

OPTICAL TURBULENCE IN HIGH ANGULAR RESOLUTION TECHNIQUES IN ASTRONOMY

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All astronomical observations are done best from space where the absorption by and turbulence in the Earth atmosphere are absent. One has access to the entire electromagnetic radiation spectrum and the absence of seeing allows unlimited angular resolution. However, the cost of facilities in space and their operation is 3 orders of magnitude of similar sized facilities on Earth. Experimental astrophysicists have therefore in the past decades pursued the development of techniques to overcome the seeing limitations by the atmosphere. So far they have been very successful at this and much more is almost certain to come. Adaptive Optics (AO) will make very large (8 - 10-meters diameter) and extremely large (30 – 42 meters diameter) telescopes diffraction limited first at infrared wavelengths and eventually at visible wavelengths. The development of fast optical turbulence/seeing wavefront sensing techniques using artificial sources (Laser Beacons) will enable doing that over the entire sky. Atmospheric Tomography (AT) needed for Multi-Conjugate Adaptive Optics (MCAO) will give 3D maps of the rapidly variable atmospheric turbulence. Large interferometers with baselines of hundreds of meters will further enhance the angular resolution using fringe tracking for both co-phasing and coherent operation. Ground-based astronomy is therefore entering a new era in which milli-arcsecond observations and better are foreseen even of objects at the edge of the universe. The astronomical techniques will result in information of atmospheric optical turbulence which is likely to be of interest for meteorologists.

1. Introduction

When I presented in 1964 my Doctor's thesis on the structures in the solar chromosphere to the Utrecht University it included among others the following the following sub-thesis (translated from Dutch):

“The study of temperature fluctuations on a small scale (~ 5 cm) in the Earth's atmosphere is of great importance for astronomical observations. More interest by the Meteorologists for such research would be most desirable.”

It is now 44 years later, and here we are having a conference between astronomers and meteorologists which is responsive exactly to this statement. Much has happened in those years in astronomy.

The detrimental effects of the atmosphere on optical astronomical observations fall in seven categories:

1. *Clouds* which obstructs any observations at optical wavelengths.
2. *Atmospheric Absorption* which limits the spectral region that can be observed from the ground to visible wavelengths (0.3 – 1.0 μm), a number of “windows” in the infrared region of the spectrum (1.0 – 24 μm), some windows in the submillimeter radio spectrum and the radio spectrum up to about 20 m wavelength.
3. *Atmospheric Scattering* due to molecules and aerosols are of special concern for observations of the solar corona and observations at night in so-called “bright time” when the illuminated moon is present.
4. *Atmospheric Emission* in the thermal infrared from aerosols and spectral emissions from atoms and molecules. Also the many spectral emission lines from OH in the near-infrared are a problem.
5. *Atmospheric Pollution* resulting, for example, from cirrus and contrails. This limits astronomical photometry.
6. *Atmospheric Scintillation* resulting from high-altitude optical turbulence limits photometry especially in cases where high time resolution is required.
7. *Atmospheric Seeing* which is the term used to describe the image deterioration resulting from optical turbulence in the atmosphere, the topic of this conference. I will review it in the second section of this paper. Sections 3 and 4 will discuss ways to overcome the seeing effects.

Because of the topic of this meeting my paper will focus on the last item (and to a lesser extent on the sixth item), I will describe the properties of atmospheric seeing and ways that have been devised to correct for its effects either by after image detection techniques (speckle interferometry) or pre-detection techniques by adaptive optics and fringe tracking in interferometry. The paper is directed largely to the meteorological attendees of the audience rather than to the astronomical audience. It is not intended to be a review paper. I will therefore not attempt to list the full literature on the topic.

