

Exposure-based algorithm for removing systematics out of the CoRoT light curves

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1. Introduction

The CoRoT space mission (Baglin et al. 2006) was operating for almost 6 yr, producing thousands of continuous photometric light curves. The readout of each CCD exposure transfers simultaneously the flux of 6000 stars. The temporal series of exposures are processed by the production pipeline, correcting the data for known instrumental effects, such as gain, background, jitter, EMI, SAA discarding, time corrections (Samadi et al. 2006; Auvergne et al. 2009). But even after these model-based corrections, some collective trends are still visible in the light curves (Fig. II.3.1). The flux gradually decreases with unknown shape and a different slope for each star. Previous work to correct these effects has been suggested, including MagZeP (Mazeh et al. 2009), that uses a zero-point magnitude correction, associated with the SysRem systematics algorithm (Tamuz et al. 2005).

Algorithms for removing systematics consist of two parts: 1) identify the effects among a set of stars by combining all light curves like SysRem (Tamuz et al. 2005), see also (Ofir et al. 2010), finding combination of a few representative stars (Kovács et al. 2005) or fitting a model for each exposure based on observational (Kruszewski & Semeniuk 2003) or instrumental quantities (Mazeh et al. 2009); then 2) remove them by properly adapting them to each light curve. An effect is a pattern that appears among a large set of independent stars. Effects can be additive, multiplicative or follow any law that needs to be determined. In the common techniques, the effects are derived from a training set of stars using correlation methods like the iterative SysRem (Tamuz et al. 2005). The training set can be a properly selected subset of stars or even the whole set itself.

After their global determination, the effects need to be scaled and subtracted from each of the light curves. Classical fitting techniques like least square are not satisfactory because the resulting coefficient is partly pulled by the light curve's natural shape and disturbs the scientific

signal. For example, the gradual loss of sensitivity visible in Fig. II.3.1 correlates with any long-period stellar variability, resulting in removing some real signal. To avoid this critical drawback, we propose here a technique similar to MagZeP (Mazeh et al. 2009) that fits the instrumental effects to each exposure independently. The effect of each exposure is a function of only two instrumental stellar parameters, position on the CCD and photometric aperture. The advantage is that the effect is not a function of the stellar flux, and therefore much more robust.

A previous version of this paper was published as a proceeding paper in SF2A meeting (Guterman et al. 2015). It is structured as follows: Sect. 2 describes the systematics removal method and its application to CoRoT, Sect. 3 reviews the derived effects and the performances of the method and Sect. 4 summarizes and concludes this work.

2. Method

We compute the residual per pixel of each star by removing its zero point

$$r(t) = \frac{f(t) - \bar{f}}{m}, \quad (1)$$

where f is the star's flux and m is the mask surface in pixels. The fluxes are divided by the photometric aperture size m because systematics are at the pixel scale. The average flux \bar{f} is integrated over the first 4 days of the run, before any drift could occur. Thus, all residuals are distributed around zero at the beginning of the run. Fig. II.3.2 (left), which depicts the histogram of the stellar flux during the 4 last days of the run, shows that by the end of the run, the residuals are significantly below zero. The fluxes loose about $30 \text{ e}^-/\text{pix}$ on average after 140 days. This offset does not seem proportional to the flux itself, but rather linked to the position of the star on the CCD (Fig. II.3.2 right). Moreover, the dependence is close to linear, hence suggesting a model

