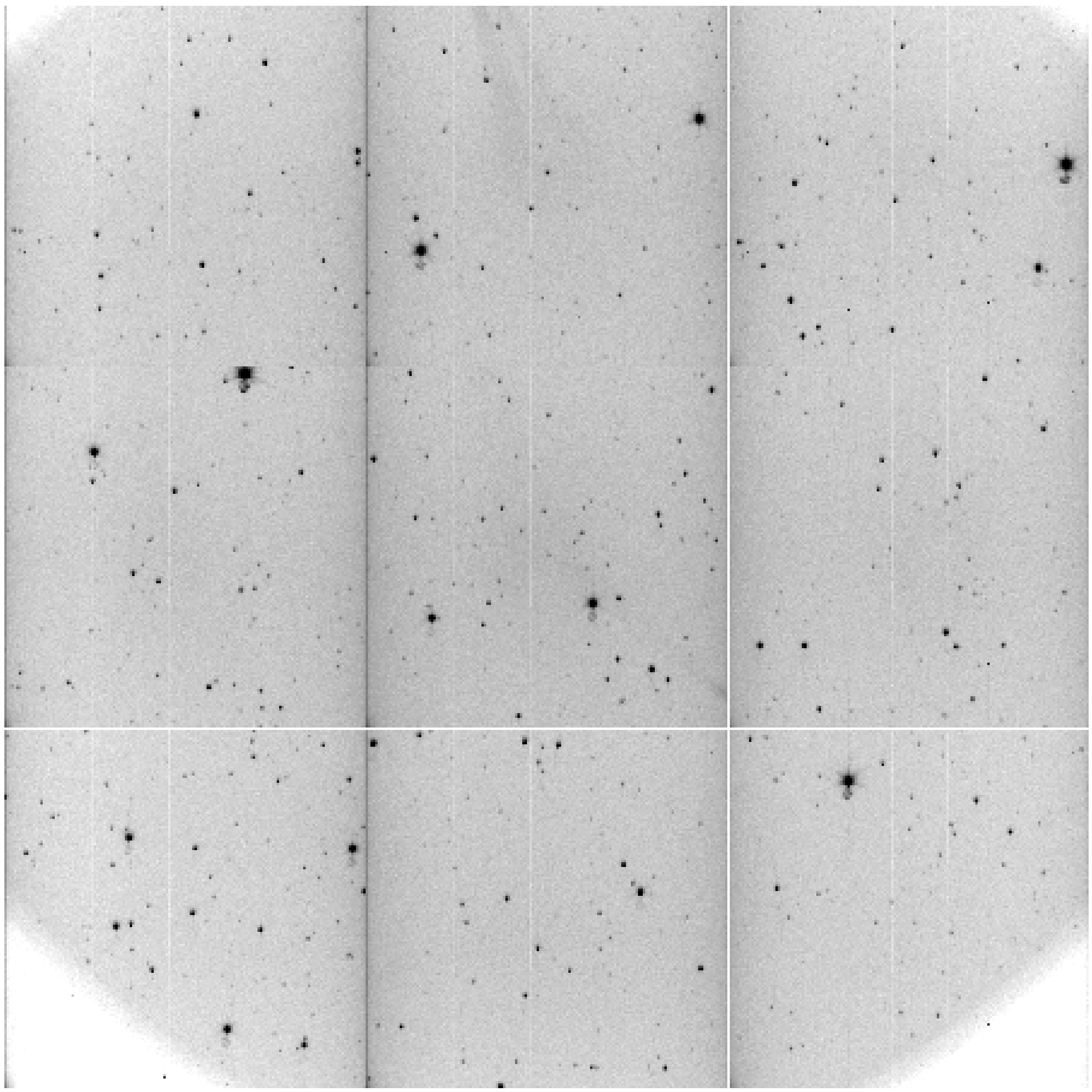
SALT Image Quality: Report To The SALT Consortium



Written: 2010 Aug 28

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1. Executive Summary

- After the recent re-installation of the SAC on SALT, and alignment with the rest of the telescope, on-sky images were obtained on only two nights of twelve attempted in modest to poor seeing. Such poor observing conditions preclude, for the moment, a stringent testing of the telescope's image quality.
- The available images of star fields showed that the SAC has been fixed: essentially round star images were seen, simultaneously in focus all over the entire field of view.
- These results are a huge improvement on images obtained with the same equipment before the SAC was taken off the telescope. At that time, star images could only be focused in small portions of the field of view.
- Various additional technical problems were uncovered such as the rotation stage wobble and instability in the autocollimator. The latter problem was fixed and the diagnosis of the former is under discussion.
- A minor residual problem remains, connected with the star images suffering from a small amount of astigmatism, probably arising from the primary mirror. Prospects for addressing this issue and fixing it are excellent.
- ***The bottom line is that SALT's IQ is no longer a "show stopper" and re-commissioning of the telescope can proceed in parallel with the last remaining steps needed to optimise the telescope's image quality.***
- Epilogue: on the last night of the observing run, good seeing prevailed for the first time and SALT produced very good image quality (FWHM 1.1 arcsec, uniform over the field).
- The Image Quality team is "standing down", at least for the present. Extensive testing in good observing conditions is required and will be undertaken by SALT Astronomy Operations. The IQ team may return later to help with final optimisation if required.