At this point one might ask why astronomers do not abandon ground-based astronomical observations altogether since all effects mentioned above are absent in observations made from satellite-borne telescopes. Indeed space observatories are of course essential at wavelengths where the radiation is absorbed by the atmosphere like most sub-millimeter and infrared wavelengths and at all UV (< 300 nm), XUV, X-ray, and γ -ray wavelengths. Even at optical wavelengths where the atmosphere is transparent the observations with the 2.4 meter Hubble Space Telescope (HST) with its 0.1 arcsec image quality over a large field-of-view are unsurpassed by larger ground-based telescopes except where the larger light gathering power of current 8 - 10-meter and future 30 – 42-meter telescopes are concerned. The 6.5-meter infrared James Webb Space Telescope (JWST) to be launched in the middle of the next decade will have a thermal telescope/atmosphere emission about a million times less than that of earth-based telescopes, will have access to the full infrared spectrum and will be diffraction limited. Nonetheless ground-based telescopes are put to good use because many science programs do not require the outstanding properties of these space facilities, because their construction and operations costs are less by two to three orders of magnitudes and because the astronomer's demand for telescope time far exceeds the time available on HST and JWST.

The realization of adaptive optics (AO) techniques in the last two decades is now correcting for atmospheric seeing. With it image qualities comparable to that of the HST (and in the future JWST) are already obtained. Further developments will improve image quality even further and extend the field-of-view for diffraction limited imaging for ground based telescopes. The 30 – 42-meter ground-based Extremely Large Telescopes (ELTs) which are to be constructed in the near future include plans to incorporate multi-conjugate adaptive optics (MCAO) to give unequalled sharp images over substantial field-of-views. Initially this will be done for near-infrared wavelengths but ultimately, as technologies improve, they will include visible wavelengths as well. It is in fact this higher angular resolution that provides the main scientific justification for these ELTs. These ground-based telescopes will exceed in angular resolution capability anything that can realistically be realized in space.

2. Refractive Properties of the Turbulent Atmosphere

An excellent reference for a description of the optical properties of the turbulent atmosphere is the paper by Roddier² titled "The Effects of Atmospheric Turbulence in Optical Astronomy". I refer to it for many of the details.

2.1. Average Atmosphere

Figure 1 shows the variation of the refractive index n of the atmospheric gas as a function of optical wavelength and relative humidity for sea level and for a mountain site. For wavelengths above 0.5 microns the variation is quite small and almost independent of the relative humidity. The latter is not the case for radio wavelength where n is very humidity dependent. Some of that humidity dependence is thought to persist at mid-infrared wavelengths ($> 10 \mu\text{m}$).

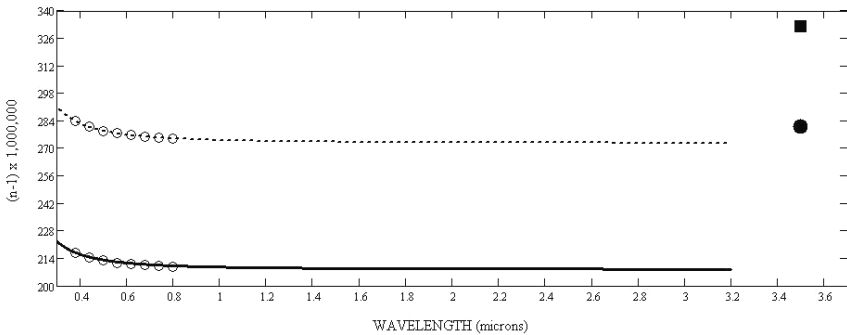


Figure 1 Refractive index variation n for a sea level site (dashed line) and for Cerro Paranal (height 2635 meters) as a function of wavelength. The curves are for zero relative humidity (RH), the open circles for RH = 1. For comparison the refractive index for radio wavelengths (sea level) is also shown in filled symbols (circle for RH = 0, square for RH = 1).

Figure 1 refers to wavelengths where the atmosphere is transparent. In the vicinity of the strong infrared absorption bands anomalous dispersion effects cause significant variations in n as shown in figure 2 taken from Mather¹.

