# Chapter 9

# Speckles and adaptive optics

A better understanding of the atmospheric seeing and the properties of speckles is important for finding techniques to reduce the disturbing effects or to correct for the seeing with adaptive optics. The main advantages of a reduced or corrected atmospheric seeing are:

- much improved angular resolution for ground-based observations,
- much higher detection sensitivity for point sources, because the signal is enhanced with respect to the background noise.

## 9.1 Atmospheric turbulence and seeing

Atmospheric turbulence produces cells of different size scales ranging from about 0.01 m to 100 m. The cells have a distribution of temperatures and therefore also of densities with corresponding differences in the refractive indices. The irregular refraction produces for astronomical sources tilted wavefronts and light rays which deviate from a strictly straight line. These phenomena are summarized under the term "astronomical seeing".

*The seeing* has the following effects:

- the images of point sources are split up into speckles,
- the number of speckles $N$ increases for more turbulent atmospheres (smaller cell scale $r_0$) and larger telescope diameter $D$ like $N \propto D^2/r_0^2$,
- the angular size of the speckles is determined roughly by the diffraction limit of the telescope ($\sim \lambda/D$),
- the speckle pattern changes rapidly with time $\tau_0$ (within ms),
- in long exposures the changing speckle pattern results in a blurred image and the angular diameter of a point source is $\approx \lambda/r_0$. The blurred point source image is called the *seeing disk*,
- the source brightness shows scintillation.

A list of characteristic parameters of the atmosphere:

| parameter | definition | dependencies | typical values |
|---|---|---|---|
| **Fried parameter** $r_0$ | diameter of an atmospheric cell producing a phase error of 1 rad | $\propto \lambda^{6/5}$<br>$\propto \mathrm{am}^{-3/5}$ | $r_0 \approx 0.2$ m (R-band) |
| **coherence time** $\tau_0$ | time interval for phase variation of 1 rad | $\propto \lambda^{6/5}$<br>$\propto \mathrm{am}^{3/5}$<br>$\approx r_0/v_{\mathrm{Wind}}$ | $\tau_0 = 1 - 7$ ms (R-band)<br>$\tau_0 = 4 - 20$ ms (near-IR) |
| **isoplanatic angle** $\Theta_0$ | angular distance with phase error less than 1 rad | $\propto 0.3 r_0/(h \cdot \mathrm{am})$ | few arcsec for R-band, few tens arcsec in near-IR |
| **seeing** $\mathrm{FWHM}_s$ | width of the PSF of a point source | $\approx \lambda/r_0$<br>$\propto \lambda^{-1/5}$ | $\lambda = 1\ \mu$m, $r_0 = 0.3$ m, $\mathrm{FWHM}_s = 0.69''$ |
| **diffraction limit** | width of the diffraction limited PSF | $\approx \lambda/D$ | $\lambda = 1\ \mu$m, $D = 8$ m, FWHM $= 0.026''$ |

am: airmass, h: height of the turbulent layer, $\sigma^2$: variance of the phase aberrations.

## 9.2 Speckle imaging

For bright targets one can take very short integrations for which the speckle pattern is essentially frozen. Speckles have a typical lifetime of about $3 - 20$ ms and frames with comparable or shorter exposure times will show a strong speckle pattern.

It will not always be possible to take short integrations because the source is too faint or because the instrument cannot take short integrations. For longer exposures ($0.1 - 1$ sec) the speckle pattern is degraded and looks more like a smoothed seeing disk with some remaining speckle pattern.
The "speckled" frames can be analyzed and processed using various methods in order to get more target information than for seeing limited observations.

**Speckle analysis.** A short exposure speckle image contains many speckles, proportional to the ratio $D^2/r_0^2$. The individual speckles are distorted but the spatial structure of the targets may still be recognized, especially if there are strong structures with an angular dimension between the diffraction limit and the seeing. Based on speckle images one can investigate the speckle structure:

– just small, round, single speckles as expected from an unresolved point source,
– double structure, due to a companion which is unresolved in seeing limited observations,
– extended structure because the source is larger than the diffraction limit.

Speckles overlap in these images because there are many speckles. This problem can be solved by selecting isolated, strong speckles and analyze their structure. Alternatively, one can carry out a Fourier transform of the whole speckle image which provides a computational version of the speckle interference pattern in an optical diffraction experiment. From this Fourier interferogram the distance, orientation, and brightness contrast of a companion can be derived, or the angular diameter and the orientation of the asymmetric shape of extended objects can be determined.

