Nancy Grace Roman Space Telescope: Wide Field Instrument Calibration Touchstone Field Recommendations

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1 SUMMARY

Table 1: Commissioning Touchstone Field Recommendations

Target	Coordinates (RA, Dec)	T_{tot} (h)	Filters	Calibrations
Large Magellanic Cloud	80.5, -69.5	24†	F062, F087, F106, F129, F158, F184, F213, F146	Photometry, Astrometry
Kepler survey field	290.7,44.5	12	F062, F087, F106, F129, F158, F184, F213, F146	Photometry
SMC-SMP-20 (planetary nebula)	14.0, -70.3	5.4	Prism	Prism wavelength calibration
NGC 2516 (Southern Beehive)	119.5, -60.8	1.3	Grism	Grism wavelength calibration
Euclid Deep Field North	269.7, +66.0	7	Prism, Grism	Grism and Prism relative flux calibration

Recommended touchstone fields to be observed during commissioning, with associated filters and calibration types. The time estimates (T_{tot}) include observing overheads.
†This time estimate includes a small dither pattern, a large dither pattern, and roll-angle set. A reduced version could partially satisfy the astrometry calibration goals and all of the photometric calibration goals.

We present the *Roman* Wide Field Instrument Calibration Working Group's recommendations for calibration touchstone fields to be observed during the mission commissioning phase. The top-level recommendations are summarized in Table 1. For planning purposes, we listed only the preferred candidates for each type of calibration; there are several additional fields still under consideration that are also described in this report. The second field listed for photometry, in the Kepler survey area, is required to achieve sufficient color diversity. The observations and the field selections are described in the report section of the corresponding category (photometry in Section 2, astrometry in Section 3, and spectroscopy in Section 4). Each of the recommended fields is located in the continuous viewing zone (CVZ) of *Roman*, within 36 degrees of the ecliptic poles.

Table 2 lists several documents related to this report. These include the Science Requirements Document, which defines the Level 2 calibration requirements; the On-Orbit Calibration Plan, which aims to summarize all the WFI calibrations that will be obtained during the mission. Some calibrations will make use of data products or knowledge acquired during *Roman* Integration & Test ground calibrations, described in a separate project document.

Table 2: Associated documents

Document Name	Description
RST-WFI-PLAN-0100	WFI Ground Characterization and Calibration Plan
RST-SCI-PLAN-0170	On-Orbit Cal. Plan (last update 7-16-2021)
RST-SYS-REQ-0020 Rev-D	Science Requirements Document

2 PHOTOMETRY

For photometric calibrations we highly recommend the Large Magellanic Cloud, due to its density of stars in the optimal brightness range, its location in the continuous viewing zone, its large amount of historic calibration data from other missions (including JWST), and the ability to use the same field for astrometric calibration. However, bright sources in the LMC field span a narrow color range; in order to achieve sufficient diversity in the Spectral Energy Distribution, a second field is required. For this purpose we recommend a region in the Kepler prime mission survey field ([TFVC16]), preferably chosen to contain the open cluster NGC 6811 for additional source diversity. The second field provides an improved calibration and powerful check against ground-based facilities in both hemispheres. Together, these two fields provide sufficient relative calibration across the field of view to meet requirements; however, they do not contain any absolute photometric standards or a significant number of low-metallicity stars. Those additional gains can be achieved with other fields listed in Table 3, including the Euclid Calibration Field, the Euclid Deep Fields, and the Draco I dwarf satellite of the Milky Way.

2.1 Recommendation

The Large Magellanic Cloud (LMC) field (05:21:57.6740, -69 29 53.36) includes the JWST Astrometric Calibration Field used, e.g., by NIRCam, but the region of high stellar density is large enough to accommodate the wider footprint of WFI. The exact boundaries of the field will depend on the roll angle, which in turn varies with the time of launch.

Through the entire working group process, the LMC calibration field remained the top recommendation. It has a nearly optimal and constant density of stars in the desired brightness range, leading to excellent predicted numbers on the resulting relative calibration across the field. It has a low density of bright foreground stars that would cause saturation issues. It is in the Roman CVZ. A portion of it has excellent historical reference data, thanks to its use as a JWST calibration field and ACS+WFC3 observations obtained in preparation for JWST. The properties of the field were also tested for calibrating astrometry across the Roman field of view, and the astrometric working group found that the same data could be used for both calibrations in this field.

The Wide Field Instrument is known to exhibit variations of the eective filter bandpass over its field of view ([Mac01]), which create photometric terms that depend on the sources spectral energy distribution (SED) and position in the field of view. This general phenomenon occurs for any optical bandpass filter used at a non-normal incidence angles and/or over a range of angles relative to the chief ray. The LMC field contains primarily upper red giant branch stars, and therefore is rich in red stars in the color interval $0.5 < J - K < 1.2$ (see Fig. 1). While the range of colors in the LMC can provide some information on such chromatic effects, a broader range of source SEDs is preferable. The region observed by the Kepler main mission contains a significant density of disk stars with generally bluer colors (Fig. 2), and thus provides a very useful complement to the LMC field in terms of chromatic characterization as well as other potential science applications (see Section 2.5.1). A second field is also desirable to identify possible line-of-sight effects and to provide a powerful validation against ground-based facilities in both hemispheres. If time permits, we strongly recommend observing a field in the Kepler target region, possibly centered on the old open cluster NGC 6811 (19:37:17, +46:23:18), using a dither strategy appropriate to the photometric requirements (see Table 4). The combination of the LMC and the Kepler fields will provide large number of stars with $J - K = 0.2$–1.3, thus enabling a better calibration of the impact of such variations on photometric uniformity.

2.2 Purpose

The field will be observed repeatedly throughout the mission to keep the Roman photometric calibration up to date, allowing us to:

1. Provide uniform (relative) photometric calibration to 5 mmag over the instrument field of view.
2. Provide uniform photometric calibration to 2 mmag over sub-FOV scales (1 detector, TBD)
3. Characterize photometric impact of bandpass variations to 2 mmag over the instrument FOV
4. Track temporal variations of the photometric response to 5 mmag (preferably 2 mmag), averaged over the instrument field of view
5. If a suitable standard is identified, achieve absolute photometric calibration to 10 mmag and absolute color calibration to 5 mmag. However, the absolute calibration may not require a Touchstone Field.

2.3 Method of assessment

The Roman Calibration Working Group had an open call for field nominations for a month in the spring of 2024. As part of this nomination process, the group was asked to provide the range of stellar densities in the Roman field of view at magnitude ranges useful for calibration, and at magnitude ranges that would cause potential saturation issues that would interfere with calibration. The nominated fields are described in Table 3.

Once the nominations were in, we had several group discussions, during which we eliminated several options, including the possibility of a globular cluster field, due to the high range of stellar densities potentially making relative calibration across the field difficult. We also decided that Galactic Plane fields, such as nearby open clusters, would not be optimal partially due to variations in foreground dust, but also due to the plane being mostly out of the Roman continuous viewing zone (CVZ). One exception to this is the Kepler field, which is in the Roman continuous viewing zone and offers significant advantages, including potential science impact (see Section 2.5); we recommended it as the secondary photometric field. We also considered potential additional uses of the large time-domain data set that will be obtained as a result of these calibration efforts, and which fields may be particularly useful beyond the calibration work.

As an extra consideration, when possible, we provide recommendations for fields in both hemispheres, to enable calibration against ground-based observatories regardless of their geographical location. Thus, we have overall recommendations, and then hemisphere-based recommendations that the mission could consider.

In addition to our qualitative discussions, we had a quantitative assessment of the fields that were the best contenders (in the CVZ, relatively constant stellar density, and well-studied). This method uses the magnitudes and positions of stars in the relevant field, obtained from 2MASS, to estimate the photometric S/N for each star, and a notional set of dithered positions to solve for the flat field in each 1000×1000 pixel region. This solution is only possible for dense fields, like the LMC and Kepler fields; for the LMC, 13 large dithers (Table 4), each consisting of four exposures dithered at the subpixel level, suffice to achieve a precision better than 0.001 mag per region. More details are given in the Appendix.

With all of this information in hand, we were able to have a final discussion in the working group where we agreed on the best options for the fields Roman should revisit throughout the mission for photometric calibration.

Table 3: Nominations for possible touchstone fields

Name	RA	Dec	mean 16-20 dens	min 16-20 dens	max 16-20 dens
47Tuc	6.022333	-72.081444	$\sim$ 20/arcmin^2	10/arcmin^2	200/arcmin^2
Draco I	260.051625	+57.915361	1.87/arcmin^2	2	6
EDFN (North)	267.0	65.5	1.64/arcmin^2	-	-
EDFS (South)	-	-	-	-	-
Euclid Self-cal	268.812745	65.2855857	1.67/arcmin^2	-	-
Kepler field	290.7	44.5	6-8/arcmin^2	$\sim$ 5/arcmin^2	$\sim$ 10/arcmin^2
LMC Astrometric field	80.5 deg	-69.5 deg	6000/detector	30/sq arcmin	2000/detector
NGC 362	15.809296	-70.848214	$\sim$ 10/arcmin^2	6/arcmin^2	40/arcmin^2
30 Dor	84.658	-69.095	$\sim$ 50/arcmin^2	$\sim$ 10/arcmin^2	>100/arcmin^2

Name	N w/ m<12	N w/ m<9	N w/ m<6	Standard?	Cluster?	LSST?	CVZ?
47Tuc	575	5	0	No	Yes	Yes	Yes
Draco I	38	7	0	No	No	No	Yes
EDFN (North)	-	-	-	-	-	-	-
EDFS (South)	-	-	-	-	-	-	-
Euclid Self-cal	5	0	-	WD	-	Yes	Yes
Kepler field	$\sim$ 100 degree^{-2}	$\sim$ 8 degree^{-2}	a few	No	open clusters	No	Yes
LMC field	69	none	none	No	-	-	-
NGC 362	110	4	0	No	Yes	Yes	Yes
30 Dor	300	20	0	No	Yes	Yes	Yes?