2.2. The Turbulent Atmosphere

Turbulence in the Earth' atmosphere results in both temperature and density variations coupled by the pressure equilibrium. Refractive index variations with wavelength follow the n variation with wavelength shown in figure 1. The optical path length variations due to turbulence are therefore also fairly achromatic at the longer wavelengths. ($> 0.5 \mu\text{m}$) when measured in linear dimensions. So are wavefront tilts and curvatures, a behavior used in astronomical wavefront sensing (section 3.1). When expressed in waves the optical path length variations decrease of course with increasing wavelengths.

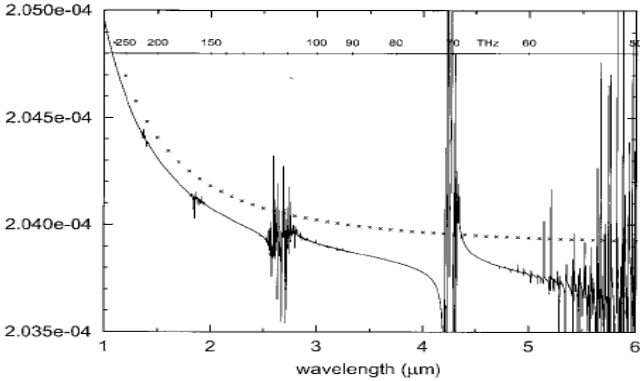


Figure 2 Effect of anomalous dispersion on the atmospheric refractive index (from Mather¹¹).

For Kolmogorov turbulence the so-called Structure Function for n equals

$$D_n(\rho) = \langle |n(r+\rho) - n(r)|^2 \rangle \equiv C_n^2 |\rho|^{2/3}, \quad (1)$$

where r and ρ are the distance between two points and C_n^2 is the refractive index structure constant. Figure 3 shows a typical $C_n^2(h)$ variation for a sea level and mountain site (Cerro Paranal).

A frequently used parameter for expressing the total seeing caused by the atmospheric optical turbulence is the so-called Fried Parameter r_0 . It equals:

$$r_0(\lambda, \zeta) = 0.185 \lambda^{6/5} \cos^{3/5} \zeta (\int C_n^2 dh)^{-3/5} \quad (2)$$

where ζ is the zenith distance. Within a circle of r_0 diameter the wavefront RMS distortion equals about 1/6 wave. A telescope with that (sub)aperture therefore give a diffraction limited image (Airy disk). Other dependencies on $C_n^2(h)$ for $\zeta = 0$ and telescope aperture diameter D are (integral is over the atmosphere):

$$\text{Image Size (FWHM)} \approx \lambda r_0 \text{ (radians)} = 5.42 \lambda^{-1/5} (\int C_n^2 dh)^{3/5} \quad (3)$$

$$\text{MS Image Motion} \approx 5.8 D^{-1/3} \int C_n^2 dh \quad (4)$$

$$\text{Scintillation Stars} \equiv (\Delta I_{\text{RMS}}/I)^2 = 19.1 \lambda^{-7/6} \int h^{5/6} C_n^2 dh \quad (5)$$

$$\text{Scintillation Sun/Moon} \equiv (\Delta I_{\text{RMS}}/I)^2 \approx 1.1 * 10^6 \int h^{-1/3} C_n^2 dh \quad (6)$$

$$\text{Time Constant } \tau \approx r_0 / \langle V_{\text{wind}} \rangle C_n^2 \quad (7)$$

$$\text{Radius of "Isoplanatic Patch"} \quad \phi_0 \approx 0.3 r_0 / \langle h \rangle C_n^2 \quad (8)$$

