Update on Sun/Moon photometer for CTA

Jakub Juryšek

Cimel CE318-T

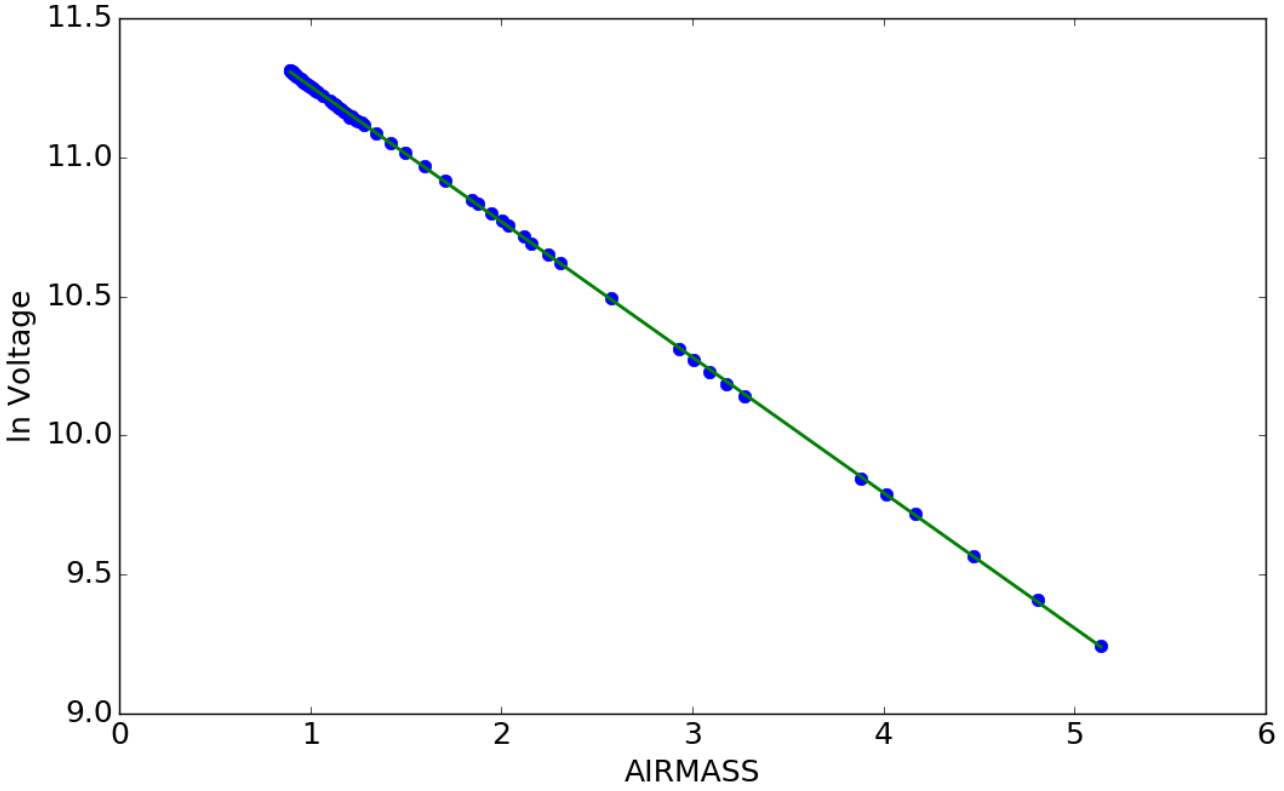
- Sun/Moon photometer for Cherenkov Telescope Array
- Installed at the Southern CTA site close to the Cerro Paranal in Chile (2154 m.a.s.l.)
- 9 photometric pass-bands, control unit with 32 GB internal memory, standalone, GPS synchronization, integrated in AERONET network providing diurnal AODs → cross-check of our methods
- High cadence of measurements – all pass-bands every three minutes
- High precission:
  Uncertainties in AOD < 0.01 (diurnal) and < 0.02 (nocturnal) in 500 nm pass-band

Cimel CE318-T

- **June – September 2016**:
  measurements at the site
- **September - November 2016**:
  diurnal calibration in Goddard
- **March – June 2017**:
  measurements at Pierre Auger Observatory, cross-calibration campaign with Raman Lidar and FRAM telescope (processing is still in progress..)
- **Since August 2017**:
  back at the CTA-S site and measuring..

Calibration: diurnal measurements

- Field photometers are usually calibrated (diurnal measurements only) at GSFC by comparison with several master instruments.
- The photometer is placed at almost perfect place → we can calibrate by ourselves with the use of long time-base data.
- Calibration of diurnal operation mode is straightforward → classical Langley method.



- Labert-Boguer's law

$$V = \frac{V_0}{R^2} e^{-m\tau}$$

$$\ln V = \ln\left(\frac{V_0}{R^2}\right) - m\tau,$$

where V_0 is extraterrestrial voltage (calibration constant), R is distance of the Sun, m is airmass and τ is optical depth.

Calibration: diurnal measurements

λ (nm)	$\sigma_{V0\,\mathrm{CTA}}$ (%)	$\frac{(V_{0\,\mathrm{CTA}}-V_{0\,\mathrm{AERO}})}{V_{0\,\mathrm{AERO}}}$ (%)
340	1.4	2.4
380	1.2	2.8
440	0.9	1.4
500	0.9	1.2
675	0.7	0.6
870	0.6	0.4

Table 1: Precision of calibration constants for diurnal observation and comparison with AERONET.

- Uncertainties of V0 within (0.6, 1.4) %
- Differences between our and AERONET calibration within (0.4, 2.8) % → under 2 % if we calibrate on data from 2016 only → consistent with declared stability of V0 for the photometer ~ 1 % change per year

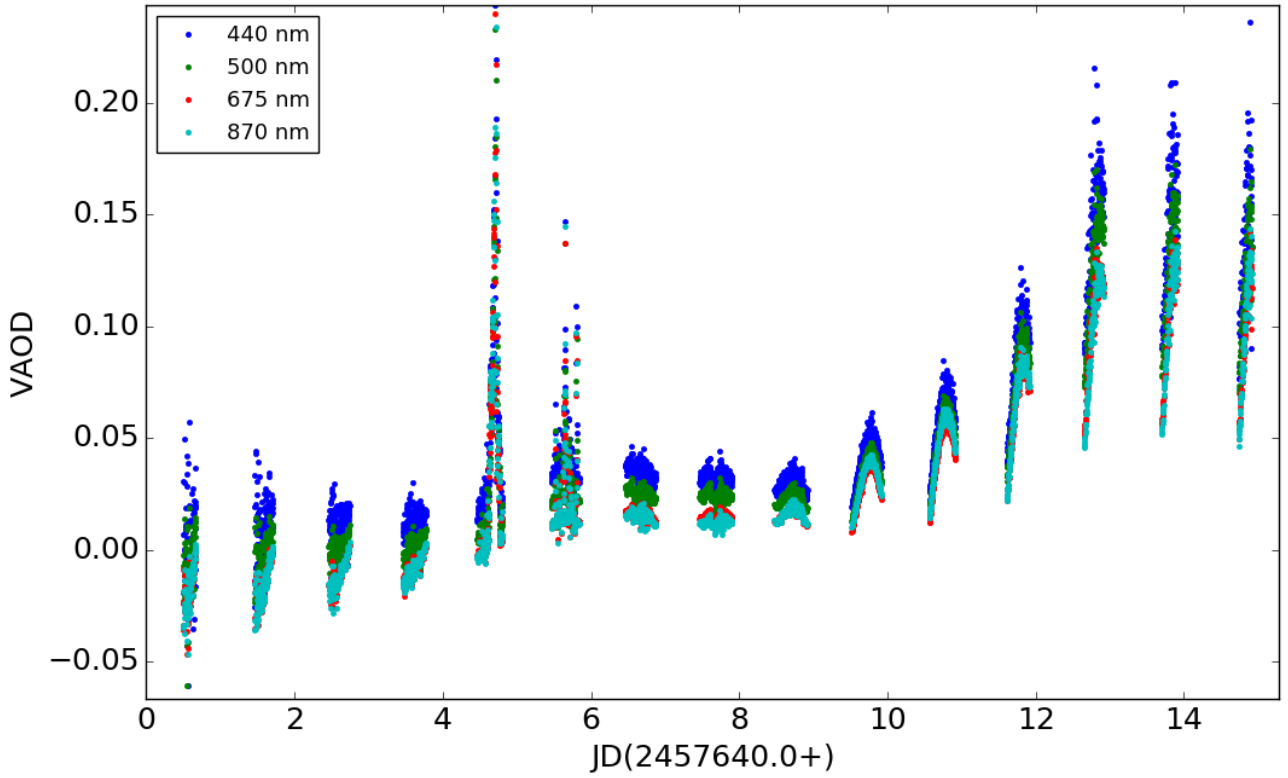
Calibration: nocturnal measurements

- Lunar-Langley:

$$\ln V = \ln \kappa + \ln I_0 - m\tau,$$

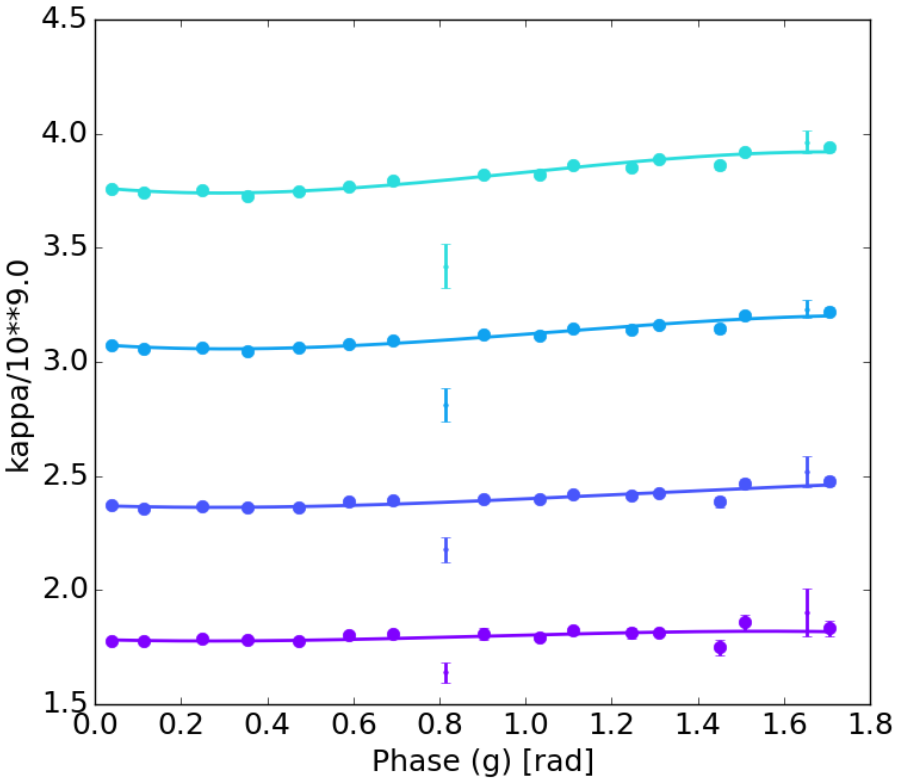
$$I_0 = \frac{A\Omega_M E}{\pi},\ E = \frac{\int E_s(\lambda) R(\lambda) d\lambda}{\int R(\lambda) d\lambda},$$

