DAYTIME OBSERVATIONS WITH EXTREMELY LARGE TELESCOPES IN THE THERMAL INFRARED USING LASER GUIDE STAR ADAPTIVE OPTICS

Jacques Maurice Beckers[1,a]

[1]Emeritus, Scottsdale, AZ 85255, USA

Abstract. Using Magneto-Optical Filters (MOFs) it is possible to see Sodium Laser Guide Stars in the daytime sky. This makes it possible to use ELT Adaptive Optics systems for diffraction limited observations 24 hours/day. Because of the bright daytime sky this LGS-AO application is only of interest in the mid-infrared wavelength region (3.5 – 25 µm) where the thermal radiation of the atmosphere-telescope system dominates the atmospheric scattering of sunlight. Incorporating MOFs in the LGS wavefront sensors substantially increases the amount of ELT observing time. The gain with respect to the JWST lies in the 5 - 6 times better linear angular resolution. The contrast gain in brightness at near-IR wavelengths is sufficient to give enough natural guide stars for tip-tilt control. The main complication associated with incorporating MOFs in ELT AO systems for daytime observations is likely the requirement to make the telescope and its enclosure robust in the daytime environment. Poorer daytime seeing conditions may also be detrimental. The use of Mica etalons and narrow band interference filters is also briefly examined. The TMT is used as a good option for the implementation of this technique.

1. Introduction

At thermal-infrared wavelengths (3.5 to 30 µm) the background in daytime astronomical observations at high altitude (≥ 3000 m) sites is dominated by the thermal emission of the sky and telescope rather than by the Rayleigh and aerosol scattering of sunlight in the atmosphere. Provided that the telescope and its enclosure are designed to be usable for observation in daylight condition, it should therefore be possible to observe a large part of the sky at any time in the 24 hour day. This would significantly enhance the power of the future Extremely Large Telescopes. These telescopes can be made diffraction limited at those wavelengths by means of adaptive optics if Na Laser Guide Stars (LGSs) can be seen against the daylight sky by using very narrow band filters to suppress the atmospheric spectrum at wavelengths away of the Na-D2 line. Magneto-Optical filters (or MOFs) using magnetized Na gas and the Macaluso-Corbino effect [1-4] are ideally suited to do so. In addition to ELTs my later papers discuss their use for solar telescopes and Antarctic observatories. Other narrow band filters like Mica solid-spaced Fabry-Perot Etalons may be other options.

In this contribution to the Adaptive Optics for Extremely Large Telescopes conference I remind the participants of this application and I develop this concept further for the case of the Thirty Meter Telescope (TMT) which appears to be well suited for its implementation.

[a] jbeckers@rcn.com

2. Principle of Sodium Magneto-Optical Filter

Figure 1 outlines the functioning of the Na MOF. The MOF is also named Faraday Anomalous Dispersion Optical Filter or FADOF. See: *http://en.wikipedia.org/wiki/Atomic_line_filter* from which some parts of figure 1 are taken.

