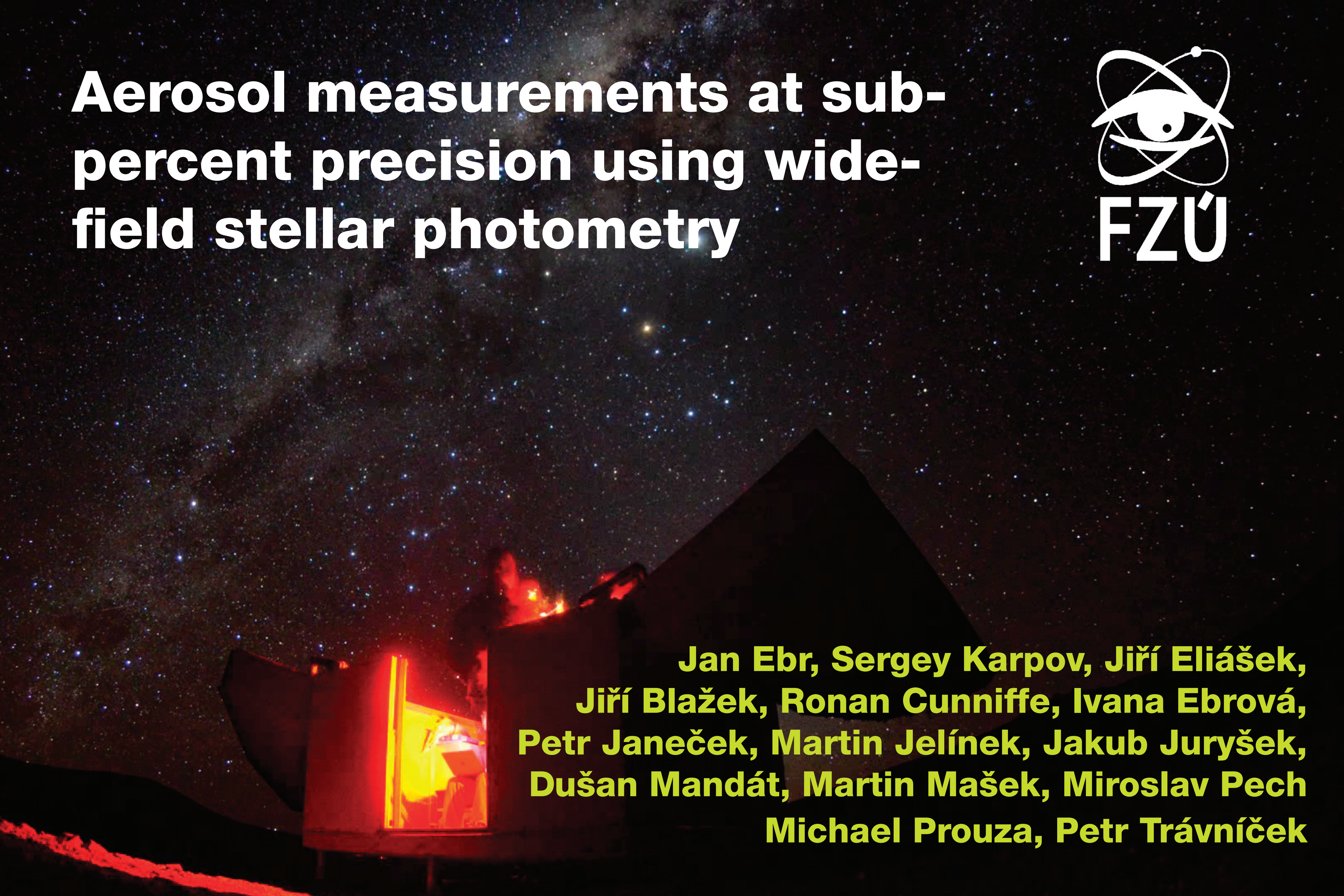

Aerosol measurements at sub-percent precision using wide-field stellar photometry

