# Gaia SUCCESSOR WITH INTERNATIONAL PARTICIPATION

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**ABSTRACT.** Astrometric data from Gaia are already revolutionizing astronomy in all branches from the solar system and stellar structure to cosmic distances and the dynamics of the Milky Way. In April 2018, the second data release based on 22 months of observations gave 5-parameter astrometry for more than 1.3 billion sources and a further 0.4 billion sources with 2-parameter solutions; while subsequent releases will give increasingly accurate and comprehensive sets of astrophysical data. The final Gaia data set will presumably be based on 10 years of observations thus providing a new astrometric foundation of all astronomy. It is however clear that a Gaia successor in twenty years is required for observation of the same stars (estimated to be ∼2 billion), providing improved parallaxes and improved proper motions with 10–20 times better accuracy, in order to maintain and strengthen the astrometric foundation of astronomy. By adding a Near-InfraRed (NIR) capability to the new mission we will be able to peer into the obscured regions of the Galaxy and measure up to 8 billion new objects and reveal many new sciences in the process.

## 1. MOTIVATION FOR GaiaNIR

The current Gaia mission has only just begun to revolutionize our understanding of the Galaxy. The first Gaia data release gave 5 parameter astrometry for more than 2 million sources but this gave just a hint of what was about to come in the second release. In April 2018 we released 5 parameter astrometry for more than 1.3 billion sources and a further 0.4 billion sources with 2-parameter solutions. The nominal Gaia mission of 5 years will eventually provide positions, absolute parallaxes and proper motions, to unprecedented accuracies (20–25 $\mu$as (yr$^{-1}$) at the magnitude G=15), with the addition of all-sky homogeneous multi-colour photometry and spectroscopy. The extended mission of up to 10 years will further improve on this with increasingly accurate and comprehensive sets of astrophysical data. These unique capabilities go well beyond and are complementary to the science cases being addressed by ground based surveys (such as RAVE, SDSS, Pan-Starrs, APOGEE, LSST, etc).

The most obvious way to improve on Gaia's capabilities is to extend them to all-sky absolute Near-InfraRed (NIR) astrometry allowing the new mission to probe through the Galactic dust to observe the structure and kinematics of the star forming regions in the disk, the spiral arms and the bulge region to give model independent distances and proper motions in these obscured parts of the sky. A new mission launched with an interval of 20 years (around 2040) would allow new measurements of objects already in the Gaia catalogue to be combined with older data giving improved proper motions with 10–20 times smaller errors. Parallaxes would also be improved in such joint solutions by a factor of $\sqrt{2}$ assuming the two missions are of equal duration. After the publication of the final Gaia catalogue the positions of stars will be accurately known at the chosen reference epoch and linked to the VLBI reference frame. However, this accurate positional information will slowly degrade due to the small uncertainties in the proper motions of the stars. Hence, it is necessary to repeat the measurements of Gaia after about 20 years to maintain the positional accuracy and the optical reference frame.

The accuracy of the new mission should be at least that of Gaia using tried and trusted instrumentation, techniques, and lessons learned from Gaia. To achieve these goals we need to explore the feasibility and technological developments needed to manufacture space qualified and passively cooled optical and NIR (400–2500 nm) Time Delay Integration (TDI) sensors needed to compensate for rotation. To maintain ESA's leadership in all-sky space astrometry it is highly desirable to develop such detector technology within Europe. The most promising NIR sensors today seem to be Avalanche PhotoDiode (APD) HgCdTe sensors which can also support TDI mode. In 2016 we successfully proposed such a technology study to ESA (Hobbs et al., 2016) in a call for "New Science Ideas" to be investigated for technologies not yet sufficiently mature. It is hoped that these ideas may become candidates for future missions in the ESA Science Program.

