Super-Resolution Imaging: The Use Case of Optical Astronomy

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SUPER-RESOLUTION IMAGING: THE USE CASE OF OPTICAL ASTRONOMY

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ABSTRACT

Super-resolution is well known to increase the resolution of images below the pixel barrier. The work outlines the use case of super-resolution in astronomy science. The current state-of-the-art of high-resolution imaging in astronomy is reviewed, which leads to the problem of super-resolved images. Fundamental properties of astronomical images are demonstrated to define requirements. Astronomical images suffer from low illumination and noise. The range of spatial resolution is found from long-exposure image limited due to atmospheric blur, and a scale of perfect sampling adapted to diffraction-limited observations. Astronomical imaging is a trade-off between resolution and signal-to-noise ratio (S/N). The success of super-resolution is interfered by the quality of data, selection of the method, and a proper definition of the image formation and image reduction pipeline. This work provides a precise definition of the ill-posed and ill-described problem of super-resolution imaging in astronomy. A new method of automatic image registration is presented, which is especially designed for astronomical imagery. Based on the exploration of real astronomical images, the new method provides an accuracy in the order of 0.05 of the pixel dimension. Future milestones are found as the selection of an appropriate method of image deconvolution. With astronomical wide-field imaging, certain optical effects introduce varying point spread and image distortion. These will define the requirements for an appropriate solution to image deconvolution and to complete the task of super-resolution in astronomy.

KEYWORDS

Super-resolution, image reconstruction, astronomy

1. INTRODUCTION

Astronomy science has a long tradition with roots found in most cultures on this planet. Astronomy enabled agriculture, as it introduced the time to measure and predict the seasons of the year. The outcome of the astronomy still builds up a fundamental key for human civilization. One example is the definition of a precise reference coordinate system which enables modern navigation of vehicles on ground, ships, airplanes and spacecrafts. Astronomy also asks questions about the origins and processes of the universe. Objects of interest are stars, star clusters, galaxies, clusters of galaxies and the interstellar matter. The more distant these objects are, the more important it seems to obtain better resolved images from the observations.

Digital image processing and analysis started in the 1970ies based on electronic imaging of radio signals and digitized photographic plates (see section 2). The detection of light is different from the detection of a radio signal. A major reason is, that the phase of the electro-magnetic wave cannot be recorded with optical imagers available. Therefore, only intensity distributions are recorded by optical sensors. A new revolution of optical imaging has begun in the 1980ies with the advent of silicon image detectors. *Mackay (1986)* described the use of charge coupled devices (CCD) in the field of astronomy. *McLean (2008)* presents the current work on imaging detectors which is still large field of interest.

With the introduction of digital imaging, the improvement of image resolution is probably one of the most important requirements to astronomical instrumentation and image analysis. An obvious reason is the inability of a ground-based telescope to perform its theoretically possible resolution. If super-resolution methods ever could be applied successfully to astronomy, there might be any expectation to find an efficient and inexpensive method of data reduction which may support or supersede current techniques of high-resolution imaging. The goal of this work is to obtain the requirements from the review, describe the preferred method of super-resolution and present a new solution to the first milestone: A reliable task of image registration is presented, which achieves high accuracy to evaluate the image motion between images.

2. ANALYSIS

2.1 High-Resolution Imaging in Astronomy

Speckle interferometry was presented by *Labeyrie (1970)* to achieve diffraction limited resolution with a ground-based telescope and a Fourier analysis of the images. *Welter & Worden (1980)* applied this technique and presented the measures of diameters of nearby stars. The image of a star usually is taken as a prominent example of the image of an unresolvable point light source. Hence, the result of *Welter & Worden (1980)* is notable. The measured diameters of certain stars are found in the order of the diffraction limit of a large telescope. Speckle interferometry will improve the resolution of an astronomical image up the optical diffraction limit. However, the technique is very limited, because short exposure times of a fraction of a second are needed. This is sufficient for the observation of a bright star, but will not match the needs to obtain a photo of a faint galaxy (see figures 1, 2). Application of several high-resolution techniques began to awake the interest of astronomers. New methods are researched, applied and improved in a competitive manner to find out which method performs best. The CLEAN algorithm and maximum entropy method have been experimentally applied to astronomical images to evaluate the performance of these methods *(Högbom 1974, Nityananda & Narayan, 1982, Sanromà & Estalella 1984)*. *Starck et al. (2002)* provided a review on performance of image deconvolution techniques modified by additional wavelet analysis. Further methods encountered with this review are the Richardson-Lucy method and a technique called the pixon method. Newer techniques are demonstrated to outperform and supersede CLEAN and maximum entropy method. The methods are well suited to high-resolution imaging at faint illumination level.