FZÚ

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Jiří Blažek, Ronan Cunniffe, Ivana Ebrová,
Petr Janeček, Martin Jelínek, Jakub Juryšek,
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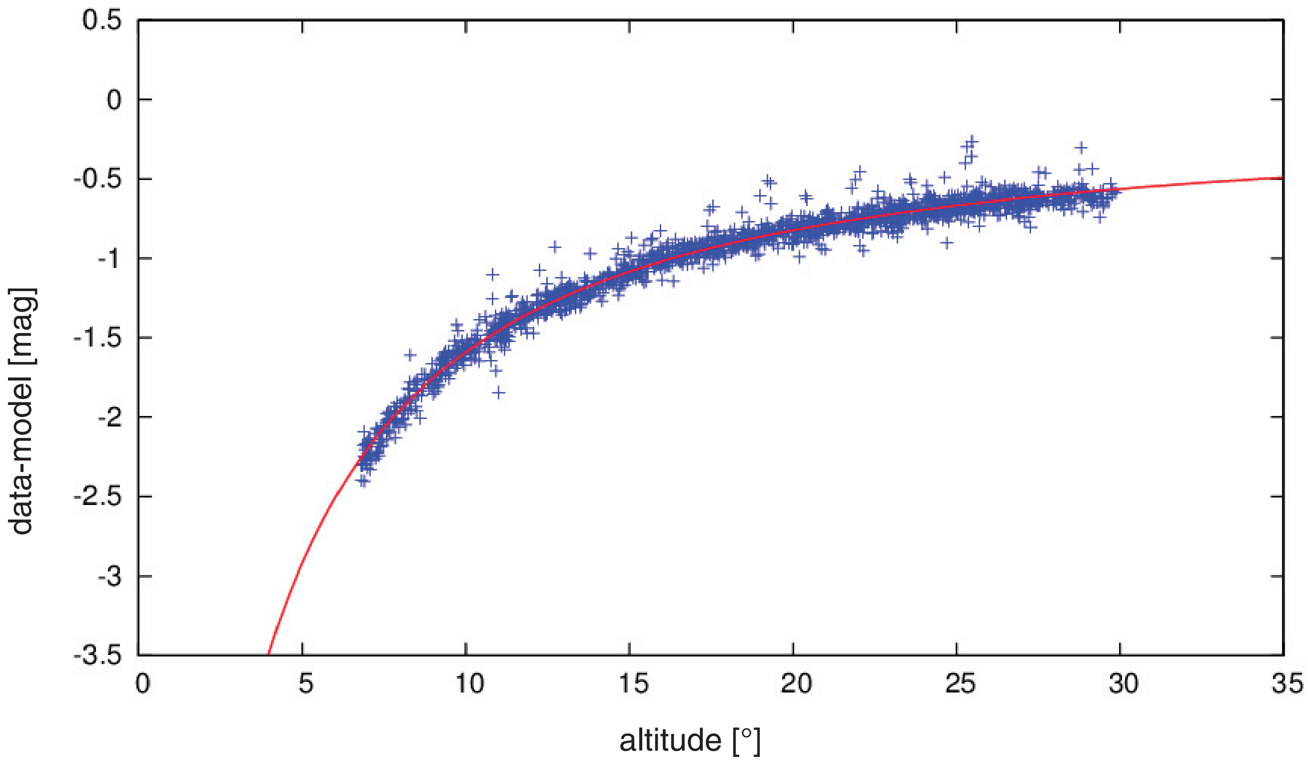
Michael Prouza, Petr Trávníček

The basics

How to measure aerosols optical depth (VAOD) from stellar photometry?

- take a series of exposures at different airmasses
- fit extinction as a function of airmass
- get instrumental parameters simultaneously
- subtract molecular contribution



$$\frac{m_{\mathrm{inst}}}{M} = m_{\mathrm{cat,B}} + Z_i + g(A_{\mathrm{M}}, A_{\mathrm{A}}, A_{\mathrm{O}}, k_i, B-V) + f(B-V, x, y)$$

J. Ebr et al.: *A New Method for Aerosol Measurement Using Wide-field Photometry*, AJ 162 (2021), 1, 6

- result of 5 years of development of the analysis
- uncertainty: 0.006 correlated + 0.005 uncorrelated

Why wide-field photometry?

Stars = the only natural reference sources on moonless nights = no additional light

- single bright stars: >10000× fainter than full Moon = systematic instrumental effects
    - one bright star at different airmass? too slow for aerosol variation!
    - multiple bright stars? catalog, spectral and mechanical systematics!
    - larger telescope? seeing (PSF) depends on airmass!
    - samples of stars at different airmass? cannot reliably exclude clouds!

- scan in airmass with a wide-field telescope (15°×15° degrees or similar)
    - fast (from zenith to horizon in a few minutes)
    - continuos coverage = efficient cloud screening
    - single star precision ~ 0.02 mag, but stength in numbers = fit uncertainty ~0.002 OD
    - stabilitiy, or even knowledge, of absolute calibration not needed

- requires careful consideration of any possible systematics that could trend with airmass