- But there is a big problem with Lunar-Langley method → Phase dependence of calibration 'constants' → imperfection of the ROLO model?
- If we assumed κ really is constant, we got wrong AODs → strong dependence on airmass, many AODs < 0 (see also Barreto et al. 2017)

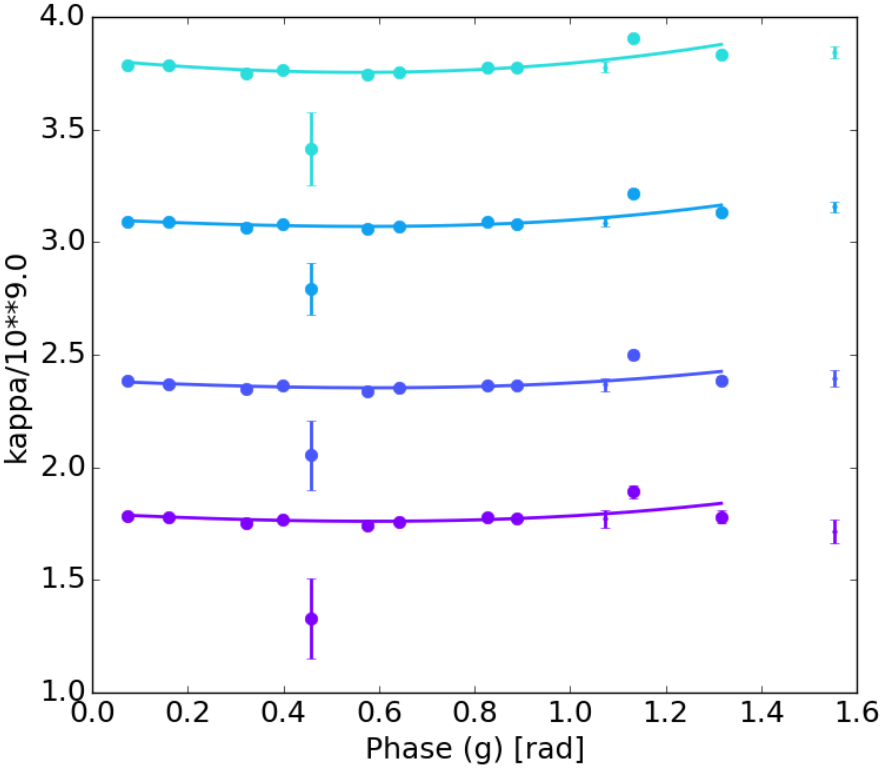


Calibration: nocturnal measurements

- **Methods of solution:**
  - Barreto et al. 2017 kept the κ constant and fitted differences between extrapolated diurnal AODs and measured nocturnal AODs by polynomial function of Moon phase, modulated by airmass.
  - Our approach is to say that κ is no longer 'constant', measure many Lunar-Langleys and fit dependency $\kappa(g)$ with a third order polynomial.



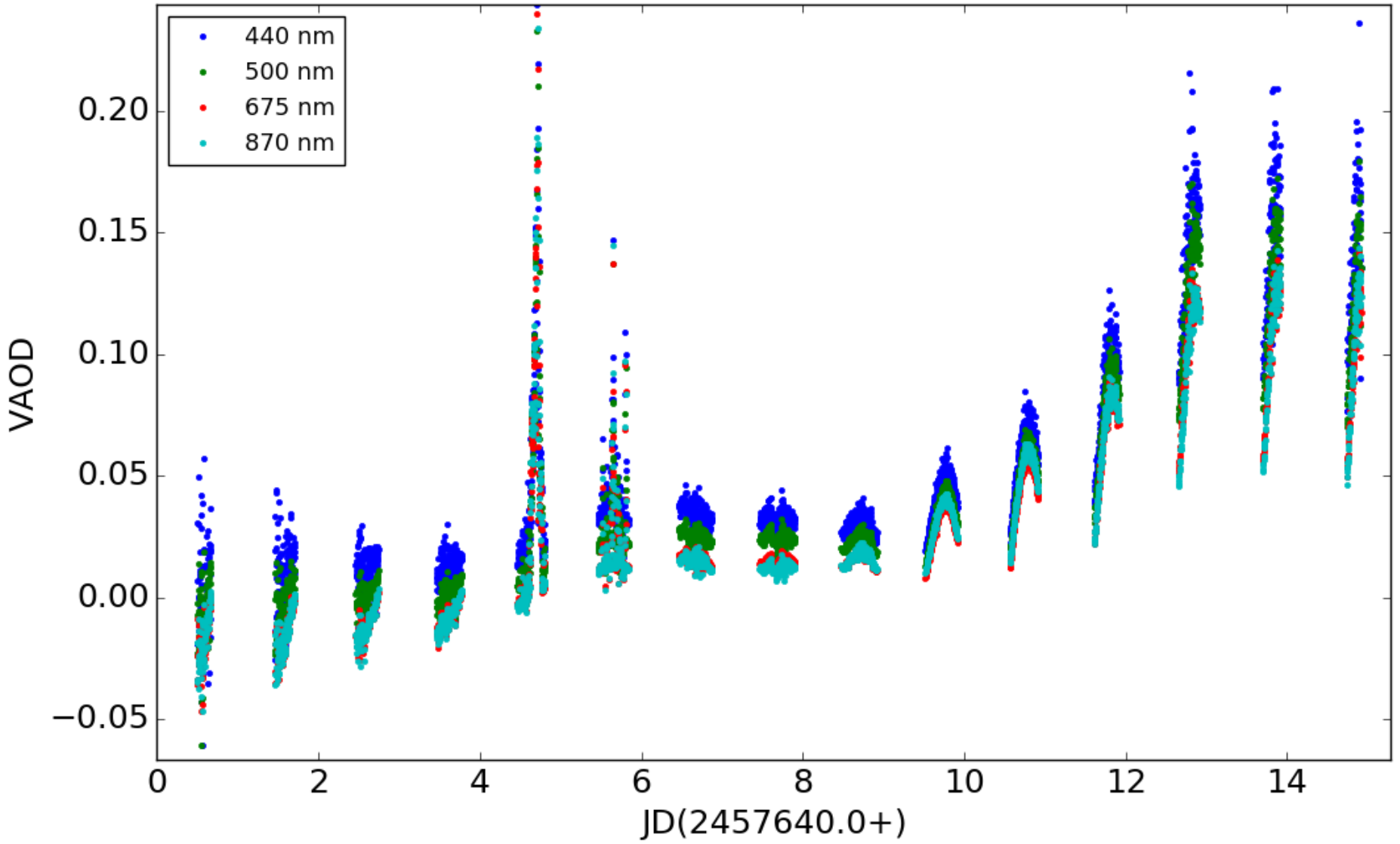
before full moon



after full moon

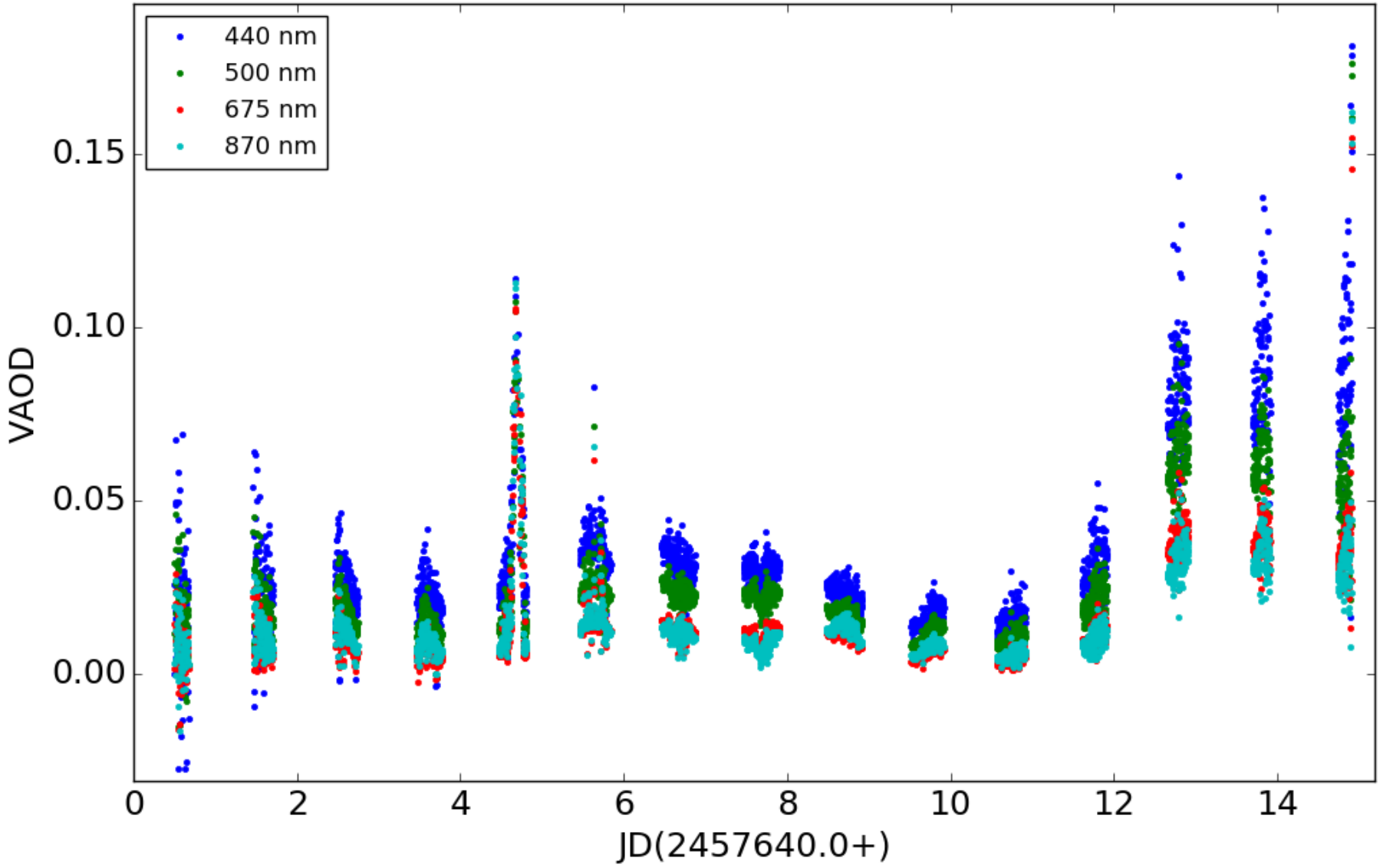
Calibration: nocturnal measurements

- Before our correction..