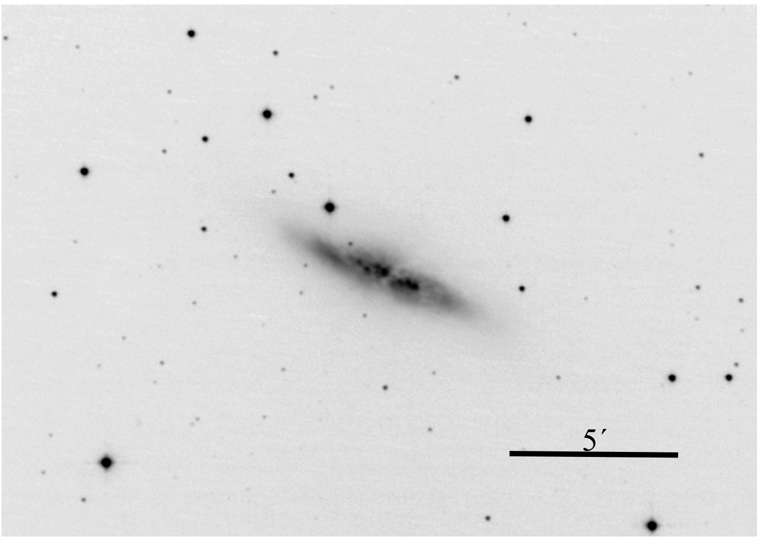

Figure 1: Image of the galaxy M82 taken by the author with a 20 cm telescope. A modified digital single-lens reflex camera provided a total exposure time of 56 minutes. Crop and magnification of the image demonstrates the small scale of the target. Only 8% of the whole field of view are shown. Atmospheric point spread limits image resolution. Use of the Hubble telescope increases resolution by a factor of 12, but required an investment of more than one Billion $US until the day of writing. Super-resolution methods also help to improve the resolution of the Hubble telescope.

From our neighboring galaxies some very bright stars have been considered as super-massive stars. One reason for thinking of a super-massive star is given by the fact, that a very luminous object will appear like an unresolved point light source due to its huge distance. An example is given with the star HD 32228 (also referred as R64) which has been successfully resolved as a dense star cluster by *Schertl et al. (1995)* and *Bauer et al. (1996)*. From the latter work it seems, larger exposure time and less images enabled a first successful astronomical examination of the single stars of the cluster. One might ask, how to optimize a given observation time frame in the sense of dividing total time into portions of exposure time to obtain optimal resolution from the number of images obtained. *Smith & Gallagher (2001)* discuss properties of a peculiar, unresolved star cluster in the distant galaxy Messier 82. Illustrations and measures provide insights in how far ground-based observations differ from observations of a space telescope. The star clusters observed remained unresolved due to the large distance of the galaxy where the cluster is embedded. Figure 1 demonstrates a typical image scale of the galaxy M82 seen by a ground-based telescope. *Jacoby (1989)* and *Ciardullo et al. (1989)* estimated distances of galaxies in the neighborhood of the Milky Way. The estimation is based on the measure of brightness of certain gaseous nebulae contained in these galaxies. Because distances of the galaxies are huge, these objects appear like point sources. It is hard to distinguish the nature of point light sources observed. Statistical assumptions about the emitted light is taken as a hint whether the identified sources represent stars, clusters or nebulae. Better resolution is clearly a requirement. *Gilliland and Dupree (1996)* presented images of the surface of a star observed with the Hubble space telescope. The result from a pixel interpolation and super-sampling is discussed as the features observed from the surface of the star. The method applied is a typical approach to statistical super-resolution (see section 3). This enumeration of examples will not claim for completeness. The field of astronomical imaging is experimental and seems to change with every new telescope built and camera used for the observations.

2.2 Properties of astronomical images

At this point one shall consider the typical properties of astronomical images. Except images of the bright surfaces of the sun, moon and bright planets like Venus and Jupiter, the vast majority of astronomical images is obtained in the dark night sky. *Geyer (2010)* presented considerations and constraints between signal-to-noise ratio and the limiting magnitude of a point light source detected in an astronomical image. The term magnitude refers to a logarithmic measure of a ratio of luminosity between two measured objects (a.k.a. Pogson´s law). The limiting magnitude describes the apparent luminosity of the faintest intensity detected in an image. Obviously, the faint light signal plays an important role in the astronomy. *Mackay (1986)*, *Berry & Burnell (2006)* and *McLean (2008)* described further properties of common detectors leading to a standard process established to the image calibration. Noise parameters are evaluated and a linearization of the image intensities is done carefully. The process chain also includes subtraction of bias and dark signal. The flatfield task compensates for the effects of varying pixel sensitivity and vignetting. Image calibration is a requirement to obtain results which shall be photometrically examined at high accuracy and even with the faintest signal available in the raw images.

