Study of cirrus clouds and implications in the variability of laser propagation light and variability of fratricide effect

Angel Otarola[a] and Paul Hickson[b]

a) TMT International Observatory

b) University of British Columbia

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TMT
Thirty Meter Telescope

Motivation

- "AO observations (mainly LGS) are difficult to make and history [at some observatories] suggests that when atmospheric conditions are worse than median, the productivity is dramatically lower… And cirrus clouds can dramatically hurt AO.

- New generation large aperture telescopes are planning to make extensive use of multiple lasers to achieve diffraction limited imaging capabilities.
  - In the case of TMT, and for early science/operations phase, the plan is to dedicate the telescope observing time approximately as:
    - 40%, Visible seeing limited imaging/spectroscopy
    - **50%, Near Infrared diffraction limited imaging/spectroscopy**
    - 10% Mid Infrared programs

- Besides, it is of interest to have a better idea of what are the clear fraction and cirrus cloud properties (altitude and thickness) for the potential sites to host the TMT project.
  - Learning the seasonal changes in cirrus cloud and atmospheric aerosol is also of interest to know.

Goals

- Learn about:
  - <u>All year around fraction</u> of **CLEAR** and **USABLE** nights in a year at various sites where Laser Systems to support Laser Guide Star (LGS) AO are operated.
  - The statistics of altitude and thickness of cirrus clouds.
  - The statistics of optical depth for cirrus clouds and atmospheric aerosols in the upper atmosphere.
  - Changes in the these parameters as a function of month through the year.
  - Effects of cirrus in the intensity of LGS

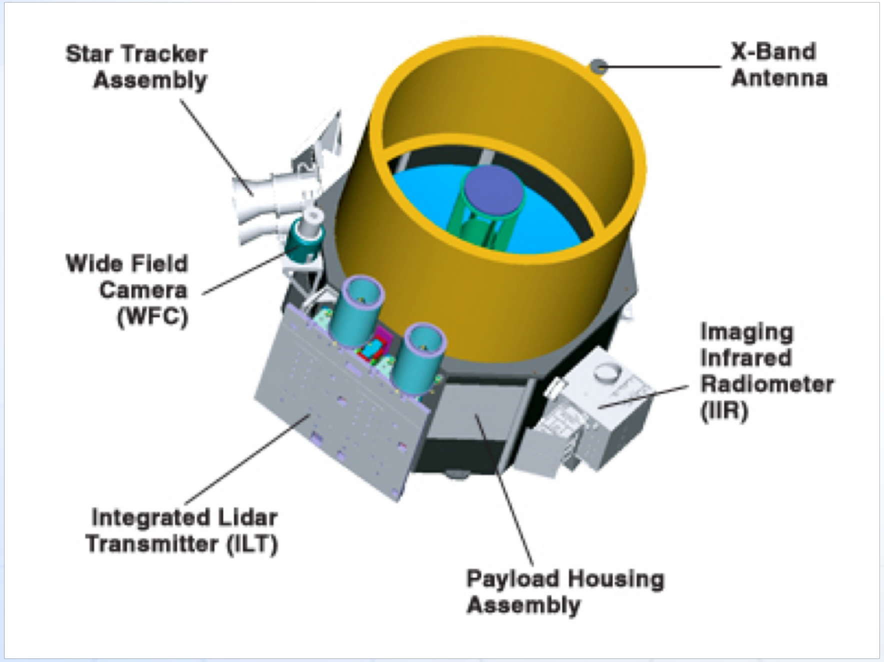
Previous Studies
Usable Nights

- Dr. Andre Erasmus and Collaborators (USABLE nights, **annual fraction**)
  - GOES-8 satellite data consist of infra-red window (10.7µm) – for CLOUDS
  - GOES-8 satellite data ((6.7µm) for water vapour
  - Images every 3 hours (0245UT, 0545UT, 0845UT, 1145UT, 1445UT, 1745UT, 2045UT and 2345UT) :
  - Cerro Tololo/Cerro Pachón (CHILE) **78.2%**
  - La Silla/Las Campanas (CHILE) **83.1%**
  - Armazones/Paranal (CHILE) **90.5%**
  - Mount Graham/Kitt Peak (USA)
  - Maunakea (USA) **71.4%**

- IAC team (Garcia-Gill et al., 2010) –from weather downtime of various telescopes
  - Canary Islands (SPAIN) (69.7% – 79.3%) **72 %**

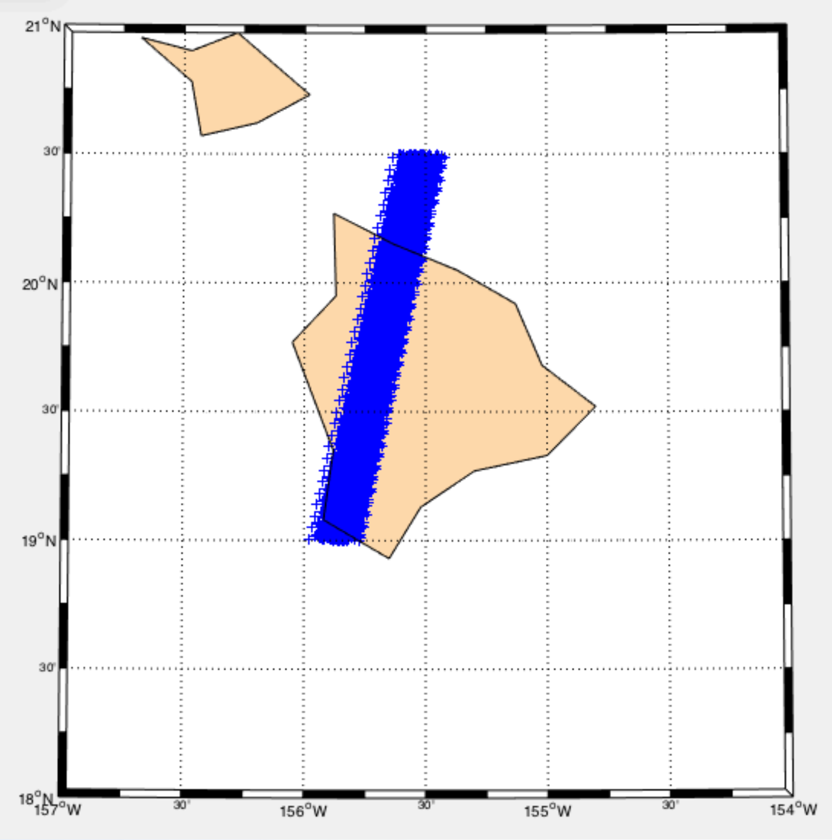
Data for this study

- We make use of observations using the CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) Sensor on board of the CALIPSO Satellite.