A new mission would also multiply the number of observed objects by a factor of 5-6 giving up to 8-10 billion newly measured objects depending on the cutoff wavelength of 1800 nm or 2500 nm. In 2017 ESA studied[1] such a NIR space observatory (GaiaNIR). The outcome was that in order to achieve the very demanding science goals it requires new types of NIR TDI detectors to scan the entire sky and to measure global absolute parallaxes. Gaia is an ESA-only mission as Hipparcos was and we thought a Gaia successor should be the same. Recently however, we have strengthen our efforts by international collaboration. Together with US, Japanese and Australian colleagues we have submitted a proposal outlining the detailed science cases to ESA's Voyage2050 call (Hobbs, *et al.*, 2019a) and two proposals for study in the US Astro2020 Decadal Survey (McArthur, *et al.*, 2019 and Hobbs, *et al.*, 2019b). Such an international collaboration would help to keep the overall cost of the Mission for ESA within the Medium-class (M-class) envelope and thus make its selection more feasible.

## 2. ESA TELESCOPE IN 2017

In 2017 ESA studied[1] the GaiaNIR concept at its Concurrent Design Facility (CDF). GaiaNIR was one of the 26 proposals received from the New Science Ideas call in 2016 (Hobbs et al., 2016) and its purpose was to:

- enlarge the achievement of Gaia to astronomical sources which are only visible in NIR;
- improve the stellar parallax and proper motion accuracy by revisiting the common sources 20 years after Gaia;
- maintain the accuracy of the Gaia optical reference frame and to extend it to the NIR.

The ESA study for GaiaNIR resulted in a new telescope design which is not un-similar to Gaia as many key ideas were reused. The optical path of the telescope is composed of:

- A primary, a secondary and a tertiary curved mirror.
- Four flat mirrors:
  - two at the entrance pupil, one for each sky direction;
  - at the exit pupil which can accommodate a de-scanning mechanism for conventional NIR detectors (static image) or a simple flat mirror for TDI like NIR detectors (moving image);
  - a folding mirror after the exit pupil located to the side of the Korsch tertiary mirror to make the overall mechanical envelope more compact.

Figure **??** shows the GaiaNIR optical surfaces and light path. Support structures of all optical instruments are directly connected to the torus structure to avoid obstructions of the light path.

[1] `http://sci.esa.int/future-missions-department/60028-cdf-study-report-gaianir/`.

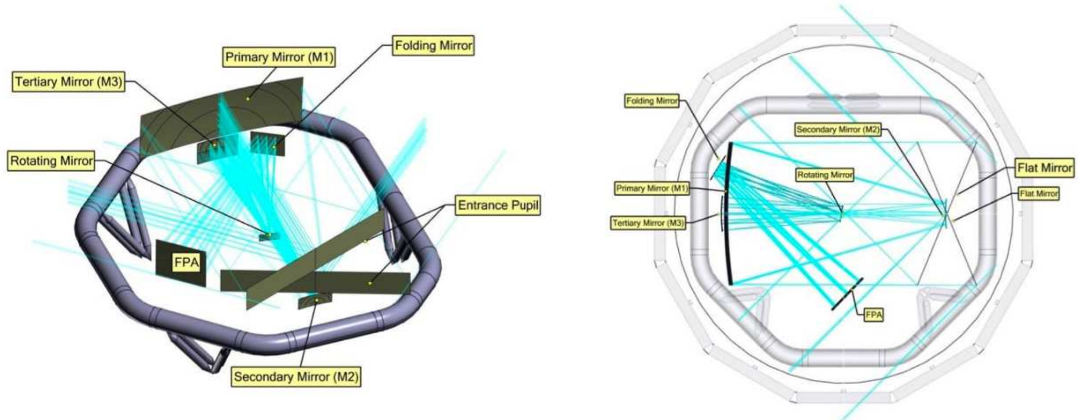


Figure 1: *GaiaNIR optical surfaces and the light path (left) and Top view of the GaiaNIR Light path (right). Images from the ESA CDF study report.*

Note the de-rotation mirror that is located in the middle of the torus structure, this is required for conventional non-TDI NIR detectors to produce a static image on the focal plane but can be replaced with a simple flat mirror when using TDI NIR detectors which give a moving image on the focal plane.

For GaiaNIR ESA designed an off-axis Korsch telescope, as it is in Gaia. But it differs from Gaia with regard to two important optical features: 1) The mirror surfaces are simple conics. This simplifies manufacturing alignment and test; and 2) The entrance pupil is at the flat folding mirror in front of the primary instead of on the primary mirror itself. This does not have a significant effect on image quality. Gaias mirrors are conics with high order aspheric coefficients and used off axis, which made manufacture and test of these elements very challenging.

