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ADAPTIVE OPTICS SYSTEM PERFORMANCES AND LARGE FIELD OF VIEW SPECTROPOLARIMETRIC OBSERVATIONS

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Abstract. In the context of the increasing interest for large aperture telescope dedicated to the Sun such as EST or ATST projects, we* present a study to evaluate the adaptive optics system limitations in regard of the scientific requirements expected for magnetic field extrapolations and data-driven MHD simulations of active regions. The questions we address are: what is the size of the field of view at high spatial resolution for a 4 meter class telescope with a spectrograph, what is the impact of the selected spectral domain on the performances in relation to the scientific goals aforementioned ? We show that the visible wavelength domain still remains difficult to explore with ground-based telescope using a classical adaptive optics system. The field of view obtained will be only few arcsecs at diffraction limit for the most part of the observation time.

Keywords: adaptive optics, spectropolarimetry, turbulence

1 Introduction

Solar physics research requires observations of magnetic features in a challenging range from one tenth of an arcsecond, for flux tubes, to a few arc-minutes, for active regions. Another demand on the image compensation system is that the observer should be able to analyze a broad field of view, in order to extrapolate the magnetic field. Even though focused studies of small delta-spots only require relatively small field of views, about 1.6 arcmin in Canou et al. (2009), the typical field of view size required for extrapolation purposes is larger than 2 arcmin: typically 3 to 4 arcmin for emerging active regions, sigmoids and medium-sized filaments (Aulanier & Schmieder 2002; Pariat et al. 2004; Schrijver et al. 2008; Canou & Amari 2010), and even up to 6 arcmin for large filaments, full AR studies and later use the results and initial conditions for MHD simulations (Lionello et al. 2002; Metcalf et al. 2008; Masson et al. 2009). Adaptive optics (AO) is used to recover diffraction-limited resolution with ground-based large telescopes, by compensating in real-time atmospheric turbulence. However, adaptive optics requires a reference source close to the object of interest in order to accurately sense the wavefront disturbed by turbulence. The limitation of the efficiency of the compensation by the adaptive optics is due to the conventional anisoplanatism effect (Fried 1982). The wavefronts incoming from two angular-separated structures on the Sun are different because of the different path through the atmosphere. This effect limits the field of view around the reference source where an efficient correction can be achieved. High image quality is an important requirement for the observation of small solar magnetic features like magnetic flux tubes. Nevertheless, accurate magnetic field topology studies which involve relatively small flux concentrations, need not only a good spatial resolution but also an homogeneous compensation of the terrestrial turbulence effects on an extended field of view. In order to evaluate the limitations due to anisoplanatism, we present useful tools to determine the quality of the measurement of the magnetic field after adaptive optics compensation (Molodij & Aulanier 2011).

2 Analysis of adaptive optics system performances

In this section, we present new simple analytic laws to evaluate both the size of the corrected field of view and the image quality for any classical AO systems and telescope apertures. Theoretical techniques to evaluate the

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effects of anisoplanatism upon the performance of adaptive optics system are detailled in Molodij & Rousset (1997); Molodij & Rayrole (1998); Molodij (2011). The image quality after AO correction is given by Noll (1976) as $\sigma_J^2 \propto \left(D^2/J\right)^{\frac{5}{6}}$, and we show that the behavior of the isoplanatic field of view after AO correction is $\theta_{cor} \propto D/\sqrt{J}$, where J is the number of compensated modes and D the telescope aperture. Figure 1 shows the optimal field of view θ_{cor} and the optimal image quality related to the residual phase variance σ_J^2 versus the number of compensated modes J of the AO for three different telescope apertures (1, 2 and 4 meter class telescope). The dashed bottom lines indicate the image quality expected after J compensated modes (the Strehl ratio is $SR = e^{-\sigma^2}$). For instance, conventional "diffraction-limited" aberration level is set at the Strehl ratio of 0.8 ; i.e, a value of $\sigma^2 = 0.2$ rad^2 (indicated by the horizontal dotted line in Fig.1). Vertical arrows defined by the intersection of the 80 % Strehl ratio and the σ_J^2 functions give both the maximum order of compensated J of the AO and the isoplanatic patch (intersection of the arrow and θ_{cor} functions). A value θ_{iso} of 5 *arcsec* is found for the Hufnagel profile (Hufnagel 1974) that has been used to calculate the different terms in the residual wavefront error $\sigma^2(J, \alpha)$. A median value of r_0 at Haleakala site is 9.7 cm, result of 92307 measurements for 651 days from 2002 January to 2004 August, has been derived from the probability exceedance function of r_0 for daytime measurements (Bradley et al. 2006). We remark first that the isoplanatic patch at diffraction after