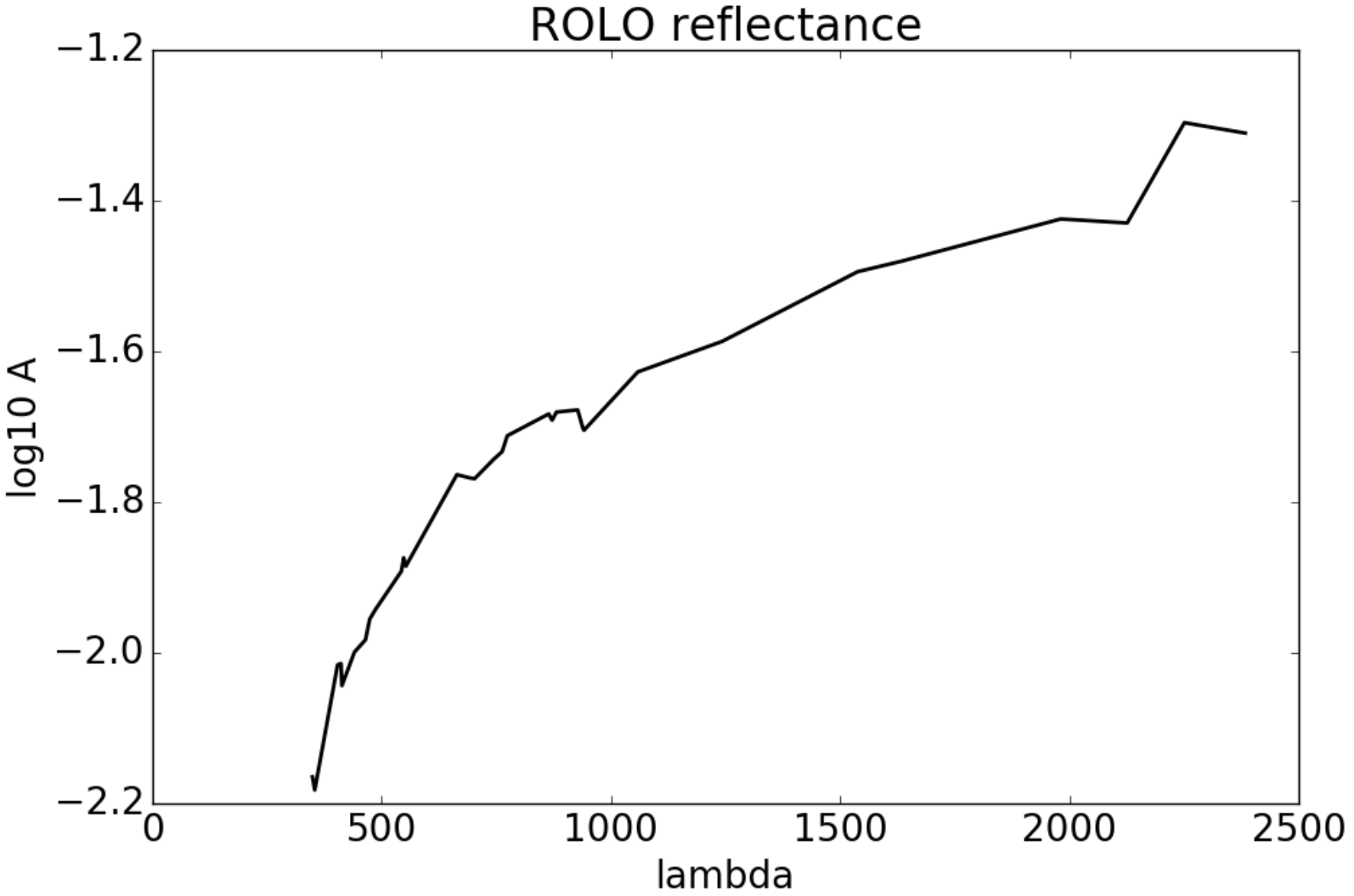
Calibration: nocturnal measurements

- After our correction..



Calibration: Apollo correction

- Calculated ROLO spectrum of the lunar reflectance is too ‘spiky’ and has to be smoothed before calculation of lunar irradiance for each time of observation.



Calibration: Apollo correction

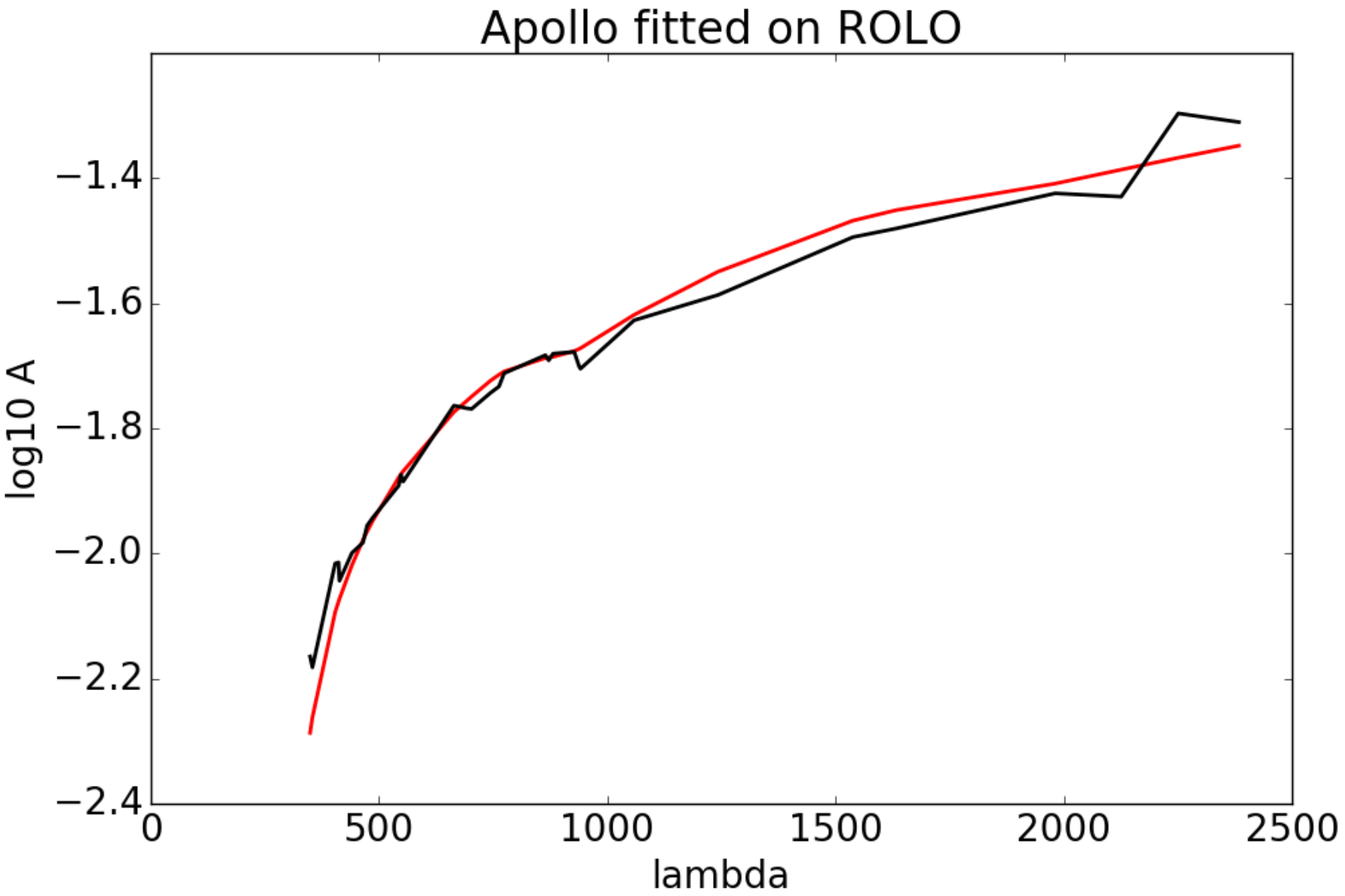
- Calculated ROLO spectrum of the lunar reflectance is too ‘spiky’ and has to be smoothed before calculation of lunar irradiance for each time of observation.

- The real spectrum has been measured on lunar surface samples brought during Apollo missions. But just for specific configuration of source of light and the sample and for specific composition (breccia and soil) of the sample → average composition of illuminated lunar surface probably varies with lunar phase.

- The measured spectrum can be used for correction of the ROLO spectrum, but the way how to do it is still matter of intensive discussions..