Old: 2007 Sep 9

New: 2010 Aug 19

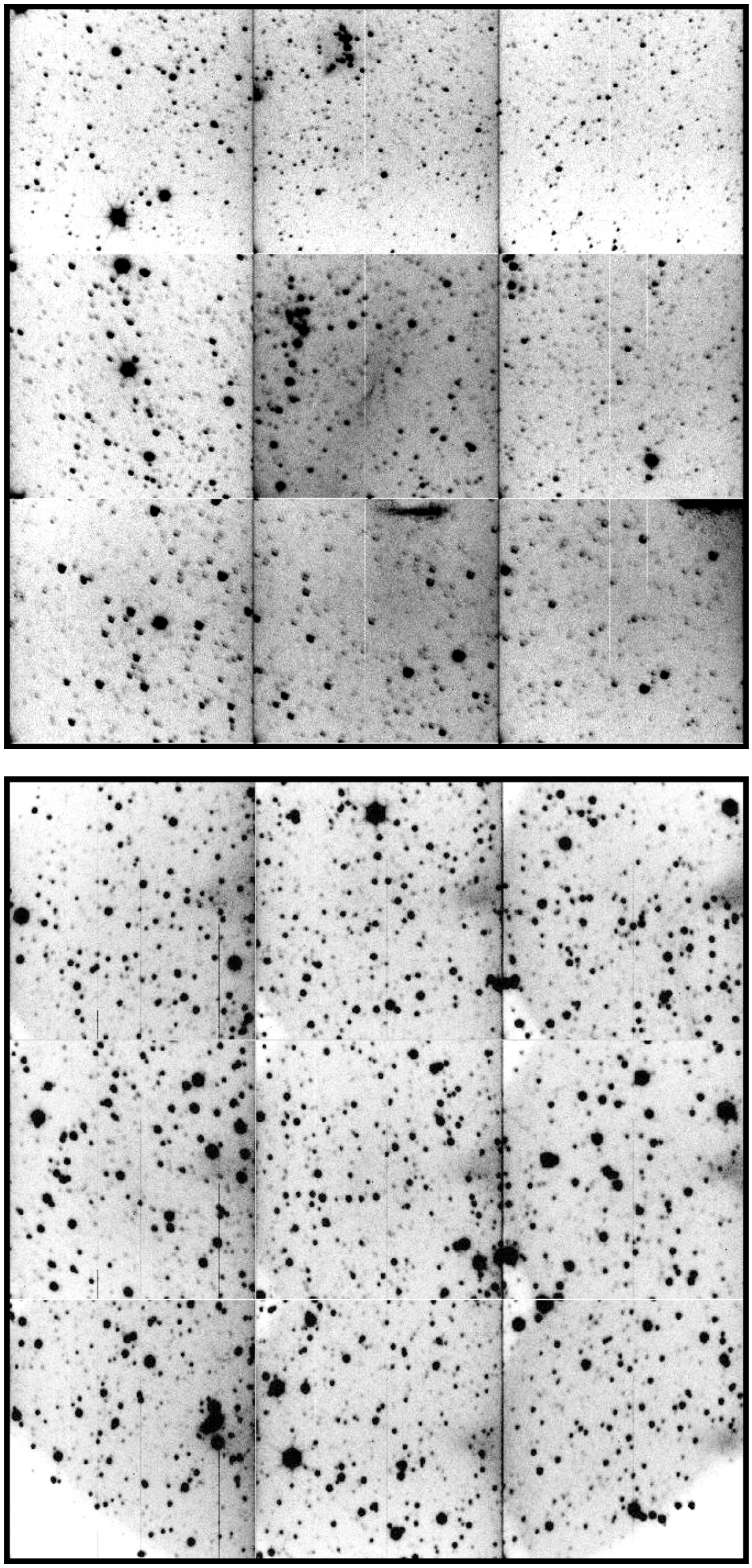

Fig. 1. (Top) Images obtained on 2007 Sep 9 (prior to the SAC repair); (Bottom) Images obtained on 2010 Aug 19.

2. On-Sky Testing

SALT Consortium members will by now know that the SAC was re-installed on the telescope on Aug 10. After that, several days of aligning it with the Tracker rho stage and the primary mirror took place. This was followed by the installation of the VI translation stage + Apogee camera for testing of image quality. With this completed, on-sky testing could begin. As this testing is incomplete, it may seem premature to issue a report at this stage. However, we recognize the understandable desire for information about the IQ performance of SALT and thus offer this account of the progress with this phase of the work.

2.1 Test Equipment Configuration

The imaging system comprised the primary mirror, the SAC and a U16M Apogee camera (see http://www.ccd.com) mounted on a 3 X 3 stage known as the VI stage as it was originally used for the Verification Instrument mode of SALTICAM. The 37 mm x 37 mm CCD in the Apogee, combined with the 38 mm grid spacing of the VI stage positions, enabled the entire science field of view of SALT to be covered by "tiling" together a set of 9 "postage stamp" images. No filter was used in front of the CCD for these first tests, but a filter set (UBVRI) and a mount is available. Short exposures were used (1-2 sec) with 8X8 prebinning giving 0.32"/pix.

2.2 Observing Strategy And Targets

The observing strategy employed was simple: the primary mirror was aligned and then the telescope slewed either to known clusters of high star density, or to arbitrary pointings at regions of the sky with large numbers of stars in an 8 arcmin field of view (but not too crowded). Sets of 9 postage stamp images were acquired for tiling together to cover the science field of view. After an hour or two of observing, the telescope was returned to the CCAS tower for primary mirror re-alignment. Targets in the south were favoured, as long tracks were possible allowing extensive imaging with the pupil centred on the primary mirror.