$$\text{Number of Speckles} \approx (D/r_0)^2 \quad (9)$$

$$\text{Speckle Size} = \lambda/D \text{ (radians)} \quad (10)$$

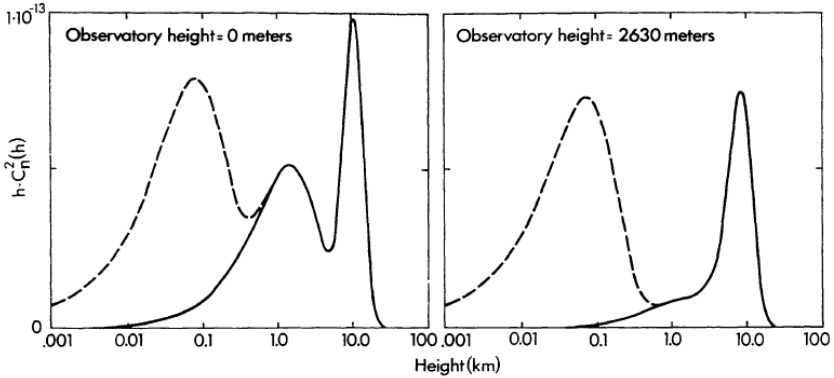


Figure 3 Variation of C_n^2 with height for the Hufnagel-Valley model. The $h \cdot C_n^2(h)$ vs. $\log(h)$ scaling was chosen to give a realistic representation of the contributions of the different height intervals. The dashed and full lines refer respectively to the boundary and free atmosphere layer contributions. The boundary layer refers to nighttime conditions. Daytime conditions are worse.

Figure 4 shows the spatial structure of the refractive index variations. It follows the dependence predicted by Kolmogorov turbulence except for large and short spatial scales beyond the so-called outer scale of turbulence L_0 and the inner scale of turbulence l_0 . The outer scale L_0 is the scale of the “input” motions which drive the turbulence through inertial decay. The inner scale l_0 is the scale at which viscous dissipation sets in (a few mm).

The inner scale l_0 is only of interest for laser propagation where the beam widths are small. For astronomical purposes the outer scale of turbulence L_0 is of primary interest. Experimental results obtained with telescopes (Hershell/La Palma, Keck/Mauna Kea, VLT/Paranal, OHP/France) and interferometers (Sydney USI, Palomar TI) show values for L_0 ranging from 2 through 50 meters with a medium of 15 meters. L_0 is thought by some to correspond to the thickness of the narrow turbulent layers in the atmosphere, others believe it to result from local vertical wind patterns and others have postulated that L_0 varies linearly with height. It is quite likely that there is a height, time and location dependence of L_0 , but I am not aware of any observations that establish that. Also when turbulence in the telescope and enclosure is an issue their size becomes important. A small L_0 improves the performance of adaptive optics in

large telescopes ($D \geq L_0$) and decreases the Optical Path Differences (OPDs) between the different arms of an interferometer.

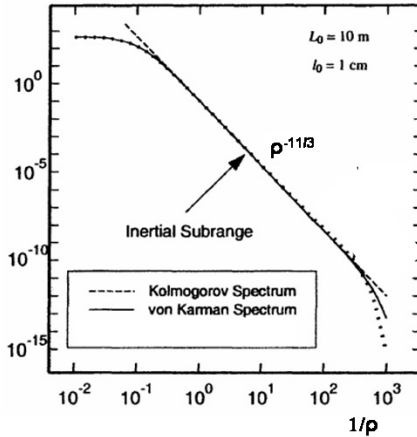


Figure 4 Spatial power spectrum of the refractive index variations. ρ is the distance between points; L_0 and l_0 are the outer- and inner-scale of turbulence (adapted from Andrews and Phillips³).

2.3. Optical Turbulence under Special Conditions

The $C_n^2(h)$ profiles given in figure 3 represent a reasonable approximation for many nighttime conditions. Because of solar heating the boundary layer in daytime is generally worse especially in the latter half of the day. There are, however, major variations in this behavior. In particular I want to point out two cases: (i) at lake sites, like the Big Bear Solar Observatory, daytime heating is minor so that the boundary layer does not change much between day and night. (ii) At Dome C in Antarctica, the best seeing in summer time occurs in the mid-afternoon and not during the night. Beckers and Travouillon⁴ interpret this to be the result of a balancing between the radiation cooling of the snow surface and the solar heating. Without solar heating the temperature difference between the surface and the air is larger thus causing larger temperature differences in the wind-driven turbulence.

