Flatfielding RVS

RVS Calibration

prepared by: C. Allende Prieto
approved by:
reference: GAIA-C6-SP-MSSL-CAP-002
issue: 1
revision: 3
date: May 12, 2009
status:

Abstract

The Gaia CCDs are operated in Time Delay Integration (TDI) mode and, therefore, pixel-to-pixel sensitivity variations and any other irregularities in the response across the along scan (dispersion) direction are effectively cancelled out. Response variations in the across-scan direction will persist, and a strategy for flatfielding is required to guarantee a high data quality. We present estimates indicating that it is feasible to use a large number of stellar spectra from the Radial Velocity Spectrometer (RVS) to flatfield the RVS CCDs in the across-scan direction.

Document History

Issue	Revision	Date	Author	Comment
1	0	2008-10-01	CAP	Draft
1	1	2008-09-23	CAP	Made a number of modifications following comments by Mark Cropper
1	2	2009-03-29	CAP	Minor edits
1	2	2009-05-12	CAP	Minor edits following comments by Jos de Bruijne

Contents

1 Introduction

CCD detectors never have perfect cosmetics. Modern science-quality detectors have typical pixel-to-pixel sensitivity variations less than 1 %, and a few percent at most. Hot and cold pixels usually show much larger response anomalies.

Fringing, a phenomenon caused by interference of nearly monochromatic light due to multiple reflections inside the pixels, can be quite severe in CCDs used at red and near-infrared wavelengths, reaching, in some cases, amplitudes of more than 50 %. A recent study focused in thinned back-illuminated CCDs such as those that will be used in Gaia for the Basic Angle Monitor (BAM) and the Radial Velocity Spectrometer (RVS) predicts that the fringe contrast in these CCDs will be 4–10 %. In the case of the RVS CCDs, operated in Time Delayed Integration (TDI) mode, a given star transit will cross a row of 3 detectors, and the signal at each frequency (or pixel) in the final spectrum will see 4500 pixels. This dramatically smooths out the fringes to an expected level of 0.05 % (GAIA-ASF-TCN-PLM-00227).

The design of RVS and the Gaia focal plane in general calls for no moving parts. In this situation, it becomes impossible to separate imperfections in the optics, that may lead to a reduced transmittance through the optical path, from blemishes or fringes in the detector. The level of these imperfections is difficult to predict, but it is hoped they will be fairly small.

The signal-to-noise ratio level per pixel that will be achieved for a single transit of the brightest RVS target will always be less than 100. The previous arguments suggest that correcting response variations across the dispersion direction (AC) in the RVS focal plane may not be critical. Nonetheless, correlations in sensitivity for all the pixels in a given CCD column (along scan, AL), unexpectedly large blemishes in the detector, hot pixels, or optical imperfections, could render a *flatfield* correction necessary. Unfortunately, Gaia will fly with no calibration sources onboard, and the satellite operation, with a non-stop data acquisition mode, does not leave room for acquiring calibration frames. Thus, a *flatfielding* strategy must rely on astronomical sources.

This document presents a flatfield calibration strategy that allows correcting average sensitivity variations for each of the RVS CCDs in AC to a level of 1%. This can be achieved by simply co-adding the signal for large numbers of spectra. The signal from each star would be assigned to its average AC position across a given CCD, and spread according to the PSF shape, building up a *stellar flatfield*.

2 Number of sources

The motion of the stars on the RVS focal plane is not always perfectly aligned with the CCDs, and a transit through a single detector can span up to 4 pixels in AC. In addition, the PSF in the AC direction has a predicted maximum FWHM of 2 pixels (before accounting for smearing due to AC motion). These complications will be largely ignored here, where for now we will consider that the motion is perfectly aligned with the CCD and a given star will only transit through a single CCD column. Under these conditions, the probability for a star to fall in one particular column (p) is the inverse of the number of columns. For n transits, the number that fall in a given pixel (k) follows a binomial distribution

$$P(k) = \binom{n}{k} p^k (1-p)^{n-k} = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k}, \tag{1}$$

and the mean and variance are $n \times p$ and $n \times p \times (1-p)$, respectively.