2.3 Poor Observing Conditions

Unfortunately, at the time of writing (Sat 28 Aug 2010), images have been obtained on only five of the thirteen nights attempted: specifically 2010 Aug 17, 19, 20, 24 and 27. The major reason was that the seeing was better than 2.0 arcsec only for a while on Aug 19. On the other clear nights, the seeing was about 2.0, ramping up to 3.0 arcsec or even larger. On Aug 17, 20 and 24, therefore, only a few images of limited usefulness could be obtained. On Aug 19 the seeing was 1.3-2.5 arcsec. Over a 100 images were obtained. On Aug 27, the seeing was 2.0-2.5 arcsec and about 100 images were acquired. So the results presented in this report are limited by the poor seeing and far more testing in better seeing is required.

2.4 Round Stars, No Focus Gradient

The key result which appears to be secure is that, once the autocollimator is properly adjusted (more on this below) and the telescope well focused, star images are round and *the focus gradient is gone*. The most convincing demonstration of this claim arises from the two tiled images shown in Fig. 1. The top tiled image shows data acquired on 2007 Sep 9, prior to the SAC repair, with the same equipment configuration as in the lower tiled image which was obtained on 2010 Aug 19 (subsequent to the SAC repair). The top tiled image shows images of FWHM ~ 1.7 arcsec for the best stars (no DIMM measurements of the natural seeing at the time were available for the 2007 data).

Objects in the top right corner of the 2007 Sep 9 image were in best focus and stars in its bottom left corner show poor focus and with distinctly asymmetrical shapes.

In contrast, in the 2010 Aug 19 image, all the stars are in simultaneous focus and apparently round in shape. (Readers may wish to view the images with the magnification of their viewing software increased to 200 per cent). The natural seeing in the bottom image, as measured by an on-site DIMM has FWHM ~ 1.9 arcsec, and the star images have FWHM of 2.5 arcsec.

The difference in quality of the old and new images can be further appreciated from the individual postage stamp images (Fig. 2) extracted from the tiled images. The left column of Fig. 2 shows two postage stamps extracted from opposite corners of the 2007 Sep 9 tiled image.

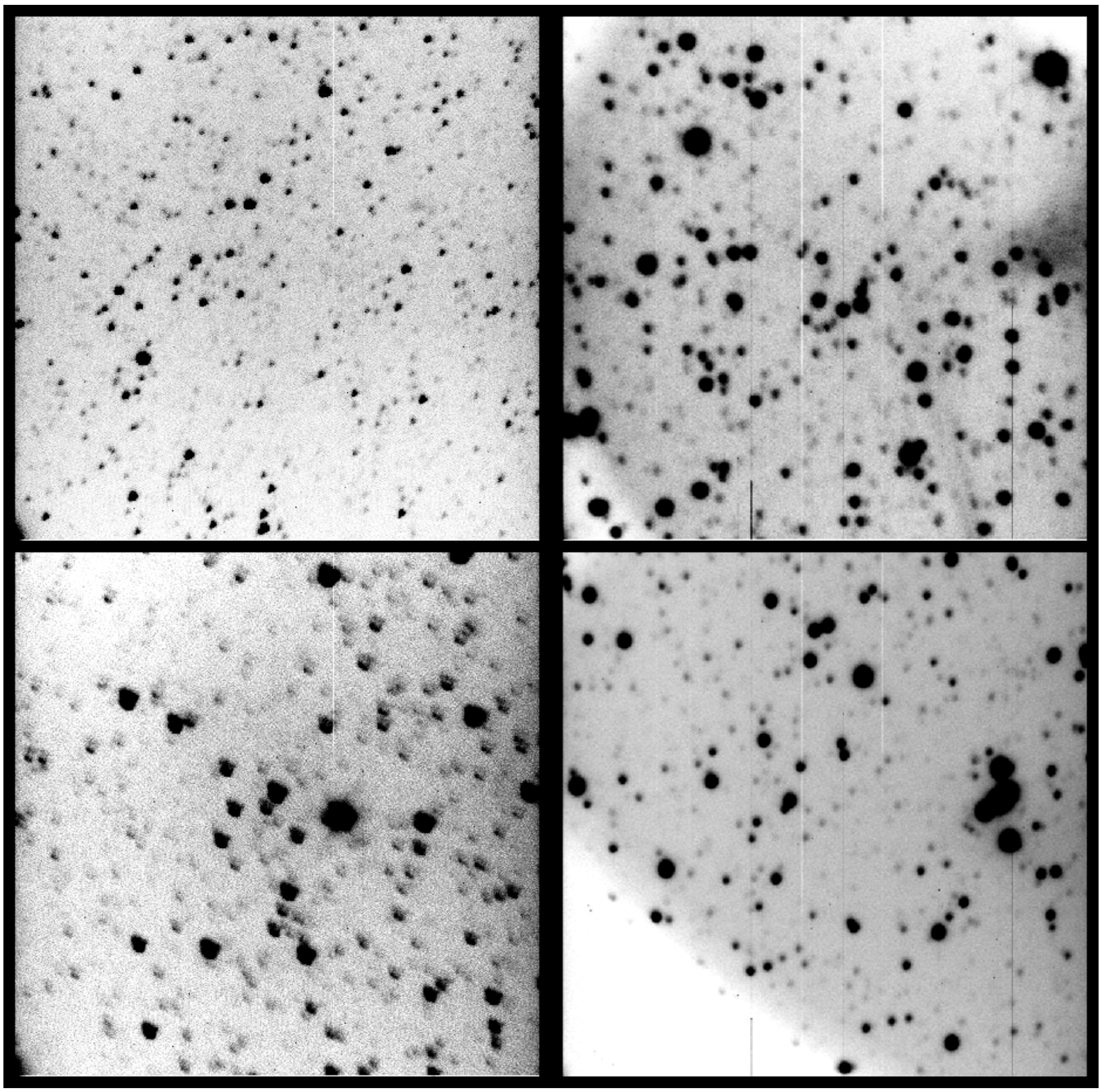

Fig. 2. (Left) The top right hand corner (upper) and bottom left hand corner (lower) of the images shown in Fig. 1 and obtained on 2007 Sep 9. (Right) The top right hand corner (upper) and bottom left hand corner (lower) of the images shown in Fig. 1 and obtained on 2010 Aug 19.

