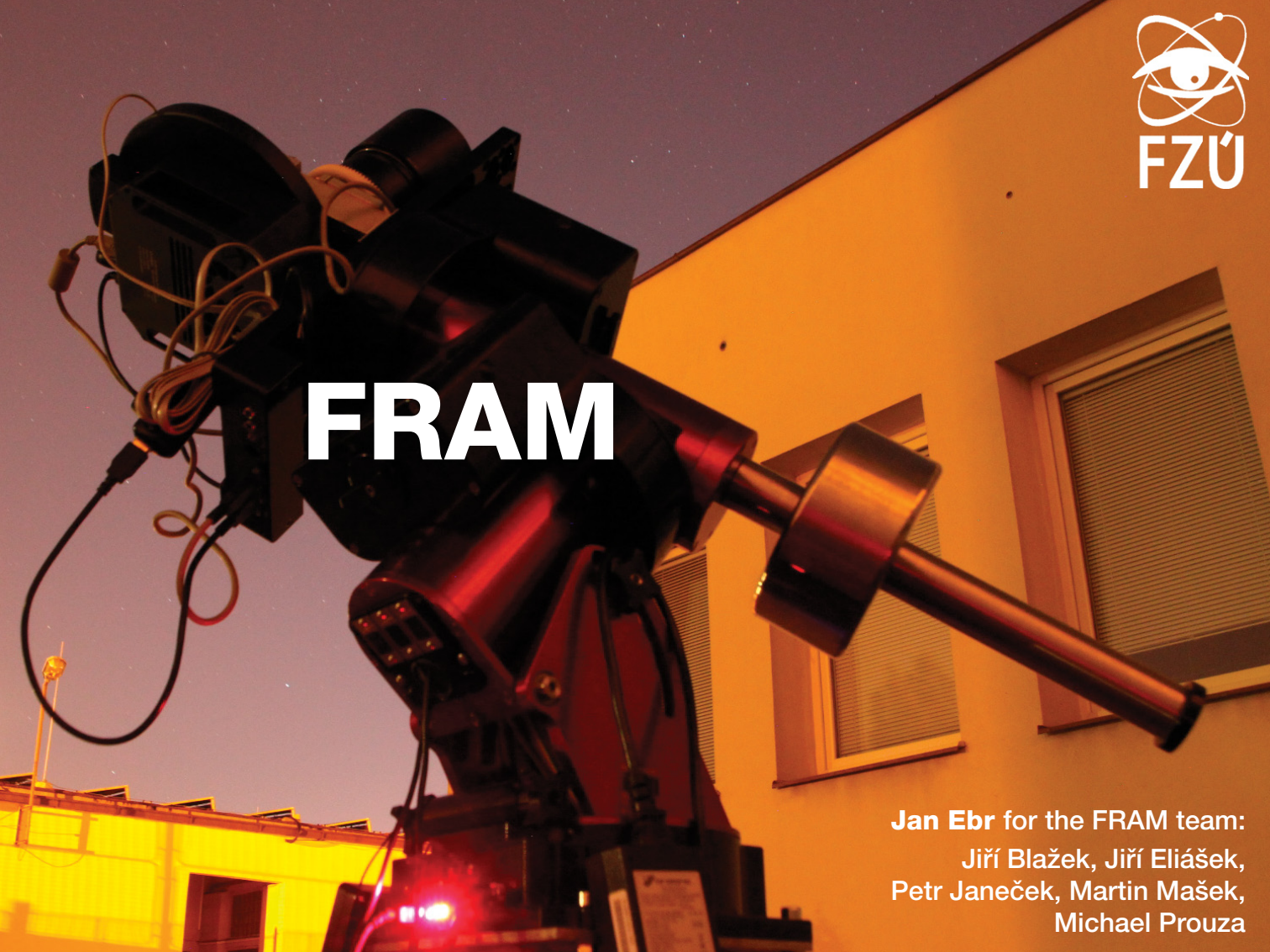


FRAM

Jan Ebr for the FRAM team:
Jiří Blažek, Jiří Eliášek,
Petr Janeček, Martin Mašek,
Michael Prouza

FRAM: F(/Ph)otometric Robotic Atmospheric Monitor

- Integral extinction (VAOD) from stellar photometry
- 10 years of experience from Pierre Auger Observatory
- FRAM for CTA
  - 2 in the South, 1 in the North
  - Paramount MYT mount, Zeiss 135/2.0, Moravian Instruments G4-16000 CCD, Elya custom enclosure, RTS2 software package
  - 15°×15° FOV, several 100s stars with 30 second exposures
- Prototype in Prague from February, ready for deployment
- Operating mode and data processing for CTA in rapid developement
  - VAOD maps in fixed FOV
  - altitude scans for self-calibration and precision VAOD