2.4 Observing strategy

As part of determining the top field recommendations, we needed to have a conceptual observing strategy that will be used for obtaining the photometric calibration data. In particular, dither strategy is very important for the relative calibration across the field. Large dithers offer the possibility of obtaining flat field calibration over the full field of view by moving stars to multiple detectors. While this type of calibration can eventually be achieved with survey data, the consensus is that obtaining a large-scale flat-field calibration in commissioning will enable a more efficient start to the Roman science mission, and will verify the ability to achieve such calibration to the required accuracy. Large-dither photometric calibration is thus recommended for commissioning; later visits to the photometric touchstone fields may not require the same dither strategy. Gap filling dithers can help cover the gaps between detectors; this is an important consideration when mapping a region of the sky using a small number of pointings, but for the present purposes, the redundancy in the large-dither strategy achieves the same goal without additional exposures. Finally, small dithers are usually recommended to average over subpixel response and to improve the quality of PSF characterization; in the absence of other observations, we recommend a four-point fractional pixel dither.

However, if the primary photometric field in the LMC is *also* the astrometric touchstone field, the recommended observing strategy needs to take into account the higher number of dithers needed for the astrometric solution. These dithers will provide additional pixel-phase diversity, and therefore obviate the need for a four-point dither at each large dither position. In this case, the astrometric observing strategy will suffice to meet the requirements of the photometric calibration. For the secondary field, the recommended strategy involves the 13 dithers of Table 4 with a four-point small dither at each position.

The notional observing strategy that has been used for our analysis consists of 13 large dithers, with X and Y offsets as given in Table 4; at each large dither point, four subpixel dithers are used to sample different pixel phases and to avoid blank regions. Offsets are approximately multiples of 1024 pixels, to maximize the overlap between different 1024×1024 pixel regions, but the details are not really critical. Each exposure is 50s long, resulting in a total exposure time of 2600s, plus overheads.

Table 4: Notional large dither strategy for photometric observations. Offsets are in arcmin (1.9 arcmin $\sim$ 1024 pixels).

Position #	ΔX	ΔY
1	0.0	0.0
2	1.9	0.0
3	0.0	1.9
4	3.8	0.0
5	0.0	3.8
6	7.6	0.0
7	3.8	3.8
8	0.0	7.6
9	14.2	0.0
10	11.4	3.8
11	7.6	7.6
12	3.8	11.4
13	0.0	14.2

2.5 Secondary field

While the LMC calibration field is as close to ideal as we could find, it can only be observed by ground-based observatories in the south. Thus, to have a calibration that can be checked in both hemispheres, and to have a consistency check on the calibration done with the LMC calibration field, we recommend observing a second field if possible. Possible candidates include the Kepler field and the Draco I field, discussed below. Our recommendation is to observe the Kepler field, and to consider the Draco I field as an alternative if necessary.

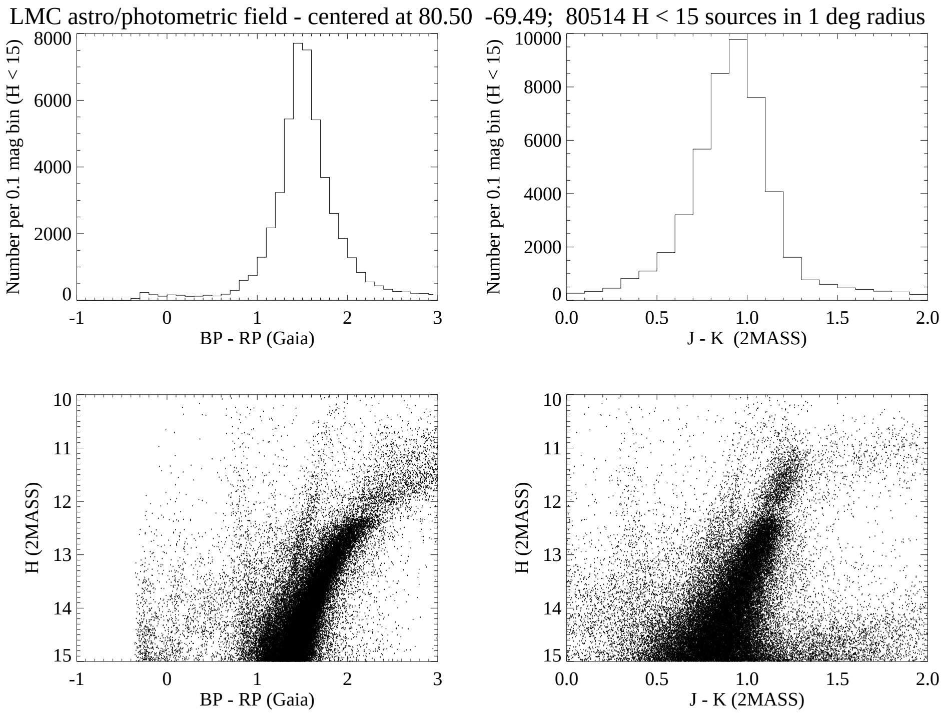

Figure 1: Color distribution (top) and color-magnitude diagram (bottom) in visible and near-IR filters for the LMC photometric field. The distributions include all stars within a 1 degree radius of the nominal center in the Gaia and 2MASS catalogs in the range $10 < H < 15$ mag. While the distribution is heavily centered at $J - K \sim 0.9$, it contains a large number of stars with colors ranging from $J - K = 0.5$ to 1.3, which will provide a basis to quantify field-dependent color terms. Note that saturation is likely a concern brighter than $H \sim 13.0$, depending on filter and stellar color.

2.5.1 Kepler Field

The Kepler field has a promising stellar density, as well as a range of stellar types and many very well characterized stars from the Kepler mission. It has the advantage of containing many Galactic stars, including open clusters, while also being in the CVZ for Roman. Furthermore, the rich history of observations would make repeated Roman visits potentially rich in scientific applications. Stars in the Kepler field are significantly bluer than those in the LMC field, as shown in Figure 2, thus providing a broader color range to quantify field-dependent color terms in the WFI photometric response.

For transiting exoplanet characterization, the combination of precision optical (e.g. Kepler/K2/TESS) and NIR (Roman) photometry may be extremely useful for eliminating contamination by grazing eclipsing binary stars, and in constraining transit depths with lower contamination from stellar magnetic activity. Long baseline comparisons with Kepler may also allow valuable transit timing variation (TTV) studies, which can be used to detect planets that are non-transiting or have very long orbital periods.

In addition, starspot modulations and flares could be detectable by Roman. Multi wavelength data enables estimates of spot-versus-temperature contrast. The long time baseline (15-20yr) also helps the search for period variations and slow starspot property evolution that can be due to, e.g., activity cycles. Eclipsing binary stars can similarly benefit by long term O-C constraints for finding hierarchical triple systems. While Roman calibration data alone will not suffice to do this science, the additional data provided by Roman could provide improved constraints.

An additional advantage of the Kepler field as secondary is the ability to obtain an improved characterization of field-dependent color terms, thanks to a significantly bluer population than the primary LMC field. The ability to constrain color terms scales with stellar density times the square of the color dispersion; that index is about 40% larger for the combination of LMC and Kepler field than for the LMC alone.

We therefore recommend the Kepler field as the preferred secondary photometric touchstone field. Within the field covered by the main Kepler mission, a possible pointing is centered on the old open cluster NGC 6811.

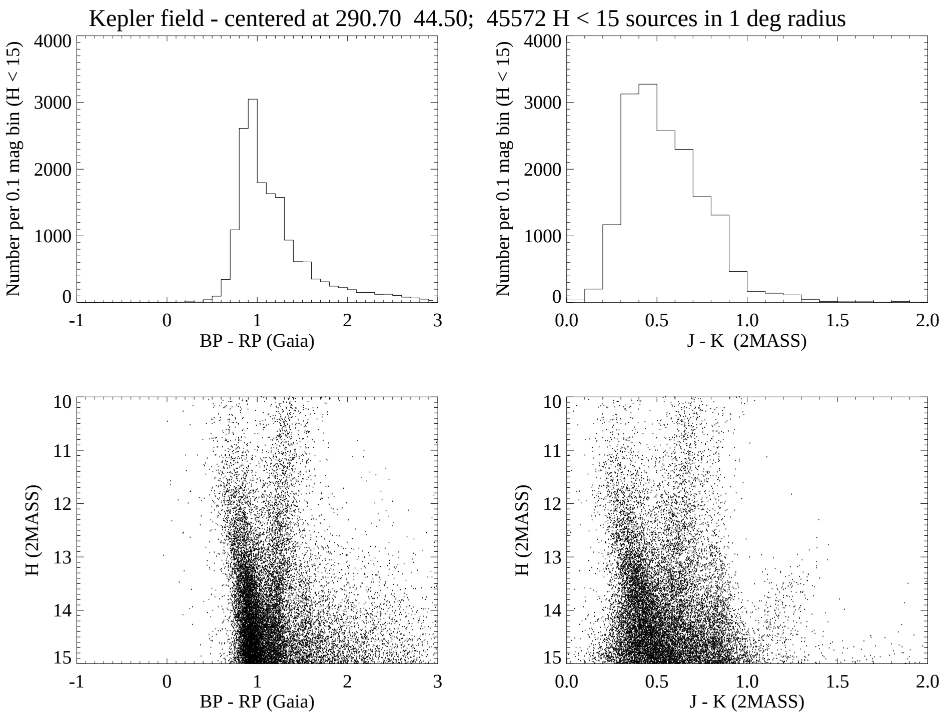

Figure 2: Color distribution (top) and color-magnitude diagram (bottom) in visible and near-IR filters for the Kepler field. The distributions include all stars within a 1 degree radius of the nominal center in the Gaia and 2MASS catalogs in the range $10 < H < 15$ mag. Stars in this field are substantially bluer than in the LMC field (peak at $J - K \sim 0.5$); the two fields together will provide good color diversity to better constrain field-dependent color terms in the photometry.