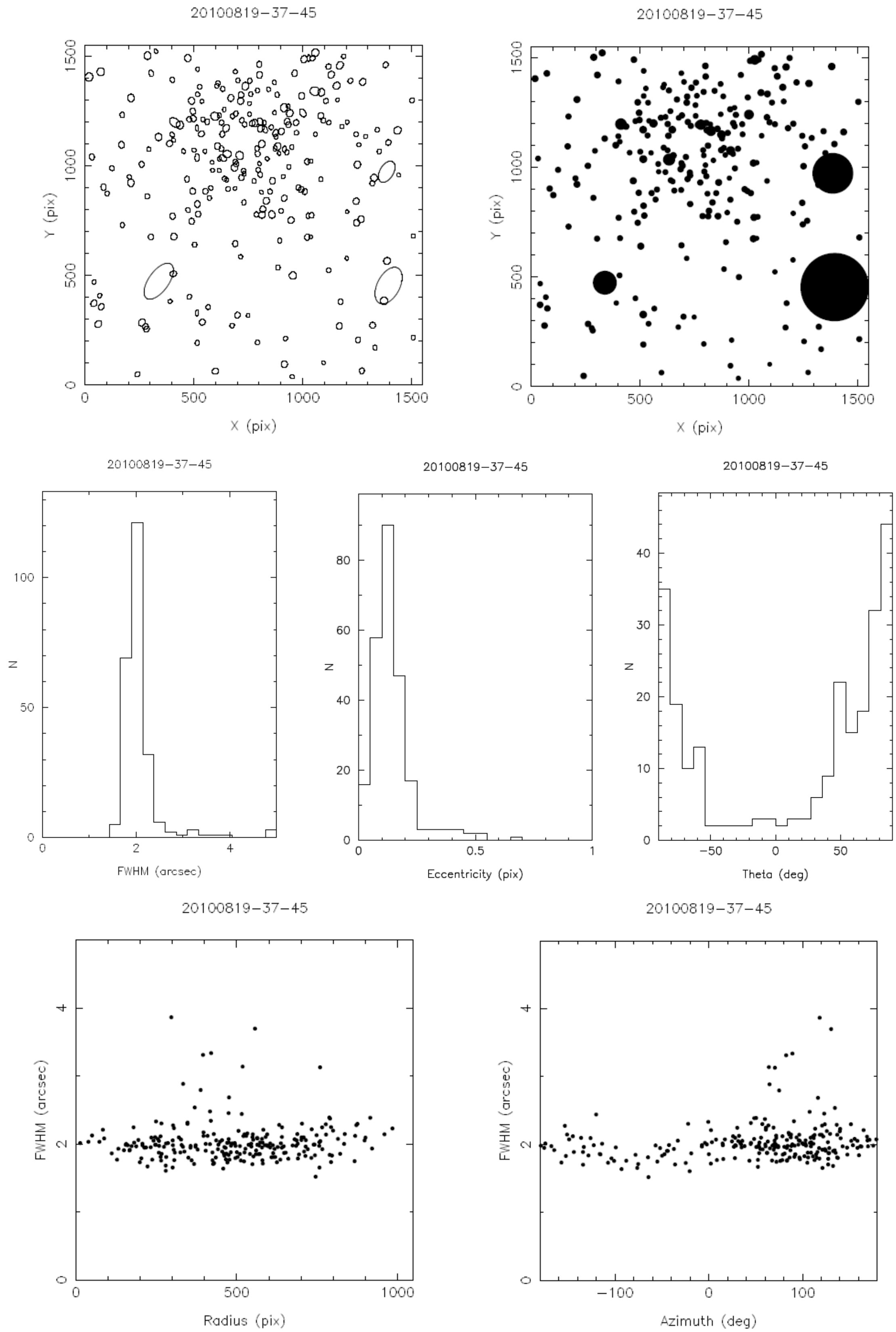

Fig. 3. Quantitative parameters of one of the tiled images from 2010 Aug 19 when the natural seeing was 1.25 arcsec. See text for details.

The same comments as made for Fig. 1 are applicable and more obvious: in the upper left image, reasonably well-focused stars are evident, while poorly-focused star images with asymmetrical shapes appear in the lower left. In contrast the postage stamp images shown on the right from the 2010 Aug 19 tiled image have uniform focus with apparently round shapes.

The quality shown by the 2010 Aug results displayed in Figs. 1 and 2 was not exceptional in the available data. Provided that the autocollimator is well adjusted and the telescope well focused, apparently round images with no focus gradient occurred in all the images obtained on 2010 Aug 19 when the autocollimator was functioning correctly (more on this below) and on Aug 27.

2.5 Quantitative Results

Each set of 9 images was tiled together using IRAF's imtile command (e.g. as displayed in Fig. 1). The tiled image was then input into the SExtractor source extraction software. This software is usually used for measuring the parameters of images of asymmetric galaxies. The software outputs a catalog of objects from the input image with associated parameters such as full width at half maximum (FWHM), ellipticity, and position angle of the ellipticity (theta). Fig. 3 shows a plot of the output from this catalog for the tiled image obtained later in the night of 2010 Aug 19. For this later image, the natural seeing had improved to 1.3 arcsec (which was the best seeing available in all the available data). It was, however, a couple of hours since the primary mirror had been re-aligned which was unfortunately overlooked at the time of the images. This is most likely the correct explanation for the sizes of the star images being significantly larger than the natural seeing.