**Shift and add.** Multiple speckle images should be lined up with a shift and add technique. In this way one can get an improved quality when compared to an isolated single speckle observation. For objects which are significantly larger than an individual speckle the shift and add method may reveal large scale structures which are hard to recognize in the individual speckle frames.
Different criteria for the determination of the image shift should be investigated. Often a good method is to line up all frames with the brightest speckle. Another approach is to align the centroid of the speckle pattern.
The shift and add method is a kind of first order, or tip-tilt, aberration correction. The improvement in the data quality is particularly large for speckle images. However the shift and add method is always useful for the combination of multiple images of a target because it corrects at least for alignment, pointing and tracking errors.

**Frame selection or lucky imaging.** In frame selection only the best images, say 50 %, 10 %, 1 % or even a smaller subsample, are used and added up for the final image. Using just the best images is equivalent to an observation taken under "better than average" seeing conditions. Seeing variations are particularly strong for short integrations because the fluctuation are not averaged in time. Therefore the improvement in the data quality with the lucky imaging technique can be particularly significant for very short speckle images.

Frame selection is also a very powerful method for small telescopes, because the smearing depends only on a few "seeing" cells and fluctuations have a large impact. For large telescopes there are hundreds of seeing cells in front of the telescope and the conditions deviate less from "average". This explains why amateur astronomers obtain excellent images of planets with 20 cm telescopes using the lucky imaging technique.

## 9.3 Adaptive Optics

The goal of an Adaptive Optics (AO) system is the correction of the wavefront deformations introduced by the atmosphere and the instrument. AO can provide diffraction limited ground-based observations.

The basic concept of adaptive optics consists of a wavefront sensor (WFS) which measures the wavefront distortions, a fast real-time computer (RTC) which calculates the corrections to be applied by deformable mirrors (DM) to the light beam coming from the telescope. The wavefront analysis and corrections are usually carried out in the pupil planes.

Basic requirements of the AO system are:

- the availability of a light source suitable for a wave-front analysis,
- measurement of the wave-front distortion with a wave front sensor (WFS) with a precision of about 1/20 $\lambda$,
- correction for the wave front distortion with deformable mirrors or other active optical components to a level of about 1/20 $\lambda$,
- good correction for atmospheric seeing requires corrections for the wavefront distortion on a spatial scale of about the Fried parameter $r_0$ with a speed of about the coherence time $\tau_0$.

**Strehl ratio.** The Strehl ratio $S$ is a measure for the performance of an AO system. The Strehl ratio is the peak intensity of the AO corrected point source relative to the peak intensity of a perfect, only diffraction limited PSF. The Strehl ratio can be related to the residual (rms) wave front aberrations $\sigma$ (after the wave front correction):

$$S = \exp^{-2\,(2\pi\sigma)^2} \tag{9.1}$$

where $\sigma$ is in units of the wavelengths of the radiation considered. For a good AO system with $S > 0.67$ the aberrations are at a level of $\sigma < \lambda/14$. To achieve this performance for a $\lambda = 1\ \mu$m means that the residual wavefront aberrations are less than 70 nm rms.

The requirements on the AO system are much more demanding for large telescopes and shorter wavelengths. For the same AO performance or Strehl ratio the number of required sub-apertures increases like $\propto D^2$ and $\propto \lambda^{-6/5}$.

### 9.3.1 Wave front sensor

A wave front sensor measures the tilt of the wave-front for sub-apertures in the pupil plane. A perfectly plane wave would show no angular gradient or tilt over the entire pupil. Most popular devices are the Shack-Hartmann wavefront sensor and the Pyramid wavefront sensor. We discuss here only the Shack-Hartmann sensors in more detail.

In a *Shack-Hartmann wavefront sensor* the pupil is divided into many sub-apertures using a micro-lens array which forms for each sub-aperture a point on a detector. A wavefront with a local tilt (or gradient) induces then an $\Delta x, \Delta y$ shift of the point on the detector which is proportional to the wavefront gradient.

For a good AO correction the Shack-Hartmann wave-front sensor should be able to measure the point offsets $\Delta x, \Delta y$ for each $r_0$-sub-aperture every $\approx 1$ ms. One should note that enough photons must be collected per sub-aperture and exposure to determine the centroids.

