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Reduction of Adaptive Optics Images

J.-P. Véran

National Research Council, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, B.C. V8X 4M6, Canada

D. Durand

National Research Council, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, B.C. V8X 4M6, Canada

Abstract. Adaptive optics (AO) now provides superb, diffraction limited images from ground-based telescopes. AO involves a very complex technology, but, in modern systems such as PUEO at CFHT, this complexity is hidden behind easy, user friendly interfaces, making the AO observations simple and efficient. The data reduction process, however, is quite difficult. The main reason is that the AO correction is always only partial, so that even if the AO point spread function (PSF) has a central core whose width is usually limited by the diffraction of the collecting aperture, a significant fraction of the light remains scattered far away from this central core. The presence of this large halo makes the image difficult to interpret qualitatively and quantitatively, unless proper data processing, i.e. deconvolution, is undertaken to remove it. This problem is made even worse by the fact that the AO PSF significantly varies in time (as the observing conditions, e.g. seeing, change) and in space (anisoplanatism). The goal of this paper is to familiarize the reader with these AO specific data processing problems, to review the work that has been done in this area over the last few years, and to suggest ways to improve the scientific output of AO. The latter involves a careful preparation of the observations, an adequate data reduction toolbox, and the availability of AO specific data, which must be provided by the AO system and archived with each AO image.

1. Introduction

Thanks to adaptive optics (AO), diffraction limited imaging from ground base telescopes has now become a reality. With several AO systems currently in operation on 4-meter class telescopes and other being actively developed and tested for larger observatories, the astronomical community is gaining access to exquisite images with unprecedented angular resolution.

AO can now be considered as a mature technology: as splendidly demonstrated by the PUEO system at the Canada-France-Hawaii Telescope (CFHT), what was once merely an engineering feat has been turned into efficient, easy to use instruments able to give useful scientific data. At the same time though, the

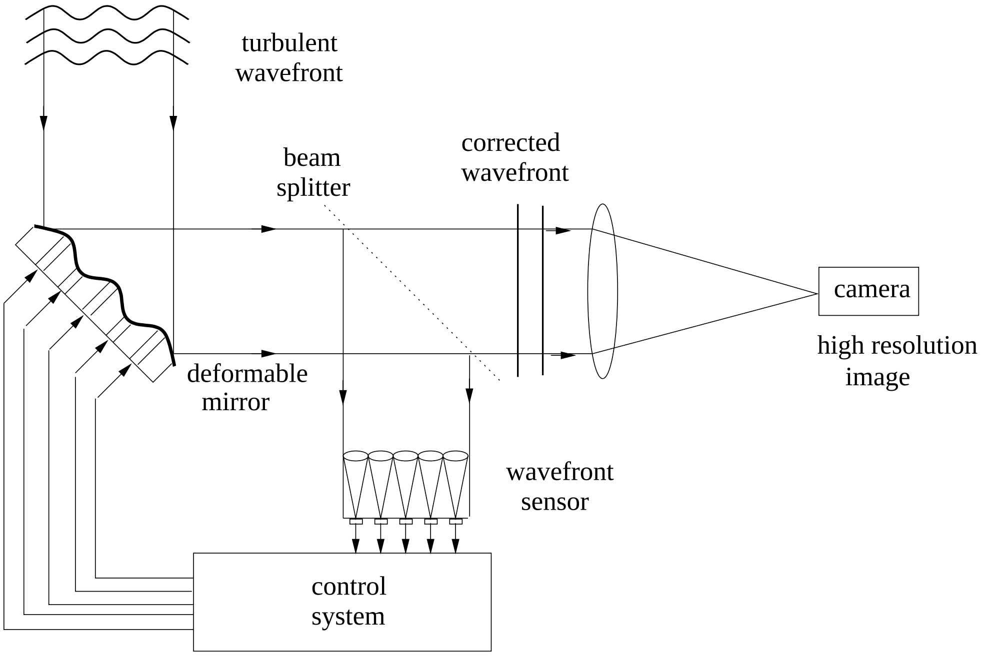

Figure 1. A Simple Schematic View of an AO System

astronomical community is beginning to realize, often with quite a bit of dismay, that actually extracting quantitative scientific measurements (e.g. astrometry and photometry) from AO data is not straightforward at all, and requires to use sophisticated methods and algorithms, most of which are still in the research stage.

