.5 magnitude interval from 0 (or less) up to 19. These files are available on the anonymous web site : mehipx.obspm.fr, on the directory transit/gaia (username : anonymous, passwd = electronic address ; further information can be obtained from yves.viala@obspm.fr).

As noted hereafter, the telemetry budget from RVS, presented in this note, was computed by using star counts from the GSC2.2 F-band alone (the red band closer to the RVS wavelength band). For purpose of comparison, we also computed the RVS telemetry budget by using star counts from the very simple galactic model presented in [4] (table 6.6, p. 242). This model is presented in table 1 where star densities up to magnitudes not listed in the original table were estimated through interpolation by assuming that the cumulative number $N(m)$ of stars up to magnitude m follows a power law variation of the type $N(m)/N(m-p) = k^p$.

Table 1: Number of stars per square degree from the GAIA-CTSR Galaxy model

Latitude	$G = 15$	$G = 16$	$G = 17$	$G = 17.5$	$G = 18$
$0 \leq \lvert b \rvert \leq 05$	1600	3800	9100	13600	20300
$5 \leq \lvert b \rvert \leq 10$	1400	3200	7400	11000	16300
$10 \leq \lvert b \rvert \leq 20$	800	1800	3900	5500	7800
$20 \leq \lvert b \rvert \leq 30$	500	1000	2100	2800	3700
$30 \leq \lvert b \rvert \leq 90$	300	500	900	1100	1500

2.2 The GAIA Nominal Scanning Law (NSL)

The GAIA NSL, described in Lindegren's papers [5, 6, 7] has recently (spring 2002) been modified to take into account changes in the payload design. To simulate GAIA observations during the mission, we used Lindegren's code [6, 7], taking into account the latest changes in the NSL, to compute the attitude matrix of the satellite versus time A(t). This matrix links up the components of any direction **u** in the GAIA reference system (GRS) : (u_x, u_y, u_z) and in the International Celestial Reference System (ICRS, equatorial coordinates) (u_l, u_m, u_n) through :

$$\mathbf{u}(GRS) = A(t) \times \mathbf{u}(ICRS) \tag{1}$$

In the GRS, axis Oz is the rotational axis and all instruments lie in or nearby the scanning plane xOy ; axis Ox lies at equal angular distance (53 deg) to the FoV centres of the two astrometric instruments. It is convenient to define any direction in the GRS through its azimuthal angle a (measured from axis Ox) and its height angle h above the xOy plane, the cosine directors being obtained by the usual formulas :

$$u_x = \cos h \cos a \ , \ u_y = \cos h \sin a \ , \ u_z = \sin h \tag{2}$$

In the new design, the centre of the RVS-FoV is located at $a(RVS) = 91$ deg and $h(RVS) = 0$ deg. The attitude matrix A(t) was computed every 120 s for an assumed 1800 days GAIA mission arbitrarily starting from day J2000.0. The chosen timestep corresponds to the transit time of the RVS-FoV along scan (size of 2 deg and scan velocity of 60"/s adopted in the new NSL). At each timestep, given the RVS-FoV angular size of 2 deg along scan and 1.6 deg across scan, from relations 1 and 2 above we get the celestial equatorial coordinates of the centre and extremities of the RVS-FoV (galactic and ecliptic celestial coordinates of the RVS-FoV, as well as its orientation on the sky, defined as the angle between the scan direction and the galactic plane, are also by-products of our computations). By using this procedure the sky observed by RVS is divided into successive FoVs, nearly juxtaposed (neglecting the drift across scan, a fairly good approximation since a drift speed of 0.171 "/s leads to across scan drift of only 20.5" between two successive FoVs).