SARAY
Aluminium Composite Panel

Photometry of stars

$m_1 - m_2 = -2.5 \log_{10} (J_1 / J_2)$

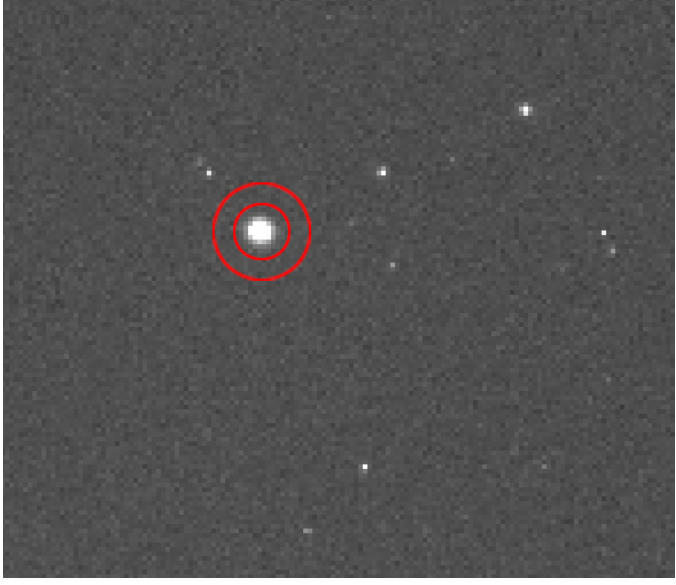
$m = -2.5 \log_{10} (J / J_{ref})$

$J = C\, J_{inst}$

$m = m_{inst} - 2.5 \log_{10} (C / J_{ref}) = m_{inst} - Z$

$\tau = \ln (J_1 / J_2) = 0.921\, \Delta m$

$A \approx \cos^{-1} z$

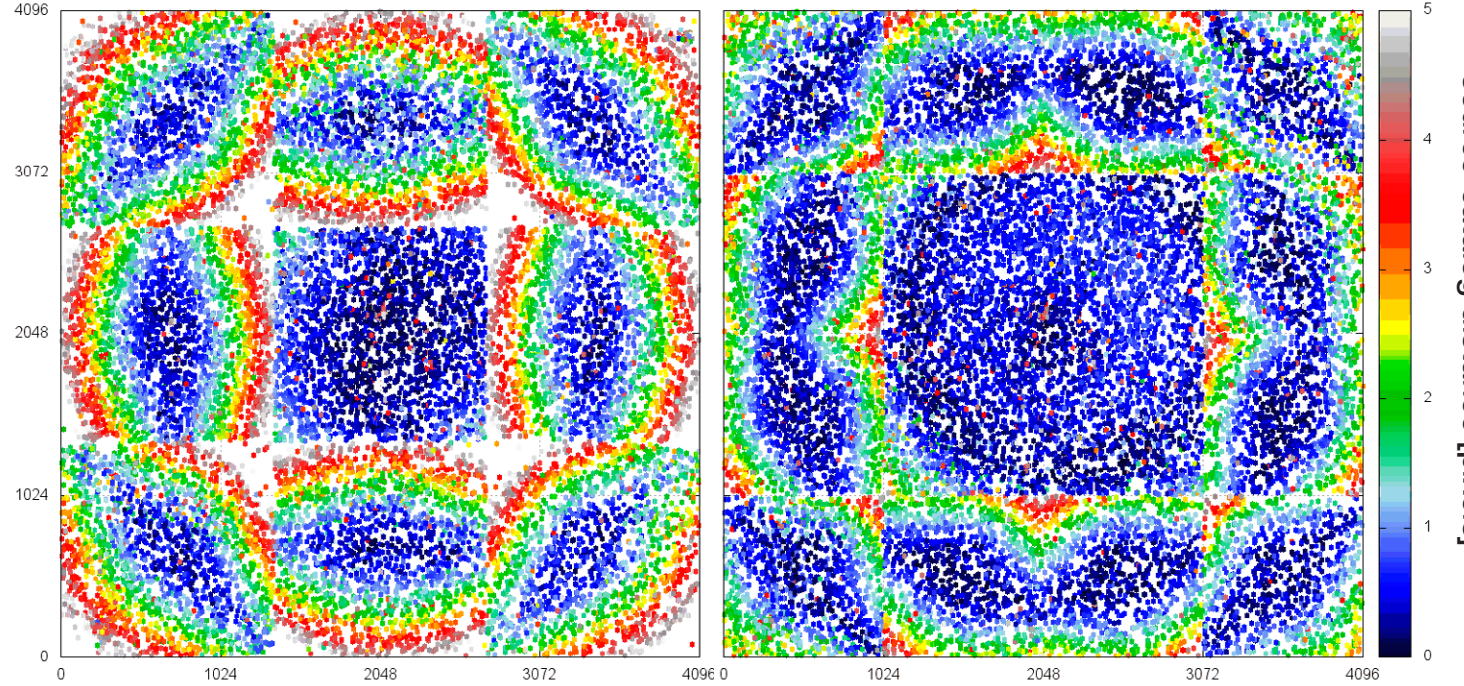


$$m_{inst} = M m_{cat} + Z_i + k_i A + c_1 (B-V)(c_2 (B-V) + 1) + R_1 r (R_2 r + 1) + k_C A (B-V)$$
$$= m_{model} + k_i A$$

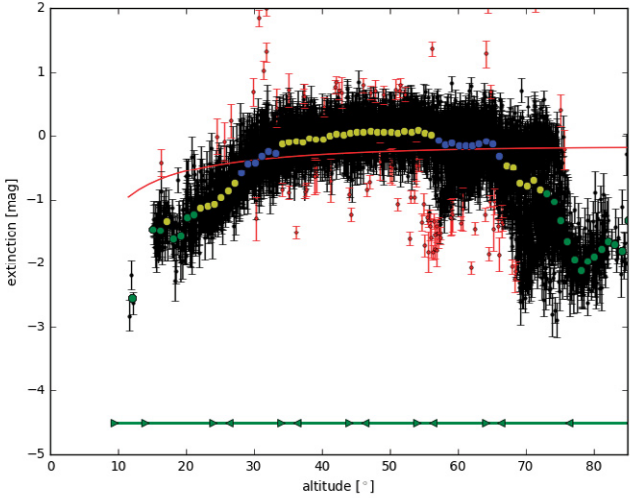
- A: airmass $B-V$: color index ($m_{cat} = B$) r: radial position on frame
- M, c_1, c_2, R_1, R_2 constant, barring small slow changes (tracked)
- (Z,k)-pair for each altitude scan
- k_C problematic (potentially varied high-VAOD enviroments, known for Rayleigh scattering, yet still mysterious)

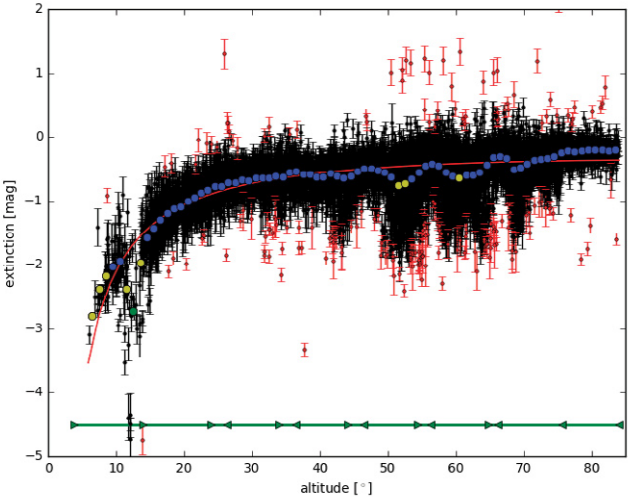
Matching with catalog

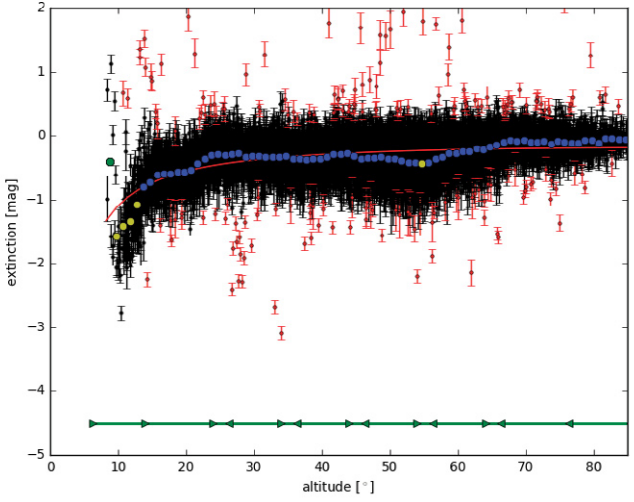
- Tycho 2 - coverage to 12 mag, reliable to ~9.5 mag, full-sky homogeneous, B_T and V_T bands
- Image distortion in large fields, optimize cutting strategy

