Augmented Images Validation

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Abstract

Four different tests were performed to assess the accuracy of the World Coordinate System (WCS) Right Ascensions (RA) and Declinations (Dec) added to the augmented images.

TEST 1

For this test, I created four versions of FITS images, each produced using a different method and then comparing the position of the same, randomly-selected, field star in each image.

The first image was produced using the SExtractor[1]-SCAMP[2] (Bertin and Arnouts, 1996; Bertin, 2006) method, hereafter simply referred to as SCAMP. This image accounts for the most effects and compares the actual field to the positions fit to the stars in that field using the 2MASS astrometric catalog. The least elaborate method simply uses the so-called "CCD matrix" or "linear projection matrix", the values for which were manually determined from the known properties of the Lowell Observatory Near Earth Object Survey (LONEOS) telescope and camera/CCD. The other two methods used either "linear projection matrix" values determined by SCAMP or all the SCAMP WCS terms except CRVAL1, CRVAL2 (which, of course, in general vary from image to image).

To compare the results obtained using these four methods I chose a star in the upper-right corner of a 2.88°x1.44° image from 2005/11/13 and compared its known 2MASS position with that obtained from the SCAMP image (1). The measured positions are given below and in pictorial form in Figure 1. The values in parentheses following each of the non-SCAMP results are the differences, in arcseconds; pixels, between the position determined by that method and its coordinates determined by SCAMP.

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1) 21:19:36.756, +09:30:13.95 SCAMP 051113_011_Cropped-SCAMP_WCS.fits 59 cards
                               CRVAL1 = '321.1198103761', CRVAL2 = '8.571250566332'
2) 21:19:37.709, +09:30:17.26 Manual linear projection matrix terms No SCAMP except CD1_2,
                               CD2_1 and CRVAL1, CRVAL2 from the original TELRA, TELDEC
                               051113_011_Cropped-WCS-Manual.fits (-14.3, -3.3; 5.6, 1.3)
3) 21:19:37.901, +09:30:16.45 With only SCAMP linear projection matrix terms and CRVAL1,
                               CRVAL2 which are from the original TELRA, TELDEC
                               051113_011_Cropped-WCS-ManualSCAMP.fits (-17.2, -2.5; 6.8,1.0)
4) 21:19:37.901, +09:30:16.45 With all SCAMP WCS terms except CRVAL1, CRVAL2, which are from
                               the original TELRA, TELDEC
                               051113_011_Cropped-WCS.fits (-17.2, -2.5; 6.8, 1.0)
```

The manual method (2), which uses the linear projection matrix and CRVAL1, CRVAL2 from the image's TELRA, TELDEC, gives the closest match to the SCAMP results (-14.3", -3.3 px). The other two methods (3 and 4) give the identical results to one another but have a marginally larger difference (~17", ~6.9 px) with respect to the SCAMP results.
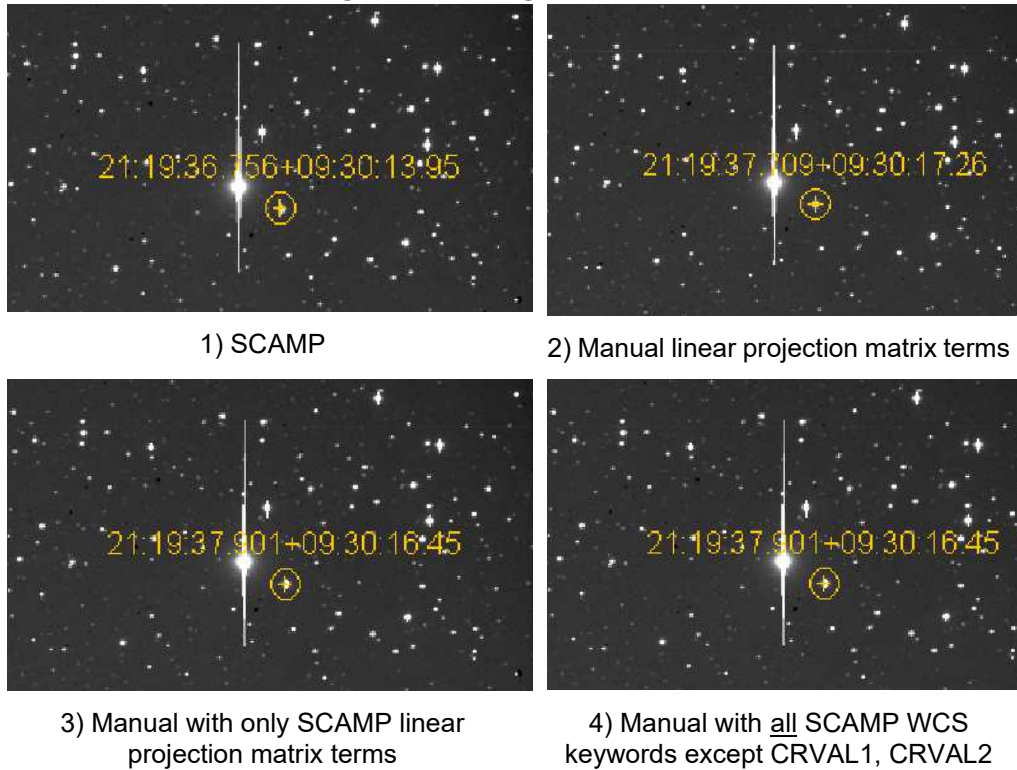
The corner coordinates were obtained by running MontagePy's (http://montage.ipac.caltech.edu) mImgtbl routine, *i.e.*, mImgtbl('/mnt/d/LONEOS/test/LOIS/4_2_0/WCS/comparison', 'images.tbl'), which returned: {'status': '0', 'count': 4, 'badfits': 0, 'badwcs': 0}, where count = 4 refers to the four example images below.

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[1] https://www.astromatic.net/software/sextractor/

[2] https://www.astromatic.net/software/scamp/

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1) SCAMP

2) Manual linear projection matrix terms

3) Manual with only SCAMP linear projection matrix terms

4) Manual with all SCAMP WCS keywords except CRVAL1, CRVAL2

Figure 1. Comparison of Added WCS Coordinates Using Four Methods.

Table 1. Corner Coordinates of Images in Figure 1

ra1	dec1	ra2	dec2	ra3	dec3	ra4	dec4
double	double	double	double	double	double	double	double
319.6608468	10.0103820	319.6655996	7.1330449	322.5661835	7.1269226	322.5830235	10.0049066
319.6655811	10.0118803	319.6707303	7.1332034	322.5718470	7.1272796	322.5887544	10.0059133
319.6665373	10.0115329	319.6716765	7.1335578	322.5709013	7.1276339	322.5877988	10.0055659
319.6656163	10.0110752	319.6703701	7.1337381	322.5709583	7.1276158	322.5877992	10.0055998
−0.00473430	−0.0014983	−0.00513070	−0.0001585	−0.00566350	−0.0003570	−0.00573090	−0.0010067
−17.0	−5.4	−18.5	−0.6	−20.4	−1.3	−20.6	−3.6

The two lines in green in Table 1 are the corners from the SCAMP fit (top) and the method 2 fit (with only the linear projection matrix terms and CRVAL1, CRVAL2 from the original TELRA, TELDEC). The two lines below the table, in purple, are their differences in degrees (top) and arcsecs. The mean differences are 19.1" in RA and 2.7" in Dec.

Given this result, it's clear that the method using only linear projection matrix terms and CRVAL1, CRVAL2 values obtained from the original image's header (TELRA, TELDEC converted to decimal degrees) is the method of choice. It eliminates the relatively time consuming SExtractor-SCAMP steps thus allowing hundreds of thousands of images to be processed with an acceptable, for the purpose for which it's intended, astrometric accuracy of ~20".

TEST 2

To further check the reasonableness of this conclusion for the second test I downloaded from the PDS an archived Near Earth Asteroid Tracking survey (NEAT) image, Bauer and Lawrence (2020 - https://doi.org/10.26033/xkmy-me08), obtained on 1996-04-19 with the GEODSS1 telescope on Haleakala, ran it through Astrometry.net (hereafter AN), and compared the position of the same star in both images. The results are shown in Figure 2. The original (archived) image's header contained 108 cards while the Astrometry.net header has 839, although all except the first 168 are COMMENT or HISTORY cards.

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NEAT Image (960419062854a.fit) NEAT AN Image (AN_960419062854a.fit)

Figure 2. Coordinates of an Archived NEAT Image vs. an Astrometry.net Fit to the Same Image.

AN - NEAT RA, Dec = 23.7", -14.0"

Next, I generated the corners for the images in Figure 2 and repeated the same analysis as for the various LONEOS test image with the results given in Table 2.

Table 2. Corner Coordinates of Images in Figure 2

ra1	dec1	ra2	dec2	ra3	dec3	ra4	dec4
double	double	double	double	double	double	double	double
142.9608747	35.1197135	140.9955198	35.1416567	140.9957822	33.5394652	142.9086617	33.5197830
142.9554179	35.1364296	140.9734516	35.1364336	140.9924076	33.5157156	142.9364527	33.5157118
19.6"	-60.2"	79.4"	-18.8"	12.1"	85.5"	-100.0"	14.7"
13.7px	42.1	55.5	17.4	8.5	59.8	69.9	10.3

The first line has the Astrometry.net results and the second the results from the archived NEAT image.

Mean |AN-NEAT| RA, Dec = 52.8", 44.8"; 75.5, 31.3px (the NEAT system CCD's pixel size is 1.43").

Comparing these results from PDS archived NEAT images with those for the LONEOS test images (see Tables 1 and 2, above) demonstrates that the adopted method for adding WCS information to the LONEOS images produces reasonable results.

TEST 3

For the third test, I returned to using Astrometry.net on an augmented pair of LONEOS images (051113_1a_014.fits and 051113_2a_014.fits). As shown in Fig. 3, AN displays these images with North Up and East to the Right. (The usual convention is North Up and East to the Left.) Note the severe vignetting and the numerous defects, primarily dark full-height and partial-height columns. To see this better open the images in ds9, set Zoom → Invert Y, and vary the stretch.

These images have many, mostly cosmetic, defects compared with most published images because they are raw images, *i.e.*, no bias or flat field corrections have been applied to them because there are few of the former and none of the latter. In any case, the primary feature I want to discuss is the obvious "banding" that divides each image into four "bands" which I designate bands 1 through 4 beginning with the bright band on the West side (the left side in these images). 1N through 4N refers to the bands in the _1 image and 1S through 4S for those in the _2 images. These bands are produced by the four amplifiers used to read out each image.
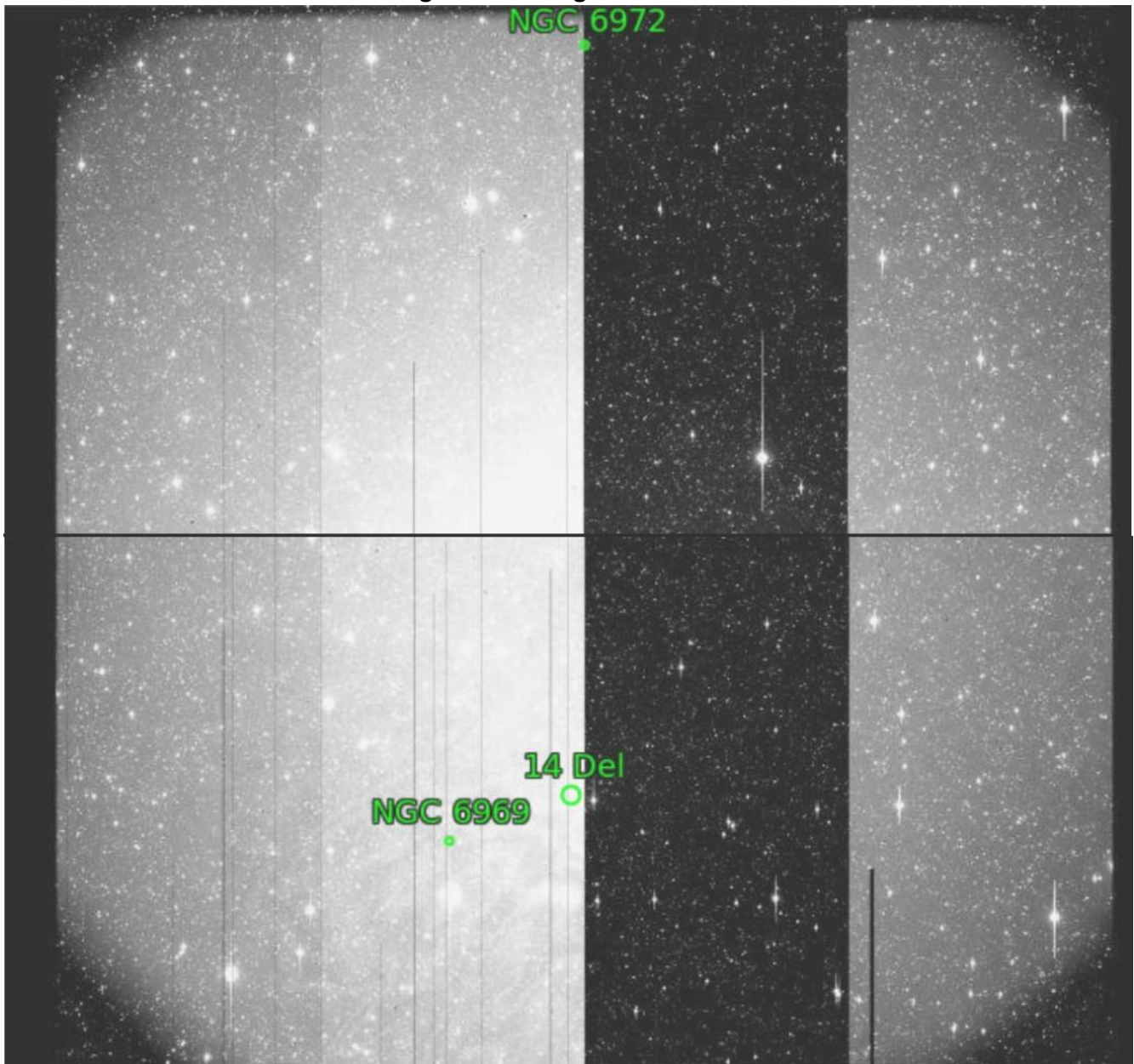
Fig. 3 The original, uncropped, images from AN fits with _1 at the top and _2 at the bottom.