The next step consists in counting the stars up to a chosen magnitude limit within each FoV, using the distribution of the star density throughout the sky derived from a star catalogue. It is convenient that the spatial resolution adopted in counting stars within the FoV is similar to the one with which the star density distribution has been derived. Since the star density derived from GSC-II counts (see next section) is given by square degree, each RVS-FoV has been divided in 4 smaller cells of size 1 deg along scan and 0.8 deg across scan. At each time step, the galactic coordinates of each cell are computed from the above relations 1 and 2 ; the number of stars within each cell is obtained by multiplying the star density of the nearest point (with integer coordinates) of the star catalogue by the area of the cell. The total number of stars within each FOV is obtained by summation over the cells.

2.3 RVS parameters and CCD filling

The number of objects observed during an arbitrarily chosen integration time t_{int} at any epoch during the mission is obtained by summing the objects within the successive FoVs covering it. Integration times and period of observations (from J2000.0) are free parameters of our calculations. The main purpose of this note is to estimate the global RVS telemetry budget and its variation during the mission : assuming that data will be sent to the ground once a day, we computed telemetric flows for integration time $t_{int} = 1$ day, obtained by summing the 720 successive FoVs covering that day. If necessary, for instance in very crowded FoVs, our model allows us to determine the telemetric flow and its variations at timescales much lower than the FoV transit time and for very short integration times (from a second or less to one day).

The telemetric flow within t_{int} is obtained by multiplying the total number of objects observed during t_{int} by the number of bits of data per star spectrum and dividing by t_{int}. The total number of bits per spectrum depends on the RVS parameters. These were adopted by the GAIA Science Team following the recommandations settled during the last (28-29/11/2002) RVS-WG meeting. These specifications are summarized in [8].

Regarding the telemetry budget, the specifications of interest are : a spectrometer resolution of 11500 (corresponding to a sampling of 0.375 Å/pixel) leading to a single spectrum extension of $\sim$ 694 pixels along scan ; it is assumed that one or two CCD rows perpendicular to dispersion, i.e. across scan, will be extracted per spectrum ; the RVS-FoV is covered by 3 CCD of 2020 x 3930 pixels (pixel angular size 0.982" x 1.473").

The number of pixels per star spectrum on a single CCD is given in the second column of table 2 for two spectrum widths of 1 and 2 CCD rows. If the RVS-FOV is covered by 3 CCD, the total number of pixels occupied by each star spectrum over its transit through the FoV is obtained by multiplying by 3 the values listed in column 2 of table 2.

Finally, it must be pointed out that, when computing telemetric flows, we have to account for CCD filling up in crowded FoVs. This occurs when all pixels of one single CCD are occupied by at least one star. Assuming a uniform distribution of stars within the FoV and no spectra overlap, the lower limit of the number of objects per square degree, N_{obj}^{crit}, above which the CCD is full, is given, on the average, by :

$$N_{obj}^{crit} = S_{CCD}(pix)/(S_{CCD}(deg) \times n_{pix/obj}) \tag{3}$$

where $n_{pix/obj}$ is the number of pixels per star spectrum on a single CCD (second column of table 2), $S_{CCD}(deg) = 0.551 \times 1.608 = 0.886$ square degree and $S_{CCD}(pix) = 2020 \times 3930 = 7938600$ pixels are

Table 2: Number of pixels per star spectrum on a single CCD and lower limit of the number of objects per square degree above which the CCD is full for an RVS resolution of 11500

spectrum width (in rows)	$n_{pix/obj}$	N^{crit}_{obj}
1	694	12900
2	1388	6450

the surface of one single CCD in square degree and in number of pixels, respectively. Values of N^{crit}_{obj} for the two possible widths of a single spectrum are listed in the third column of table 2. The critical density derived from relation 3 is a lower limit of the true density required to fill the CCD in the sense that it assumes no overlap of spectra. On the other hand, it must be noted that spectrum contamination due to overlap between neighbouring objects, becomes significant much before the critical star density listed in table 2 is reached.

