# THE GAIA FOCAL PLANE TO SKY MAPPING: A SAMPLE OF CALIBRATION ISSUES

**M. Gai**[1], **D. Busonero**[2], **D. Gardiol**[1], **D. Loreggia**[1]
[1] INAF - Osservatorio Astronomico di Torino, Italy
[2] Università degli Studi di Siena, Italy

## ABSTRACT

The Focal Plane to Sky Mapping (FPSM) describes the detailed response of the Astro instrument, including the optical transfer function over the field, the detector response and operations. Its definition at the microarcsecond ($\mu$as) level requires good knowledge of inflight instrument parameters. Science data can be used to trace directly the instrument response, taking advantage of the repeated measurements of stars over the field. We discuss the sensitivity of simple data analysis procedures to several instrument parameters, which can be either disentangled from each other or estimated as collective contributions in case of degeneration.

Key words: Astrometry; Gaia; Instrumentation: miscellaneous; Methods: numerical.

## 1. INTRODUCTION

The overall description of the Gaia mission goals (Mignard 2005), its profile (Perryman 2005), hardware implementation (Pace 2005), and measurement principles (Lindegren 2005), are described in other contributions to this meeting. The measurement is based on two telescopes, set at a large *basic angle*, and a large area CCD mosaic (Short 2005) operated in Time Delay Integration (TDI) mode, with on-board detection and subsequent read-out of the windows occupied by detected targets throughout each device (Arenou 2005).

The planar wavefront from a remote point-like (unresolved) source passes through the optical system, at a given time, and it is focused onto the focal plane (FP) as an instantaneous photon distribution, i.e., the Point Spread Function (PSF). The images from two telescopes, Astro1 and Astro2, pointing in two directions separated by a basic angle (BA) of $\sim 99^\circ$, are superposed onto the same focal plane (FP). The nominal optical configuration is the same for both telescopes, but the flight configuration is in general different from the nominal case, with residual differences between the telescopes. Also, the inflight BA value may be perturbed.

The PSF generates a distribution of photo-electrons onto a CCD, accordingly to the detector sensitivity, i.e., the quantum efficiency (QE). The effective charge distribution collected in the pixels is also affected by the local Modulation Transfer Function (MTF) of the device. Even ideal pixels, due to their finite size, introduce a smoothing of the optical PSF. Due to TDI, the continuous motion of the instantaneous image is matched by the discrete CCD clocking; the nominal contribution is a small blurring, corresponding to a pixel fraction (1/8 – 1/4), which is acceptable. Further image degradation is provided by the attitude disturbances at frequency higher than 0.1 Hz. A representation of the measurement scheme is shown in Figure 1. The definition of the Focal Plane to Sky Mapping (FPSM) is based on this detailed signal model; its numerical implementation is described in another contribution to this meeting (Busonero et al. 2005). It should be noted that on-ground measurements are insufficient due to launch stress and following variations.

The calibration requirements are different for parameters referred to on-board operation or to on-ground data reduction, due to the peculiarity of Gaia, targeting an elementary measurement precision of $\sim$ 300 $\mu$as (for a $V = 15$ mag target, corresponding to roughly 100 $\mu$as at transit level and 10 $\mu$as end-of-mission), with an image RMS width of $\sim$ 40 mas, i.e., two orders of magnitude larger. Most on-board parameters (used for detection, read-out etc) must be stable and known at a level sufficient to preserve the image quality and ensure the readout of the appropriate pixels during the star transit; this is typically $\sim$ 10% of the pixel size (1 $\mu$m, i.e., 4 mas). Most on-ground parameters (used in data reduction) must be calibrated to the $\mu$as level, i.e., three orders of magnitude better, to cope with the desired mission performance. Our assumption is that this separation of orders of magnitude is applicable, in general, although specific values depend upon the parameters.

The rate of variation of instrument parameters is supposed to be sufficiently slow, usually, to ensure the possibility of calibration, either in the First Look framework (Jordan 2005), or by dedicated monitoring procedures operating on shorter term data sequences (e.g., few minutes), or by auxiliary data, e.g., BAM, metrology, etc. Assuming e.g., a *linear* perturbation with a projected impact of $\sim$ 1 $\mu$as per minute (already critical with respect to on-ground calibration), the time required to reach the on-board threshold of sensitivity ($\sim \pm$ 2 mas or $\pm$ 0.05