The top left panel in Fig. 3 shows the shapes of the images as determined by SExtractor plotted as a function of pixel on the Apogee CCD. The top right panel shows the FWHM on the same plane with the symbol sizes in proportion to the FWHM. Both have three very large images arising from blobs of stray light and should be ignored. In the region of highest star density (the centre of the cluster), blends produced additional larger objects with significant ellipticities. These blends produced some outliers in the subsequent plots so these should also be ignored.

The central row of plots in Fig. 3 shows histograms of the FWHM, ellipticity (labeled eccentricity) and position angle of the ellipticity for all the objects in the catalog. Ignoring the outliers, it is apparent that there is a very uniform distribution of FWHM and ellipticity amongst all the objects.

Notable, however, from the central and leftmost plot is the fact that the peak of the distribution of ellipticities does <u>not</u> occur at zero, and the distribution of position angles is not random (as would be expected for perfectly round images). Further investigation showed that although the images are almost round, they are not perfectly so. The cause of this is a small amount of coma and astigmatism. The coma arises from incorrect setting of the autocollimator which causes tear-dropped shaped (comatic) star images all over the field. The astigmatism will be discussed later. Nevertheless, the amount of departure from roundness is very small.

The lowest row of plots in Fig. 3 shows the FWHM vs distance from the centre of the detector and vs azimuthal angle around the detector. It is apparent that there is no trend in either of these plots indicating that there is no dependence of focus with position on the detector. The focus gradient is indeed gone!

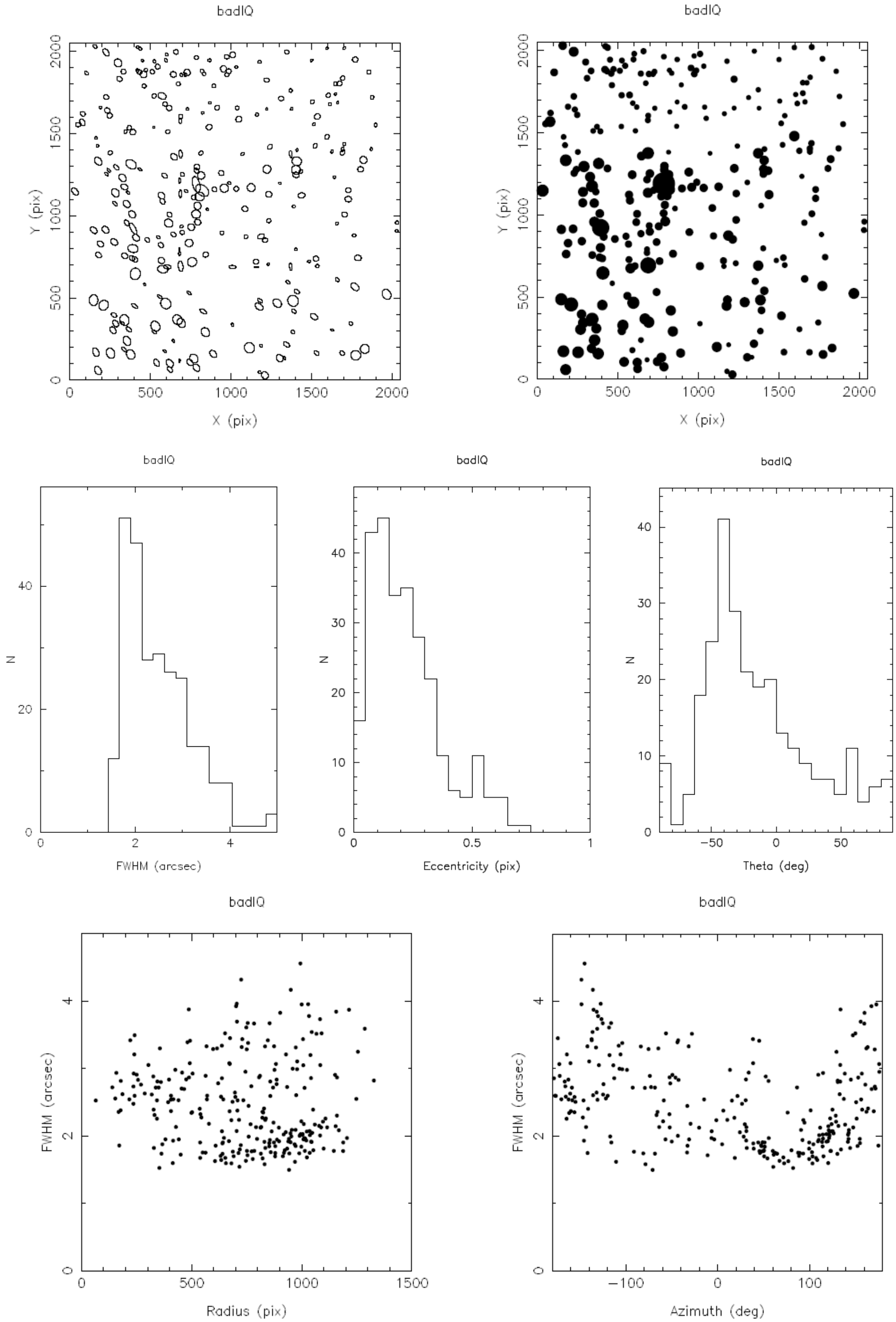

Fig. 4. Quantitative parameters of the tiled image from 2007 Sep 9.