3 Number of objects observed by RVS versus time during the GAIA mission and FoV filling

Figure 1 displays the number of objects up to magnitude limit 18 observed per day versus time during a 1800 days mission duration. Three plots are shown which correspond to the total number of objects (star + non star) counted in the two F and J band of GSC-2.2 as well as in the G band of the simple CTSR model.

During a 5 years mission, 23 peaks in the total number of objects scanned per day by RVS, and by the other GAIA instruments, can be clearly identified. These peaks can extend from 10 to 30 consecutive days of observation. They correspond to periods during which the the GAIA rotation axis points near (within $\sim 10\,$deg) the poles of our Galaxy so that the instruments scan the densest regions close to the galactic plane. The maximum number of scanned objects per day occurs between days 411 and 412 (from J2000.0) and amounts to 74 millions of objects in the F-band. The minimum number of scanned objects per day, occuring much more frequently, lies in the range 10-15 millions, still in the F-band.

The number of scanned objects also depends on the band of observation. The number of objects counted in the blue J-band is between 3 and 6 times lower than in the red F-band. The difference is less pronounced, at most a factor 2, between counts if the F-band and in the GAIA (CTSR Galaxy model) G magnitude.

Because the GSC-II F-band (around $\lambda \sim 0.71\mu$) is closer to the RVS wavelength band $(0.848-0.874\mu)$, star counts in the F-band must be preferably used for predicting the RVS telemetry budget. Figure 2 displays the number of objects observed per day in the F-band : separate curves are plotted for stars, non-star objects and total.

Throughout most of the mission, a similar number of star and non-star objects are scanned per day. Non star objects dominate the population of scanned objects during the 23 identified peaks. Apart from nebulae and galaxies, clearly non dominant at the magnitude limit $m_F \leq 18$, most "non-star" objects in GSC-2.2 are unresolved double or multiple stellar systems. In computing the telemetric flows expected from RVS (next section), we will take into account the sum of both stars and non stars objects listed in the GSC-2.2 release.

4 Telemetric flows, compression factors and data transmitted

In this note, we present telemetric flows integrated over one day of observation throughout the whole GAIA mission. Flows of data are computed separately for each FoV cell by multiplying the total number of objects within the cell by the number of pixels per spectrum. This last parameter depends on the RVS "configuration" or parameters set.

Of course, when computing the total number of pixels to be sent per FoV cell, we took into account CCD filling in crowded areas by limiting, when necessary, the number of objects within the cell to the maximum value above which the CCD is full : the maximum number of objects within a cell is obtained