AO images are most of the time acquired in the near infrared (J to H band). These images require "cosmetic" data reduction such as bad pixel removal, dark current and sky subtraction and flat fielding. While these operations are critical, they are not at all specific to AO imaging and therefore will not be discussed here. The goal of this paper is to explain the specificities of the AO data that make them difficult to handle after the cosmetic reduction process and to suggest observing strategies and post-processing methods that may improve the accuracy of the final scientific measurements by several order of magnitude.

2. Partial Correction with Adaptive Optics

One of the main problem with adaptive optics is that the images are never fully corrected. To understand that, we look at Figure 1, showing the traditional lay-out of an AO system: the turbulent wave-front is corrected by means of a deformable mirror and the corrected wave-front is directed toward a science camera to produce a high-resolution image. Because the atmospheric turbulence is changing continuously, the shape of the deformable mirror that corrects the wave-fronts must be updated continuously. To this effect, a beam-splitter collects part of the corrected wave-front (either from the object itself or from a nearby guide source) and sends it to a wave-front sensor. The wave-front sensor measures the residual aberrations in the corrected wave-front and a control computer determines the commands to cancel these aberrations and applies them to the deformable mirror. In order to keep up with the turbulence, an update rate of typically 1 kHz is required. There are them several reasons why the correction can not be perfect:

- The deformable mirror has a finite number of degrees of freedom (actuators) and therefore is not able to perfectly reproduce the turbulent wave-front;
- The wave-front sensing entails detecting photons from the guide source in a very short time, typically a millisecond. Except when the system can use a very bright source, the photon noise and detector noise introduce errors in the measurements of the residual wave-front and these errors propagate through the AO loop. Similarly, the spatial sampling of the wave-front is never sufficient and the subsequent aliasing errors further degrade the correction;
- The latency due to the integration / read-out of the wave-front sensor and to the computing time of the control computer introduce a time delay in the AO loop. Any evolution with a time scale smaller than this delay will remain uncorrected;
- Finally, differential aberrations after the beam-splitter, between the imaging path and the wave-front sensing path will show-up in the final image unless they are properly calibrated.

In addition, off-axis acquisitions, i.e. when the AO guide source is not the science object itself, are affected by anisoplanatism errors due to the distribution of the turbulence at different altitudes. These errors start to significantly impact the quality of the image when the angular distance between the science source and the guide source is larger than the so-called isoplanatic patch, typically 20-30 arcsec.

Thus, the AO correction is always partial. For most cases, this still allows the image to achieve the maximal resolution of the telescope, that is the image of a point source has a narrow central core with a width given by the diffraction limit of the primary mirror. However, because the correction is partial, this central core contains only a fraction of the total energy. The rest of the energy is scattered in an halo that extends far away from the central core. The ratio of the energy contained in the core to the total energy in the image is roughly what is referred to as the Strehl ratio of the image: a Strehl ratio of 1 therefore corresponds to a full correction. This effect is demonstrated in Figure 2, where a fully corrected, AO partially corrected and uncorrected images are plotted. The first plot shows a cut of the three images scaled to the same energy. Note that the scaling factor is chosen so that the vertical axis gives the Strehl ratio, with the fully corrected image having a unity Strehl ratio. In this plot, we can see that the AO corrected image has about the same full-width at half maximum than the diffraction pattern. However, the central core does not contain as much energy. The second plot of Figure 2 shows the encircled energy of the three images, that is the fraction of energy as a function of the distance from the center of the image. We can see that close to the center of the image, the concentration of energy in the partially corrected image is about as good as in the fully corrected image.

However, far from the center, in the wings of the image, the correction seems to be no longer effective and the energy concentration in the partially corrected image and in the uncorrected image is similar. The presence of this strong halo reduces the contrast and smears the fine details of the image. This is clearly shown in the third plot of Figure 2 that gives the modulation transfer function (MTF) of the three images. We can see that, contrary to the non-corrected image, the spatial content of the partially corrected image is preserved up to the cut-off frequency of the telescope. However, the amplitude of the MTF is reduced, compared to the MTF of the fully corrected image.