2.5.2 Draco Dwarf Satellite of the Milky Way

While the Draco Dwarf is very low stellar density, it covers an area within the northern CVZ that is relatively well matched to the Roman FoV. While it does not have a wide range of star colors either, it does provide a sample of some of the lowest metallicity stars available in the desired brightness range for Roman calibration, and they are spread across the Roman field of view. Moreover, the many epochs of deep photometry that would come from calibration observations would likely have additional science value for internal motions of the stars as well as constraints on the galaxy's orbit around the Milky Way and the detailed structure and characteristics of its entire population of stars. As shown in Figure 3, the stellar distribution has two peaks at $J - K \sim 0.3$ and 0.9 mag, corresponding to a combination of the LMC and Kepler fields. The Draco I field can thus be used as an additional cross-check of field-dependent photometric terms for low-metallicity stars: however, the stellar density is significantly lower, making it rank lower than the LMC and Kepler fields on our recommendation list.

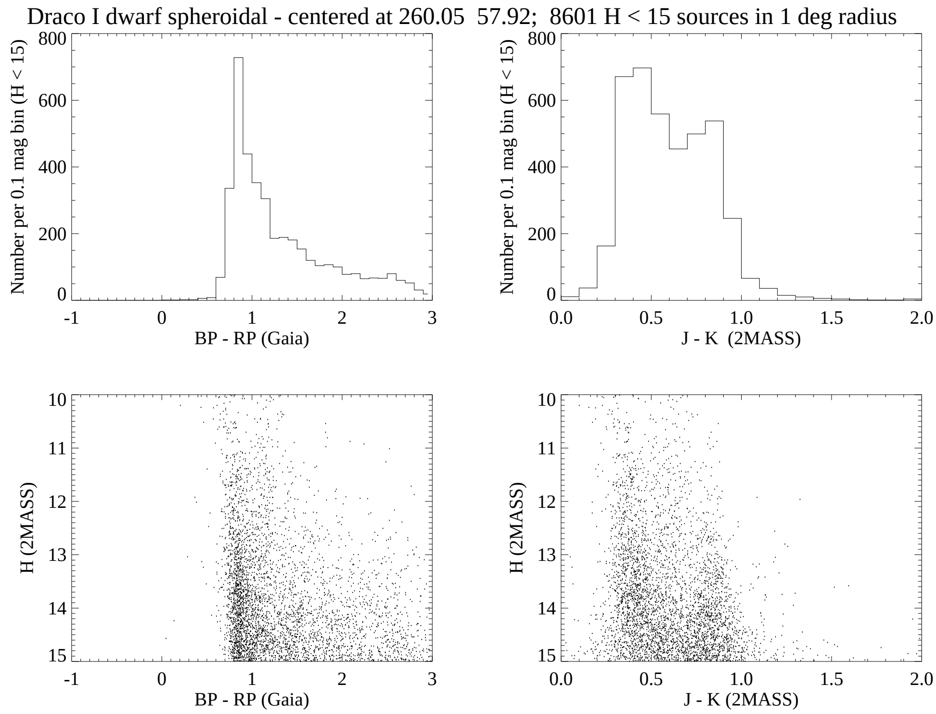

Figure 3: Color distribution (top) and color-magnitude diagram (bottom) in visible and near-IR filters for a field including the Draco I dwarf spheroidal. The distributions include all stars within a 1 degree radius of the nominal center in the Gaia and 2MASS catalogs in the range $10 < H < 15$ mag. The stellar distribution has two peaks at $J - K \sim 0.3$ and 0.9 mag, corresponding to a combination of the LMC and Kepler fields; in addition, the field contains low-metallicity stars, with a different SED than stars in either of those fields. The Draco I field can thus be used as an additional cross-check of field-dependent photometric terms for low-metallicity stars.

2.5.3 Other possible secondary fields

The 30 Doradus region (30 Dor, also knows as Tarantula Nebula), located in the LMC is an additional secondary field candidate. 30 Dor is an active star-forming complex, hosting several young clusters (including the supermassive star cluster R136). As visible, e.g., from HST photometry [SAL+13, SLA+16] 30 Dor hosts a large population of massive, blue stars ($J - K \sim 0$ mag), which could potentially be beneficial for characterizing the field-dependent color terms.

Located in the LMC, the 30 Dor region has similar overall stellar density to the primary photometric LMC field. Due to its location, this field would obviously not provide any advantage in term of ground-based, Northern Hemisphere cross-calibration, but would provide advantages in terms of execution strategy (i.e. reduce slew times between primary and secondary photometric fields). Finally, the diffuse, bright nebulosity associated to the star-forming gas in the region may hamper ultra-precise photometry.

3 ASTROMETRY

3.1 Recommendation

We strongly recommend as Astrometry touchstone field a relatively large region (about 1.5×0.9 sq.deg.) of the Large Magellanic Cloud, at around (R.A., Dec.) = (05^h22^m, $-69°30'$). This field contains the JWST Astrometric Calibration Field. The recommendation is based on preliminary field explorations occurred in 2021 within the Roman Astrometry Working Group (and summarized in Sect. 6.1 of the On-orbit Calibration Plan, [CAA+21]), as well as on more recent discussions within the Roman Calibration Working Group during the spring of 2024.

3.2 Purpose

The main purpose of the Astrometry touchstone field is to provide a filter-dependent, high-precision geometric distortion (GD) solution for the entire WFI focal-plane array and throughout the Roman mission. Because of the strong interdependency between the GD solution and the adopted PSF models, the Astrometry touchstone field is expected to also self-consistently allow for the derivation of high-precision effective PSF models.

The GD solution based on the Astrometry touchstone field must be able to satisfy the following science requirements on astrometry (see [Kru23]):

HLIS 2.1.1, SN 2.1.1, GO 2.1.1: "RST shall be capable of producing mosaic images of the HLIS fields using data in each filter, and using coordinates tied to the astrometric frame defined by the ICRF".

HLSS 2.1.10: "RST shall provide HLSS science data records with relative position measurement uncertainties less than 3.4" over the entire survey area".

HLIS 2.2.5: "RST shall be capable of providing HLIS calibrated data records with the astrometric solution in the WFI images having a relative error (offset between two images of the same galaxy or star, possibly taken at different times during the survey) of < 1.3 mas".

HLIS 2.2.6: "RST shall be capable of providing HLIS calibrated data records with the astrometric solution in the WFI images having an absolute error, relative to the astrometric frame defined by the ICRF of:
< 26 mas RMS per component for $\log_{10} l = 1.5$–2.0
< 11 mas RMS per component for $\log_{10} l = 2.0$–2.5
< 5.1 mas RMS per component for $\log_{10} l = 2.5$–3.0
< 2.2 mas RMS per component for $\log_{10} l = 3.0$–3.5".[1]

EML 2.1.6: "RST shall be capable of providing science data records with relative astrometric measurements having a systematic precision of ≤ 100 μas over each microlensing season, for sources imaged on the same detector in at least two passbands".

EML 2.2.3: "RST shall be capable of providing calibrated data records with relative astrometric measurements having a statistical precision of ≤ 1 mas per measurement for a star of H_{AB} $= 21.4$ in at least two passbands".

GO 2.2.6: "RST shall be able to provide GO calibrated data records with a known systematic uncertainty in the astrometric accuracy, with a goal of 10 mas for absolute positions and 5 mas for relative positions of objects within a given SCA".[2]

All in all, these science requirements are significantly more stringent than those of other space missions like *HST* and JWST (e.g., cfr. the 0.1 pixel relative astrometry for *HST* with the < 0.01 pixel relative astrometry of EML 2.2.3. As a consequence, particular care needs to be taken on detailing a calibration plan for both relative and absolute astrometry.

HLIS 2.1.1, SN 2.1.1, GO 2.1.1, HLSS 2.1.10, HLIS 2.2.6 and GO 2.2.6 are more concerned with absolute astrometry and/or with errors in the tiling of wide mosaics. Thanks to expectations based on *Gaia* end-of-mission errors, these requirements can all be easily met as long as transformations from pixel to sky coordinates are based on PSF fitting of *Gaia* sources in Level-2 data (see discussion in Sect. 3.4).

The remaining requirements are more focused on relative astrometry and the precision of PSF and/or GD solution models, with the most stringent requirement being EML 2.2.3. For them, a careful determination of the key characteristics the Astrometry touchstone field is critical.

[1] Note that l here refers to the multipole moment.
[2] SCA stands for Sensor Chip Assembly; the WFI is made up of 18 SCAs.

3.3 Field key characteristics

Discussions within the Astrometry Working Group back in 2021, recently further supported within the Roman Calibration Working Group, led to the identification of a set of attributes the Astrometry touchstone field must or should have. We provide a brief description of them below.

3.3.1 Required

- Size: the field should be at least as large as approximately 1.5×0.9 sq.deg., roughly corresponding to 2×2 barely overlapping full-frame WFI pointings. This will allow for corner-to-corner dithering of the WFI, which is a critical aspect of the self-calibration method employed during the modeling of the GD. More on this in Sect. 3.5.