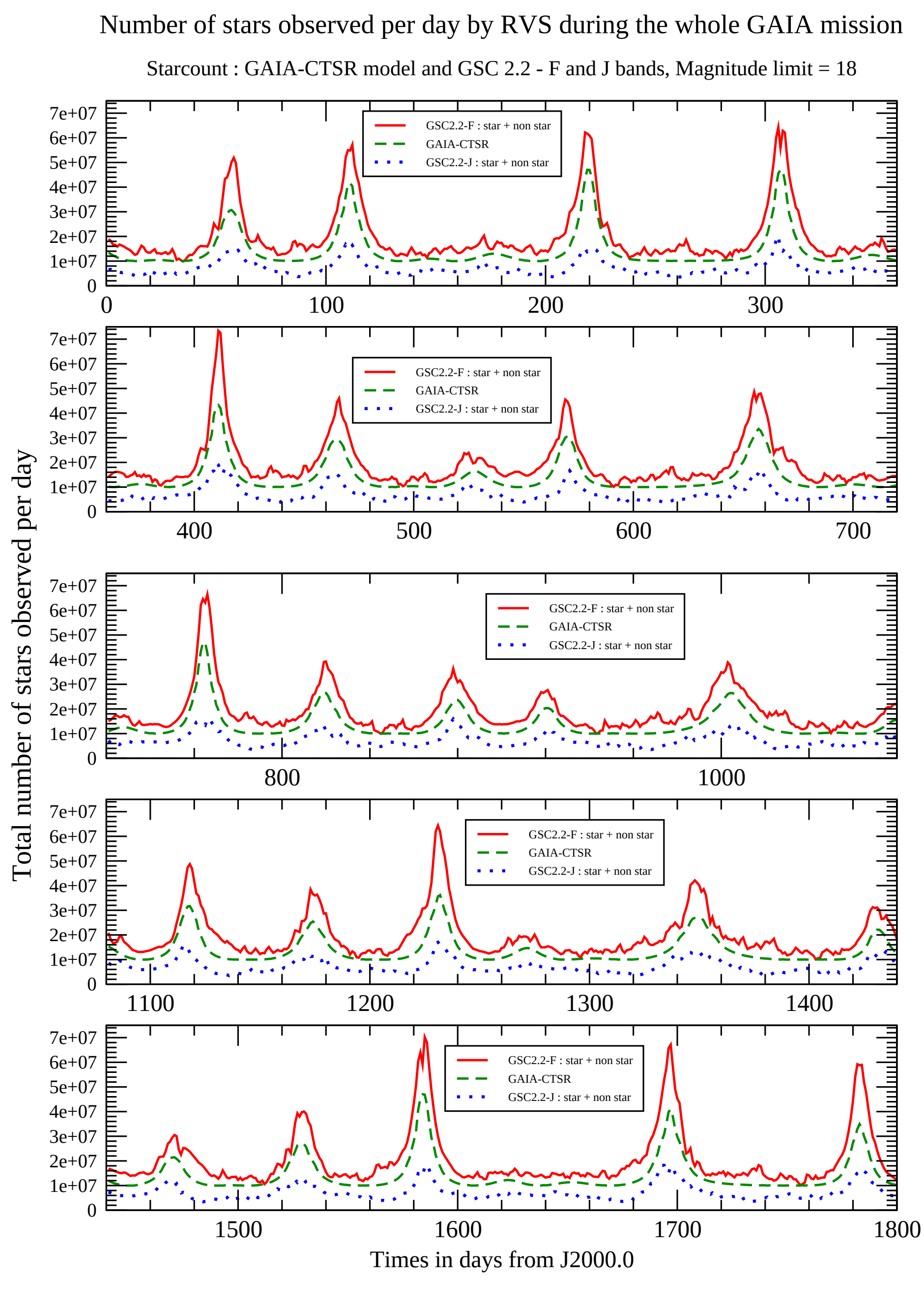

Figure 1: Number of objects up to $mag = 18$ observed per day by RVS

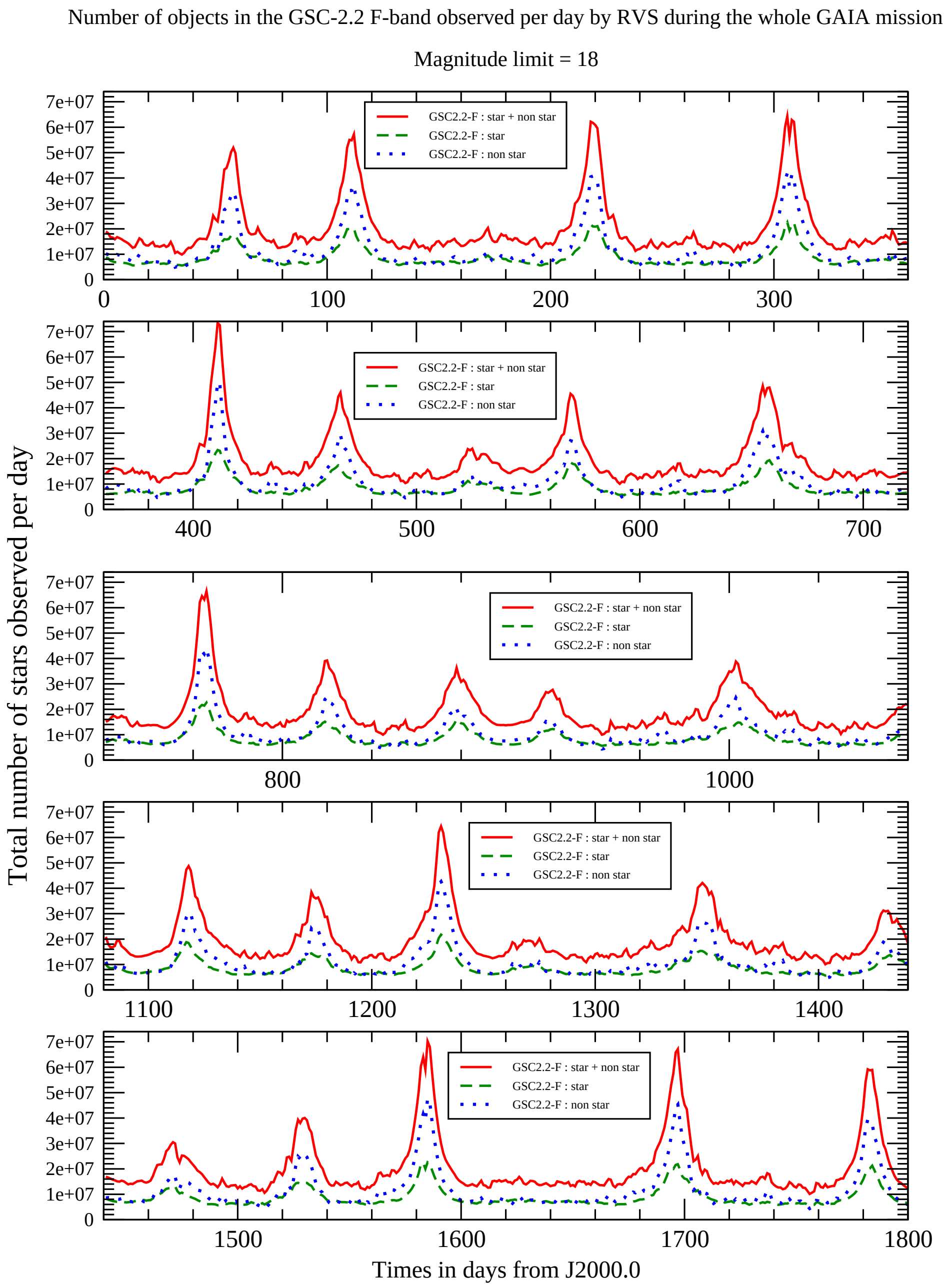

Figure 2: Number of stars, non-stars objects and total, observed per day by RVS, in the GSC-2.2 F-band up to $mag = 18$

by multiplying the critical density listed in the third column of table 2 by the cell area. Summation over the cells give the total number of pixels to be sent to the ground within each FOV. The telemetry rate per day (in bits/s) is obtained by summing all pixels of the 720 successive FoVs scanned in one day, by multiplying this total number of pixels by 16 (each pixel is coded in 2 bytes) and dividing by $t_{int} = 86400s$.

As concluded during the RVS November Workshop, it is necessary to sum on-board the 3 CCDs in order to approach the allocated telemetry budget. In what follows we assume that the 3 CCDs are summed on-board.

With the current design, the estimated RVS limiting magnitude is $F \simeq 17 - 17.5$. We computed daily telemetry rates for two magnitude limits 17 and 18 and for two scenarios of data pre-processing. 1) Two rows extracted per spectrum. 2) One row per object is sent for one half of the time, and two rows per object are sent for the other half, according to the across scan position of the spectrum with respect to the CCD rows ; moreover, in both cases, a full spectrum is sent for objects with $F < 16$ (about 25% of the total if $F_{lim} = 18$ and 50% of the total if $F_{lim} = 17$), and only half a spectrum, limited to the three Calcium lines, is sent for objects with $F \geq 16$ (about 75% of the total if $F_{lim} = 18$ and 50% of the total if $F_{lim} = 17$). In the second scenario, the mean number of pixels per observed object is 651 for $F = 18$ and 781 for $F = 17$; the corresponding lower limits of the number of objects that fill the CCD are 13760 and 11470 objects per square degree, respectively. Telemetric flows computed with the two scenarios, labelled by magnitude limit and number of pixels per object, are plotted on figure 3.

