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2MASS/*Gaia* as an Absolute Astrometric Reference Frame

A. Bellini, S. Casertano, E. Nelan, J. Kruk

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Abstract

We explore the possibility of using 2MASS/Gaia catalogs as a reference for the absolute astrometric registration of WFIRST exposures. We consider two methods: the first method (hereafter "a priori") relies on the position of the few (typically four) sources used to guide the telescope during image acquisition; the second method (hereafter "a posteriori") is instead based on the position of all the 2MASS/Gaia sources within the FoV that do not saturate when observed with WFIRST.

We find that 2MASS stars have sufficient density to provide enough guide stars everywhere in the sky in both imaging and grism modes. There are a few locations on the sky where WFIRST will not be able to perform grism spectroscopy if the faint magnitude limit for guide stars in grism mode is set to $H_{\rm AB} = 13$ *mag or brighter.*

For the imaging mode, based on the expected Gaia's end-of-mission astrometric errors, we estimate the a priori method to reach absolute astrometric precisions of the order of about 0.075 mas (or about 7×10^{-4} *WFIRST WFI pixels). The a posteriori method relies on fainter—but more plentiful— sources than the a priori method. We find half the sky to offer around 1800 or so Gaia sources for the a posteriori method, providing an estimated a posteriori absolute astrometric precision of about 0.05 mas (or* 5×10^{-4} *WFI pixels).*

For both methods, we estimate an astrometric error upper limit of 0.1–0.2 mas (1–2$\times10^{-3}$ *WFI pixels), even in the sparsest regions of the sky. For the planned WFIRST mission surveys, repeated WFIRST observations spanning several years will be used to improve Gaia's proper-motion accuracy, especially at the faint end, and to derive absolute positions and proper motions for many fainter sources, thus improving the overall absolute astrometric position of sources in their fields.*

1. Introduction

In broad terms, two main methods exist to determine the absolute astrometry of a scientific observation. The here-defined "a priori" method is based on the information available before an observation is made, essentially the same information that is used to point and guide the telescope. This includes the celestial coordinates of the guide stars (GSs) and the locations of the scientific instruments relative to the guide stars on the focal plane. At present, the accuracy of *Hubble Space Telescope*'s (*HST*) absolute astrometry with the a priori method is at the level of about $0.5''$, where most of the uncertainty comes from: (1) errors in the celestial coordinates of the adopted GSs used by the Fine Guidance Sensors (FGS), and (2) their relative location with respect to the scientific detectors on the focal plane (metrology).

A clear advantage of WFIRST with respect to *HST* is that GSs will be placed somewhere within the wide-field imager's (WFI) field of view (FoV), so that the same instrument will be used to both guide the telescope and acquire scientific data. This automatically removes the metrology contribution to the error budget. Another advantage of WFIRST is represented by the combination of the very large FoV of the WFI and the (relatively) faint magnitude limit for GSs ($H_{\rm AB} < 17$) so that, in principle, there will always be sufficiently bright, well-measured stars that can be used for guiding. This is not always possible with *HST*, mostly because of the necessity to use brighter ($V < 14$) GSs.

The second method (hereafter the "a posteriori" method) to determine the absolute astrometry of a scientific observation is based on the information available after an observation is made, namely the positions of all the (potentially fainter) sources within the FoV with accurate positions in external catalogs (e.g. *Gaia*). Four GSs will be typically used to guide WFIRST (one per chip), but many more stars imaged in each exposure can be used in principle to improve the absolute astrometric registration with the a posteriori method.

Both methods assume that the geometric distortion of the WFI has been already properly corrected.

In this technical report, we consider the possibility of using the 2MASS catalog (Skrutskie et al. 2006)—with a discussion about the *Gaia* catalog (Gaia Collaboration 2016a,b)—as a reliable source of GSs for WFIRST observations (a priori method) at any location in the sky. We consider both the imaging and the grism observing modes. We also estimate the number of 2MASS and *Gaia* stars within a typical scientific exposure that can be used for the a posteriori method. Needless to say, *Gaia* is expected to significantly improve the achievable astrometric accuracy. Note that *Gaia* will likely provide reliable estimated IR magnitudes thanks to multiband photometry and stellar parameter determination down to $V \sim 17$.

Previous studies on similar topics were more focused on particular regions of the sky (e.g., Nelan et al. 2015, 2016), or on a particular observing mode (e.g., Hirata 2016). This technical report is complementary to (and a continuation of) the exploratory works of Nelan et al. (2015, 2016). We analyze the entire sky in both imaging and grism modes, and provide estimates of the achievable absolute astrometric precision in imaging mode for both the a priori and the a posteriori methods.

2. The a priori method

2.1 The WFIRST WFI guiding system

WFIRST is especpected to guide using typically to four GSs at the same time, one GS per WFI chip. In principle, WFIRST can actually use all 18 detectors at the same time for guiding, and more than one GS can be placed within a given WFI chip. In practice, keeping only one GS only per chip simplifies the on-board software, and four GSs for the entire WFI are sufficient to guarantee accurate telescope guiding. The exact total number of GSs that will be eventually chosen for the WFIRST mission may change. For the purpose of this technical report, we assume that up to four GSs will be used, one per chip.

Following a slew to a new position on the sky, the attitude control system (ACS) will set a flag indicating when the attitude and angular rate errors have fallen below a suitable threshold, indicating that conditions are acceptable for acquiring GSs. Once a GS is pre-selected on a particular chip, a pre-guide window of 64×64 pixels is centered around the GS to lock its position. The size of this window is set large enough to accommodate 3-σ uncertainties in the attitute.

To qualify as a GS, a source has to be bright and relatively isolated, so that the on-board guiding software is not tricked into locking on another nearby star, thus introducing systematic astrometric errors. The isolation requirement is met when a star of magnitude $m_{\rm guide}$ has no neighbors of magnitude $m_{\rm neigh.} = m_{\rm guide} + 2.5$ or brighter within the pre-guide window.

After the post-slew attitude error has been reduced by the ACS, typically in just a few seconds, the size of the pre-guide window can be reduced to 16×16 pixels, which are then read with an update rate of 5.86 Hz (or about every 1/6 seconds) during image acquisition. The minimum brightness level of a GS is ultimately defined by the minimum S/N a source must have to be locked into the guide window.