### 9.3.2 Deformable mirrors

The wave front correctors must compensate for the measured wavefront deformations to a precision of about $1/10 - 1/20\ \lambda$ for many sub-apertures within about a millisec. Essentially all wave front correctors are based on the deformable mirror concept. Important parameters of deformable mirrors are:

- the actuator spacing which defines the size of the system,
- the dynamic range of the actuators defining the maximum wavefront correction,
- the response time.

Different types of deformable mirrors are:

- deformable mirrors based on Piezo actuators: actuator distance a few mm, dynamic range of a few $\mu$m, and response time of about 100 $\mu$s,
- micro-electro-mechanical systems (MEMS or MEOMS) based on silicon chip technology: actuator distance about 100 $\mu$m, dynamic range small, response time fast,
- adaptive secondary mirror or other telescope mirror using magnetic actuators (like for loud speakers): actuator separation of the order cm, dynamic range 100 $\mu$m, response time a few msec.

All three systems are currently used or tested. All have advantages and disadvantages. Critical issues are: for Piezo actuators the hysteresis effects, for MEMS the small dynamic range, for adaptive secondary mirrors the control of the actuators and the reliability (lifetime) of the large, deformable mirror.

### 9.3.3 AO guide star

The wave-front sensing requires a suitable light source. There are two types of light sources used in astronomical adaptive optics:

- natural guide stars,
- artificial laser guide stars

The requirement is that the guide stars are located at a suitable location in the field of view and provide enough light for the analysis of the wavefront deformations. The wavefront deformations should be probed at a similar or shorter wavelength as the science wavelength range because the atmospheric aberrations are stronger for shorter wavelengths. A wave front analysis at longer wavelengths does not contain enough information for a good correction of the wavefront at shorter wavelength.
An ideal solution provides a dichroic beam splitter which sends all the short wavelength light (e.g. visual) to the wave front sensor and the long wavelength light (e.g. near-IR) to the science camera. This solution can sometimes not be realized because the source does not provide enough light at shorter wavelengths for an accurate wave-front analysis. In this case the light has to be split by a grey beam splitter between science and wave-front-sensor channels.

**Natural guide stars.** Natural guide stars are in principle ideal light sources for the wave front analysis. The problem is that sufficiently bright natural guide stars are usually not available in the field of view. A "single star" AO system provides only a good AO correction for a field of view of a few arcsec (visual) to $\approx 30''$ at $\lambda = 10\ \mu$m and this means that one should have one such star every few arcsec. A few numbers:

– *R-band:* a good AO correction $S \approx 50$ % in the R-band requires a guide star with a brightness of about $V = 10^m$. The well corrected area is only a few arcsec in radius around this star. Therefore, high Strehl AO observations in the visual using natural guide stars is only useful for the investigation of the spatial structure of the guide star itself or its immediate surroundings, e.g. for extra-solar planet science, or the study of circumstellar material.
– *K-band:* a good AO correction in the K-band (2.2 $\mu$m) requires a star brighter than $K = 13^m$ and it provides a field of view of about 1 arcmin in diameter. This allows AO imaging of about 30 % of the sky near the galactic plane, but less than 1 % of the "extragalactic" sky near the galactic poles. Again, natural guide star AO is limited to studies of selected regions in the Milky Way (galactic center) and of the circumstellar material around bright near-IR objects.

It is clear from these examples that natural guide stars provide only a limited range of applications for the AO technique.

**Laser guide stars.** Essentially all artificial guide stars systems used or tested currently are based on sodium lasers. The basic idea of this technique is to excite with the laser a sodium rich layer in the exosphere at about 90 km above ground. The sodium at this height originates from the debris of asteroids and comets. The laser light excites sodium in the resonance transition Na I $D_2$ at 589 nm and the decay emits then an observable emission.
The advantages of laser guide stars are:

– they can be placed at any desired location in the field of view,
– the artificial star has the same parameters for "all" observations (e.g. location in the field of view, brightness, wavelength etc.),
– multiple laser guide stars can be placed in the field of view allowing a better correction for the wave front distortion.