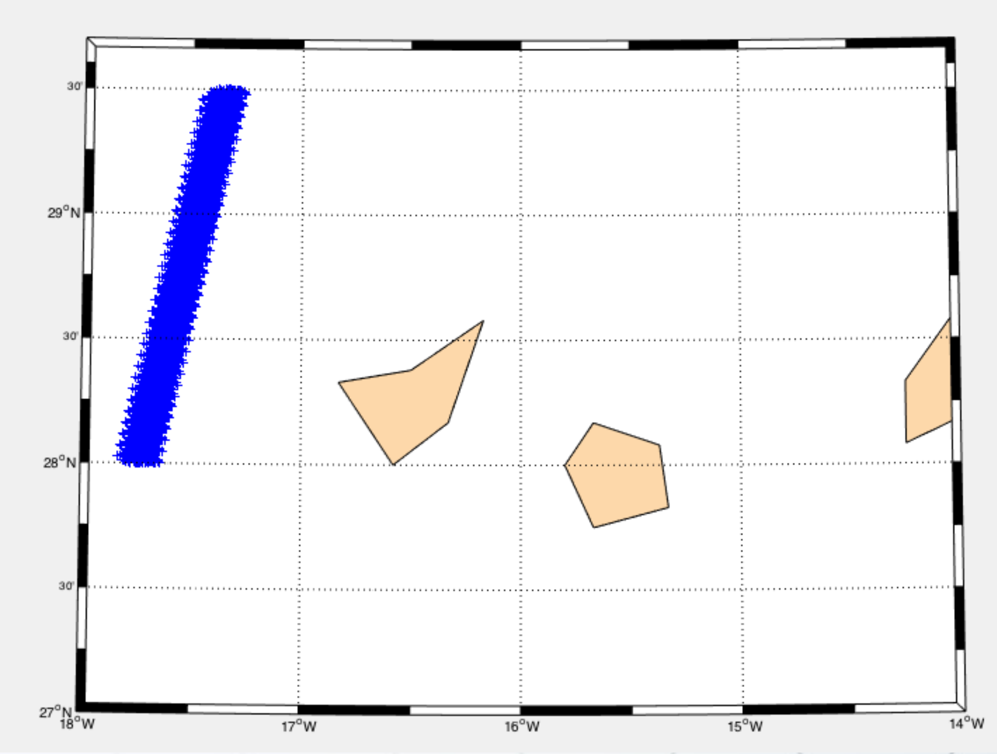


Parameter	Magnitude
Laser	Nd:YAG, diode-pumped, Q-switched frequency doubled
Wavelength	532 nm, 1064 nm
Pulse Energy	110 mJ/channel
PRR	20.25 Hz
Receiver diameter	1.0 m
Polarization	532 nm Lidar
Footprint/FOV	100 m / 130 urad
Verticl Resolution	30 – 60 m
Horizontal Resolution	5 km (above 8000 m) 333 m (below 800 m)

Examples of CALIPSO (A-Train Orbit) Data period 2006-2016



Maunakea



Canary Islands

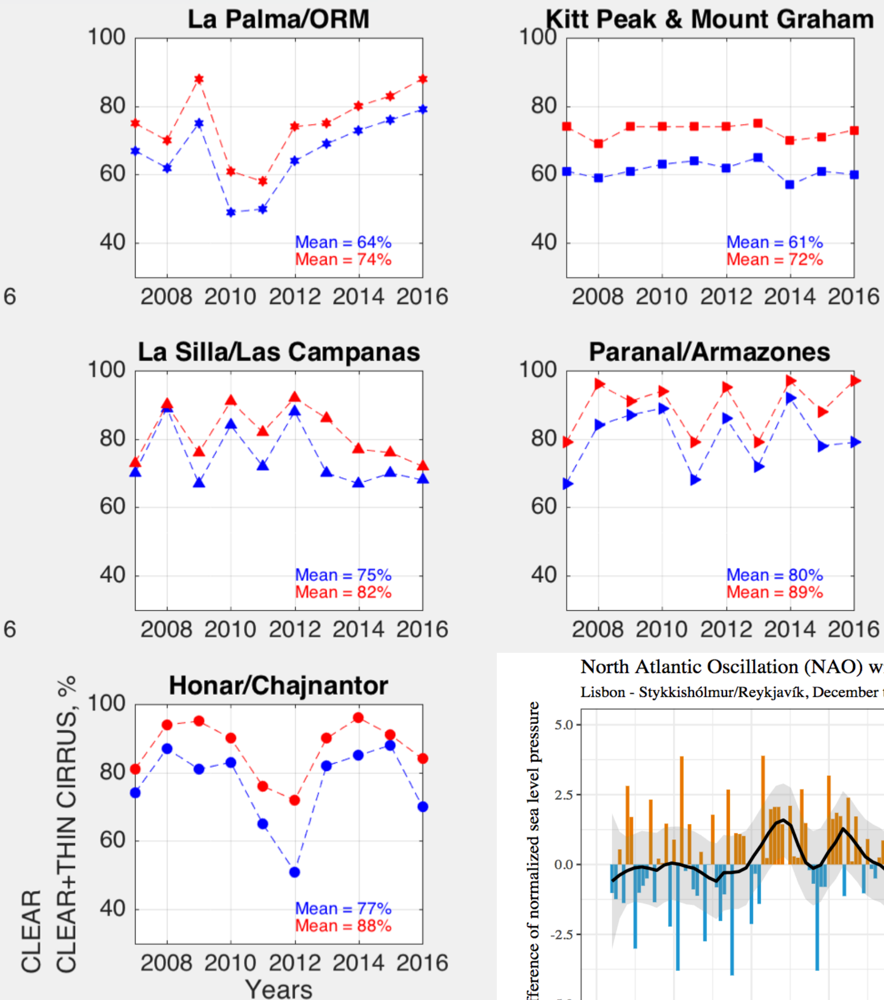
Assumptions

- Clear fraction is that when no clouds where detected by the 532 nm Lidar in the CALIPSO satellite at any level between the altitude of the site and above.