- Source uniformity: the field should be reasonably uniform in terms of source density, to maximize calibration efficiency. A patchy field might result in some detectors having less than optimal density of reference sources to characterize both PSF spatial variability and local GD. This could in principle be mitigated by an increased number of exposures and dithers, thus affecting calibration efficiency.

- Reddening: reddening and differential reddening across the field should be as low as feasible to maximize source uniformity and minimize potential color-dependent effects on the PSF and GD models.

- Observability: the field should be in the CVZ, or as close as possible to it, to secure that the astrometry calibration happens during Commissioning regardless of when Roman reaches its operational orbit.

- Source density: the density of reference sources used for astrometric calibration falls into two categories: the density to construct high-precision PSF models, and the density to derive high-precision GD models. Based on experience with *HST* and JWST, as well as on ground telescopes, the optimal source density for both is approximately in the range of 2000-10,000 sources per detector. Note that PSF modeling favors a somewhat less dense field than what GD modeling would prefer, especially for what concern the modeling of the PSF wings but, since source positions will be measured using the few dozen high S/N pixels in the sources' cores, the need for well characterized PSF wings is of secondary importance for astrometry. Significantly fewer sources than the desired star-density range of densities could lead to a suboptimal characterization of the spatial variability of the PSF and of local distortion effects, while significantly more sources can lead to crowding issues and source confusion.

- Source S/N: The minimum S/N of reference sources should be 100, which should allow for single-measurement positional precision of about 0.02 pixels. Ideally, the S/N should be around 250, corresponding to single-measurement positional precision of $\lesssim 0.01$ pixels. A diminishing return is expected for higher S/N levels.

3.3.2 Desired

- Source color: in order to mitigate potential color-dependent systematic effects in both PSF and GD models, it is recommended that PSF and GD models be based on reference stars in the field with a similar, average color/temperature or, alternatively, on reference stars uniformly spanning a wide range in color/temperature.

- Proper motions: all other things being equal, it would be beneficial if reference stars in the field have low internal velocity dispersion, to minimize errors in proper-motion propagation when comparing positions taken at different epochs.

The best field in the sky satisfying both required and desired characteristics is along the bar of LMC. Other fields have also been discussed and dismissed. For instance, fields within large globular clusters are sometimes used for calibration (e.g., NGC 104 and NGC 5139 for *HST*), but their very uneven stellar density, with high crowding conditions near the core and often low spatial density in the outskirts, would force observing campaigns on such fields to be more time demanding than they should, in order to map all parts of the WFI with a desirable number of sources. In addition, most globular clusters are not in the CVZ, which would potentially prevent distortion and PSF to be characterized as soon as possible during the Roman mission. Another discarded class of fields is represented by low-reddening windows in the Galactic bulge (e.g., the Baade and Sagittarius windows), the primary reason being that these fields are also not in the CVZ.

3.4 Method of assessment

There are three main technical reports that provide estimates and simulations to evaluate the achievable precision for both relative and absolute astrometry: [Bel18, SBDC21, Bel24]. All three of them provide estimates on the achievable relative astrometry, with the most recent ([Bel24]) being based on realistic full-frame image simulations of the recommended LMC field, and using an observing strategy closely following the prescriptions given in the On-orbit Calibration Plan document ([CAA+21]). The results of these investigations clearly show that the proposed LMC field contains a goldilocks amount of uniformly-distributed reference stars that can be used to solve for the GD of the WFI. Specifically, in [Bel24] the final GD solution is capable of providing single-exposure measurements with precision around 0.002 pixels($\sim 220\,\mu$as), consistent with the Poisson noise floor of simulated data. Real data do contain more sources of errors than those included in the [Bel24] simulations, however similar approaches have been applied to both *HST* and JWST detectors, and in those cases real-world precision of better than 0.01 pixels (or 1.1 mas at Roman's WFI pixel scale) has in fact been achieved.

It is important to note that classic polynomial-based distortion solutions, even when accompanied by simple look-up tables of residuals, are unlikely to meet science requirements, due to the manufacturing characteristics of H4RG detectors. In fact, epoxy underfilling in HgCdTe detectors has already been shown to cause sudden systematic astrometric effects near the boundaries of the underfilling regions. One of these cases has been analyzed by [LBv+23], in which the authors derived high-precision PSF and GD models for the NIRISS instrument of JWST, and showed that these effects can be accounted for to well within Roman science requirements by using a pixel-based distortion solution. Ground testing has already identified epoxy-void-like structures in the flat-field images of several Roman detectors.

For what concerns absolute astrometry, [SBDC21] also discusses the pros and cons of different techniques for mapping pixel to sky coordinates. These techniques ultimately rely on a combination of single-exposure position errors (whether through PSF fitting or simple centroiding) and on the precision of a reference absolute catalog. The authors show that only transformations based on PSF fitting of *Gaia* sources in each exposure are able to meet all science requirements on absolute astrometry (see Sect. 5 of [SBDC21] for details).

3.5 Observing strategy

The On-orbit Calibration Plan document ([CAA+21]) already details a potential observing plan for astrometry. The plan contains three sets of dither patterns designed to address distinct distortion issues. Please note that, while the suggested dither patterns are not currently directly implemented in APT, there are ongoing discussions on the feasibility of including them in the near future. Meanwhile, they can be manually defined in APT as mosaic patterns.

The small dither pattern set is an array of 7×7 distinct pointings roughly covering from corner to corner of a single detector. It will be used to solve for the GD of each of the 18 detectors and is specifically designed to take advantage of the a-posteriori calibration approach, in which both distortion solution *and* positions in the reference catalog are iteratively solved for simultaneously.

The large dither pattern set is an array of 9×5 distinct pointings, this time roughly covering from corner to corner of the full-frame WFI. It will be used to tie together the 18 detector-based GD solutions coming from the small-dither set and allow the pixel-to-sky mapping of the pixels of each detector relative to the pixels of any other detector. In addition, this set will also be instrumental for cross-detector calibration.

The roll-angle set consists of 6 pointings with the same aperture but at different telescope roll angles, and will be used to constrain the skew terms of the distortion.

It is important that none of the pointings have the same exact R.A. or Dec. position of other pointings, to avoid possible issues related to, e.g., bad columns or other similar detector effects.

Example dither offsets for the small and large sets are reported in Tables 1 and 2 of [Bel24]. Red clump stars in the LMC are the primary reference-star candidates for astrometric calibrations: they all have similar average color and brightness, and are relatively isolated (most other stars in the field being significantly fainter). A S/N of about 100 can be achieved in about 60 seconds of exposure time (with some variance among different optical elements).

3.6 Secondary fields

The Astrometry touchstone field is posed to be a major reference field for many ground-based facilities. While the South hemisphere already has several high-quality fields such as the JWST astrometric calibration field in the LMC, or the *HST* calibration fields in the globular clusters NGC 104 and NGC 5139, there is no comparable field visible from the North. If more than one Astrometry touchstone field is selected, it will be very important for the astronomical community at large to have one of the field easily accessible from ground facilities in the Northern hemisphere.

3.7 Error and time budgets

Based on comprehensive simulations ([Bel24]), relative astrometric precision is expected to be somewhat better than 0.01 pixels ($\lesssim 1$ mas), comparable to that of other space missions like *HST* and JWST. Absolute astrometric errors are expected to be of the order of 0.1–0.2 mas and be mostly dominated by *Gaia* errors.

Assuming a 60 second exposure per pointing per filter, and including overheads like guide-star acquisition, slew and settle time, electronic sync and reset read, the total execution time for the three dither sets and for all 8 imaging optical elements is of the order of 23–24 hours during commissioning (see also Table 7 in [CAA+21]). Roman science data themselves can then be used to monitor temporal variations of GD and PSF models, potentially resulting in less need for a full repeat of the observing strategy in the following years of the mission.

4 SPECTROSCOPY

4.1 Recommendation

- Southern Beehive for grism wavelength calibration (monitoring) field. There are a small number of stars in the field that could be challenging to avoid. On the Roman detectors they could saturate, off they would contribute to a significant amount of scattered light. As a promising backup, Kepler prime field is proposed, centered on the open cluster NGC 6811.
- Planetary nebula (PN), likely SMC-SMP-20, for prism wavelength calibration (monitoring) field.
- EDFN or EDFS for the relative flux touchstone field.

4.2 Purpose

The purpose of the spectroscopic touchstone fields is to:

- Measure the large-scale chromatic illumination pattern (relative flux calibration correction) or sometimes called large-scale flat field (or even l-flat).
- Monitor changes in relative spectral throughput across the full field-of-view with time using a specific repeat field.
- To provide repeated measurements of the blue-edge and wavelength solutions across the full field-of-view to both measure and monitor changes in wavelength calibration initially and over time.

[CAA+21] recommends having two touchstone fields for the grism and one for the prism. For the grism touchstone fields; (1) one dedicated to the relative flux calibration and (2) one for the wavelength calibration (monitoring). For the prism, it was suggested, because of its sensitivity, to combine these into one. The main reason to break up the grism into two touchstone fields is the depth required to measure the Paschen-β (1.2818072 μm) absorption feature (per [RCH+19] on M67). However, for the prism it is likely not feasible to measure the similar absorption features (within the region of interest 800-1000 nm) because the resolution of the prism (more work needs to be done to verify this). Typically PN are used for wavelength calibration, in which we will go into greater detail in the next section. From this we recommend breaking the prism into two touchstone fields, similar to the grism.

