Analysis of "fratricide effect" observed with GeMS and its relevance for large aperture astronomical telescopes

Angel Otárola[1], Benoit Neichel[2], Lianqi Wang[1], Corinne Boyer[1], Brent Ellerbroek[1], François Rigaut[2,3]

[1]Thirty Meter Telescope Project, 1111 South Arroyo Parkway, Pasadena, CA, 91105, USA

[2]GEMINI Observatory, c/o AURA, Casilla 603, La Serena, Chile

[3]Mt. Stromlo Observatory, Australian National University, Australia

What is the Fratricide Effect?

Fratricide effect, in the Adaptive Optics (AO) field, is when photons back-scattered from a laser propagating through the atmosphere are detected in the Wave Front Sensor (WFS) detectors used to monitor the Laser Guide Stars (LGS) created by other lasers in a given LGS asterism. The photons due to fratricide effect increase the noise in those detector's pixel affected by this effect. This, decreases the accuracy in the computation of the WFS centroids, ultimately degrading the performance of the LGS's wavefront reconstruction algorithms.

Goals of this study

◆Learn about the absolute magnitude and time-variability of the "fratricide" photon flux, observed with the Gemini Multi-Conjugate Adaptive Optics System (Gemini MCAO, a.k.a. GeMS).

◆Attempt the physical modeling of fratricide photon-flux resulting from photons back-scattered in:

- Atmospheric molecules (so Called Rayleigh backscattering)
- Atmospheric aerosols (dust particles in the atmosphere)
- Cirrus clouds (Ice crystals). Cirrus clouds form in the upper levels of the troposphere at varying altitude and can be of varying thickness.

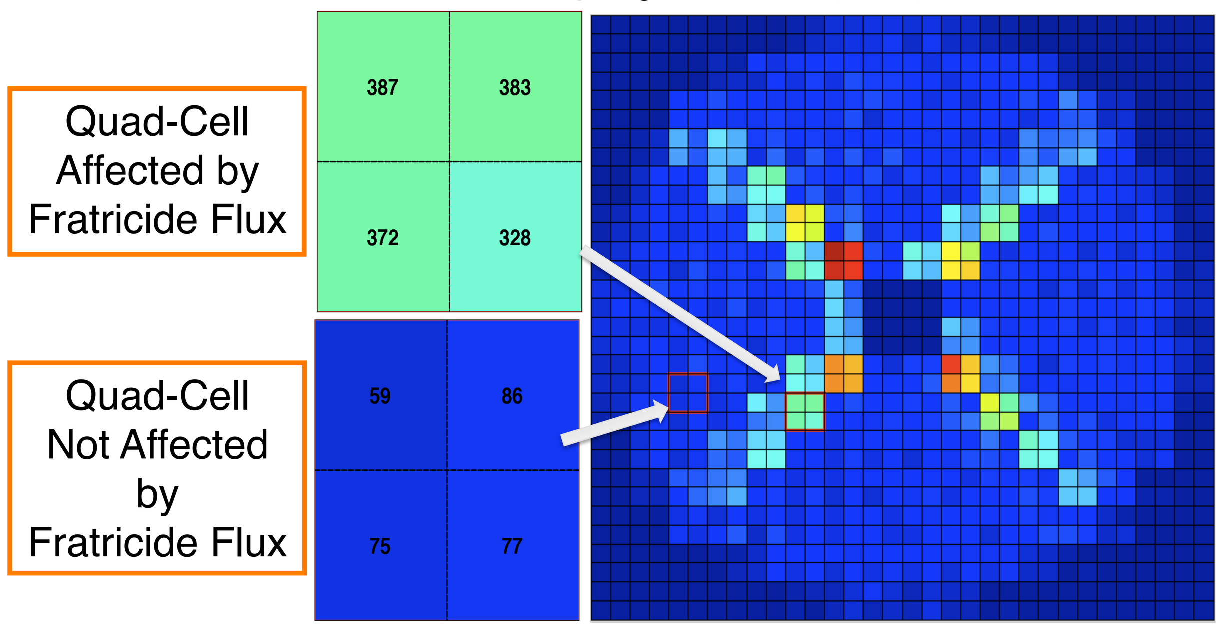
Data used in this study

The data available for this study consists of:

- 19 GeMS WFS data-cubes, that were obtained at different times in the course of 2011 and 2012. **In each case, lasers are propagated in the local zenith direction.**
- Each data-cube is a 3D array that includes the time series of photon-fluxes detected in a 32x32 pixels detector array for each of the 5 LGS in the GeMS asterism (5 Wavefront Sensors).

