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Roman SOC Absolute Astrometric Uncertainty Science Validation

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Abstract

This report contains the scientific validation of the Level 4 Science Operation Center requirement SOC-1057, which states that in Wide Field Imaging mode, the DMS shall provide calibrated images with a known systematic uncertainty in the absolute astrometry.

1 EXECUTIVE SUMMARY

SOC ID	Capability	Description	Result
SOC-1057	Absolute Astrometric Uncertainty	The goal for absolute uncertainty of the astrometric solution of an image is 10 milliarcsec, per the SRD.	Pass

INTRODUCTION

In the fall of 2025, the Roman Telescope Branch (RTB) in the Instruments Division at the Space Telescope Science Institute (STScI) performed science validation of the System-Level requirement SOC-1057, levied on the Roman Science Operations Center (SOC; Nieto-Santisteban et al. 2024). The validation is part of SOC Release 4 but made available for testing ahead of the full validation with SOC Build B19. The scientific validation includes the Data Management Subsystem (DMS) part of the SOC.

Science validation by the RTB differs from the verification process performed by the Integration and Testing (I&T) team in that the validation checks either that: 1) specific inputs produce **scientifically correct** outputs that meet the user's expectations; or 2) functionality delivered by the SOC is consistent with the expectations of the user community. Both verification and validation are essential steps in assessing the successful development of the Roman DMS and documenting that development with the Roman Project.

To perform the validation, this requirement was assigned to a team of testers who determined the success criteria and created code (when applicable) to evaluate the tests in the DMS software released with Build 25Q4_B19 (Build 19) on August 2025.

2 REQUIREMENTS TESTED

2.1 SOC-1057: Absolute Astrometric Uncertainty

2.1.1 Requirement Description

SOC-1057 states that:

> `In Wide Field Imaging mode, the DMS shall provide calibrated images with a known systematic uncertainty in the absolute astrometry.`

A comment refers to the SRD requirement GO 2.2.6 which states that:

> `The absolute uncertainty is based on the mean offset for sources with known and sufficiently accurate absolute position in an image. The goal for absolute uncertainty of the astrometric solution of an image is 10 milliarcsec, per the SRD.`

The requirement does not specify exactly what has to be measured: mean values or dispersion of the uncertainties of the star positions. In the report, we looked at the distribution of the positional difference between input and detected *Gaia* stars. We computed the location and dispersion of the distributions for each detector and checked if the 90% confidence interval of the distribution was smaller than 10 mas.

2.1.2 Testing Strategy

The ROMANCAL pipeline utilizes by default *Gaia* DR3 stars observed in the WFI detectors to improve the astrometric precision of the images obtained with the Roman telescope. Since the positions of *Gaia* stars are accurate down to 24 μarcsec[1] and the goal of the Roman astrometric accuracy is 10 mas (milli-arcsec) we can consider the absolute error on *Gaia* positions negligible in our computations.

To check if the pipeline is robust enough to recover positions within this accuracy, we simulated Roman images by adding sources from the *Gaia* catalog and random-generated galaxies. To simulate the error due to the uncertainty in the reconstruction of the astrometry, we altered the position of the sources in these simulations by shifting their coordinates by a few arcsecs or by rotating the field by one arcsec. Since the pointing accuracy of the Roman telescope after acquiring guiding stars is expected to be around a few mas, it is sufficient for our scopes to test if the pipeline can correct shift up to a few arcsecs. This will also account for pointings with no available solution with guiding stars since the initial (blind) pointing accuracy is expected to be better than one arcsecond.

Another source of uncertainty is a possible small rotation of the field. Since the correction computed by the ROMANCAL pipeline assumes the center of rotation as the center of the WFI aperture, we simulated images with *Gaia* stars rotated by 1 arcsec around the center of the WFI aperture that is conserved in the pointing field of the meta data as WFI_CEN.target_ra and WFI_CEN.target_dec. This naturally makes the displacements due to the rotation more noticeable in the outer detectors.

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[1] `https://www.esa.int/Science_Exploration/Space_Science/Gaia/Gaia_factsheet`

The tests were initially done by using simulations with no displacement, then by using simulations with a simple shift of coordinates, and finally by considering simulations with a rotation of the field. The displacements between input and recovered *Gaia* positions were then computed. The accuracy of the astrometry was estimated by calculating robust estimates of the mean displacement and of its dispersion.

2.1.3 Testing Description

The simulations were obtained using the version 0.10 of Roman-I-Sim, which generates level 1 products compatible with the version of RomanCal (0.20.2) tested in this report. The level 1 products were then processed with the RomanCal (0.20.2) pipeline to obtain source catalogs.

