RADIAL VELOCITY SPECTROMETER: TECHNICAL ISSUES

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ABSTRACT

We examine the main technical issues which constrain the Gaia-RVS scientific performance, and drive its design. These are the need to maximise the number of detected photons given the *Spectro* telescope size and fixed exposure durations, and to minimise the internal instrument noise. The resulting design combines an elegant high efficiency optics solution, with L3CCD detector technology on high resistivity Si material, to maximise the quantum efficiency and minimise the readout noise. To cope with the data rate from the instrument, data from individual CCDs are combined on board, after remapping onto a common spatial scale and removal of blemishes and cosmic rays, then compressed with a lossless algorithm, necessary for the preservation of the low level signals in the data.

Key words: Gaia; Space vehicles: instruments; Instrumentation: spectrographs; Surveys; Stars: fundamental parameters; Galaxy: kinematics and dynamics.

1. GAIA-RVS SCIENCE DRIVERS AND CONSTRAINTS

In the Gaia payload, RVS provides the 6^{th} dimension of phase space information, correction for the perspective acceleration to the astrometric parameters, astrophysical parameters for brighter objects, and information on binarity and peculiarity (Katz et al. 2004, 2005). The RVS spectral survey will be orders of magnitude larger than any other spectral survey, and its good resolution, the multi-epoch nature of its measurements and the clear sample selection function will enable fundamental advances on the nature of the Galaxy and how it was formed and has evolved.

Gaia-RVS is specified to provide radial velocity measurements for G5V stars with an accuracy of 10–15 km s^{-1} to V = 17 by the end of the mission (Katz et al. 2004). There are similar requirements for metal poor stars and stars of later spectral type. The spectral range of the instrument is 848–874 nm (in the far red around the Ca triplet) and the spectral resolving power $\lambda/\Delta\lambda = 11\,500$. The aperture of the telescope feeding the RVS is modest at 0.25 m^2, so at the faint limit, spectra from many scans need to be combined to produce this radial velocity accuracy. For brighter objects, the resolution is sufficient to provide astrophysical information ($T_{\rm eff}$, $\log(g)$, etc).

Spectra drift over the focal plane as Gaia rotates, so the RVS detectors must operate in a TDI (Time Delay and Integrate) mode. The exposure duration across whole focal plane is $\sim$ 120 s and there are $\sim$ 100 transits of each object over the mission lifetime of 5.5 years. The TDI operation prohibits the use of a slit in the spectrograph, so there is no control over the crowding and overlapping of spectra on the focal plane. The particular nature of the Gaia scan law induces across-scan (AC) motion of up to 165 μm during a transit. The dispersion direction in RVS is along the scan (AL) direction, so that this AC motion does not reduce the spectral resolution.

The modest telescope size and fixed exposure duration set by the scan rate results in very few photons per transit for stars at the $V = 17$ faint limit. Moreover, these photons are spread over a large number of pixels, typically 700×2 (AL$\times$AC). Generally the star density is such that there is some spectral overlap, and spectra cover much of the focal plane.

These science requirements and constraints drive the Gaia-RVS design strongly. We consider next the main factors impacting on RVS performance.

2. MAIN TECHNICAL ISSUES

2.1. Photon Rate

We have simulated the output from a single focal plane CCD in order to examine the photon rates expected for stars of different brightness using the MSSL RVS simulator[1]. The assumptions for throughput for the system

[1]http://www.mssl.ucl.ac.uk/gaia-rvs

follow those given in Katz et al. (2004). The star densities and range of spectral types is as given in Perryman et al. (2000). A simulated image from a high Galactic field is shown in Figure 1. Here the strong Ca lines can be seen in the brighter spectra, and only modest overlapping of spectra occur. The background is a mixture of Zodiacal background flux and instrumental noise (mostly readout noise in the CCD detectors). It should be noted that the readout noise in this image is as expected from the L3CCDs used in Gaia-RVS (see Section 3.2).