- assumes stratification (horizontal uniformity) of aerosols

Data analysis

altitude scans

dark/flat fields

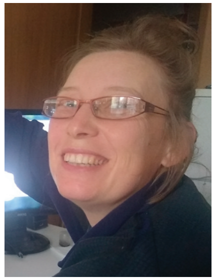
CCD non-linearity measurements

calibration

star identification photometry

test field data

clear scan selection



photometric error model

ECMWF atmospheric profiles

spectral measurements of components

MODTRAN

numerical integration with stellar spectra

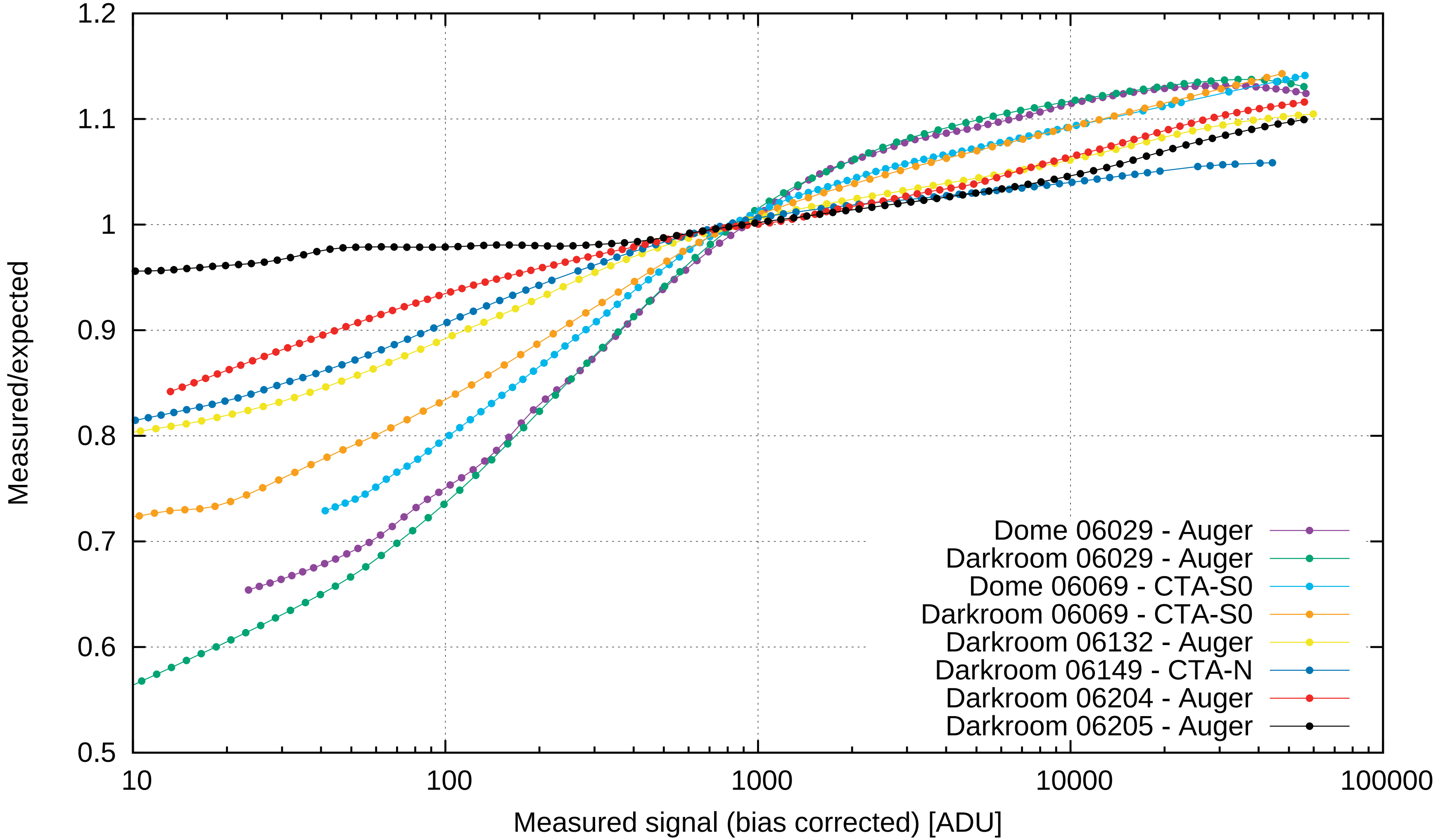
molecular atmosphere model

simultaneous fit of VAOD and corrections

RESULTS

Ingredients: non-linearity measurements

- the single most crucial discovery: no CCD camera is linear in entire range
  - VAOD measurements uses far larger dynamical range than typical astronomy
  - even the manufacturers surprised