Outside the peaks, covering nearly half of the mission, the telemetry rate varies between 0.65 and 1.2 Mbits/s if $F_{lim} = 17$ and between 1 and 2 Mbits/s if $F_{lim} = 18$. The other half corresponds to peaks of the telemetry budget which rise up to 3 to 4 Mbits/s. The peaks are about 10 to 30 days wide. The on-board memory, currently sized to store 1 or 2 average days of data flow, will not smooth/flatten the peaks.

To refine our determinations of the amount of data that can be downloaded, table 3 displays, as a function of the data compression factor that could be available, the fraction of data that can be sent to the ground, for the four cases discussed above. The first line of the table corresponds to the case in which there is no compression apart from possible data pre-processing.

Table 3: Fraction of data saved versus compression factors for two magnitude limits $m = 17$ and 18 and two scenarios of data pre-processing characterized by the mean number of pixels sent per object

Compression factor	$m_F = 17$		$m_F = 18$	
	$n_{pix/obj}$		$n_{pix/obj}$	
	1388	781	1388	651
1	14.5%	20.4%	11.2%	16.3%
2	28.9%	40.8%	22.5%	32.5%
3	43.4%	61.2%	33.7%	48.8%
4	57.8%	77.2%	45.0%	65.0%
5	72.2%	84.7%	56.2%	77.6%
6	80.8%	89.6%	67.4%	84.0%

The second pre-processing scenario allows us to download around 1.4 times more data than the first one.

It should be noted that the gain in term of data transmitted is smaller than the reduction of the average number of pixels per spectrum (about a factor of 2). This is because, when integrated over one day (which corresponds to 720 successive RVS-FoVs), regions of very large star densities contribute to the telemetric flow. The star densities of those regions can exceed the critical density that fills the CCD by factors well above 2 (up to 10-100 in extremely dense regions). In such crowded FoVs the telemetric flow reaches its maximum value, which corresponds to all pixels occupied, "whatever" the area of a single spectrum. Reducing the size (in pixels) of single spectra impacts on the telemetric flow only in those regions where the star density is "low".

Assuming that the telemetry budget allocated to RVS remains 0.25 Mbits/s and that a compression factor of 3 is applied to the data, from 34 to 61 % of the spectroscopic data could be transmitted to the ground, according to the pre-processing scenario and the limiting magnitude chosen.

In our simulations, we used the F photometric band of the GSC-II. It is likely that the number of