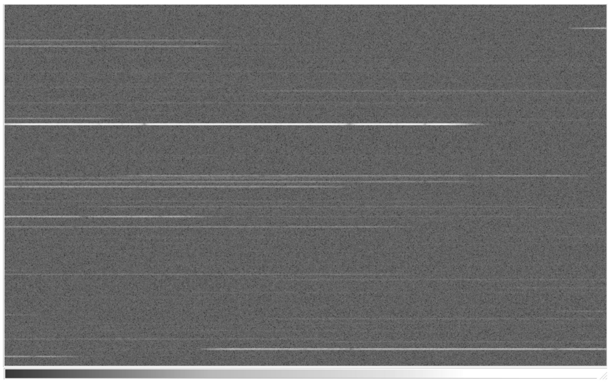


Figure 1. Simulated image from a portion of one of the Gaia-RVS focal plane CCDs after the 12 sec transit. The brightest spectrum is from a V = 10.3 F0V star. The scaling is square root of intensity, and 2 e^{-} readout noise is assumed.

We have first set all noise sources to zero and then extracted two example spectra from a re-simulated image as in Figure 1. We have extracted one line per spectrum only. The bright spectrum of a $V = 10.3$ K0V star is shown in Figure 2 (top). Here the strong Ca triplet is evident, together with other lines of Fe, Si etc. The overall shape of the spectrum is set by the RVS bandpass filter. There are a significant number of counts per pixel even for the transit of only one CCD.

We have also selected a fainter spectrum from a $V = 16.9$ F0V star, and this is shown in Figure 2 (bottom). Here the count rate is much lower, with on average less than a single photon per pixel. This indicates the expected source exposure for a star at the limiting magnitude of the RVS.

The first main technical issue arising is therefore that every photon collected by the instrument is valuable. The throughput of instrument is paramount, requiring high efficiency optics and high sensitivity detectors. It is clear that the required 10 km s^{-1} radial velocity accuracy will be achieved only by adding data from each CCD in a transit, and all 100 transits, and then only by cross-correlating all 700 pixels in the spectrum with a radial velocity template, effectively folding all pixels into a single derived spectral shift. The implication is that it is necessary to preserve data intact all through the transmission chain to achieve final radial velocity performance.

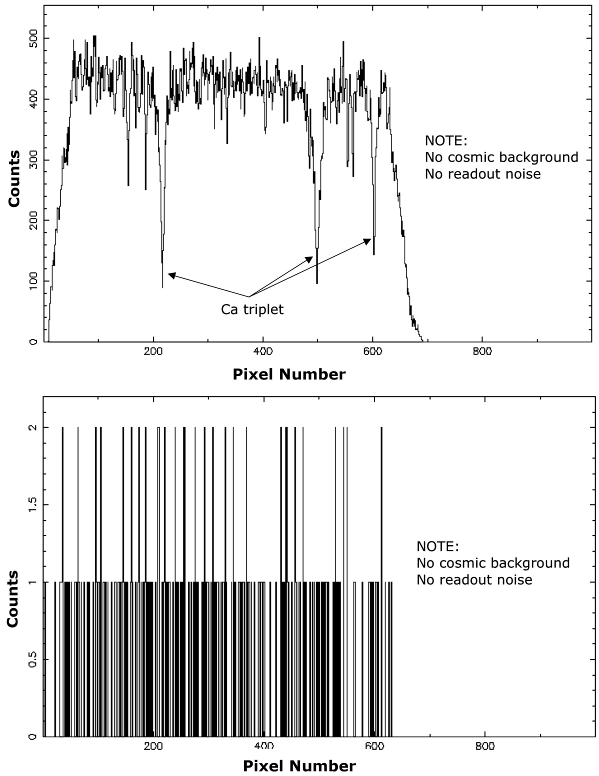


Figure 2. (top) The extracted spectrum for a V = 10.3 K0 star from a simulated image as in Figure 1, but with all noise sources set to zero. This is the brightest spectrum in Figure 1. (bottom) The extracted spectrum from a V = 16.9 F0V star. Note the y-axis scale.