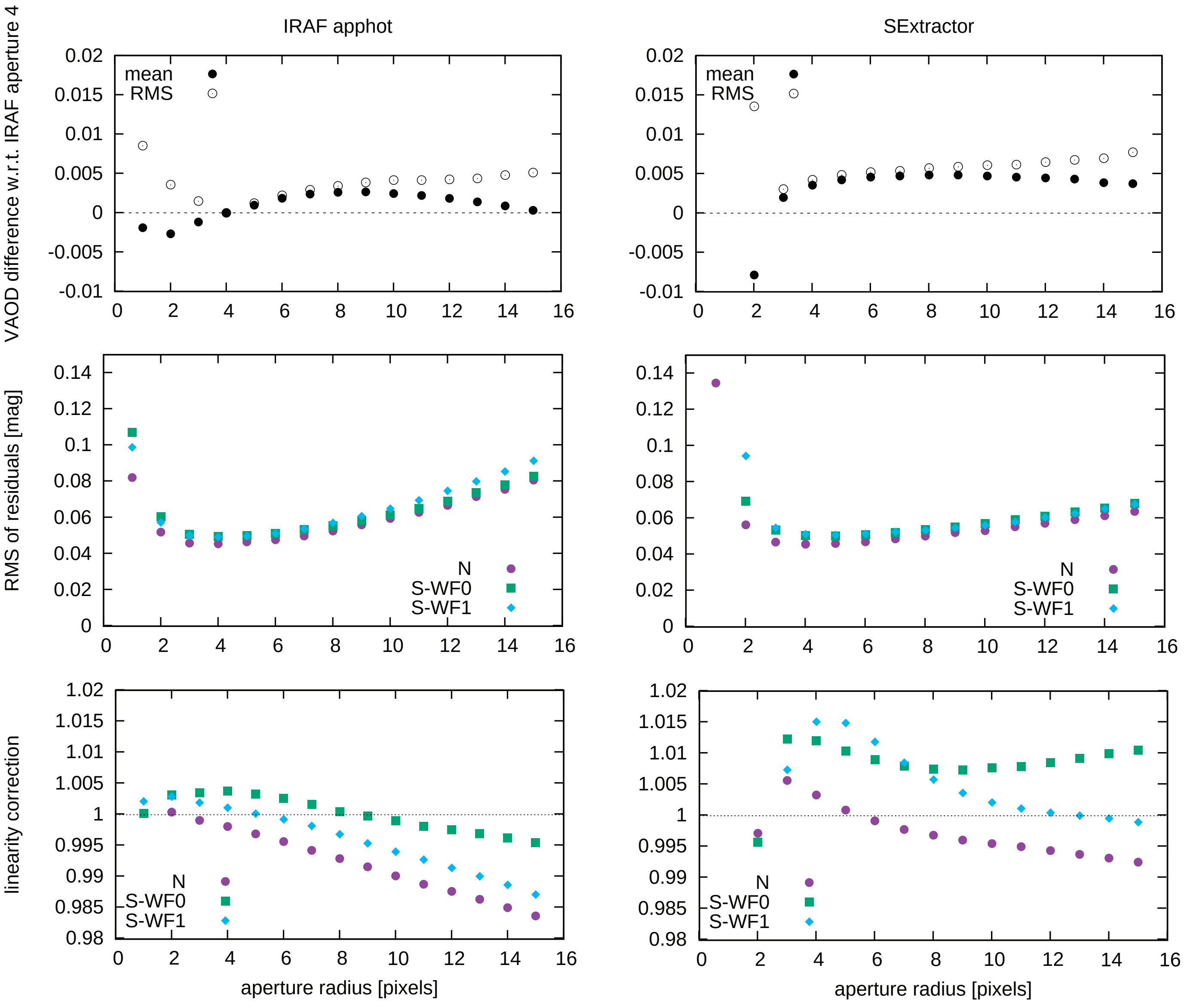


Ingredients: aperture photometry

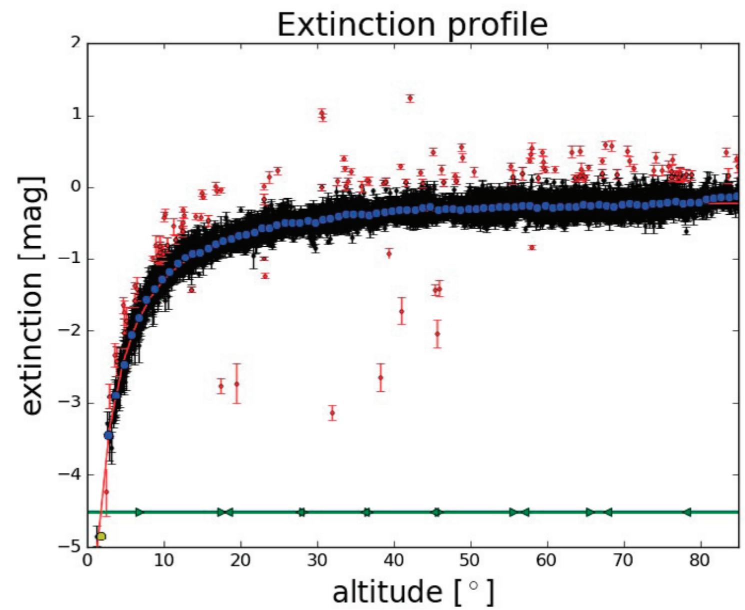
- choice of photometric aperture optimized to the specific setup

- good background estimate in crowded stellar fields
  - no alternative to IRAF found yet

- may still be the weakest part due to wildly varying star shapes
  - see Shefali's talk on PSF fitting