Fundamental problems of laser guide stars are:

– *cone effect:* the laser guide star is located at a finite distance (90 km) and probes the atmosphere only in a cone from that point down to the telescope mirror, while the light from a target goes through a cylinder along the line of sight.
– the atmosphere disturbs not only the light path from the target down through the atmosphere, but also the path of the laser beam going upwards. This introduces a tip-tilt error, which requires that tip-tilt stars are used to track this laser beam "jitter". Fortunately a faint star of 19 mag in the field of view of 1 arcmin can be used as tip-tilt guide star and such natural tip-tilt stars are always available.
– thin cirrus clouds attenuate the upward beam seriously so that the brightness of the artificial star can be affected.

In addition there are many engineering problems related to the laser, which range from issues like achieving enough power (about 20 W are required) to air-traffic safety, which are not discussed here.

### 9.3.4 Multi-conjugated adaptive optics

Simple adaptive optics systems consider the wavefront deformation just like for a 2-dimensional screen. This treatment provides only a good correction for a small field around the wave-front source, the so called isoplanatic patch. Further away from the guide star the AO correction is no longer valid.

This limitation can be removed if the atmosphere is treated in 3-dimensions considering an altitude dependence of the turbulence. If different layers are corrected with different deformable mirrors then the correction is valid for a larger field of view.

We consider two stars, the AO guide star and the target star which are separated by a larger amount (e.g. 3 $\times$) than the isoplanatic angle. The aberrations introduced by the ground layer turbulence are still valid for both stars because the rays pass essentially through the same air cells. However, the aberrations introduced by a high-altitude layer are completely different for the target star when compared to the AO guide star. For this reason one needs to sense the wave front for several guide stars well distributed over the field of view in order to disentangle the "ground layer" and the high altitude layers. In this way one can correct for the wave-front errors for a larger field of view.

More than one wave-front sensor and more than one deformable mirror are required for a "wide-field" AO correction. The individual deformable mirrors then correct the aberrations introduced by a specific layer/region in the atmosphere. The mirrors are conjugated with respect to this layer, meaning that they are located in the beam at the location where the corresponding layer is imaged (focussed) accurately. A typical system has one deformable mirror for the ground layer and one deformable mirror for the high altitude layer at about 10 km. Of course the analysis of the wave-front aberrations is complicated significantly because the effects of the two layers have to be distinguished.

Artificial laser guide stars are the ideal light sources for the wave front sensing in multi-conjugated AO systems because they can always be placed at the same position in the field of view. This simplifies the difficult task of the wavefront sensing significantly because the same guide star parameters can be used for all measurements.

## 9.4 Examples for AO systems

### 9.4.1 SPHERE planet finder

**Project overview.** SPHERE is the abbreviation for the Spectro-Polarimetric High contrast REsearch project. The goal of the SPHERE instrument, which is currently built for the VLT, is the discovery and study of extra-solar planets orbiting nearby stars by direct imaging of their circumstellar environment. The scientific requirements are very demanding because planet detection will only be possible if the instrument achieves:

- a very large contrast between host star and planet, larger than $12.5^m$ or more than $10^5$ in flux ratio,
- the high contrast must be achieved at a very small angular separation of $0.1'' - 0.5''$, inside the seeing halo.

SPHERE has different focal plane instruments for the detection of young and evolved planetary systems. Young planets are still contracting and therefore "hot" ($\approx 1000$ K) and they emit a lot of thermal radiation in the IR which will be measured with differential imaging and integral field spectroscopy in the near-IR. Evolved planets are "cold" and their main emission is reflected stellar light which will be investigated with a differential polarimeter (ZIMPOL = Zurich Imaging Polarimeter) in the visible.

The main components of the SPHERE experiment are:

- an 8.2 m VLT telescope providing a diffraction limited resolution of 20 mas at 0.8 $\mu$m and 40 mas at 1.6 $\mu$m
- an extreme AO system providing a high Strehl ratio
- two coronagraphic systems which block the light from the bright host star. One coronagraph is installed in the near-IR science arm, the other in the visible science arm.
- three differential imagers: IRDIS, the infrared dual imaging spectrograph; IFS a near-IR integral field unit; and ZIMPOL, a high precision imaging polarimeter.