2.2. The Effect of Background

To demonstrate the effects of background, we extracted the $V = 16.9$ F0V star spectrum from the simulated image in Figure 1, which assumed 2 e^{-} readout noise. Then we re-simulated the image with 8 e^{-} readout noise and extracted the spectrum. Both images have nominal Zodical background (Katz et al. 2004). The extracted spectra in the presence of noise are shown in Figure 3.

It is evident from Figure 3 that the signal from a single transit of a single CCD is deeply buried in the noise. This is particularly pronounced for the 8 e^{-} case. The second main technical issue is therefore that low noise performance of the instrument is paramount.

Special measures are required to reduce the readout noise to a minimum (2e^{-}): except for exceptionally slow readout rates (not applicable in the case of RVS), this is achieved only with particular types of CCDs (L3CCDs, Section 3.2). Beyond the CCDs themselves, attention must be paid to the noise performance of the complete analog detection chain.

Such low signal-to-noise ratios are atypical of normal CCD operation, where the exposure duration can be chosen. A consequence of the low signal levels is that most of the information sent to ground is readout noise with

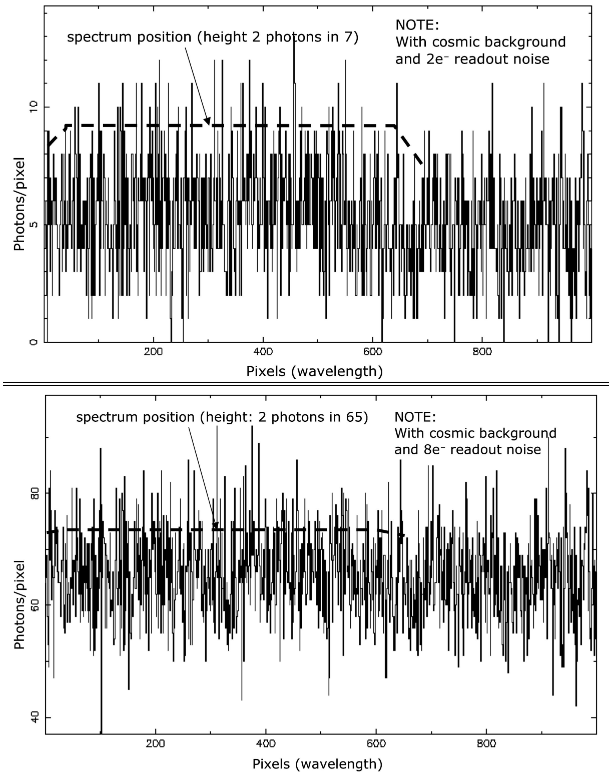


Figure 3. The extracted spectrum from a V = 16.9 F0V star with 2 e^- readout noise (top) and 8 e^- readout noise (bottom). The dotted lines indicate the position of the spectrum.

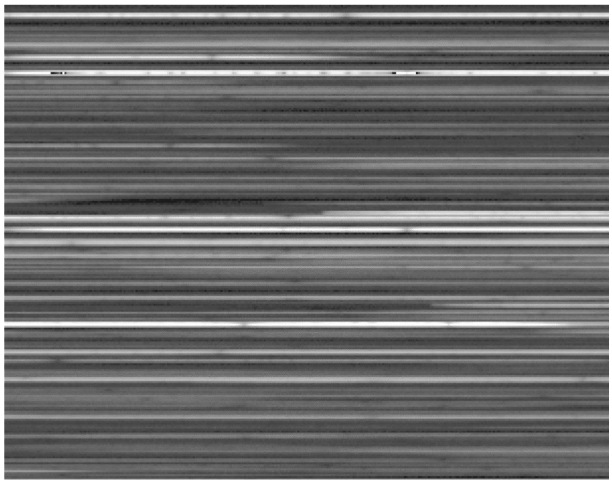


Figure 4. Simulated image from a portion of the Gaia-RVS focal plane accumulated over the full mission for a star density of 9000 stars deg^{-2}, typical of a Galactic latitude of $|b| \sim 10\,\mathrm{deg}$. Again, the scaling is square root of intensity, and 2 e^- readout noise is assumed. Some brighter spectra have exceeded the 16 bit dynamic range in this image. All scans are assumed to have occurred in the same direction on the sky.

the signal deeply buried in the noise. Only lossless compression schemes are therefore acceptable: because lossy schemes work by modelling the noise, these would remove the traces of the signal. It is necessary to preserve the data intact to the ground where it can be combined, in order to achieve the final radial velocity performance.