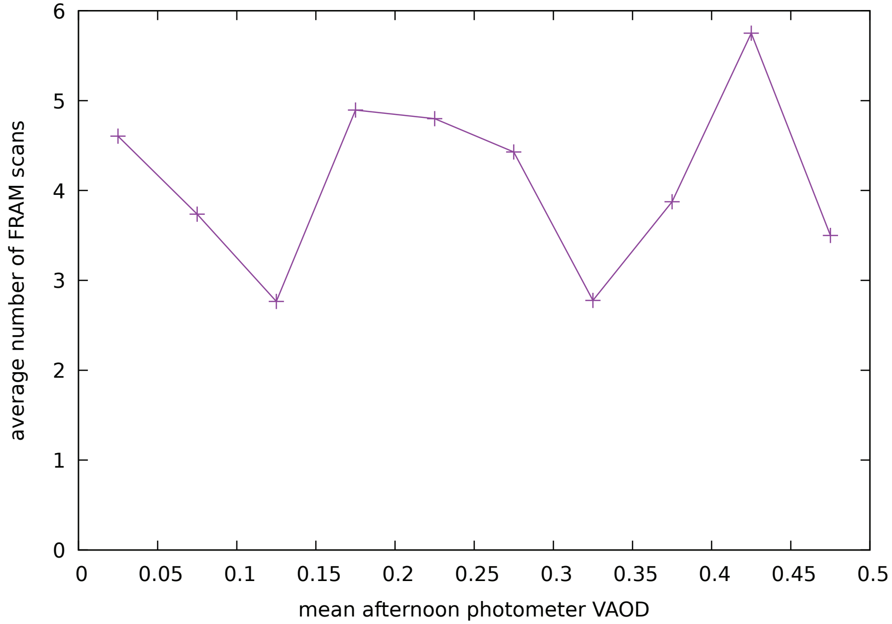
Ingredients: clear scan selection

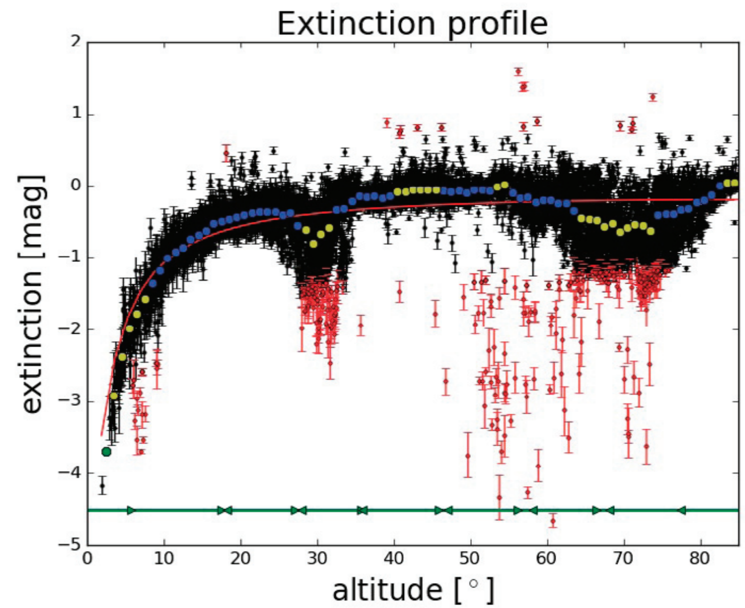


- can't fit anything if there clouds are present

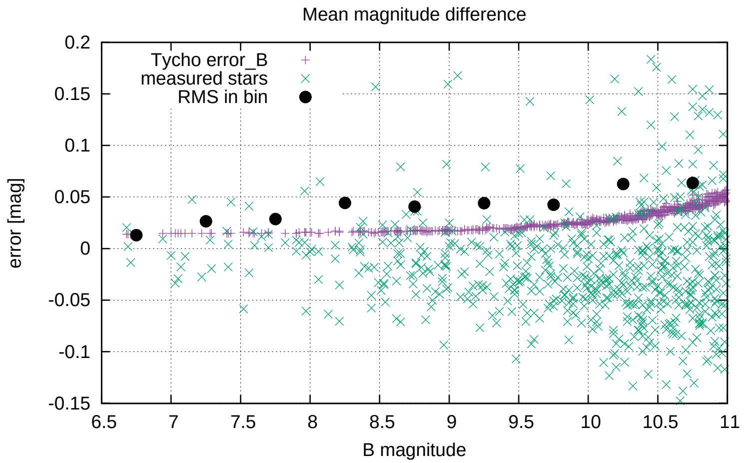
- not always *this* easy = requires "a human"
  - Ivana selected >16000 clear scans in 3 days

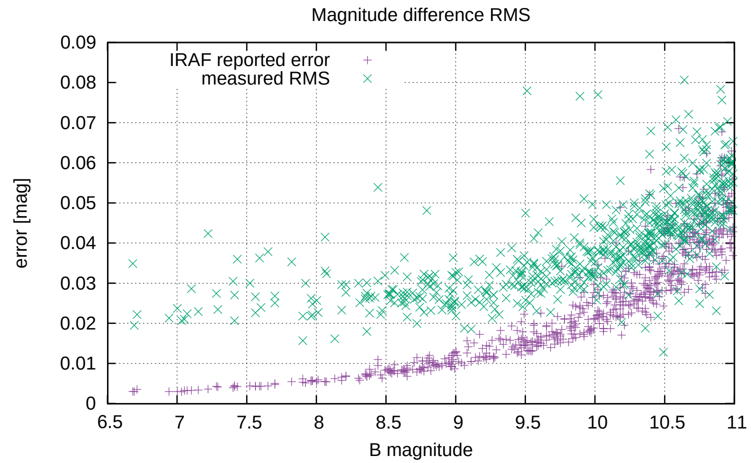
- possibility to skew statistic by removing also "dirty" nights?
  - Sun Photometer comparison at ORM good





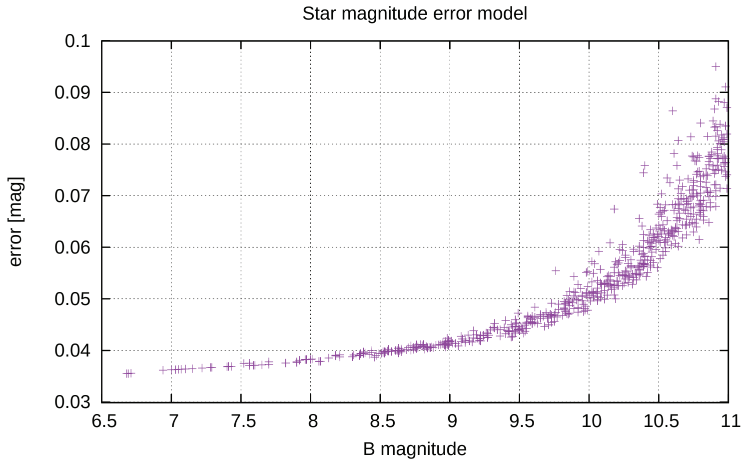
Ingredients: error model





- uncertainties underestimated both in catalog and by IRAF

- error model derived from repeated obsevations of the same stellar field in good conditions