Level 1 products were generated according to the following procedure. Once a catalog containing *Gaia* sources and randomly-generated galaxies was obtained, the level 1 products are generated with the following Python instructions:

```python
import argparse, galsim
from romanisim import gaia, bandpass, catalog, log, wcs, persistence,
                                      parameters, ris_make_utils as ris
from astropy.table import Table
from astropy.coordinates import SkyCoord

center = SkyCoord(270.94, -0.2, unit='deg', frame='icrs') # Center
                                      coordinates
full_catalog = Table.read('full_catalog.ecsv')

obs_date = '2026-10-31T00:00:00'  # Datetime of the simulated exposure
sca = 1  # Detector number
optical_element = 'F106'  # Optical element to simulate
ma_table_number = 3  # Multi-accumulation (MA) table number
level = 1  # WFI data level
cal_level = 'cal' if level == 2 else 'uncal'
filename = f'r0003201001001001004_0001_wfi{sca:02d}_{optical_element.lower
                                      ()}_{cal_level}.asdf' # Output file
                                      name on disk.

# Set other arguments for use in Roman I-Sim. The code expects a specific
                                      format for these.
parser = argparse.ArgumentParser()
parser.set_defaults(usecrds=True, stpsf=True, level=level, filename=
                                      filename,
                    drop_extra_dq=True, sca=sca, bandpass=optical_element,
                                       pretend_spectral=None)
args = parser.parse_args([])

# Set reference files to None for CRDS
for k in parameters.reference_data:
    parameters.reference_data[k] = None

# Set Galsim RNG object
seed = 7 # Random generator seed
rng = galsim.UniformDeviate(seed)
```

```

# Set default persistance information
persist = persistence.Persistence()

# Set metadata
metadata = ris.set_metadata(date=obs_date, bandpass=optical_element, sca=
                                    sca, ma_table_number=ma_table_number,
                                     usecrds=True)

# Update the WCS info
wcs.fill_in_parameters(metadata, center, boresight=False, pa_aper=0.0)

# Run the simulation
ris.simulate_image_file(args, metadata, full_catalog, rng, persist)
```

To generate simulations with a shift in the coordinates we used the following technique:

```
from astropy.table import Table

full_catalog = Table.read('full_catalog_LH.ecsv')
# Move coordinates by a few arcsec
new_catalog = full_catalog.copy()
delta = 5/np.sqrt(2)/3600.  # Total displacement of 5 arcsec
new_catalog['dec'] += delta
new_catalog['ra'] += delta
```

Finally, to rotate the coordinates around the aperture we used Rodrigues' rotation formula [2]:

$$\mathbf{a}_{\rm rot} = \cos(\theta)\,\mathbf{a} + \sin(\theta)\mathbf{k}\times\mathbf{a} + (1-\cos\theta)(\mathbf{k}\cdot\mathbf{a})\mathbf{k}, \tag{1}$$

where **a** is the vector corresponding to the position of a source on the celestial sphere from the catalog of simulated sources, **k** is the unit vector that defines the direction of the rotational axis, and θ is the angle of rotation. We defined the following function to apply Eqn. 1 to sources of a generic catalog:

```
def rotatecoords(catalog, center, angle):

    #Inputs
    #------
    #catalog: a Roman-I-Sim catalog
    #center: the center of rotation (R.A.,Dec.) in degrees
    #angle:  the angle used for rotation in degrees

    #Outputs
    #-------
    #None.
    #The coordinates of the input catalog are modified.

    #Description
    #-----------
    #Rotate the coordinates in the input catalog by angle around the
                                     direction center.
```

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[2] https://en.wikipedia.org/wiki/Rodrigues%27_rotation_formula#Derivation

```

    import numpy as np
    ra0, dec0 = center
    phi = catalog['ra'].value * np.pi/180
    theta = (90 - catalog['dec'].value) * np.pi/180
    ax = np.sin(theta) * np.cos(phi)
    ay = np.sin(theta) * np.sin(phi)
    az = np.cos(theta)
    Phi = ra0 * np.pi/180
    Theta = (90 - dec0) * np.pi/180
    kx = np.sin(Theta) * np.cos(Phi)
    ky = np.sin(Theta) * np.sin(Phi)
    kz = np.cos(Theta)
    beta = angle * np.pi/180
    cbeta, sbeta = np.cos(beta), np.sin(beta)
    ka = kx * ax + ky * ay + kz * az
    Ax = ax * cbeta + (ky * az - kz * ay) * sbeta + ka * kx * (1-cbeta)
    Ay = ay * cbeta + (kz * ax - kx * az) * sbeta + ka * ky * (1-cbeta)
    Az = az * cbeta + (kx * ay - ky * ax) * sbeta + ka * kz * (1-cbeta)
    phi = np.atan2(Ay,Ax) * 180/np.pi
    theta = 90 - np.atan2(np.sqrt(Ax*Ax+Ay*Ay), Az)*180/np.pi
ty     catalog['ra'] = phi
    catalog['dec'] = theta
```