Example of a WFS Frame and the Fratricide Photon contamination

Power Transmitted: 26.3W
Units are photons/pixel/frame
Frame sampling = 200 Hz (5ms)

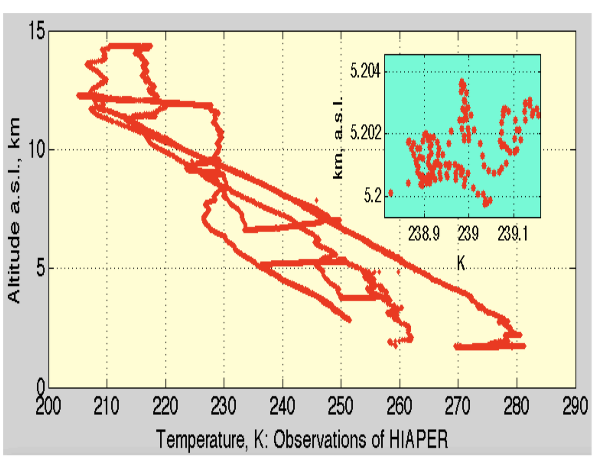


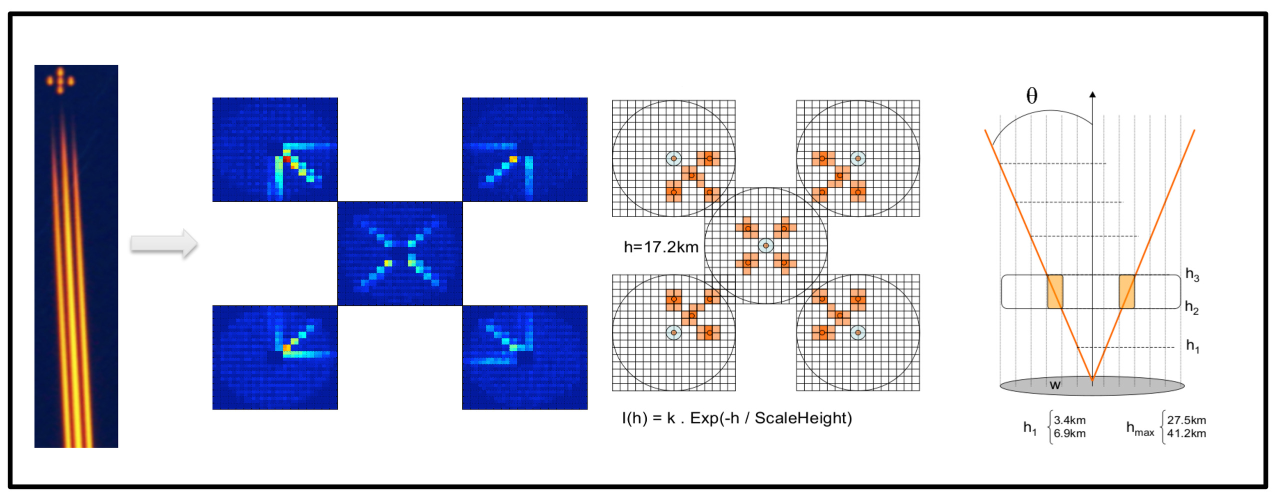
The fratricide pattern generated by GeMS and its sources

- The geometric pattern of the Fratricide Effect depends on the number of lasers being launched (number of stars in the artificial asterism), and on the angular geometry of the asterism.
- Sources of back-scattered photons:
  - The molecular volume back-scattering (β) is proportional to the atmospheric density (air molecules number density). It can be shown that molecular photon-flux variability is proportional to the fractional variability of atmospheric temperature (see equations below). **Temperature fluctuations in 1-s time scale are below 1%.**
  - Cirrus clouds back-scattering affects specific pixels depending on clouds altitude and their thickness.
  - Atmospheric aerosols (dust), it contributes to back-scattering at lower altitude levels, and depends on the concentration of dust particles. Advection of dust a mid levels in the troposphere with local wind can be a source of variability in the fratricide photon flux due to aerosols.