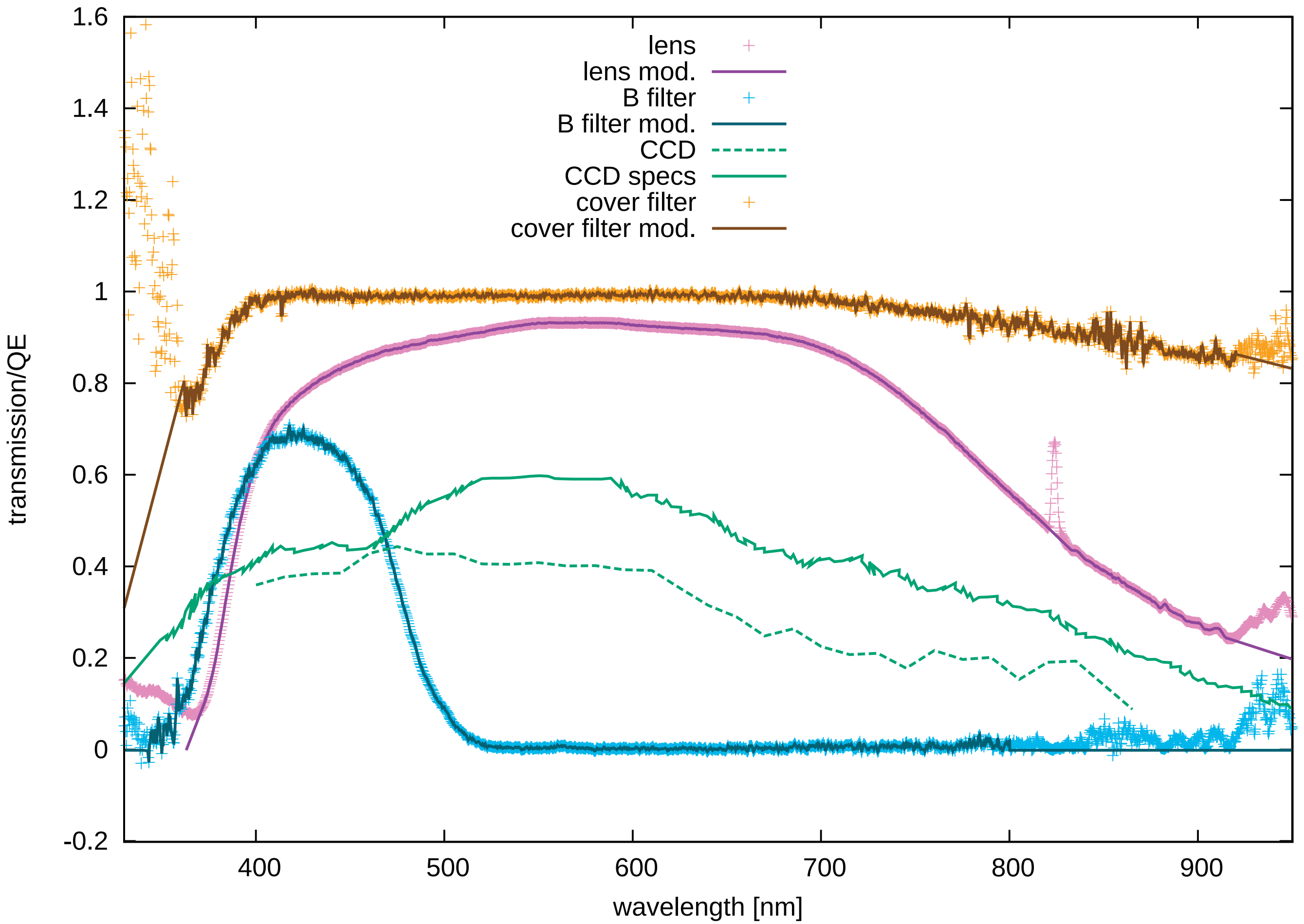


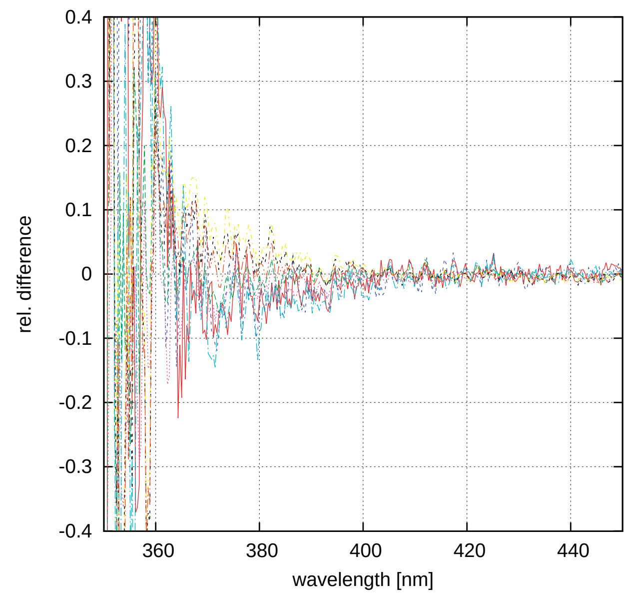
- surprisingly large effect on stability of the fit
  - removed most dependence on cuts in airmass and mag

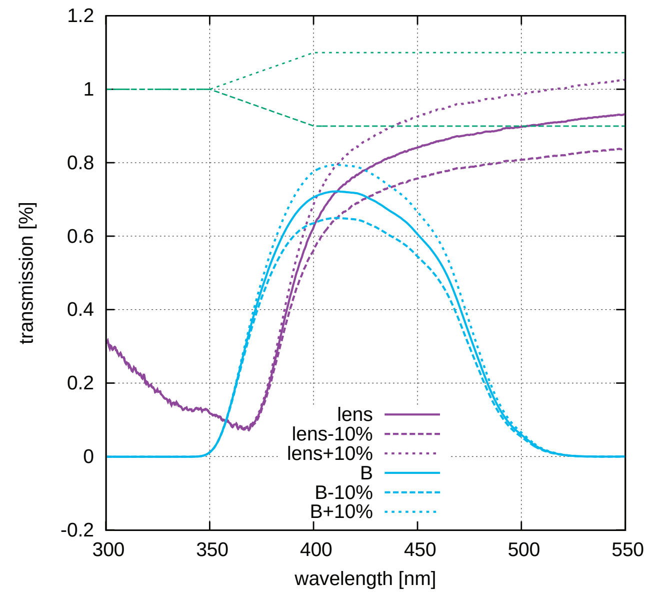
- could be still improved (RMS error not from catalog mag)

Ingredients: spectral properties of components

- key for molecular subtraction = uncertainty in overall offset
  - dominated by precision at “blue” end of transmission
  - at the edge of range available instrumentation
  - uncertainty conservatively taken from worst case







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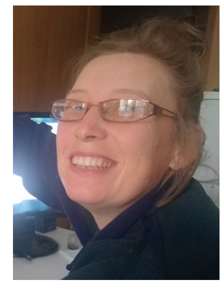