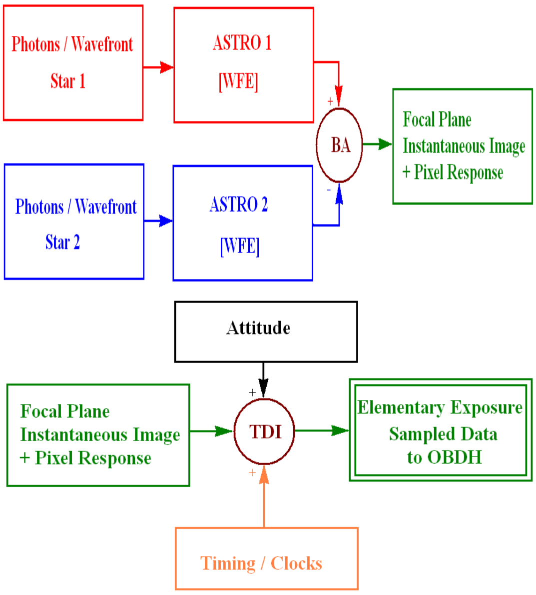

*Figure 1. Schematic of the measurement process.*

pixel) is 2000 minutes, i.e., 33 hours. It is possible in this case to update the on-board parameters used for operation infrequently, e.g., once per telemetry period, with marginal impact on performance. The case is even more favourable in case of accumulation of *random* disturbances, with the square root of time.

In Section 2 below we define the FPSM and its measurement on science data, for each field. In Section 3 we describe the impact of detector geometry on the FPSM. In Section 4 we comment on possible additional information achievable from science data, in support to FPSM maintenance. In Section 5 we draw our conclusions.

## 2. FOCAL PLANE TO SKY MAPPING

The separation of two stars is estimated on the FP by the photocentre difference deduced from their images. With an ideal optical system, described by the effective focal length (EFL) $F$ only, and an ideal detector, the relationship between linear coordinate $y$ on the FP and angular coordinate $\eta$ on the sky is simply linear: $y = \eta \times F$ (gnomonic projection). The nominal EFL (46.67 m) corresponds to an optical scale $s = 1/EFL \simeq 4'' \text{ mm}^{-1}$.

Due to the aberrations of a realistic instrument, the true function is no longer linear and the angular position on the sky is affected by a displacement vs. the ideal position, depending on the focal plane position. The simplest case of aberration influencing the image position is the classical distortion, inducing a variable contraction (or expansion) over the field. It is convenient to use the image position discrepancy with respect to geometric optics, since its values are comparably small. Reversing the relationship, to obtain the on-sky angular coordinate corresponding to a photocentre position estimated on the FP

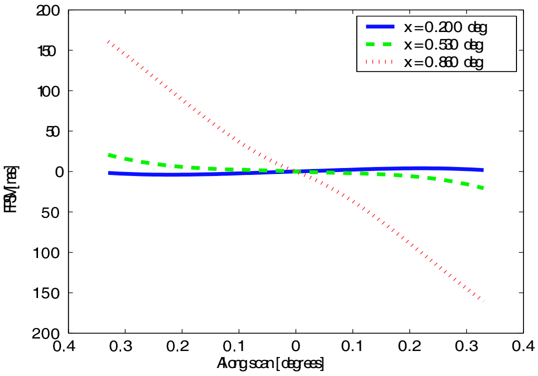

*Figure 2. FPSM: trajectories of stars at different across scan positions.*

for a star, and taking into account the BA, we get Equation 1:

$$\eta = y/F + FPSM \pm BA/2 \tag{1}$$

where the positions are referred to the median axis between the two fields, for a more symmetric description.

The sequence of measurements of a star, during its transit, is not equally spaced, but displaced accordingly to FPSM. It can be described as a *trajectory*, associated to the stellar transit, describing the variations with respect to the ideal case ($FPSM = 0$). A representation of the trajectories associated to the baseline design, with nominal values for all parameters, is shown in Figure 2. The cases considered are the extreme borders and the central section of the FP, in the across scan direction $x$; the lower edge ($x = 0^\circ.20$) is closest to zero, the discrepancy increases slowly in the lower half of the field, then the variation is remarkably steeper up to the upper edge ($x = 0^\circ.86$). Here lower values of the across scan coordinate are closer to the optical axis; using an off-axis configuration for allocation in the satellite, an off-axis field is imposed by vignetting and optical optimisation reasons.

The sequence of observations of each star *measures* the actual FPSM, since the photocentres are derived according to the current signal profile, for each image, corresponding to the system configuration. Basically, we take advantage from the fact that stars do not move during the transit level observation; therefore, the measured changes are only due to the instrument. Any star provides a set of photocentre values, with magnitude depending precision; from the above considerations, stars brighter than $V = 15$ mag have sub-mas precision at the elementary exposure level; even at the faint limiting magnitude ($V = 20$ mag), the transit level precision is quite comparable with the minimum signature, close to the optical axis.

The desired precision on FPSM monitoring, at the $\mu$as level, can be achieved by *averaging* over a sufficient number of bright objects; of course, this requires a calibration framework able to factor out the different contributions, e.g., chromaticity, TDI, spin rate, etc. A significant number of bright sources is in any case required, to cover the whole field of view in each line of sight.