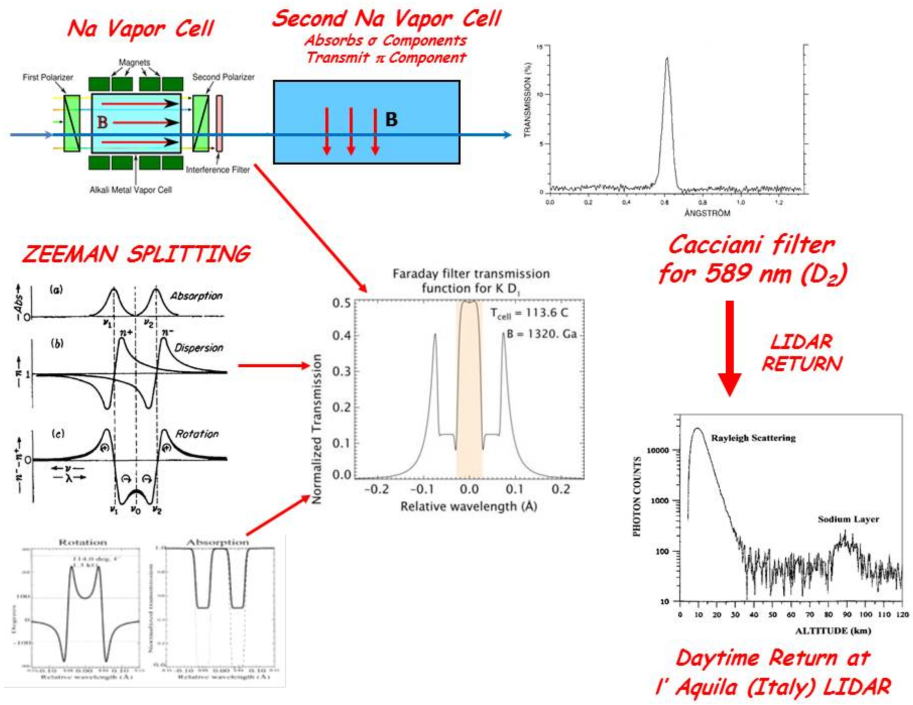

Fig. 1. Diagram explaining the working of the Magneto-Optical Filter for Na-lasers. Note that the second Na vapor cell may be omitted for the present application

In the upper left the filter itself is shown. It consists of a heated glass cell filled with Na vapor with optical entrance and exit windows placed in a magnetic coil which provides a magnetic field B in the kilogauss range directed along the optical path. Below it is a sketch of the Zeeman splitting of the D lines (in this case for a simple triplet splitting) for both (a) the absorption coefficient, (b) the anomalous dispersion n^+ and n^- and (c) the resulting circular birefringence $n^- - n^+$. The linear polarized radiation transmitted by the entrance polarizer in front of the glass cell therefore suffers both absorption and polarization rotation in the cell. The direction of polarization of a second polarizer at the exit of the cell is at right angle to that of the first polarizer. The transmission of this first Na MOF is 0% outside the Na lines but shows a complex behavior in the Na line shown in the central graph. There is a strong undisplaced transmission component and with lesser transmission peaks on both sides. The latter can be blocked by a second Na vapor cell identical with the first one (details not shown) but with a magnetic field at right angles to the optical path. An interference filter (shown between the two cells) selects the Na-line to be used. The graph in the upper right corner is from [3]. In it Cacciani shows the achieved transmission of the system for the D2 line using a vapor temperature/density of 200 C and B = 1.8 KG. (for unpolarized incident light). Its bandwidth (FWHM) is 0.0053 nm and peak transmission for polarized light 30%. The figure in the lower right corner shows the use of such a filter in Lidar observations of the height variation of the atmospheric sodium density [3]. In the following I assume that further optimization will lead to a peak transmission of 40%.

3. Suppression of Daytime Sky Radiation

Figure 2 shows on top the spectrum of the daytime sky in the vicinity of the Na D-lines (taken from my atlas of the solar irradiance [5]). Directly below it is the expanded spectrum near the D2 line core. Its central intensity is low, 5% of the continuum intensity. It is followed by the LGS spectrum and the transmission of the MOF shown in Figure 1. In the bottom graph the MOF transmission is further narrowed by a Fabry-Perot etalon. The Fabry-Perot option is shown in case the fine structure of the LGS D2 needs to be resolved. It is not pursued further in this paper.