4.2.1 Prism Wavelength Calibration Touchstone Field

The prism wavelength calibration touchstone field is to provide repeated measurements of the blue-edge and wavelength solutions across the full field-of-view to both measure and monitor the wavelength calibration initially and over time. According to the On-Orbit Calibration Plan ([CAA+21]), the grism wavelength calibration touchstone field was to be visited twice per year, we anticipate the prism requiring a similar cadence. In order to reliably calibrate the prism and monitor any changes a PN may be one of the best options until another plan is fully developed (i.e. extragalactic field with emission-line galaxies).

For Euclid, the wavelength calibration is primarily based on observations of a compact PN ([EPS+23]). This calibration is very expensive for observing time because it is necessary to step the PN through multiple positions on each detector and for all grisms; which took about two weeks. Immediately after a PN observations with one grism, Euclid is slewed to their self-calibration field without moving the grism. There a number of spectro-images were taken to establish secondary stellar calibrators with sharp absorption lines. These are used on a monthly basis to check for wavelength drifts.

According to the Euclid team ([EPS+23]), finding suitable PN for Euclid slitless spectroscopy was extremely challenging. They searched a number of suitable databases, even including a dedicated custom-search in all-sky Gaia spectra that were made available to upon request. Out of the handful of candidates, there was just one that was good (i.e. bright, plenty of emission lines, compact, no nearby contaminating sources) SMC-SMP-20, which was very successfully observed during the Euclid performance verification. HST observations have it at about 0.2" intrinsic diameter. It is bright, and it is in a low-density stellar area. There are also more compact PN, but it would be necessary to venture further out into the local group at which they rapidly get very faint and crowded. All of the PNe candidates were followed up with VLT/XSHOOTER observations (roughly R$\sim$4000 in the NIR) to carefully establish an absolute wavelength reference so that systematics were not introduced into the Euclid redshifts. This is described in better detail with a PN catalog and the wavelength atlas in [EPS+23].

Roman will be capable of observing additional PN for calibration, with a larger telescope aperture than Euclid making fainter PN accessible. For this reason, it is worth investigating candidates from [EPS+23] for PN backups. Finally, there are number of PN used for JWST commissioning and calibration, such as SMP LMC-058 and NGC 6543, which are also worth investigating [AGL+23].

4.3 Field characteristics

Consideration of the On-orbit Calibration Plan ([CAA+21]) and discussions within the Roman Calibration Working Group led to the identification of a set of attributes that the Spectroscopy touchstone fields should have. Below we provide a description of them:

- Field Size and Uniformity: In order to ensure good coverage of the edges of the field-of-view (spectra are dispersed over 1000 pixels for every bright star targeted) the field should extend over a similar area to that of the previous touchstone fields, namely at least 1.5$\times$0.9 deg^2, equivalent to 2$\times$2 overlapping WFI pointings. Good uniformity is needed to ensure good sampling of the large-scale illumination pattern. The same field size and coverage is also expected for the prism. While the throughput is not expected to change (much) as a function of position on the focal plane for the prism, there are still telescope and instrument angle of incidence effects that are not accounted for which could affect large-scale illumination pattern.

- Useful magnitude range for spectroscopy: The On-orbit calibration plan ([CAA+21]) recommends a magnitude range of $14 < H < 17$ mag for the grism, and $14 < H < 19$ mag for the prism. It was discussed during the Calibration Working Group meetings that for any observations that require imaging to go along with the spectroscopy, 14th magnitude stars may saturate and slightly fainter (H > 15 mag) stars might be needed.

- Source density: The On-orbit Calibration Plan ([CAA+21]) recommends roughly 1000 sources density per detector for both the wavelength monitoring and relative flux calibration. In the calibration of slitless spectroscopy it is ideal that source spectra should not collide, if a source needs to be decontaminated from other sources, it will significantly lower its SNR. However, there is an optimization between the maximum number of spectra that can fit on a detector with the fewest number of contaminated spectra. This optimization depends on the spectral length; the grism spectra are ∼1000 pixels long and the prism spectra are ∼200 pixels long. The type of calibration will determine how much of the spectra are used, that is the relative flux calibration utilize the full spectrum whereas wavelength monitoring only utilize a small portion of spectrum. Simulations of random source positions at a source density of 200 per detector has a contamination rate of about 10%. At 500 per detector is 18% and 1000 per detector is 27%. If the observations of lower density fields are dithered multiple times we can avoid high contamination rates and still achieve 1000 sources per detector.
- Cadence: The On-orbit Calibration Plan ([CAA+21]) recommends cadences for the relative flux to be monthly, for the wavelength calibration (monitoring) twice a year.

4.4 Observing strategy

4.4.1 Spectro-photometric field

The purpose of the spectro-photometric field is to correct for variations in the spectral throughput across the Roman FoV, correcting for variations in the optics and coatings that are not detector level effects. The on-orbit calibration plan proposed a minimum of 20 dithers, with 300 seconds total integration time of the grism and 100 seconds for the direct image, with the goal of achieving SNR of 100 over the continuum, with 10-20 spectral bins. The total exposure per visit is 3.5 hours (including overheads), with the expectation of visiting monthly (12 times per year). This observing strategy also works for the prism. Figure 4 shows the spectrum of a 17th magnitude K0.5III star. The SNR of 100 is achieved for the prism for a 17th magnitude star, without binning. The grism on the other hand will need ∼100 spectral bins to achieve an SNR of 100.

The goal was to correct for the relative flux on the scale of 128 × 128 pixels (spatially binning each detector by 32×32). Based on the current design, the number of on-sky pixels are 4088×4088 and we recommend a minor change of using 146×146 pixels (spatially binning each detector by 28×28).

4.4.2 Wavelength calibration field

For the grism wavelength calibration field, the main goal is to monitor changes in the wavelength solution. The On-orbit Calibration Plan ([CAA+21]) suggested to use open clusters to measure the Paschen-β (1.2818072 μm) absorption feature (per [RCH+19] on M67). The initial proposal was to use 5 dithers, with 500 seconds exposures of the grism and 100 seconds for the direct image, with the goal of achieving SNR of 100 over the Paschen-β absorption feature. With overheads the total time will be 1.3 hours per visit, with the expectation of visiting at least twice per year, or as needed.

Planned observations of the prism wavelength calibration touchstone field was scoped out in On-Orbit Calibration Plan ([CAA+21]). The initial proposal was to observe each PN in two locations of each of the 18 Roman detectors for about 300 seconds with the prism and 100 seconds for the direct image, with overheads will be 3.8 hours per visit (90 slew followed by 36 x 21 second moves). For Euclid, they observed 5 positions (4 corners and center) of the PN for each detector. Adapting this to Roman would translate to 8.6 hours per visit (18 x 5 x 300 sec + overheads). Based on the wavelength solutions that Euclid derived, 3 positions would have been sufficient for the wavelength calibration. In this plan, we would have 3 positions evenly spaced across the detector which would end up being 5.4 hours per visit (18 x 3 x 300 sec + overheads).

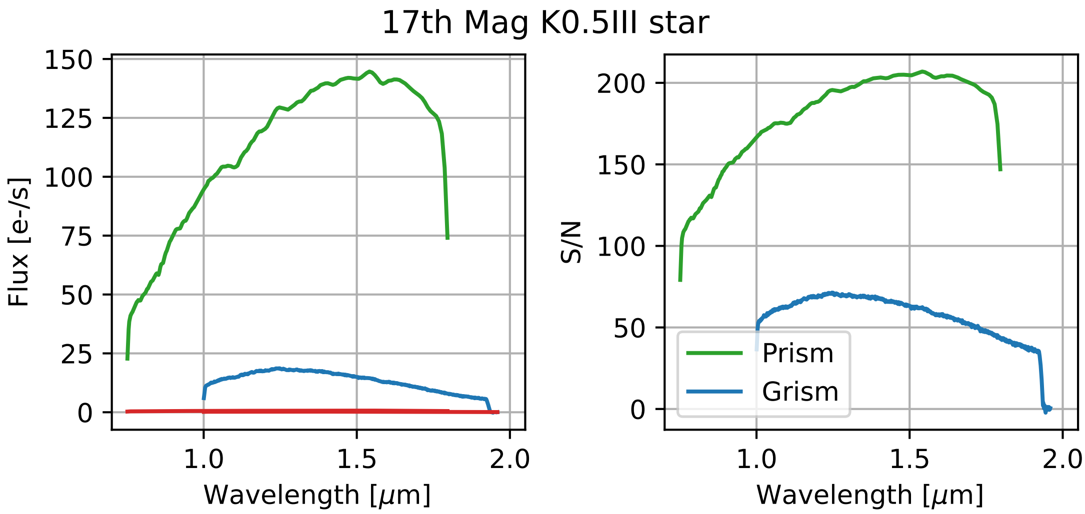

Figure 4: The left panel shows the counts/s for a simulated observation of a 17th magnitude (AB) K0.5III star using the Roman grism (blue) and prism (green). The right panel shows the SNR for the star.

4.5 Fields for Consideration

4.5.1 Euclid Deep Field North

The northern deep field selected by Euclid, the Euclid Deep Field North (EDFN) is one of the proposed fields as a relative flux field in the On-Orbit Calibration Plan ([CAA+21]). EDFN covers an area of 20 deg^2 and planned to have 40 visits with Euclid and in the CVZ for Roman. Within EDFN is the self-cal field (2 deg^2) which will be visited monthly during the Euclid mission. There are three WDs in EDFN, one of which is within the self-cal field. WDs can be useful for the verification of relative flux calibration and absolute flux calibration. Using the Gaia star catalog fields' center location, we find the mean number of stars is about 30 per detector, which is a little less than proposed in the On-Orbit Calibration Plan ([CAA+21]). Adding a few extra dithers will achieve the density needed for a relative flux field.