The entrance pupil area was equivalent to 1600 x 250 mm$^2$, where the long side of the pupil is in the direction of rotation and the field-of-view was $0.6° \times 0.47°$ and the effective focal length was 35 m similar to Gaia.

| Star magnitude [Gaia-band magnitude] | Gaia NIR with TDI | | | Gaia NIR baseline | | |
|---|---|---|---|---|---|---|
| | G2V | M0V | M3III | G2V | M0V | M3III |
| 7 (bright) | 9 | 9 | 9 | 9 | 9 | 9 |
| 15 | 48 | 34 | 19 | 165 | 81 | 27 |
| 21 | 4129 | 1881 | 426 | 38660* | 16843 | 2919 |

*** Indicates that the detection limit has been reached.**

Figure 2: *Summary of the astrometric performance comparison in micro-arcsecs between the GaiaNIR with TDI and GaiaNIR baseline (with de-rotation mirror) and for three stellar types and a 5 year mission. Table from the ESA CDF study report.*

During the CDF study the baseline mission concept used conventional non-TDI NIR detectors together with a de-rotation mirror to remove the image motion as the spacecraft rotates. This baseline astrometric solution was compared to using the same detectors but with a TDI mechanism and the results of the CDF study are presented in Table **??**. It is clear that the baseline solution with conventional detectors gave very poor astrometric performance for faint stars (up to a factor of 10) while a TDI detector solution gave performances comparable to Gaia. The difference in results is mainly due to the reset time for the de-rotation mechanism which does not allow the star light to be integrated for long enough. The science performance for the faint stars is critical for this mission - most stars are faint and most of the GaiaNIR science cases are aimed at the faint stars. In conclusion this mission concept requires that we use a TDI like approach to integrate the light as it passes across the focal plane - this important and obvious conclusion was unfortunately ignored in the ESA CDF study report.

## 3. DETECTORS AND FILTERS

In the recent APC white paper in Astro2020 Hobbs, *et al.*, 2019b investigated 4 different detector technologies which could be used to achieve TDI in NIR detectors. From these four approaches we identified electron initiated Avalanche PhotoDiodes (e-APDs) as the most promising for our application. APDs are semiconductor electronic devices which exploit the photoelectric effect and can be considered the semiconductor analogue of the photomultiplier. They are very promising technology with the limitation of increasing the dark current at temperatures above 100K. The very fast read out of these devices makes APDs inherently suited to a TDI like signal processing mode.