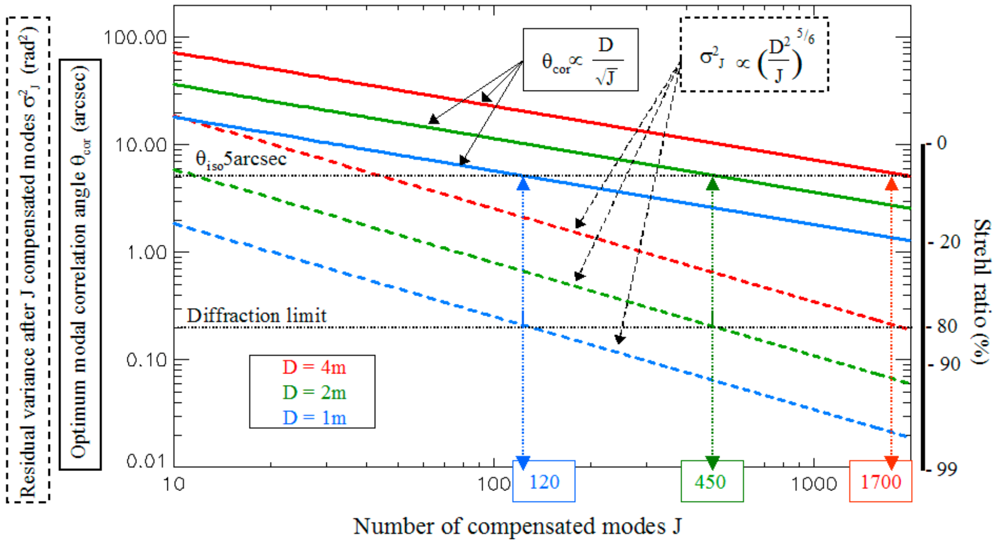

Fig. 1. Optimal field of view θ_{cor} (plain lines) and optimal image quality related to the residual phase variance σ_J^2 (dashed lines) versus the number of compensated modes J of the AO for three different telescope apertures (1, 2 and 4 meter class telescope respectively indicated in blue, green and red). Vertical axis on left shows both the residual phase variance expressed in rad^2 and the optimum field of view (arcsec) in log units. Right vertical axis indicates the Strehl ratio related to the residual phase variance. Notice that the conventional diffraction-limite aberration level is set at the Strehl ratio of 0.8 ; i.e, a value of $\sigma^2 = 0.2$ rad^2

AO compensation is independent of the telescope aperture. Secondly, in the case of a 4 meter class telescope, increasing the number of freedom J from 450 actuators up to 1700 does not lead to a considerably increase of the Strehl ratio but reduce 66 % of useful field of view. Figure 2 gives the isoplanatic domain (twice the defined isoplanatic angle θ_{iso}) for $\sigma_0 = 2\pi/5$ corresponding to $\lambda/5$, i.e., a Strehl ratio around 20 %. This arbitrary value of the residual error is the minimum image quality expected for astronomical observations. Figure 2 shows the isoplanatic domains estimated for a 4 meter class telescope after compensation by different adaptive systems from a low-order system after J = 10 corrected modes up to J = 1540 to reach the diffraction limit in visible wavelength range. We show that the capacity of high order adaptive optics system is suitable for high spatial resolution observations with a severe reduction of the field of view. As expected, the isoplanatic angle θ_{iso} increases with the increase of the observation wavelength. The near infrared spectral domain remains the only possibility to obtain large field of views using classical AO system for a 4 meter class telescope. Examples are the COMEon+ 52 actuators (Léna 1994) or the NAOS 185 actuators system (Lagrange et al. 2003). Two phenomena confer a serious advantage to choose the infra red spectral domain for the magnetometry for large aperture telescope. The first is due to the higher sensitivity of the IR spectral lines to the Zeeman effect: Zeeman shifts are proportional to $g\lambda^2$ where g is the Landé factor. The second is coming from the properties of the turbulence: the value of the Fried's parameter $r_0 = 10$ cm in the visible wavelength range becomes 60 cm at 2.2 μm, for instance. Figure 3 shows that the expected isoplanatic field of view is 4 more times larger in the 1.6 μm IR band than in the visible range.