$$S_{ij} = C_i + A_i x_j + B_i y_j, \quad (2)$$

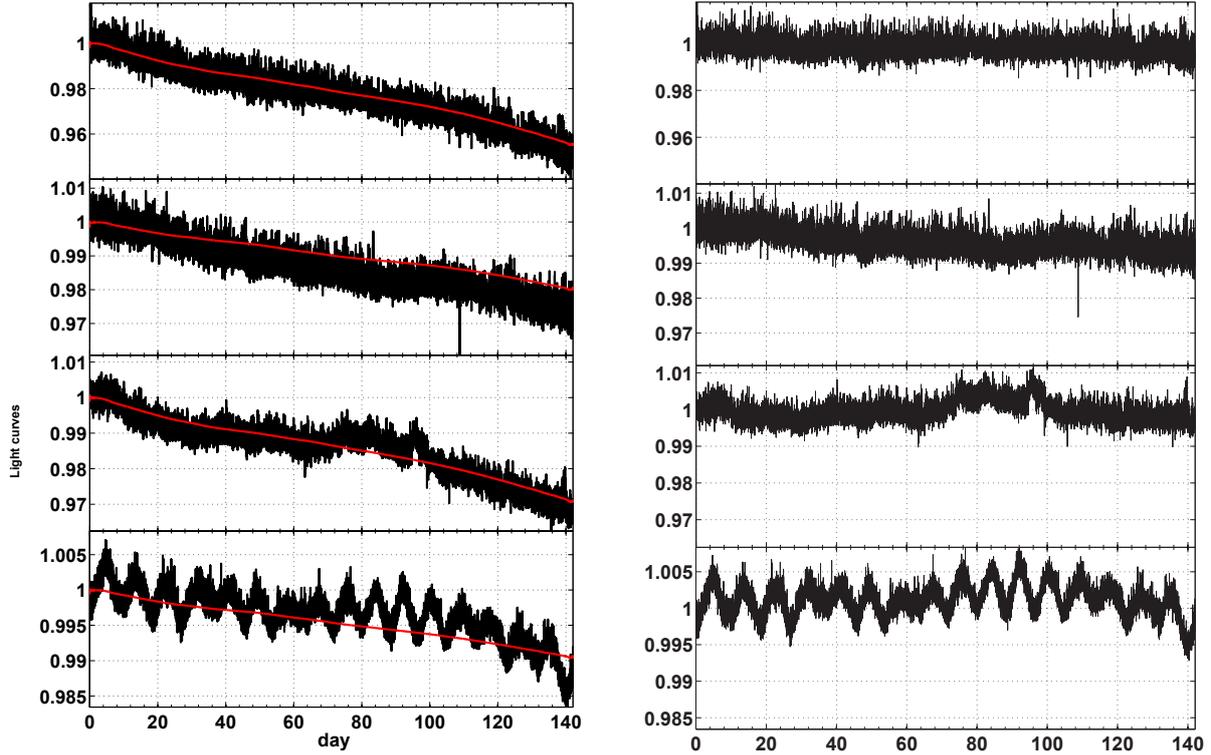


Fig. II.3.1. Corrected stellar trends. *Left:* light curves without correction. The considered light curves are from run LRc01, CCD 2. The black line is the normalized flux, the red line is the predicted systematic (see below). *Right:* same curves after correction.