Fig. 4 displays an AN graphical goodness of astrometric fit as a so-called "red-green" plot where the red circles show stars extracted from the image and green circles show the computed positions of astrometric catalog reference stars in this image's region, including those in its so-called "over-scan" area. The over-scan area is the area of the CCD that did not include the image circle (presumably because it was physically blocked out) but which, nevertheless, were read out (scanned) by the electronics and written into the image's FITS file. For the present purposes, they contain no useful information; and, I thought, might negatively affect the astrometric fit, primarily in RA because the over-scan columns are present as the first 201 columns (1 through 201) on the west (left) and the last 79 columns (4298 through 4376) on the east (right) sides of the image, where x,y pixel (1,1) is the upper left (NW) corner and (4376, 2050) is the lower-right, (SE) corner. Columns 1 through 200 have pixel values between ~150 and 190 and column 201 is a dead column (value = 0 for all rows in that column).

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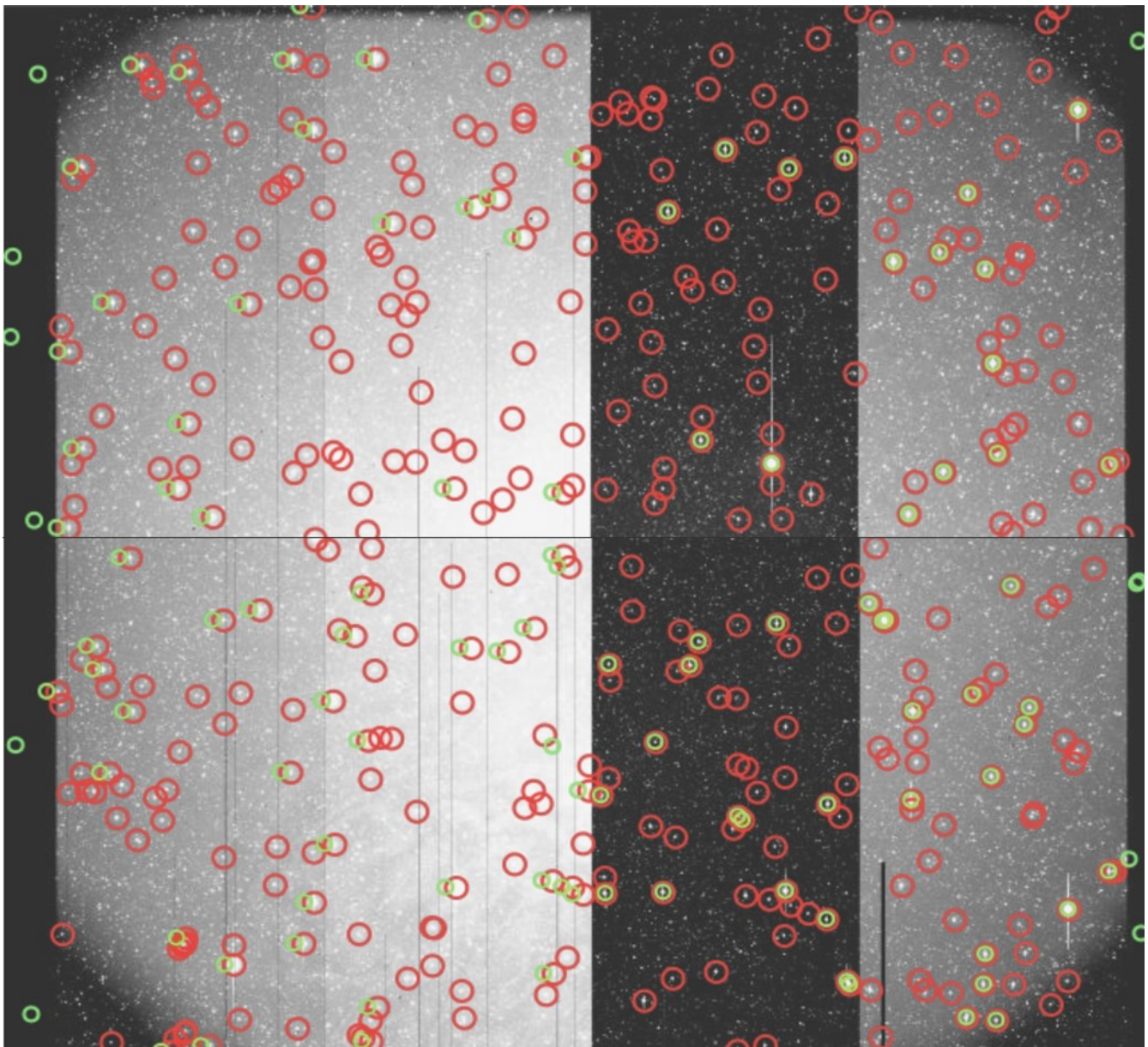
Fig. 4 The red-green plot corresponding to the image in Fig 3.

The astrometric fit on the right side of the images for both the _1 and _2 images looks good, *i.e.*, the green circles are centered within the red circles, however, the same cannot be said for the left side. Table 3 shows AN's summary of the calibration for these two images.

Table 3. Astrometry.net Calibration for the Original, Unaltered, Images.

| Calibration for 051113_1_014.fits		Calibration for 051113_2_014.fits	
Center (RA, Dec):	(312.448, 9.288)	Center (RA, Dec):	(312.445, 7.847)
Center (RA, hms):	20h 49m 47.563s	Center (RA, hms):	20h 49m 46.857s
Center (Dec, dms):	+09° 17' 16.156"	Center (Dec, dms):	+07° 50' 48.577"
Size:	3.07 x 1.44 deg	Size:	3.08 x 1.44 deg
Radius:	1.698 deg	Radius:	1.699 deg
Pixel scale:	2.53 arcsec/pixel	Pixel scale:	2.53 arcsec/pixel
Orientation:	Up is -179.7 degrees E of N	Orientation:	Up is -179.7 degrees E of N

Next, I used the crop image code to create the over-scan column-free images shown in Figs. 5 and 6.

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For these images, the astrometric fit is different from the images containing the over-scan columns. For this fit, the upper left side of the image looks good, rather than the upper right side which looks worse. Curiously, the bottom image's fit did not change substantially. Table 4 shows AN's summary of the calibration for these two images. Thus, the fit to the image without the over-scan columns was no better, and might possibly be worse, than the fits to the images including the over-scan columns.

Table 4. **Astrometry.net Calibration for the Original, but without over-scan columns, Images.**

Calibration for 051113_1_014.fits		Calibration for 051113_2_014.fits	
Center (RA, Dec):	(312.461, 9.288)	Center (RA, Dec):	(312.489, 7.847)
Center (RA, hms):	20h 49m 50.575s	Center (RA, hms):	20h 49m 57.382s
Center (Dec, dms):	+09° 17' 18.576"	Center (Dec, dms):	+07° 50' 49.247"
Size:	2.88 x 1.44 deg	Size:	2.88 x 1.44 deg
Radius:	1.608 deg	Radius:	1.609 deg
Pixel scale:	2.53 arcsec/pixel	Pixel scale:	2.53 arcsec/pixel
Orientation:	Up is 180.0 degrees E of N	Orientation:	Up is -179.8 degrees E of N
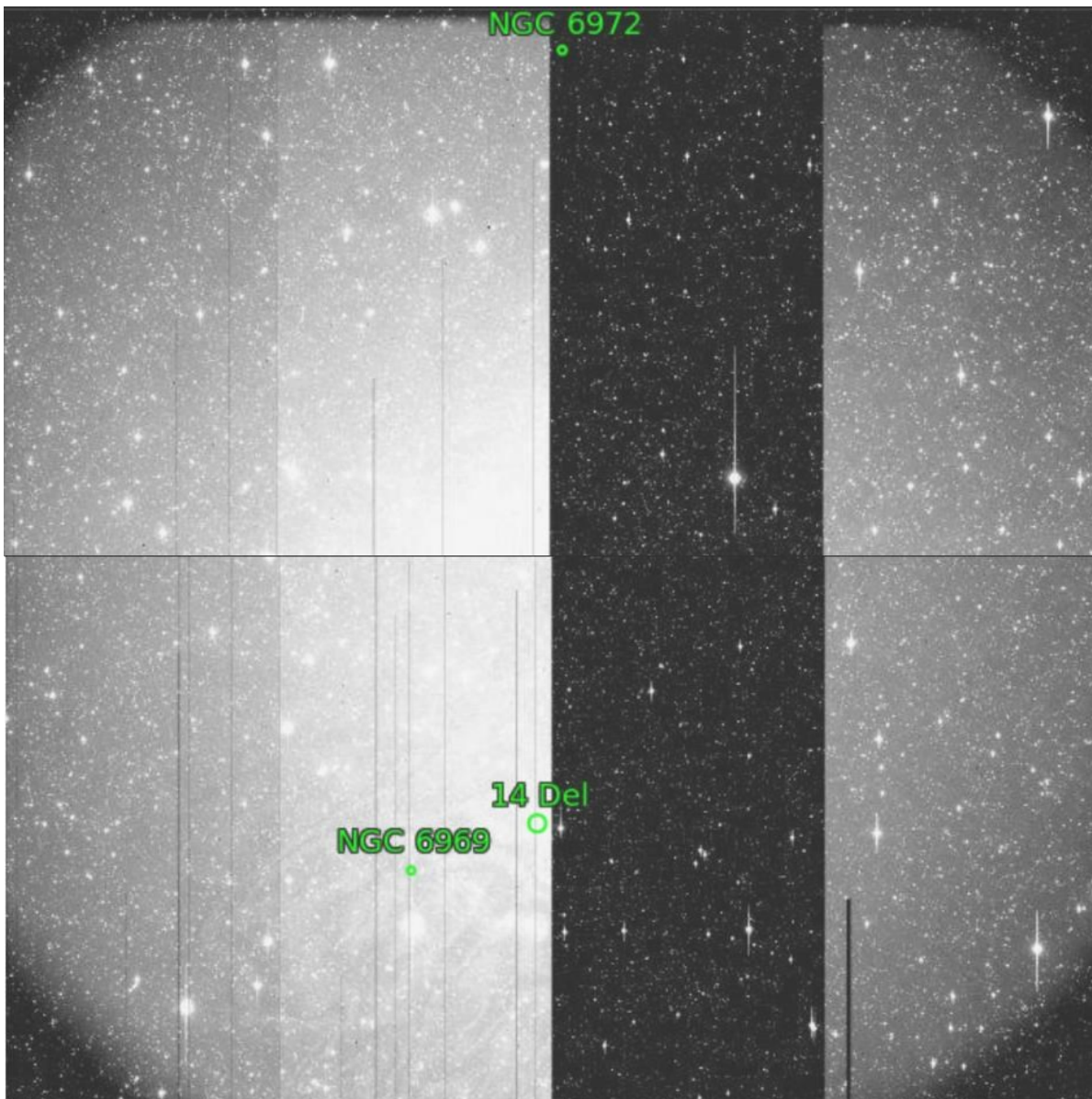
Fig 5. The original images from AN fits with _1 at the top and _2 at the bottom but without the over-scan columns.