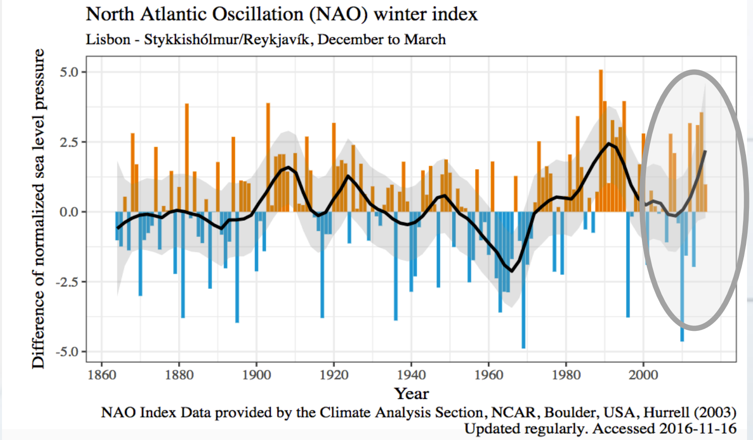
- Usable time is defined as the Clear Fraction plus the existence of **Thin Cirrus** clouds with optical depths of up to 0.3 nepers (~ 0.28 mag/airmass)
  - Typical optical depth due to molecular scattering ~ 0.05
  - ➔ Minimum atmospheric transmission ~ exp(- [0.3+0.05]) ~ **0.7**

- Only night-time data used for the statistics (information from CALIOP for day time is available but not fully analyzed)

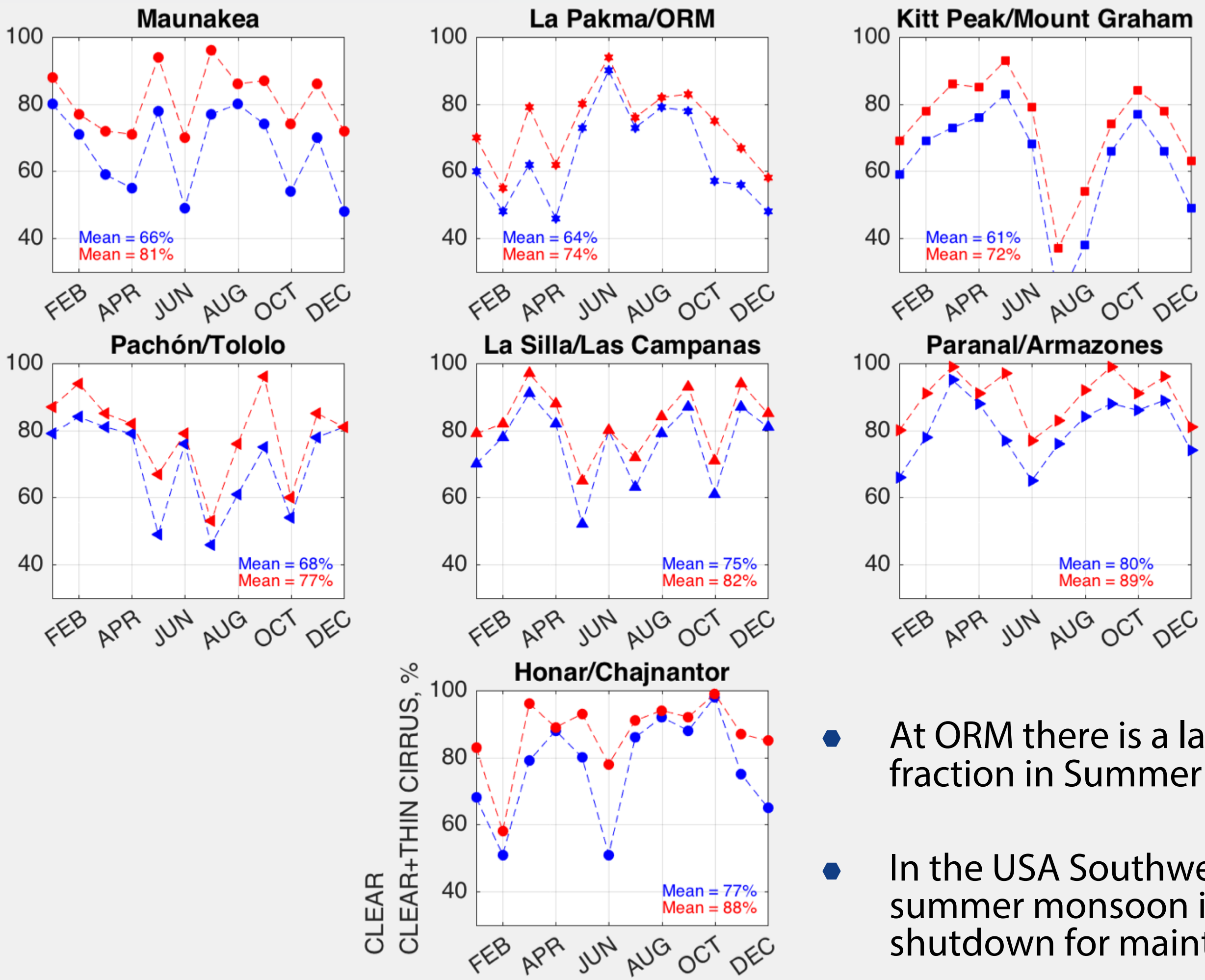
ANNUAL Trends in Clear (Blue) and Usable Time (red) for various sites of astronomical interest



- ORM Site: There is evidence the increase in usable nights ➔ + Phase of NAO
- Chile: a clear trend in the usable nights In the northward direction.