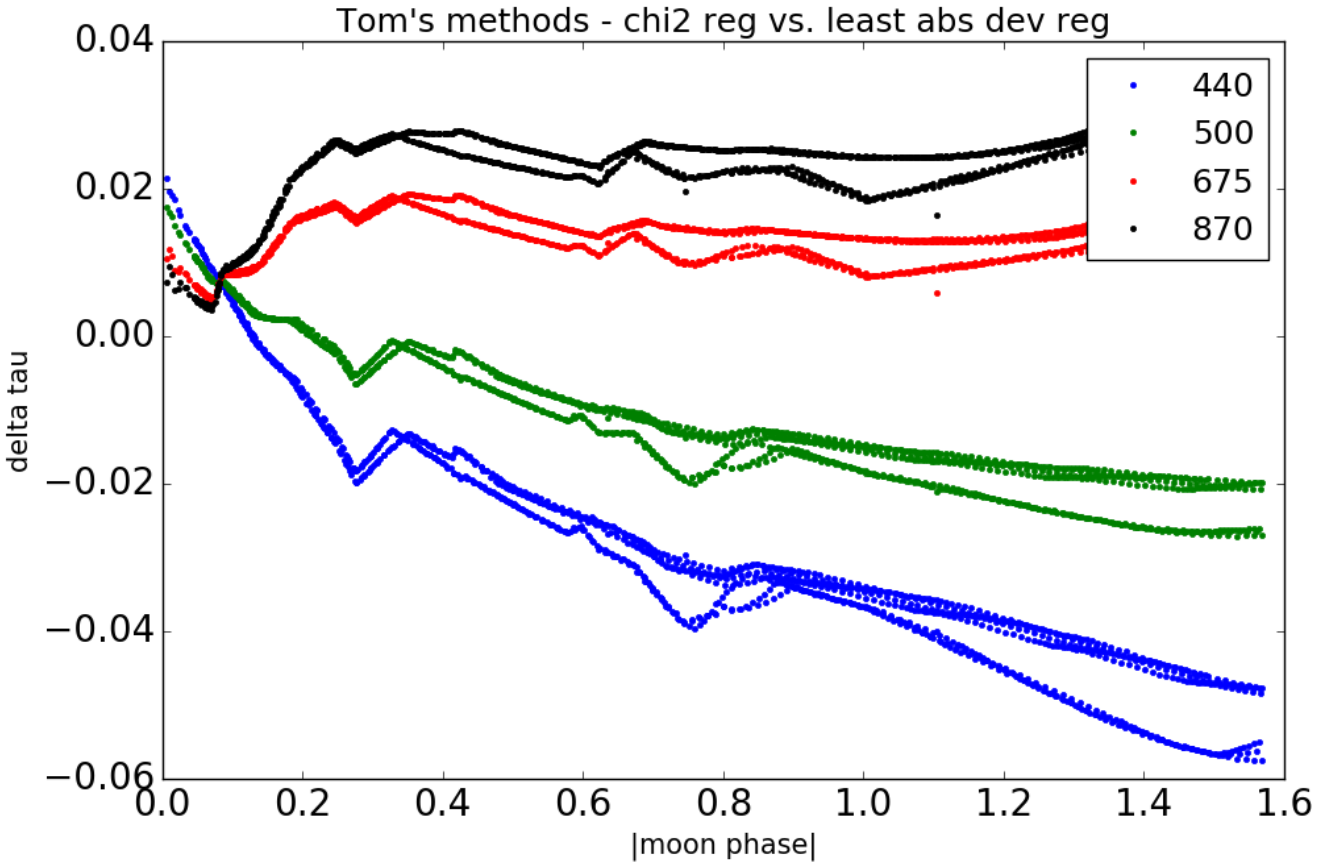
- Our correction is based on suggestions given by Tom Stone:
  - fixed soil and breccia ratio since we don not know how it changes with lunar cycle
  - fitting the spectrum on ROLO just by vertical stretching and shifting

Calibration: Apollo correction



Calibration: Apollo correction

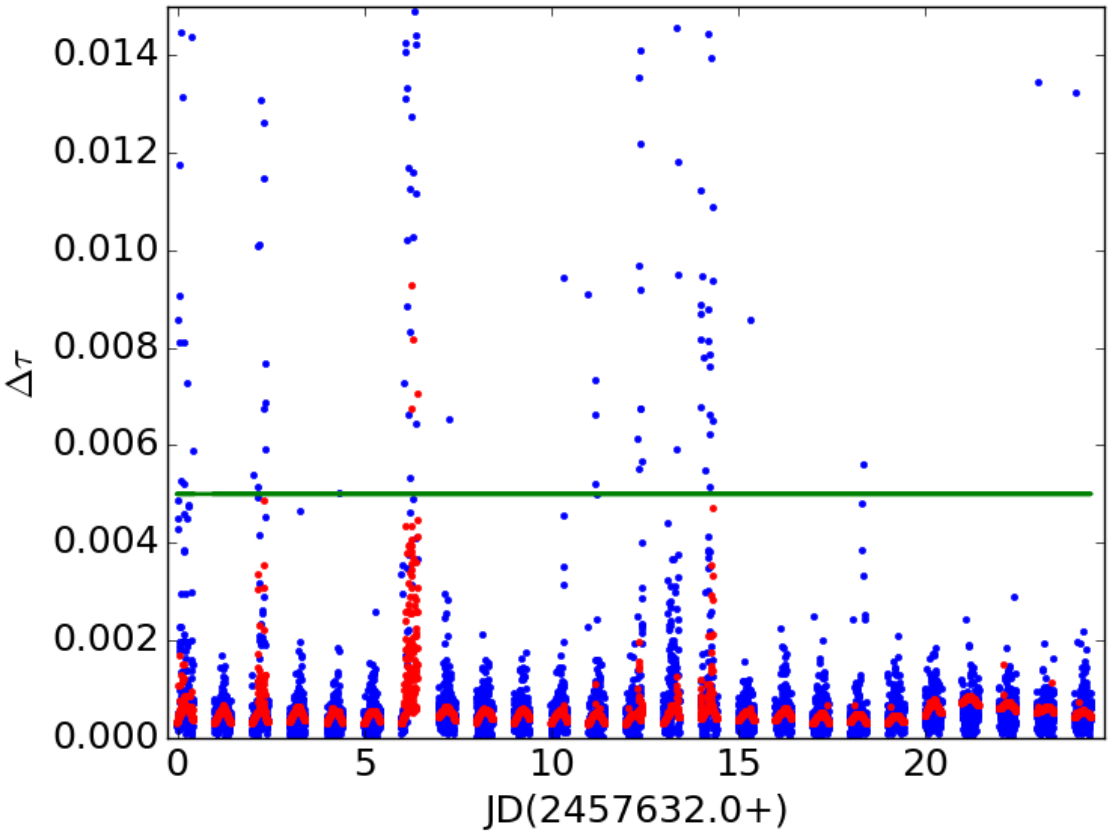
- Results strongly depends on the way of Apollo correction!
- Maybe one of causes for the ROLO phase dependence..



Cloud-screening

Triplet stability criterion, diurnal measurements

AERONET V3 algorithm: $\tau_{max} - \tau_{min} < \max(0.01, 0.015\ \tau)$ in all 675, 870, 1020 nm bands.

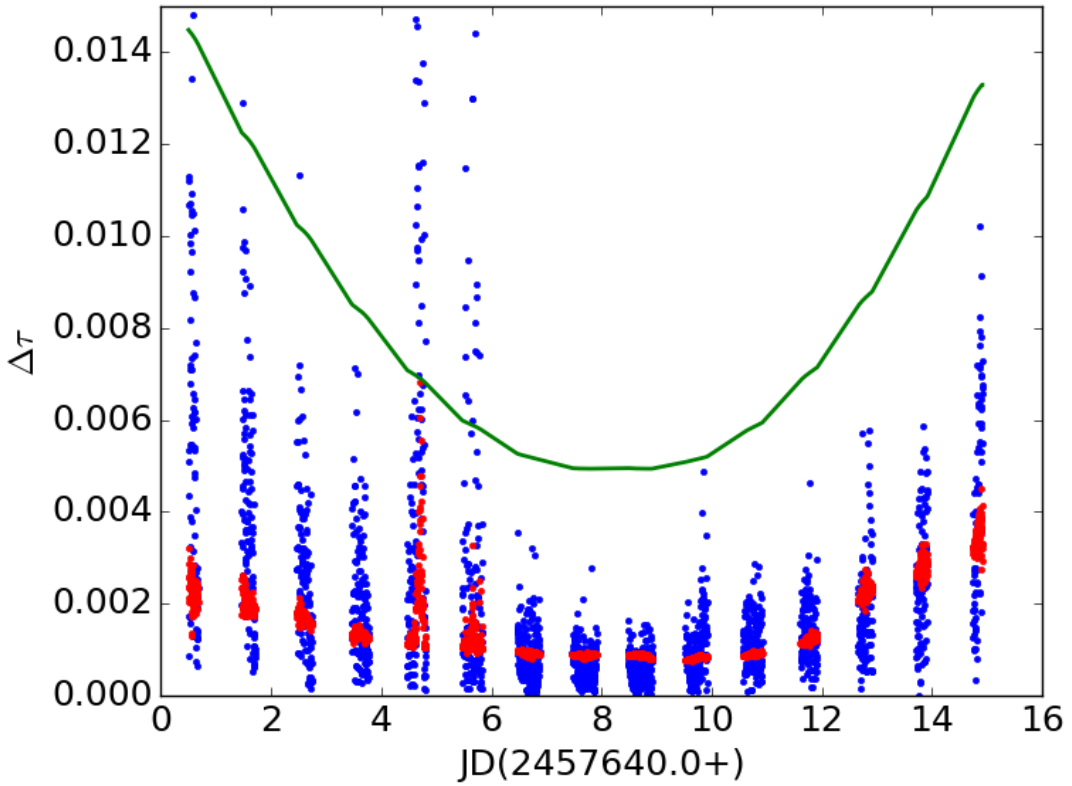


Too loose for our site with clear stable conditions. In our analysis we lower the 0.01 threshold to 0.005

Cloud-screening

Triplet stability criterion, nocturnal measurements

AERONET has no algorithm for cloud-screening of nocturnal measurements.



