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A Posteriori Guidance for Astronomical Images

P. Melon, M. Guillaume and Ph. Refregier

Laboratoire Signal et Image, Ecole Nationale de Physique de Marseille, Domaine Universitaire de Saint Jerome, 13397 Marseille Cedex 20, France

A. Llebaria, R. Cautain and L. Leporati

Laboratoire d'Astronomie Spatiale du CNRS. Marseille. BP 8, Traverse du Siphon, 133376 Marseille Cedex 12, France

Abstract.
Astronomical ultraviolet images were obtained from a balloon-borne telescope equipped with a photon-counting detector. The final images are built from the list of temporal photoevent addresses produced by the detector. We take advantage of the high temporal resolution available, to significantly reduce, during the image reconstruction process, the blur induced by the residual movements of the guidance system.

1. Context of image acquisition

For many years the FOCA experiment (Milliard et al. 1991) has been the main instrument for a balloon-borne middle-UV imaging programme in astronomy. The present version of the experiment consists of an UV camera of 40 cm diameter equipped with a 2D photon-counting device. The image field of view is about 1° of diameter with an angular resolution of 12 arcsec.

The camera is flown in a stratospheric gondola actively stabilized. The guidance error signal is taken from an independent star tracker centered on a guide star (using the visible part of its spectrum). An active system compensates for most of the astronomical field rotation around the central guide star. The residual movements are in the range $2-10$ arcsec. They consist mainly of a slow X-Y drift and of small, random and faster oscillations in X-Y and in angular rotation. Significant power is still present at frequencies above 1 Hz.

In the focal plane the photo-counting device gives the 2D position of each detected photo-event. Position coordinates are digitized and they define a 1024×1024 array of pixels each 3.4 arcsec wide.

Telemetry sends to the ground equipment a sequence of position coordinates in the order of time arrival for each event. They are grouped in sets of photoevents detected in the same short interval of time; each group is called a "frame". An interval of 20 ms per frame is then standard. The full sequence of frames consists of the ordered (in time) set of groups of events. When processed, successive frames are grouped in blocks of the same size (between 1 and 10 frames per block). The block size must be chosen to be small enough to sample fast movements and big enough to include enough events, between 25 and 100 typically. This point is discussed later in this paper. The typical flow of data is about of 2000 events per sec.

The image is built from individual events in a 1024×1024 array by increasing by one the pixel value whose address is defined in the event. If the final image is built without any correction of residual movements of the guidance system a significative blur will be added.

2. Algorithm

Thereafter we consider that an elementary, i.e., a high temporal resolution image, is built from all events included in a block of frames by a simple pile-up of photoevents at their original X-Y address.

We consider the sequence of such elementary images at high temporal resolution. We make the following assumptions about these images:
1) The noise present in the images is photon shot noise and is described by Poisson Law.
2) The scene does not change during the acquisition.
3) The movement is negligible during the block duration.
4) The images are periodic.
5) Rotations are negligible, so we consider only the translations between the different images.
6) We do not have any *a priori* knowledge either about the translations or the imaged astronomical field.
Let $s_p(i)$ denote the intensity of the p^{th} observed image s_p at pixel i where $i \in [1, N]$, and N is the number of pixels of the image (we use one-dimensional notations for simplicity). Let $r(i)$ denote the intensity of the imaged astronomical field at the same pixel i. It is the perfect, non-noisy and non-blurred image of the observed portion of the sky. The observed image s_p is translated by j_p pixels from the reference r. Without any *a priori* knowledge of the movement, we determine the likelihood of the hypothesis that the translation between the images s_p and r is j_p pixels. In a previous article (Guillaume et al. 1997), the value of $r(i)$ is considered known, and it has been proved that the optimal estimation of j_p is obtained by maximizing the intercorrelation between the observed image and the logarithm of the reference image $r(i)$:

$$j_p^{ML} = \arg\max_{j_p} \left[\sum_{i=1}^{N} s_p(i + j_p) \; ln[r(i)] \right] \tag{1}$$

In the present paper, the true value of the reference image $r(i)$ is considered to be not available. In this case, we consider the maximum likelihood estimation of the reference $r_{ML}(i) = \sum_{p=1}^{P} s_p(i + j_p)$, and then the set of relative translations $\bar{J} = (j_1, j_2, ...j_P)$ of the P observed images s_p. Assuming the statistical independence between the images, it can be shown that the maximum likelihood estimate $\bar{J}^{ML}$ of $\bar{J}$ is found as:

$$\bar{J}^{ML} = \arg\min_{\bar{J}} \left[-\sum_{j} r_{ML}(j) \ln r_{ML}(j) \right] = \arg\min_{\bar{J}} S(\bar{J}) \tag{2}$$