Back to the viewpoint of a software engineer, one shall assume image content in the astronomy is completely different from conventional photography and artwork. Rakishly spoken, astronomical images taken in the night sky contain a handful of photo events detected, which are mixed up with certain amount of detector noise of nearly the same count rate. Anything which seems interesting appears small and almost close to noise level of the astronomical image itself. The impact of noise is omnipresent and different from conventional photography and artwork.

2.3 Limitations to resolution

There are certain limiting factors of resolution at different scales. These are defined by properties of the telescope optics and detector. Resolution is also given by environmental influence at the observing site. Finally, there are limits introduced by the method of observation and processing the data.

The limit to clearly separate two images of point light sources is approximated by the equation $\alpha=1.22\lambda/D$ with the angular separation α, the wavelength λ and the aperture diameter D of the optics. This is also referred as the classical Rayleigh criterion of the optical diffraction limit. It is seen as a fundamental limit to resolution and caused by the physics of light *(Born & Wolf, 1953)*. *Den Dekker & Van den Bos (1997)* presented a comprehensive review on resolution from several viewpoints, including optics and information theory. *Den Dekker & Van den Bos (1997)* found the term „resolution limit“ an arbitrary limit. One shall assume any resolution beyond any (arbitrary) limit, like the Rayleigh criterion. Resolution will depend on certain impacts, like design of optics, detector, and noise properties found. As resolution is found arbitrary, this will mean the achievable resolution is unlimited. However, the exercise is left open to estimate the effort needed to obtain a certain resolution. Because image quality also depends on noise characteristics, resolution is usually a trade-off between signal quality and spatial resolution. Optimal detector performance is obtained, if the Whittaker-Shannon sampling theorem is fulfilled. Hence, resolution undergoes limitations introduced by the design and adaptation of the telescope optics and camera used for the observations. Finally, a limit to resolution will also be introduced by the method of data reduction.

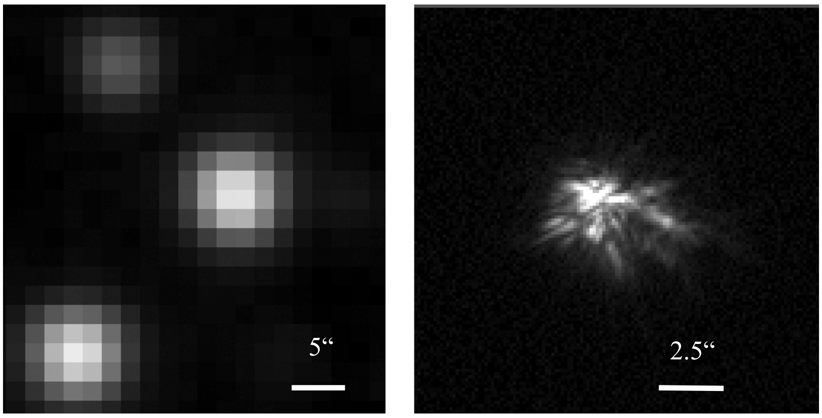

Figure 2: Resolution at different scales: Detail of a long exposure of a star cluster dominated by large pixel dimension, with sampling adapted to the dimension of seeing (left). This is compared to a short exposure of a bright binary star observed with speckle interferometry at the Hoher List 1 m Cassegrain telescope with focal length extended to 30 m (right, taken in the year 1994). Pixel scale is given in arcseconds.

3. SUPER-RESOLUTION AND THE ASTRONOMY

Until the day of writing this review, super-resolution cannot be seen as a term referring to a well-defined expression, precisely describing a certain technique or referring to a certain limit of resolution. This is especially true with the review of the literature available in the interdisciplinary fields of information technology and astronomy. *Baranov et al. (1996)* and *Farsiu et al. (2004)* described digital super-resolution algorithms and also referred to astronomical applications. *Cristóbal, et al. (2008)* presented a comprehensive survey of current super-resolution techniques. They also mentioned applications to astronomy. *Willet & Nowak (2004)* presented a wavelet based approach to super-resolution in astronomy. *Willet & Nowak (2004)* applied their method to simulated images, which more likely seem to resemble satellite observations of the surface of the earth, but do not match deep sky imagery found in the astronomical literature (see section 2). It shall be outside the focus of this article to count all interdisciplinary work reviewed until the writing of this paper. From the interdisciplinary side no work referring to astronomical applications showed significance, whether the proposed methods of super-resolution could be applied to astronomical images. Samples provided with the literature more likely resemble conventional photography and artwork, which is well exposed and does not contain too much noise.