Considering stars of uniform brightness, if we aim at correcting sensitivity variations at a level of 1 %, we can easily see that $n = (1-p)/(0.01^2 p)$ transits are required. Given that the Gaia CCDs have about 2000 pixels in AC and a minimum FWHM for the AC PSF of 2 pixels, assuming a star illuminates uniformly two AC pixels we have $p \sim 10^{-3}$, and need about 10^7 transits. Given that RVS will read and telemeter spectra for about 10^8 sources that will make 10^9 transits on each of the four sets of three CCDs, we can see that this is a feasible possibility.

In addition to the number of transits, the uniformity of the added signal for all the considered sources will require a signal-to-noise ratio of at least 100, or a contribution of 10^{-5} electrons per transit integrated over all wavelengths, which will be amply satisfied. Another source of inhomogeneity is the non-uniform brightness of the sample. Such effect can be arbitrarily reduced by limiting the magnitude range of the sources used to construct the flatfield image, although this is done at the expense of reducing the number of sources. We perform more detailed simulations below to show that this will not be a problem either.

3 Simulations

3.1 Brightness distribution

We use an empirical approach to analyze the brightness distribution of the RVS sources. We extract photometry information for a 1 deg^2 field from the Sloan Digital Sky survey (SDSS). The field was selected at an intermediate galactic latitude $(\alpha, \delta) = (258.4, 60.0) \sim (l, b) = (89, 35.4)$ deg, for an average star density. We use the photometry in the SDSS i band, centered at about 750 nm – recall that the RVS spectral range spans 847-874 nm. The stellar density as a function of magnitude is shown in Fig. 1. This survey is complete down to $i \sim 21-22$, and stars brighter than about $i \sim 14$ are excluded due to saturation.

The stellar density between $14 < i < 20$ can be reasonably well approximated with a power law $\log N \propto 0.18 \log i$, as illustrated by the red line in the Figure, which we will adopt for our calculations. This field contains 29,001 stars, of which there are 165 stars in the range

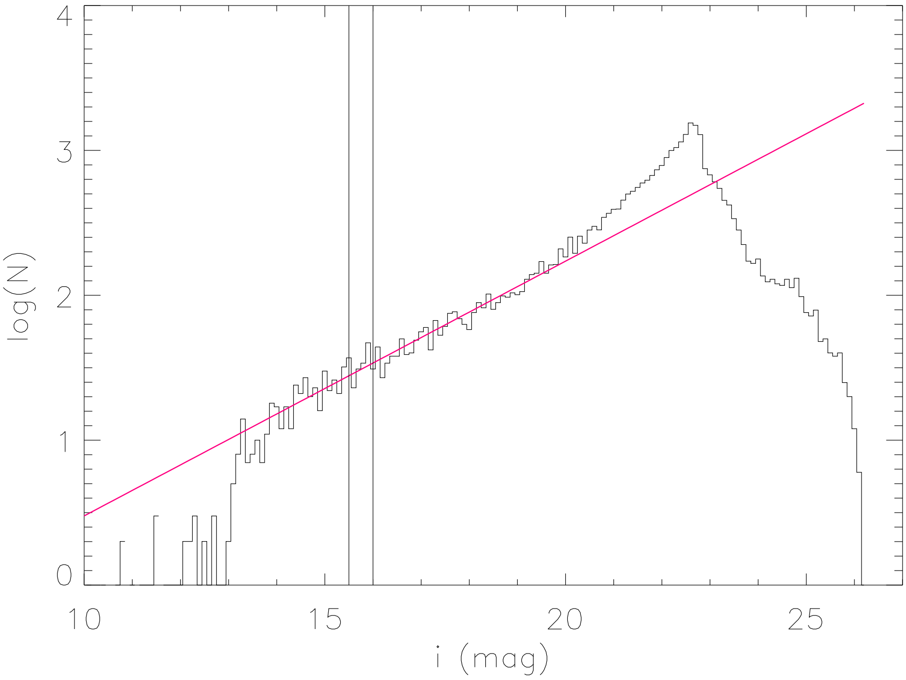

Figure 1: Stellar density as a function of SDSS i magnitude for a 1 deg^2 field near $(\alpha, \delta) = (258.4, 60.0)$. The red line is a linear least-squares fitting to the data in the range $14 < i < 20$ mag: $\log_{10} N = -1.28 + 0.18i$. The black vertical lines mark the position of $i = 15.5$ and $i = 16.0$ mag.