2.2 Guide-star magnitude ranges

For the imaging mode, the current GS faint limit is set to $H_{\rm AB}$=17 (Kruk 2014), which corresponds to $H_{\rm 2MASS} \simeq 15.65$. (We use a zero-point correction value of 1.354, based on Table 2 of Cohen et al. 2003.) Note that the actual zero-point correction also depends on the color of the stars. We will see later, in Sections 3.2 and 3.3, that the stars considered in this report have roughly the same color at any given magnitude, so that a simple zero-pointing between the 2MASS and the AB photometric systems is sufficient. To be somewhat conservative, we will adopt the value $H_{\rm 2MASS}$=15.5 as the faint magnitude limit for the imaging mode. The Galaxy-Survey Exposure Time Calculator[1] predicts that about 227 electrons will land on the central pixel of a $H_{\rm 2MASS}$=15.5 star in 1/6 seconds (the update rate for GSs) when observed through the H158 filter, assuming the star is centered on the center of the pixel.

Using Monte-Carlo simulations in which the center of a star is randomly placed at different subpixel locations within a pixel, we estimate that about 22% of the total flux of a star lands within its central pixel. These simulations include both jitter effects and small allocation for wavefront errors (see Kruk 2014 for details). Saturated stars, in general, are not used to guide a telescope. There are two types

[1]GS ETC: https://wfirst.ipac.caltech.edu/sims/tools/wfDepc/wfDepc.html

of saturations: the numerical saturation depends on the electronics of the detectors. Typically, modern science detectors use 16 bits, implying a numerical saturation of about 65 000 counts[2]. The physical saturation occurs when enough electrons are collected by a pixel to reach the detector's well depth. For the WFI, well-depth levels of 60 000 and 120 000 electrons have been suggested. To be conservative, let us assume a well-depth of 60 000 electrons. Let us also assume that numerical saturation occurs after physical saturation (i.e., GAIN$\geq$ 1 for 16-bit detectors). These figures imply that saturated stars are $2.5 \times \log(60\,000/227) \simeq 6$ mag brighter than the faint limit, and therefore the usable GS magnitude range for the image mode is $9.5 < H_{\rm 2MASS} < 15.5$.

For the grism mode, since the zeroth order image is expected to be strongly aberrated, telescope guiding is currently assumed to make use of the blue and red edges of the first-order traces of bright stars. In this case, the expected GS magnitude range is $8 < H_{\rm AB} < 14$, which corresponds to $6.65 < H_{\rm 2MASS} < 14.65$. Hirata (2016) raised some concerns about the possibility of using stars as faint as $H_{\rm AB} \sim 14$ for the grism mode, and that the faint limit be set at brighter magnitudes ($H_{\rm AB}$=13 or even $H_{\rm AB}$=12). In the following, we will address all three cases.

2.3 Mapping the sky: imaging mode

To create a map of the number of available 2MASS GSs per WFIRST pointing over the sky, we proceeded as follows. We started by selecting 2MASS stars within circular regions (with the same equivalent area as the WFI FoV) at the center of each whole degree in R.A. and Dec. We assume these circular regions to be representative of the local GS density.[3]

Next, we rejected all 2MASS stars that were: (1) outside the adopted magnitude range; and (2) in close proximity (within $5''$, i.e., within the pre-guide window) to other bright neighbors, as defined in Sect. 2.1.

Figure 1 shows (on top) a Mollweide projection of the celestial sphere in which we color-coded each probed region according to the expected number of GSs that should lie within a WFIRST FoV. The location of the Milky Way center is shown in white. The color scheme is indicated by the color bar in the middle of the figure. For completeness, we indicated in parentheses the minimum and maximum numbers of GSs at the extremes of the color bar. A histogram of the percentage of sky as a function of of the available GSs per pointing is on the bottom of the figure. Colored vertical lines mark the location of the mode (red), the median (green), and the mean (blue) of the distribution.

As previously mentioned, WFIRST will typically use up to four GSs, one per chip. If we assume a homogeneous density of available GSs within the WFIRST FoV, then there will be —on average— at least ~8 GSs per chip to choose from for the imaging mode, even in the sparsest regions of the sky. As an example, we show a $1.1{\times}1.1$ deg^2 region in close proximity of the South Galactic Pole (SGP, Fig. 2).

[2]Note that some systems use instead 18 bits, while the second-generation detector WFPC2 on board *HST* until 2002 used 12 bits.

[3]Note that this selection of sampling points oversamples polar regions with respect to the Equator. This oversampling will have no effects on our lower-bound estimates, but it does skew our estimates of median, mean, and mode numbers of available GSs in the sky. We appropriately weighted our estimates to take into account for the oversampling effect.