3. Adaptive Optics

Figure 5 is a schematic of a classical adaptive optics (AO) system for astronomical telescopes following Babcock's⁵ suggestion. For more detailed general descriptions I refer to Beckers⁶ and Roddier⁷.

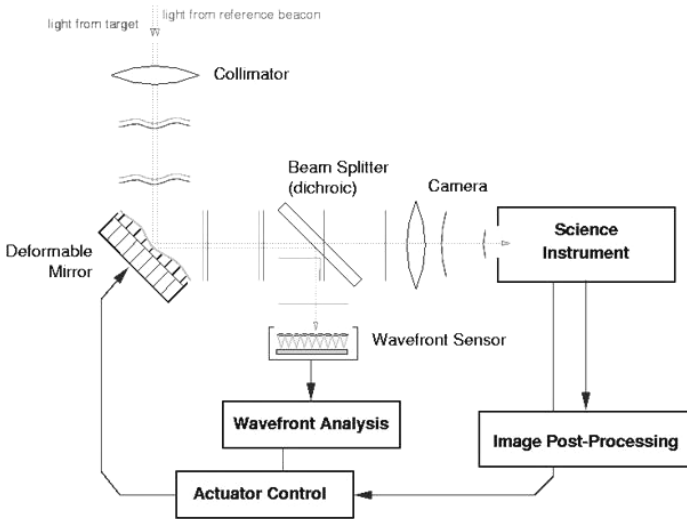


Figure 5 Schematic diagram of an astronomical Adaptive Optics (AO) system. The collimator forms an image of the telescope aperture on the deformable mirror (DM) and on the Shack-Hartmann (S-H) wavefront sensor. Equation (9) gives the approximate number of sub-segments of the DM and S-H. A rapid processor closes the fast (equation 7) complex servo loop that couples both to flatten out the distorted wavefront.

In his talk during this conference Wizinovitch⁸ also discusses various AO systems and shows a number of interesting results of the improved imaging that can be obtained with them.

3.1. Wavefront Sensing

There are three ways that are frequently used to sense the wavefront of real or artificial stars. They are: (i) Shack-Hartmann (S-H) sensors shown already in figure 5. It measures the wavefront tilts across the telescope aperture, (ii) Roddier-Beckers⁹ (R-B) curvature sensors which uses out-of-focus images to measure the wavefront curvature, and (iii) knife edge sensors using the Foucault optics test. It also measures the wavefront tilts. The Pyramid Wavefront sensor by Ragazzoni¹⁰ used the latter in a sophisticated way. From the wavefront tilts and curvatures the wavefront itself can be determined but in some AO system the tilts and curvatures are used directly for tilt and curvature actuated DMs.

Most AO systems use the S-H sensors combined with modal control using Zernike polynomial fitting to recover the wavefront. Figure 6 shows it in more detail.

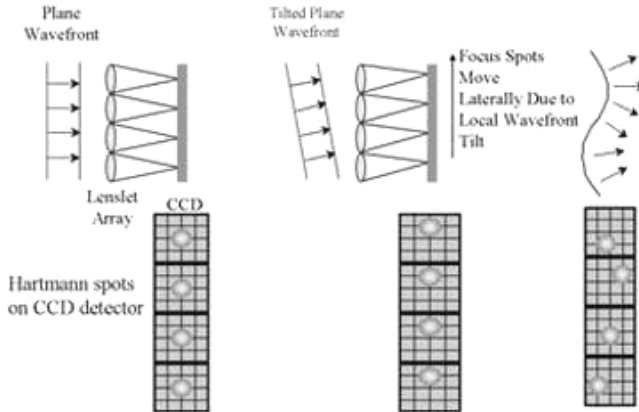


Figure 6 Schematic of a Shack-Hartmann sensor. A 2-D lenslet array placed in an image of the pupil conjugate forms multiple images of the stellar object. General or local tilts of the wavefront move these images around by an amount directly proportional to the wavefront tilts. A CCD array measures the displacements (from Boston Micromachine Corporation website; David Williams).