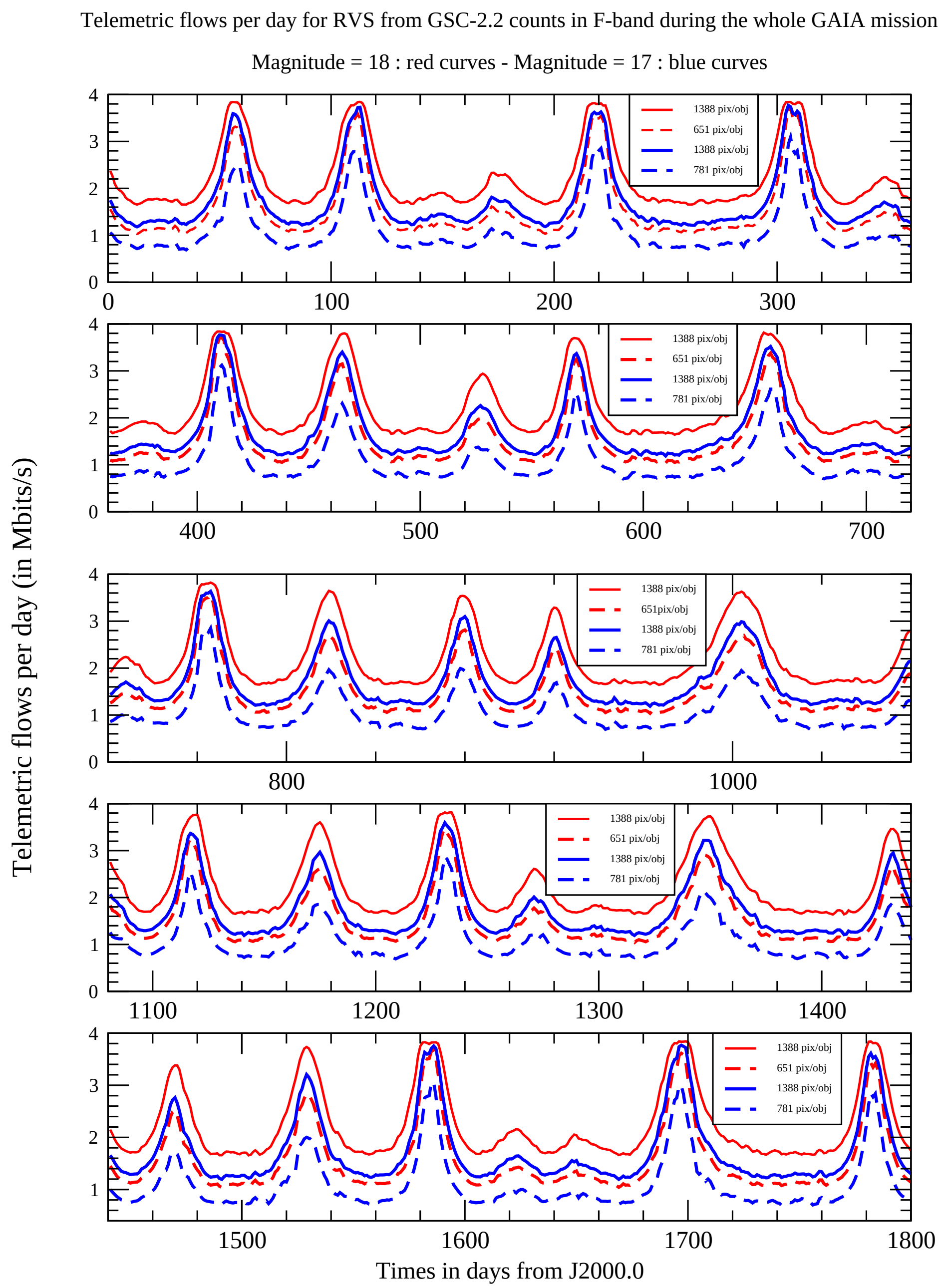

Figure 3: Telemetric flows expected per day for RVS from counts in the GSC-2.2 F-band, for four observational scenarios identified by the magnitude limit reached by RVS and the mean number of pixels per object sent to the ground

objects observed in the RVS band will be a bit larger and so will the telemetric flow. On the other hand, our simplified approach of the crowding of the FoV overestimates a bit the number of pixels downloaded. The results above gives the first order assessment of the telemetry budget. The next steps we foresee to refine this first estimate are presented in the next section.

5 Future works

Let us try to define what remains to be done in order to improve estimations of the telemetry budget expected from RVS until the end of phase A (end 2004). This is, of course, widely open to discussion within the RVS-WG and outside ; all suggestions are most welcome.