In the above, we have found that partially corrected images have strong halo-like wings that extend many FWHM units from the center of the image. Therefore, objects that are resolved by the AO system contaminate each other through their halo. This effect prevents us from detecting faint structures and from extracting any quantitative information such as photometry from the raw AO images. One of the most important step in the reduction of AO data is therefore to reconcentrate the energy from the halo back to the central core. This process is in fact deconvolution, but we note that in the case of AO, the resolution is already granted by the system. So it is important to insist that we do not seek to improve the angular resolution of the images, we just want to get rid of the halos. The successful completion of this task leads to an increased contrast and therefore a better detection of the faint structure in the image. Most importantly, it allows astronomers to perform accurate quantitative measurements on the image, such as photometry and astrometry.

If we neglect the spatial variation of the correction due to anisoplanatism, all the information we need to remove the halo is contained in the image of a point source or point spread function (PSF). In an AO image, it is very rare that there is a point source isolated enough so that the PSF can be obtained from its image. Then, the AO PSF is very difficult to estimate: it has a very complex structure (no analytical model) that changes with time as the observing conditions (turbulence strength and speed) evolve. One possibility is to give up on PSF estimation altogether and use blind deconvolution schemes (Kundur et al. 1996) to extract both the underlying object and the PSF only from the image. However, such methods are usually artifact-prone and plagued with numerical instabilities. In astronomy, they can be applied only to very simple objects and/or require a very high signal-to-noise ratio.

3. AO PSF Determination

There are different ways to estimate the PSF related to any AO image. It is important to understand these methods because of their implication in the observing strategy at the telescope.

3.1. Empirical Method

The default all-around method is to empirically obtain the PSF from the image of a point source (star), taken before and/or after the science acquisition. This PSF calibration operation must be planned in advance by carefully selecting a calibration star that is close to the object (at least same air-mass) and of same color and magnitude, so that the AO correction is the same for the object and