Lucy (1992a, 1992b) and *Semintilli et al. (1993)* presented considerations to the dependency between the signal-to-noise ratio and super-resolution. Here super-resolution means to break the optical diffraction limit. *Hook & Fruchter (2000)* presented a method to obtain sub-pixel resolution by the drizzle method with an application to astronomy. The drizzle tool is a command-line oriented software, designed to perform resampling and image co-adding with certain parameters, like image motion, rotation and predefined distortion functions. The tool will not evaluate these parameters from the data and will not provide better physical resolution in the sense of any image enhancement, like a deconvolution, however.

The use of the term super-resolution is ambiguous and sometimes misleading if comparing the viewpoints of physics and information technology. Opticians, astronomers or physicists in general tend to speak about super-resolution only, if the resolution achieved is better than diffraction limit of the optics. Following the common trend in the literature of information technology, the term super-resolution more likely shall reflect a digital method to obtain any resolution at a finer sampling grid. A certain danger is indicated to compare different methods and leading to possible misinterpretation of the results, like the comparison of results obtained from statistical super-resolution and single image super-resolution techniques presented by *Puschmann & Kneer (2005)*. Hence, the term super-resolution shall be substantiated to clearly describe the goal and method.

4. DESCRIPTION OF THE PROBLEM

In astronomy a super-resolved image shall be reconstructed without any a priori knowledge about the source. The source itself defines the objective which shall be examined. Hence, one shall assume statistical super-resolution is the preferred way to proceed.

Shall M, N be the dimensions of the measured low resolution images in width and height. These requirements have to be fulfilled by methods of *statistical super-resolution*:

1. ***Enhancement of sampling:*** *Super-resolution shall provide a high-resolution image representing a larger number of pixels with any multiple K=[2,3,4,...[of the original pixel amount of the low-resolution input images in both dimensions M, N.*
2. ***Enhancement of angular (spatial) image resolution:*** *Super-resolution shall incorporate certain image sharpening (like deconvolution) which reflects the gain in the number of pixels.*
3. ***Fidelity of photometry:*** *Intensities detected shall be preserved with the proposed method of super-resolution.*

These requirements reflect the situation of having said „information found and confirmed between pixels at improved point spread and intensities preserved“. Any result obtained with a (small) telescope and reaching super-resolution performance, therefore, shall present better sampled image with point spread of better angular resolution, and compared to original seeing conditions found with the observations. If this is found and structures can be confirmed with independent observations of any telescope with better seeing performance or compared to observations with a space telescope not suffering from atmospheric image degradation, super-resolution is assumed to be successfully demonstrated. A method presenting a larger amount of pixel, smoother images, but not showing reduced point spread (better angular resolution) shall not be taken as a super-resolution method. Breaking the diffraction limit of optics could be a secondary outcome, but is not necessarily a requirement. Thus, super-resolution beyond the diffraction limit is a special case of the problem. The effort to break the Rayleigh criterion might be worth to be evaluated. Fidelity of intensities detected shall be preserved with the super-resolution method chosen. The method is expected not only to demonstrate a better spatial resolution, but also shall allow photometric evaluation of the source.

5. A NOVEL METHOD OF IMAGE REGISTRATION

5.1 Development of the idea

Statistical super-resolution is the process of combining a sequence of low-resolution images in order to obtain a high resolution image. The task of statistical super-resolution imaging can be divided into a two stage process consisting of (1) the image registration of a set of low resolution images to be put into a larger pixel grid and (2) sharpening of the resulting oversampled image. This work shall consider the first step to establish a robust task of motion estimate for the image registration. *Cristóbal, et al. (2008)* presented a review of super-resolution methods. From the work of *Zitová & Flusser (2003)* and *Borman (2004)* the task of motion estimation is found crucial to the success of super-resolution methods. *Robinson & Milanfar (2004)* discussed fundamental performance limits to the image registration based on considerations of the several features found in images, like gradients or edges. Such features more likely will resemble conventional artwork and photography. With typical images demonstrated in this work, one hardly will find similar features in astronomical imagery. To collect the many images needed to obtain a single super-resolved image, the total exposure time has to be divided into smaller portions to obtain short exposures. In most cases of observation of galaxies and nebulae, short exposures will not yield a reliable image of the object itself. Therefore, a robust anchor to measure image motion cannot be obtained from the observed object itself (see figure 3). Hence, it seems more reasonable to obtain a motion estimate from a stellar reference coordinate system. In other words, parameters like image motion, rotation and distortion shall be obtained from the amount of brighter stars found in the image. A fundamental question will be the determination of the precision and limit of an estimated position of a star. *Guseva (1995)* and *Anderson & King (2000)* reported the possibility to obtain precise position measures with subpixel accuracy. However, systematic errors have been found in the order of a small fraction of a pixel dimension. *Bauer (2009)* presented a review of methods to the fit the point spread of stars and to measure stellar positions. *Bauer (2009)* also proposed a new approach to eliminate the systematic errors introduced by the methods of digital image processing. The new method to determine the position of a star now is understood as a new method to determine a motion estimate with high precision.