4.5.2 Euclid Deep Field South

The southern deep field selected by Euclid, the Euclid Deep Field South (EDFS) is one of the proposed fields as a relative flux field in On-Orbit Calibration Plan ([CAA+21]). EDFS covers an area of 23 deg^2 and planned to have 45 visits with Euclid and in the CVZ for Roman. There are three WDs in EDFS. Using the Gaia star catalog at the fields' center location, we find the mean number of stars is about 16 per detector, which is less than proposed in the on-orbit calibration plan ([CAA+21]), additional dithers will be needed to achieve the density for a relative flux field. There may be more optimal locations in the EDFS field where the stellar density is higher and needs investigation.

4.5.3 Euclid Deep Field Fornax

The Euclid Deep Field Fornax (EDFF) covers an area of 10 deg^2 and planned to have 52 visits with Euclid. The benefit of such a field is that it provides access to ground based telescopes based in the southern and northern hemispheres. Using the Gaia star catalog at the fields center location, we find the mean number of stars is about 18 per detector, which is less than proposed in the On-Orbit Calibration Plan ([CAA+21]), additional dithers will be needed to achieve the density for a relative flux field.

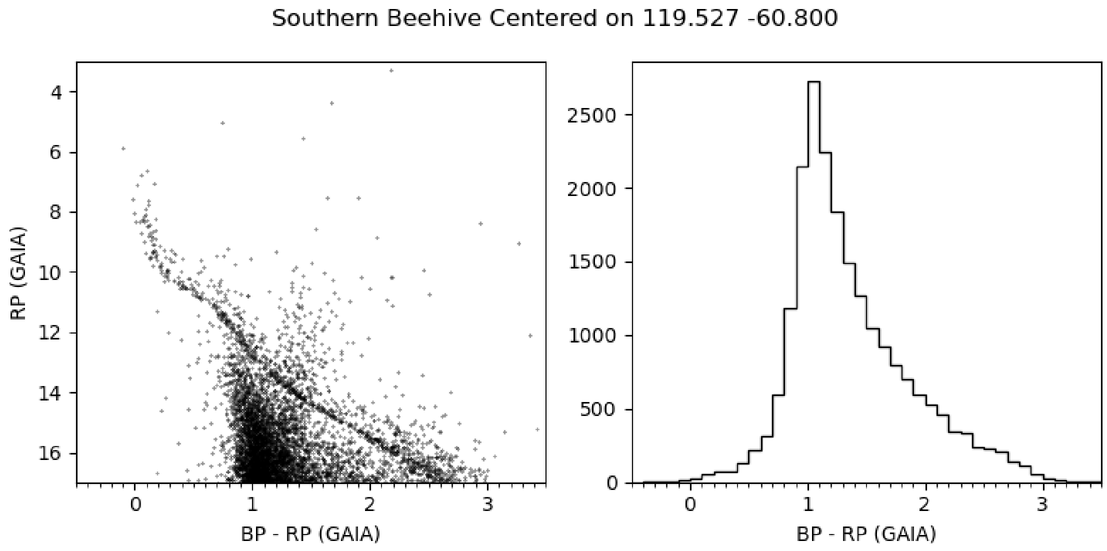

Figure 5: Color-magnitude diagram (left) and color distribution (right) in visible filters for the Southern Beehive wavelength calibration field.

4.5.4 Southern Beehive (NGC 2516)

The Southern Beehive (NGC 2516) was proposed as wavelength calibration (monitoring) field in On-Orbit Calibration Plan ([CAA+21]). Figure 5 shows the color-magnitude diagram for the Southern Beehive open cluster, with a prominent stellar main sequence. The mean stellar density down to 17th magnitude (Gaia RP band) is about 100 stars per detector (2.3/arcmin^2). There are a few bright stars which could be difficult to avoid, even with different roll angles. To evaluate potential spectral contamination we go two magnitudes deeper than the target SNR (100), in which the mean stellar density down to 19th mag is about 320 stars per detector (5.7/arcmin^2). This is a spectral contamination (i.e. the percentage of pixels with more than 1 source contributing to the spectra) rate of ∼13-14%, which is a very workable solution.

4.5.5 Kepler Prime Field

The Kepler prime field is a field much larger than WFI's field-of-view; which means that there are many choices for position in the field. There is an extensive amount of APOGEE H-band spectra, close to 200 per square degree. There is also an abundance of archival LAMOST spectroscopy in the optical. The stellar density over the entire field is very uniform and is about 7 per arcmin^2 betweeen the Gaia magnitude ranges of $14 < R < 19$, and is about 2 per arcmin^2 between $14 < R < 17$.

There are four open clusters in the Kepler prime field, which are NGC 6791, NGC 6811, NGC 6819 and NGC 6866. Table 5 shows the stellar density of each of the fields. The stellar density for NGC 6791 and NGC 6819 may be too high, many of the members (∼900) would fall within a single detector and would have a spectral contamination rate of about ∼23%. NGC 6811 looks promising as its cluster members are spaced over 3 detectors and the spectral contamination rate would be low (∼10%). Additionally, there are not too many bright stars in the field (<8th mag). NGC 6866 cluster members are spaced much larger than the Roman FoV and may not provide the needed density for wavelength monitoring.

4.5.6 Additional Fields

During the assessment period three additional fields were identified; COSMOS, Extended Groth Strip / AEGIS and GOODS-North. Additional work needs to be conducted to vet these fields.

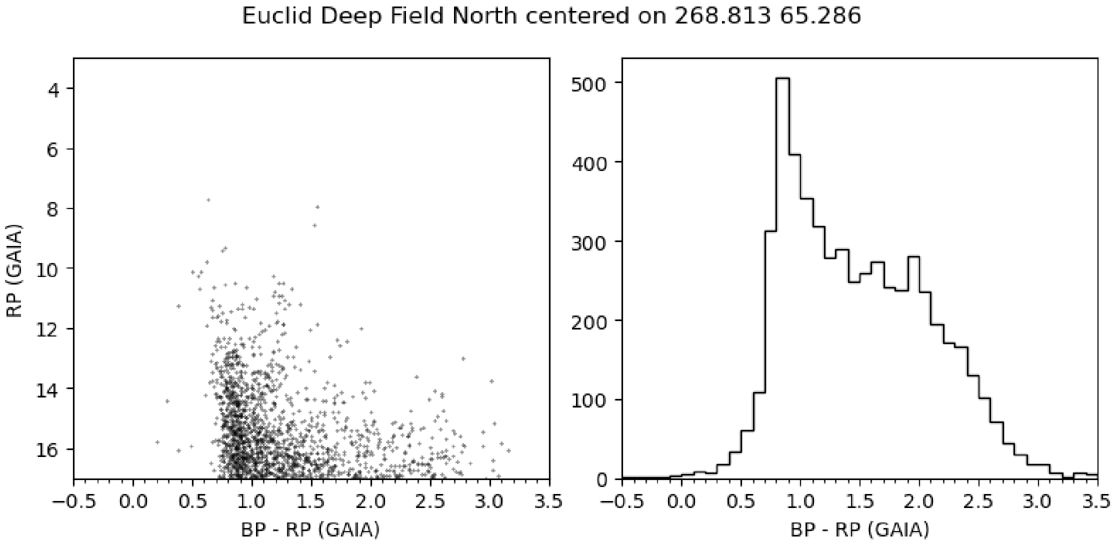

Figure 6: Color-magnitude diagram of sources in Gaia magnitudes with the RP and BP filters (left) and the color distribution of sources (right) for the EDFN wavelength calibration field.

Target	Min Density [#/SCA]	Mean Density [#/SCA]	Max Density [#/SCA]
NGC 6791	140	230	900
NGC 6811	110	160	200
NGC 6819	190	330	920
NGC 6866	130	240	370

Table 5: Stellar density of the open clusters within the Kepler prime field.

4.5.7 Extragalactic field with emission-line galaxies

Another approach to the wavelength calibration post-commissioning is by choosing an extragalactic field with bright emission-line galaxies with known redshifts. The benefit of this approach is that the dispersion solution can be re-derived in-flight without the need to bootstrap the ground measurements. Repeated observations at many roll angles would be required to deal with source contamination. Over time the wavelength solution improve with repeated observations and provide a very accurate way to calibrate and monitor the wavelength solution. One of the caveats of this approach is that an extragalactic touchstone field would need to chosen soon, as the Roman launch is rapidly approaching. Ground-based telescope spectroscopic time would need to be obtained for measuring redshifts for a Roman-sized field. The spectra would need to be at sufficient resolution (i.e. at higher resolution) to calibrate both the Roman grism and prism.

Suitable galaxies for such a technique would have strong emission lines in the prism and grism wavelength ranges and should be compact enough that one does not have to worry too much about source morphology (but one *does* have to worry about separate RA/Dec centroids for each ion).

To figure out the source density, the JADES Extragalactic Ultra-deep Artificial Realization (JAGUAR) was used. Working with that source density, the number of observed emission lines over ∼4 deep prism pointings (roughly the HLTDS deep prism tier) is about 1 million, or about 2 million line centroids (in x/y). If one assumes it takes 10 parameters to get the wavelength solution for the prism at one point in the FoV, times a 2D quadratic (6 parameters) for each detector (18), that is $10 \times 18 \times 6 = 1080$ parameters for the wavelength solution. One also needs the RA/Dec/wavelength of each emission line, so that is another ∼21,600 parameters. There is no 0th order, so one also needs to fit for the offset and rotation of each pointing, so that is ∼1752 parameters. So there are ∼100 observations per parameter. In short, the solution should work pretty well!