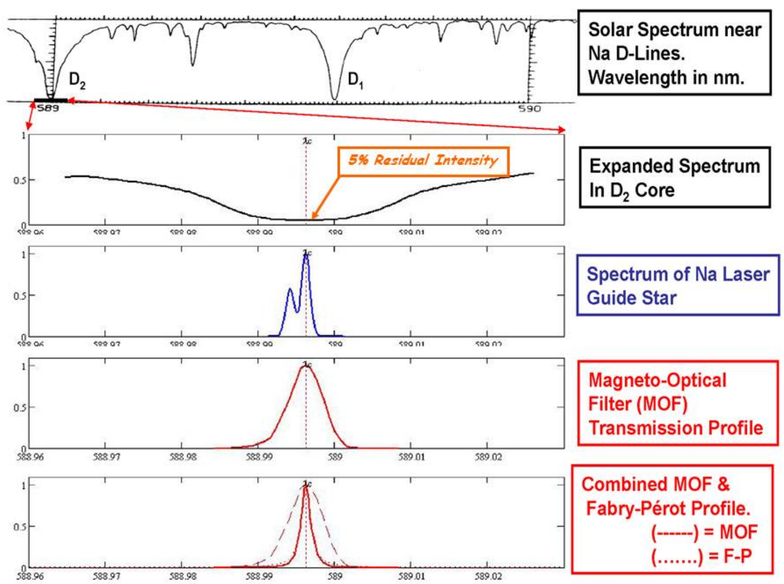

Fig. 2. Spectrum distribution of day sky, Na D2-LGS and filter transmission.

Tables 1a and 1b gives estimates for the V-magnitude of the clear sky and the Na D2-LGS at the location for the mid-latitude location of the planned ELTs. The sky magnitudes refer to an angle of 1 arcsec^2 which is the assumed size of the LGS. I also assume that at the observatory site the sky surface brightness equals 10^{-6} of that of the average solar disk.

Table 1a. Sky V magnitude

Sky V-Magnitude	**V-Change (ΔV)**	V_{Sky}
Total Solar Disk V-Magnitude		-26.7
Solar Disk/arcsec^2	+16.2	-10.5
Clear Sky (10^{-6} of Sun)	+15.0	+4.5
In MOF Band (BW = 0.0053 nm)	+10.0	+14.5
In Center of Solar D2 Line (5%)	+3.2	+17.7
MOF Transmission for Sky Polarized Light (20%)	+1.7	+19.4

Table 1b. Na-D2 Laser Guide Star V magnitude and Comparison with V_{Sky}

Na-LGS V-Magnitude	**V-Change (ΔV)**	V_{LGS}
Assumed Magnitude for 10 Watts Laser Guide Star		+10.0
MOF Peak Transmission for LGS Polarized Light (40%)	+1.0	+11.0
V_{LGS}-V_{Sky}		-8.4
I_{LGS}/I_{Sky}		2300

I did not consider in the calculations above the various options for treating the polarization of the sky and the LGS. Most lasers and resulting Na-LGSs are circularly polarized to maximize the LGS brightness. I therefore assume above that λ/4 plate is placed in front of the MOF's first polarizer to match the resulting LGS linear polarization with that of the polarizer. The sky is strongly linearly polarized at an angle orthogonal to the direction to the Sun. The λ/4 plate/polarizer combination therefore transmits about only half of the MOF transmission for fully polarized light.

Linear polarization of the LGS by using a linearly polarized Na laser is another option. The sky is strongly linearly polarized at an angle orthogonal to the direction to the Sun. In the linearly polarized case the laser/LGS linear polarization direction should be rotated to be orthogonal to the sky polarization while the MOF entrance polarizer should be matched to the LGS polarization direction (by MOF rotation or by a λ/2 plate). At the cost of a lower intensity of the LGS this option might result in a higher LGS-Sky contrast. It is not clear to me at present what the optimum approach is.

Since the estimated LGS to sky contrast is very high (~2300) one should consider other options for sky suppression which are simpler and less costly. One option is to omit the second Na Vapor cell and accept the extra transmission in the two side peaks. It would less than double the sky background which should be acceptable. Other options include the replacement of the MOF by a solid Fabry-Perot etalons (using mica spacers) or more common narrow band interference filters. I will examine these options next.

4. Use Other Narrow Band Filters Instead?

In solar observations narrow band imaging is common. Among the filter options most common ones are Lyot-Öhman birefringent filters; Fabry-Perot etalons; solid Fabry-Perot etalons using mica spacers; regular narrow band interference filters and MOFs as described above. Birefringent filters are bulky, expensive and have low transmission. Regular Fabry-Perot etalons require accurate spacing and parallelism control. Solid Fabry-Perot (or mica) filters and regular interference filters provide attractive alternatives for the application described in this paper. I will therefore examine both briefly.