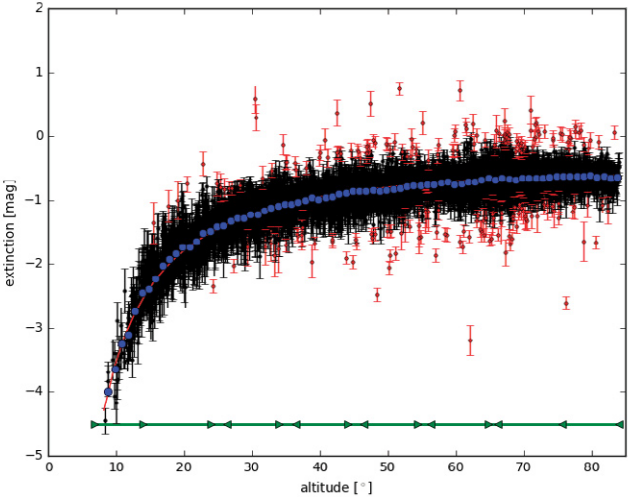


Altitude scans

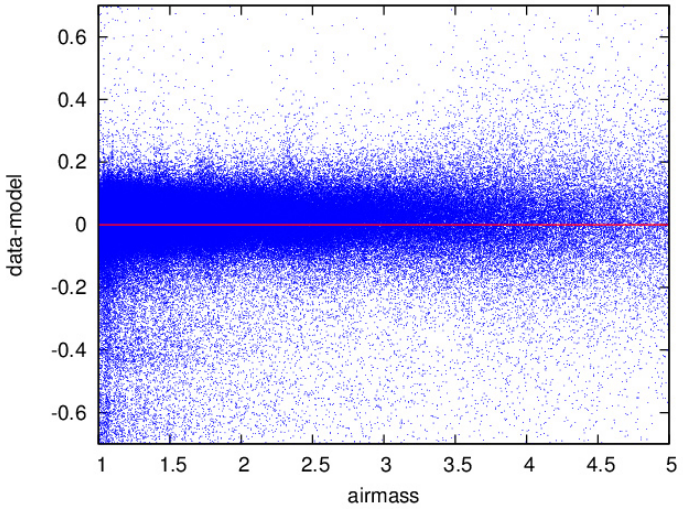


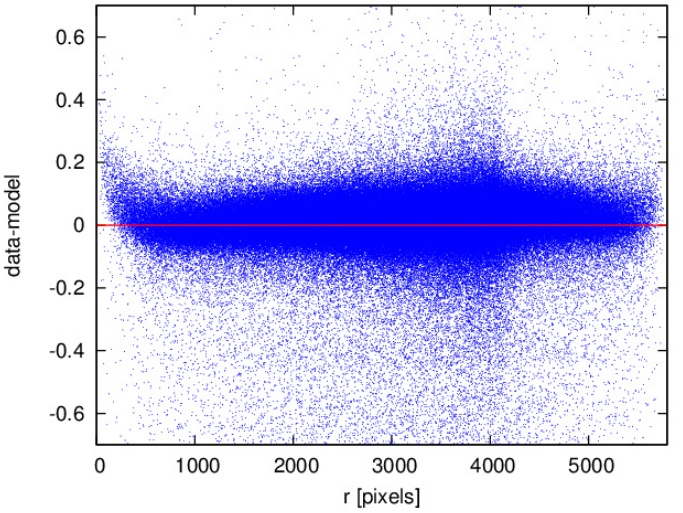


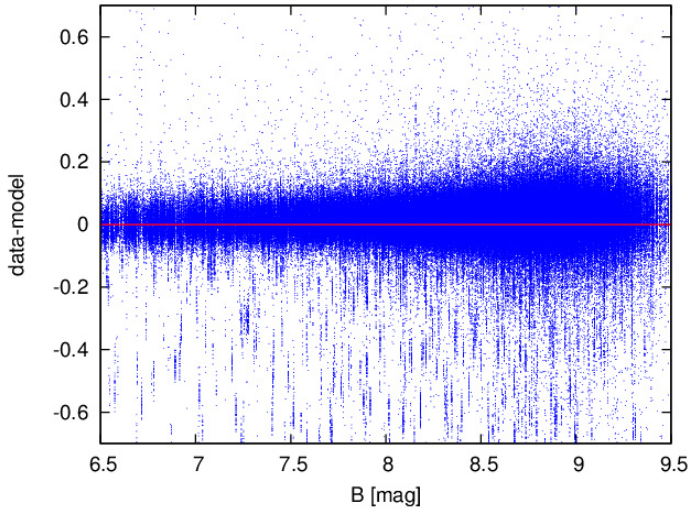


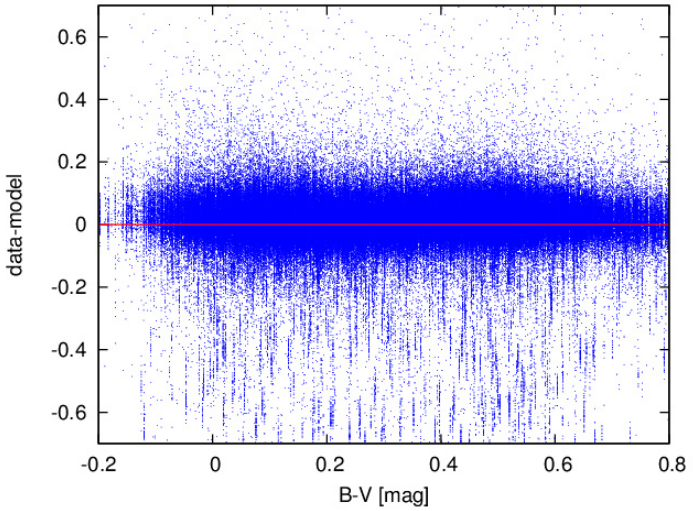


How does the model describe the data?