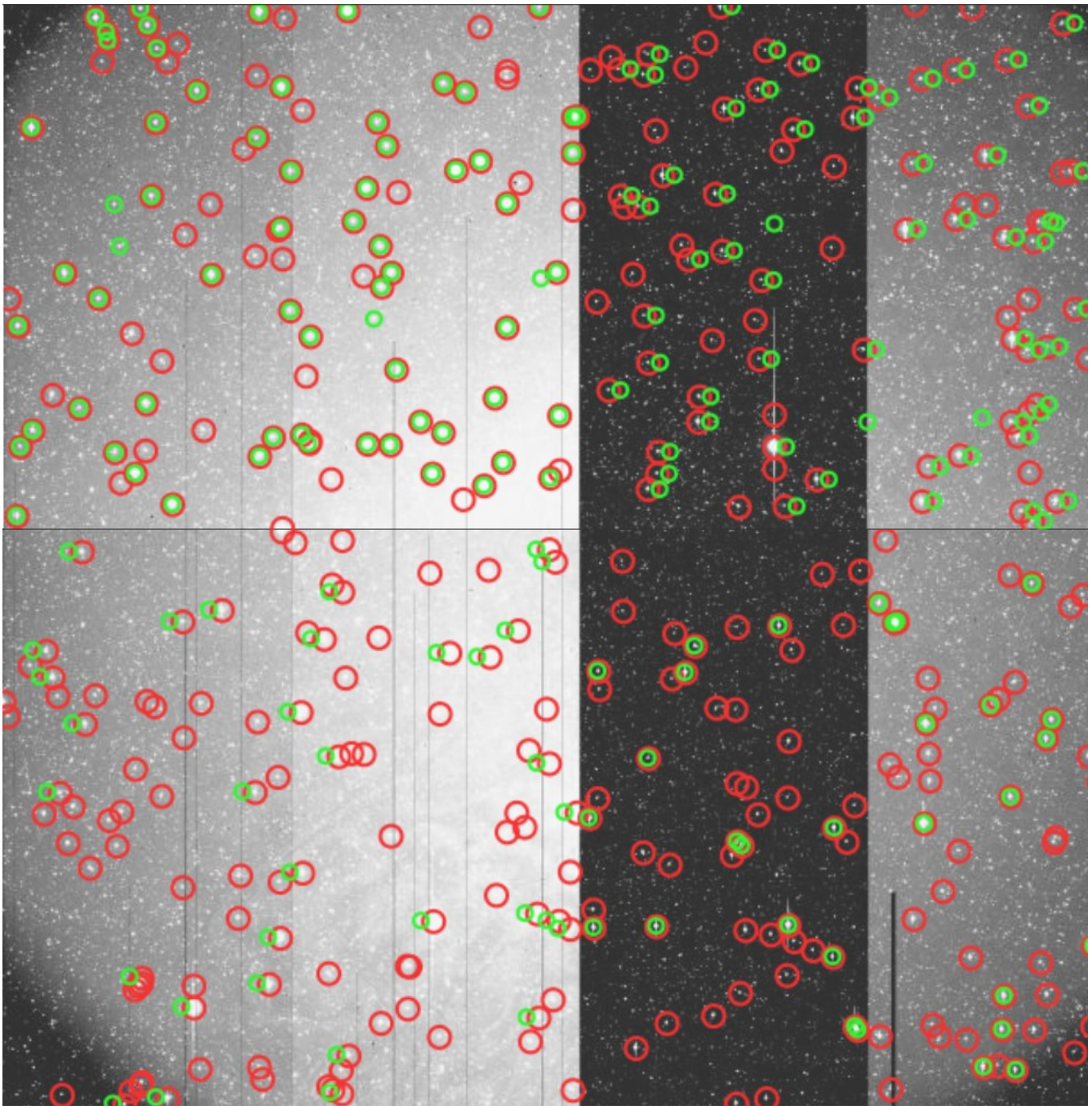
Fig 6. Original images' red-green plot from AN fits with _1 at the top and _2 at the bottom but without the over-scan columns.

Creating the Quarter FOV (Bisected) (1.44°x1.44°) Images

I split the original images (051113_1_014.fits and 051113_2_014.fits in this example), which include the over-scan columns, into two ~1.44°x1.44° images, which is equivalent to dividing them into two images, one containing bands 1 and 2 and a second containing bands 3 and 4. Before doing this, I examined them and noticed that the bands were sometimes separated by a dead column (*i.e.*, one with a value of 0 for all rows). For example, the column (201) dividing the over-scan columns from band 1, is a dead column as is column 1226 dividing bands 1 and 2 (hence, band 1 is 1024 columns wide, not counting the dead columns). Likewise, column 3274 divides bands 3 and 4 but that between bands 2 and 3, *i.e.*, column 2251 is a dark (not dead) column with values in the 7000s and the adjacent columns have values in the 9000s in band 2 and ~500 counts higher in band 3. Hence, I created the left image (band 1 and 2)

to contain columns 202 through 2251 inclusive and the right image to contain columns 2252 through 4297. Thus, the left image is 2050 columns wide, and the right is 2046 columns wide. Both images are 2050 rows high, including row 1 which contains values from the mid-20000s through the mid-30000s.

As noted, the left image is 2050x2050 and the right 2046x2050. Despite their differing widths, these two images include all the columns interior to the over-scan columns. They also include row 1 with its high, but not saturated, values as those are present in both original images and I saw no reason to remove them.

I next ran each of the four ~1.44°x1.44° images through Astrometry.net and copied, via screen captures, its output for each image. These are presented in Fig 7 and Fig 8 but note that, because they are screen captures of images displayed within Astrometry.net's website interface, the stretch is not the same as shown in the other figures herein which, while all were also created from screen captures, the stretch could be controlled from within ds9.

The AN fits to the images in Fig 7 are given in Tables 5 and 6.

Table 5. Astrometry.net Calibration for the Original _1 Images without their over-scan columns.

Calibration for 051113_1_014_L.fits		Calibration for 051113_1_014_R.fits	
Center (RA, Dec):	(311.733, 9.288)	Center (RA, Dec):	(313.221, 9.286)
Center (RA, hms):	20h 46m 55.979s	Center (RA, hms):	20h 52m 53.072s
Center (Dec, dms):	+09° 17' 17.363"	Center (Dec, dms):	+09° 17' 08.227"
Size:	1.44 x 1.44 deg	Size:	1.44 x 1.44 deg
Radius:	1.019 deg	Radius:	1.017 deg
Pixel scale:	2.53 arcsec/pixel	Pixel scale:	2.53 arcsec/pixel
Orientation:	Up is -179.9 degrees E of N	Orientation:	Up is -179.8 degrees E of N

Table 6. Astrometry.net Calibration for the Original _2 Images without their over-scan columns.

Calibration for 051113_2_014_L.fits		Calibration for 051113_2_014_R.fits	
Center (RA, Dec):	(311.733, 7.848)	Center (RA, Dec):	(313.216, 7.845)
Center (RA, hms):	20h 46m 56.030s	Center (RA, hms):	20h 52m 51.754s
Center (Dec, dms):	+07° 50' 51.587"	Center (Dec, dms):	+07° 50' 41.246"
Size:	1.44 x 1.44 deg	Size:	1.44 x 1.44 deg
Radius:	1.018 deg	Radius:	1.018 deg
Pixel scale:	2.53 arcsec/pixel	Pixel scale:	2.53 arcsec/pixel
Orientation:	Up is -179.9 degrees E of N	Orientation:	Up is -179.8 degrees E of N

Fig 8 shows that, unlike the fits to the 2.88°x1.44° (or 2.88°x2.88° image not shown herein) these fits were all good. For larger images of these AN fits see Appendix I.

Fig. 7a. AN image of 051113_1_014_L.fits
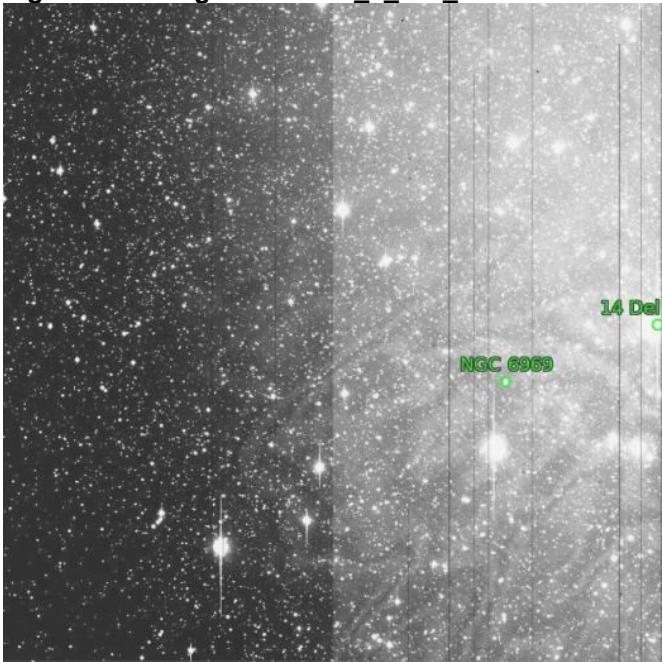