4.1 Solid-Spaced Fabry-Perot Etalons (“Mica Filters”)

Invented by Dobrowolski in 1959 [6], mica filters have been used in a number of solar astronomy applications. They use a thin mica sheet as the spacer in a Fabry-Perot etalon. Mica as a crystal can be sliced in constant thickness spacer. They are birefringent which causes dual passbands unless the spacer has a retardation of exactly a multiple of half waves. I will assume the latter to be the case. They are commercially produced and are frequently referred to as Daystar filters. Among them are filters tuned to the D line (see: *http://www.daystarfilters.com/Sodium.shtml*). Bandwidths of 0.04 nm (FWHM) are achieved with peak transmissions of around 8%. Unlike the MOF the transmission profile has broad wings resulting in a higher sky background. Using the sky and LGS parameters used in Table 1 and a blocking filter with 0.4 nm bandwidth, one obtains a value for V_{LGS}-V_{Sky} of -2.7 or I_{LGS}/I_{Sky} = ~50. The LGS is still much brighter than the sky background. The drawback as compared with the MOF is the lower LGS brightness and the narrow angular acceptance angle for the Mica filter.

4.2 Narrow-Band Interference Filters

Interference filters come in various transmission profiles, transmission wavelengths, transmittances and bandwidths. Multi-cavity filters have transmission profiles which approach top-hat shapes. Transmittances in the D line wavelength rage are around 40% and bandwidths reach as low as 0.2 nm (FWHM). Occasionally they are used in astronomy for observing line profiles [7]. For simplicity I will assume a filter transmission profile with a top-hat shape with 0.4 nm bandwidth and a transmission of 40%. They do not use polarization components so that these parameters are polarization insensitive. Under these conditions I_{LGS}/I_{Sky} = 1. The much higher sky background is the obvious major drawback of this option.

5. Comments on Daytime Use with Future ELTs

5.1 Which ELT?

All planned ELTs, the European ELT (E-ELT), the Thirty Meter Telescope (TMT) and the Giant Magellan Telescope (GMT) currently have Telescope-Enclosure combinations which are planned for nighttime observations. They need major modifications of the enclosure to allow observations during daytime of a large part of the daytime sky. As they are planned now, the TMT appears to be the best option for incorporating the daytime observing mode. Without further modification the TMT is not illuminated by sunlight at sun angles ≥ 90^O. Figure 3 shows the fraction of the sky the TMT can access in its current configuration and with an eventual future modification of the enclosure or aperture flaps which would allow sun angles as small as 60^O.

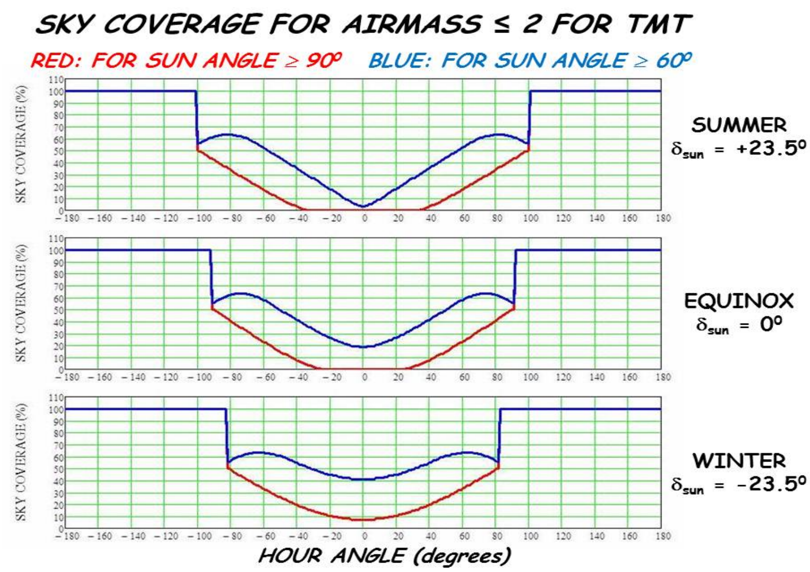

Fig. 3. Fraction of the sky covered for the TMT at Mauna Kea. It assumes observations are only allowed at zenith distance ≤ 60^O and at daytime sun angles ≥ 90^O (red = lower curve) and ≥ 60^O (blue = upper curve). Coverage is normalized to nighttime conditions.