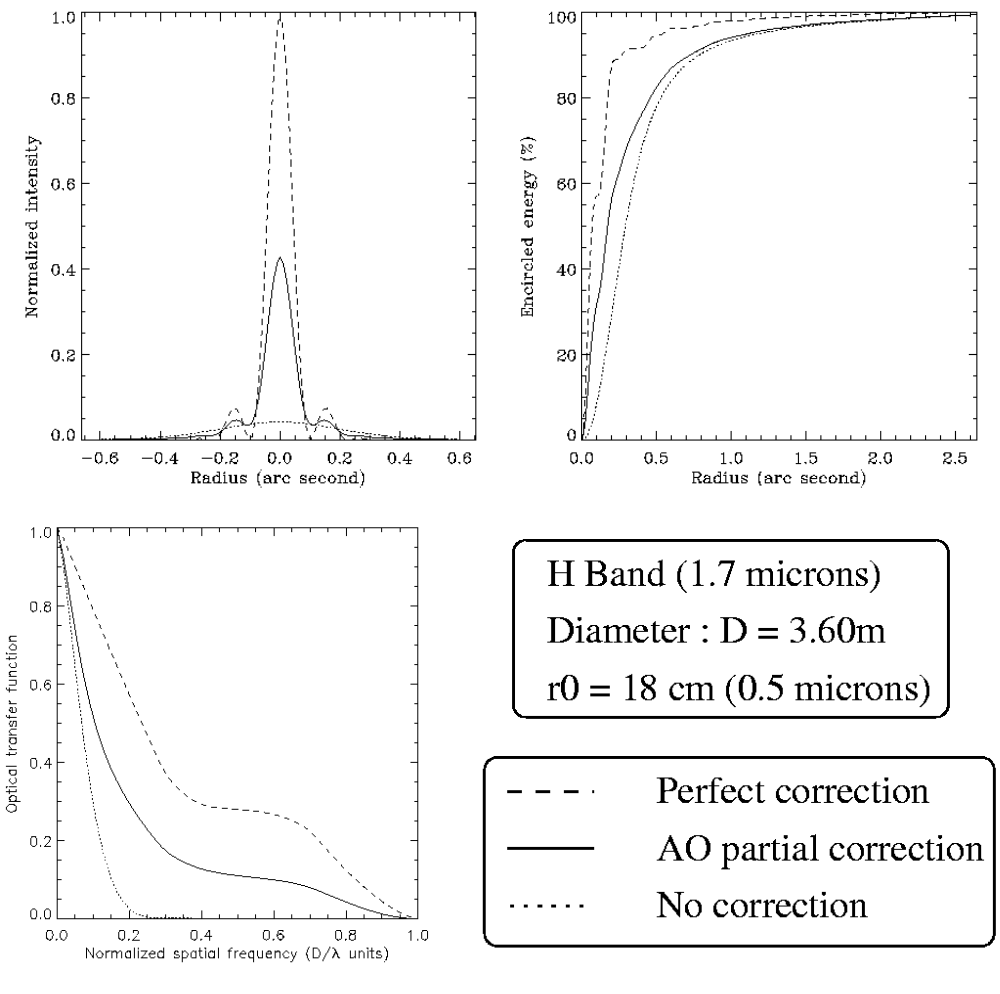

Figure 2. Comparison between an uncorrected image, an AO corrected image and a diffraction limited image. Top left: image cut; Top right: encircled energy plot; Lower left: modulation transfer function.

the calibration source. Observing with AO very often leads to surprises, such as well-known guide stars turning out to be close binaries or even more complex systems, making them unsuitable to PSF calibration. It is therefore a very good idea to select at least two calibration stars for each observation. One way to find such calibration stars is to use on-line catalogs, such as the GSC or USNO catalogs. Several interfaces to these catalogs exist, but the one provided by the Canadian Astronomy Data Centre is very efficient and user friendly.

This empirical PSF determination method has several obvious drawbacks though. The first one is the waste of observing time, with a multi-million, very high resolution system, spending a significant portion of time observing an unresolved source. The second drawback is that since the turbulence evolves in time, one is never quite sure that the calibrated PSF will be accurate for the science acquisition. The only way around this problem is to calibrate the PSF very frequently, which leads to even more loss in observing time. The observer has also to contend with the technical difficulty to make sure that the correction provided by the AO system is the same for the science object and for the PSF star, that is make sure that the WFS noise is the same, etc.

3.2. Automatic Method

On CFHT, a much more efficient PSF determination method has been implemented (Véran et al. 1997a). It is an automatic method whereby the AO system determines its own PSF by itself, using the real time data processed by the AO loop such as the wave-front sensors measurements. This method runs in the AO real time computer, in parallel with actual AO correction process. The advantage is that the PSF reconstruction does not required any extra observing time and that it uses data exactly synchronous to the acquisition. After each acquisition, an extra file is produced, containing all the informations required the reconstruct the PSF for this acquisition. The actual PSF reconstruction is performed by the observer during the data reduction stage. The reason why the PSF is not fully reconstructed on the fly by the AO system is that the reconstruction still requires at least one image of a point source, mostly to calibrate the non-common path aberrations. There are, however, little constraints on when and how this point source should be acquired. For instance, photometric calibration stars are a good choice. More information on this can be found in reference Véran et al. (1997b).

This automatic PSF reconstruction method has been shown to give very accurate PSF provided the guide source is magnitude 13.5 or brighter. Unfortunately, it is so far only available on PUEO and while adapting it to any other curvature system should be easy, this is not the case for Shack-Hartmann systems because of intrinsic specificities. Work on this problem is on-going in various AO teams.

This type of automatic PSF reconstruction method really seems to be the way most AO system will operate in the future, that is when the difficulties with the Shack-Hartmann systems will be solved. It is then critical that any AO system be designed so that PSF files can be computed, saved and archived routinely, in synchronization with each science acquisition.

Finally, one should also be aware of the two fundamental limitations of this type of method:

1. The PSF estimation is based on a statistical analysis of the AO data. What is computed is therefore the long (infinite) exposure PSF. Even if the estimation is perfect, this estimated PSF differs from the actual PSF by the speckle noise. Speckle noise decreases as the exposure time increases. For the estimated PSF to be useful, the exposure time should be typically at least a few seconds;
2. The PSF estimation is based on wave-front sensing data and is therefore accurate in the direction of the AO guide source. Away from the guide source, anisoplanatic effects will degrade the correction, and this degradation will not be taken into account in the estimated PSF.