Fig. 7b. AN image of 051113_1_014_R.fits

Fig. 7c. AN image of 051113_2_014_L.fits
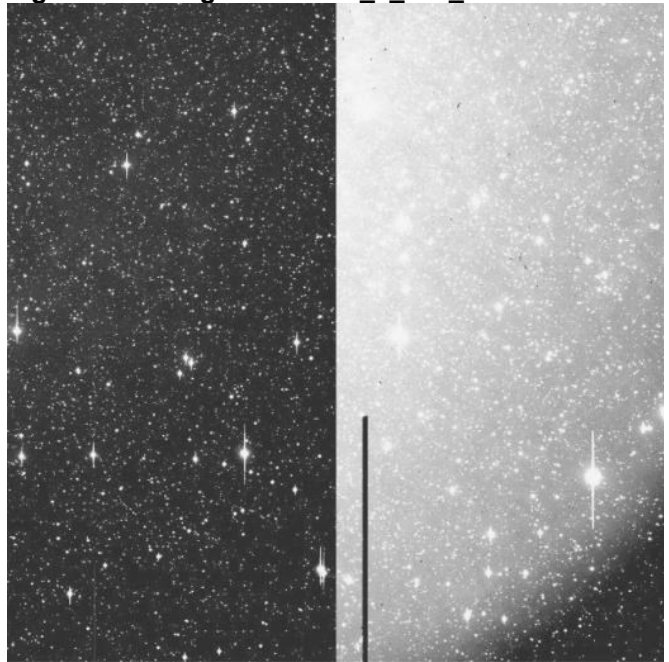
Fig. 7d. AN image of 051113_2_014_R.fits

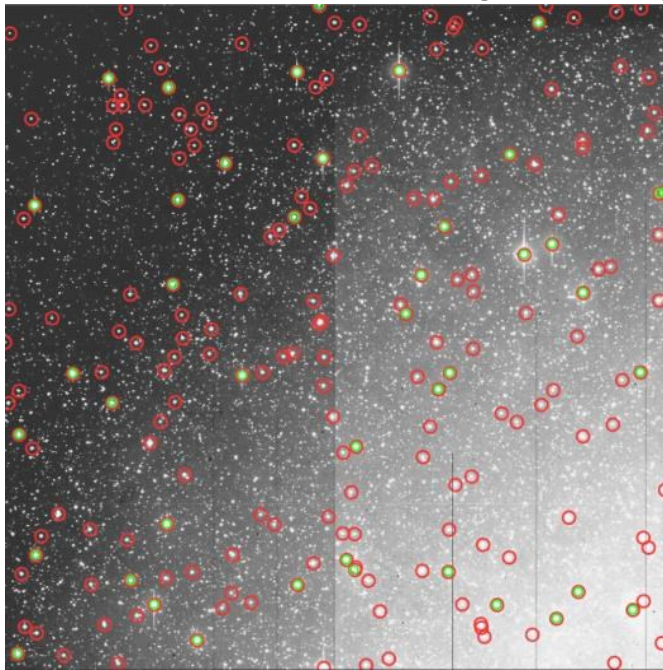**Fig. 7. Astrometry.net solution for bisected 051113_1_014.fits and 051113_2_014.fits images.**
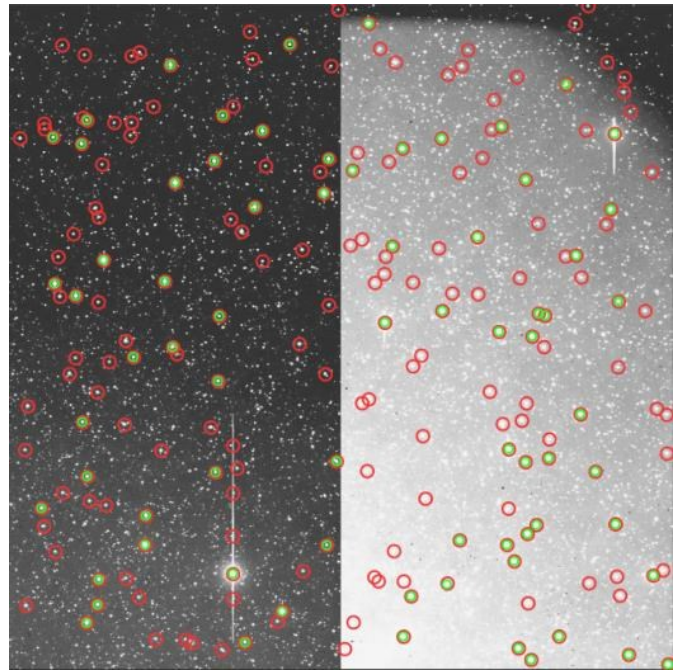
Fig. 8a. AN Red-Green image of 051113_1_014_L.fits   Fig. 8b. AN Red-Green image of 051113_1_014_R.fits

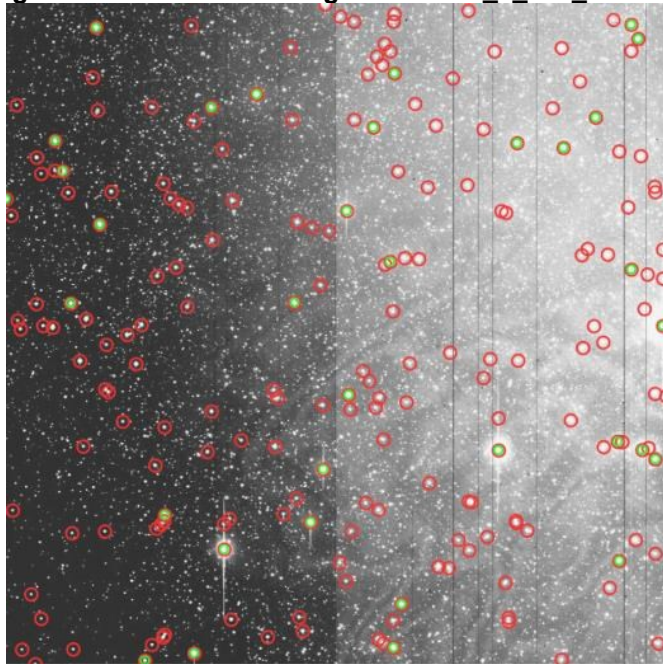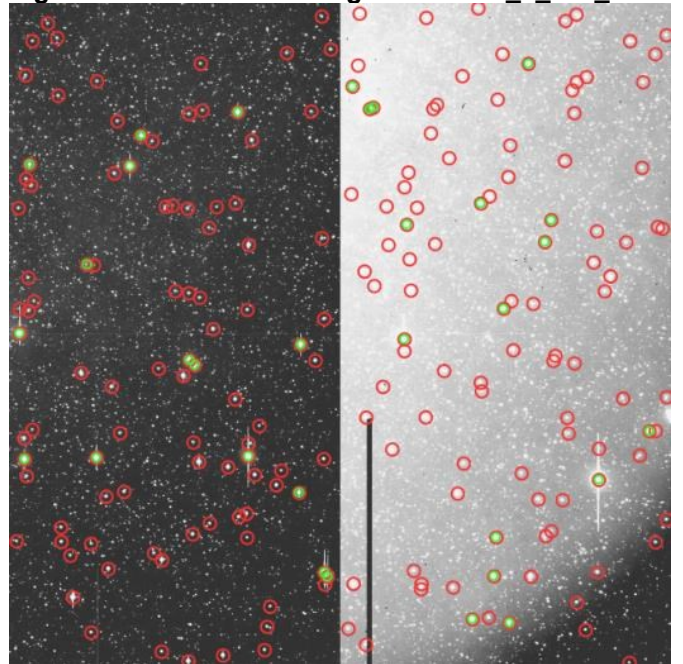Fig. 8c. AN Red-Green image of 051113_2_014_L.fits   Fig. 8d. AN Red-Green image of 051113_2_014_R.fits

Fig. 8. Same as for Fig. 7 but with red-green Astrometry.net solution images.

In validating the augmented images, it was discovered (by reviewer Michael S. P. Kelley) that the star fields around known asteroids in the images appeared to "dance" around when they were blinked.

I determined that this was a consequence of the way in which each image is read out using four amplifiers. As you can see in the images herein if you stretch the image's dynamic range you can see four "bands". There is usually a dead (all DN values = 0) column between each band. As demonstrated in this document, the global WCS fit is poor for some of the bands, *i.e.*, is inaccurate because all bands cannot be fit using the same WCS parameters. This is the cause of the "dancing". (The fit in Dec is accurate, it's that in RA that differs from band to band.)

When the portion of the image you are dealing with has sources of interest that are in different bands, then the viewer displays them in different positions because it's getting inconsistent WCS coordinates from the different bands. Hence, if you compare them with an image of the same field, from say the Deep

Sky Survey (DSS), you will only be able to match the stars from within one band at a time. This makes it look like there are "missing columns" between the two portions of the image but there are not. This is confirmed by examining the values, *e.g.*, in table format in the PDS4 Viewer.

This behavior has two consequences: 1) it leads to inaccurate positions within the poorly-fit bands and 2) on the scale of the entire 2.88°x1.44° image, it results in underestimating the RA "width" of the image due to the accumulation of the dead columns.

Hence, the final step in this analysis was to investigate the cause of the incorrect WCS coordinates embedded into the 2.88°x1.44° images which led to the "dancing stars" blinking / "missing columns" issues. In each of these cases, I traced the cause to moving sources being involved on both sides of a dead column, *i.e.*, in different amplifier bands.

Because my WCS coordinates are close to those generated by Astrometry.net, the following, based solely on what I see in Figures 9 and 10, should be correct. If all the sources being examined are in bands 1 or 2 there should be no issue as there the astrometry is good, as shown in the left half of Fig. 10. However, if some are in band 2 and others in band 3 then there will be issues. And if all the sources are in bands 3 or 4 then there will still be issues because the coordinates for the stars in those regions are off so DSS images will not overlay the LONEOS images – and the differences should be primarily in RA.

Test 4

For this test I used a region near 14 Del, which is in band 2 on the border with band 3, to further investigate this issue. Note: In these images, as in most LOIS 4.2.0 images, column 1 is a dead column and the bottom, *i.e.*, the southern row has DN values in the mid-30000s.
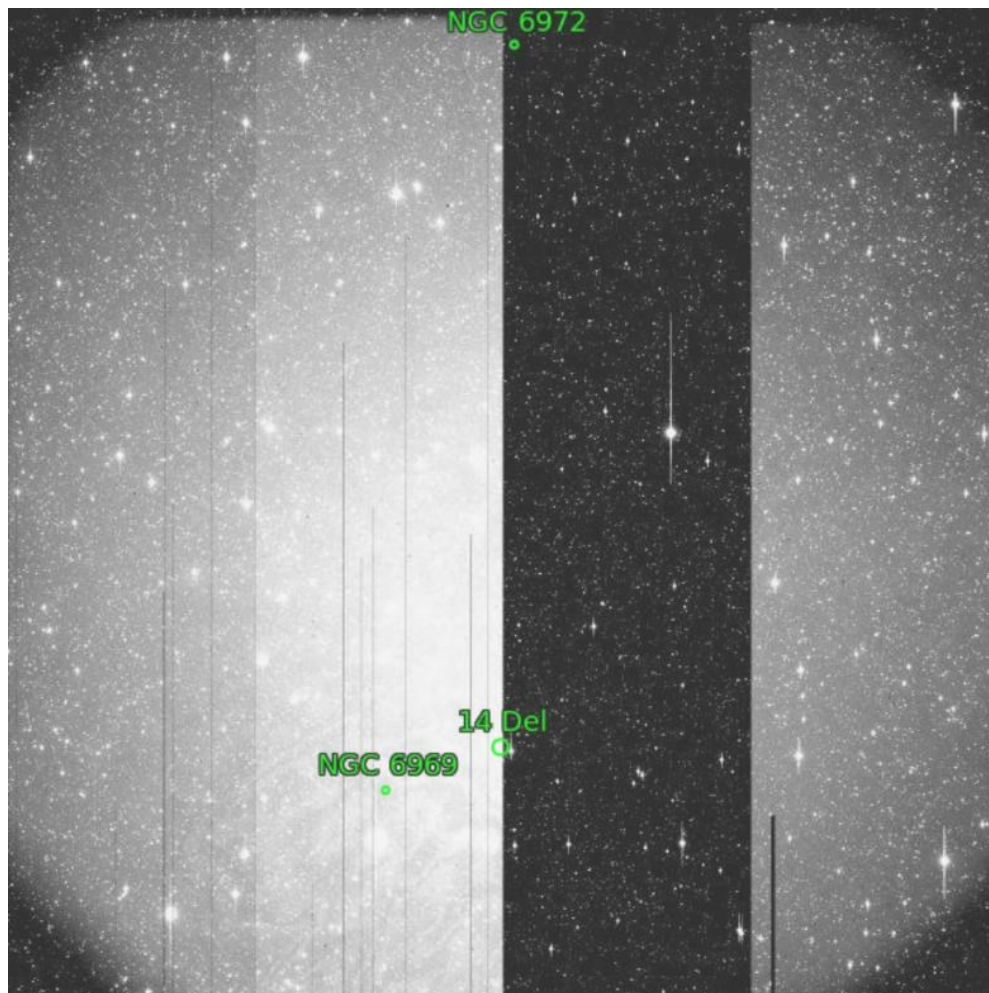

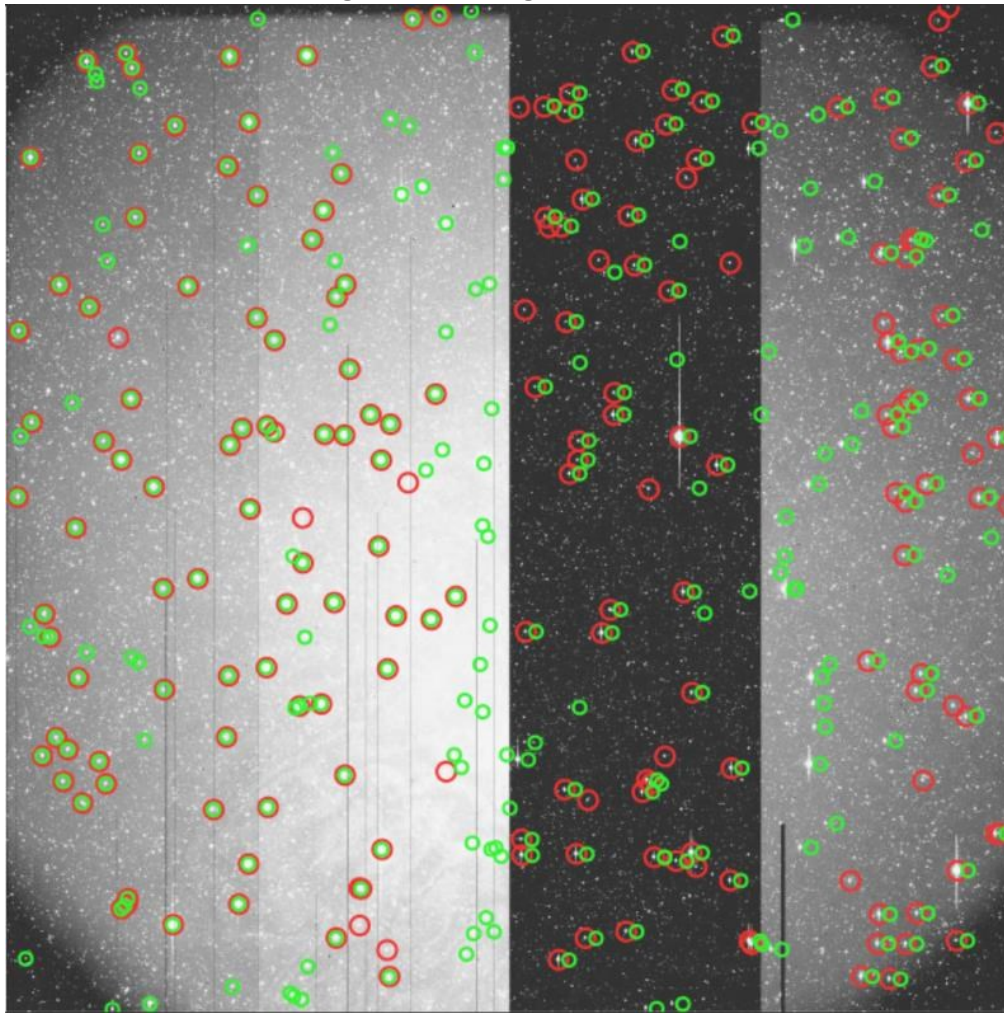**Fig 9. Merged image 051113_014.fits.**

Fig 10. AN red-green fit to merged image 051113_014.fits.