Improved statistical treatment of the crowding

In this note, we have merely identified the FoVs (or parts of FoVs) in which the star density is large enough to fill the CCD. The crowding problem is more complicated and requires to be examined further. Crowding should be taken into account as soon as individual spectra of stars overlap on the FoV and this occurs for star densities well below the critical densities that fill the CCD. A preliminary study of crowding in GAIA RVS has been done by Zwitter and Henden [9]. From their work, with the resolution chosen for RVS and pre-processing, we will undertake a statistical study of the degree of crowding (spectrum overlap) of the RVS-FoV versus the stellar density, i.e the number of pixels occupied as a function of the stellar density. Combined with the NSL, this will lead to a better estimation of the telemetry budget all along the mission.

Pre-processing of the data

In this note we started to address the pre-processing strategy (number of rows extracted per spectrum, selection of the Calcium lines, ...). As a next step we will (i) test the feasibility of the proposed pre-processing operations and (ii) assess in a more realistic way the impact of the pre-processing on the telemetry budget (refine distribution of spectrum positions and profiles with respect to the CCD rows, magnitude distribution from the GSC-II, ...).

Stars selection strategy

Depending on compression factors available and stellar densities on the sky, it should be feared that not all data up to the faintest stars observable by RVS will be sent to the ground.The strategy to select objects that will be observed according to scientific objectives must be clearly defined if one wants to take it into account. Our telemetry model will be used to check several possible selection algorithms ("first in first out", different magnitude limits versus star densities, galactic coordinates, etc.) and estimate the flow of data that can be downloaded and the location and quantity of data that are lost.

Counts in the RVS band

As shown in this note, the estimation of the total number of stars that will be observed by GAIA, depends on the adopted catalogue and on the wavelength of the band used to determine their magnitude. To come closer to the real observing conditions on GAIA-RVS, it is necessary to convert the magnitudes of objects determined in the different bands corresponding to the various catalogues into RVS-band magnitude. Because it is close to the photometric I band, we plan to establish, as a first step, correlations between I magnitudes and magnitudes in the various bands in catalogues, for selected sets of well identified photometric standards.

Comparison with other catalogues

To refine our predictions of the number of objects that will really be observed by GAIA and the corresponding telemetry budget, comparison of star counts and telemetric flows computed from different catalogues would be very desirable. We are intending to do this in the very near future by using the the USNO-B1 catalogue, which also covers the entire sky. We also plan to use the point source DENIS catalogue in band I : the main advantage is a photometry in a wavelength band closer to the one at which RVS works, but the main drawback is that the DENIS survey does not covers the entire sky and does not go as faint as the GSC-II and USNO-B1 catalogues.

Spatial resolution of the counts

Another way to improve telemetric flow predictions can also be obtained if star counts are performed within smaller areas on the sky. The results presented here rely on the implicit assumption that the star distribution is uniform at a scale lower than one square degree, which is a very rough approximation. We started to perform star counts from GSC-2.2 over sky areas 100 times smaller, i.e. within 6'x6' boxes. For the moment, to save computing time, we restricted the counts to low galactic latitudes in the range $-10\,\mathrm{deg} \leq b \leq +10\,\mathrm{deg}$.

Finally, all the work done on the telemetry budget of the RVS can of course be extended, if worthwhile, to other GAIA instruments such as the astrometric and photometric instruments (in particular to assess the telemetric flows versus antenna bandwidth in the 10-30 days telemtry peaks). This would require to use star catologues going deeper in magnitude, up to 20 or 21. The computational procedure would also have to take into account the fact that the telemetric flow for an individual object depends on its magnitude, which can easily be accounted for in our model in which stars are counted as a function of their magnitude. A further complication arises from the fact that the resolution of the astrometric and photometric instruments on GAIA is much better than the one used in building general star catalogues. The latter tend to underestimate the stellar density of faint objects in crowded regions and correction factors must be applied to get the true density : such correction factors are available for the GSC-II source counts in the F band [10] up to $F = 20$.

Acknowledgements Star counts have been performed by using the version of the GSC-II catalogue settled at the Centre de Données Stellaires de Strasbourg and the software of the Vizier database environment. Thanks are also due to F. Arenou and S. Mignot for a critical and useful reading of the manuscipt.

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