5.2 Collection of data

Optimal sampling is derived by considerations on the point spread of a star image. This will depend on the telescope and observation site. Geometric consideration yields the equation tan(ß)=d/f with the angle ß, focal length f and pixel dimension d (f and d measured in the same unit). With atmospheric seeing angle of approximately 3 arcsec and using an image sensor having a pixel dimension of 10 microns, this yields a focal length of about 1.5 m. The requirement is fulfilled using a mid-range amateur telescope of 20 cm aperture, relative aperture f/8. A digital single lens reflex camera or a dedicated CCD are typical detectors (RGB cameras with Bayer pixel pattern yield twice the pixel dimension of the individual color pixels).

From the review it is seen, that certain authors prefer simulated imagery. However, a primary goal is to demonstrate the capabilities and limits of algorithms with real observations. In the year 2007 new astronomical observations have been started by the author of this work. The telescope selected for the observations is a dedicated 20 cm Cassegrain telescope, designed for photographic applications. A respectable amount of images has been collected until today. Some 10.000 images of different celestial objects have been photographed, manually inspected and archived in a digital database containing more than 250 GB of images. The individual image series for the several objects contain between 20 to 300 images of star clusters and nebulae contained in our Milky Way and also images of the very faint and distant galaxies containing unresolved star clusters and nebulae at noise level. A similar amount of calibration data has been collected run to apply the standard image calibration process defined within the astronomy.

5.3 Implementation of the method

The new method of image registration proposed with this work will perform the following tasks: (1) Take a series of (many) low-resolution images of an astronomical object, (2) determine parameters of relative image motion, rotation and image distortion between the images, (3) over-sample the images and (4) co-add the images to a composite image at a larger pixel grid.

The determination of image motion is divided into the following sub-tasks: (1) The standard image calibration is applied to every single input image. (2) A *search of local maxima* is used to detect the stars within the calibrated image. (3) With every star successfully detected, a fit of a synthetic point spread function is performed to obtain a position with sub-pixel accuracy. A correction of the systematics of a relative deviation function (RDF) is applied in this processing step *(Bauer, 2009)*. (4) From a correlation of two consecutive images, the relative image motion, rotation and distortion are determined. The images finally are registered and oversampled with sub-pixel accuracy.

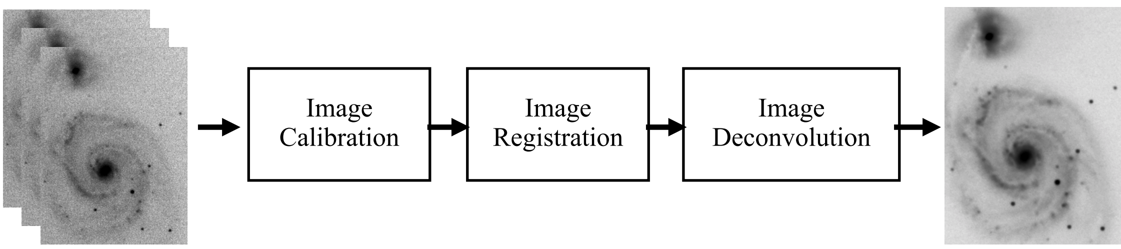

Figure 4: The process chain of statistical super-resolution in astronomy to be completed by future work.