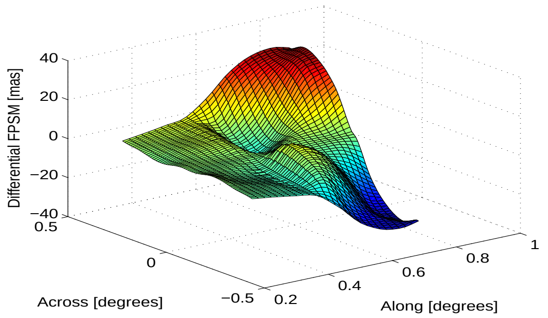

*Figure 3. Differential FPSM distribution between Astro1 and Astro2.*

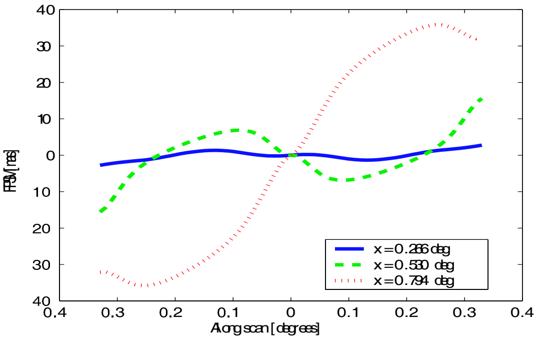

*Figure 4. Differential trajectories of stars from Astro1 and Astro2, at different across scan positions.*

## 2.1. Differential FPSM

Our definition of the BA is the angle on the sky separating the two directions associated to a given FP point, through the two telescopes, measured along the scan direction. Besides, the two telescopes have different FPSM, due to the across scan offset corresponding to one CCD strip, so that a given FP point is projected on the sky with different deviations from gnomonic representation by the two instruments, even in the nominal design. Such difference, in the common part of the FP, is shown in Figure 3; as for the FPSM, the values are quite small in the part of the field closer to the optical axis, and rapidly increasing at larger distance. Additional differences are induced by the unavoidable individual errors associated to manufacturing, on-ground integration, and in-flight re-alignment. This could be represented as a BA variation, carrying the contribution from one term to the other in Equation 1. The contribution of optics and system can be separated, in principle, since the field dependent effect described above is purely optical, whereas the BA can be considered as a global instrument parameter, which could change e.g., by moving vs. each other two unperturbed telescopes.

The differential FPSM does have an impact on operations, since the trajectories of stars from either field are slightly different from each other; three sections of the differential FPSM, corresponding to the extreme values of the superposed FP area and its central part, are shown in Figure 4. The peak value, in the FP region at large off-axis distance (dotted line), is close to ± 1 pixel. As for the FPSM itself, the effect is measurable, since each object will provide signals centred accordingly to its own FPSM, including field signature: the trajectory difference of stars from either field is thus directly derived. Averaging the measurement over several stars, the necessary precision and field coverage can be achieved. The on-board representation must be maintained to preserve operation, i.e., read the appropriate pixels for each object.

A large fraction of stars are observed in both fields within a temporal interval of less than two hours (about 100 minutes), and they are expected to retain the same position on sky over this brief period. The difference of average transit coordinates from the leading to the trailing field provides a combined measurement of the BA plus additional global contributions, i.e., scan rate and residual optical terms from each telescope. Assuming the individual field parameters are monitored by suitable procedures, the BA could be uniquely identified. In order to factor out the spin rate (attitude), integrated over the two hour time elapse between transit level measurements, it is necessary to retain the 1$\mu$as precision in attitude reconstruction on-ground over this time scale.

## 3. CCD POSITION AND ORIENTATION

In the nominal case described above, the CCD position and alignment does not provide an evident effect. In practice, displacement of one device by few $\mu$m from the nominal position results in an equivalent variation of several mas on the apparent photocentre measurement, i.e. a large FPSM variation, compared to the smooth distribution of Figures 2, 3 and 4.

It is necessary to provide an initial measurement of the FPSM, at the beginning of the mission, because launch stress and settling in the operating conditions, quite different from ground ambient, are likely to induce variations in the FP geometry large with respect to the $\mu$m scale. Also, the optical response after re-alignment may be quite changed with respect to the on-ground case, which is different from the design case. It may be convenient to derive the FPSM by successive approximation, namely starting from the nominal values and adjusting for one CCD strip at a time, from the sky mapper onwards. The optical contribution, at least, can be expected to have smooth variation, and this initial search can be performed by using larger windows than those foreseen for operations, to provide the required margins. Depending on the selected strategy and resources, it may be performed either on-board or on-ground. After initial measurement, the FPSM may be maintained by monitoring procedures included in the on-ground data reduction, and the relevant data could be uploaded to the satellite when necessary to follow the instrument ageing or other slow variations. In Figure 5 we show the six degrees of freedom of each CCD. The main contribution from CCD alignment is the along scan displacement, labelled ‘y-decenter’. It is the largest term of FPSM apart classical from optical distortion. It must be known to $\mu$m level for on-board operation, and at sub-nm level for on-ground data reduction.