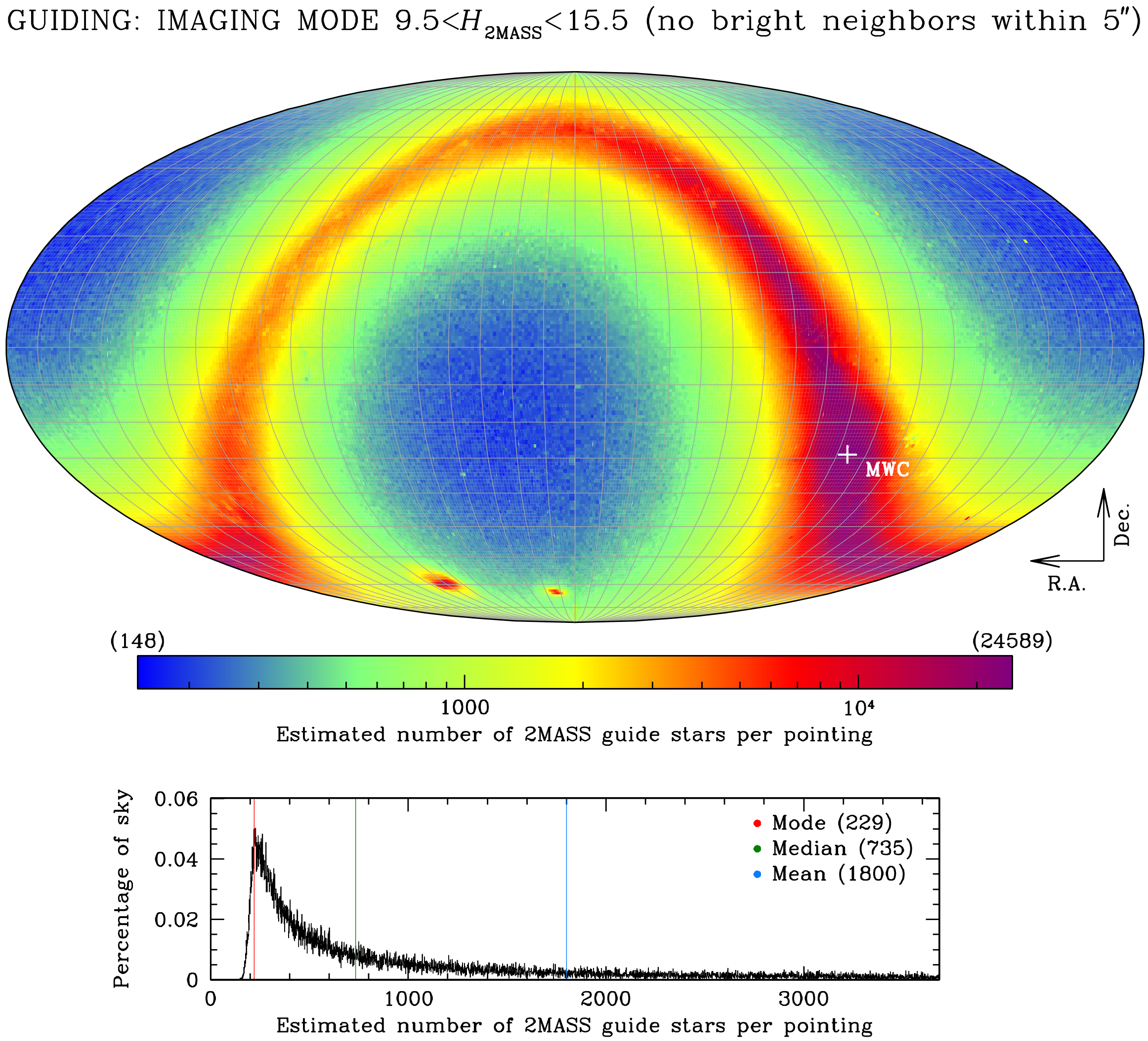

Figure 1: Top: 2MASS-based, GS density map for the imaging mode, color coded according to the number of available GSs within a WFIRST WFI FoV. The location of the center of the Milky Way is marked in white. The minimum and maximum numbers of available GSs are reported in parentheses at the edges of the color bar. Bottom: histogram of the distribution of GSs. We expect half the sky to have at least about 700 available GSs per WFIRST pointing (or about 40 GSs per chip).

The SGP location is marked by a 6-arcmin-wide yellow crosshair. The footprint of the WFI FoV is at the center of the figure, at a random roll angle. The clump of stars close to the top-left corner of the figure is the globular cluster NGC 288.[4] All 2MASS stars that qualify as possible GSs for the imaging mode are in red. Different symbols refer to different magnitude intervals (see the legend on the top right). The few 2MASS stars that are within the correct magnitude range ($9.5 < H_{2\mathrm{MASS}} < 15.5$) but that are rejected because of the isolation requirement (see Sect. 2.1) are shown with open blue squares.

[4]According to the Harris (1996) catalog, the tidal radius of NGC 288 is 13.2 arcmin. Therefore, the presence of the globular cluster should not significantly alter the number of expected GSs within the assumed WFIRST FoV.

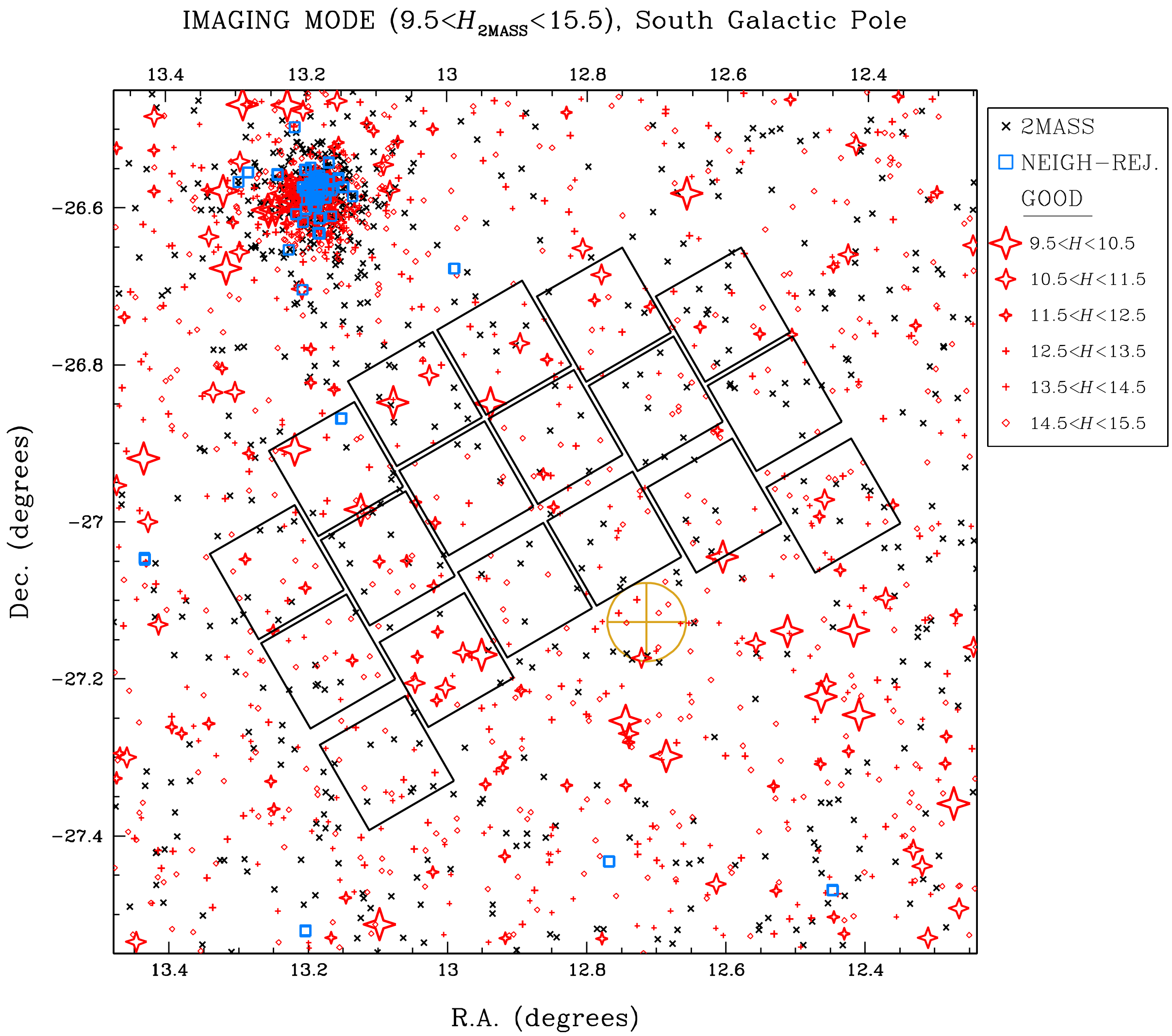

Figure 2: A 1.1×1.1 deg^2, tangent-plane-projected region in close proximity of the South Galactic Pole (marked by the yellow crosshair). The clump of stars near the top-left corner is the globular cluster NGC 288. The layout of the WFIRST WFI FoV is centered on this region, at a random roll angle (black outlines). In red we show all 2MASS stars that qualify to be used as GSs (within the allowed magnitude range, no bright neighbors); different symbols and sizes refer to different magnitude intervals. 2MASS stars with the appropriate brightness but rejected because in close proximity of bright neighbors are shown as open blue squares. All other 2MASS stars in this region are represented by black crosses (see the legend on the right-hand side of the figure, where the magnitude H here means H_{2MASS}).