The *search of local maxima* yields a first position estimate of stars detected above a certain noise level. The star detection is done by the computation whether the central pixel of a 3x3 pixel frame represents the maximum intensity of all 9 pixels. If this condition is true, and the maximum intensity found is larger than a multiple of the standard deviation of the sky background (noise), then it is assumed a star is detected at the position (x,y) of the central pixel. The determination of a multiple of the standard deviation yields control about the probability to safely detect a star. From the *fit of the point spread function* a precise sub-pixel position is obtained. The correction of systematic deviations of measures from the true positions is performed by the *relative deviation function* described earlier *(Bauer, 2009)*. There are several models of point spread discussed within the astronomy and also asymmetric point spread found from the real observations. Within this work, a simple Gaussian function is fitted to the observed point spread to obtain a sub-pixel position of the intensity distribution. Parameters, like full-width at half maximum of the Gaussian, are estimated from the point spread (seeing) found in the image. It shall be mentioned, however, that a wrong estimation of the parameters of the Gaussian function will have an impact to the position accuracy. However, the examination of the systematic deviations are not in the focus of this work and shall be evaluated with future work. It is sufficient for the moment to have found a very stable method of image registration with an accuracy below 1/10 of a pixel dimension.

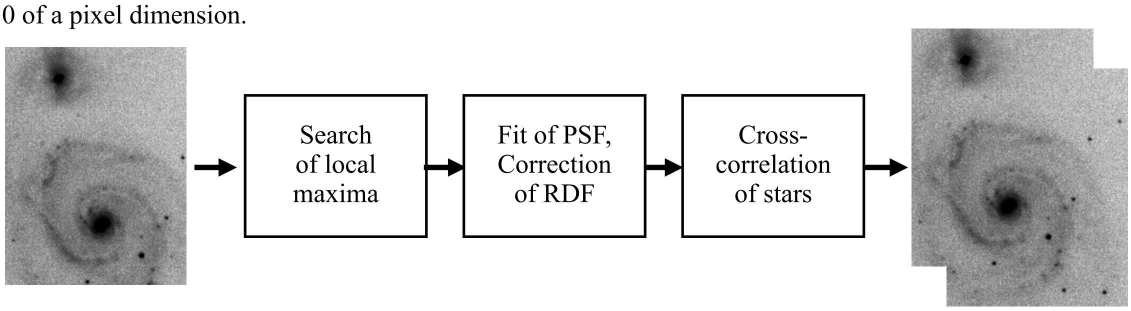

Figure 5: The image registration task proposed by this work. The fit of stellar positions include a correction of systematic errors from the relative deviation function.

5.4 First results

The author implemented and applied the proposed method to the image sequences collected. Certain sequences or parts of large sequences have been inspected, and images rejected due to impacts of observation errors, like technical problems with the telescope mount, accidentally defocused images or other mistakes, like the authors cat climbing the telescope. As a secondary outcome, the method enabled the complete image gallery of the authors website over years *(Bauer, 2011)*. Therefore it is demonstrated, the method works with every material collected so far. This is a great success and the stability of the approach is demonstrated well as the first fully automatic method of image registration in astronomy with high position accuracy.

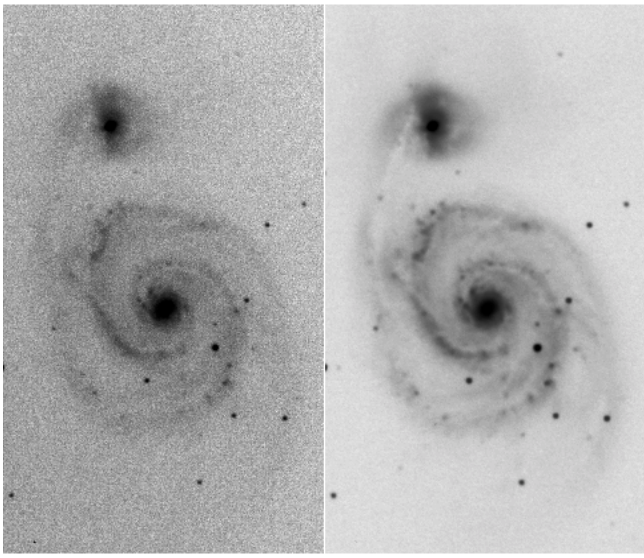

Figure 3: A single raw image of 4 minutes exposure time of the galaxy M51 (left image) is compared to the result of the image registration of 24 input images (right image). The proposed algorithm to determine image motion with sub-pixel accuracy has been applied to the image registration. The image registration is automatic and stable with imagery of such a low illumination and does not show image displacement.