In contrast to the results from 2010 Aug 19, the 2007 Sep 9 tiled image gives extremely erratic results (Fig. 4). The focus gradient is evident from the top right panel which shows much larger stars in the lower left than upper right; the stars have significant ellipticities with a large spread in them and a preferred direction (-40 deg); the variation of FWHM with distance from the centre of the detector and azimuthal position around the detector is far from flat.

The images selected to illustrate the comparison of new and old demonstrate the results clearly. They are, however, typical of other images acquired on 2010 Aug 19, 27 and 2007 Sep 9.

As the focus gradient has been the most damaging symptom of SALT's poor image quality due to it limiting the field of view of the telescope to a small area where good focus could be obtained simultaneously, the results presented here constitute a huge improvement in SALT's image quality.

2.6 Fixing The Autocollimator

Until the night of Aug 27, the autocollimator, which is required to keep the SAC "pointing at" the primary mirror perpendicularly, showed erratic behaviour. Star images were round and stable for considerable periods of time (2 or 3 hours, say). However, for no obvious cause, asymmetries in the images would then appear. Adjustment of the autocollimator fixed this problem but not for very long. All aspects of the stability of this sub-system were investigated. The behaviour of this sub-system prior to the SAC being taken down required it to be adjusted only monthly, not every couple of hours or even more rapidly.

The solution to the problem appears to be to use a much more stable mount for the unit and to move the autocollimator from the Non-Rotating Structure to the SAC steel collar. This was intended from the outset of the SAC/NRS redesign, as the key requirement is to maintain the correct attitude of the SAC with respect to the Primary Mirror. Implementing this was delayed until Aug 27 when it had become an obvious problem. On that night, the instabilities in the autocollimator disappeared along with coma in the images and the sub-system was stable all night.

2.7 Is The Demonstrated IQ Good Enough?

Until images in good seeing are obtained, it will be impossible to claim this. A slight source of concern is the much larger star images than the natural seeing in the Fig. 3 tiled image. The tiled image in Fig. 1 from 2010 Aug 19 also has larger star images than the natural seeing. However, we believe that these results are due to the primary mirror not being aligned sufficiently frequently on a night with a steep temperature gradient, as well as the erratic behaviour of the autocollimator alluded to in the previous subsection. In colloquial terms, on Aug 19 we were still "trying to figure out what we were doing".

In contrast, by the time of 2010 Aug 27, the autocollimator problem had been fixed, the night was stable, we were aligning the primary mirror sufficiently frequently and concentrating on maintaining focus. Although the seeing was poor, the results shown in Fig. 5 (typical for that night) demonstrate NO degradation of natural seeing by the telescope's optics. Of course, this result is not a penetrating test due to the poor seeing but it does at least address questions that might arise in the minds of the readers from the results from Aug 19.