All other 2MASS stars that do not qualify as GSs are represented by black crosses.

2.4 Mapping the sky: grism mode

To quantify the availability of GSs all across the sky for the grism mode, we followed the same

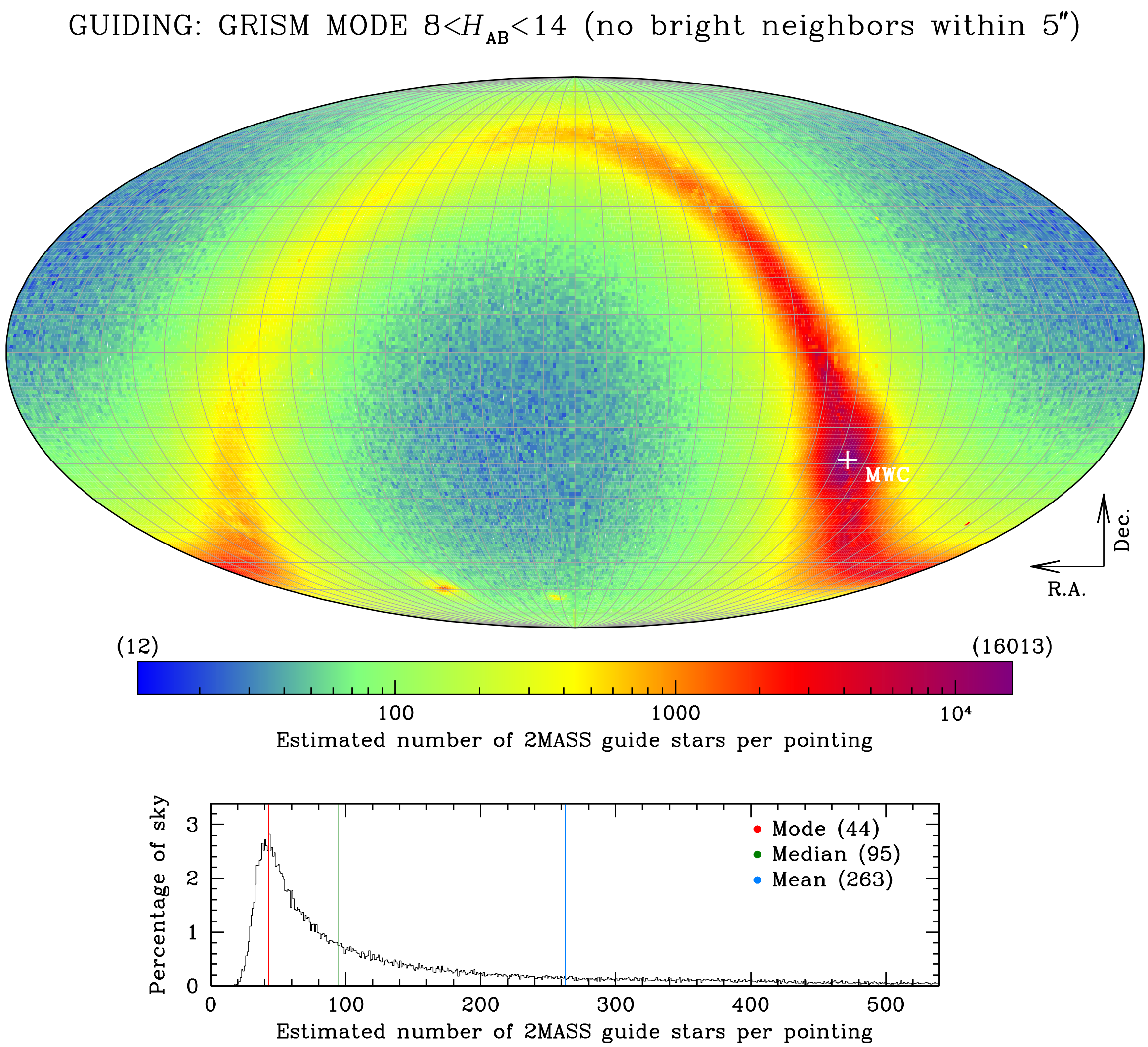

Figure 3: Similar to Fig. 1, but for the grism-mode case. See the text for details.

procedures as for the imaging mode, but using the brighter magnitude range of $8 < H_{\rm AB} < 14$ ($6.65 < H_{\rm 2MASS} < 12.65$).[5] The results are shown in Figs. 3 and 4.

Figure 3 is analogous to Fig. 1 for the grism mode. In this case, the minimum number of available GSs per WFIRST pointing drops to about 12. This implies that it can happen that a few of the WFI chips will have no available GSs (see, e.g., Fig. 4), but, assuming these stars to be randomly distributed, it will be very unlikely that WFIRST will have to guide using less than 4 chips (see also Section 2 in Nelan et al. 2015).

[5] In principle, the neighbor rejection criterion we applied to the imaging mode might not work as is for the grism mode, since nearby stars may sometimes blend if they are aligned along the dispersion direction. Nevertheless, given that stars in the adopted magnitude range are quite sparse on the sky, removing the neighbor rejection criterion or even doubling its searching radius will have formally no impact on the GS density estimates we provide.