$$\beta(\lambda,h)=\beta_S(\lambda,h=0)\cdot\frac{T(h=0)}{P(h=0)}\cdot\frac{P(h)}{T(h)}$$

$$\frac{\delta\beta}{\beta}=\frac{\delta P}{P}-\frac{\delta T}{T}\propto-\frac{\delta T}{T}$$





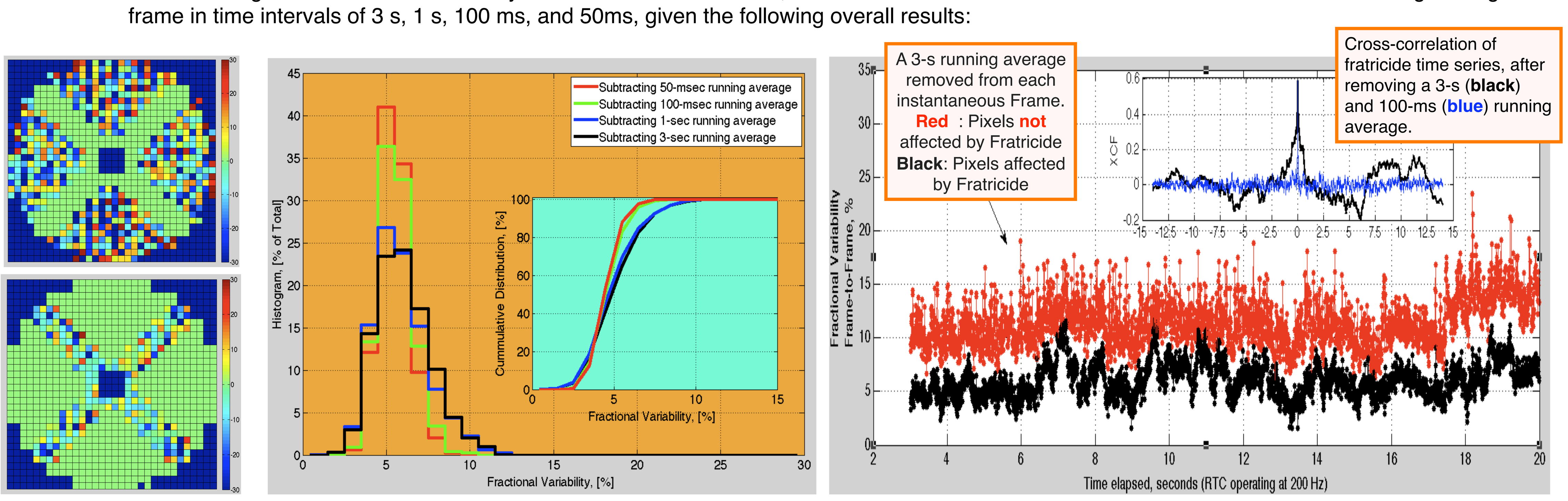
Analysis Methods & Results

◆ ***Method 1: WFS Frame-to-Frame time fractional-variability of the fratricide effect.*** This can be done by subtracting consecutive frames during an observation and studying the statistics of those differences.

- The photon flux in a given pixel identified by its position (*i,j*) in the WFS detector at a a given time (*t*) is the sum of the photon fluxes from: the LGS star which can vary in time as a function of the Na atoms column density (C_{Na}), of laser power (*P*), and of changes in the atmospheric optical depth (τ_{atm}), as well as the detector photon-noise (assumed of normal distribution with magnitude σ_e). Besides, those pixel affected by fratricide effect (for which the $\delta_{i,j}=1$) get contributions from three sources of back-scattering: Molecular Rayleigh (*R*), Atmospheric Aerosols (*A*), and Cirrus Clouds (*C*),**. Each of these contributions has its own time-scale variability**.