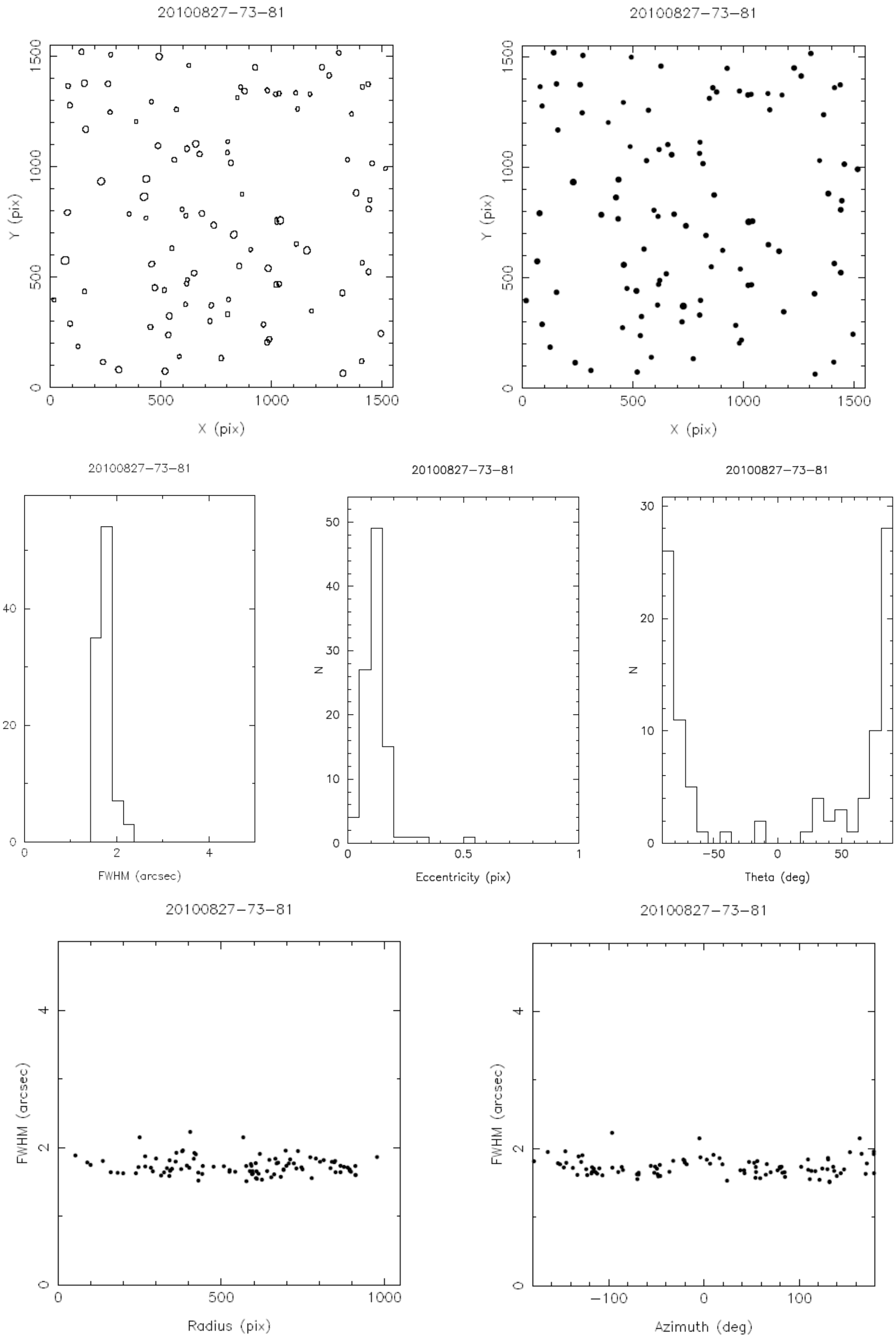

Fig. 5. Quantitative parameters of the tiled image from 2010 Aug 27.

3. Is SALT's IQ Fixed?

3.1 YES

Even with the limited number of images and the poor seeing, we believe that

- The SAC is working properly.
- SALT's IQ has been hugely improved compared to before the SAC repair.
- The telescope is scientifically usable with almost round images and no focus gradient across its field of view.
- Prospects for addressing the remaining issues (see below) and optimizing the image quality are excellent.
- The IQ issue is no longer a "show stopper". Optimizing IQ can proceed in parallel with other re-commissioning activities of the telescope.

3.2 How Certain Are We That It Is Indeed Fixed?

Given the poor seeing and limited data set, we cannot claim absolute certainty that SALT's IQ will meet its IQ specification. As has been mentioned repeatedly, imaging in good seeing is required to check that there is indeed no degradation of the natural seeing as per the specifications. IQ must also be demonstrated to be stable over the entire parameter and operational range of the telescope: testing against temperature, wind conditions, telescope azimuth; Tracker position; rho stage position and so on. It is also not known if targets at the limit of the telescope are as faint as they should be, nor if stray light is an issue, as all the images presented here were obtained in bright moon conditions with poor baffling around the camera. There are also specific optical issues remaining as will now be discussed.

3.3 Remaining Problems And Residual Astigmatism

A problem not mentioned so far is that of the rho ring wobble. When the Tracker rho stage was being aligned with the primary mirror, a wobble in its motion of 180 arcsec, peak to peak, was uncovered. This problem was "sensed" in the telescope alignments carried out years ago, but the laser equipment used then was too poor compared to the alignment telescope now available to define the issue and measure its size. For this reason, all the imaging reported here was carried out at rho = 0. Plans for diagnosing the cause of the problem are under discussion by SALT Technical Operations.

There is no doubt that a small amount of astigmatism in the telescope's optics was evident on the best of the nights discussed in this report (Aug 19 and 27). Adjusting focus showed, on one side of best focus, elongated images in one orientation which rotated by about 90 deg on the other side of best focus (at best focus the images are round or nearly so).

The small amount of ellipticity in the images at a specific orientation as shown in Figs. 3 and 5 is a symptom of the same problem and arises from the orientation of the astigmatism being vertical at best focus. Inspection of contour plots of the images shows that the ellipticity is evident as a small departure from symmetry in the base of the point spread function; the core of the stellar image is round.

There are only two possible origins for the above effects: the SAC or the primary mirror (as the Apogee camera is incapable of producing optical aberrations). Given the excellent results from the SAC optical testing before installation on the telescope, we believe that it is more likely that the primary mirror is the cause. The primary mirror, it will be recalled, was strenuously interrogated about its performance in the diagnostic phase of the work, and no specific problems were uncovered. However, the size of the problems being considered then was so large that a small problem in the primary mirror may have become visible only now that the major IQ problem has been fixed: the focus gradient and astigmatism arising from the internal SAC misalignment. Plans to investigate this remaining astigmatism are already being discussed. *It is expected that this remaining issue will be orders of magnitude easier to solve than fixing the SAC.*

3.4 What About The "Feared" Doubled Images?

Interestingly enough, these are still evident when: (i) the telescope is out of focus; (ii) the autocollimator is badly adjusted so that there is a lot of coma in the images; (iii) the pupil is decentred with respect to the primary mirror; (iv) the lookup table in the display is adjusted to hide low surface brightness regions of the images. With careful attention to adjustment of the autocollimator, doubled images or other peculiar image shapes do not seem to be evident with suitable adjustment of the display lookup table and when the pupil is centred on the primary mirror. There is no sign whatsoever of doubling when the telescope is optimally focused.

With the focus gradient and astigmatism from the SAC "squared away", the peculiar image shapes do not seem to be as much of a problem as was thought, although this claim needs more testing to confirm it.

4. Summary

- After the recent re-installation of the SAC on SALT, and alignment with the rest of the telescope, on-sky images were obtained on only two nights of twelve attempted in modest to poor seeing.
- The results showed that the SAC has been fixed: essentially round star images were seen, simultaneously in focus all over the field of view.
- These results are a huge improvement on images obtained with the same equipment before the SAC was taken off the telescope.
- The autocollimator was found to be a problem before its mount was improved and moved from the Non-Rotating Structure to the SAC itself. After this, its performance appeared to be satisfactory.
- There are minor residual problems connected with the star images suffering from a small amount of astigmatism, probably arising from the primary mirror. Prospects for addressing these issues and fixing them are excellent.
- ***The bottom line is that SALT's IQ is no longer a show stopper and re-commissioning of the telescope can proceed in parallel with the last remaining steps needed to optimise the telescope's image quality.***
- On the last night of observing by the IQ team, unexpectedly clear conditions with good seeing occurred. SALT's image quality was not embarrassed by the turn of events and delivered images with FWHM 1.1 arcsec all over the field: see the Epilogue below which was added on after the bulk of this report was completed.