Calibration for merged image 051113_014.fits

Center (RA, Dec):   (312.458, 8.567)
Center (RA, hms):   20h 49m 49.962s
Center (Dec, dms):   +08° 34' 02.080"
Size: 2.88 x 2.88 deg
Radius: 2.034 deg
Pixel scale: 2.53 arcsec/pixel
Orientation: Up is 180.0 degrees E of N

From PDS4 Viewer on 051113_1_014.xml

To compare with x,y values elsewhere in this document add 1 to all the x,y coordinates below. This is because the PDS4 Viewer uses a zero-based system starting with the upper left pixel's x,y coordinate being 0,0 whereas ds9 uses 1,1 for the upper left pixel's x,y coordinate.

 x, y = value   4297,1025 = 194 first of RHS over-scans
0,1025 = 188   4375,1024 = 153 last --> 79 cols total
199,1025 = 154
then 200,1025 = 0 first dead column
and 1225,1025 = 0 second dead column
and 3273,1025 = 0 third dead column
201-4296 = 4096 non-over-scan columns
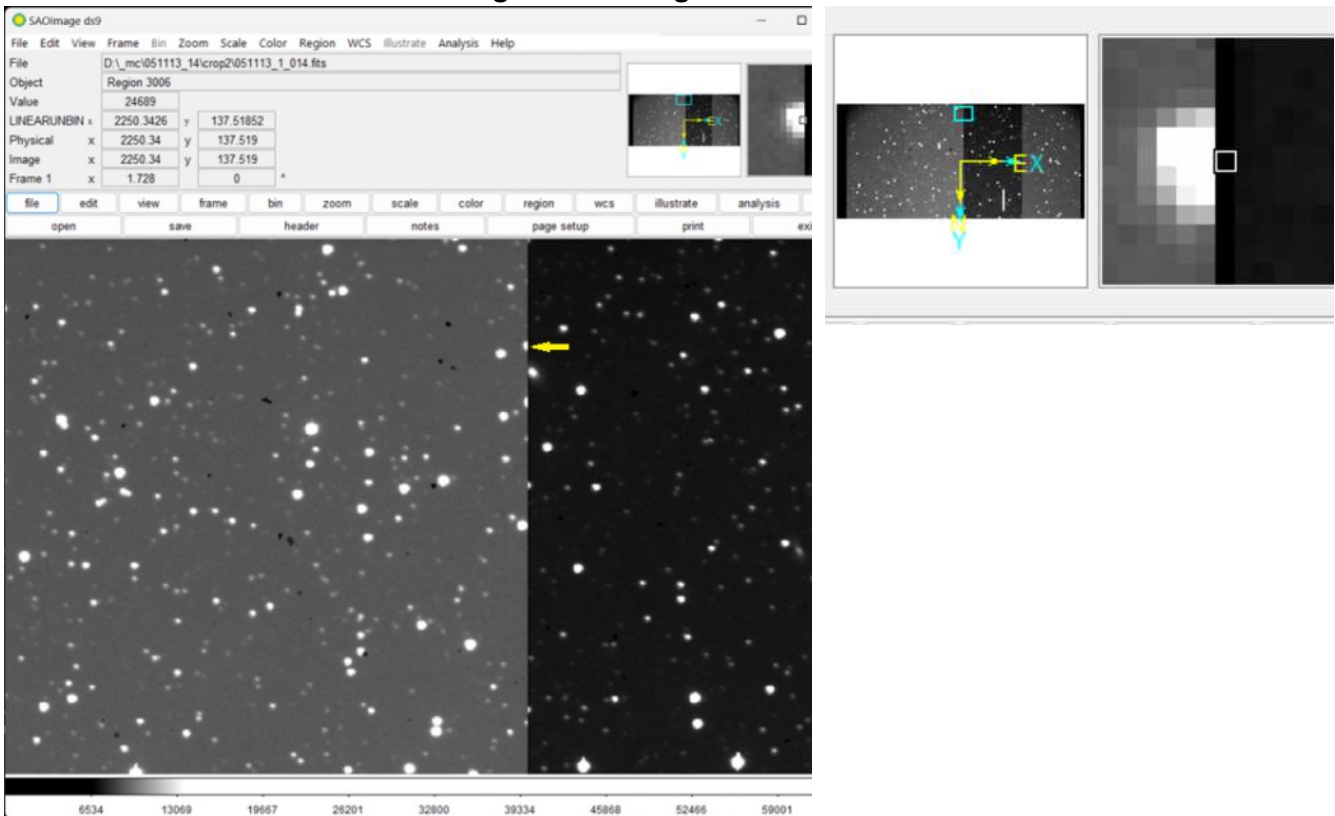
Fig. 11. Original 051113_1_014.fits image showing a star on the band 2 side of the band 2-band 3 border.

From Fig. 11 it's clear that column 2251 in the original, uncropped, _1 image contains unreliable values. The last column in this image before the start of the over-scan columns is 4297. Therefore, the portion of this image with reliable columns is from 2252 through 4297, *i.e.*, a total of 2046 columns. I therefore cropped all right-side original images to include only these columns and so, unlike the left-hand sides, they are 2046x2050, rather than 2050x2050 pixel images.

Examination of the _2 image showed it had this same issue and so its right-side images are also 2046x2050.

A preliminary look at the images from 2000 (LOIS 1.1.0), in particular those from 000204, shows that they also have issues, as shown in Fig. 12. These 4192x2050 images have two broad sets of dark columns, one from 2044 through 2093 and another from 2100 through 2149 with those between them (columns 2094 through 2099) appearing mostly normal although with something strange going on around column 2097 in that, while there are several stars in this five-pixel-wide band, no stars in this band have values on both sides of column 2097. In addition, there are dead columns at 1022 and 3171 that exhibit the same truncated star issue as described above for image 051113_1_014.fits and 051113_2_014.fits around the dark (not dead) column 2251. However, unlike for the 2005 image, as shown in Fig. 12, the majority of the 2000 image's dark columns only black-out the column of the star's values where it passes through them.
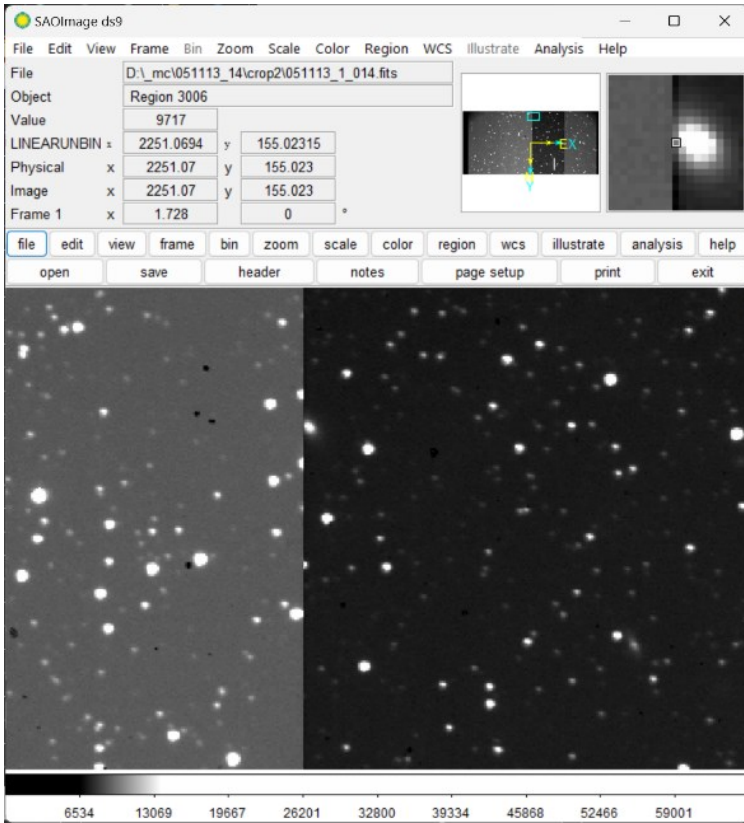
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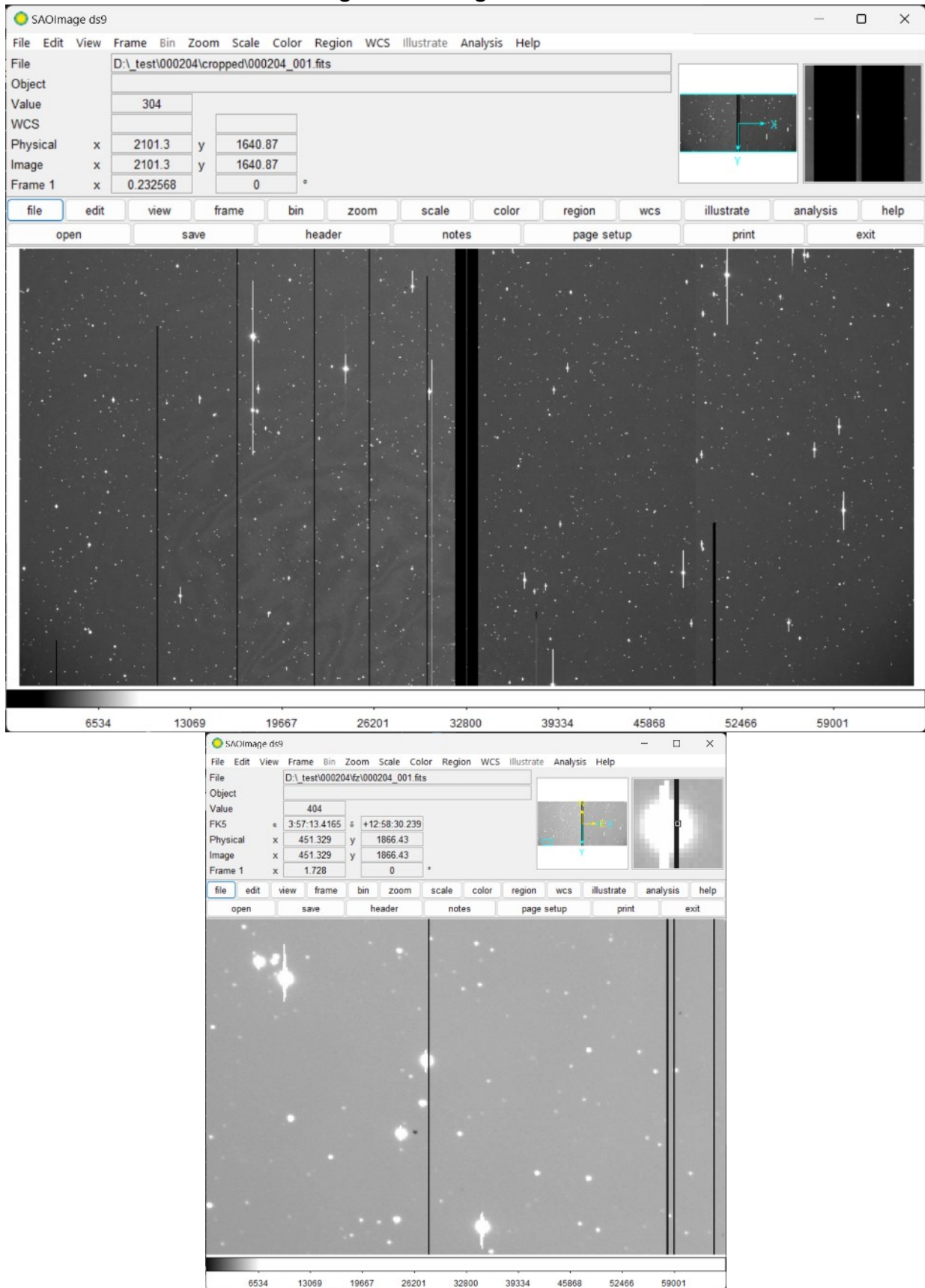
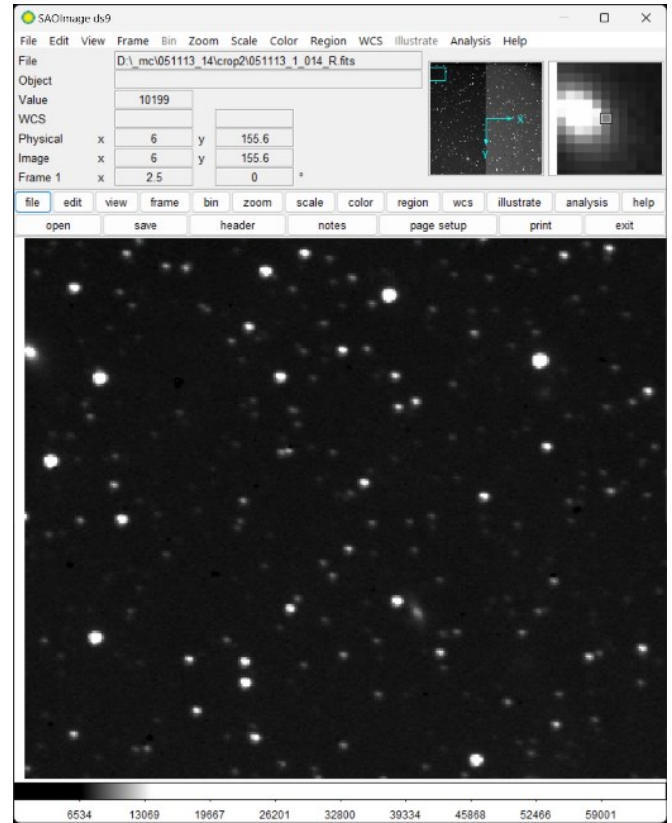Fig. 12. Top: The central dark column bands; Bottom: A dark column's effect on a star.