2.3. Crowding

Figure 4 shows a low Galactic latitude field (9000 stars deg^{-2}) for an end of mission exposure accumulated from a full RVS focal plane. It is evident that almost all of the field of view is occupied by wanted spectra. The third main technical issue therefore is that there is significant overlap of spectra in all fields (and particularly at lower Galactic latitudes). Minimising the spatial profile of the spectrum is therefore important, even in the case of large AC motions due to the scan law.

A further implication is that it is necessary to read out the whole CCD (rather than only windows around the spectra) at all times. This leads to very large potential telemetry rates from Gaia-RVS (42 Mbits/s compared to an average availability of 1.2 Mbit/s for Gaia). Significant on-board processing must therefore be performed, while at the same time, attention must be paid to minimise information loss due to this processing.

Gaia-RVS data will require particular spectral extraction schemes in the ground processing to maximise information retrieval.

All RVS performance predictions need to include the effect of spectral overlap. This is mitigated to some extent by the fact that individual scans will be orientated at different angles on the sky, so that overlaps in one scan may not be repeated in others.

2.4. At the Faint Limit

While the requirements for maximising signal-to-noise ratio in RVS, and for minimising the effect of crowding are stringent, if the data can be transmitted without further degradation, the $\sim$ 10 000 s total exposure allows sufficient information in the accumulated spectra for stars at the faint limit for the velocities to be extracted. An example of such a spectrum is shown in Figure 5.

The relationship between input and output radial velocities is shown in Figure 6 (top), and the deviations in km s^{-1} are shown as a histogram in Figure 6 (bottom). These velocities are derived using non-optimised extraction and cross-correlation scheme. Nevertheless, it is clear that the RVS performance requirements are met in this simulation.

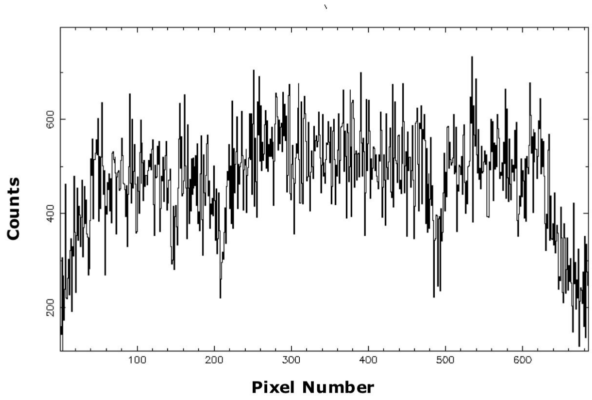


Figure 5. (top) The extracted spectrum for a $V = 17.3$ K0 star from a simulated image as in Figure 1, but for end of mission.

3. TECHNICAL SOLUTIONS

3.1. Optical Layout

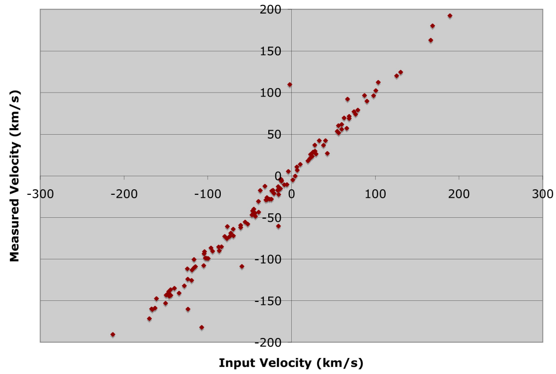
RVS is fed from the central field of the *Spectro* telescope on Gaia. The field of view is fairly large at $2.45\,^\circ \times 1.6^\circ$ AL$\times$AC.

