Cosmic rays on BAM CCDs data delivery note
## APPROVAL

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1 INTRODUCTION

While considered self-contained for the purpose of the data delivery, this note will not go into details about the Gaia mission, spacecraft and/or data processing, and the interested reader is recommended to consult other Gaia publications as background information, if needed. Some references are given though already in the text for specific topics.

Gaia’s Focal Plane Assembly (FPA) with its 106 CCDs is the biggest radiation monitor is space [RD1][RD2]. The interactions with space radiation are detected on the CCDs in form of:

1) Permanent performance degradations caused by:
   a) Flatband voltage shifts as result of the Total Ionising Dose (TID)
   b) Increased Charge Transfer Inefficiency (CTI) as result of newly created charge trapping sites through displacement damage under Non-Ionizing Energy Loss (NIEL)

2) Transient effects leaving charge cloud tracks in the CCD pixels, when high-energy particles create electron-hole pairs along their trajectory through the silicon lattice. Different particles can leave these tracks, but for simplification the appearance of the deposited signal track on the CCD images will be called “Cosmic Rays” (CR) throughout this document.

While the permanent performance degradations are subject to other studies, the interest for this data release is the detection of cosmic rays. Gaia has no shutter and therefore no dark images are taken to be able to assess the radiation background without any other external signal sources. Furthermore nearly all CCDs are read out in windowing mode with the windows centred on the on-board detected objects, which makes cosmic ray analysis on the received science data a difficult task.

The high volume of object detections and the limited transmission bandwidth between L2 and Earth lead to optimization of the generated on-board data volume and due to Gaia’s self-calibrating scheme, only few additional calibration data needs to be acquired in addition to the science objects.

One of the most suitable sets of data items for cosmic rays is the occasional engineering data from the readout process of the Basic Angle Monitor (BAM) CCDs acquired through the on-board Service Interface Function (SIF), which allows downlinking information otherwise discarded on-board before transmission. The BAM is Gaia’s metrology system to measure the variations of the angle between both telescopes’ line-of-sights based on laser interferometry [RD3][RD4]. To be able to expose the static laser interference pattern, these are the only CCDs on board Gaia, which are operated in a stare mode with several seconds exposure time in addition to the TDI readout mode.

The BAM readout windows are centred on the highest signal interference fringes and therefore unsuitable for cosmic ray analysis. In regular intervals throughout the mission an extended length readout strip with the same BAM window width and location is recorded through the SIF mode. These window extensions contain a substantially reduced signal, which in the extreme areas of the window is completely dominated by the TDI transfer signal integration and not by exposure. Cut-outs of these extreme areas are pre-processed for the purpose of cosmic ray assessment. This technical note describes the data format and content of the images.
2 REFERENCE DOCUMENTS


3 ACRONYMS

AC  ACross scan
ADU  Analogue-Digital Unit
AF  Astro Field
AL  ALong scan
BAM  Basic Angle Monitor
BP  Blue Photometer
CCD  Charge Coupled Device
CR  Cosmic Ray
CTI  Charge Transfer Inefficiency
FITS  Flexible Image Transport System
FPA  Focal Plane Assembly
HDU  Header Description Unit
NIEL  Non-Ionizing Energy Loss
OBMT  On-Board Mission Timeline
RP  Red Photometer
SIF  Service Interface Function
SNR  Signal-to-Noise Ratio
TDI  Time Delay and Integration
TID  Total Ionising Dose
UTC  Universal Time Coordinated
VPU  Video Processing Unit
4 CONTEXT

The two BAM CCDs are located at one corner of the Gaia FPA (see Figure 1). They are divided into a nominal and redundant system marked BAM_N and BAM_R, respectively, both fed from its independent laser interferometry system. Only one system is working at a given time, and redundancy is meant here as duplication with the best performing system working during operations.