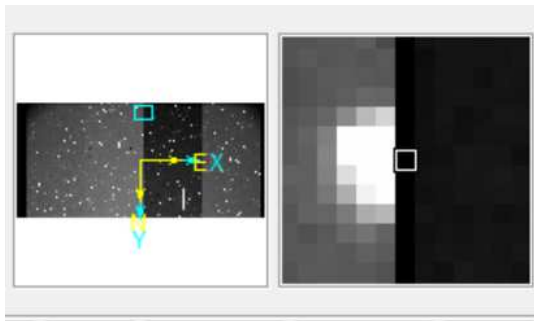
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Returning to the 2005 images now, in Fig. 13 we see that cropping the 2.88°x1.44° image into two ~1.44°x1.44° images solves the issue of the dancing stars in the blink by getting rid of the 108" boundary (43 pixels) between bands 2 and 3.
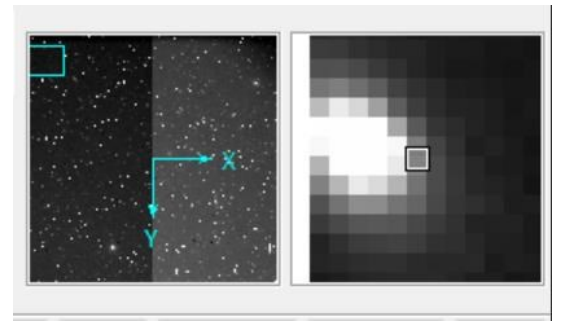

Fig. 13a. Uncropped 051113_1_014.fits

Fig 13b. Image in 13a cropped to 051113_1_014_R.fits

Fig. 13c. Closeup of border star in 13a.

Fig. 13d. Closeup of border star in 9b.

Fig. 13. Two ~1.44°x1.44° images cropped from the 2.88°x1.44° image leaving out the 44 pixels (108") between bands 2 and 3.

In the 2.88x1.44 image 051113_1_014.fits the star at (2063, 204) has RA, Dec 312.472493, 9.864667 whereas that same star in the cropped 1.44x1.44 image 051113_1_014_R.fits is at (13, 205) and has RA, Dec 312.502663, 9.864686. This star's DSS position is 312.502718, 9.864736. This star is not in _L and the test star in _R is not in _L because they are on opposite sides of the band 2-3 border. However, both stars are in the original image and, of course, have DSS positions.

Test star 1
```
Org 2063,204 312.472493 9.864667   -108.81  - 0.18
_R   13,205 312.502663 9.864686   -  0.29  - 0.18
DSS         312.502718 9.864736     108.81" = 43 pixels
```

Test star 2
```
Org 2034, 185 312.451863 9.878979  -0.72   - 0.44
_L  2034, 185 312.452271 9.879185  -0.75   - 0.30
DSS           312.452062 9.879101
```

ARCHIVED IMAGES USEFULNESS

As was stated in this proposal's program element (PE) C.23.1.2 NEO Science bullet 3, the purpose is to archive "… *legacy NEO survey and follow-up data with the goal of finding previously undiscovered NEOs, finding pre-discovery detections for extending astrometric arcs of NEOs* …". And the Lowell Observatory Near Earth Object Survey (LONEOS) was one such legacy NEO survey.

The goal of finding pre-discovery detections of NEOs requires knowledge of the date, time, and region of sky covered by an image. Thus, uncertainties of ~20" in the positions of individual point sources, especially in 2.88°x1.44° images, is negligible. Moreover, in practice, if a predicted precovery image is found in a given image then its position would be determined using the best then-available astrometric catalog and restricting it to the portion of the image containing the source, rather than that provided by the image's embedded WCS information for the entire image. An astrometric accuracy of ~20" for the source's coordinates would be unacceptable for reporting astrometric positions to the MPC[3]. And pointing out that these results are more than a factor of two better than those of the archived NEAT images (as shown in augmented_images_validation.pdf) doesn't change that. Nevertheless, for the purpose for which these images are intended, it is sufficient.

The reason for this is that, while more accurate plate solutions could be produced for these images by using the SCAMP method, tests doing this established that the time required to do so is prohibitive. And, even if this were not the case, the benefit of doing so is not justified because more accurate results, limited solely by the precision of which the telescope/camera/CCD is capable will not be possible until the Gaia catalog becomes the *de facto* standard.

Currently, "*It is the recommendation of the Minor Planet Center[4] that observers should migrate to using the GAIA-DR2 catalogue. Other acceptable catalogues include UCAC4 and UCAC5.*" (Note: GAIA-DR3 has been out since June 2022 - https://gea.esac.esa.int/archive/documentation/GDR3/) SCAMP does not list Gaia among its astrometric catalogs and it was last updated in 2014 so it's unlikely to be using Gaia. Astrometry.net uses the 2MASS and Tycho-2 astrometric catalogs (http://astrometry.net/doc/build-index.html?highlight=catalog).

Theoretically, it is possible to get Astrometry.net, and possibly SCAMP (although that is not documented) to use the Gaia catalog. However, I don't believe this would be worthwhile because they would still be fitting the entire 2.88°x1.44° image and if one is interested in getting the best position for a single source that would be better accomplished by cutting out a smaller region around the source and using that to obtain the astrometric position.

The second effect, underestimating the RA "width" of the image, is more important since it leads to a smaller than actual sky area being used for each image (see Fig. 9). This can be addressed by adding 6' in RA to each of the corner values to be sure no potential positions predicted for a precovery position that actually lies within the image will be missed.

CONCLUSIONS

As discussed in my proposal "Archiving LONEOS NEO Survey Images" – award number 80NSSC22K0513 funded under ROSES 2021 §C.23 to archive the LONEOS Survey images, the primary use for these images is to search an area of sky for NEOs that are suspected of having been present in the area covered by one or more of these archived images on a given date and time and if any are found,

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[3] There is no documentation on how the LONEOS project obtained the coordinates they submitted but, clearly, their accuracies had to have been better than those obtained here.

[4] https://minorplanetcenter.net/iau/info/Astrometry.html , item 4, last updated Nov 2018.

then to search those images for their previously unrecognized NEO images and obtain their coordinates. The archived images allow this to be done.

As noted in loneos_processing_details.pdf, §4.1: "The primary purpose of archiving the LONEOS images was to make them available to be searched for pre-discovery observations of recently-discovered NEOs that are predicted to have been present in the area covered by one or more of these archived images on a given date and time. The PDS's Comet-Asteroid Telescopic Catalog Hub (CATCH) is a moving-target search tool that was designed to do this."

CATCH was used by reviewer Michael S. P. Kelley (personal communication, 2023) to search for asteroid (952) Caia and comet 171P/Spahr which CATCH predicted should be in LONEOS images 051113_1a_375.fits, 051113_1a_401.fits, 051113_1a_427.fits, and 051113_1a_453.fits. He then made a manual inspection of the images to determine the offset between the positions of the targets derived using the WCS and times of the augmented images and the predicted ephemeris positions from Horizons. The two objects were on different amplifier readouts. The position of (952) Caia differed from the Horizons predicted position by about 1.7 arcminutes, and that of comet 171P/Spahr by about 2.7 arcminutes from which he concluded that the LONEOS images are supported by CATCH.

Due to the issues discussed herein, the areas used in searches should add ~3 arcminutes in RA and perhaps 1 arcminute in Dec to the archived positions of each image's corners.

Although the augmented 2.88°x1.44° images have significant issues, with care accurate positions for images near or adjacent to a dead column can be extracted, however, automating processing of these images may be challenging.

As discussed in Appendix II, by using a matched filter algorithm it will be possible to identify moving sources 0.5 to 0.7 mag fainter than those identified in the original survey.

Finally, see Appendix III for additional examples comparing Astrometry.net vs. embedded coordinates.

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Gural, P.S., Otto, P.R., and Tedesco, E.F. (2018). Moving Object Detection Using a Parallax Shift Vector Algorithm. *Publications of the Astronomical Society of the Pacific*, 130:074504. DOI: 10.1088/1538-3873/aac1ff

AN image of 051113_1_014_L.fits

AN red-green image of 051113_1_014_L.fits

AN image of 051113_1_014_R.fits

AN red-green image of 051113_1_014_R.fits

AN image of 051113_2_014_L.fits

AN red-green image of 051113_2_014_L.fits

AN image of 051113_2_014_R.fits

AN red-green image of 051113_2_014_R.fits

Augmented Images Validation

Appendix II. The Matched Filter / Parallax Shift Vector Algorithm

This algorithm, with example results using images from several NEO surveys, is described in Gural, *et al*., 2018 (https://doi.org/10.1088/1538-3873/aac1ff). Other, similar algorithms are available, as noted in this paper and likely in others since its publication. I mention this algorithm because I'm familiar with it as I processed the images on which Gural *et al.'s* Table 3 is based using my PC.

The matched filter, template generator, and pattern matcher source code for the software described in Gural, *et al*. are available via GitHub (https://github.com/NASA-Planetary-Science/SALTAD).

Although the Gural, *et al*., 2018 paper's Table 3 doesn't show it (because the data were not publicly available at the time) I also ran some LONEOS images through this algorithm with results comparable to those for NEAT.

According to the paper: "*Wall-clock runtime on the largest image set from the sample in Table 3 (a registered 4080×4080 pixel NEAT image) using a PC with an Intel Core i7 5930K 3.5 GHz CPU and an NVIDIA GeForce Titan X Maxwell GPU was ~5.5 minutes.*" With a current (2023) generation PC and nVidia GPU the wall-clock runtime on a 1.44°x1.44° LONEOS image would likely be around 10 seconds.

However, the bottleneck in using this method is not the runtime but rather vetting the results it generates. As stated in the paper: "*Using a maximum likelihood estimate (MLE) metric for its multi-frame integrated detection criteria, set to 11.5 dB, i.e., approximately equivalent to S/N = 4 per frame. This MLE level resulted in a conservative false alarm rate of 3% across all candidate detections. All detections were reviewed by visual inspection and declared reliable by examining individual frames and concatenated multi-frame colorized snapshots, where the analyst could confidently declare visibility of the asteroid against the background and consistent object motion across all frames. Marginally visible and noise cases were rejected as false alarms.*"

Having done the above with images from six surveys (including LONEOS), I can attest that, while rather time consuming, it's a straightforward process. And, with AI nearly upon us, even this step may soon be automated. But, even in its current state, doing this for a handful of rather small images looking for a moving source in the vicinity of a predicted precovery position is quite doable, and (for LONEOS images) gains you 0.5 to 0.7 mag in the effective limiting magnitude.

Obviously, no Matched Filter was actually used on any of the archived LONEOS images.

Appendix III. Additional Examples of Astrometry.net vs. Embedded Coordinates.