To test the robustness of the solution, we also generated simulations in the direction of the Lockman Hole, a region with little Galactic absorption (a sort of hole in our Galaxy) which is representative of cosmological studies. This region has a limited amount of *Gaia* sources (typically 15 to 30 per detector), making the tweaking of the astrometry rather challenging. However, similar regions will be extensively surveyed by Roman for cosmological studies, and testing the accuracy of the astrometric reconstruction in a region with such a dearth of *Gaia* stars seems appropriate and justified.

2.1.4 Results

We executed several tests with different shifts in coordinates and rotation of the field. In the first test, we considered a stellar field (R.A., Dec.) $= (270.^\circ7, -0.^\circ2)$ with a star cluster at the center. Fig 1 shows the difference in coordinates between the real position of *Gaia* stars in each WFI detector and the position recovered by the pipeline when the simulated level 1 product had the input coordinates shifted by 3 arcsec. The plots are arranged in the same way as the respective detectors are in the WFI array (see the WFI manual for a description of the array and the indexing of the detectors [3]). The pink disk shows the required accuracy (10 mas) while the orange circle is centered on the mean displacement and has a radius corresponding to the 90% confidence interval of the distribution of displacements, which corresponds 1.645 times the 1 σ interval for a univariate Gaussian distribution. Location and dispersion of the distribution has been computed using the biweight robust estimator (Beers et al. 1990) available in the Python library astropy.stats.biweight. Table 1 reports the number of *Gaia* stars matched between the original catalog and the output catalog, the mean shift

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[3] https://roman-docs.stsci.edu/roman-instruments-home/wfi-imaging-mode-user-guide/wfi-design/description-of-the-wfi

measured in their positions, and the 1σ dispersion of distribution of the shifts for each detector in the WFI array. It is clear that the pipeline recovers the position of *Gaia* stars in all 18 detectors with a accuracy similar or better than the science goal of 10 mas.

However, the number of available stars can sometimes be much smaller. In cosmological fields such as the Lockman Hole (R.A., Dec.) = ($161\overset{\circ}{.}25$, $58\overset{\circ}{.}0$), there can be a real dearth of stars, with a typical number of *Gaia* stars between 15 and 30 for each detector. For this reason, we also tested the pipeline in this more extreme condition (but typical for cosmological studies) to see the limitation of this technique. We show here the results for a shift of 0 and 1 arcsec (Fig 2), 3 and 5 arcsec (Fig. 3), and for a rotation of 1 arcsec (Fig. 4). Even in the case with a shift of zero (see Fig 2), the center of the distribution is often off by several milli-arcsecs. For most of the detectors, however, the accuracy is well within the science goal of 10 mas.

As we add a shift of 1 and 3 arcsecs to the initial coordinates, we notice a failure of the pipeline for detector WFI10. The recovered position is, in this case, well beyond the required accuracy (up to 3 arcsec) to the point that no residuals are visible in the plot (see Fig. 2, bottom panel and Fig. 3, top). The addition of a larger shift (5 arcsec) (see Fig 3, bottom panel) somehow leads to an unexpected recovery of the astrometry of detector WFI10.

Our final test involved the addition of a rotation of the field, since the pipeline is able to fit a combination of shifts and rotation. The recovery of the astrometry is successful also in this case. Table 2 reports the number of *Gaia* stars matched between the original catalog and the output catalog, the mean shift in their positions, and the 1σ dispersion of the shifts for each detector in the WFI array in the five simulations considered.

Table 1: Distribution of Position Residuals for the Cluster Field

WFI	**shift: 3 arcsec**		
No	N$_{Gaia}$	$\Delta\alpha$ $\Delta\delta$ [mas]	σ [mas]
01	1471	−0.7 −0.1	5.0
02	1260	−0.2 −0.1	3.7
03	1380	−0.1 −0.1	3.3
04	1412	−0.2 +0.2	3.0
05	1078	−0.1 +0.0	1.3
06	0769	−0.7 +0.6	4.8
07	1494	−0.4 −0.1	4.4
08	1231	−0.1 +0.1	3.1
09	1382	+0.0 +0.1	1.9
10	1018	−0.1 +0.0	3.0
11	1485	−0.6 +0.1	3.1
12	1188	−0.4 +0.1	4.5
13	1586	−0.1 −0.3	2.1
14	1731	−0.1 −0.1	1.8
15	1282	−0.3 +0.0	3.8
16	1493	+0.5 +0.5	2.8
17	1162	−0.2 +0.1	4.7
18	1644	+0.0 +0.0	3.0