The S-H sensor works not only with stellar images but also with images of extended objects like the Sun. Figure 7 shows an example of a solar S-H sensor using a sunspot region.

3.2. *Laser Beacons or Guide Stars*

Normally there are, especially at short wavelengths, not enough natural stars available to apply AO to any object in the sky. Foy and Labeyrie¹¹ therefore suggested the use of artificial stars created by laser scattering on very high atmospheric layers (similar to those used by LIDAR) for measuring wavefront distortions. These can be placed anywhere in the sky. These stars are commonly referred to as Laser Beacons or Laser Guide Stars (LGSs).

Most frequently used are Sodium LGSs where the laser light is scattered off the neutral Sodium layer in the mesosphere at an altitude of about 90 km. This layer is about 10 km thick and time variable so that Na-LGSs vary in brightness with time. By transmitting the laser from the center of the telescope the LGS looks like a star in the center of the aperture. Near the edge one has to correct for

the so-called perspective elongation resulting from the Na layer thickness¹². Because of the finite distance of the LGS it is necessary to correct for the so-called “cone effect”. This is done by Atmospheric Tomography^{13,14} (occasionally also referred to as “Laser Tomography”). Occasionally Rayleigh scattering with fast shuttering on atmospheric molecules lower in the atmosphere is used. It creates brighter LGSs but suffers from a larger cone effect and possibly more perspective elongation.

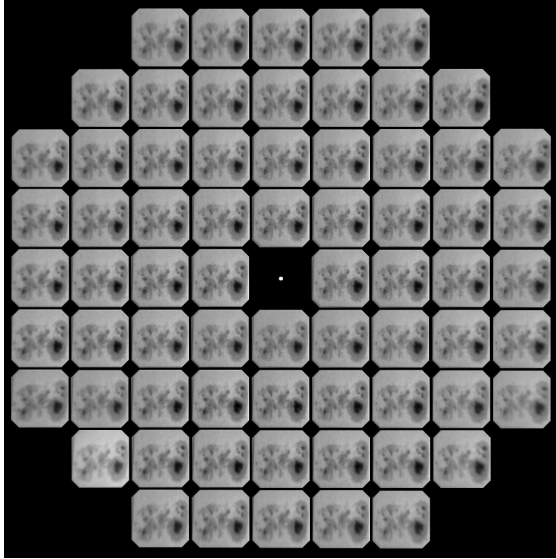


Figure 7 Shack-Hartmann wavefront sensor used to measure the wavefront distortion of a solar sunspot region. It results from a 9 x 9 lenslet array placed across an image of the 76 cm diameter entrance aperture of the Dunn Solar Telescope at the National Solar Observatory at Sacramento Peak, New Mexico. Each image covers a 127 x 127 arcsecond area on the Sun. This large area was needed for an atmospheric tomography/ multi-conjugate adaptive optics experiment.

3.3. Multi-Conjugate Adaptive Optics

One of the major limitations of classical AO is the small angular area on the sky over which the atmospheric seeing is corrected. It is called the “Isoplanatic Patch” (equation 8). I^{13,14} suggested the use of Multi-Conjugate Adaptive Optics (MCAO) to increase that area. The concept is illustrated in figure 8.

Atmospheric Tomography benefits from the knowledge of the vertical structure of $C_n^2(h)$. A number of papers in this conference and in the literature describe methods to obtain this height profile. I refer to those.

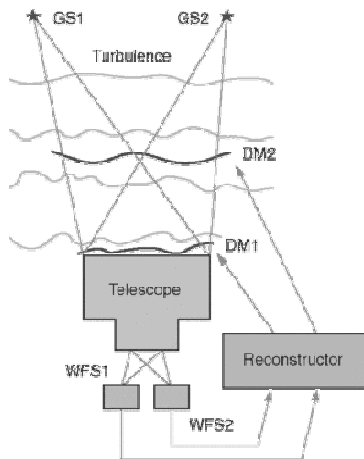


Figure 8 Concept of Multi-Conjugate Adaptive Optics. In it a number of natural stars (NGSs) and/or LGSs are used to measure the atmospheric wavefront disturbances in 3-D using Atmospheric Tomography (AT). A number of DMs are then used at optimum conjugates to correct these wavefronts in 3-D.