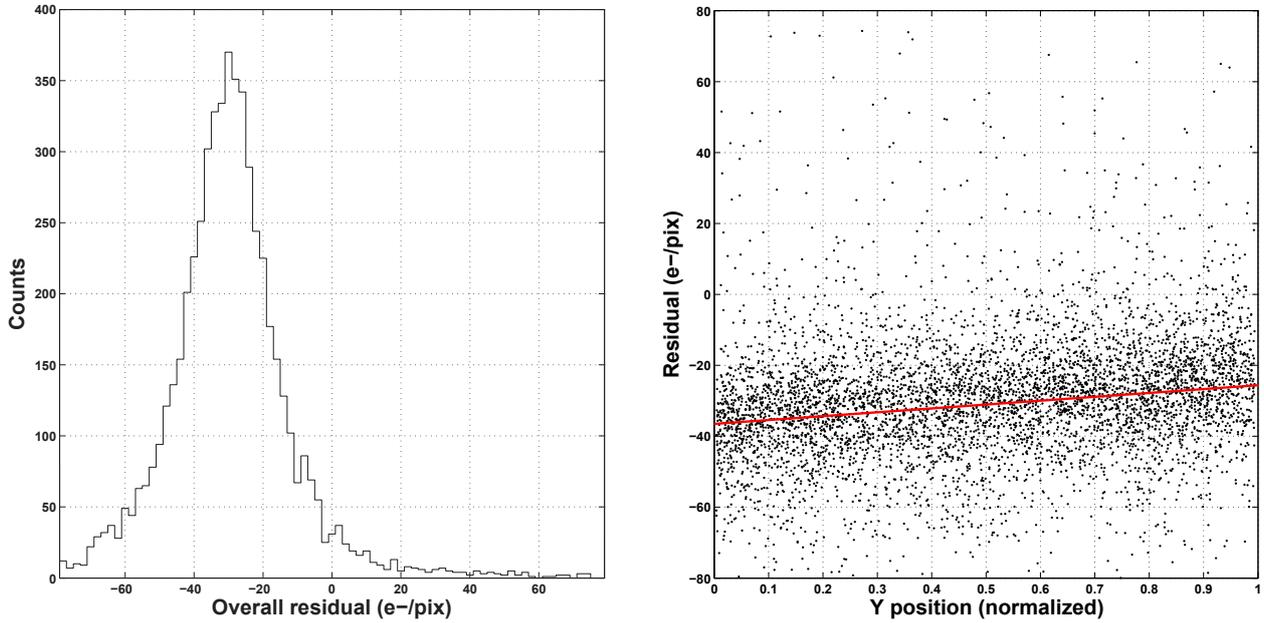


Fig. II.3.2. Systematic offset. *Left:* an histogram of all light curves residuals for a single exposure at the end of LRc01. *Right:* same residuals as a function of x positions. The red line is the linear approximation of the dependence.

with S_{ij} being the systematic offset of the i th exposure of the j th star located at position x_j, y_j on the CCD. The coefficients A_i and B_i form the position dependence and C_i is the common offset at exposure i . For each exposure we fit the three parameters A_i , B_i and C_i using a robust estimator. Next, we smooth the derived A , B and C temporal curves (Fig. II.3.3), and then subtract the resulting S_{ij} model from each exposure of each star.

2.1. Processing

Several steps are necessary to process the CoRoT data.

1. Resynchronising the run data
The CoRoT data is a collection of files, each containing the run light curve of a single star. We pack all the files of a run into a single matrix of star \times exposure that contains the whole data of that run. The difficulty is that

although simultaneously acquired, the time label of an exposure differs across files, depending on star position and roundoff errors among others. Consequently we had to gather all measurements within a common 4-s interval across the whole file set as belonging to the same exposure.

2. Binning to 512-s

Some of the stars are sampled at a 32-s cadence while the rest are at 512-s cadence. A 512-s measurement is the onboard concatenation of 16 successive 32-s exposures. The timestamp is the center of the exposure interval in both cases. The present step consists on binning the data matrix to a common 512-s time frame in the same way that CoRoT would have done onboard.

3. Deriving the effects coefficients

We compute the residual of each star (Eq. (1)) and produce the residual matrix of the run. Then, for each exposure i of that matrix, we estimate the coefficients A_i , B_i and C_i (Eq. (2)) using robust multi-linear regression (Holland & Welsch 1977). This way, the procedure is insensitive to outliers due to spurious cosmic rays or stellar variability. Another benefit of such an estimator is that there is no need to select a training set.

The resulting A , B and C temporal coefficients are then strongly smoothed using a 30-days sliding average to remove high-frequency noise caused by the fitting process and modeling imperfections. Fig. II.3.3 shows the temporal evolution of the A , B , C coefficients for the run LRc01.

4. Removing the systematic effects model

We derive the S_{ij} matrix (Eq. (2)) and subtract it from the residual matrix. The resulting residuals are then reverted back to light curves through the inverse of Eq. (1). This part is performed by the production pipeline that stores the result into a specific extend of the legacy fits files. This process takes place after the gap filling and the jumps corrections stages.

3. Results

3.1. Effects

Figure II.3.3 shows the evolution of the model coefficients during the 142 days of run LRc01. In blue, the common offset coefficient C shows that all light curves gradually loose up to $37 e^-/\text{pix}$ during the 142 days of the run. This long-term trend may reflect the loss of efficiency of the CCD, attributed to ageing effects. In red (green), the x (y) coefficients A (B) show patterns of lower amplitude, probably caused by the star shift inside its mask, probably due to small rotational depointing or aberration. The larger value of the B coefficient (red) relative to the A coefficient (green) could come from stretching of the CoRoT PSF along the x direction (Lebaria et al. 2004). Thus, a small displacement in the y direction influences the signal proportionally more than the same displacement along the x axis.