As shown in Figure 2 the CCDs are relatively well shielded inside the Silicon Carbide (SiC) FPA cold radiator. Sector analysis made by Airbus DS, France, estimates about half the End-of-Life 10MeV proton fluence received on the BAM CCDs compared to CCDs located in the centre of the FPA (see [RD1]).
The CCDs are the e2v technology’s CCD91-72, a CCD optimized for TDI operation and custom built for the Gaia mission [RD5]. Throughout this document the image area orientation of the CCD follows the Gaia convention with the 4500 TDI lines (CCD rows) in horizontal direction for the TDI scan from left to right (called the Along Scan (AL) direction) and the 1966 CCD columns in vertical direction (called the ACross scan (AC) direction) with serial readout to the single output amplifier towards the upper right corner. This effectively is a 90 degrees rotation with respect to the traditional representation used by CCD manufacturers.

The Gaia CCD pixels are rectangular with 10 µm in AL to optimize resolution in scan direction and 30 µm in AC to achieve the required full well capacity. The BAM CCD is the most red-sensitive type of the three manufactured CCD variants, called the Red Photometer (RP) variant. It is fabricated on high-resistivity silicon with a device thickness of nominally 40 µm.

Figure 2: Location of the two BAM CCDs with respect to the FPA cold radiator (highlighted with yellow frame as in Figure 1). Image courtesy of Airbus DS.
5 DATA CONTENT AND FORMAT

The following sections describe the data content, pre-processing steps and the file format.

5.1 Image content and pre-processing steps

As stated in section 1 (Introduction), the images are taken from the occasional SIF recordings of the BAM CCD readouts and limited to a region outside the BAM laser interference pattern (see Figure 6 for reference), which provides the lowest background signal level, which additionally is uniform in AL. This is due to having the signal accumulation in these areas dominated by the TDI transfer through the BAM interference pattern rather than the static exposure of the pattern itself.

The size of the image section is 141 columns by 720 rows (TDI lines). The first column is a pre-scan column containing the bias reference followed by 80 columns corresponding to a first readout section and the last 60 columns corresponding to a second readout section coming from different AC column ranges on the CCD. The pixel values are encoded as 16-bit integers.

Figure 3: Top: unprocessed raw combined image windows from a part of the CCD outside the high SNR central BAM interference patterns acquired through the SIF. Bottom: pre-processed image as included in the delivery subtracting off the integrated signal bands. The images have been rotated and mirrored to display them conforming to the Gaia convention with TDI readout from left to right and serial register readout to upper right corner.

Figure 3 (top) shows an example of such a raw image section. The non-uniformity in AC is the result of the approximately Gaussian envelope of the BAM laser beam footprints. The last 99 TDI lines of each SIF recording lay outside the physical CCD image area and are therefore not affected by the exposure time. These lines have been averaged applying outlier rejection in order to produce an averaged AC signal profile, which is used to subtract the background off. An artificial signal offset of 1500 ADU (counts) has been added that avoids noise clipping as well as preserving the
original dynamic range. The resulting values have been casted back into 16-bit integer for image encoding.

The result of pre-processing this way the image in Figure 3 (top) is shown in Figure 3 (bottom). Due to the non-uniform AC profile of the subtracted signal background the image noise in the pre-processed image varies as well in AC. The AC dependent noise prediction in ADU considering the pre-processing steps is included as first row of the image. The final image size is therefore 141 x 721 pixels of 16-bits per pixel.

![Figure 4: AC dependent noise prediction in ADU included as first row in the pre-processed image. The estimation includes contribution from background signal shot noise, signal subtraction and CCD readout noise. The first column of the image is the prescan, so the first column of this AC dependent noise prediction corresponds to the CCD readout noise in ADU. The border from pre-scan and in between the two readout window sections is marked with yellow bars.](image)

The pixels of the BAM CCDs are on-chip binned by 4 in AC to increase the SNR of the interference pattern. Together with the rectangular pixel geometry of 10 μm x 30 μm this leads to image pixels, which correspond to a physical area on the CCD of 10 μm (AL) x 120 μm (AC). The effect is that the cosmic ray tracks viewed on the images appear predominantly oriented in AL direction.

The pre-processed image of Figure 3 (bottom) has been re-scaled with an aspect ratio of 1:12 to illustrate the actual physical size of the two readout window sections. This is shown in Figure 5 together with the outlines of the two sections.