5. Epilog: Good Seeing At Last

All the previous parts of this report were completed on the afternoon prior to the last night of the IQ team's scheduled time on the telescope. On that afternoon, conditions were looking very poor and it was not anticipated that any observing would be possible that night. However, by sunset the cloud went away and very good seeing prevailed for the first time since on-sky testing began. The writer decided to report the resulting good news by the addition of this epilog (as opposed to revamping the entire report).

The best news of all is that SALT's image quality was not embarrassed by the good conditions: the telescope produced images of FWHM 1.5 arcsec or less.

The image on the front cover of this report was one of the best images from that night (28 Aug 2010). It has stars with 1.1 arcsec FWHM. Unfortunately the DIMM must have been malfunctioning as it was reporting at the time natural seeing of FWHM 1.5 arcsec. When this excellent image was run through SExtractor, the analysis of the plots (as in Figs. 3-5) appears in Fig. 6 (overleaf). The residual astigmatism problem is apparent from the middle plot showing ellipticities of 0.2. However, the FWHM are the best seen so far and there is no dependence with position in the field of view.

6. Au Revoir

The Image Quality team will now "stand down", at least for the present, and leave the extensive testing mentioned previously to SALT Astronomy Operations. If required they may return later to help with the small residual astigmatism problem or any other remaining IQ optimization (provided that their forwarding address can be located!).

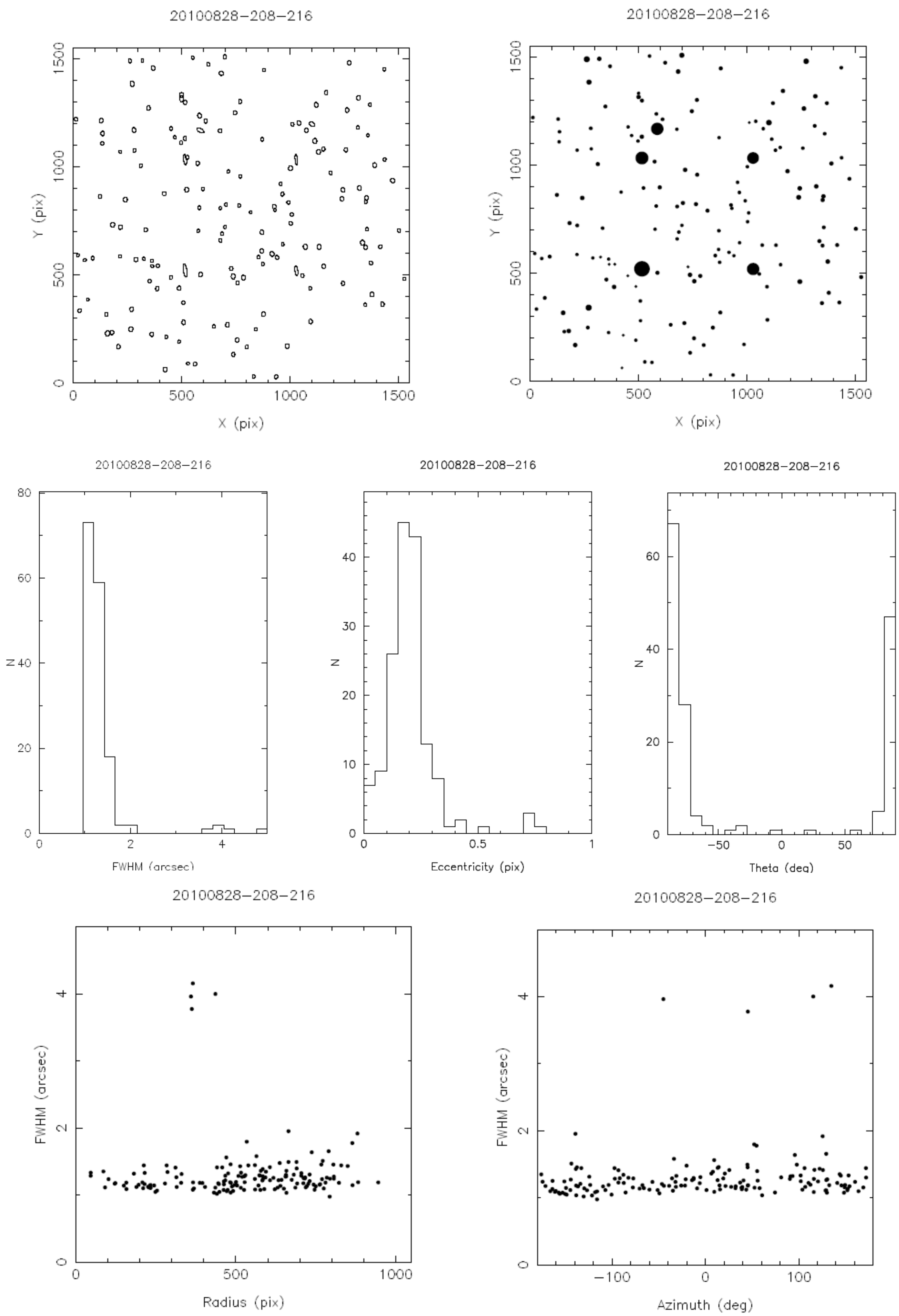

Fig. 6. Quantitative parameters of the tiled image from 2010 Aug 28