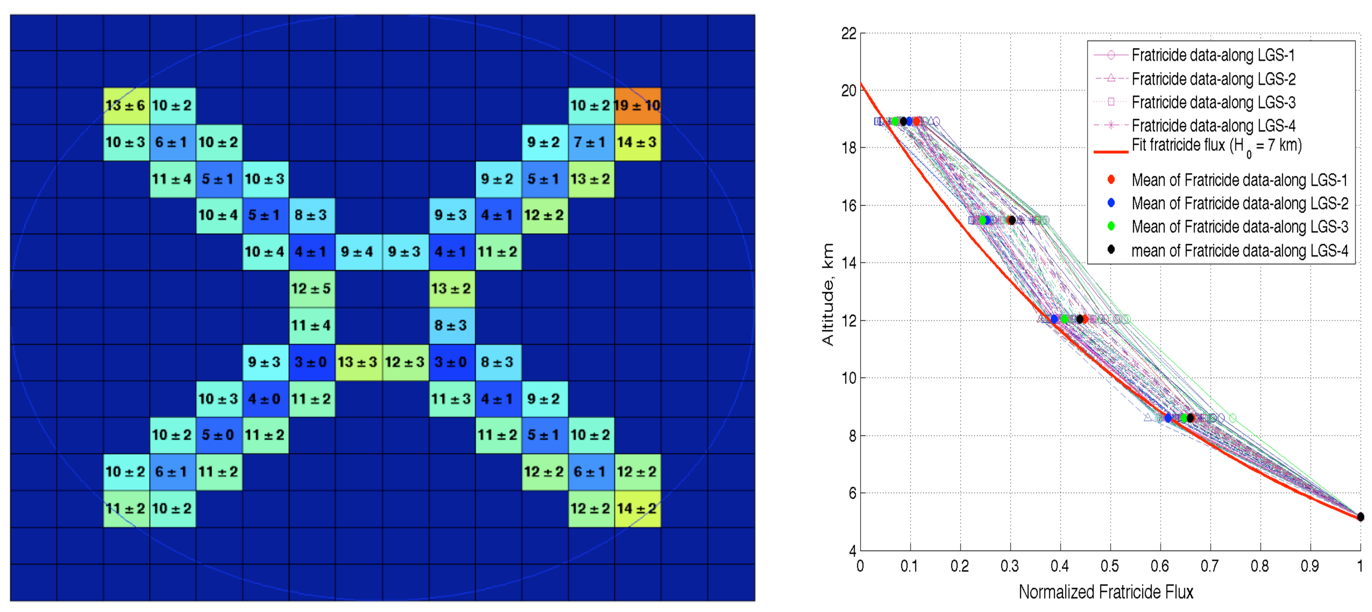
$$\Phi_{i,j}(t)=\Phi_{LGS}(t,P,C_{Na},\tau_{atm})+\sigma_e\cdot N(0,1)+\delta_{i,j}\cdot\left\{\Phi^R_{i,j}(t,P)+\Phi^A_{i,j}(t,P)+\Phi^C_{i,j}(t,P)\right\} \qquad \text{(Eq. 1)}$$

- When looking at the fratricide variability from WFS frame-to-frame, we subtracted from each instantaneous WFS frame the running-average frame in time intervals of 3 s, 1 s, 100 ms, and 50ms, given the following overall results:



◆***Method 2: Fractional-Variability is obtained by subtracting from each fratricide-affected Sub-Aperture (a Quad Cell composed of 2x2 detector pixels) the signal from a neighbor Sub-Aperture not affected by the fratricide effect.*** In this approach, it is assumed that the 1st and 2nd terms in the Equation 1 are of similar magnitude between the sub-apertures. So, everything that will be left behind in the subtraction is the photon-flux due to fratricide effect.

- Results are shown below in percentage. It is very easy to notice that the fractional variability is smaller in those cells close to the center (and of order 5%, 1-sigma/mean-fratricide-flux) increasing to about 10% at the edge (where the fratricide flux magnitude is lower). The figure on the right shows the profile of the fratricide photon-flux as a function of altitude (i.e. as a function of Sub Aperture position radially out from the center). The profiles are normalized to the fratricide photon flux observed in the corresponding center Sub Aperture) **The purely atmospheric Rayleigh backscattering should decrease with the scale height of atmospheric density**.