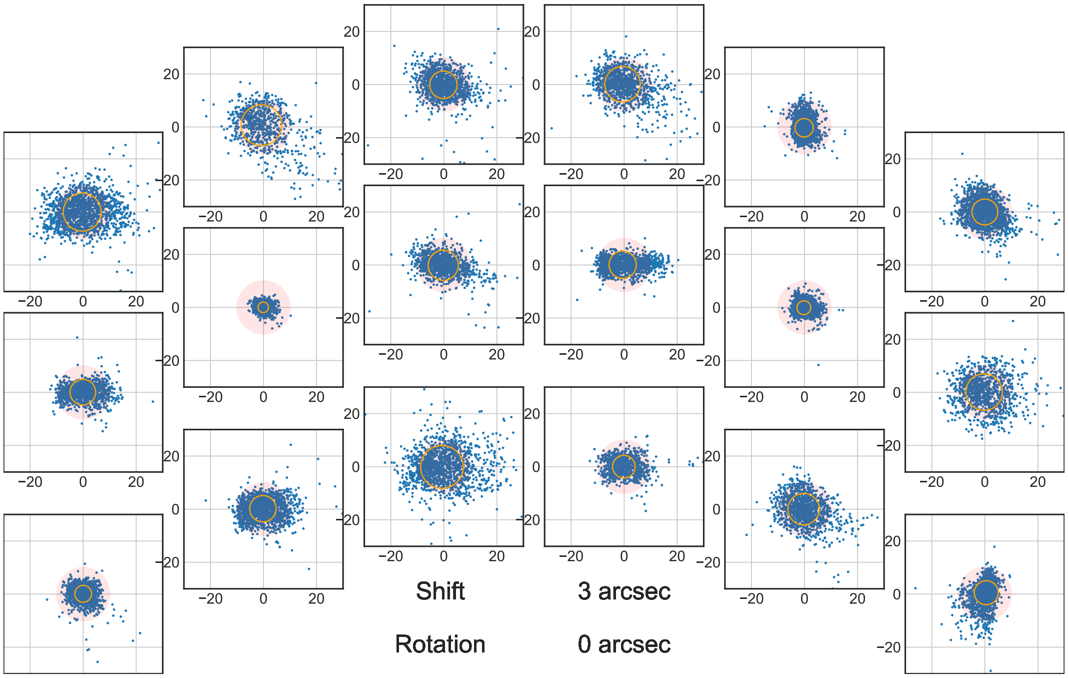

Figure 1: Position residuals in mas between input and detected positions of *Gaia* sources from a simulation with 3-arcsec shift for a field including a star cluster. The plots are arranged according to the positions of the detectors in the WFI array. Residuals in each detector are shown on the top of 10 mas radius pink disks. The orange circles correspond to the 90% confidence interval of the distribution, and are centered on the mean values of the distributions.