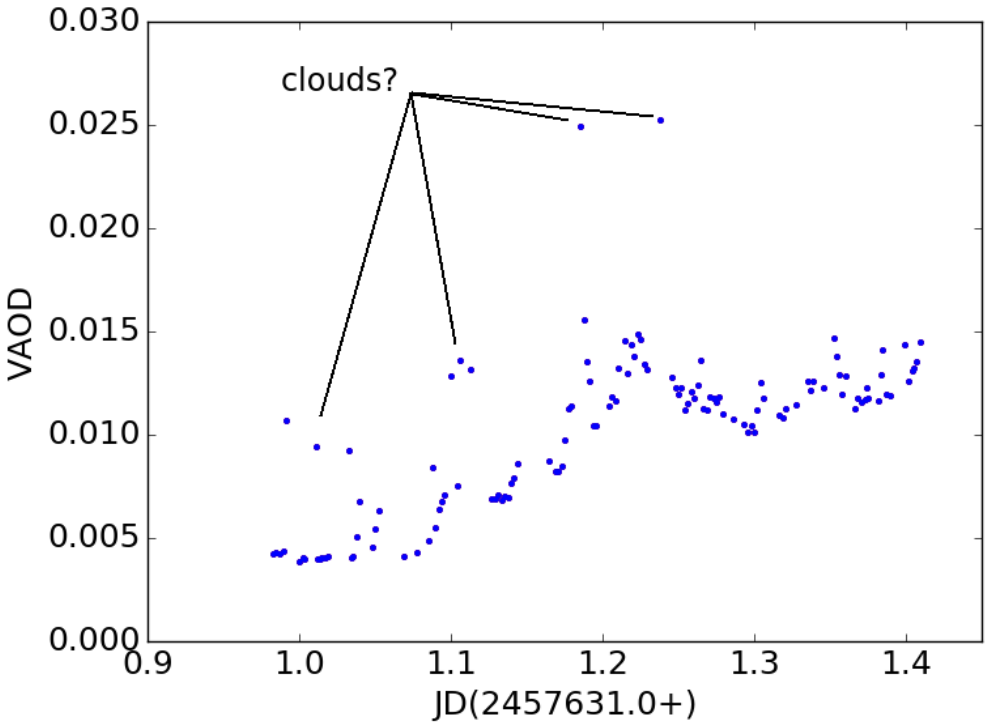
- In case of lunar measurements, Δτ strongly depends on phase of the Moon and the criterion has to be modified
- The dependence seems to be parabolic
  → We modify the criterion like

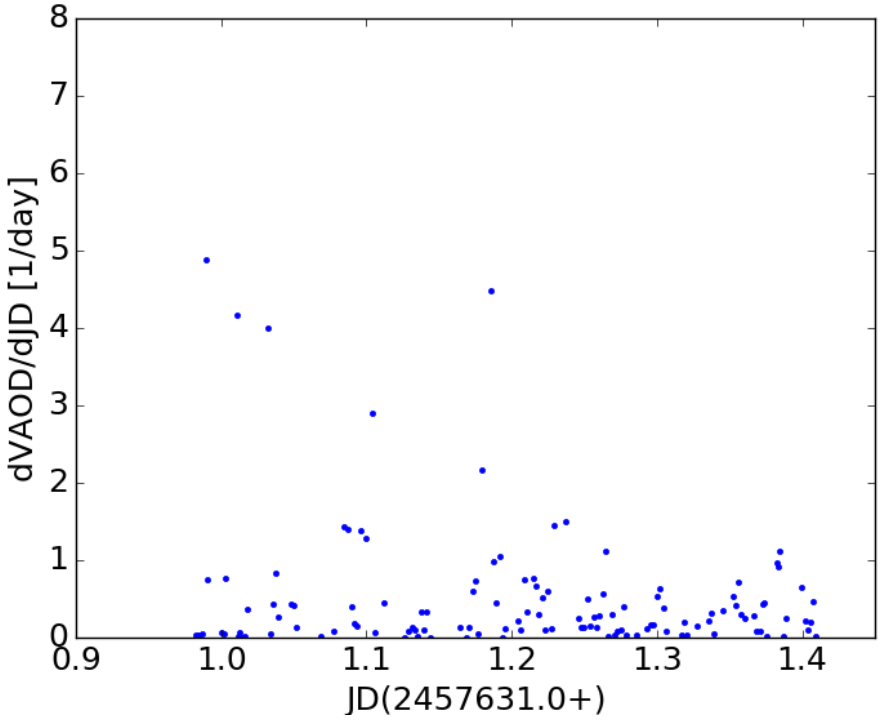
$$\Delta\tau < \max([0.005, 0.015\tau]P(g))$$
$$P(g) = 0.8g^2 - 0.2|g| + 1$$

Cloud-screening

Smoothness check, diurnal measurements

- AERONET V3: OK if ΔAOD(500 nm) < 0.01 per minute, measured from each pair (AOD[i+1] – AOD[i]) / (JD[i+1] - JD[i]) → threshold is 14.4 day^{-1}
- But in our data out-liars correspond with values of ΔAOD/ΔJD > 1.

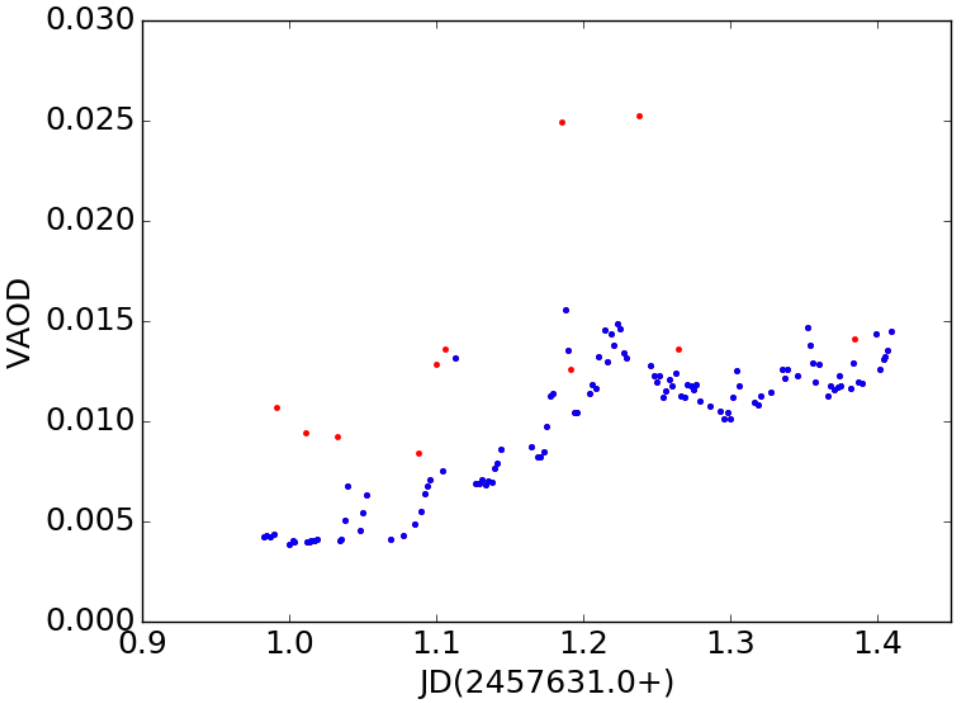


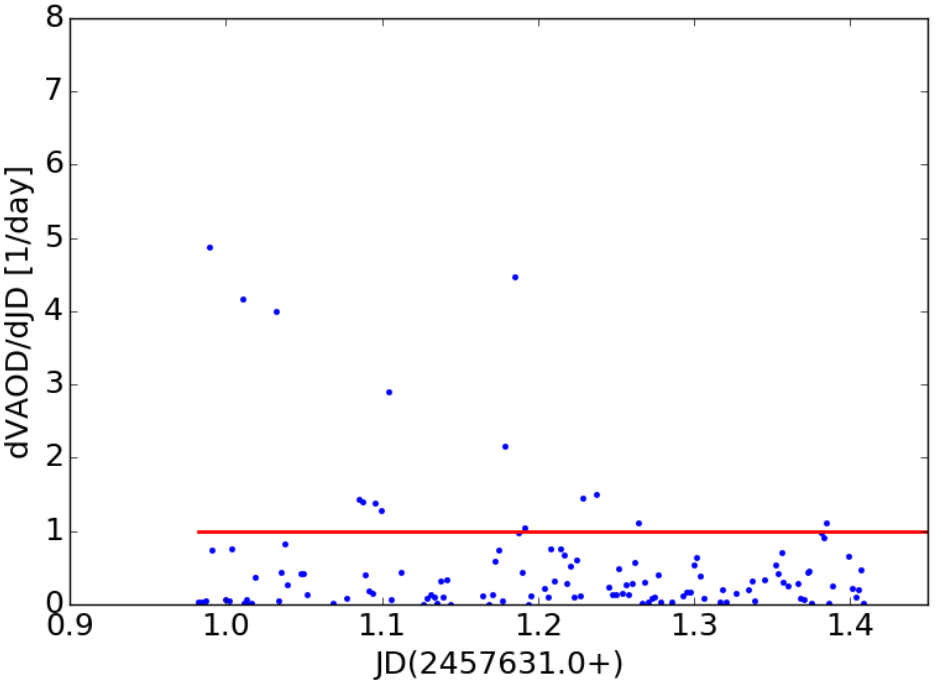


Cloud-screening

Smoothness check, diurnal measurements

- AERONET V3: OK if ΔAOD(500 nm) < 0.01 per minute, measured from each pair (AOD[i+1] – AOD[i]) / (JD[i+1] - JD[i]) → threshold is 14.4 day^{-1}
- But in our data out-liars correspond with values of ΔAOD/ΔJD > 1.
- We lower the threshold like: OK if ΔAOD/ΔJD < 1 day^{-1}