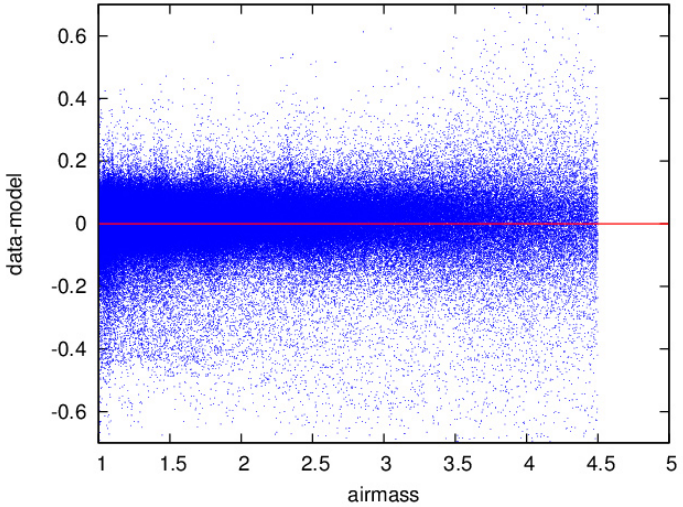


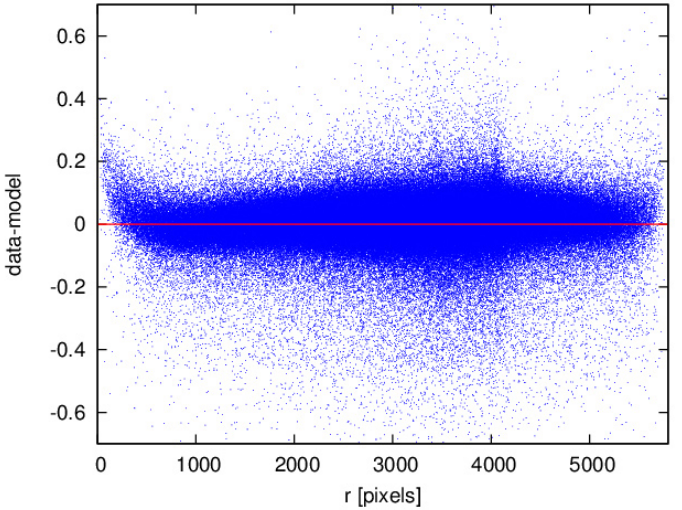


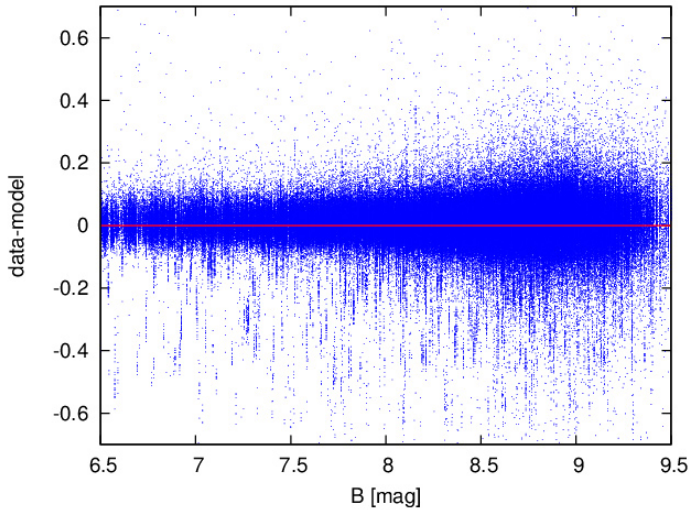


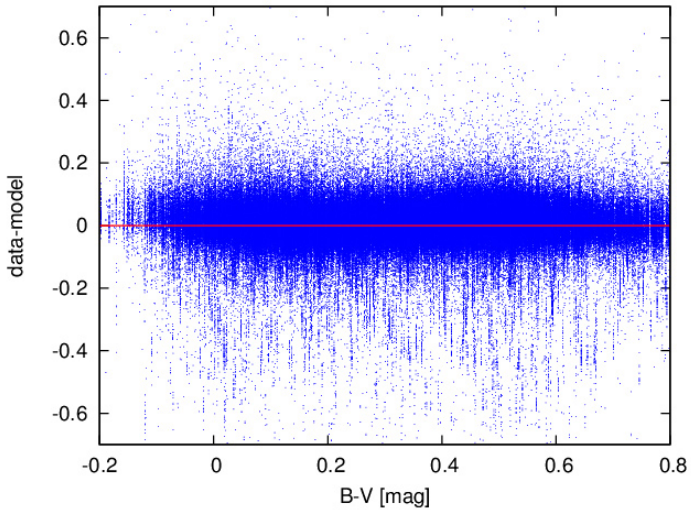
RMS ~ 0.13 mag

How does the model describe the data? (new)