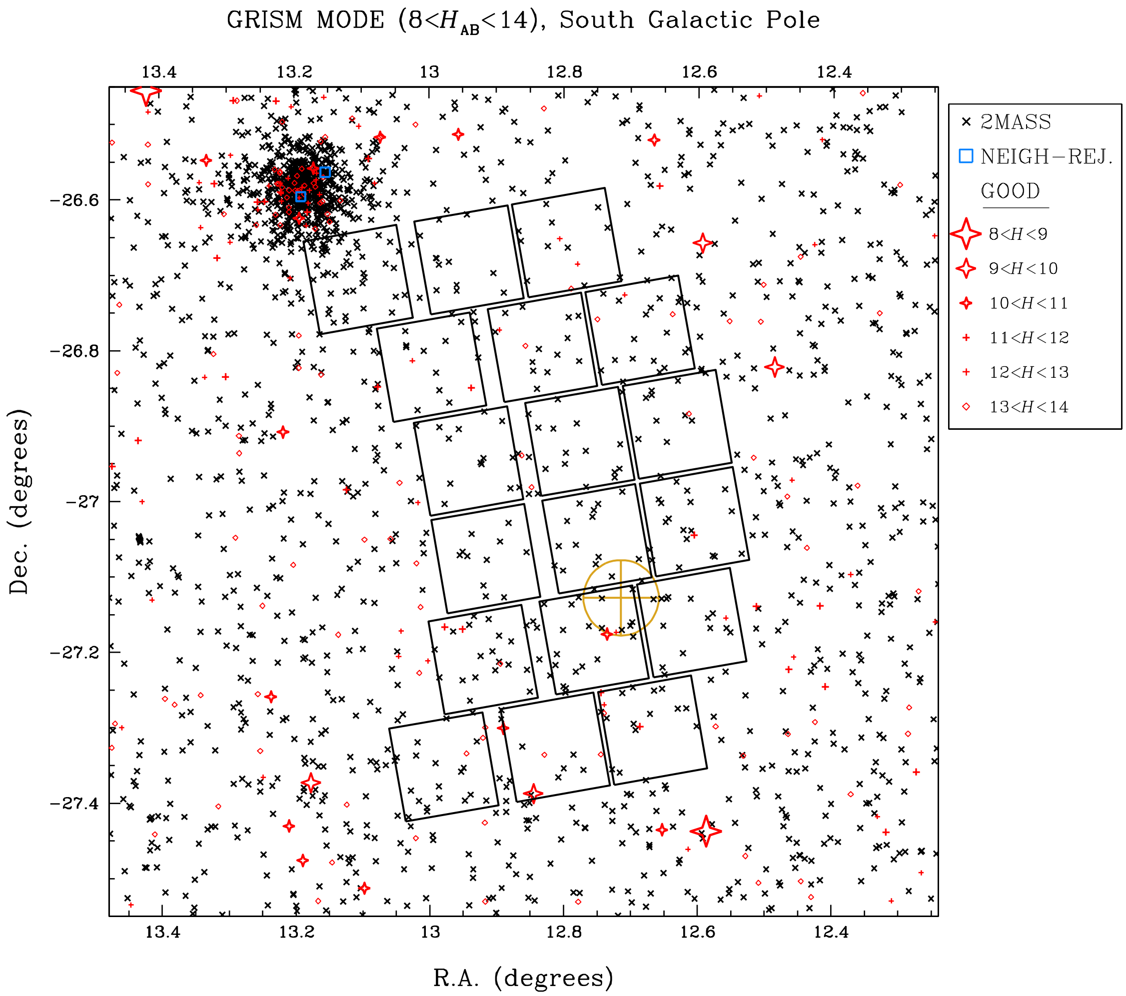

Figure 4: Similar to Fig. 2, but for the grism-mode case. See the text for details.

Figure 4 is analogous to Fig. 2 for the grism mode (note the different magnitude range). NGC 288 stars are now clearly present in at least one of the top WFI chips, due to the different roll angle of the pointing. Nevertheless, no GSs are found on that chip. There are a total of 26 GSs within this particular pointing. Six WFI chips have no available GSs, but any four of the remaining 12 chips can be used to guide the telescope.

In his report, Hirata (2016) warned that the faint limit of the suggested magnitude range for the grism mode might be too optimistic. Stars of different spectral types, in fact, can produce a strong enough signal at one edge of the first-order trace but not at the other edge. The author suggests the faint limit to be decreased to $H_{\rm AB}$=13, or even $H_{\rm AB}$=12, in order to guarantee an adequate S/N at both edges of the first-order trace, regardless of the stellar spectral type.

If the faint limit is set to $H_{\rm AB}$=13, then a few regions of the sky (about 0.001%) toward both Galactic poles will have only four or fewer available GSs for the entire WFI FoV. (Note that when four GSs are expected, the real number of actual GSs within a given pointing might be less that four, and even when four GSs are available within the FoV, they could land on fewer than four chips.) If the faint limit is further decreased to $H_{\rm AB}$=12, then about 3.5% of the sky will have four or fewer GSs. The lack of GSs will especially affect the regions around the Galactic poles. In addition, we find that ∼0.13% of the sky will have less than two available GSs. The 2MASS catalog is essentially complete in low-density regions at this bright magnitude level; therefore there will likely be some locations on the sky that cannot be reliably observed by WFIRST in grism mode if the faint magnitude limit for GSs turns out to be as bright as $H_{\rm AB}$=12.

The estimated numbers of GSs we found for both the imaging and grism modes are consistent with the probability analyses of Nelan et al. (2016).

3. The a posteriori method

3.1 The 2MASS catalog

The a posteriori method to link WFIRST exposures to an absolute astrometric reference frame can take advantage of the many sources imaged in each exposure. On the other hand, these sources are significantly fainter than those employed by the a priori method. This is due to the much different time scale over which stars saturate in the two methods. The 16×16-pixel guide window is read every ∼1/6 seconds, so GSs must not saturate before this time interval. On the other hand, the read-up-the-ramp technique used during image acquisition to register a pixel's flux as a function of time will fail if a pixel saturates before the fourth read (i.e., before ∼8.19 seconds). When this happens, the pixel "hard" saturates, and the precise location of a hard-saturated source is difficult to obtain using aperture-based centroids or PSF fitting. Specific techniques aiming at measuring the precise position of saturated sources are under development (e.g., those relying on the flux distribution of unsaturated pixels along the PSF "spider" artifacts, Melchior et al. 2017). To be conservative, in what follows we will only consider sources that do not hard-saturate.

There is a factor of 48 in flux between stars that saturate in 1/6 seconds (guide stars during telescope guiding) and in 8.19 seconds. This translates into a bright limit difference of $2.5 \times \log(48) \sim 4.2$ magnitudes between the a priori and the a posteriori methods. We therefore set the a-posteriori bright limit to $H_{\rm 2MASS}$=13.7. The vast majority of WFIRST images will be taken with exposure times much longer than 8.2 seconds, so that even the faintest sources in the 2MASS catalog can be used for the a posteriori method. For an exposure time of 60 seconds, assuming we still need at least 227 electrons in the central pixel of a star (same as for the a priori method) to be used for the a posteriori method, the faint limit turns out to be $H_{\rm 2MASS} \simeq 22$, about two magnitudes fainter than the faintest 2MASS stars.

For completeness, we show in Fig. 5 a map of the sky with the expected number of 2MASS stars that can be used for the a posteriori method, that is, all 2MASS stars fainter than $H_{\rm 2MASS}$=13.7. We found that hundreds of sources are typically available within the WFIRST FoV, even around the Galactic poles. The minimum value of 55 sources is instead found in close proximity of the Galactic center, likely due to source confusion.