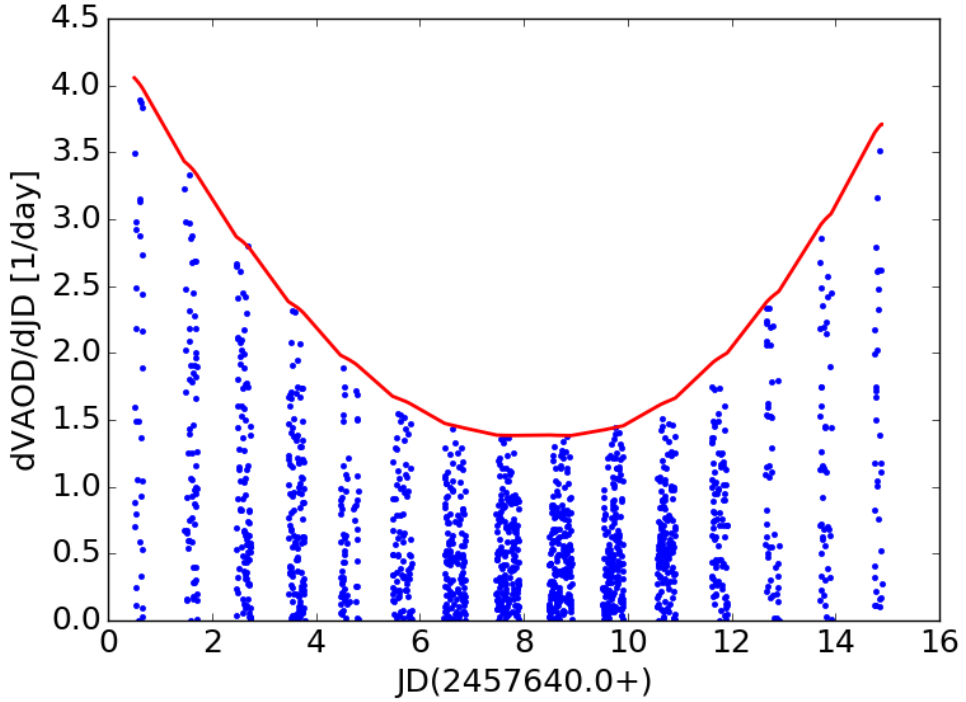


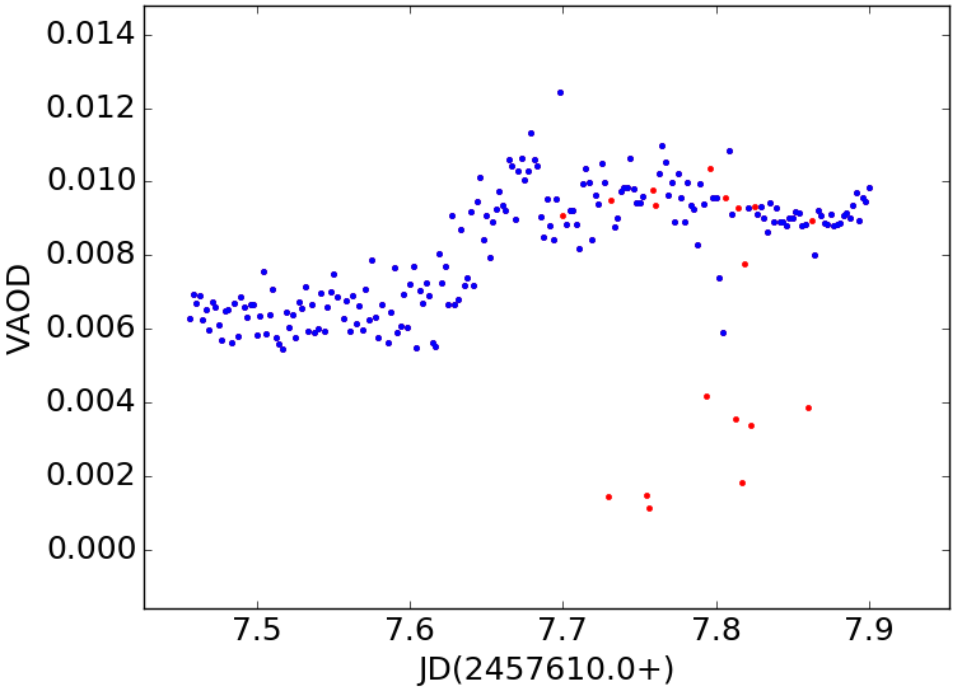


Cloud-screening

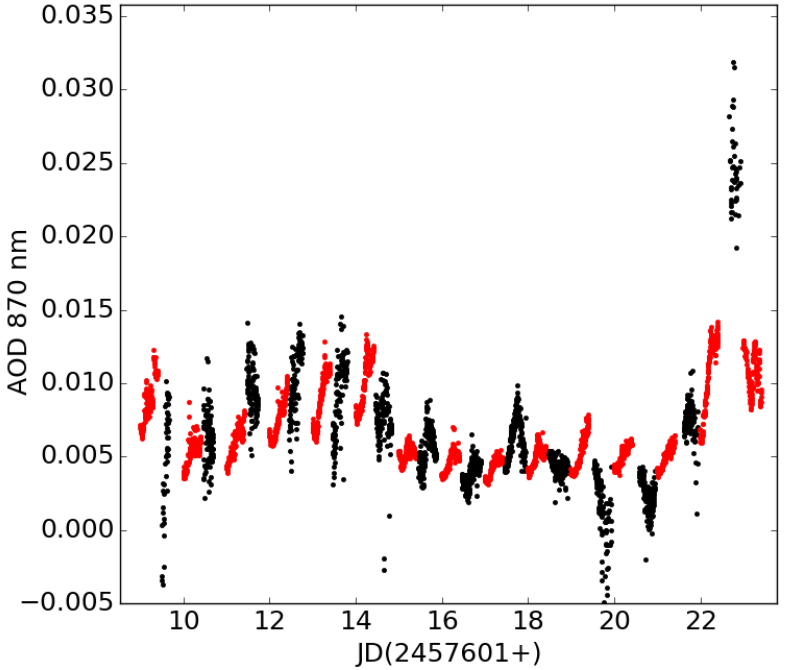
Smoothness check, nocturnal measurements

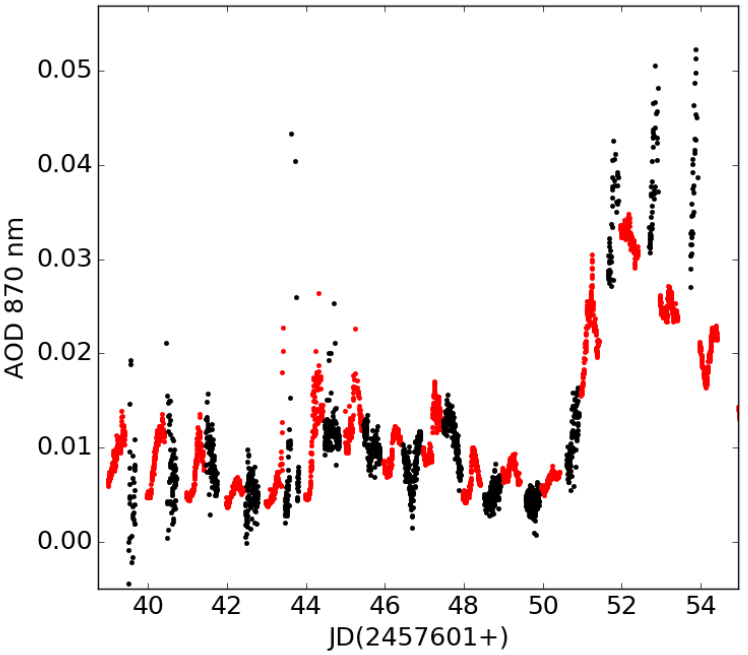
- In case of nocturnal measurements, the situation is again more difficult, ΔAOD/ΔJD is phase dependent
- Our approach is the same as before: $\Delta\mathrm{AOD}/\Delta\mathrm{JD} < 1.4\,\mathrm{P(g)}$