Below are the Astrometry.net (AN) results using the 2.88°x2.88° version of 051113_014.fits
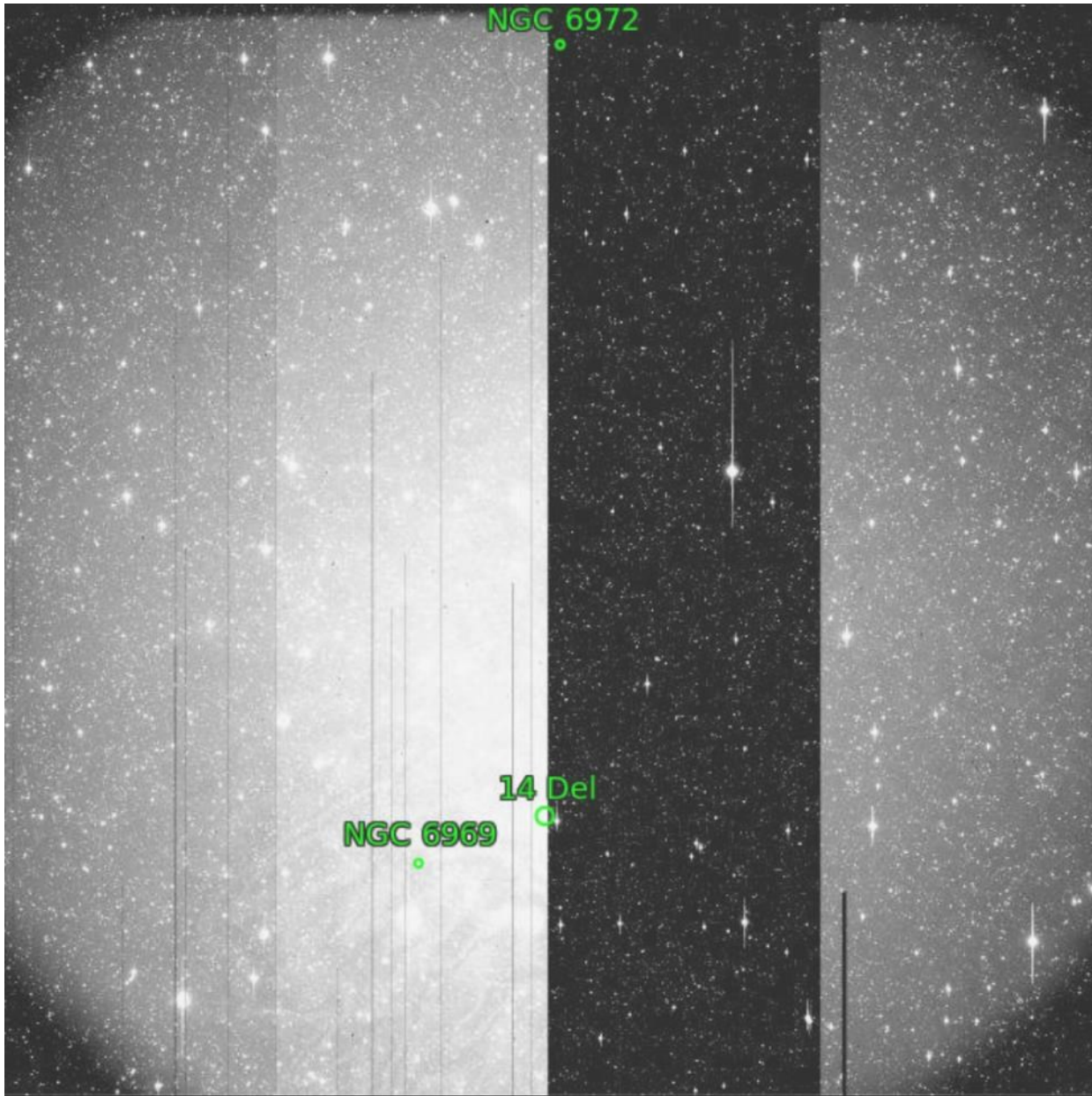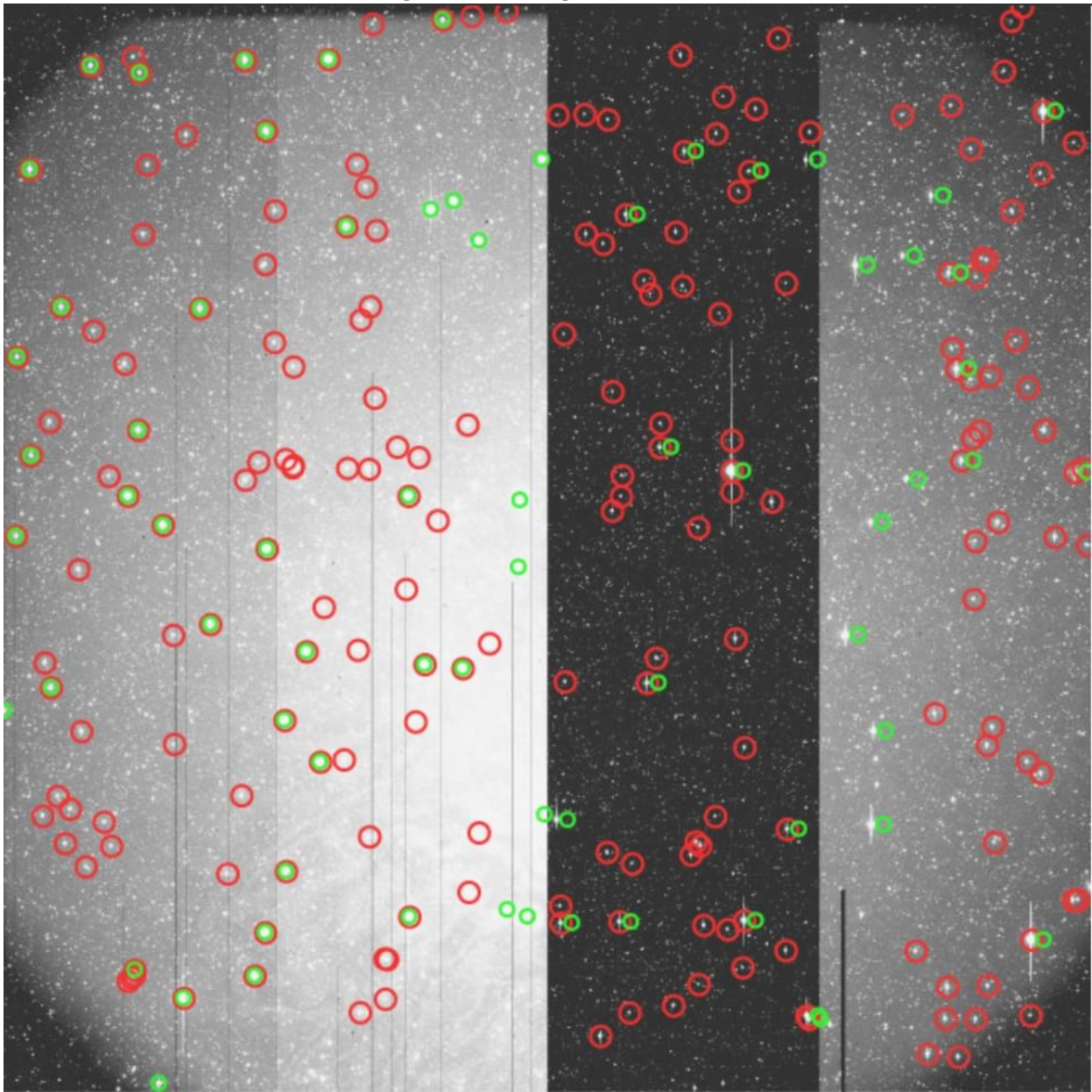

Fig 1. AN results for the 051113_014.fits 2.88°x2.88° image.

 Fig 2. AN red-green fit to the 051113_014.fits 2.88°x2.88° image.

As Fig. 2 shows, the fit to the left side (bands 1 and 2) is good while that to the right is not.

Calibration for 051113_014.fits

Center (RA, Dec):   (312.460, 8.566)
Center (RA, hms):   20h 49m 50.393s
Center (Dec, dms):   +08° 33' 57.326"
Size: 2.88 x 2.88 deg
Radius: 2.035 deg
Pixel scale: 2.53 arcsec/pixel
Orientation: Up is 180.0 degrees E of N

Below, in figures 3 and 4, are the results for images obtained two years after those in the analysis above.
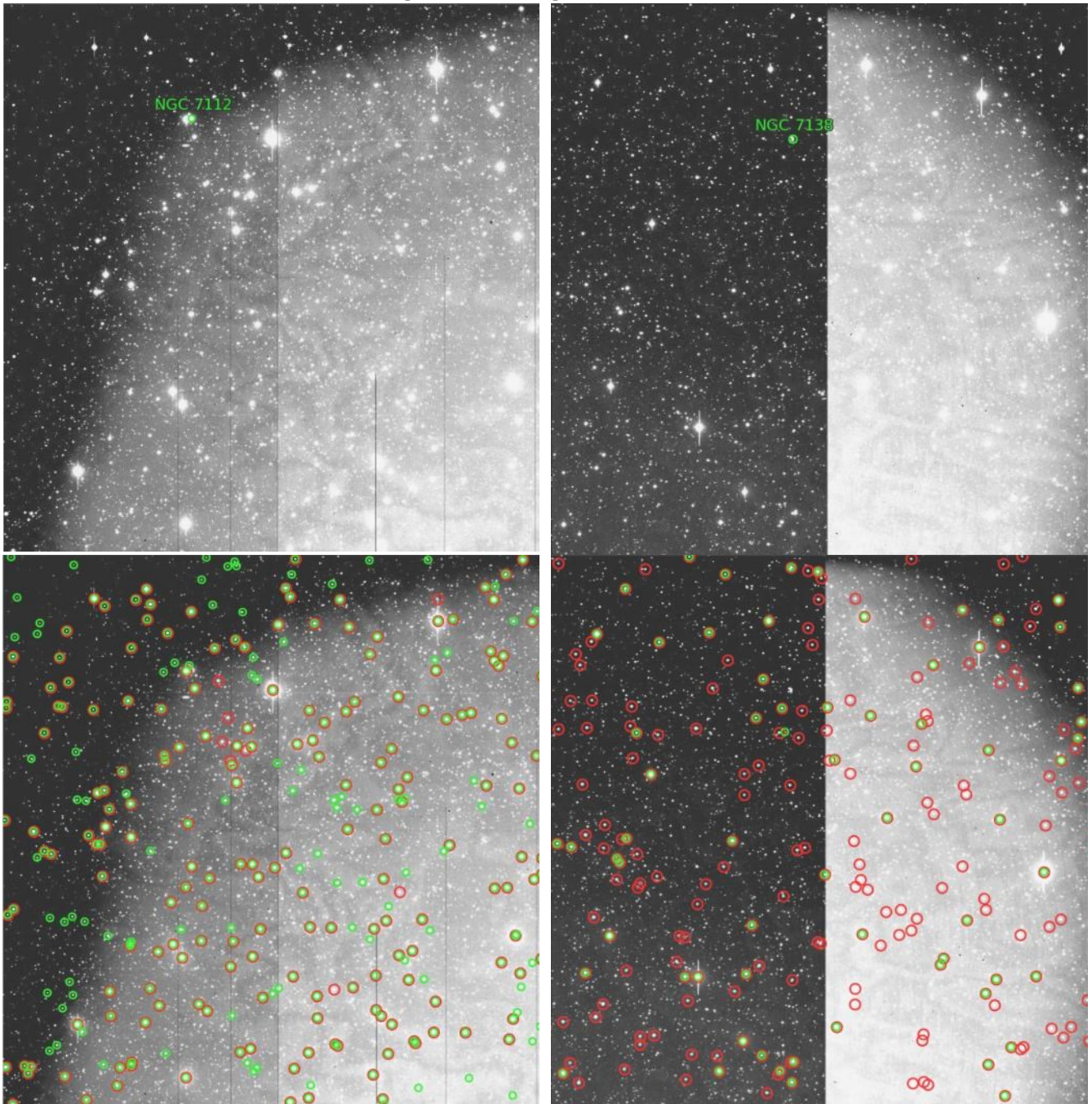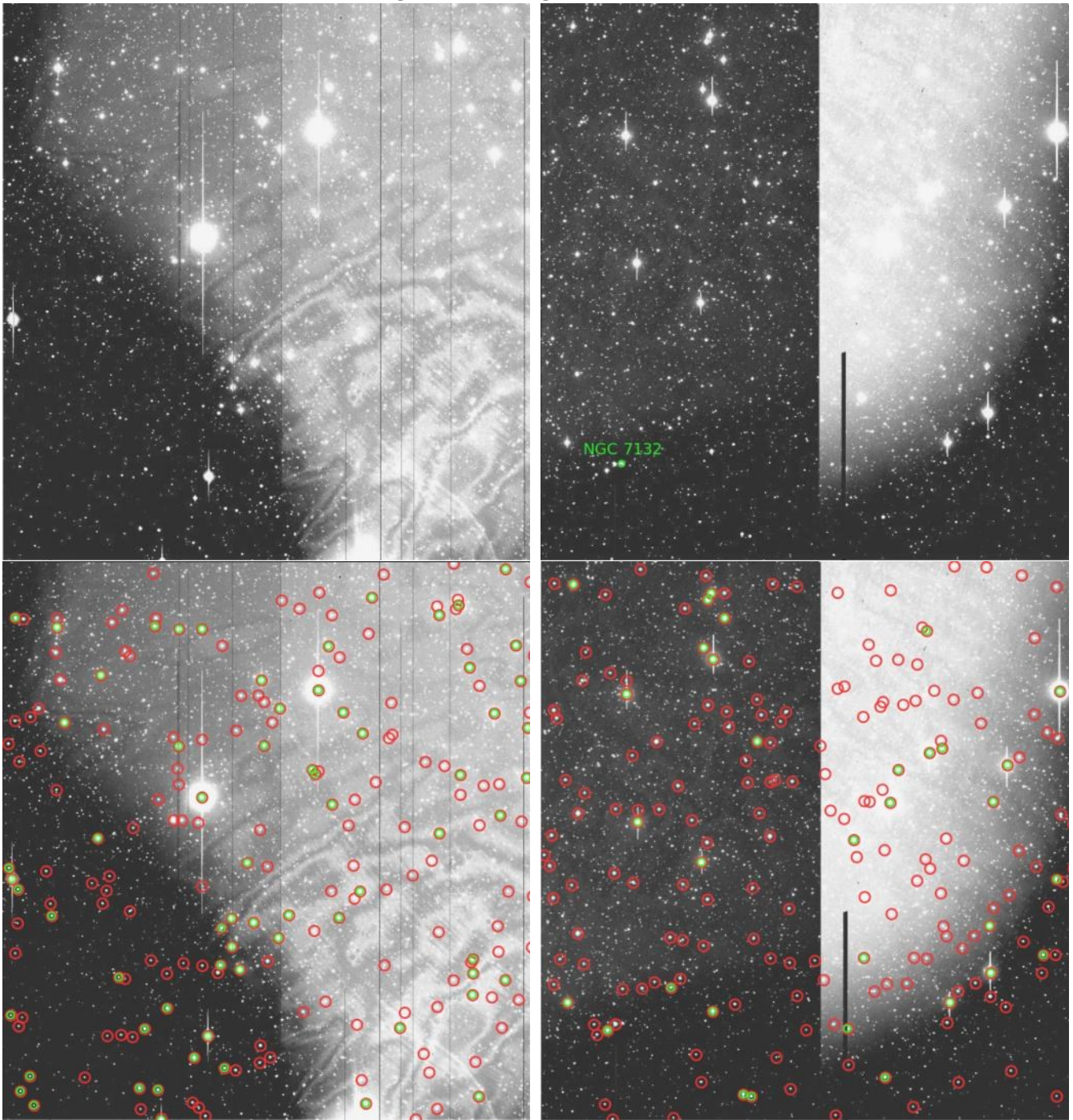
**Fig. 3. 071113_1_014_L.fits (left) and 071113_1_014_R.fits (right). Top: Regular image, Bottom: Red-green image.**

Fig. 4. 071113_2_014_L.fits (left) and 071113_2_014_R.fits (right). Top: Regular image, Bottom: Red-green image.