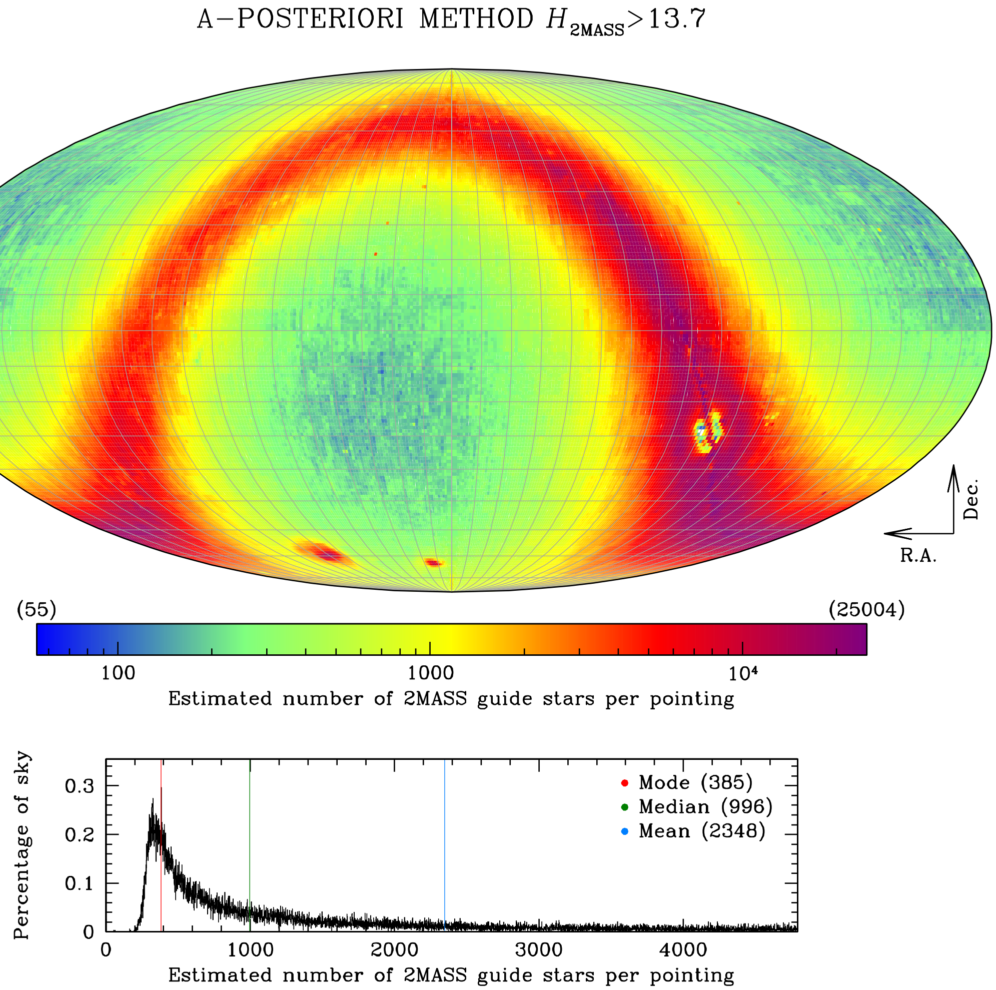

Figure 5: Similar to Fig. 1, but for the a posteriori method using 2MASS stars. See the text for details.

3.2 The *Gaia* catalog

The *Gaia*'s end-of-mission catalog is expected to include over a billion sources with absolute positions and proper motions known with unprecedented precision down to about $G_{\rm Gaia}$=20. It is expected that formally **all** 2MASS sources will also be in the *Gaia* catalog. Moreover, the *Gaia* catalog contains many more sources than 2MASS: sources that WFIRST can use in particular for the a posteriori method.

To verify this, we cross-identified the 2MASS and the *Gaia* catalogs in two regions of the sky, one near the Galactic center (where 2MASS offers the minimum number of useful stars), and the other near the North Galactic Pole (NGP). The first region takes advantage of archival *HST* data and is primarily used to find a first-order zero-point approximation between $H_{\rm 2MASS}$ and $G_{\rm Gaia}$ for typical Disk main-sequence (MS) and Bulge red-giant-branch (RGB) stars. The region near the NGP is instead used to provide a lower limit of the number of available *Gaia* stars for the a posteriori method. The *Gaia* data-release-1 (DR1) catalog is not homogeneously complete in those regions of the sky that haven't been scanned enough times by the telescope. As a result, the *Gaia*-based lower limit of available sources within the WFI FoV that can be used for the a posteriori method is not reliable. The NGP region should instead provide a more robust estimate.

3.3 Sagittarius window

The field near the Galactic center is located in the relatively low-reddening Sagittarius window and is based on a 1-pointing *HST*'s ACS/WFC deep F606W observations (R.A.=$17^{\rm h}$:58′:47″, Dec.=$-29°$:15′:28″, GO-13057, PI: Sahu). The 4K×4K pixels ACS/WFC detector has a pixel scale of 50 mas and a total FoV of 3.3×3.3 square arcminutes (about 20% of one WFIRST chip). Several thousands of Disk and Bulge stars can be found in this ACS/WFC exposure. We cross-identified these stars with both the 2MASS and the *Gaia* catalogs, and found 410 sources in common with 2MASS, and 1171 sources in common with *Gaia*.

The faintest 2MASS stars in the field have $H_{\rm 2MASS} \sim 13.4$ (supporting the fact that 2MASS is severely incomplete near the Galactic center). Both the upper Disk MS and the Bulge RGB are roughly vertical on a color-magnitude diagram based on both $m_{\rm F606W} - H_{\rm 2MASS}$ and $G_{\rm Gaia} - H_{\rm 2MASS}$ colors. Therefore, we applied a simple zero-point correction to transform $H_{\rm 2MASS}$ magnitudes into $m_{\rm F606W}$ and $G_{\rm Gaia}$. We find that $H_{\rm 2MASS} = 13.7$ (our adopted bright limit for the a posteriori method) corresponds to $m_{\rm F606W} = 17.8$ and $G_{\rm Gaia} = 17.3$. Of the 1171 *Gaia* sources in the field, 566 are fainter than $G_{\rm Gaia} = 17.3$. Since the ACS/WFC FoV is about 87 times smaller than the WFIRST WFI FoV, we expect around 50 000 *Gaia* stars to be usable for the a posteriori method in the Sagittarius window.

3.4 North Galactic pole

There are no *HST* observations near the NGP, so we directly compared the 2MASS catalog to the *Gaia* catalog. The $G_{\rm Gaia} - H_{\rm 2MASS}$-based color-magnitude diagram of common sources reveals again a mostly vertical sequence of Disk MS stars. Stars at $H_{\rm 2MASS} = 13.7$ mag have, on average, $G_{\rm Gaia} = 17.1$ (a slightly smaller magnitude offset with respect to that found in the Sagittarius window, due to the lower reddening of the NGP).