While initial concepts for Gaia-RVS considered lens-based designs incorporating a collimator-disperser-camera system, these were dropped more recently in favour of an Offner-type spectrometer. This elegant solution has the advantage of the minimum number of optical elements, thus maximising the throughput. Nevertheless, symmetries in the system produce good optical performance. In addition, the technologies used for the mirrors can be similar to those used elsewhere in the Gaia payload. The optical layout for the RVS is shown in Figure 7.

In any instrument such as RVS operating in TDI mode, optical distortions translate directly into a broadening of the point spread function (PSF) in both AL and AC directions. In addition, variations of dispersion over the field of view also broadens the PSF in the AL direction. The optical design for RVS must therefore control the distortions and the spatial variation of dispersion to a greater extent than would normally be required. We reduce some of these effects in Gaia-RVS by breaking the focal plane into narrower detectors, so that the distortion and dispersion errors do not build up significantly before the images reach the detector readout (Section 3.2). The larger scale remapping to a common spatial scale is then performed as part of the on-board data processing task, after which the data from individual CCDs are co-added to reduce the telemetry rate (Section 3.3).

3.2. RVS Focal Plane Assembly

It has been a complex process defining the optimal focal plane for RVS. Firstly, the AC motion from the Gaia scan law must be compensated for. This can be done by introducing a mechanism into the RVS (potentially degrading the astrometric measurements), by populating the focal plane with CCDs narrow in the AL direction (so that only negligible AC motion occurs before the spectrum reaches a readout node), or by introducing a 2-dimensional clocking capability into the CCDs directly (this has been demonstrated, and there is ESA funding to take this further, but it is not a widely available technology). All of these have been considered. The mechanism and 2-dimensional clocking have the further disadvantages that they compensate only the AC motion due to the scan law, and not the optical distortions, and also that radiation damage reduces the data quality to a greater extent. This is because of increased charge transfer inefficiency and the loss of a full CCD column in TDI mode when a single pixel is damaged.



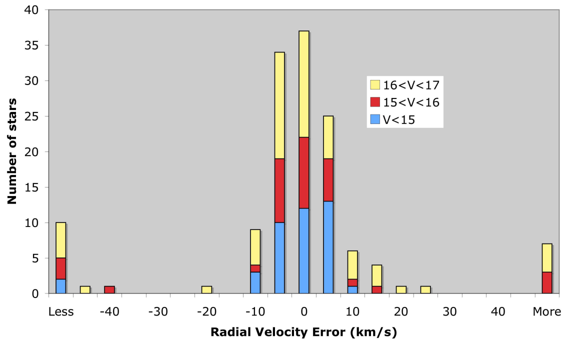


Figure 6. The derived velocities for stars with $V \leq 17$ from a high Galactic latitude field (900 stars deg^{-2}) for end of mission as a function of magnitude. (top) Input vs derived velocities. (bottom) Deviation from input velocity.

The narrow CCD option provides the best solution in terms of performance, system impact and development costs. This is shown in Figure 8. The difficulty with the higher readout noise resulting from the larger number of readout nodes can be countered by resort to L3CCD technology (Jerram et al. 2001). This uses an avalanche multiplication process to increase the CCD signal before the readout, effectively decreasing the readout noise by the gain factor. A schematic of the L3CCD is shown in Figure 9. In RVS we will use modest gains of ~ 10, limiting the voltages required in the avalanche gain register, while

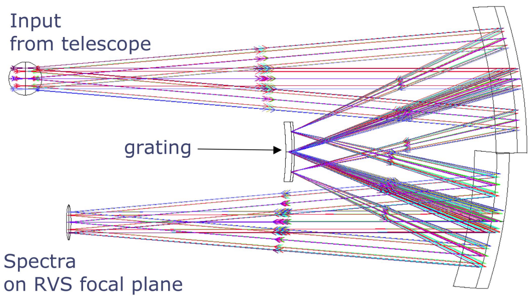


Figure 7. The optical layout of the RVS. The two mirrors are off-axis aspheres, while the grating is ruled on a convex spherical surface.