5.2 Effect of Daytime Seeing

For nighttime observatories located on mountain tops the daytime seeing is generally worse than the nighttime seeing because of the heating of the surroundings and enclosure by sunlight. In the early morning the nighttime seeing conditions last for an hour or two

[8]. After that the image quality deteriorates but recovers somewhat in the late afternoon. In planning the Advanced Technology Solar Telescope (ATST) a number of sites were tested for daytime seeing [9]. Four sites were located on mountain tops like the ELTs will be; two of the sites were located on sites near or in mountain lakes. The lake sites showed no daytime deteriorations. The four mountain sites show best seeing in the early mountain, deterioration during the day and partial recovery during the evening. Early morning hours are therefore best for ELT observations. However the seeing improves with wavelength (proportional to $\lambda^{0.2}$). So does the Fried's parameter (proportional to $\lambda^{1.2}$). The ELT adaptive optics systems designed for shorter wavelength wavefront correction. So good thermal-IR observations should be possible all day.

5.3 Comments on Adaptive Optics Tip-Tilt Control

The TMT AO system is good enough to provide full wavefront flattening at shorter wavelengths. In the J to K band region there are enough stars available for tip-tilt control in the galactic belt. At the galactic pole the coverage is only partial.

5.4 Integration of Filter with Wavefront Sensors

The D2 filters must be integrated with each Hartmann-Shack wavefront sensor. The bulkier MOF has a relatively wide acceptance angle so that it could be located in the ELT LGS focus (f/15 for the TMT). With the LGS image located in the center of the MOF the required filter's optical diameter is minimized. Mica Filters and other interference filters are thinner and can have larger optical diameters, however the Mica Filter has a very narrow acceptance angle. Those filters should be located in the cavity between the collimator lens and the lenslet array.

6. Conclusion

Adding narrow band filters originally developed for solar observations to the Laser Guide Star adaptive optics systems of Extremely Large Telescope significantly enhances their capabilities for thermal infrared observations ($\lambda > 3.5$ μm). With properly designed enclosures they will allow 24 hours/day observation at these wavelengths. As compared with the power of the 6.5 meter aperture James Webb Space Telescope (JWST) this gain lies especially in the 5x larger angular resolution allowed by the 30-meter class ELTs. Even with the D^4 gain in contrast to the sky/telescope background, the JWST low background will have a sensitivity well exceeding that of the ELTs. The Na-D2 Magneto-Optical Filter is most attractive because it is perfectly matched to the wavelength and providing the best LGS to sky contrast. But the Mica Filter is an attractive alternative if the lower LGS magnitude resulting from its lower transmission can be accepted. Use of multi-cavity interference filters should be further explored.

This use of MOFs was first explored in a joint paper with my dear friend and colleague Alessandro Cacciani. Alessandro passed away 5 years ago.

7. References

1. J.M. Beckers, Applied Optics **9**, 595, (1970)
2 J.M. Beckers, Venice Conference on *"Beyond Conventional Adaptive Optics*" = ESO Conference and Workshop Proceedings **58**, 8 (2001)
3 J.M. Beckers, A. Cacciani, Experimental Astronomy 11, 133, (2001)
4 D. Macaluso, O.M. Corbino, Comptes Rendues **127**, 548, (1898)
5 J.M. Beckers, C.B. Bridges, L.B. Gilliam, AFGL Environmental Research Paper No. 565 (AFGL-TR-76-0126), (1976)
6 J.A. Dobrowolski, JOSA **49**, 794, (1959)
7 D. Clark, I. McLean, T.H.A. Wyllie, Astron. & Astrophys. **43**, 215 (1975)
8. J.M. Beckers, et al. PASP **91**, 857 (1979)
9. F. Hill, J. Beckers, et al. SPIE Proceedings **6267**, 57 (2006)