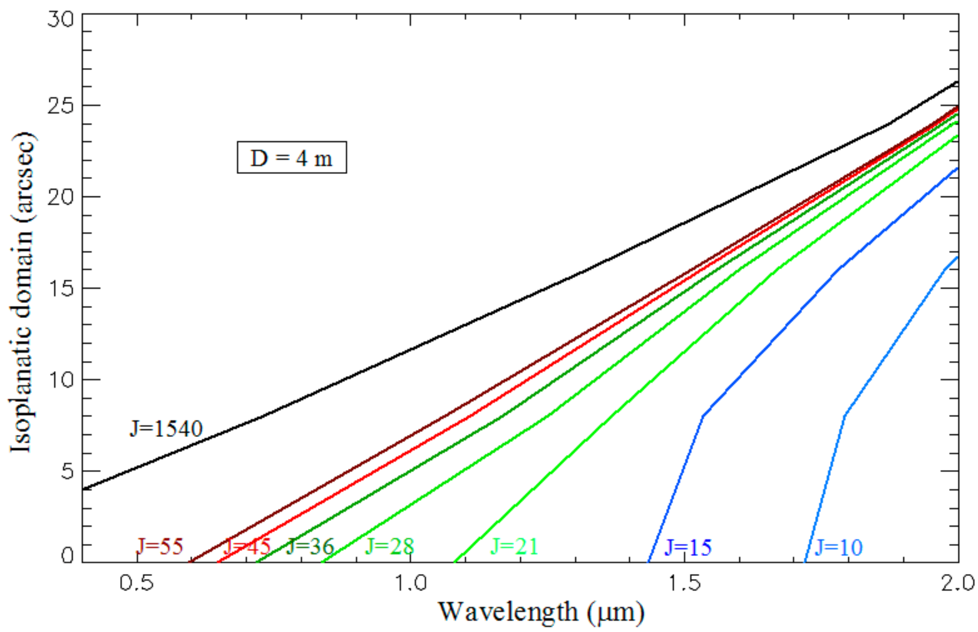

Fig. 2. Isoplanatic domain corresponding to an image quality criterion of $\frac{\lambda}{5}$, versus wavelength, for a 4 meter class telescope after compensation of J = 10 up to 1540 modes. Curves are computed with the Hufnagel C_n^2 turbulence profile ($r_0 = 10$ cm @ λ=0.5 μm).

3 Conclusion

We presented a study to evaluate the adaptive optics system limitations in regard of the scientific requirements expected for magnetic field extrapolations and data-driven MHD simulations large field of views. Questions we addressed are: Can ground based telescopes with adaptive optics systems fulfill the requirements of extrapolations and data-driven MHD simulations? In other words, are large field of views of few arcminutes size accessible at high spatial resolution from the ground ? We show that the visible wavelength domain still remains difficult to explore with ground-based telescope using a classical adaptive optics system. The isoplanatic field of view resulting of the compensation of a classical adaptive optics system is only few arcsecs at diffraction limit for usual condition of the atmospheric turbulence. The classical adaptive optics system is unable to reach the required performances in the visible wavelength range in usual conditions of observation. The near infra-red spectral domain remains the only possibility to obtain large field of views using classical AO system for large aperture telescopes. The expected isoplanatic field of view at diffraction is 4 more times larger in the 1.6 μm IR band than in the visible range for usual conditions of observation but it still remains to small to cover a whole active region in a single scan passage. Another advantage comes from the higher sensitivity of the IR spectral lines to determine the magnetic flux from spectropolarimetric observations with ground-based observations at 1.56 μm (Beck & Rezaei 2009) and at 1.083 He I (Kuckein et al. 2010) to study the chromospheric dynamics. A 4m class telescope would be well-sized to the only study of the magnetic field dynamics at the granule scale. A question remains on the adequacy of a 4m class by comparison to a 2m class diameter class telescope except to the purpose of collecting more photons.

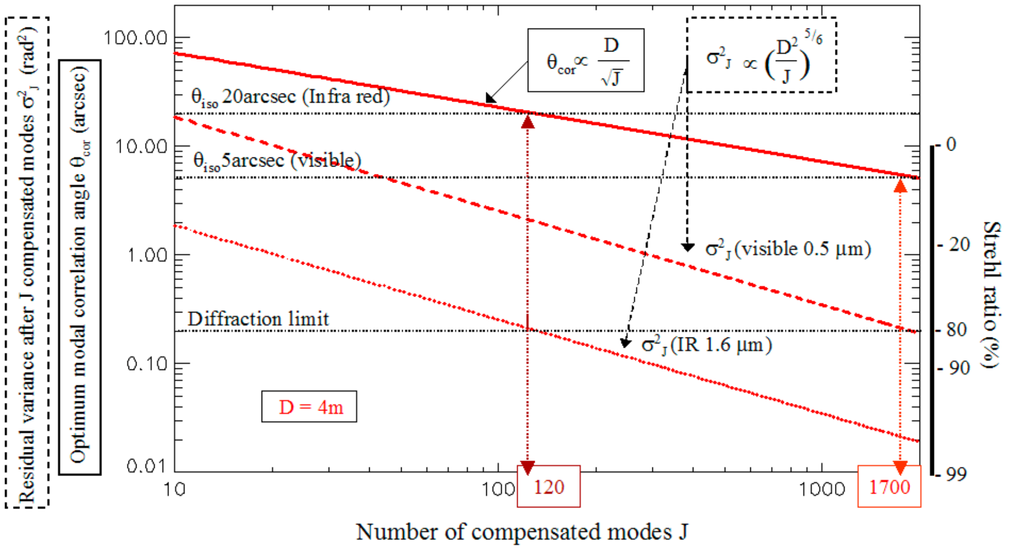

Fig. 3. Comparison of the optimal field of view θ_{cor} (plain lines) and optimal image quality related to the residual phase variance σ_J^2 (dashed lines) versus the number of compensated modes J of the AO for the visible and the infra red spectral domain (4 meter class telescope). Vertical axis on left shows both the residual phase variance expressed in rad^2 and the optimum field of view (arcsec) in log units. Right vertical axis indicates the Strehl ratio related to the residual phase variance.

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