Table 2: Distribution of Position Residuals for the Lockman Hole

WFI	**shift: 0″**				**shift: 1″**				**shift: 3″**				**shift: 5″**				**rotation: 1″**			
No	N_{Gaia}	$\Delta\alpha$	$\Delta\delta$	σ	N_{Gaia}	$\Delta\alpha$	$\Delta\delta$	σ	N_{Gaia}	$\Delta\alpha$	$\Delta\delta$	σ	N_{Gaia}	$\Delta\alpha$	$\Delta\delta$	σ	N_{Gaia}	$\Delta\alpha$	$\Delta\delta$	σ
		[mas]		[mas]		[mas]		[mas]		[mas]		[mas]		[mas]		[mas]		[mas]		[mas]
01	29	−3.9	−0.6	6.3	28	−0.6	+0.3	4.9	28	−1.7	−4.4	5.0	26	−0.4	+1.7	4.8	29	−4.3	−0.9	6.1
02	20	−0.8	−0.4	3.9	21	−0.1	+0.6	3.1	21	−0.2	+0.3	3.3	23	−0.4	+0.9	4.5	22	−1.1	−0.2	3.9
03	23	−2.1	+1.2	7.0	22	−0.1	+0.1	2.9	22	+0.3	−0.2	3.6	22	+0.1	−0.8	4.4	23	−0.7	+0.9	3.4
04	19	−0.1	−0.3	2.7	19	+0.0	+0.5	2.4	19	−0.1	−0.0	2.9	19	+0.2	+0.3	3.5	19	+0.1	−0.0	2.5
05	28	+0.1	+0.4	1.7	30	+0.1	+0.3	1.3	30	−0.1	+0.3	1.7	29	−0.2	−0.5	1.8	29	+0.2	+0.2	1.4
06	32	−1.3	+1.5	7.5	32	+0.3	−0.9	5.0	32	−0.5	+1.1	5.4	32	−1.9	+0.2	7.1	32	−1.3	+1.6	7.4
07	36	+0.3	−0.0	4.3	36	+0.1	+0.2	4.1	36	+0.6	+0.3	4.5	37	+0.5	−0.4	3.6	36	+0.4	+0.1	4.9
08	25	−0.1	+0.2	3.1	25	−0.5	+0.1	2.5	24	−0.1	+0.4	3.4	25	+0.1	+0.1	4.2	26	−0.1	+0.4	3.0
09	25	−0.4	+0.1	1.6	25	−0.1	+0.3	2.8	23	−0.2	+0.5	2.0	23	+0.4	+0.1	1.5	24	−0.5	+0.5	1.7
10	16	−0.2	−0.4	2.5	15	−370	−703	4.9	15	−1119	−2118	4.8	16	+0.2	−0.1	3.1	17	−0.5	−0.0	2.7
11	32	−0.5	−0.2	3.6	32	−0.4	+0.2	2.6	30	−0.1	+0.1	2.9	32	−1.0	+0.3	3.6	32	−1.5	−0.1	2.9
12	23	−4.1	+6.9	8.3	23	−6.2	+4.9	5.5	23	−0.9	+0.4	4.8	23	−1.0	+1.7	6.1	23	−6.1	+7.6	9.4
13	29	+0.1	−0.2	1.8	29	+0.0	−0.0	2.0	29	−0.1	+0.1	2.3	28	−0.0	−0.2	2.1	29	−0.4	−0.1	1.7
14	18	−0.3	−0.1	1.8	17	−0.6	+0.3	1.2	16	−0.3	−0.1	1.6	17	+0.3	+0.1	2.3	17	−0.4	−0.3	1.5
15	29	−0.3	+0.1	3.6	32	−2.3	−0.1	2.8	31	−0.1	+0.4	4.4	31	−0.3	+0.4	2.4	31	−0.1	+0.3	3.3
16	21	+0.4	−0.1	2.9	21	−0.0	+0.4	1.8	21	+0.7	+1.1	2.3	22	+0.2	+1.3	2.8	21	+0.9	−0.5	3.4
17	20	+0.6	+1.0	4.1	21	+0.4	+0.8	5.3	20	−0.2	+1.1	5.6	23	−0.2	+1.7	6.1	23	+0.2	+0.6	4.2
18	20	−0.4	+0.0	2.4	20	+0.3	−0.1	2.7	20	−0.0	−0.6	3.7	21	−0.5	−0.1	3.4	20	−0.4	+0.1	2.9