A change of the CCD temperature is visible as a discontinuity at $t \sim 50$ days, particularly in the red curve. Smaller details are visible down to the order of $1 e^-/\text{pix}$ in the 1.5-day magnified section. The faster oscillations are the residual of the CoRoT satellite orbital period, namely 13.97 day^{-1} . A daily pattern variation is also clearly visible. Although interesting for analysis purposes, such

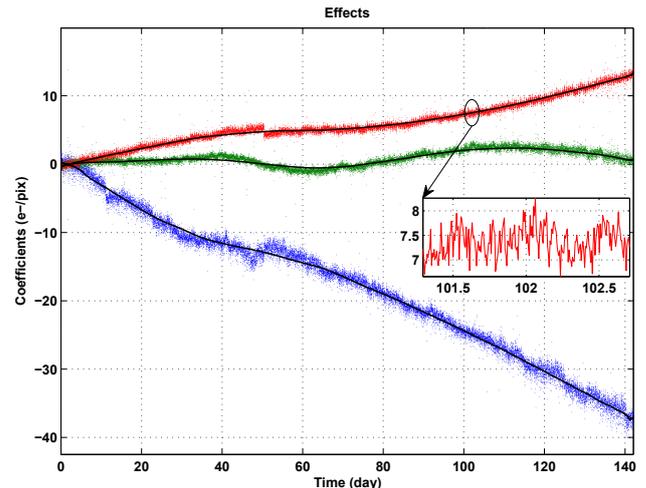


Fig. II.3.3. Effects as a function of time for the long run LRc01. Blue—offset C ; green— A (x dependence); red— B (y dependence). The magnified section illustrates finer details on a shorter time scale which we ignore. The time is the number of days since the beginning of the run.

details are removed from the operational coefficients by the smoothing process, because the model is not accurate enough for these patterns.

3.2. Absolute offset

Fig. II.3.4 represents the raw variation of the common offset C across the whole CoRoT mission. Separately, the effect of each run starts from zero by definition of the residuals (Eq. (1)). The Fig. II.3.4 concatenates all individual relative effects into the absolute variation of C during the mission. There are little gaps between two runs. In this figure, each run starts from the level reached by the end of the previous run, layered down during the gap with a $-0.15 e^-/\text{pix}/\text{day}$ step. This slope corresponds to the best linear fit of the 2096 days. The slope is derived by iteratively leveling the individual effects, computing the residuals of a linear fit and so on. The result is the dashed line on Fig. II.3.4.

The steepest decrease occurs at the beginning of the mission for LRc01 and LRa01 (Fig. II.3.4). The profile of the C effect turns gradually more patterned and noisy as time passes. An anomaly is seen for LRa04 whose offset shows strong variations.

3.3. Performance

Figure II.3.5 shows the flux loss histograms in LRc01 before and after the correction, and illustrates that our method efficiently corrects the flux decrease. Before correction (solid line), the overall difference $\Delta = f_{\text{end}} - f_{\text{begin}}$ spreads around 2% loss in 142 days. This 2% loss is equivalent to $\sim 1000 e^-/\text{pix}$, assuming an average mask area. After correction (dashed line), in addition to removal of the bias, the histogram is sharper. This reduction of differences between stars illustrates the effectiveness of the position-based approach.

While this method is efficient on average, visual inspection of many stars reveals its limitations. For many