4. Deconvolution of the AO Images

4.1. Generalities

With a well calibrated / estimated PSF, one can try to deconvolve the AO images. Again, this means trying to re-concentrate the flux in the halos surrounding each point source back into the core associated to the source. It is a well known fact that deconvolution is an ill-posed problem and therefore prone to yield artifacts. There are two main forms of artifacts: noise amplification and ringing. Because the images are always recorded with an imperfect detector in a finite exposure time, low signal regions are contaminated by noise, usually a combination of detector and photon noise. The essence of deconvolution is to attempt to find an underlying object "consistent" with the data, that is the object convolved by the PSF should be "consistent" with the data. "Consistent" is of course the operative word. If no special care is taken the deconvolution algorithm may try to fit the noise. Because the PSF is essentially a low pass filter, small noisy bumps can only be fitted if large spikes are introduced in the estimated object. This is how noise amplification occurs. The second type of artifact, ringing, is not related to noise and can appear even in noiseless data. Contrary to noise amplification which affects the deconvolved image more or less uniformly, ringing appears in the vicinity of sharp discontinuities in the object, such as point sources or edge of planetary disks. Ringing manifests itself as a set of rings, whose intensity decreases as one moves away from the discontinuity.

Ringing and noise amplification artifacts are illustrated by figure 3, where the image of a point source (typical AO PSF) is deconvolved by itself using a simple inverse filter. The important thing here is to look at the vertical axis. Indeed, the deconvolution process results in a much higher flux concentration in the central core. But artifacts are evident: amplified noise + ringing in the noisy case (left) and ringing only in the noiseless case (right). In both cases obviously, an extended emission around the star would be destroyed by the artifacts.

4.2. General-Purpose Deconvolution Methods

There exists a range of general purpose deconvolution methods, available within traditional astronomical processing softwares such as IRAF, MIDAS and IDL. These methods apply to any kind of image, requires no or few parameters setting and are therefore very easy to use. They come in different names and flavors: the linear method of choice is the Wiener filter (Andrew et al. 1977) and is

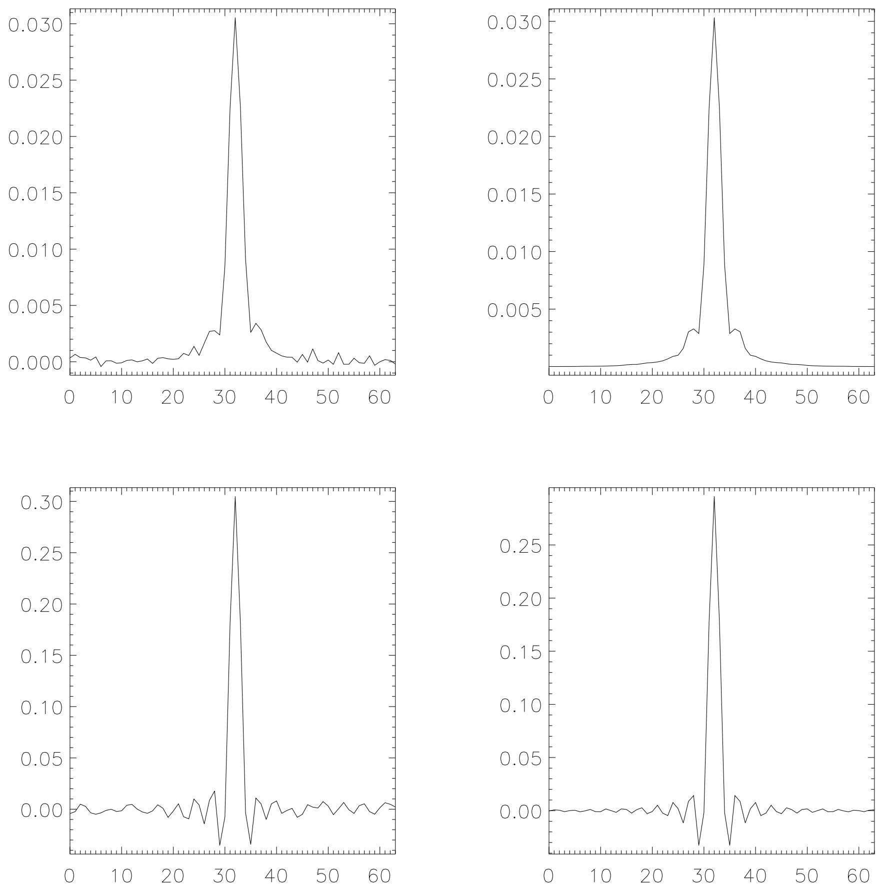

Figure 3. Illustration of the classical deconvolution artifacts. Top left: PSF + noise; bottom left: PSF + noise deconvolved by PSF; top right: PSF; bottom right: PSF deconvolved by PSF.