There are a number of variants of the MCAO concept like Dual Conjugate Adaptive Optics (DCAO), Ground Layer Adaptive Optics (GLAO), Layer Oriented Adaptive Optics (LOAO) and Multi-Object Adaptive Optics (MOAO). Nice recent descriptions of MCAO can be found in Esposito¹⁵ and other papers in the same issue of that journal. Recently spectacular results have been obtained both in solar and nighttime astronomy with the first generation of MCAO facilities¹⁶. The era of MCAO is just beginning. The plan is to incorporate MCAO in all major future extremely large solar and nighttime telescopes.

4. Astronomical Interferometry

In interferometry an array of telescopes is used to achieve extremely high angular resolution. This resolution equals the maximum telescope separation divided by the wavelength used. For maximum sensitivity each of the telescopes should be outfitted with AO. Because of the optical turbulence the optical path differences (OPDs) between the telescopes fluctuate. Sometimes it is possible to “fringe track” on a field star. In general triple correlation between triads of telescopes can be used to achieve phase closure and do images provided the OPDs are within the so-called coherence length¹⁷. I refer to Wizinovich paper⁸ in this conference for results obtained with current interferometers.

5. Conclusion

In the last few decades it has become clear that the correction for optical turbulence in astronomical imaging is possible. This opens up huge new capabilities for ground-based astronomical telescopes and interferometers. The path to achieve this will be expensive and time consuming. It took 30 years to realize Babcock's AO concept. It took two decades to implement MCAO. These first realizations are so far limited. Future progress requires: (i) extension of AO to shorter wavelengths, (ii) the construction of DMs with many actuators, (iii) the implementation of Deformable Secondary Mirrors, (iv) increasing the brightness of Na-LGSs, (v) correction of perspective elongation techniques, (vi) optimization of Atmospheric Tomography, and (vii) full exploitation of interferometers including optimized imaging algorithms and the use of long base lines. The next decades in ground-based astronomy will be very exciting!

References

1. R.J. Mather, *Applied Optics* **43**, 928 (2004)
2. F. Roddier, *Progress in Optics* (Ed. E. Wolf) **XIX**, 281 (1981)
3. L.C. Andrews and R.L. Phillips, "Laser Beam Propagation through Random Media", *SPIE Optical Engineering Press* (1998)
4. J.M. Beckers and T. Travouillon, *Proceedings of the ARENA-2 Potsdam Meeting*, EDP Sciences, in press (2008)
5. H.W. Babcock, *Publ. Astr. Soc. Pacific* **65**, 229 (1953)
6. J.M. Beckers, *Ann. Rev. Astron. and Astrophys.* **31**, 13 (1993)
7. F. Roddier (Editor), *Adaptive Optics in Astronomy*, Cambridge University Press (1999)
8. P. Wizinovich, proceedings this conference (2008)
9. J.M. Beckers, *J. Opt. Soc. America* **A11**, 425 (1994)
10. R. Ragazzoni, *Modern Optics* **43**, 289 (1996)
11. R. Foy and A. Labeyrie, *Astron. and Astrophys.* **152**, L29 (1985)
12. J.M. Beckers, M. Owner-Petersen and T. Andersen, 2003, *Proceedings SPIE* **5169**, 123 (2003)
13. J.M. Beckers, *ESO Conference and Workshop Proceedings* **30**, 693 (1988)
14. J.M. Beckers, *Proceedings SPIE* **1114**, 215 (1989)
15. S. Esposito, *Comptes Rendus Physique* **6**, 1039 (2005)
16. E. Marchetti and co-authors, *The ESO Messenger* 129, 8 (2007)
17. J.M. Beckers, *Experimental Astronomy* **2**, 57 (1991)