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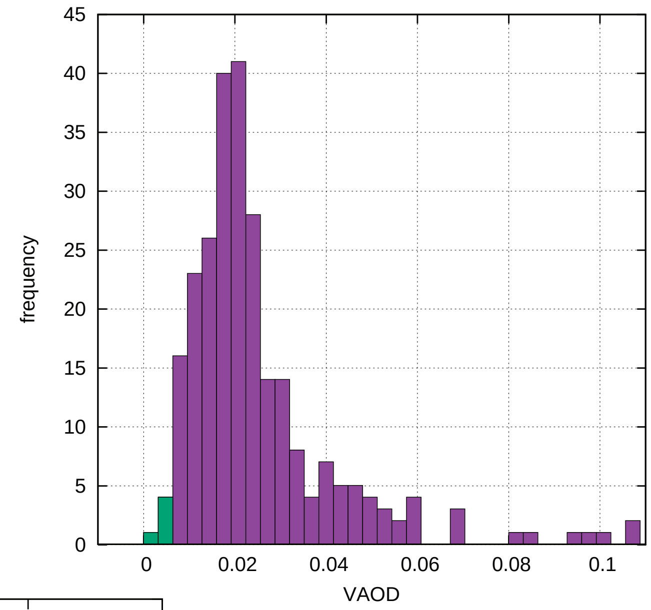
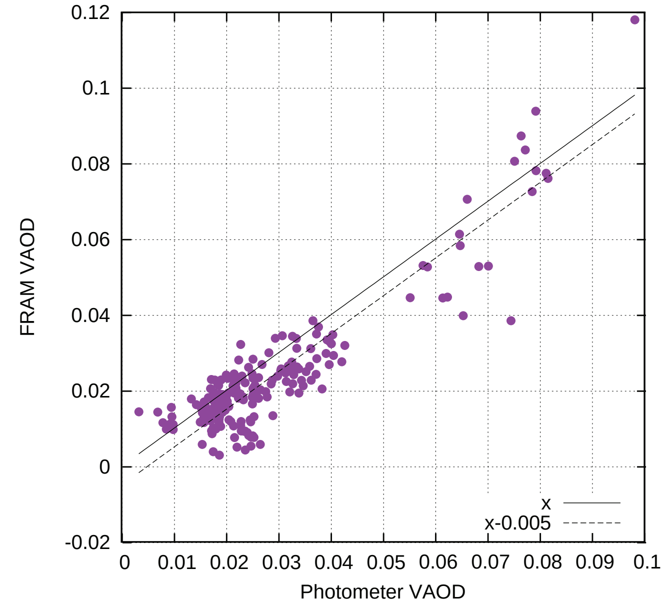
RESULTS

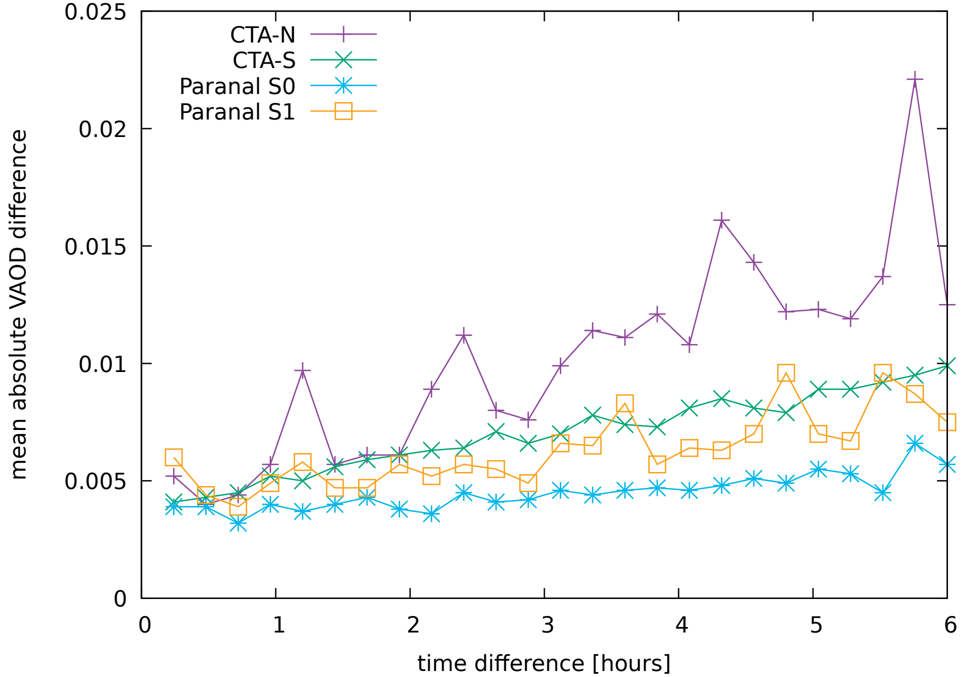
Can we trust the precision?