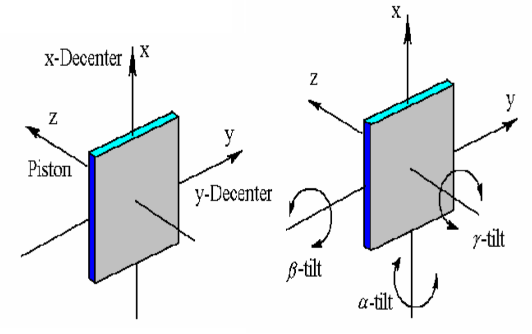

*Figure 5. Translation and rotation degrees of freedom of each CCD.*

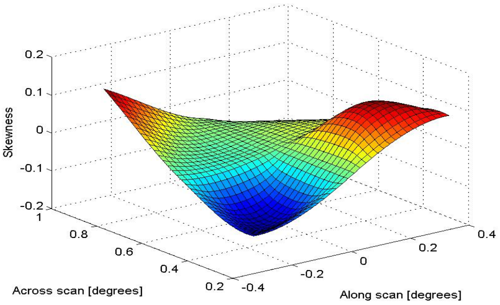

*Figure 6. Variation over the field of the image skewness.*

CCD translation along $x$ (across scan coordinate) is not measured in science data due to signal binning, but is relevant to the placement of read-out windows. It must be known to few $\mu$m for on-board operation, and at sub-nm level for on-ground data reduction; it could be measured by full resolution, bi-dimensional read-out of a few stars, for initial definition, then similarly maintained throughout the measurements. A convenient approach, for a comparably dense spatial and temporal sampling, may consist in full resolution read-out of a few stars, compatibly with the current star density constraints on operation. CCD translation along $z$ is not easily measured, because its effects are negligible due to the significant depth of focus of the telescope (few hundred $\mu$m). Besides, this also means that it is not necessary to detect and maintain such parameters, relying on the FP mechanical stability and including the residual contribution to image quality degradation in the overall budget. CCD rotation vs. $z$, labelled $\gamma$-tilt in Figure 5, is the dominant angular degree of freedom, since its effect is an along scan displacement variable over the device. The threshold is at the arcsec level for operation, and at the mas level for data reduction. This behaviour can also be identified by FPSM monitoring, since the measured discrepancy has a linear trend across the CCD.

## 4. AUXILIARY PARAMETERS

In order to ease the astrometric payload diagnostics, it may be convenient to define auxiliary parameters. The FPSM depends on both optical response and detector geometry; the factors must be separated, and this requires additional information. The photocentre is the first-order moment of the signal; the higher order moments, by definition, are independent from the photocentre. In particular, due to the smooth image profile variation over the field, the CCD position does not affect the higher order moments. Besides, the instrument configuration generates a specific structure of the FP images, which are reflected in the moment distribution. In Figure 6, the distribution of skewness over the FP is shown; this is the normalised third order central moment, and it represents the image asymmetry. The moments, derived from the measured data, are all referred to the effective signal, including the combined effects of optics, detector, and TDI operation. The possibility of deducing the effective instrument aberrations from the moment distribution has been investigated (Cancelliere & Gai 2003), in simple cases, and it represents a promising tool for diagnostics. In practice, specific parameters can be addressed individually; current investigations are focused on diagnostics of chromaticity.

## 5. CONCLUSIONS

The high precision measurement targeted for Gaia is quite challenging, since many instrument parameters may contribute significant perturbations. Some of the tools for describing the measurement process with sufficient detail are outlined. In the future, we will further the definition of the procedures for diagnostics and separation of the critical instrument aspects, analysing in detail the mutual influence of the parameters and the sensitivity associated to error propagation.

## ACKNOWLEDGMENTS

We thank all our colleagues who contributed to the development of the Gaia measurement concept.

## REFERENCES

Arenou, F., 2005, ESA SP-576, this volume

Busonero, D., Gai, M., Gardiol, D., Lattanzi, M.G., Loreggia, D., 2005, ESA SP-576, this volume

Cancelliere, R., Gai, M., 2003, Applied Numerical Mathematics, 45 (1), 87

Jordan, S., Biermann, M., Bastian, U., et al., 2005, ESA SP-576, this volume

Lindegren, L., 2005, ESA SP-576, this volume

Mignard, F., 2005, ESA SP-576, this volume

Pace, O., 2005, ESA SP-576, this volume

Perryman, M.A.C., 2005, ESA SP-576,this volume

Short, A., 2005, ESA SP-576, this volume