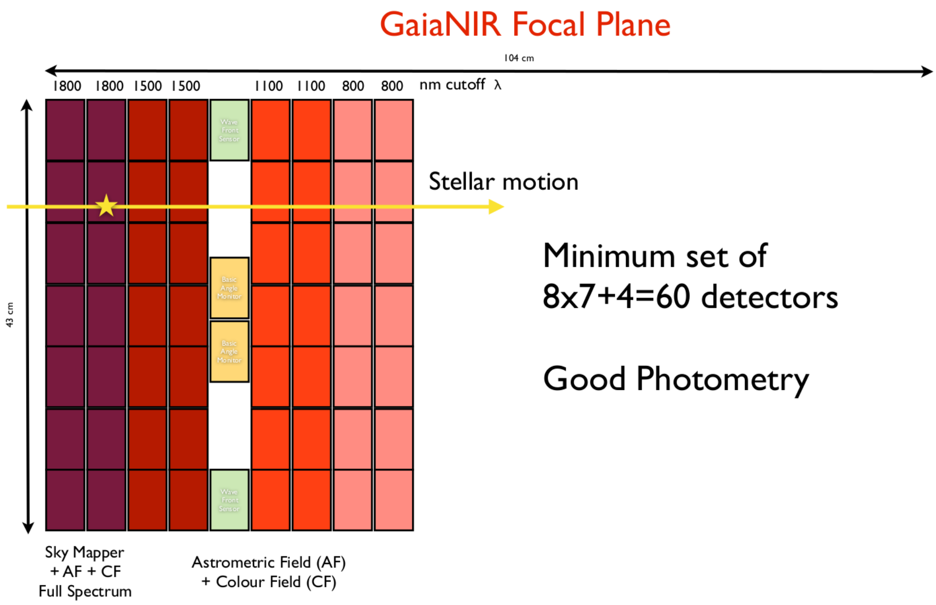


Figure 3: *Overview of the minimal focal plane array design for GaiaNIR with 4 pass bands from 400 nm to the indicated cut-off wavelength. The arrowed line on top indicates the 104 cm size of the Gaia focal plane. The new design is less than half the size of Gaia's and could be expanded to included more detectors if affordable. If the cut-off wavelength is selected to be 2500 nm it would be ideal to add a fifth band of filters on the left giving 74 detectors in total.*

One of the reasons e-APD arrays have matured so quickly in recent years is that they can be constructed using near-standard manufacturing processes. e-APDs offer voltage controlled gain at the point of photon absorption, electron gain values up to 1000, virtually zero power consumption, bandwidths to GHz, high stability, high uniformity, no impact on the pixel design and non-destructive readout schemes with subpixel sampling are possible with negligible added noise. Nevertheless there are still some technical challenges, namely 1) they exhibit large dark currents even at low gain while conventional HgCdTe detectors do not and 2) the visible response of the devices needs to be enhanced - normally achieved through substrate removal. It remains to be seen if these challenges can be overcome but APD development looks promising at this point.

The focal plane design used in the ESA CDF study is show in Figure **??** and was a minimal focal plane designed to meet the science requirements but also to reduce the costs given that the new detectors were expected to be more expensive than the ‘conventional’ CCDs used for Gaia. Crucial differences between the GaiaNIR focal plane and Gaia’s are that:

1. The sky mapper field has been removed and dissemination between the two fields-of-view (FoVs) will be done by on-board tracking of the motions of stars (which are different) for each FoV across the focal plane.

2. The photometric and astrometric FoV are combined into a single field.

3. The radial-velocity spectrometer is removed and not considered necessary given the large number of planned ground based surveys.

The design consisted of 60 NIR detectors, arranged in 7 along-scan rows and 9 across-scan strips (8 are for the astrometric/photometric field, the other is used for monitoring purposes), divided into 4 photometric fields each with different upper cut-off wavelengths. The design can easily be extended to 2500 nm by adding one extra photometric field. Stars enter the focal plane from both FoV on the left and will move in slightly different directions depending on the which FoV they originate from, on-board software can then anticipate their motion across the rest of the focal plane. The leftmost photometric band is the broadest to detect all stars and subsequent bands are narrower. Spectral filtering can be achieved by depositing filter material directly on the detectors which is a relatively new technique to simplify the optics and reduce costs.

## 4. SO WHAT DO WE DO?

The study by ESA in 2017 concluded that the GaiaNIR mission would be Large-class (L-class) even after reducing costs. However to enhance our chances of being selected we need to fit in the M-class cost category for ESA. This can only be achieved by attracting external partners who could help fund the project (US, Japan, Australia, etc. have indicated interest) and we plan to intensify our efforts in this direction in the coming years.

We are currently closely following the SAPHIRA e-APD being developed by Leonardo MW Ltd. (see Gilbert, *et al.*, 2019). On-sky performance has been demonstrated in imaging mode a number of times and early success with one such system at the Australian National University (ANU) has led to a space-based TDI mission for astronomy. The Emu mission will demonstrate space-flight readiness for SAPHIRA with a $\sim$100 mm telescope deployed on the International Space Station (ISS) which mitigates many of the technical hurdles associated with deploying small payloads, instead focusing on technology demonstration. A prototype system was successfully demonstrated on-sky in April 2019. While the current generation SAPHIRA e-APD has only a modest scale (320x256 pixels, but with a high pixel operability, approaching 100%), a number of active collaborations are underway to deliver large format (1k$\times$1k) devices more relevant for the extended focal plane mosaics typically needed for large survey missions. ESA have recently issued tenders for the development of 2k$\times$2k APD devices and it is this large format that would be suitable for our mission.

## 5. REFERENCES

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