MONTHLY Trends in Clear (Blue) and Usable Time (red) for various sites of astronomical interest

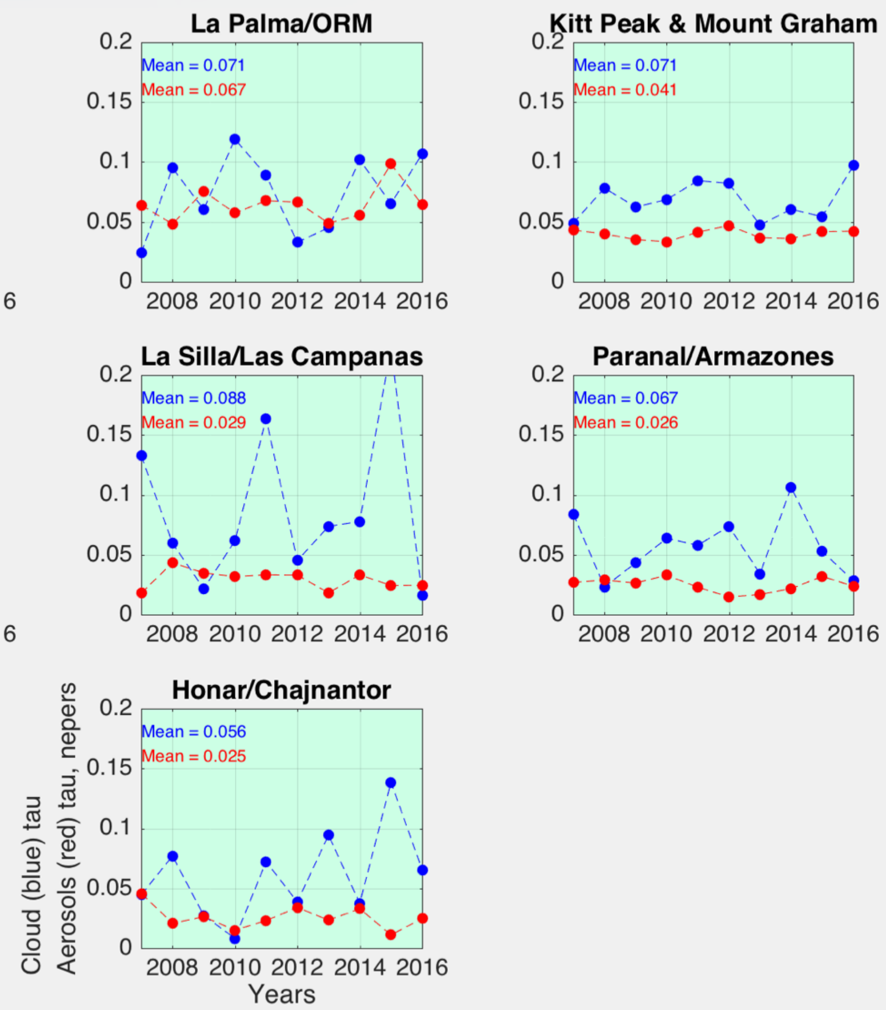


- At ORM there is a larger usable nights fraction in Summer
- In the USA Southwest the effect of the summer monsoon is evident (telescopes shutdown for maintenance)

Cirrus Cloud Parameters Statistics (Base Altitude, Top Altitude, Thickness)

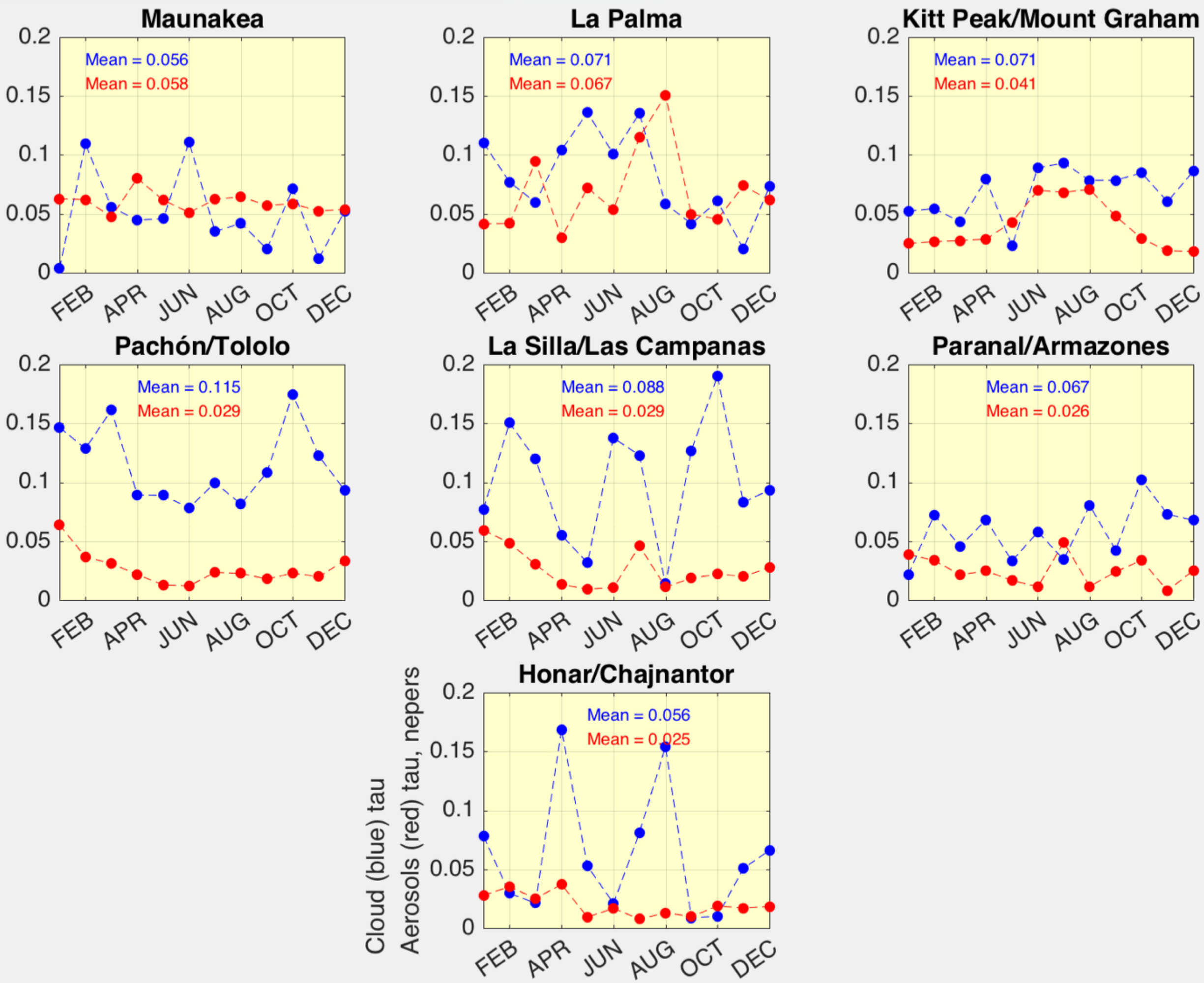
Site	Base Altitude + 1-sigma [km]	Top Altitude + 1-sigma [km]	Cloud Thickness + 1-sigma [meters]
Maunakea	11.7 ± 2.7	12.9 ± 2.7	1257 ± 713
La Palma/ORM	9.3 ± 2.0	10.7 ± 2.1	1332 ± 748
KP/MG	9.6 ± 2.8	10.8 ± 3.0	1188 ± 693
Pachon/Tololo	9.7 ± 1.9	10.7 ± 2.0	1036 ± 535
La Silla/Las Campanas	9.5 ± 2.0	10.7 ± 2.1	1152 ± 754
Paranal/Armazones	11.1 ± 2.6	12.1 ± 2.7	1032 ± 602
Cerro Honar	11.7 ± 2.5	12.8 ± 2.5	1068 ± 595