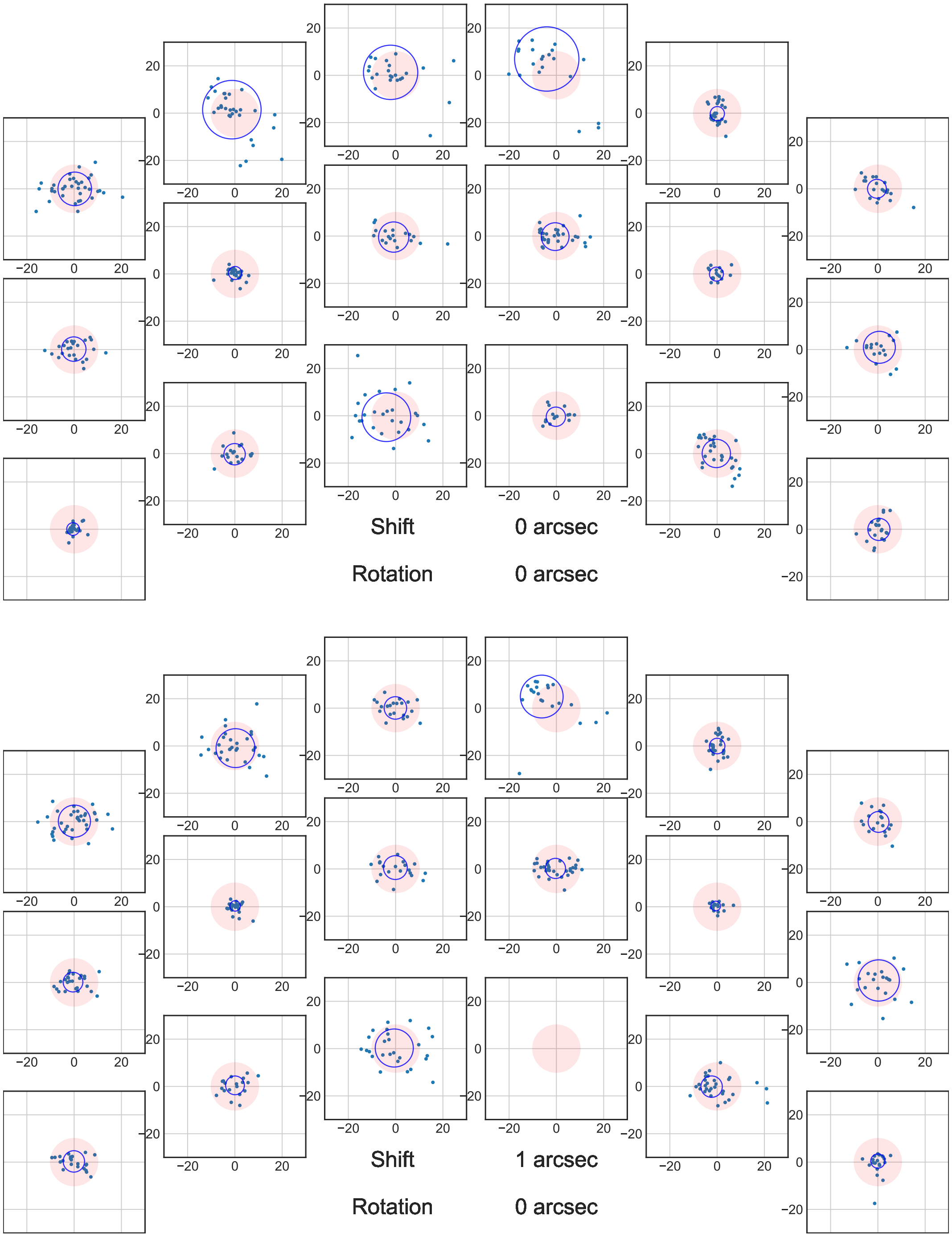

Figure 2: Position residuals in mas between input and detected *Gaia* stars from two simulations of the Lockman Hole field with 0 arcsec (top) and 1 arcsec (bottom) shifts applied to input positions. The panels are arranged according to the positions of the detectors in the WFI array. The distribution of residuals in each detector is shown on top of a 10 mas radius pink disk. The blue circles correspond to the 90% confidence interval of the distributions and are centered on their mean values.