The determination of $\bar{J}^{ML}$ is performed by an iterative algorithm which is very close to a steepest descent procedure:

- Choose the size m of the search window and the number of iterations
- For each iteration k:
  - For each image p of the sequence:
    - Calculate the variation $\Delta S(\bar{J}^k)$ of $S(\bar{J}^k)$ for all the $m \times m$ neighbours of j_p^k
    - Choose the value j_p^{k+1} for which $\Delta S(\bar{J}^k)$ is negative and minimum

We take advantage of the low photon level (only few pixels have non-zero value) and we develop a fast algorithm inspired by the Nieto-Llebaria algorithm (Nieto, Llebaria & di Serego, 1987) by calculating $\Delta S(\bar{J}^k)$ on tables of photo-events addresses rather than on images. For example, for 2000 images with a hundred photons per image, the computation time can be reduced from 40 hours for the direct calculation to 5 minutes for the fast algorithm on a Sun Sparc station 10.

We note that:
1) In practice, for all the performed simulations, the convergence for $S(\bar{J})$ has always been attained with less than 10 iterations (i.e., 10 presentations of all the images).
2) The size m of the search window can be adapted to the amplitude of the translations in order to avoid local minima of $S(\bar{J})$.

3. Results

This algorithm has been tried on simulated fields as well as real images from balloon flights. We present here the results produced in an image centered on the M3 globular cluster. The experimental event series includes 24000 frames 1024×1024 pixels size and a mean of 25 photons/frame.

In the algorithm, the only free parameter is the number of frames per block. Previous simulations (Melon 1997) showed (see Table 1) that for each block the probability of *exact* recentering drops as the number of photons per block decreases. As rule of thumb: the threshold is between 50 and 100 photons per block depending on the spatial arrangement and flux distribution of stars, and background intensity.

Nb of blocks	Photons/block	Frames/block	Percentage
5000	110	4	75
10000	45	2	45
20000	22	1	20

Table 1. Probability of exact correction of a block

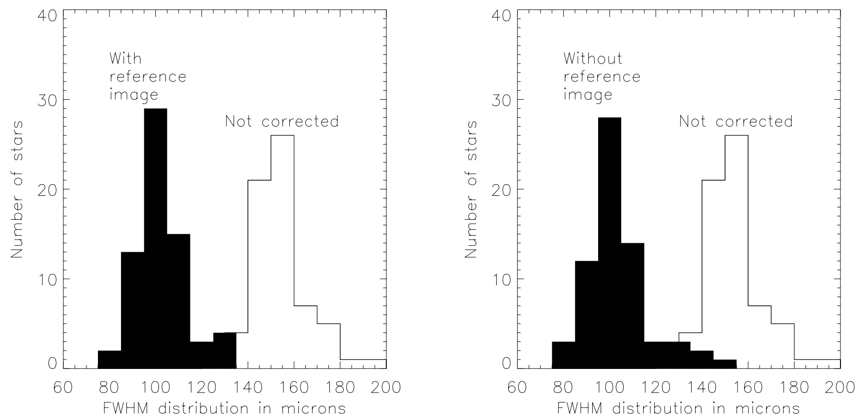

Figure 1. Left: Histograms of FWHM for case 1) & 2). Right: Histograms of FWHM for case 1) & 3)

In our case a block of 2 frames, that is, a 40 ms interval was enough to assure a good bandwidth to sample the movement and to get a correct reconstruction. To characterize the effects of the algorithm we measured for a limited set of stars ($N \simeq 50$) their FWHM (full wide to half maximum). We build the FWHM distribution for: 1) Stars from an uncorrected image, 2) Stars from a corrected image using a reference (see algorithm 1), 3) Stars from a corrected image without reference (see algorithm 2).

Figure 1 shows the histograms of these distributions. On the left side we compare 1) with 2) and in the right side we compare 1) with 3). As can be seen, a decrease of 20 μm over 120 μm is clearly visible for both corrected images. From that and from other work, not shown here, we can conclude that the new algorithm improves resolution as efficiently as the algorithm with reference image. The new algorithm does not show any ringing side-effect and has the major advantage of not needing a reference image

The lack of ringing side effects and the "self-sufficient" use of event series with any loss in accuracy are encouraging results for a large and deep study of this new method.

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