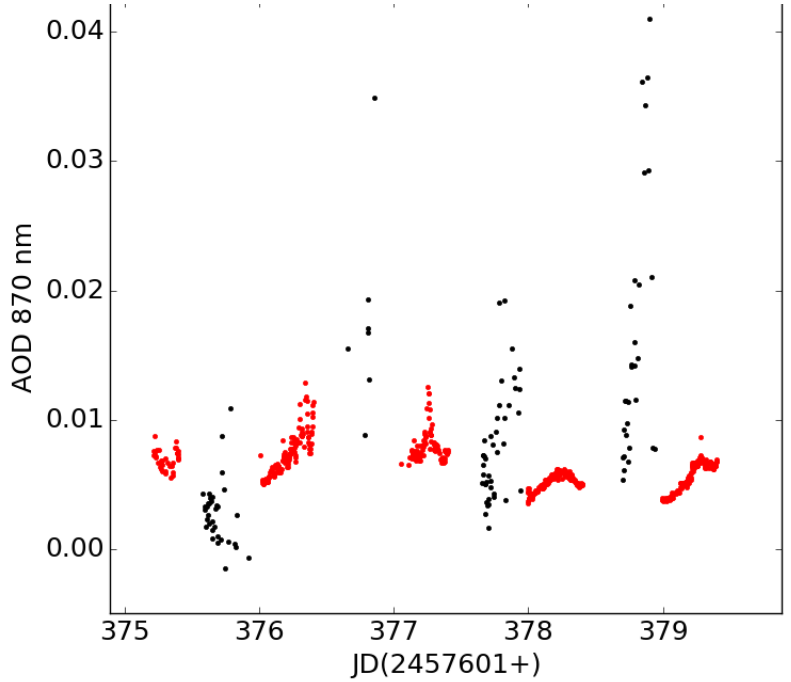


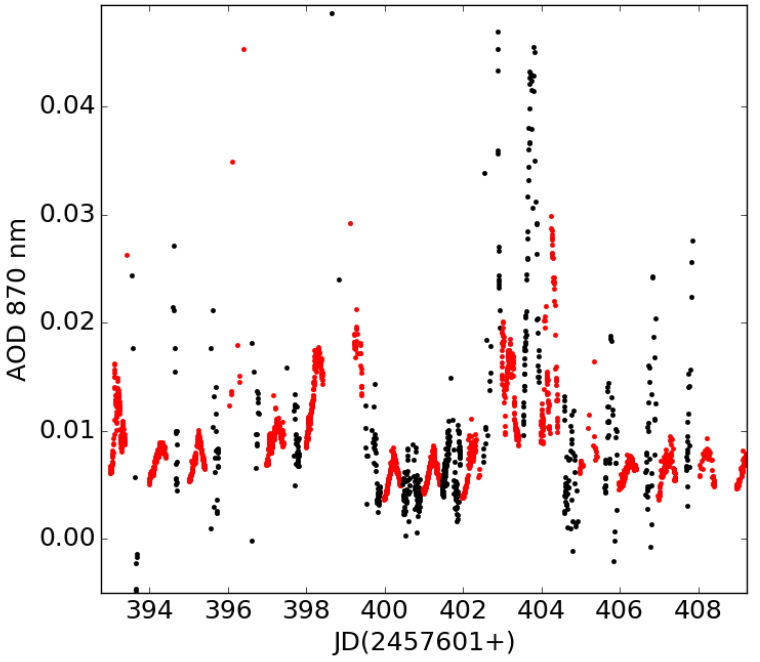


Updated AODs



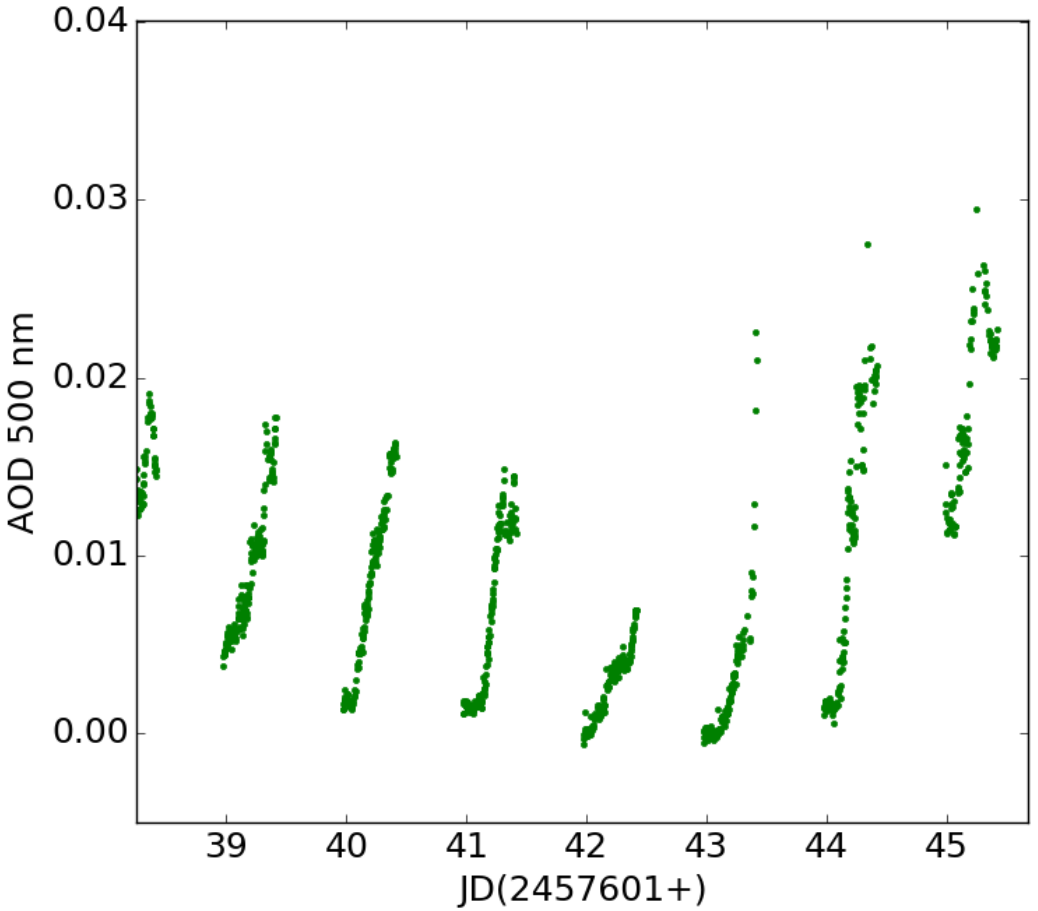






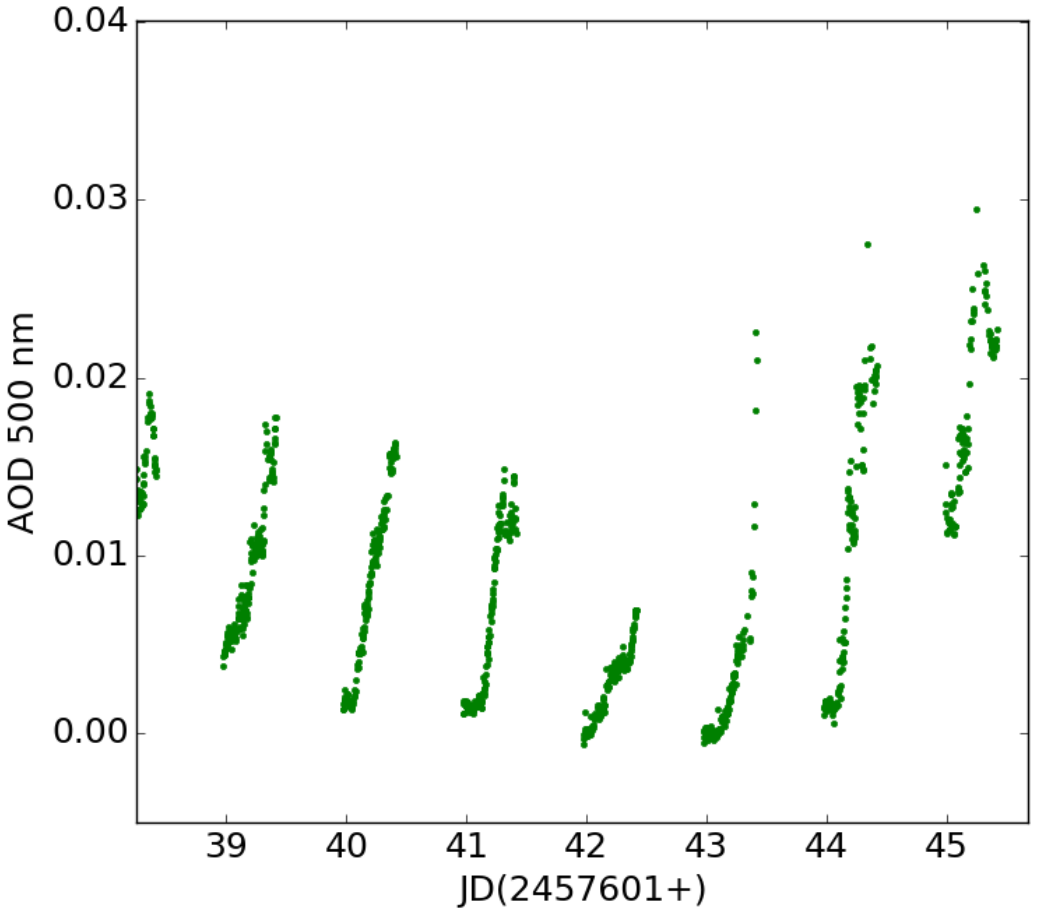
Question of diurnal trends

- A lot of observations show increasing AOD during the day – is it real change of AOD or rather some systematic effect?



Question of diurnal trends

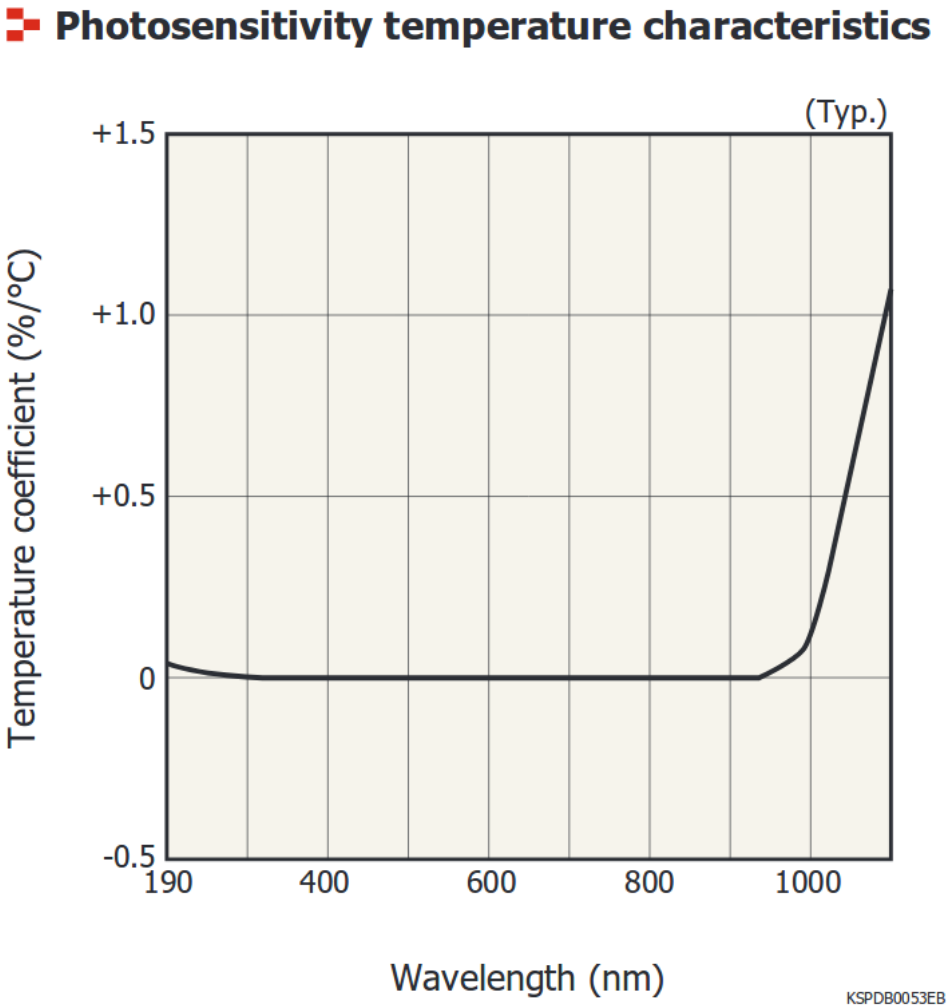
- A lot of observations show increasing AOD during the day – is it real change of AOD or rather some systematic effect?



- Can it be caused by temperature instability?

Question of diurnal trends

- A lot of observations show increasing AOD during the day – is it real change of AOD or rather some systematic effect?