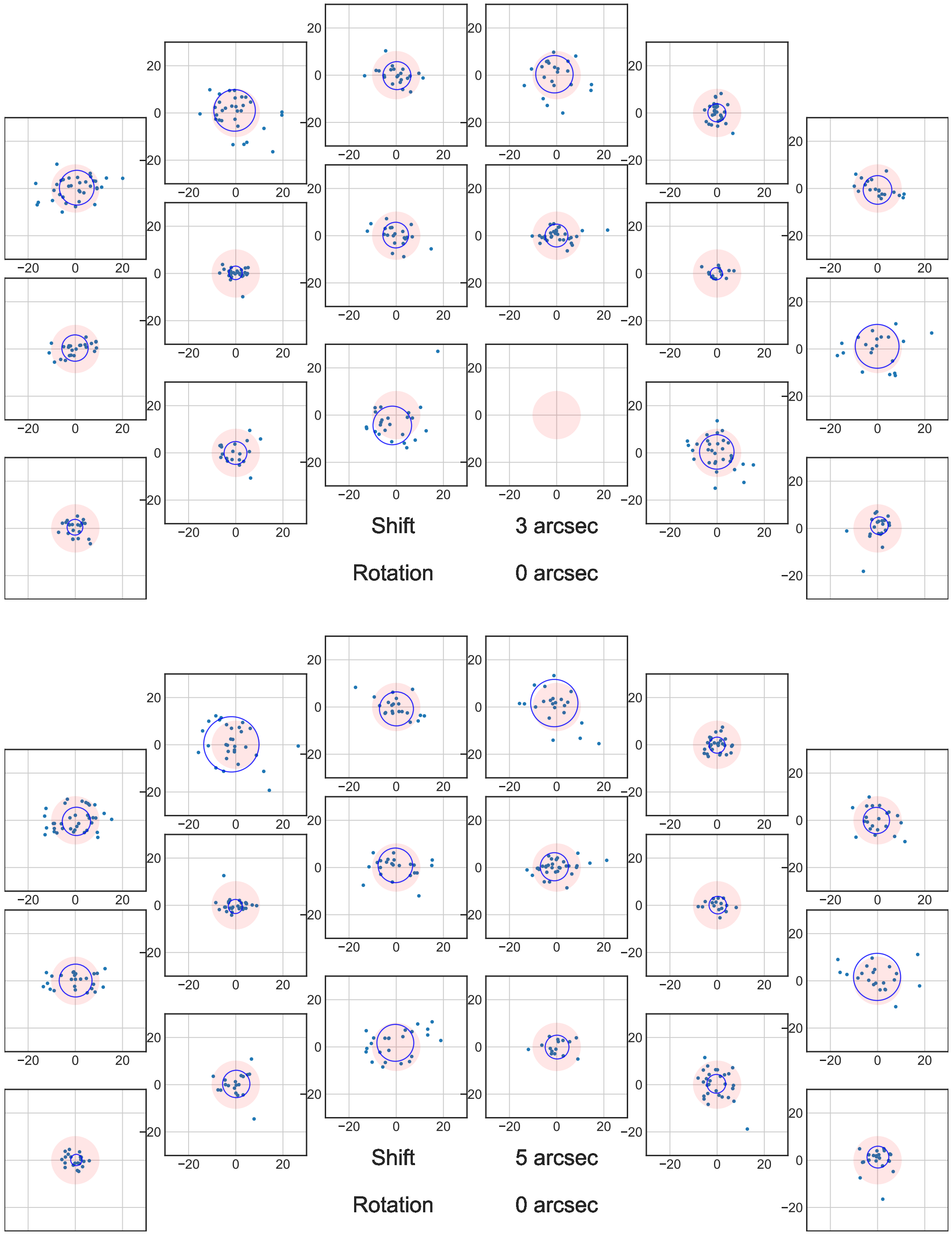

Figure 3: Residuals between input and detected positions of *Gaia* sources from two simulations of the Lockman Hole field with 3 arcsec (top) and 5 arcsec (bottom) shifts applied to input positions. The panels are arranged according to the positions of the detectors in the WFI array. The distribution of position residuals in each detector is shown on top of a 10 mas radius pink disk. The blue circles correspond to the 90% confidence interval of the distribution and are centered on their mean values.

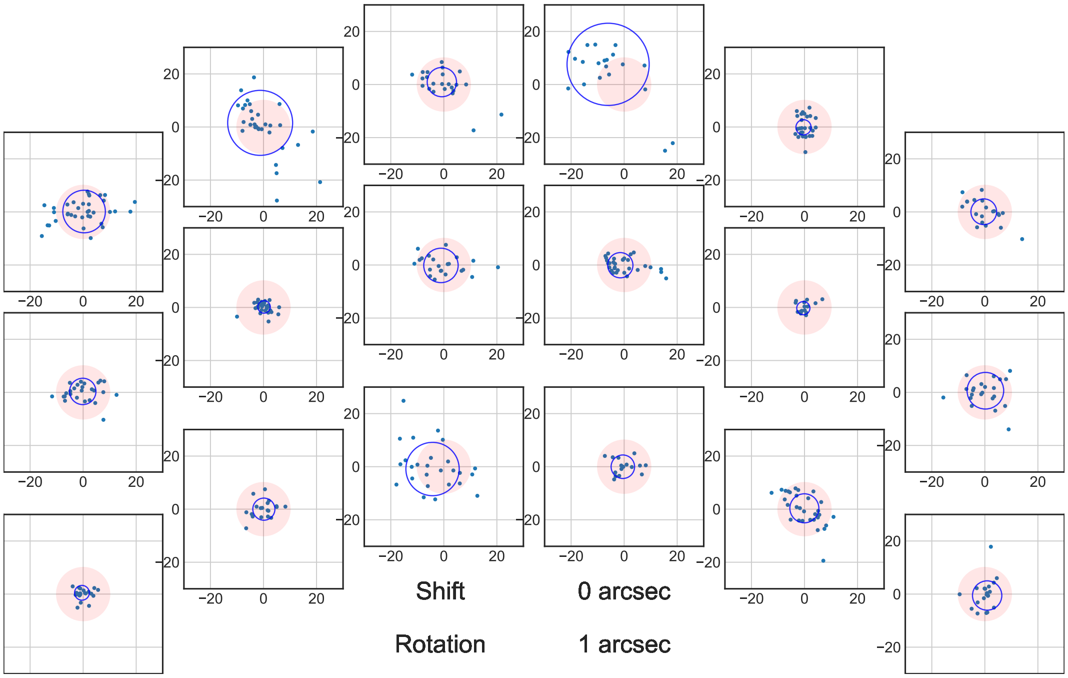

Figure 4: Residuals between input and detected positions of *Gaia* sources from a simulation of the Lockman Hole field in which we applied a 1-arcsec rotation of input positions around the WFI aperture. The panels are arranged according to the positions of the detectors in the WFI array. The distribution of residuals is shown on top of a pink 10 mas radius disk. Blue circles correspond to the 90% confidence interval of the distributions and are centered on their mean values.