• sharp rise at 0 VAOD at extremely clean locations encouraging

• Sun/Moon Photometer lunar data comparison RMS 0.007





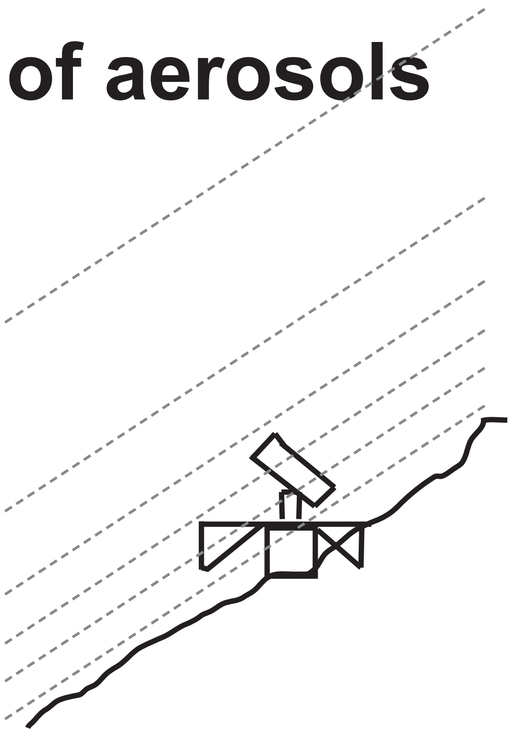


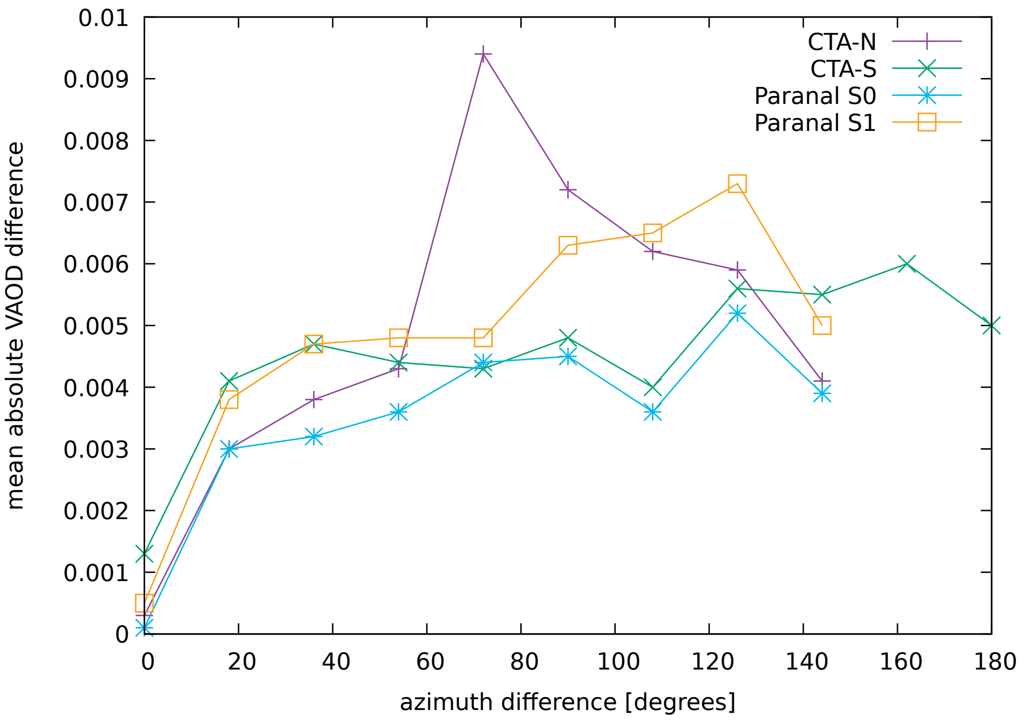
• comparison with Sun or ARCADE data complicated by time difference

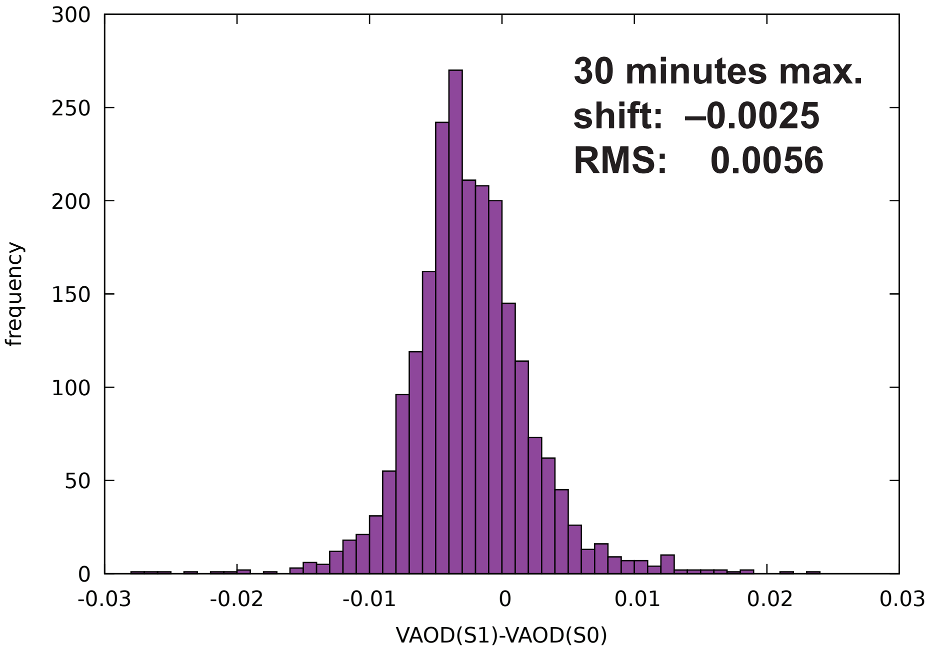
• self-correlation in time starting from ~0.005 however quite nice ...

The Elephant in the Room: stratification of aerosols

- simplest model: aerosols inclined along a slope
  - can potentially lead to large effects while looking up/down-slope
  - effects multiplicative, contradicted by slope of Photometer correl.
- difference vs. azimuth: largest for sites on/near slopes?
  - still small effect and shape wrong
  - note step from 0 to 20 – shows nature of uncertainty!
  - Paranal S0-S1 (flat vs. hill) comparison very close







Conclusiuons

• we can measure (integral) VAOD with uncertainty: 0.006 correlated + 0.005 uncorrelated using just starlight and a wide-field telescope

• we are hungry for data to compare with

• 16000 data points from CTA sites and nearby (CTA-S, Paranal, ORM) available from me at any time

- data from Malargüe may be available in the future

• method even suitable for statistical studies (climatology)

• technically complicated, but we know all the steps and can help you!