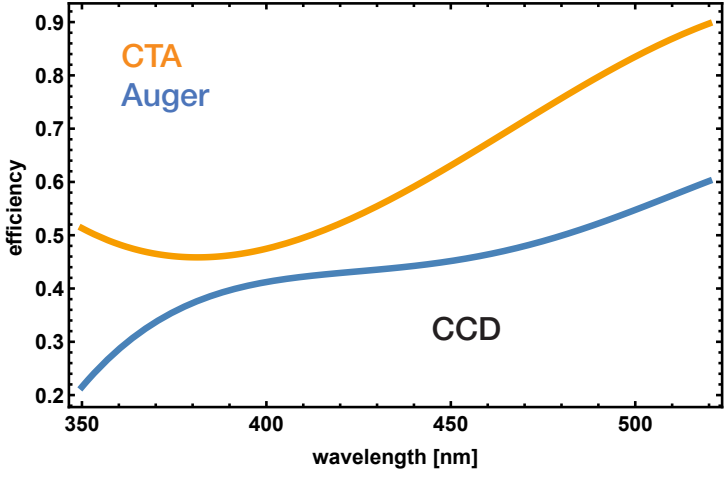


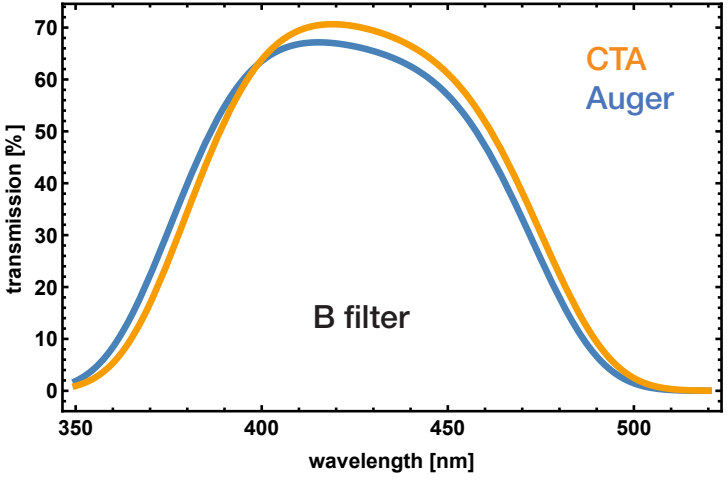


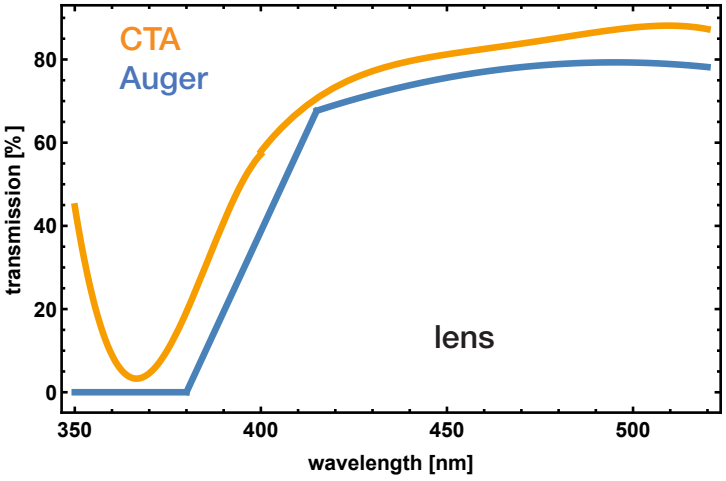
RMS ~ 0.09 mag

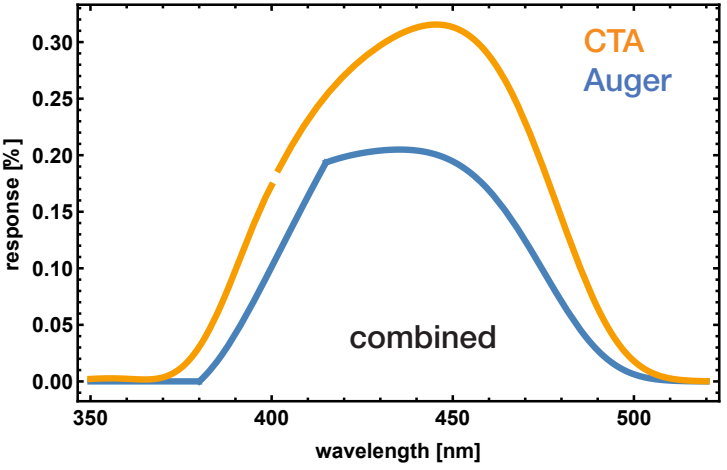
Rayleigh subtraction

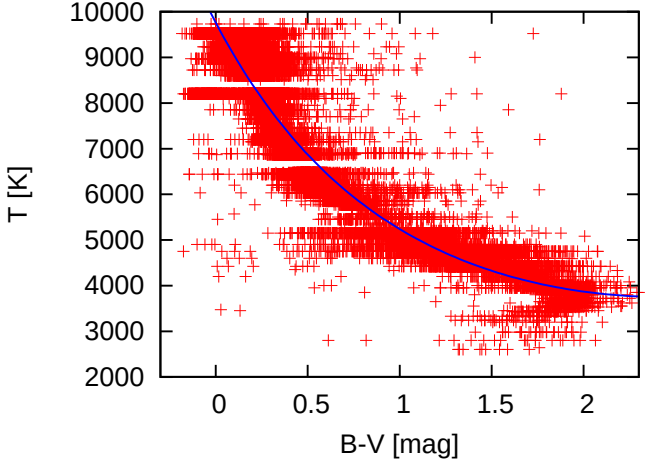
- laboratory measurements of optical components by Dušan Mandát
- B–V to temperature: Wright, C. O. et al. *AJ* **125**:359-363 (2003)
- Planck's law
- Rayleigh OD: Frohlich, C., Shaw, G. E. *Applied Optics* **19**:11 (1980)
  - Bucholtz, A. *Applied Optics* **34**:2765 (1995) changes negligible
  - pressure correction, local atmospheric profile etc. to be applied

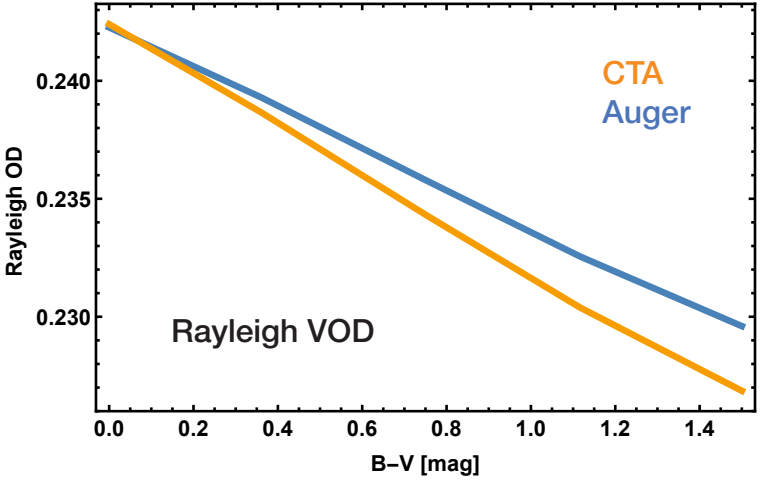




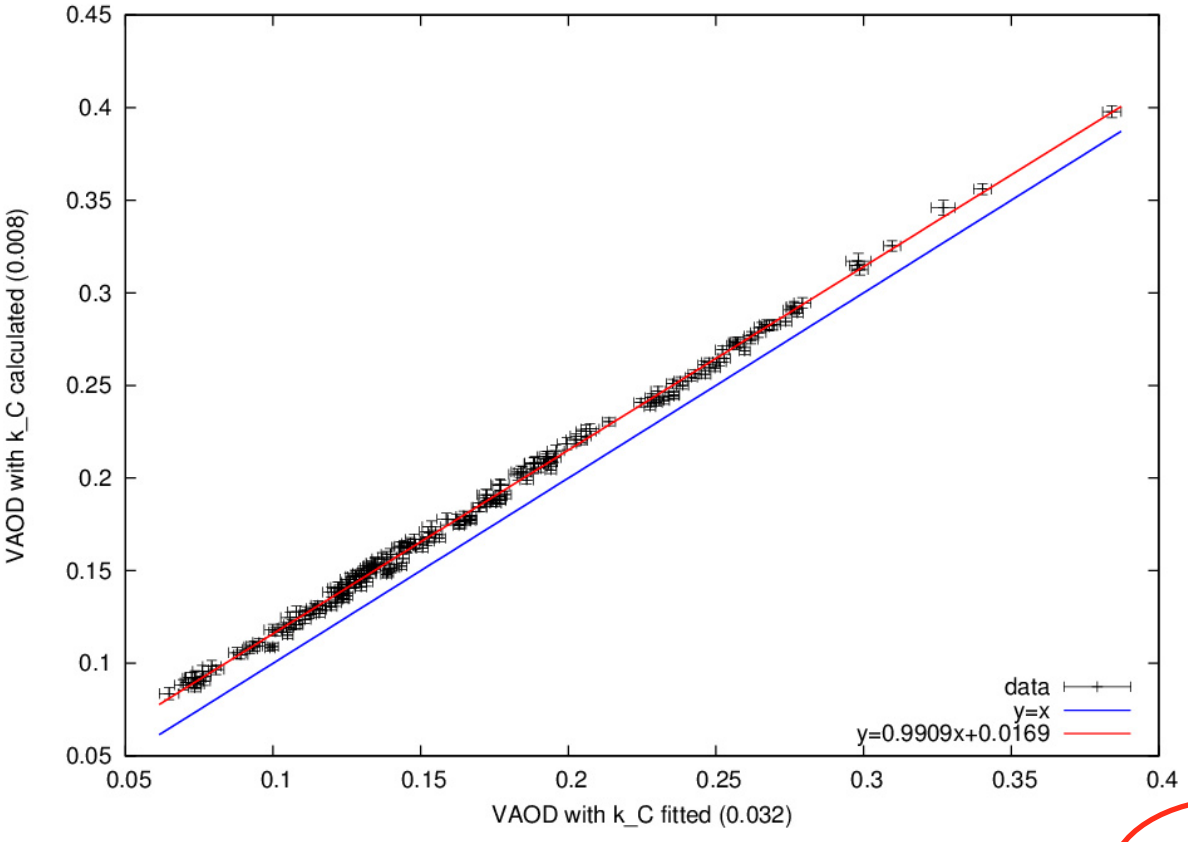

CTA
Auger
lens
transmission [%]
wavelength [nm]


CTA
Auger
combined
response [%]
wavelength [nm]


T [K]
B-V [mag]