**The SPHERE AO system.** The SPHERE AO system is a so called extreme AO system for high Strehl ratio ($S = 0.85$ in H-band). A bright star, brighter than $R = 10^m$, is required for the AO guide star, in order to provide enough light for the very accurate wave front sensing. The search for planets around bright stars is ideal for extreme adaptive optics because the target star serves at the same time as AO guide star. Key requirements for the AO system are:

- Strehl ratio of $S \approx 0.5$ in the visible (600 nm) and $S \approx 0.85$ in the H-band.
- a good suppression of diffraction and halo stray light out to a radius of about $0.3''$ in the R-band and $0.5''$ in the H-band.

Technical properties of the individual AO components:

- fast, 1.2 kHz, tip-tilt mirror for the correction of the overall gradients in the wavefronts,
- fast, 1.2 kHz, deformable mirror with $41 \times 41$ actuator for the correction of the small scale wave front aberrations,
- a slow, 0.1 Hz movable pupil tilt mirror which corrects for slow pupil shifts due to the tracking by the telescope,
- a 10 Hz tip-tilt plate which corrects for the differential effects like atmospheric dispersion between the visible path of the WFS and the infrared science path,
- a $40 \times 40$ lenslet Shack-Hartmann wavefront sensor covering the wavelength range from 0.45 to 0.96 $\mu$m using a $240 \times 240$ pixel electron multiplying CCD which achieves a temporal sampling of $> 1.2$ kHz with a read-out noise smaller than 1 $e^-$,
- a differential tip-tilt camera which measures offsets of the IR-beam with respect to the visible beam.

Despite the very good AO correction the "typical" planet signal will still be fainter than the variable Speckle halo from the central star. For this reason differential measuring methods are required to compensate for the "Speckle noise". Most dangerous are systematic instrumental Speckles which drift in a uncontrolled way. For this reason the SPHERE system is optimized for stability and it will be located on the Nasmyth platform.

### 9.4.2 MUSE

**Project overview.** The Multi Unit Spectroscopic Explorer (MUSE) is a future VLT instrument for the investigation of faint sources with an AO assisted integral field spectrograph. In a single observations MUSE will produce a data cube consisting of

– 90'000 spectra,
– each spectrum covers the spectral range 480 nm – 930 nm,
– with a resolving power of $R = 3000$,
– sampling fully a field of view of $1 \times 1$ arcmin$^2$ with $0.2 \times 0.2$ arcsec$^2$ apertures in the wide field mode,
– or sampling fully a field of view of $7.5 \times 7.5$ arcsec$^2$ with $25 \times 25$ mas$^2$ apertures in the high resolution mode.

The spectral resolution is high enough to observe between the strong OH sky emission lines in the red / near-IR spectral region. The AO system shall provide a seeing correction which improves the PSF for the wide field mode to enhance the encircled energy per spatial resolution element. For the high resolution mode the AO system provides a moderate Strehl ratio of $S \approx 0.1 - 0.3$. Some key science goals of MUSE are:

– study of intrinsically faint galaxies at high redshift,
– study the physics of Lyman break galaxies,
– detection of Ly$\alpha$ emission out to the epoch of re-ionization,
– spatially resolved spectroscopy of luminous distant galaxies including lensed objects.

**The MUSE AO system.** The MUSE AO system provides a seeing enhanced correction for the MUSE wide field mode and a moderate Strehl $S = 0.1 - 0.3$ AO correction for the MUSE high resolution mode. The AO system is based on:

– a deformable secondary mirror with about 1170 actuators for the VLT telescope,
– a closed loop operation with a speed of up to 500 Hz,
– the VLT laser guide star facility based on four artificial sodium laser guide stars,
– a system to use one natural guide star to correct for the jitter of the laser guide stars.

*Wide field mode:* The four laser guide stars will be placed about 1 arcmin from the center of the field of view. Thus there will be one guide star at each side of the square $1 \times 1$ arcmin$^2$ field of view. The natural guide star should have an R-band magnitude of $R = 18^m$ and should be located outside the field of view but inside a circle $r = 2$ arcmin from the center of the field of view. This should allow to cover even at high galactic latitudes (extra-galactic fields) at least half of the sky. The seeing correction for the wide field mode should provide a PSF FWHM of $0.3''$ over the whole field of view.

*High resolution mode:* In the high resolution mode the natural guide star is in the middle of the $7.5'' \times 7.5''$ field of view. The laser guide stars are placed $5''$ from the center, again just outside the square field of view. In the high resolution mode the MUSE AO system should provide an AO performance with a Strehl of $S = 0.1 - 0.3$.