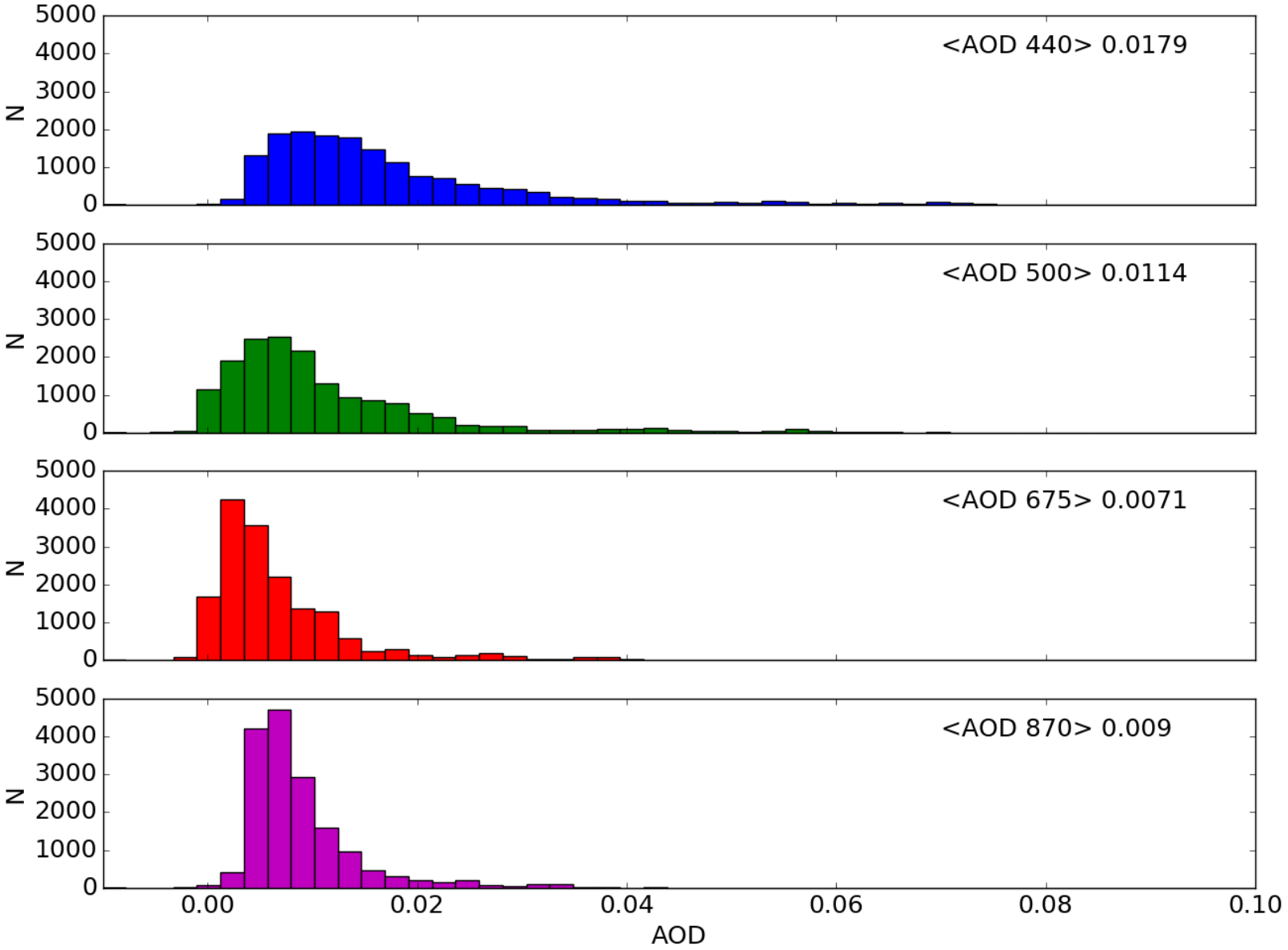


- Can it be caused by temperature instability?

PROBABLY NOT

- Discussed with Ilya Slutsker from AERONET → their pipeline gives similar results for our data. Diurnal trends of increasing concentration of aerosols are probably real.

Updated AODs

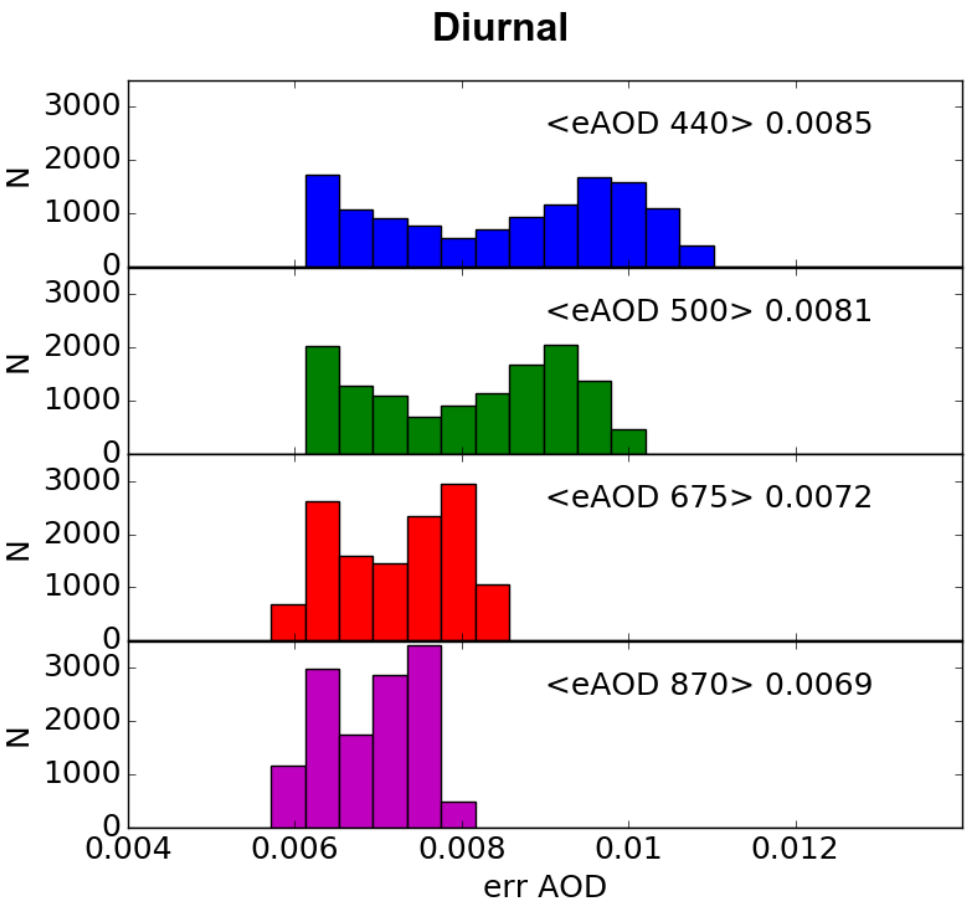


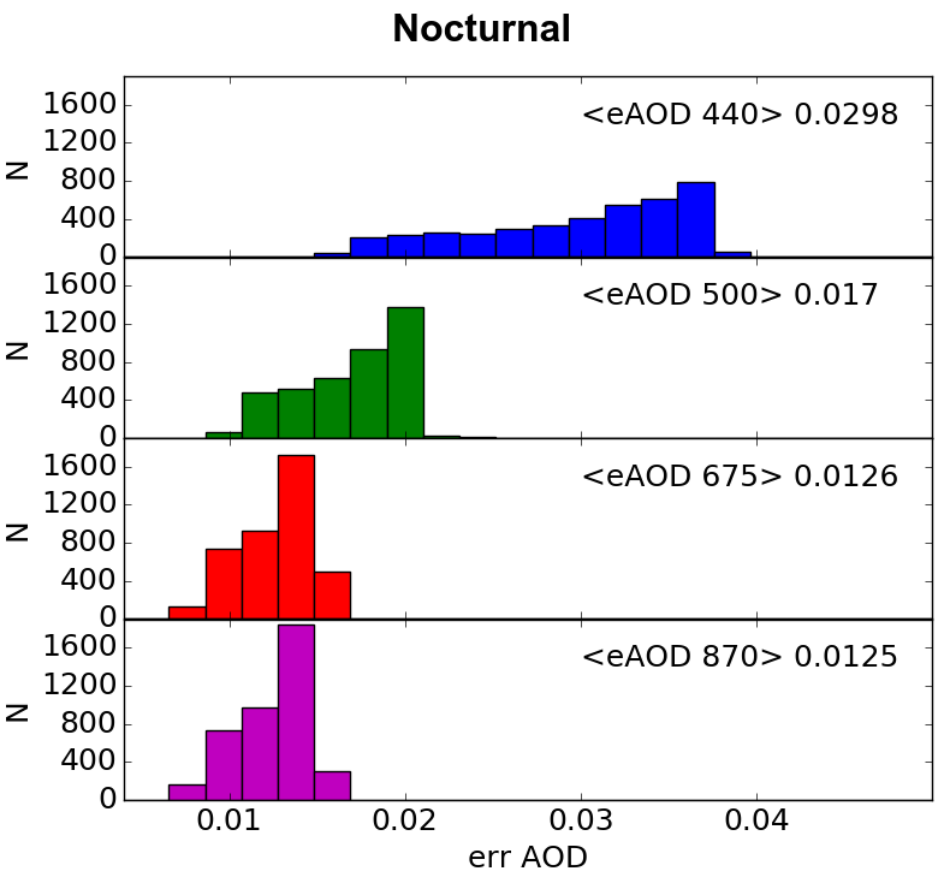
Updated AODs: Uncertainties

- Systematic uncertainty estimated from differences between our and Aeronet's diurnal calibration $u_{SYS} \approx 0.006$

$$(u^{\mathrm{D}}_{\mathrm{AOD}})^2 = \frac{1}{m^2}\frac{u(V_0)^2}{V_0^2} + u^2_{\mathrm{sys}}$$

$$(u^{\mathrm{N}}_{\mathrm{AOD}})^2 = \frac{1}{m^2}\left(\frac{u(\kappa)^2}{\kappa^2} + \frac{u(I_0)^2}{I_0^2} + \frac{u(V)^2}{V^2}\right) + u^2_{\mathrm{sys}}$$





Thank You for Your attention

jurysek@fzu.cz