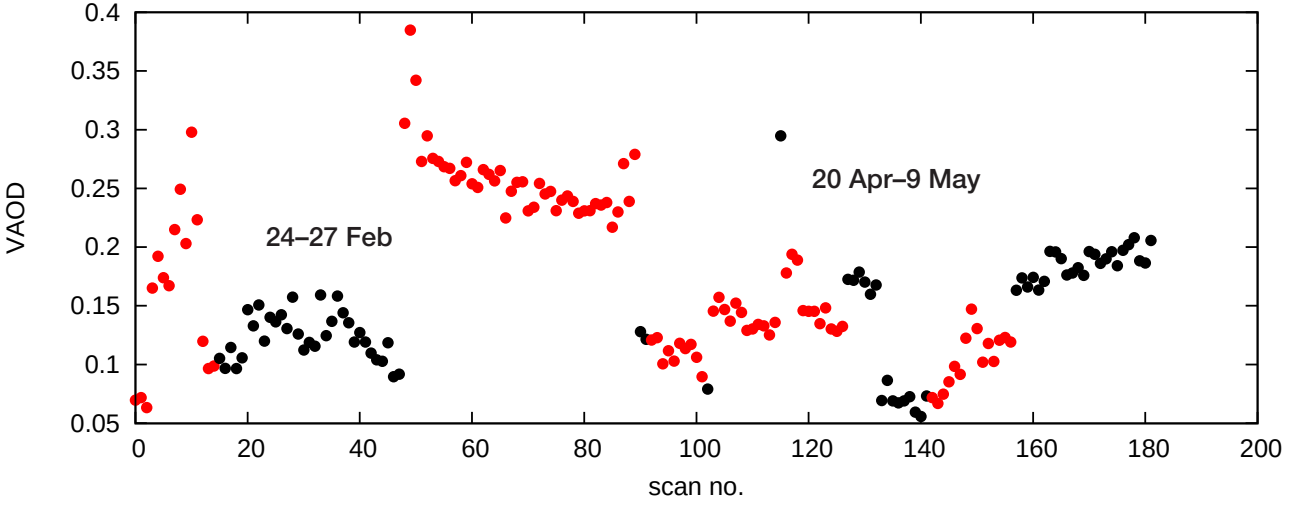

CTA
Auger
Rayleigh VOD
Rayleigh OD
B–V [mag]

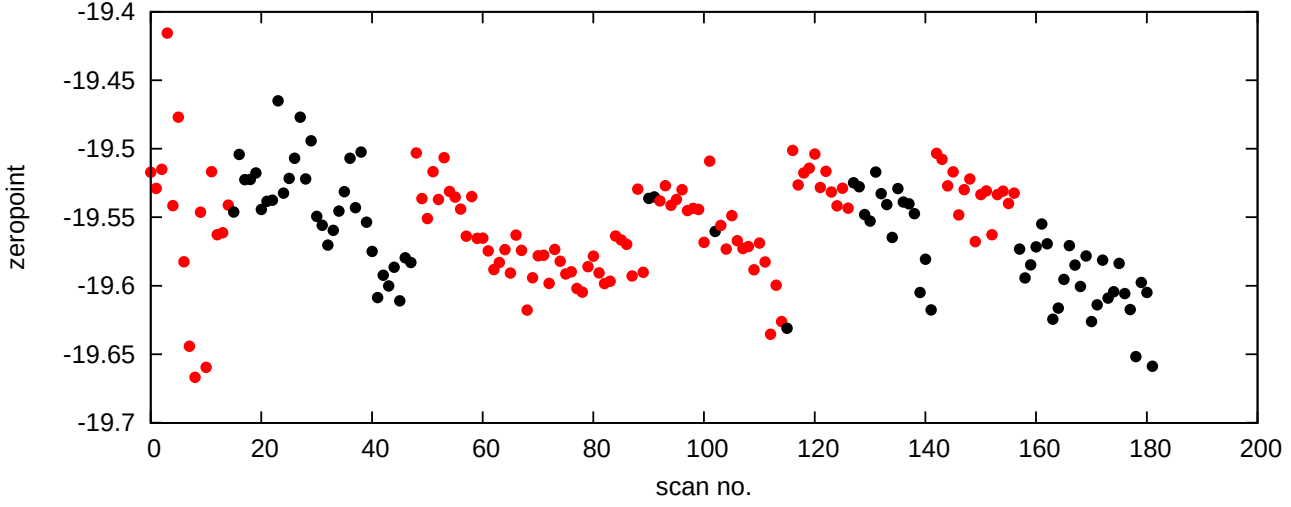
The „k_c problem“



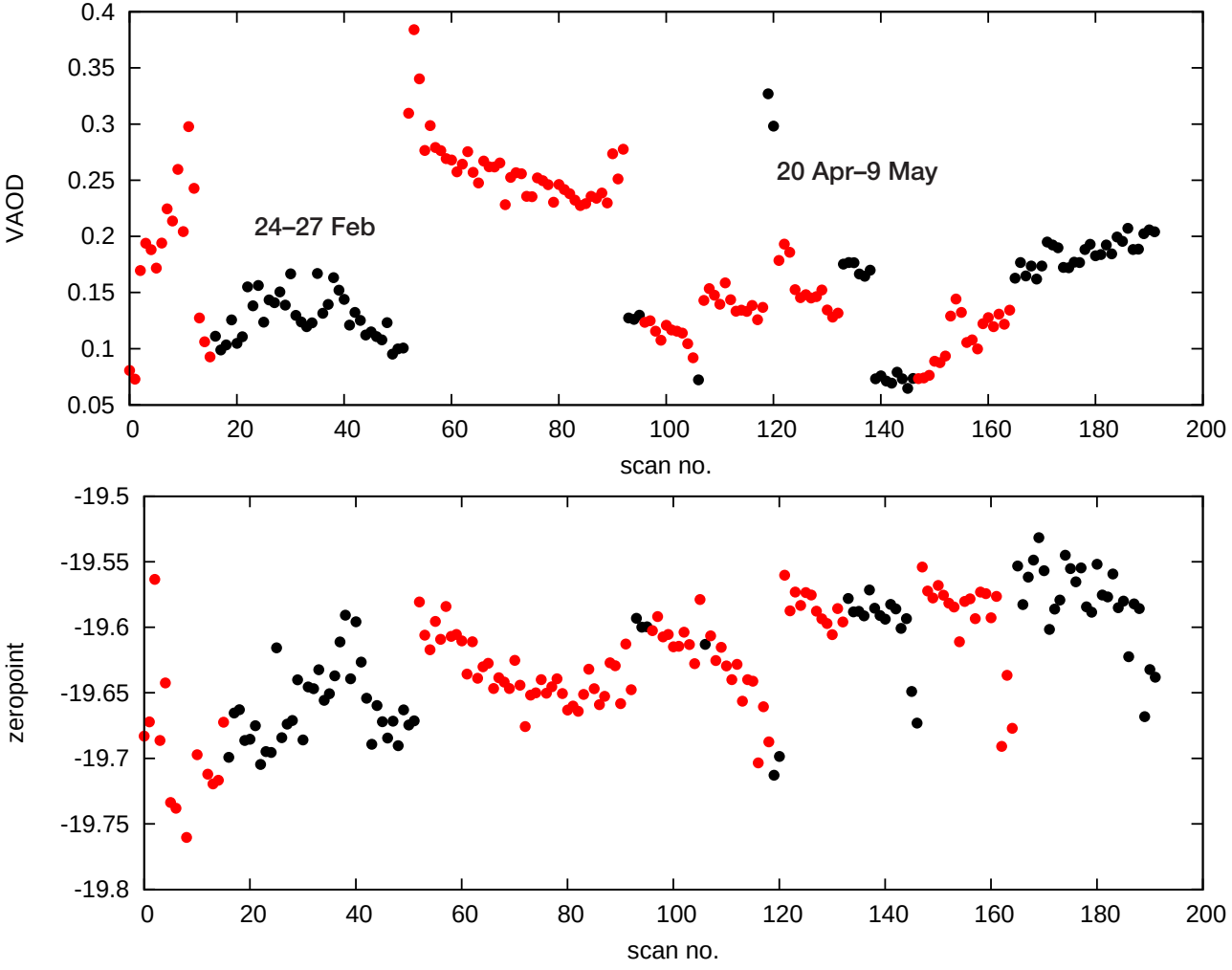
$$m_{inst} = M m_{cat} + Z_i + k_i A + c_1 (B-V)(c_2 (B-V) + 1) + R_1 r (R_2 r + 1) + k_c A (B-V)$$