A couple of possible fields are 1) directly observing the northern HLTDS prism fields with PFS/DESI/MOSFIRE, or 2) using the HLTDS fields for the uber calibration up to an unknown

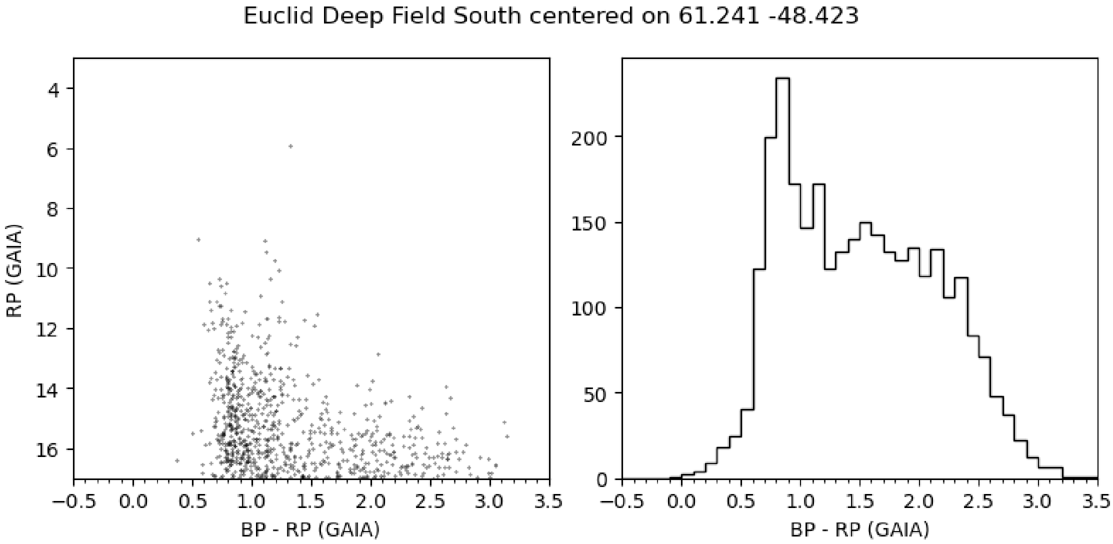

Figure 7: Color-magnitude diagram of sources in Gaia magnitudes with the RP and BP filters (left) and the color distribution of sources (right) for the EDFS wavelength calibration field.

absolute wavelength solution and then some smaller number of pointings and rotations in the northern touchstone field (e.g., the NEP) to constrain the absolute wavelengths by inter-calibration with the ground.

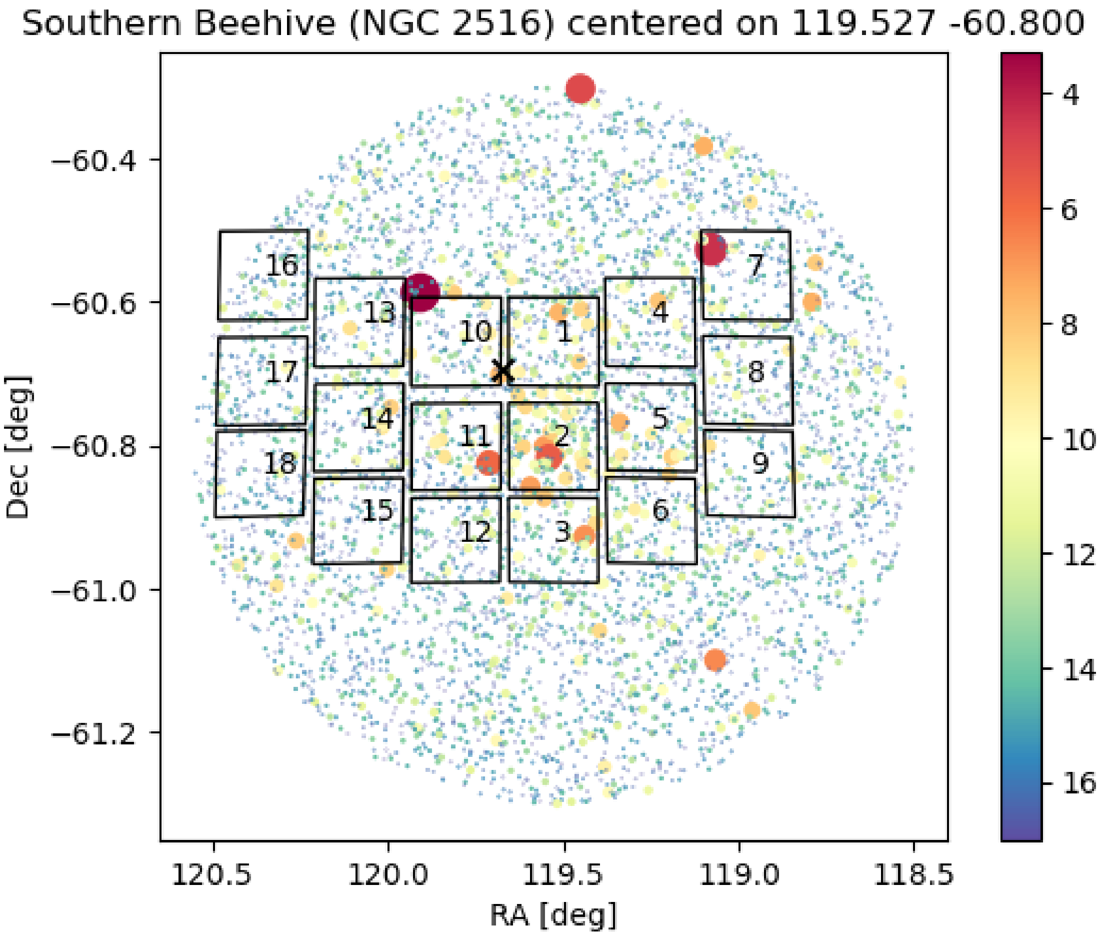

Figure 8: Roman FoV centered on the Southern Beehive (NGC2516). Larger points are brighter stars (color-coded red) and smaller points are fainter stars (color-coded blue).

Appendix A Estimating the quality of the photometric uniformity calibration

One of the goals of the observations of the photometric touchstone field is to determine the large-scale flat field of WFI by comparing the photometry of the same source at different locations in the field of view. This calculation assumes that the pixel-level flat field can be determined independently from internal flats to a precision better than 1% (the goal is 0.1%). The precision with which the large-scale flat field can be determined depends on the number of stars available, their individual S/N, and the scale of the measurement. For simplicity, we assume a representation in which the photometry correction is constant over each 1024×1024 pixels region (16 regions per detector); in practice, a continuous representation with a similar number of independent components would probably be preferable. The 2MASS catalog provides magnitudes of sources in the LMC calibration field to a depth $H \sim 15$ mag; based on the WFI sensitivity information on the GSFC site, a $H \sim 15$ star can reach S/N well in excess of 100 in a 55 s exposure. We solved for the large-scale flat field using a nominal 13-dither observing sequence (Table 4), and assumed a floor of 0.01 mag per measurement. With those parameters, we can achieve an uncertainty of 0.001 mag or better on a 1024×1024 pixel scale.

On the other hand, the density of stars in the Northern Euclid Calibration Field is insufficient to constrain the WFI flat field on the same scale with comparable exposure times. The flat field can be verified or constrained on larger scales, approximately 2000×2000 pixels, to a precision of 0.01 mag.

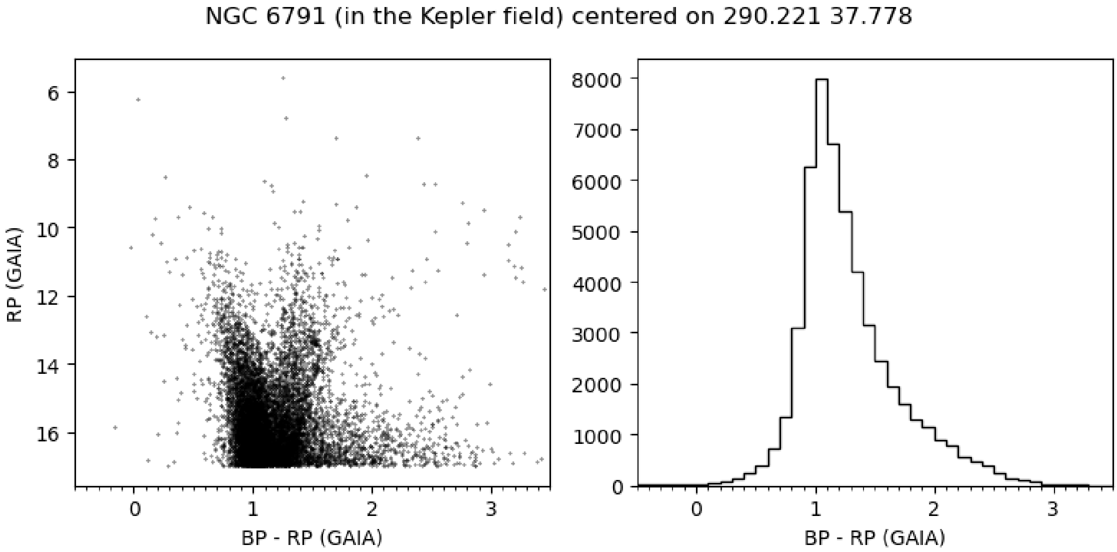

Figure 9: Color-magnitude diagram of sources in Gaia magnitudes with the RP and BP filters (left) and the color distribution of sources (right) for the NGC 6791 wavelength calibration field.