ANNUAL Trends in Optical Depth Cirrus (Blue) and Aerosols (red) for various sites of astronomical interest



- Norther hemisphere sites show a higher level of aerosols than the southern hemisphere sites. (almost a factor of 2)

ANNUAL Trends in Optical Depth Cirrus (Blue) and Aerosols (red) for various sites of astronomical interest



- ORM Site: There is clear evidence of increase in aerosols level (dust) in summer → Calima

Summary of Aerosols &Cirrus Clouds Statistics
Maunakea & La Palma only

Maunakea Quartiles	Aerosols optical depth [nepers]	Cirrus clouds optical depth [nepers]	Cirrus Clouds Thickness [m]	Cirrus Clouds Base altitude [km]
25%	0.022	0.015		
50%	0.058	0.056	1257 ± 713	11.7 ± 2.7
75%	0.130	0.130		

La Palma/ORM Quartiles	Aerosols optical depth [nepers]	Cirrus clouds optical depth [nepers]	Cirrus Clouds Thickness [m]	Cirrus Clouds Base altitude [km]
25%	0.029	0.034		
50%	0.067	0.071	1332 ± 748	9.3 ± 2.0
75%	0.146	0.149		

Lombardi et al., A&A , 483 (2008) – ORM - Dust Storms with extinction up 0.2 mag/airmass

How Cirrus Could Affect AO Performance

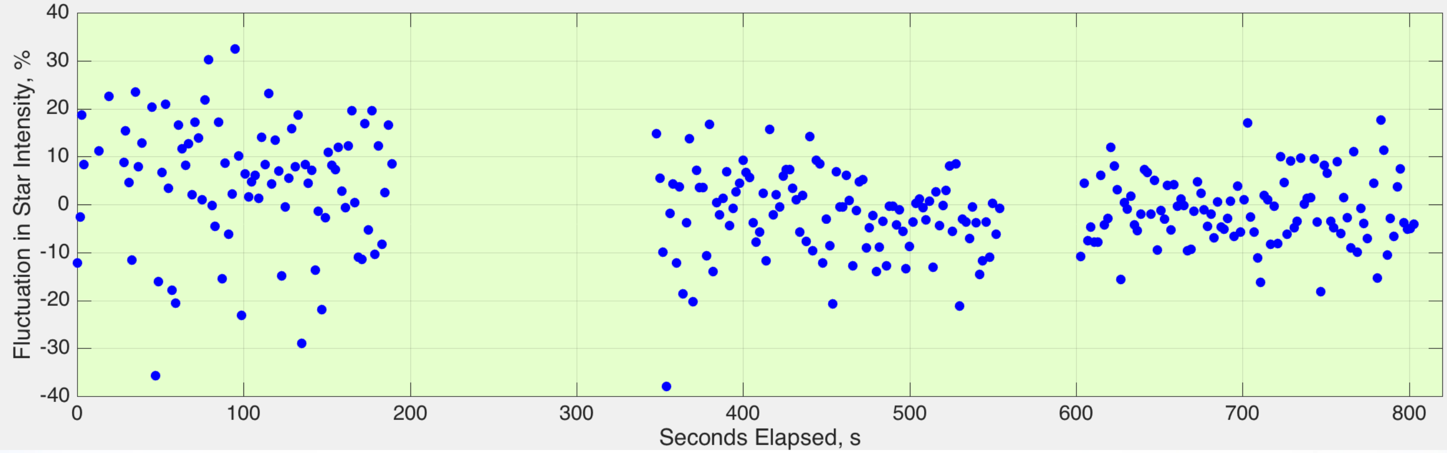
- Introducing fluctuations in the laser power propagating from the telescope to the mesosphere.
  - Therefore reducing the intensity of the LGS photon flux return