Results of altitude scans: VAOD and zeropoint



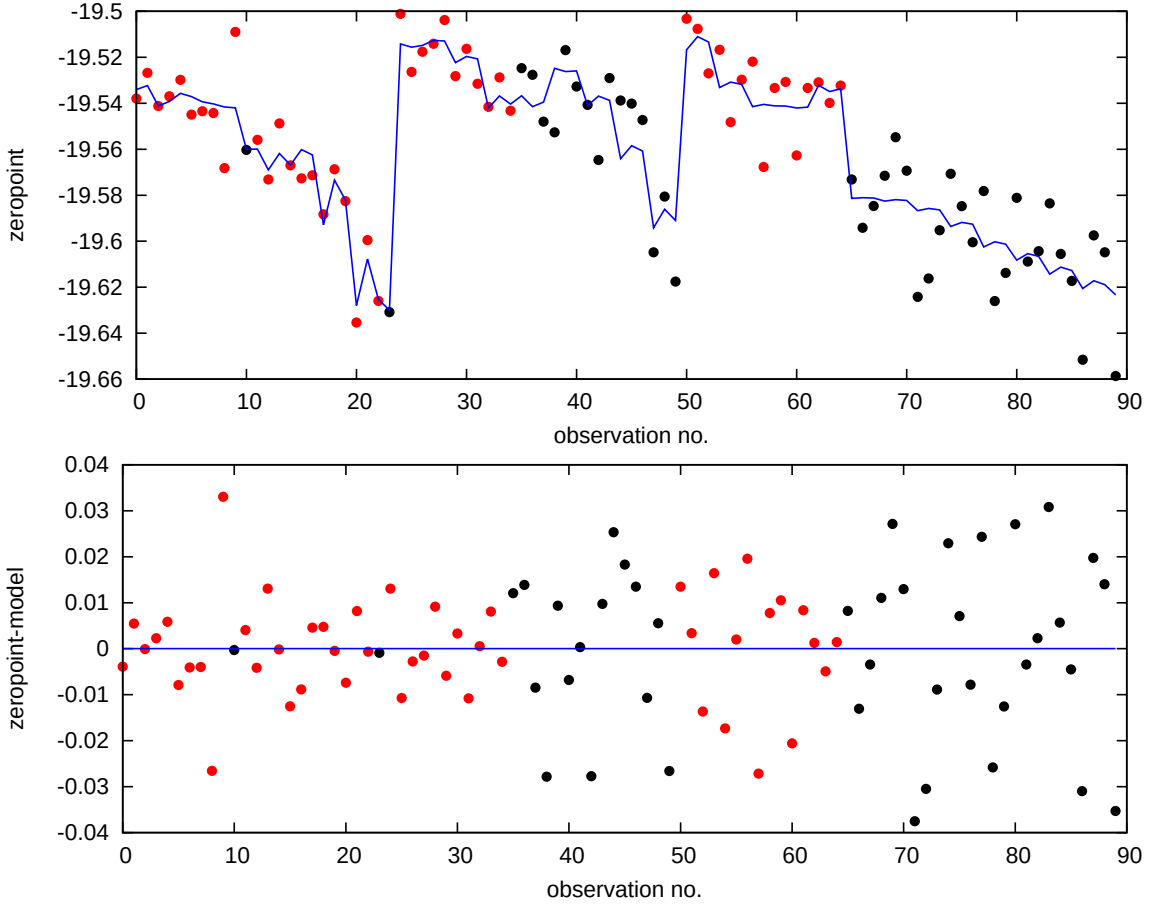


Results of altitude scans: VAOD and zeropoint (new)



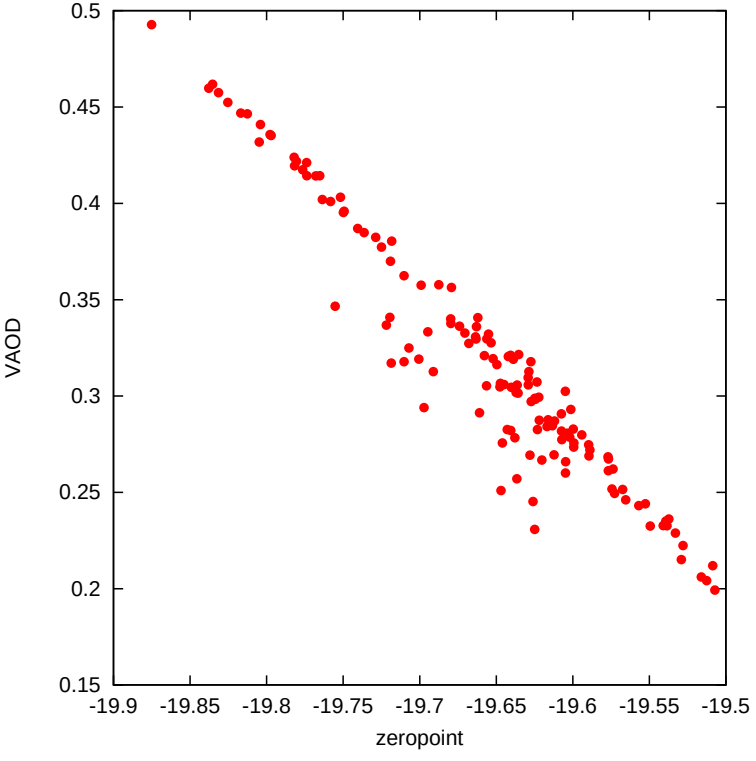
Single-field operation

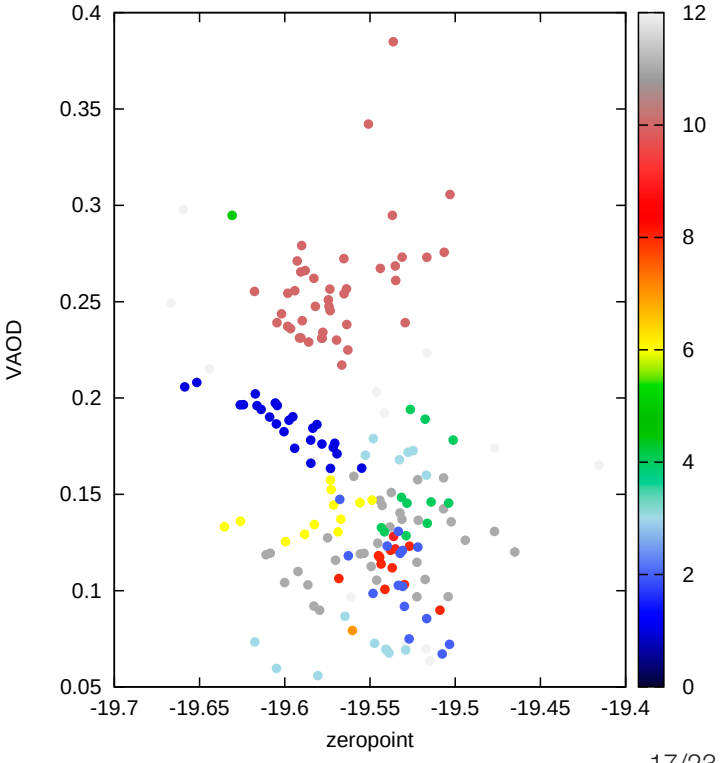
- zeropoint clearly non-constant: self-calibration using altitude scans