As noted earlier, point spread of a star will vary over the field of view. A real optics also suffers from geometric distortion of the image. This causes an additional impact to super-resolution *(Gilliland and Dupree, 1996)*. Several systematic deviations can be found which affect the process of image registration. This will require a more sophisticated method of correction for image distortion and rotation, if super-resolution requirements shall be fulfilled with a large field of view required at the same time. With a small relative image motion, errors are found very small. The following drawings shall give insights into the accuracy and constraints between location and deviation of stars detected from the observations. The accuracy of the method depends on the brightness of the stars. A first limit can be found at a few 1/100 of the pixel dimension (figure 5). Starting from a certain illumination of a star, the accuracy will not increase towards brighter stars. This limit is caused by the method of fitting a point spread into digital data which introduces systematic deviations *(Author*, 2009)*. It can be improved by a relative deviation function modeled to the data. Position deviations also are found dependent on the location of the star detected. Such errors can be made visible, if the position detection is very accurate and a large amount of images is used for the computations. Figure 6 shows the dependency between position deviations and the distance of the star from the center of the image obtained from the same images of a stellar region. Such constraints are expected due to geometry of optics and usually described in the literature about astrometry (the astronomical task to measure positions).

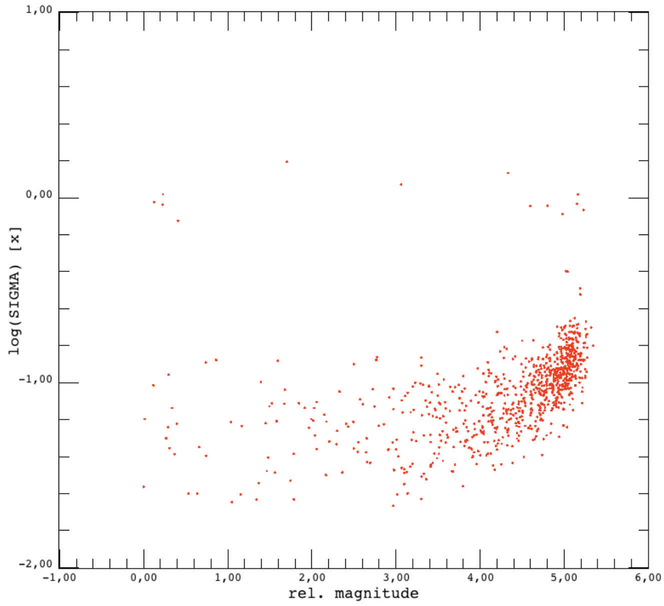

Figure 5: Evaluation of the position accuracy of several star clusters clearly demonstrates the dependency on the signal-to-noise ratio. In this double-logarithmic drawing the evaluation of the position error is shown for 25 images of the star cluster Messier 29. A first lower limit bound is found in the order of 0.07 pixel. With the few brighter stars (logarithm close to zero, left side) the error again tends to increase due to non-linearities. A few points in the center are caused by wrong detection of stars.

Image calibration is needed to avoid non-linearities which may introduce erroneous positions. This influence is seen in figure 5: Bright or saturated star images will yield an increase of the position error. The best accuracy is detected with mean values of star intensities.

A few issues have been found by the experimental use of the large library and shall be mentioned. The method is found to work well especially with imagery of very low intensities detected. This is especially true for the faint galaxies, where the signal-to-noise ratio of intensities of the object is clearly found below the value one, which means no significance to have a signal detected. However there has been a limit found, where the method will produce certain problems with dense star clusters, like globular clusters. This is an impact caused by the noise. Globular clusters are very dense star clusters, with many stars concentrated and partially overlapping in a small portion of the image. Due to noise the faint stars cannot always be detected at the same places. Therefore, some stars disappear, while others are detected at different positions. This may lead to misalignment detected between images, and is caused by the large number of stars found scattered. However, excluding stars with certain small distances from the cross-correlation identification, will avoid such misalignment.

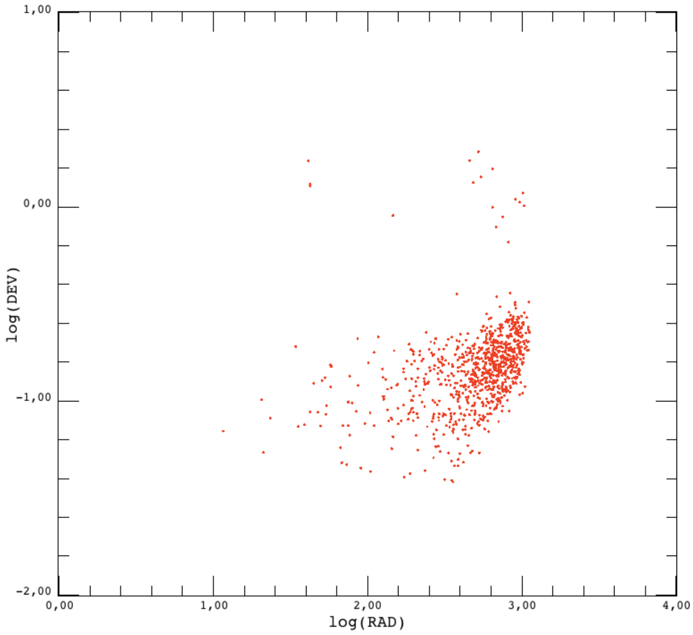

Figure 6: The position deviation (DEV) as a function of the radial distance (RAD) to the image center. A systematic deviation towards the outer image regions shows the dependency on the optical field distortion. This evaluation was taken from the same positions of stars detected from the images shown in figure 5. The images have a total size of 1944x1296 pixel at a field of view of about one degree.