- Inducing variations in the intensity of the fratricide effect (in LGS systems with center-launched lasers)

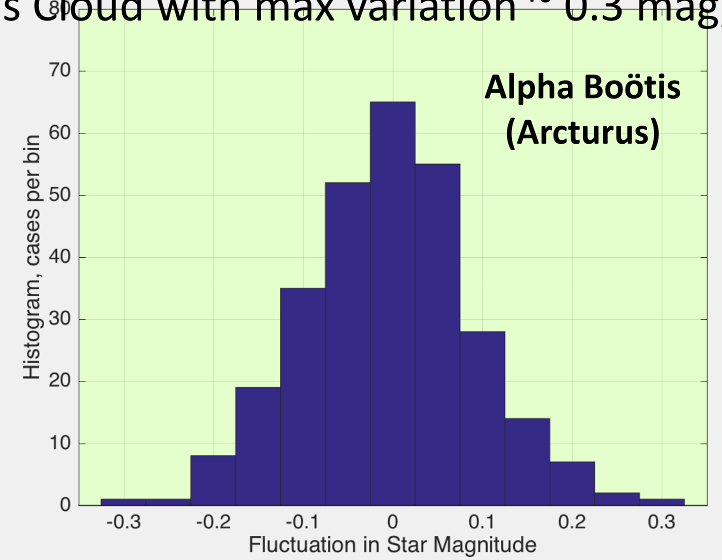
- Inducing photon noise in the WFS sub-apertures that could be harder to calibrate out

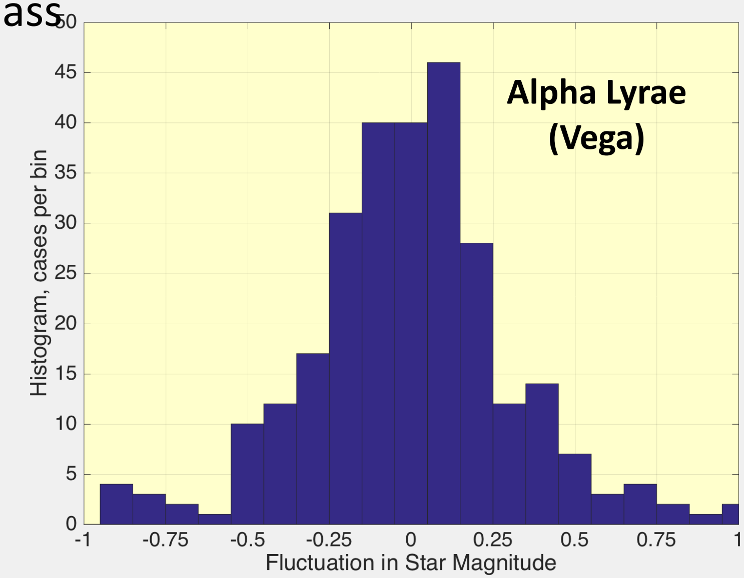
Time Variability on Cirrus Optical Depth

1σ ~ 0.1 mag/airmass (10%) in time scales of 3 secs



Cirrus Cloud with max variation ~ 0.3 mag/airmass





LGS Photon Flux Return

	Optical Depth MK	Optical Depth ORM
Rayleigh	0.045	0.056
O3 Chappuis Band	0.031	0.031
Aerosols (dust)	0.060	0.063
Cirrus Clouds	0.049	0.074
Total	0.185	0.224
Atmospheric Attenuation	**0.831**	**0.799**

	MK	ORM
Laser Power	20 W	20 W
Zenith Angle	0 deg	0 deg
D2b repumping	10%	10%
Na Atoms (atoms/m^2)	4x10^{13}	4x10^{13}
LGS spot size	0.6	0.6
Geomagnetic Field	(that of the site)	(that of the site)
Site Altitude	4050 m	2250 m
LGS Photon return at tel. aperture	**16.5x10^6** ph/m2/s	**14.7x10^6** ph/m2/s