Figure 6 shows a 23×23 arcmin^2 DSS region around the NGP in which we highlight qualifying 2MASS stars (red circles), and *Gaia* stars (blue squares) for the a posteriori method. The expected density of a posteriori *Gaia* stars in this region is about 450 per WFI FoV.

3.5 *Gaia*'s a posteriori sky map

Now that we have a bright limit for the a posteriori method in the $G_{\rm Gaia}$ band, we can construct a Mollweide projection of the sky for the a posteriori method using the *Gaia* catalog (Fig. 7). About 0.4% of the sky provides fewer than 100 *Gaia* stars per WFIRST FoV, while the median number of expected stars is about 1780. The end-of-mission catalog will contain many more stars, in particular in those patches of sky that have been scanned just a few times by *Gaia* during the first year: the minimum and

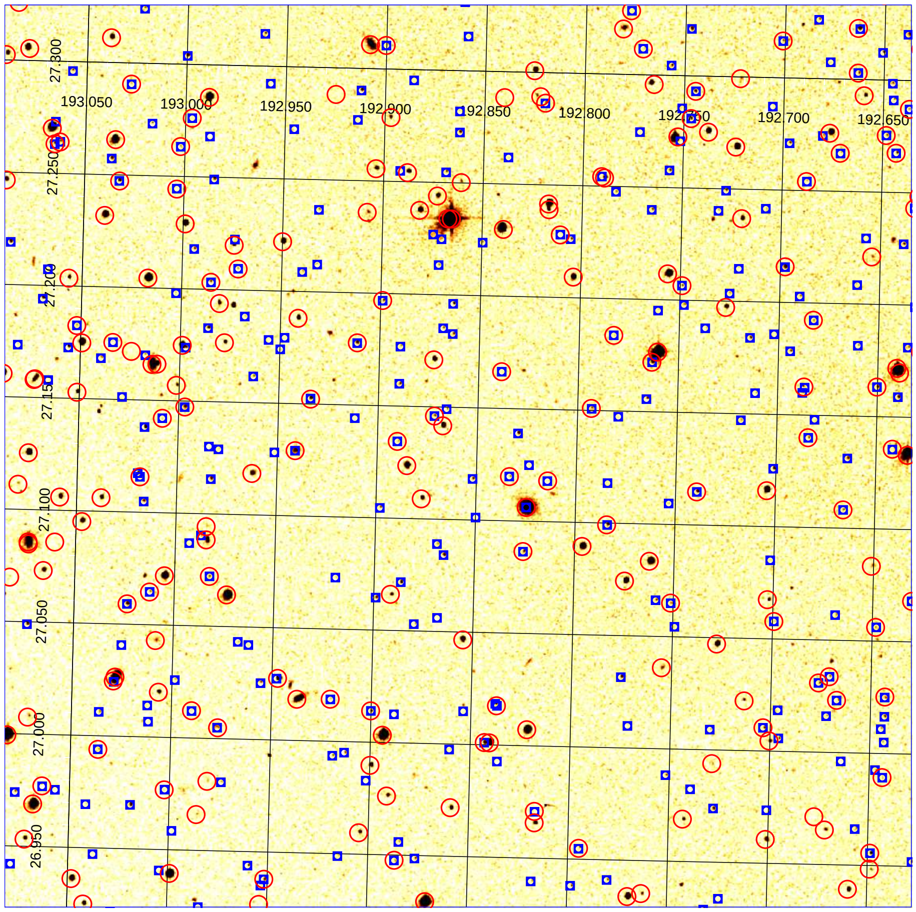

Figure 6: A 23×23 arcmin^2 DSS image around the NGP. Red circles highlight 2MASS stars with $H_{\rm 2MASS} > 13.7$. Blue squares mark the position of *Gaia* stars with $G_{\rm Gaia} > 17.1$. Stars selected in both catalogs can be used for the a posteriori method.

median number of stars we find are intended as lower limits.

4. Absolute astrometric precision estimates

The WFIRST mission will commence operations in the second half of the 2020s, several years after *Gaia* has completed its 5-year mission in 2019.[6] Near the faint *Gaia* limit ($19 < G_{\rm Gaia} < 20$), proper motions in the *Gaia* catalog are expected to have an end-of-mission error of about 0.2–0.3 mas yr^{-1} (de Bruijne 2012). This translates into a position uncertainty of about 1.4–2.1 mas (or ∼0.01–0.02 WFIRST WFI pixels) at the time WFIRST will become operative, and about twice as much during WFIRST's fifth year of operations.

Position errors of this size start to be significant if the goal is to achieve high-precision (to better than 0.01 pixels) absolute astrometric measurements with WFIRST. Single-epoch GO/GI observations of a random location of the sky have to rely solely on the information contained in prior astrometric

[6]There is the possibility that the Gaia mission will be extended five more years.