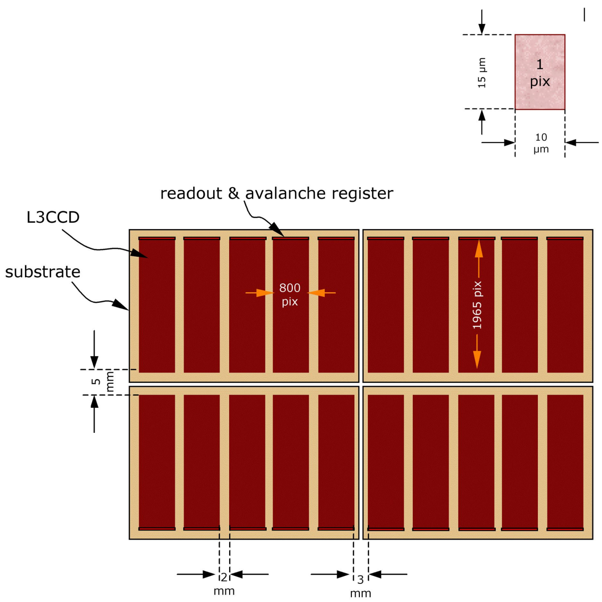


Figure 8. The RVS focal plane. This is derived from the MBP focal plane, so has the same 4 × 5 CCD layout, each of 800 × 1965 pixels AL×AC. Each pixel is rectangular with dimensions 10 × 15μm.

at the same time reducing the readout noise to below that of other noise sources in the video chain.

Some developments are required to space-qualify the L3CCD technology. Radiation testing with protons and with ionising radiation has indicated that there are no particular damage mechanisms for the L3CCDs over and above those for normal CCDs (Smith et al. 2003; Hadwen et al. 2004). Since the detected quantum efficiency (DQE) and modulation transfer function (MTF) of the CCDs must be maximised, high resitivity Si ($\sim$1000Ω-cm) material must be used . No high resistivity L3CCDs have yet been made, although a batch is being processed at the time of writing by e2v technologies. There is some indication (still to be investigated) that higher voltages will be required in these devices to produce the avalanching, which may impinge on device lifetime. This will become clearer with the delivery of the batch noted above.

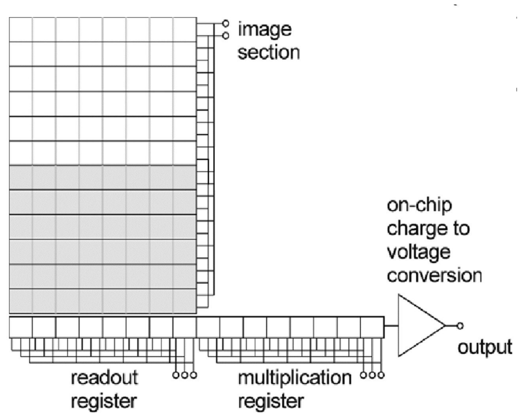


Figure 9. A schematic of the L3CCD showing the avalanche gain register after the readout register. From Hadwen et al. (2004).

3.3. On-board Processing

Unlike other instruments on Gaia, data processing is necessary in RVS to reduce the data rate. This is accomplished principally by combining the data from different CCDs. As noted in Section 3.1, a spatial remapping is required before the co-addition, and in order to minimise the effect of cosmetic blemishes on the detectors arising during fabrication or caused by radiation damage, no defective pixels should be included in the co-addition. Similarly, cosmic ray events should be detected in the on-board processing routines, and no affected pixels used. After the co-addition, only those areas of the CCD which contain spectra need to be downloaded, so those areas not selected by the RVS Starmapper (which is used for this purpose) are set to zero. These will be compressed strongly by the compression algorithm, which in the RVS case must be lossless, to ensure the low signals mixed with the noise are not eliminated.