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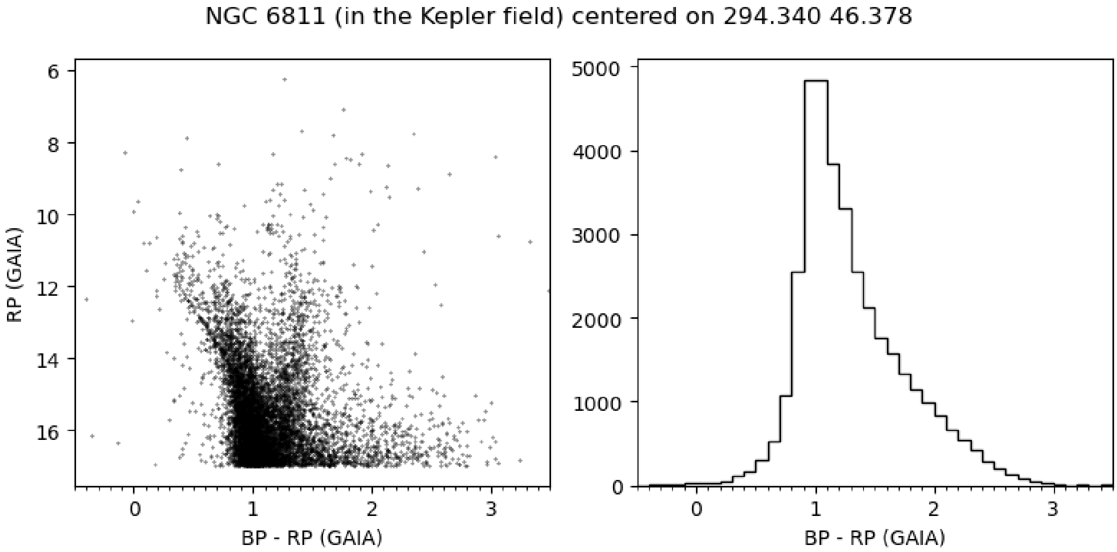

Figure 10: Color-magnitude diagram of sources in Gaia magnitudes with the RP and BP filters (left) and the color distribution of sources (right) for the NGC 6811 wavelength calibration field.

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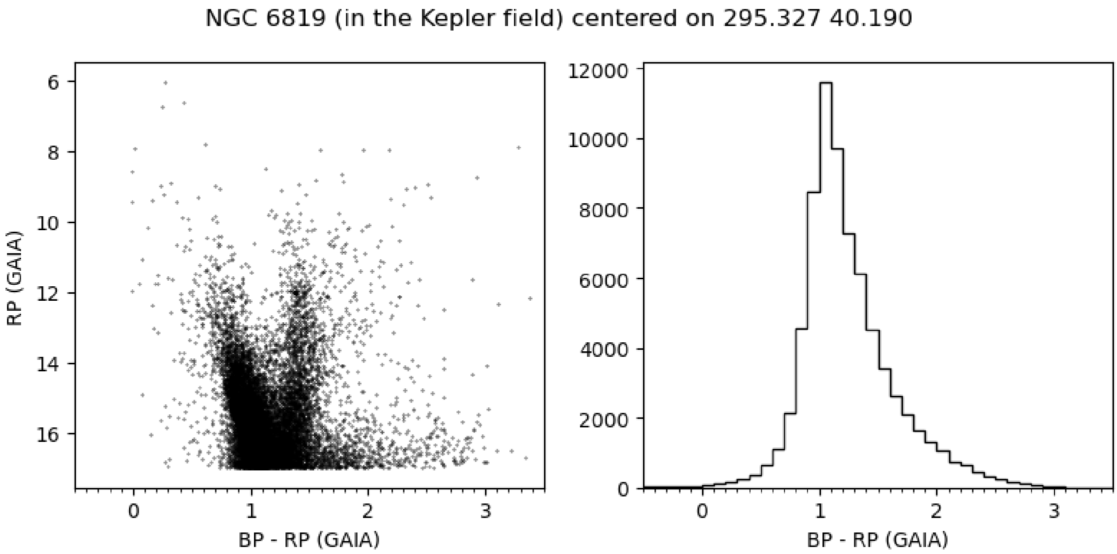

Figure 11: CColor-magnitude diagram of sources in Gaia magnitudes with the RP and BP filters (left) and the color distribution of sources (right) for the NGC 6819. wavelength calibration field.

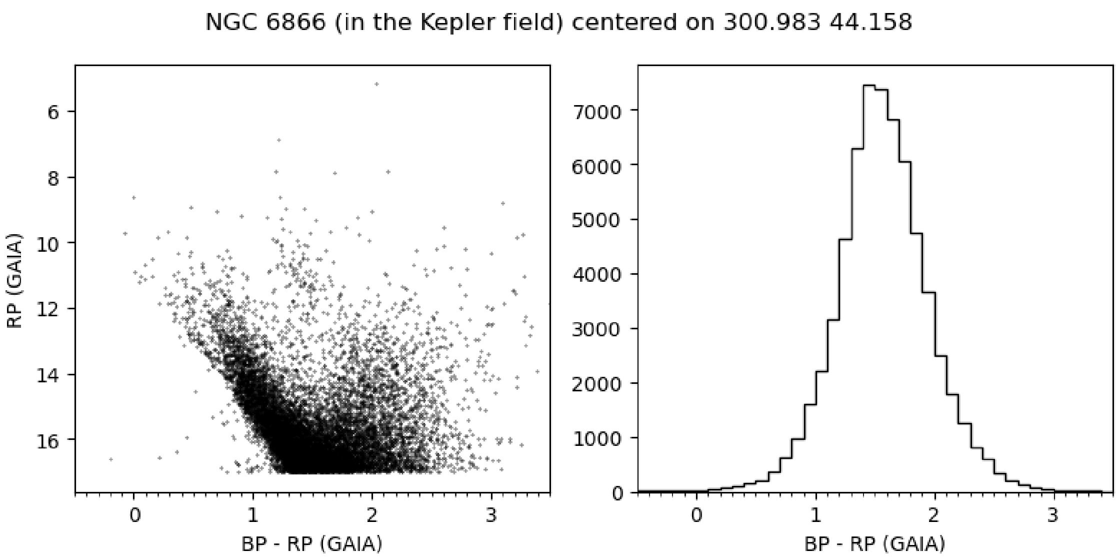

Figure 12: Color-magnitude diagram of sources in Gaia magnitudes with the RP and BP filters (left) and the color distribution of sources (right) for the NGC 6866 wavelength calibration field.

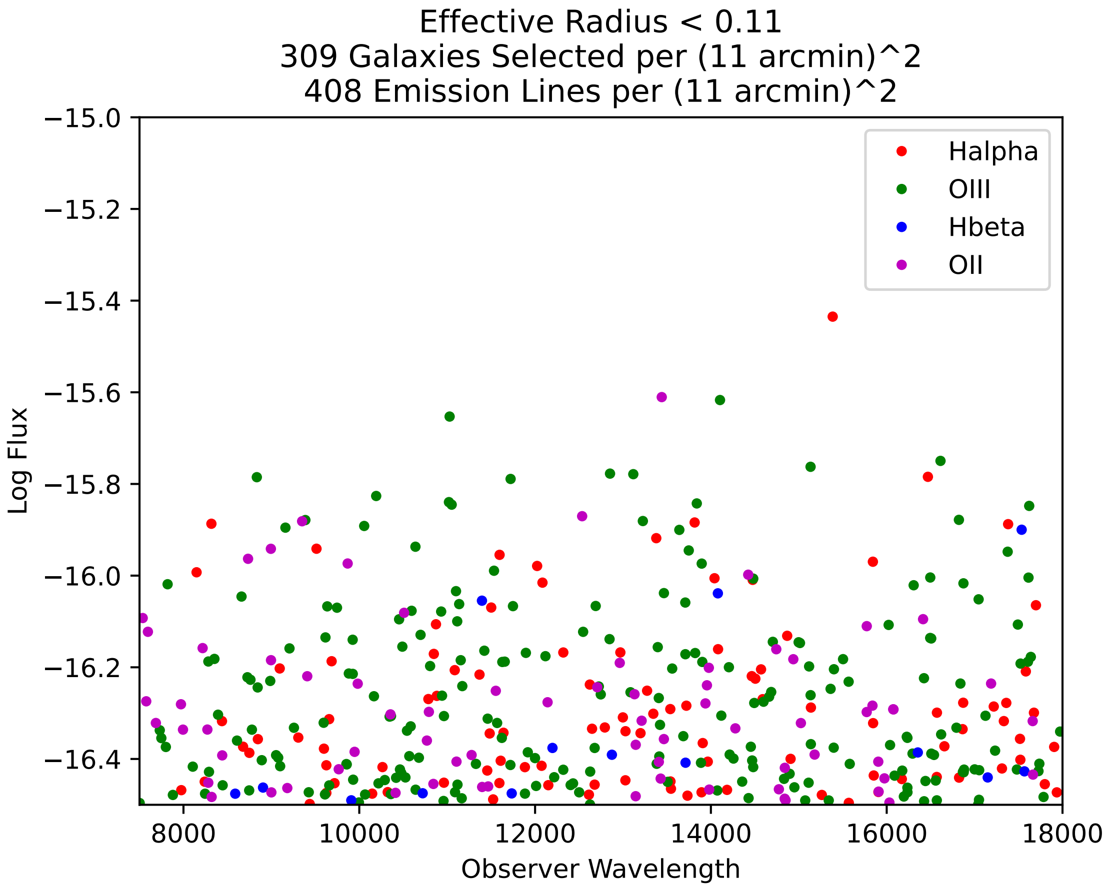

Figure 13: After limiting galaxies to ∼1 pixel in radius, there are at least ∼100 sources per detector with line fluxes brighter than a few times 10^{-17}ergs/cm^2/s and that the emission lines are well distributed over the prism wavelength range. The figure shows (11 arcmin)^2 or about 2 detectors worth of area.