Detection throughput = 0.3477

Frame = 800 Hz

SA size = 0.5^2 m^2

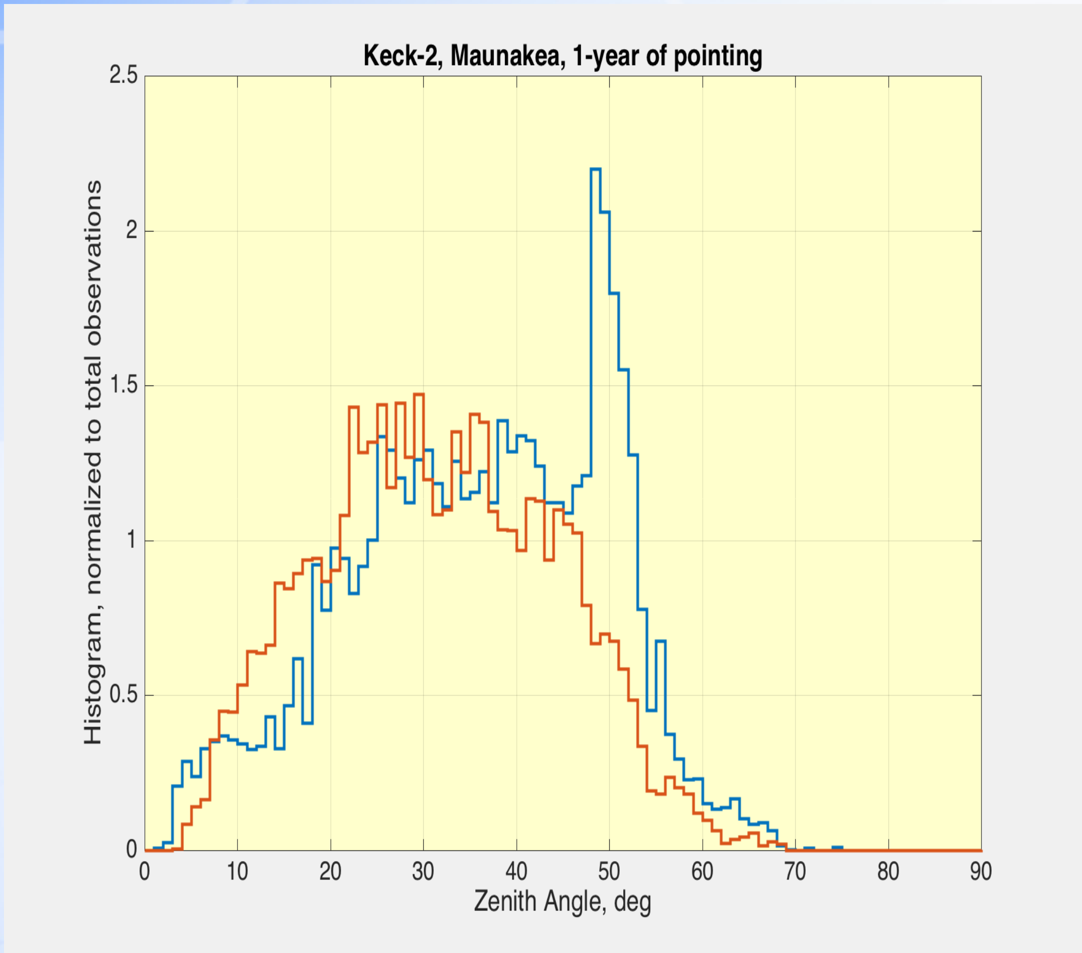
PDE (MK) = 1793 ph/SA/frame

PDE (ORM) = 1597ph/SA/frame

TMT Requirement 900 ph/SA/frame

30% increase in cirrus optical depth → 3.6% decrease in PDE

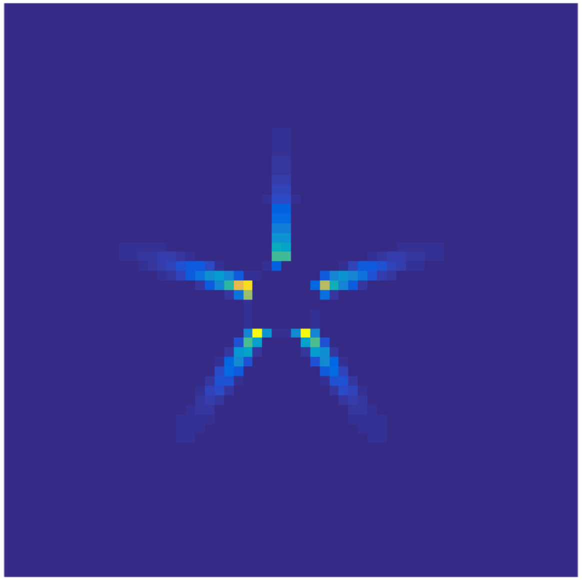
Zenith Angle Histogram
Keck 2 – one year of pointing
blue-South / red-North



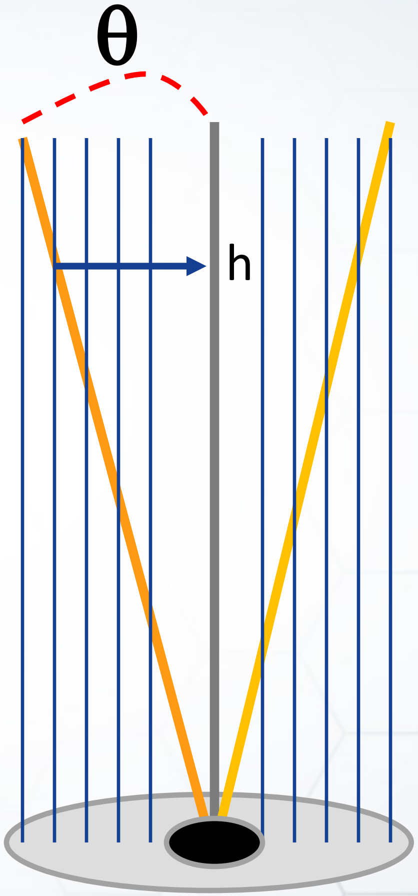
- Ron Holzlöhner as shown that in MK the “sweet spot” for LGS return is ~ 36o elevation (54o ZA) which matches the location of the Galactic Center.
- Domenico Bonaccini & collaborators have shown important variability (factor of 2 to 3) in the LGS photon flux return as the laser propagates in directions that benefit less from D2b re-pumping.
- Nightly fluctuations in the Na column density can be large too.
- If we add the effects of cirrus cloud and atmospheric aerosols that will limit the zenith angle range where is possible to meet specifications

TMT Fratricide Pattern on WFS-0

Due to Molecular Rayleigh Backscattered Photons (for Center Launch LGS systems)