The processing tasks in sequence are as follows:

1. CCD gain correction
2. Blemish reduction
3. Scan law and Across Scan optical distortion correction
4. Along Scan optical distortion correction
5. Cosmic ray removal
6. Co-adding
7. Output data selection
8. Lossless compression

Most of the remapping and rescaling tasks can be performed using lookup tables. The data selection tasks are carried out using a mask generated from the RVS Starmapper data. The on-board processing tasks require some system resources. They are reasonably deterministic, given the input from the RVS Starmapper, so it is conceivable that they are performed by a sequential processing engine realised in hardware. However, a software solution will provide superior capability and more adaptability in realisation.

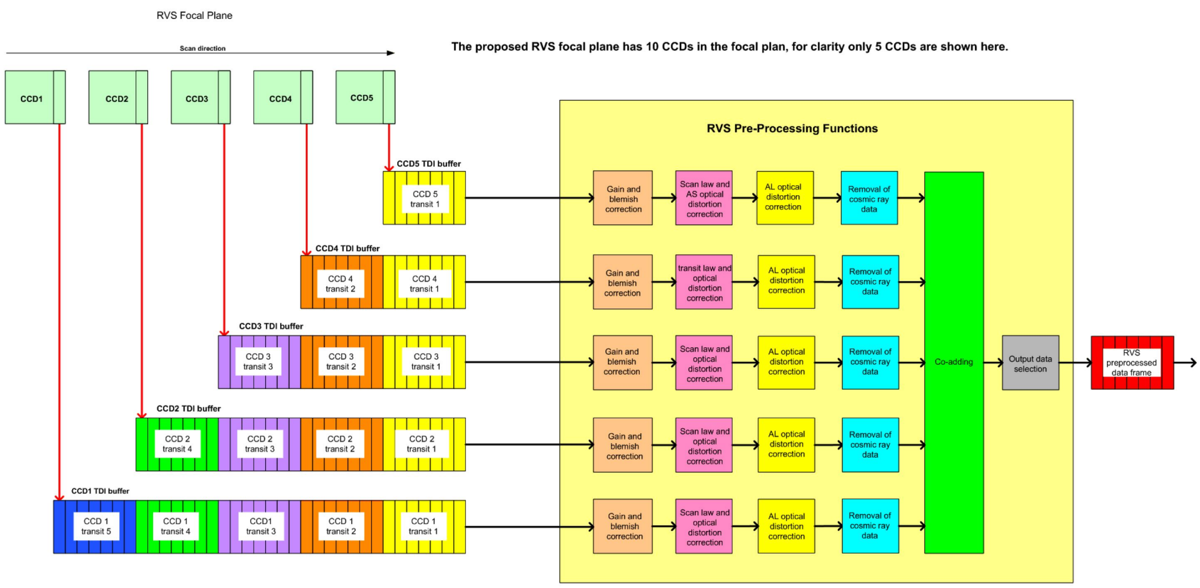


Figure 10. Schematic of the RVS processing. Data from individual CCDs are stored in delay-line buffers so that data for a particular spectrum from all CCDs are aligned. Remapping and blemish removal tasks are carried out before co-addition and data selection. Note that only 5 CCDs are shown here for clarity: in RVS this will be 10, with the upper and lower banks of CCDs being processed independently.

4. SUMMARY

In summary, Gaia-RVS has a number of critical technical issues which require particular attention if its performance is to be maintained: maintainance of high throughput drives the optics and detector design; minimisation of instrument noise levels drives the choice of detector to L3CCD types; and the data rate from focal plane requires carefully designed on-board data processing. Of course there are other important issues as well; for example it is vital that mechanical and thermal disturbances to the Astro payload are minimised.

Ensuring the performance of Gaia-RVS extends beyond the instrument itself to the ground system. In particular, the extraction of spectra requires careful algorithm design for the treatment of crowding and spectral overlaps.

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