Table 1: Expected signal and standard deviation in a given pixel pair in AC after co-adding the signal for 10^7 stars.

G_{rvs} range (mag)	$< G_{\mathrm{rvs}} >$ (mag)	ΔG_{rvs} (mag)	Signal e-	σ(Signal) e-
15.5–16.0	15.76	0.5	5.433×10^6	55694.3
15.0–16.5	15.83	1.5	5.471×10^6	58263.2
13.5–16.5	15.30	3.0	1.117×10^7	141990.
11.5–16.5	14.81	5.0	2.954×10^7	551103.

$15.5 < i < 16.0$; for comparison, the linear model predicts 157 in the same range. The fraction of stars in this magnitude range is about 15 % of the total predicted by the model for the range $5.7 < i < 16.5$. Assuming a uniform stellar density over the whole sky, this model will then predict 4.5×10^7 stars in the $5.7 < i < 16.5$ range, which is close to the 10^8 stars expected for the RVS.

3.2 Experiments

We simulated the observation of 10^7 stars on one of the Gaia CCDs. The stars were first assumed to have a uniform brightness $G_{\mathrm{rvs}} = 15.76$, which corresponds to approximately 538 e^- for the entire spectrum ($G_{\mathrm{rvs}} \simeq= -2.5\log(e^-) + 22.5866$ [1]). They were randomly spread over 1000 pixels (or more precise pairs of pixels) with a uniform density, then the statistics for the number of the electrons resulting from adding all the signal were derived. The average signal was of course $538 \times 10^7 \times 10^{-3} = 5.380 \times 10^6$, and the standard deviation was 54861.9 or $\simeq 1.020\%$, as estimated in §2.

We then repeated the experiment generating a distribution of G_{rvs} magnitudes in the range $15.5 < G_{\mathrm{rvs}} < 16.0$, using the power law derived in the previous section. The mean magnitude corresponds to the same value considered in the previous experiment $Grvs = 15.76$, and the average signal per pixel is similar 5.433×10^6. In this case the standard deviation was 55694.3, or 1.025 %, essentially unchanged compared to the case of stars with uniform brightness. We also performed runs for wider magnitude ranges, as reported in the Table. It is necessary to exceed a range of 3 mag in order to see the impact of the non-uniform brightness on the scatter (1.3 % for a range of 3 mag and 1.9 % for a range of 5 mag).

4 Conclusion

Our estimates indicate that of the order of 10^7 *star* transits are necessary to get a coadded signal uniform to a level of 1 % over 1000 pixel pairs in the spatial direction (AC) of any of the RVS

---

[1] This is derived from the integration time and the zero-point magnitude from the Gaia Parameter Database

CCDs. (The CCDs have about 2000 pixels in AC, and the minimum AC FWHM is 2 pixels). This estimate was done for stars of uniform brightness, but the extra dispersion introduced by the real, power-law, magnitude distribution over a range of up to 3 magnitudes is negligible. The signal level in the coadded *flatfield* will in all cases exceed 10^6 e^-/pixel (addition of all pixels in an AL column), which would be enough to reduce the photon noise to a level of 1 part per thousand.

RVS will observe about 10^8 sources and about 15 % of them will be in the range $15.5 < G_{\rm rvs} < 16.0$, with an average of 40 transits per object. The RVS focal plane consists of 12 CCDs, arranged in 4 rows in such a way that each row will see 1/4 of the total RVS transits, leaving about 1.5×10^8 observations per CCD. Given that 10^7 transits will suffice to reach uniformity of the signal across AC to a 1% level, it would be possible to create about 15 stellar *flatfield* images during the mission life time. Alternatively, if all the stars in that range were combined to create a single flatfield, it would make it possible to detect non-uniformities in the AC direction to a level of about 0.3 %, assuming such features remain constant during the Gaia lifetime.

The figures drawn above are based on the assumptions that the star motion is perfectly aligned with the AL direction in the CCDs and that one star illuminates uniformly two AC CCD columns. The former assumption is not always true and transits can span a range in AC between the two extremes of a CCD of up to 4 pixels. This will lead to a blurring of the resulting flatfield over a few pixels.