well behaved in the sense that it is not iterative and therefore there is no ambiguity in stopping the algorithm. Non-linear methods such as Lucy Richardson (Richardson 1972, Lucy 1974) and Maximum Entropy (Narayan & Nityananda 1986) are non-linear so they can enforce the positivity of the estimated object, which is of great help to reduce the artifacts if the background is indeed zero, that is there is no extended emission. On the other hand, these algorithms are iterative and usually an ad-hoc criterion must be use to decide when to stop the iterations.

While these general purpose methods are useful for a first look at the images, they can usually be outperformed by methods where some strong constraints on the object can be introduced. We explore those below.

4.3. Object-Specific Deconvolution Methods

Planets and planetary objects These objects are usually extended bright object and can be recorded with a very high SNR. For these objects, noise amplification is not a worry, but ringing is, because the edge of the object is a very sharp discontinuity in the image. Virtually all the general purpose methods cited below would result in ringing effects on the surface of the planet, preventing any attempt of photometric measurements for instance. Recently, a specific method where such large discontinuities are explicitly expected has been proposed and has already been used with success.

Stellar fields Whether they are dense globular clusters or simple binary stars, stellar fields have in common that we know a priori that they are a collection of unresolved point sources with no extended emission, except maybe some constant background. Then restoring the object as a pixel map is a poor approach to the problem. Much better is to consider that the object is a set of Dirac impulses whose positions (astrometry) and amplitudes (photometry) are unknown. Well known methods to deal with this problem include CLEAN and DAOPHOT. In some cases, these can be outperformed by newer methods, such as AOPHOT (Véran et al. 1998) or the method from reference Currie et al. (2000), which are more specifically adapted to AO imaging.

Point sources super-imposed on an extended emission These are the most difficult objects to deconvolve but they are also the most common. The point sources are liable to introduce ringing whereas the extended emission usually has low SNR and is very sensitive to noise amplification. Specific methods to deal with this type of objects include Lucy et al. (1994 - PLUCY method), Magain et al. (1998) and Hook et al. (2000 - CPLUCY method). An other potentially powerful method but with which we do not have any first hand experience is the so-called “Pixons” method (Pina & Puetter 1993, Puetter & Yahil 1998).

4.4. Myopic Deconvolution Methods

It may happen sometimes that the PSF can not be estimated with enough accuracy. This is the case for example if the AO guide source is too faint or if the acquisition is off-axis. In that case, one might try to refine the PSF estimation during the deconvolution itself. This process is referred to “myopic deconvolution”, because the initial estimate of the PSF is still reasonable, as opposed to blind deconvolution, where no assumption on the PSF is made. Recent work on blind deconvolution methods for AO includes Christou et al. (1998) and Fusco et al. (1999).

4.5. Wide Anisoplanatic Fields

When the observed field is larger than the isoplanatic patch, the PSF significantly varies across and the deconvolution becomes very tricky. This problem has only received little attention so far, probably because the modest size of the current infrared detectors does not allow them to cover a very large field, as the pixel size must be small enough to sample adequately the AO corrected PSF. However, as the detectors get bigger and the AO correction is achieved at lower wavelength (the isoplanatic patch decreases with the wavelength), this problem will become more critical. To our knowledge, the only method that specifically addresses this problem is the DAOPHOT algorithm for stellar fields, which take into account a possible spread of the PSF in the field.

5. Conclusion

In this paper, we hope we have been able to convey that post-processing of the data acquired with adaptive optics is absolutely crucial to extract useful scientific informations from them. One of the main difficulty is to obtain an accurate estimate of the AO PSF. This requires a careful design of the AO system itself and of the data handling system that supports it, as well as a careful preparation and execution of the AO observations. With good quality data and PSFs, accurate deconvolutions can be performed, but one should watch carefully for artifacts such as noise amplification and ringing. To avoid those, it is recommended to use, whenever possible, an object specific deconvolution method, where strong a priori informations on the underlying object are included, as opposed to general purpose methods.

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