Height above ground	Sub Aperture
10 km	4
30 km	11
40 km	14

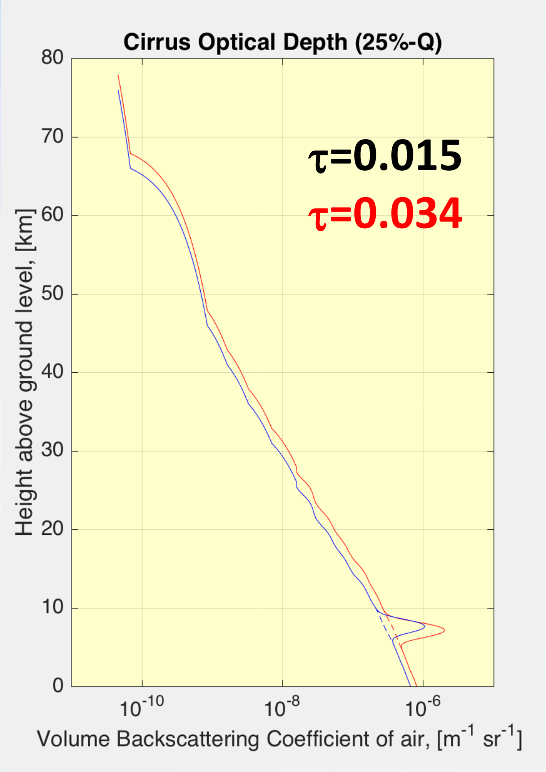


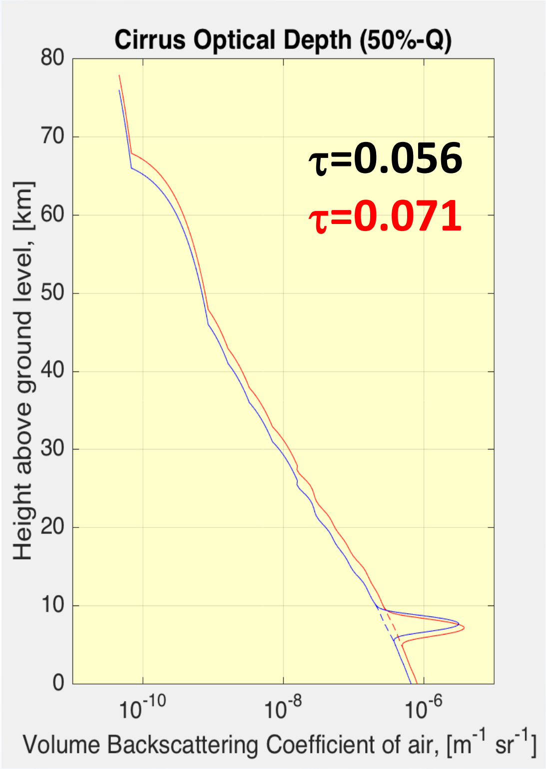
WFS-0 Aperture Plane

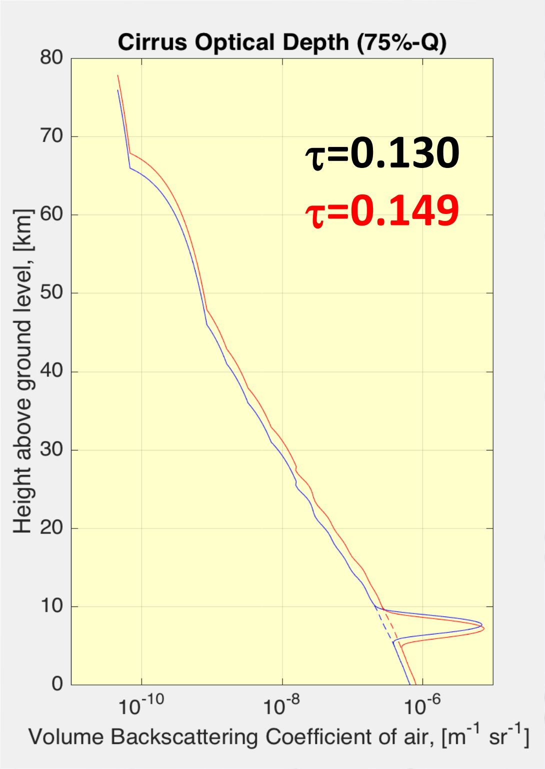
SA = int { h*sin(θ)/0.5 }

Volume Backscattering Coefficient $[m^{-1}\ sr^{-1}]$

Blue (Maunakea) Red (ORM)







- **At the ORM site, because of its higher density, we expect a ~30% higher level of backscattered photons**
- **Relative to the ground, Cirrus Clouds will affect rely the same Sub Apertures (independent of the site)**

Conclusions

- Within ± 5% both sites are comparable regarding the usable number of nights.
- At ORM the cloudiness/precipitation is influenced by the +/- phase of the North Atlantic Oscillation.
- At ORM, there is a clear winter/summer signal in the statistics of usable nights (more in Summer season).
- Chile: a clear trend in the usable nights In the northward direction.
- ORM Site: There is clear evidence of increase in aerosols level (dust) in summer → Calima.
- The CALIOP data, seems to indicate the integrated aerosol levels in northern hemisphere is almost a factor of 2 higher than in southern hemisphere sites.
- Cirrus clouds introduce changes in optical depth of order 10%-30% in time scales of few seconds. This affects the laser power able to reach the mesosphere, and the magnitude of the LGS photon flux return. But also, will induce fluctuations in the photons backscattered to the WFS's apertures from the lower levels of the atmosphere.
- Due to the lower altitude (and consequently increase in atmospheric density) it is expected about 30% larger photon noise in the SA affected by fratricide effect.

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- The CA[illegible] aerosol levels in northern hemi[illegible] in southern hemisphere sites.
- Cirrus [illegible] depth of order 10%-20% in time scales o[illegible] laser power able to reach the mesosph[illegible] of the LGS photon flux return. But also, will induce flu[illegible] hotons backscattered to the WFS's apertures from the lo[illegible] the atmosphere.
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¡Gracias!

Acknowledgments

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TMT Laser Guide Star Asterisms

3.4.1.1 Asterism generation requirement

[REQ-2-LGSF-0400] The LGSF shall be able to project the NFIRAOS asterism, which consists of 6 LGS, 5 equally spaced on a circle of radius of 35 arcsec and one additional on-axis guide star.

Discussion: NFIRAOS is the TMT early light LGS Multi Conjugate Adaptive Optics (MCAO) system.

[REQ-2-LGSF-0410] The LGSF shall be able to project the MIRAO asterism, which consists of 3 LGS equally spaced on a circle of radius of 70 arcsec.

[REQ-2-LGSF-0420] The LGSF shall be able to project the MOAO asterism, which consists of 8 LGS, 3 equally spaced on a circle of radius of 70 arcsec and 5 equally spaced on a circle of radius of 150 arcsec.

[REQ-2-LGSF-0430] The LGSF shall be able to project the GLAO asterism, which consists of 5 LGS, 4 equally spaced on a circle of radius of 510 arcsec and one additional on-axis guide star.

[REQ-2-LGSF-0440] The LGSF shall be able to project additional asterisms with up to 9 LGS and radii varying from 5 arcsec to 510 arcsec.

Discussion: The LGSF asterisms for the early light and first decade AO systems are represented in Figure 4.