2.1.5 Summary

We performed a series of tests based on simulations of stellar and cosmological fields to validate the ability of the pipeline to recover the astrometry of the images in case of small shifts in coordinates or minimal rotation of the field. The simulations include real *Gaia* stars present in the fields and several randomly-generated galaxies. We show that, in stellar fields, the required astrometric accuracy is easily reached. In cosmological fields such as the Lockman Hole, characterized by a dearth of *Gaia* stars, the pipeline generally provides results within the science requirements (goal of 10 mas), but with a few exceptions. In the case of WFI10 for shifts of 1 and 3 arcsec the pipeline fails to adjust the astrometry. Looking into the warnings of the reduction we noticed that the minimum amount of stars accepted for tweaking the astrometry is 15. In the matching of the 1 and 3 arcsec shift only 12 matches with *Gaia* were found while in the case of the 5 arcsec shift, there were exactly 15 matches (see also the documentation where 'minobj' has a default value of 15 [4]).

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[4] https://roman-pipeline.readthedocs.io/en/latest/roman/tweakreg/README.html

2.1.6 Conclusions and Recommendations

According to the tests we performed, **we can affirm that SOC-1057 passed science validation.**

The only failure found is due to the minimum number of *Gaia* stars used as default. A minimum of 2 matches are sufficient to characterize a 4-parameter linear transformation. Therefore, requiring a minimum of 15 stars is an overkill. Even when considering a 6 parameter fit (including the skew terms) a lower number of stars is needed to obtain a good fit. **We recommend lowering this threshold to 5 stars to avoid failures in fields with a low number of *Gaia* stars**. An issue in the RomanCal github repository has been filed to make this modification (see `https://github.com/spacetelescope/romancal/issues/2099`).

A better solution can be in principle obtained by using all the detectors at once (meta solution) and not only one at the time — as done by the current version of the pipeline — relying on a global WFI distortion solution. In the case of the Lockman Hole, this would have enriched the sample of *Gaia* stars used for the fit and also made possible a more robust fit of the field scale and rotation.

We did not explore in this report cases with high density stellar fields, such as those in the Galactic plane. If the density is very high, there is a possibility of mismatch of sources with the *Gaia* catalog that could disrupt the astrometric solution. It is possible to identify these cases by checking the dispersion of the matches. **The pipeline should warn the users if the dispersion in relative position of the matched sources is much higher than the expected dispersion** due to the astrometric accuracy of *Gaia* positions and proper motions. If such a high dispersion is found, the pipeline could consider a further step to refine the astrometry such as using a higher flux cut to lower the number of *Gaia* matches.

The current version of the pipeline only considers shifts, rotation, and scale. This corresponds to the default ('rscale') for the parameter 'fitgeometry' of tweakreg (note that the documentation seems to be wrong about the description of this parameter). Nevertheless, we note that the expected plate-scale change due to outgassing during the first two months after commissioning alone will introduce spatially-dependent systematic effects of the order of ∼45 mas [5] just within a single WFI detector, therefore invalidating a meta solution. The use of general, six-parameter linear transformations during the matching-to-*Gaia* step (shifts along two directions, rotation, change of scale, and the two skew terms) would mitigate the systematic effects due to outgassing; **therefore, we strongly recommend to always use a six-parameter linear transformation and to apply it independently to each of the 18 WFI detectors, to obtain the best astrometric accuracy. Furthermore, we recommend comparing the solutions for all 18 detectors to verify that they are sufficiently consistent. There should be a routine warning if the relative offsets, rotations, and scales are inconsistent.**

Finally, we also noticed that the coordinates saved in the L4 catalog are not updated after the astrometry correction is computed by the pipeline, while the astrometry of the L2 image is updated. Although the update of the catalog can be achieved by using specific tweaking parameters, we think that this should be a default behavior of the pipeline.

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[5] about 0.4 pixels (Jeffrey Kruk, private communication)

References

Beers, T. C., Flynn, K., & Gebhardt, K. 1990, AJ, 100, 32, doi: 10.1086/115487

Nieto-Santisteban, M., et al. 2024, Science Operations Center (SOC) Requirements Document, Tech. Rep. Roman-STScI-000009, SE-03, Revision D, Space Telescope Science Institute