The Astrometry.net calibrations for the images in Figs. 3 and 4 are given in the table below.

Augmented Images Validation

Calibration 071113_1_014_L.fits		Calibration 071113_1_014_R.fits	
Center (RA, Dec):	(325.843, 12.152)	Center (RA, Dec):	(327.345, 12.150)
Center (RA, hms):	21h 43m 22.427s	Center (RA, hms):	21h 49m 22.840s
Center (Dec, dms):	+12° 09' 07.516"	Center (Dec, dms):	+12° 08' 58.955"
Size:	1.44 x 1.44 deg	Size:	1.44 x 1.44 deg
Radius:	1.018 deg	Radius:	1.017 deg
Pixel scale:	2.53 arcsec/pixel	Pixel scale:	2.53 arcsec/pixel
Orientation:	Up is 179.9 degrees E of N	Orientation:	Up is -179.7 degrees E of N
Calibration 071113_2_014_L.fits		**Calibration 071113_2_014_R.fits**	
Center (RA, Dec):	(325.845, 10.711)	Center (RA, Dec):	(327.339, 10.709)
Center (RA, hms):	21h 43m 22.793s	Center (RA, hms):	21h 49m 21.333s
Center (Dec, dms):	+10° 42' 40.954"	Center (Dec, dms):	+10° 42' 32.030"
Size:	1.44 x 1.44 deg	Size:	1.44 x 1.44 deg
Radius:	1.018 deg	Radius:	1.017 deg
Pixel scale:	2.53 arcsec/pixel	Pixel scale:	2.53 arcsec/pixel
Orientation:	Up is 179.9 degrees E of N	Orientation:	Up is -179.7 degrees E of N

Below is a look at the problem columns that showed up in the 071113_014 images. I could not use PDS4 Viewer on these 071113_014 images because their corresponding xml files did not yet exist when I performed this analysis, so all cell values are from ds9.
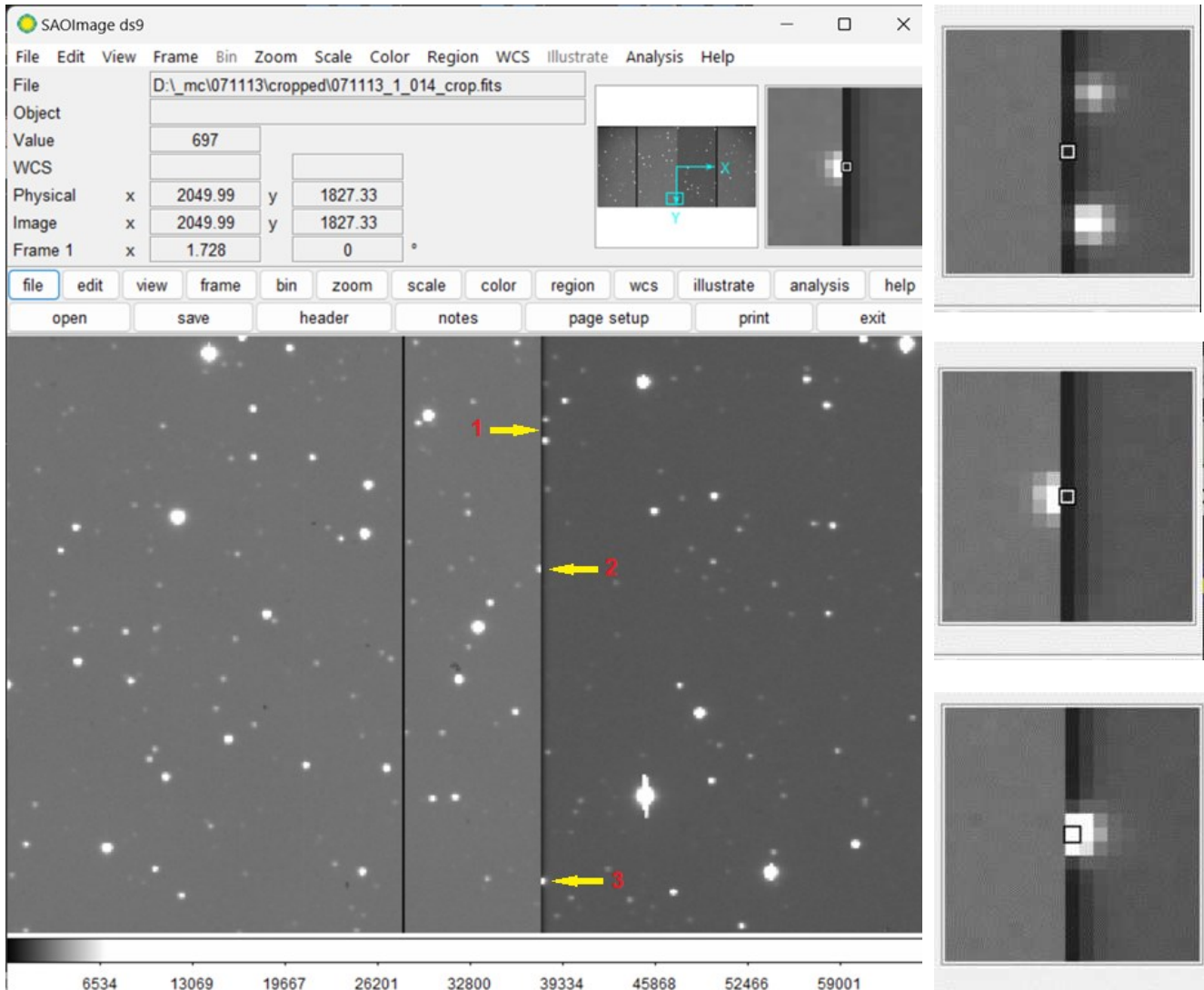
Fig. 5. Dead column (DC) x=2050 between amps 2 and 3 in image 071113_1_014_crop.fits

Neither of the stars at arrow 1 appear left of DC; they are only to its right (in rows 1758 and 1768).

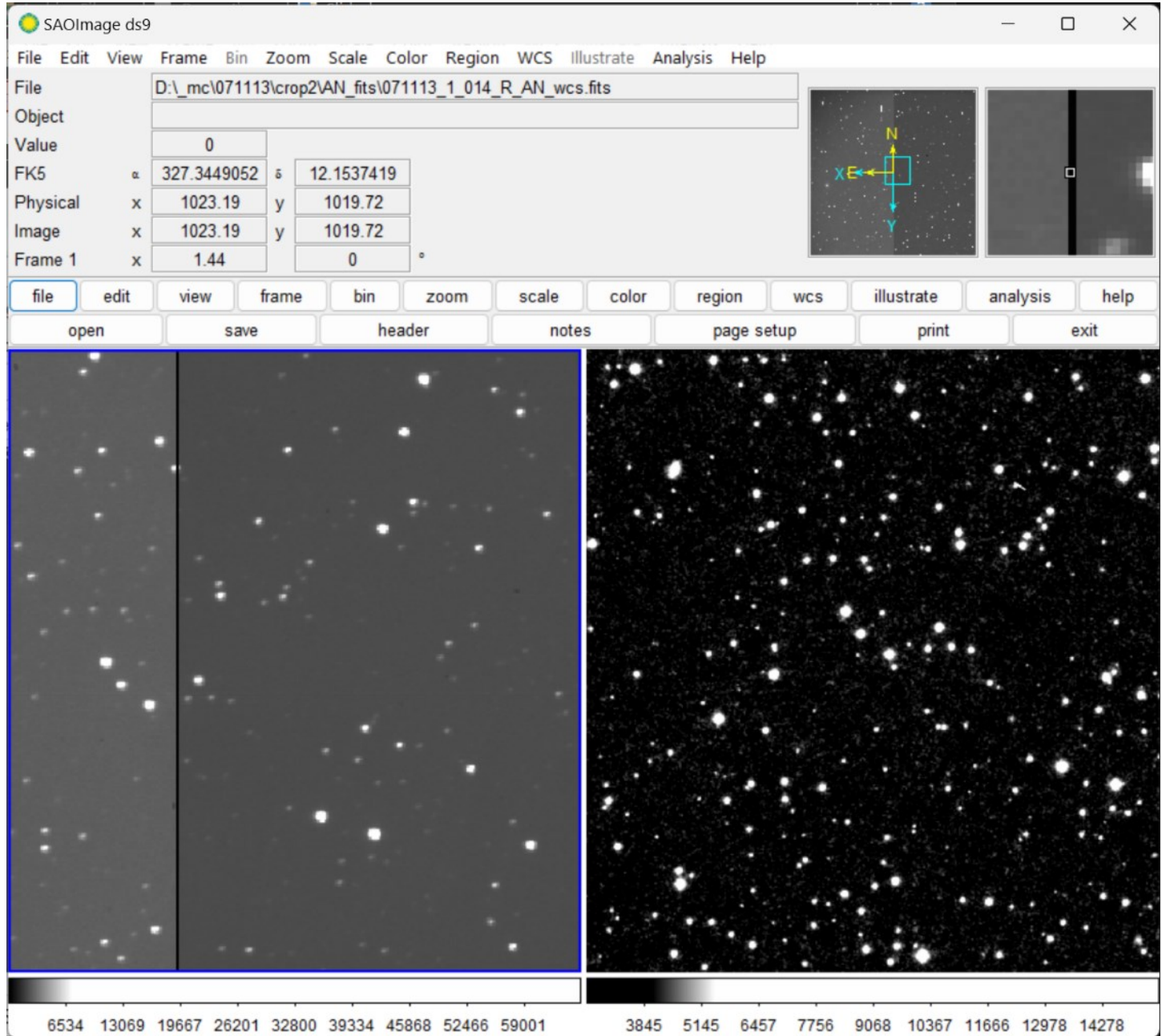# Augmented Images Validation

Star 2 appears only left of DC (in rows 1827-1828; it is not to the right of DC).

Star 3 appears both left and right of DC (in row 1972 in both). However, while its AN Decs are in nearly perfect agreement their RAs differ significantly (by ~44 px).

RA Diff (L-R) is -0.030848° (-111.05") -43.89 px and Dec Diff (L-R) is +0.000166° (+ 0.60") + 0.24 px

Fig. 6. Dead columns in image 071113_1_014_R_AN_wcs.fits

The positions of stars on either side of the dead column on the left in Fig. 6 have coordinates in both the LONEOS image and the DSS catalog that agree to within <2" as measured using only the ds9's 1-pixel square cursor. This suggests that only the columns that separate amplifiers 1 - 2, 2 - 3, and 3 - 4 cause errors in the (primarily RA) coordinates.