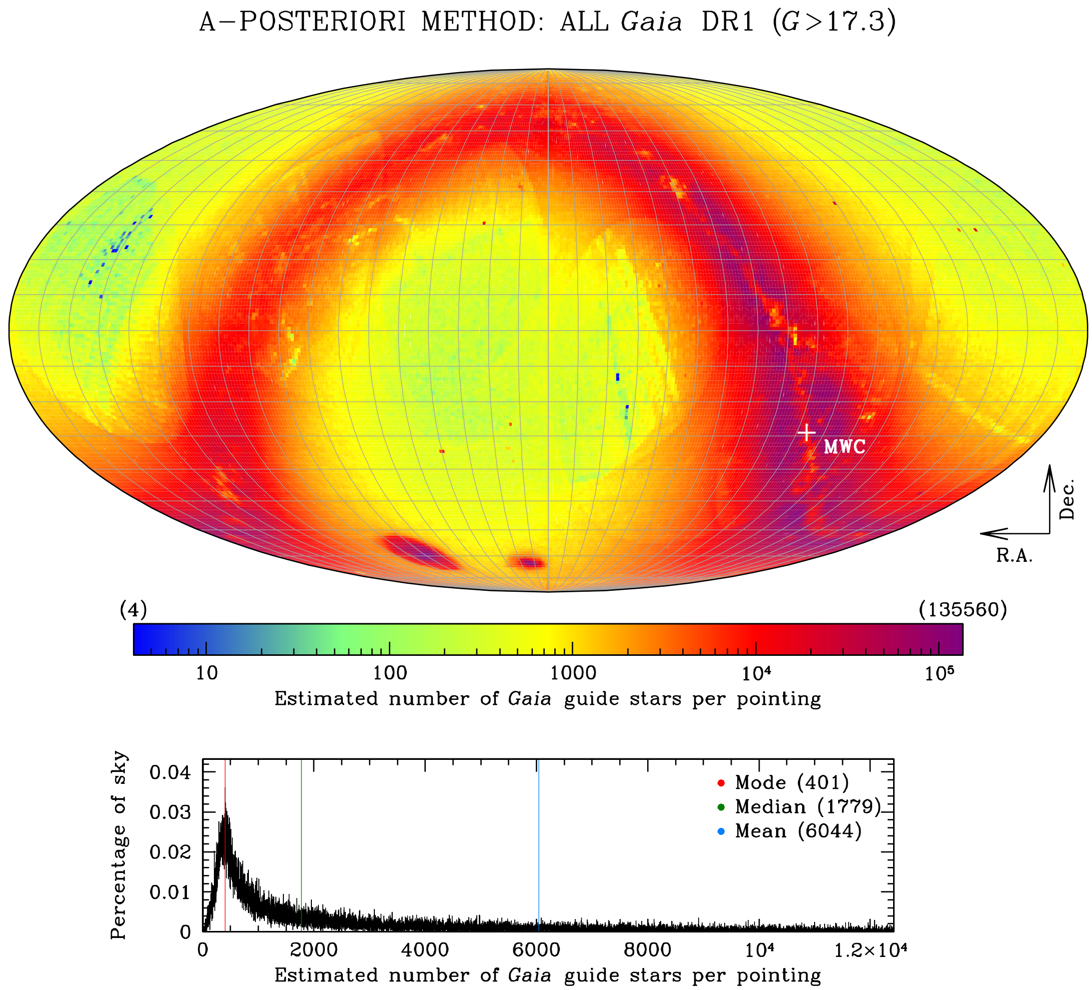

Figure 7: Similar to Fig. 1, but for the a posteriori method using *Gaia* stars.

catalogs (in particular, the *Gaia* catalog) to determine the absolute position of their sources. If we assume an average per-star positional error of 2 mas (corresponding to the expected *Gaia*'s end-of-mission astrometric error for $G_{\rm Gaia} = 19$ stars, extrapolated to the late 2020s), and ignore all other sources of errors (e.g., geometric-distortion or source centroiding errors), then for half the sky it will be possible to obtain absolute a posteriori positions to better than $2/\sqrt{1780}$ mas ~ 0.05 mas (or about 5×10^{-4} WFI pixels). In very-low-density stellar regions (e.g., the NGP), the expected absolute position error increases to $\sim$0.1 mas ($\sim 10^{-3}$ WFI pixels). When other astrometric catalogs are available (e.g., LSST for the south hemisphere), the WFIRST absolute position error is expected to be further reduced.

For the planned WFIRST mission surveys (e.g., microlensing, HLS), repeated WFIRST observations spanning several years will be used to improve *Gaia*'s proper-motions, especially at the faint end, and to derive absolute positions and proper motions for many fainter sources. The absolute astrometric precision for the planned surveys is expected to be significantly better than what can be done with *Gaia* alone, but it is hard to properly quantify it at this stage.

For the imaging mode, the GS magnitude range transformed into the *Gaia* system is approximately $13.1 < G_{\rm Gaia} < 19.1$. De Bruijne (2012) estimates an end-of-mission astrometric error of 10–80 μas yr^{-1} for stars in this range. WFIRST will likely choose GSs among the brightest available sources. We estimate half the sky to provide 7 GSs in the range $10.0 < H_{\rm 2MASS} < 10.2$. If these stars land on at least four different WFI chips, assuming their average magnitude is $H_{\rm 2MASS} \sim 10.1$ (corresponding to $G_{\rm Gaia} \sim 13.7$), and assuming they have a *Gaia*-extrapolated position error of ∼0.15 mas in late 2020s, then the a priori method is expected to offer absolute position measurements at the 0.075 mas level or better ($7{\times}10^{-4}$ WFI pixels) for half the sky. On the other hand, at least 7–8 GSs are expected to be always within any given WFI FoV if their magnitude is $H_{\rm 2MASS} = 12.0$–12.4 (or roughly $G_{\rm Gaia} = 15.8$). This translates into an upper limit for the expected a priori astrometric error of 0.2 mas (or about 2×10^{-3} pixels).

If the *Gaia* mission is extended for 5 further years, then each *Gaia* source will have twice the measurements spanning twice the time baseline, thus providing an increase in precision by a factor of $2\sqrt{2}$. Moreover, to obtain late 2020s absolute positions, we will need to extrapolate *Gaia*'s positions for only about 5 years instead of 10 years, resulting in an additional factor of 2 improvement.

4. Conclusions

We estimated the average number of available stars at each location of the sky that can be used for the absolute astrometric registration of WFIRST WFI exposures. We considered both the a priori (i.e., using the astrometric information provided by GSs) and the a posteriori (i.e., using all suitable sources in a WFIRST exposure) methods.

For the a priori method in imaging mode, we find that WFIRST can use 2MASS stars (and therefore *Gaia* stars) everywhere in the sky, supporting Nelan et al. (2016) results. There will be enough 2MASS GSs also for the grism mode, as long as the GS faint limit is $H_{\rm AB}$=14. If the faint limit for the grism mode is set to brighter magnitude levels, e.g. $H_{\rm AB}$=13, or even $H_{\rm AB}$=12, then it will be hard (or even impossible) to perform grism spectroscopy in about 0.13% of the sky.

Many more (but fainter) sources can be used for the a posteriori method (imaging mode), with typically over a thousand *Gaia* stars in each WFIRST observation. We compared the 2MASS and *Gaia* catalogs in two extreme fields, one near the Galactic center and the other near the NGP, in order to estimate first-approximation zero-point magnitude conversions and local stellar densities for the a posteriori method. In both cases, the *Gaia* catalog contains many more fainter stars than 2MASS that can be used for the a posteriori method.

Images of the planned WFIRST surveys will be used to improve *Gaia*'s stellar positions and proper motions, and it will be possible to derive accurate positions and proper motions for much fainter stars. These sources can then be used to improve the achievable absolute astrometry of the a posteriori method.

Single-epoch GO/GI observations will probably have to rely solely on *Gaia*'s measurements. In this case, ignoring all other sources of errors, we expect the a priori method to provide absolute astrometric accuracies of about 0.075 mas (7×10^{-4} WFI pixels), assuming GS proper-motion errors to be of the order of about 15 μas yr^{-1} in the final release of the *Gaia* catalog. We estimate half the sky to have

$\gtrsim$1800 usable —but fainter— *Gaia* sources for the a posteriori method, which is expected provide absolute source positions to better than 0.05 mas, or (5×10^{-4} WFI pixels) for half the sky. If the *Gaia* mission is extended for five more years, then the quoted estimates are expected to be further improved by at least a factor of 5.

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