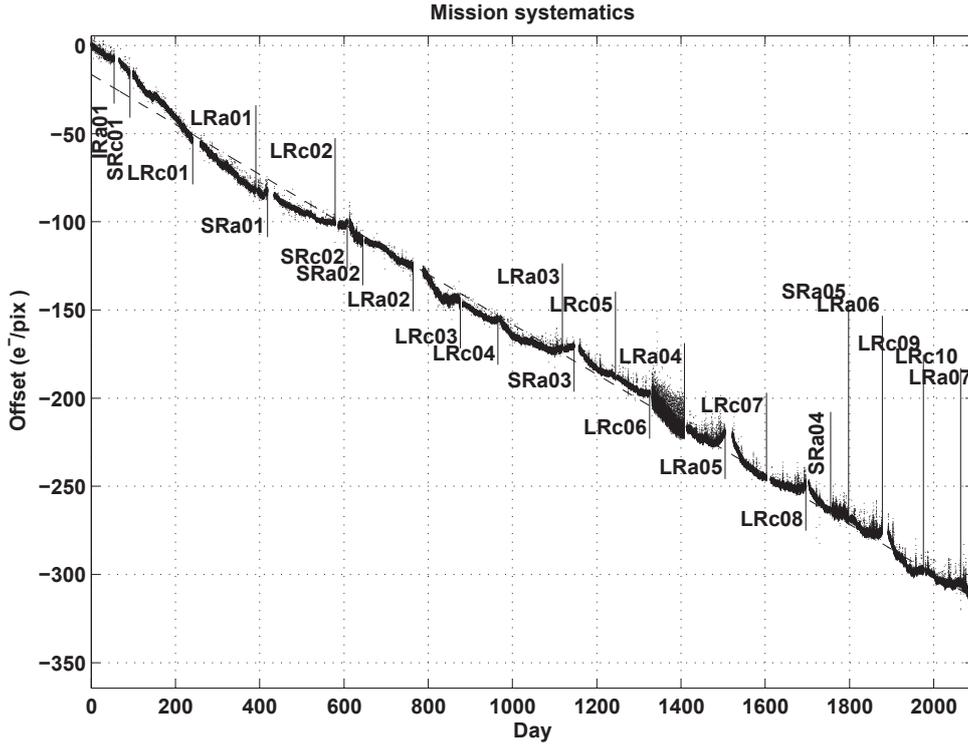


Fig. II.3.4. Absolute offset. Dots: the offset C of successive runs concatenated. Dashed: linear fitting.

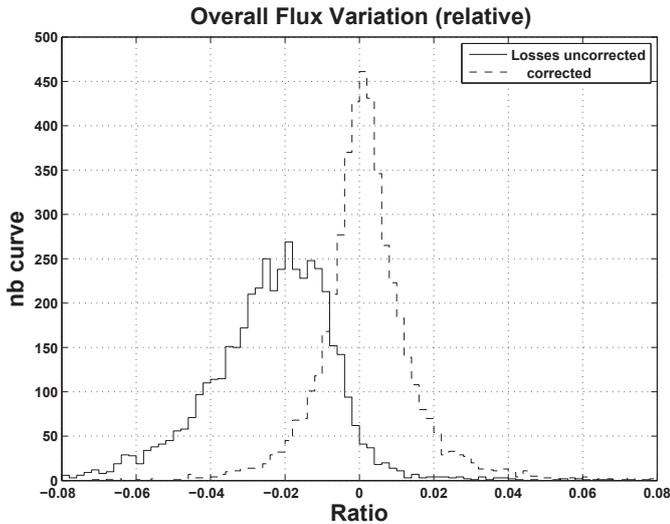


Fig. II.3.5. Results. Black line: histogram of flux losses at the end of run LRC01. The loss is intended relatively to the initial flux. Dashed: same after correction.

stars, the systematics model nicely fits the light curve. However, for other stars over/under corrections can be seen. We tested several possibilities for explaining this. We checked the influence of the photometric masks geometry with collective depointing. For this, we used the full pixel images recorded before the run. We also checked the smearing due to readout pattern across columns. We even performed a blind search for correlations with combinations of available parameters like spectral type, magnitude, mask surface and others but we were not able to identify any additional factor that could explain the suspected over/under correction.

4. Summary and conclusions

We present a simple method to remove systematics from the light curves of the CoRoT satellite without altering the scientific information. We apply a 3 parameter linear model per exposure to identify and correct most long-term systematics. The robust estimation algorithm allows to use the full information of the CoRoT sample of a run without selecting a training subset. The derived systematics only depend on the stellar position and mask area and not on the corresponding light curve. Consequently, no fitting based on the light curve itself can modify the real stellar variation, even when it resembles the systematics profile.

As an example, we show that the $\sim 2\%$ long-term variation of the early LRC01 is nicely detrended on average, and the spread of stars variations is reduced. This systematics removal process is part of the CoRoT legacy data pipeline.

Acknowledgements. This research has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant-agreement numbers 291352 (ERC).

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Acknowledgements: The CoRoT space mission has been developed and operated by CNES, with the contribution of Austria, Belgium, Brazil, ESA, Germany, and Spain.