6. CRITICAL EVALUATION

Astronomy defines strong requirements to any super-resolution method. Astronomical imaging suffers from very low intensities measured and a serious impact of noise. The development of a novel and reliable method to the image registration is presented with this paper. The proposed method is a very intuitive and basic approach. On the other hand, and over the last years, it is shown as a very stable method of automatic image registration. The method was enabled by the examination of methods which already have been applied to astronomy, but (originally) meant for a completely different use. Not any method of image registration reviewed has been shown to provide a similar performance expressed in units of a fraction of a pixel dimension. This is especially true, if considering the noise found in astronomical images. One requirement shall be fulfilled, however: There must be a certain amount of stars detectable. From the current experience with the method, the author found at least 50 stars with any observation to be taken for a position estimate to image motion. In such regions of the sky, galaxies are observed apart from the disk of the Milky Way. These are portions of the sky where the number of stars used for the image registration drops from at least thousand stars to only a few. With an angular field of view of about one degree, and until the day of writing, the author did not found an area on the sky where the method could not be applied. However, this could mean some restrictions to the usability with a very large telescope providing a smaller field of view. Several issues and limitations have been predicted and confirmed by the data analysis. These are limitations caused by the geometry of optics: optical distortion and varying point spread within a large field of view. A few issues could be solved in the meanwhile, like the problem to detect image motion from crowded star fields. The exercise to complete the process chain of super-resolution shall be a future task. From this review a few methods shall be considered proper to image enhancement. These include the wavelet modified Richardson-Lucy method used by *Bauer et al. (1996)* and several methods reviewed and demonstrated by *Starck et al. (2002)*. However, these algorithms are linear methods of image deconvolution. Taking into account the effects of varying point spread and optical distortion, such methods shall not be assumed to work in any case without further modification. At least one shall expect any method of super-resolution to produce artifacts from residual errors introduced by the optics. Therefore, super-resolution in astronomy, which also requires a large field of view, will be a future task to convert a linear image deconvolution into a reasonable non-linear approach to solve remaining issues like spatially variant point spread. Therefore the image formation process shall be formulated very carefully. Certainly, such an approach is quite different from most linear methods to conventional super-resolution imaging. However, one shall expect similar problems to occur with any real optics. Hence, the basic ideas might be transferred to „normal“ applications of super-resolution.

7. CONCLUSION

This work presented a review on super-resolution in astronomy. Requirements are strong and the problems are identified with the low illumination of detectors and the impact of noise. Further issues extracted are spatially variant point spread found with real images and geometric distortion of fields. These issues clearly demand for new approaches to super-resolution compared to the methods described earlier and applied to conventional imagery. Hints are found from the review, that methods of image registration and deconvolution may supplement or supersede the more expensive methods of astronomical imaging including the use of space telescopes. As super-resolution was not found a well-defined term or method, the author presents a precise formulation of the problem. A new method of detection of image motion with high precision was developed based on the requirements. The novel technique is well adapted to typical astronomical image content and was applied to a large amount of real astronomical images. The new method is able to provide measures with a precision in the order of 1/50 of a pixel dimension. It is found as a systematic error which is introduced by the methods of digital imaging. The method shall form the first milestone of an accurate image registration within the statistical process of astronomical super-resolution imaging. The next milestone shall complete the super-resolution process chain. This will be the task of selection and/or development of a proper image deconvolution method to obtain a super-resolved image from an super-sampled high-resolution image. If wide-field imaging and super-resolution shall be requirements at the same time, this will lead to certain non-linear approaches to solve issues like spatially variant point spread and geometric image distortion. Aside from the hints collected to have already broken the optical diffraction limit of resolution, the task to estimate the effort by a simple super-resolution approach still is seen as a challenge. The author suggests the myth to be reality will be demonstrated only, if the obtained resolution clearly demonstrates more than twice the diffraction limited resolution. This must be taken from real observations and confirmed by independent observations in different colors and/or taken by a different, preferably larger telescope. Such a method shall demonstrate a resolution, which is more than six times better than the resolution found with the long-exposure images shown with this work and observed with a telescope of the same aperture.

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