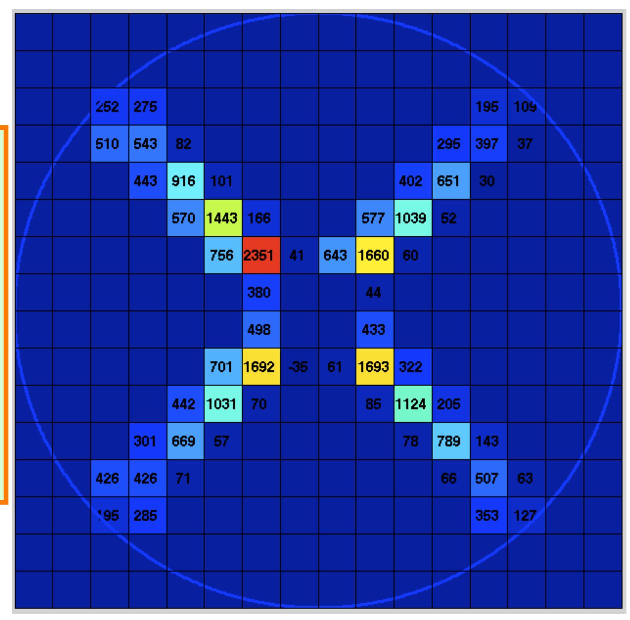
Physical Modeling of the Fratricide Effect: Comparison of the magnitude of photon flux Observations & Model

- A physical model following the contributions in Eq. 1 was developed by Lianqi Wang (Wang et al., 2010) The following figures compare the absolute magnitude of the observed Fratricide effect by GeMS and the results from a physical model that uses a profile of temperature and barometric pressure for the GEMINI South Observatory location.

GeMS Observation

Magnitude of the Photon Flux due to Fratricide Effect In WFS-0

Date: Dec 16, 2012
Total Power (5 laser) = 26.3 W



Model Parameters

Power = 26.3W Total
(5.26 W per Laser Beam)

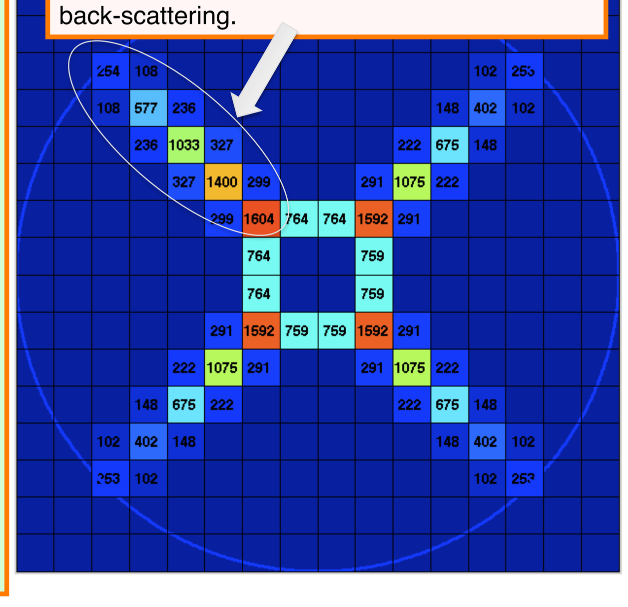
BTO Throughput = 0.53
Downlink Throughput = 0.483

Temperature & Pressure Profiles for the GEMINI South Observatory site

Cirrus Cloud centered at 13 km above ground and of 6 km thick.

Total Optical Depth =0.16
Cirrus Cloud Optical Depth = 0.0451

The region indicated by the arrow includes the effect of a Cirrus Cloud. The others, only include the effect of molecular and aerosols back-scattering.



Conclusions

[1] A total of 19 CB files, observed in the period of 2011-2012 by GeMS, including the photon flux detected in the WFS-0 were analyzed to learn the level of fractional variability in the time fluctuations of fratricide effect. This fluctuation was found to be of 5% (1-sigma/mean). The data was analyzed by two methods, one subtracting consecutive WFS frames and another by removing from a given Quad-Cell affected by fratricide, the flux detected in a nearby cell not affected by fratricide photons**. The level of observed photon-flux fractional variability is larger than expected from purely atmospheric temperature fluctuations.**

[2] The 5% (1-sigma/mean), or 10% (2-sigma/mean) is **well within the margin of uncertainty assumed by the TMT Project for simulations of the AO system NFIRAOS.**

[3] A physical model was developed to represent the fratricide effect for simulations of centroiding algorithm performance. The results indicate the physical model is able to represent the photon fluxes magnitude due to fratricide.

Further Reading

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Cortés, A., et al., Atmospheric Turbulence Profiling Using Multiple Laser Star Wavefront Sensors, 2012, *Mon. Not. R. Astron. Soc., 427, 2089-2099.*