The approximate physical location of the two readout window sections is illustrated in Figure 6.
**Figure 5:** Same image as Figure 3 (bottom) but with re-scaled aspect ratio of 1:12 to display the correct physical geometry of the two readout windows, marked green and blue in the right image. The first section covers columns 2 to 81 (green) and the second section columns 82 to 141 (blue).

**Figure 6:** Left: Image of a Gaia CCD oriented conforming to Gaia convention with charge injection structure to the left, serial register to the right and readout to the upper right corner. Right: Full frame readout image of one of the BAM CCDs re-scaled to the correct physical geometry and oriented in the same way as the CCD image on the left. The BAM laser beam footprints containing the interference pattern during the 19 or 24 seconds exposure time are visible together with the signal band caused by the about 4.4 seconds TDI readout with the laser continuously on. While the footprints are visible, the interference pattern is not due to the chosen grey-scale range. The nominal readout mode of the BAM CCDs is a window mode with windows centred on the central part of the BAM interference pattern. The shown full frame image is taken through a special readout sequence used only during early Gaia commissioning and is presented here for illustration purposes only.
5.2 FITS file format and used keywords

The pre-processed image data are formatted as Flexible Image Transport System (FITS) files following FITS standard Version 3.0. The FITS header is 2880 bytes long (maximal 36 keyword records of 80 bytes each, 31 used). An example is given in Figure 7 and a description of the keywords can be found below.

![Figure 7: FITS header information.](image)

There is only one Header Description Unit (HDU), the Primary HDU containing the pixel data. Name of the Primary HDU is “PRE_PROCESSED”. The data section consists of a 2-dimensional array of 141 x 721 pixels of 16-bit integer values each. The total size is 203322 bytes (141 x 721 x 16 bit). To comply with the FITS standard the data section is extended by 1158 bytes all with zero value to complete 71 FITS blocks of 2880 bytes each. Together with the header, the complete file size is 72 FITS blocks or 207360 bytes.

The following keywords have been used in the FITS header:

- **SIMPLE** [mandatory keyword for primary header]
- **BITPIX** Number of bits per pixels in data section [mandatory keyword]
- **NAXIS** 2-dimensional data array [mandatory keyword]
- **NAXIS1** Number of columns [mandatory keyword]
- **NAXIS2** Number of rows (TDI lines) [mandatory keyword]
- **EXTEND** [not mandatory, but included here to indicate possible future extensions]
- **EXTNAME** Name of the primary array [considered as IMAGE extension]
- **BZERO** Data value offset to be applied (for change of signed to unsigned integer)
- **BScale** Data value factor to be applied (unity)
- **BUNIT** Description of data value units
- **NTDI** Original number of TDI line readouts recorded through SIF
Some keywords are of internal use and irrelevant for processing the images to extract the cosmic ray information, but the following notes shall be considered:

1) The effective “exposure time” for cosmic ray interaction is EXP_TIME + TRO_TIME

2) The interaction volume per image pixel is 48000 μm³
   (30 μm x 4 [AC] x 10 μm x 1 [AL] x 40 μm [depth])

3) The interaction area for section 1 (green in Figure 5) is 0.6912 cm² and for section 2 (blue in Figure 5) is 0.5184 cm² giving a total area of about 1.21 cm².

4) The conversion gain is approximate and was measured on-ground. There is no in-orbit gain measurement possible.

6 DELIVERY PACK

In total 152 pre-processed image files have been generated for public use. The files cover a time range from May 2014 to January 2015. The UTC date stamps corresponding to the data acquisition time as derived from the OBMT time stamps are both included in the filename in the following format in order to ease identification:

Filename: CR_[OBMT_time_stamp]_[UTC_date_stamp].fits

The [OBMT_time_stamp] is a 21-digit number with preceding zeros.

The [UTC_date_stamp] has a year, month, day date format in form of YYYY-MM-DD.

Example: CR_000028871209903564700_2014-09-28.fits

The complete UTC date/time time stamp is included in the FITS header (see section 5.2).

The files are organized in folders grouped by year and month with naming format YYYY-MM, 9 folders in total for the 9 months of the covered time range.