Importance of varied airmass

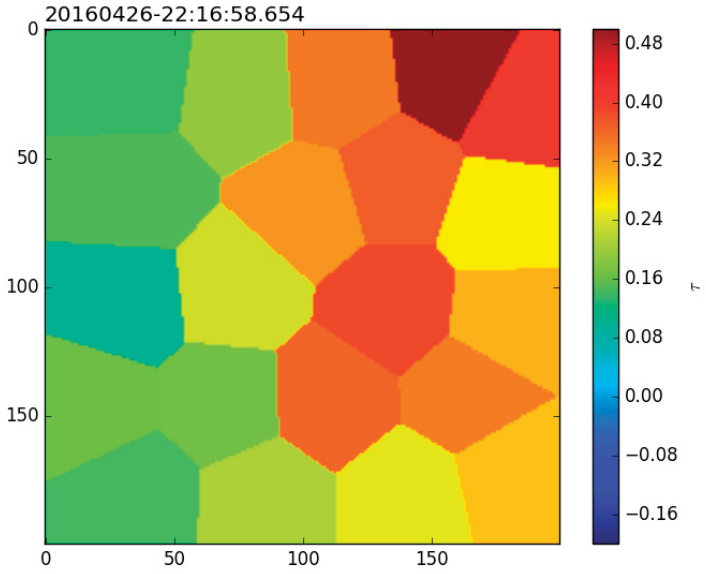
- zeropoint and extinction obviously degenerate
  - span of airmass over single image insufficient





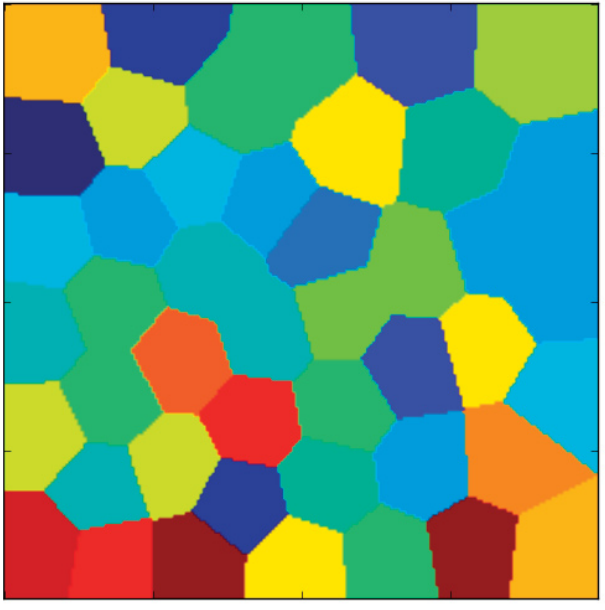
VAOD maps

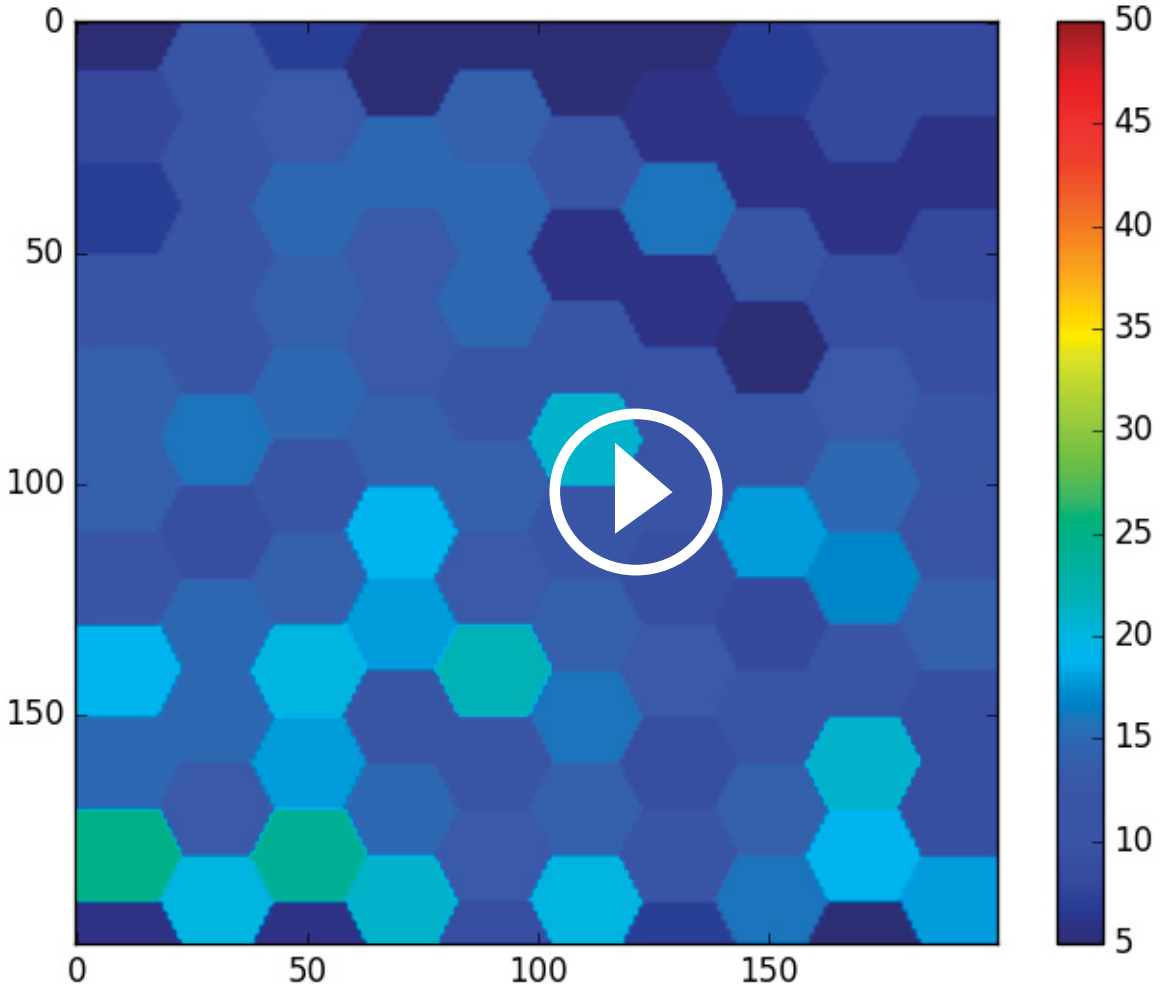
- main FRAM product during CTA operation
- average of ($m_{inst} - m_{model}$) / *airmass* × 0.921 – $\tau_{Rayleigh}$ over stars in bin
  - estimated „statistical“ error 0.02 mag
- using mean zeropoint calibrated by altitude scans
  - estimated error 0.02 mag
- est. precision 0.03 in VAOD (+ potential 0.02 shift from k_c)
- Prague: „worst case scenario“
  - bright and uneven sky background complicates photometry
  - horizon not accessible, trees and buildings
  - aerosol-dominated extinction

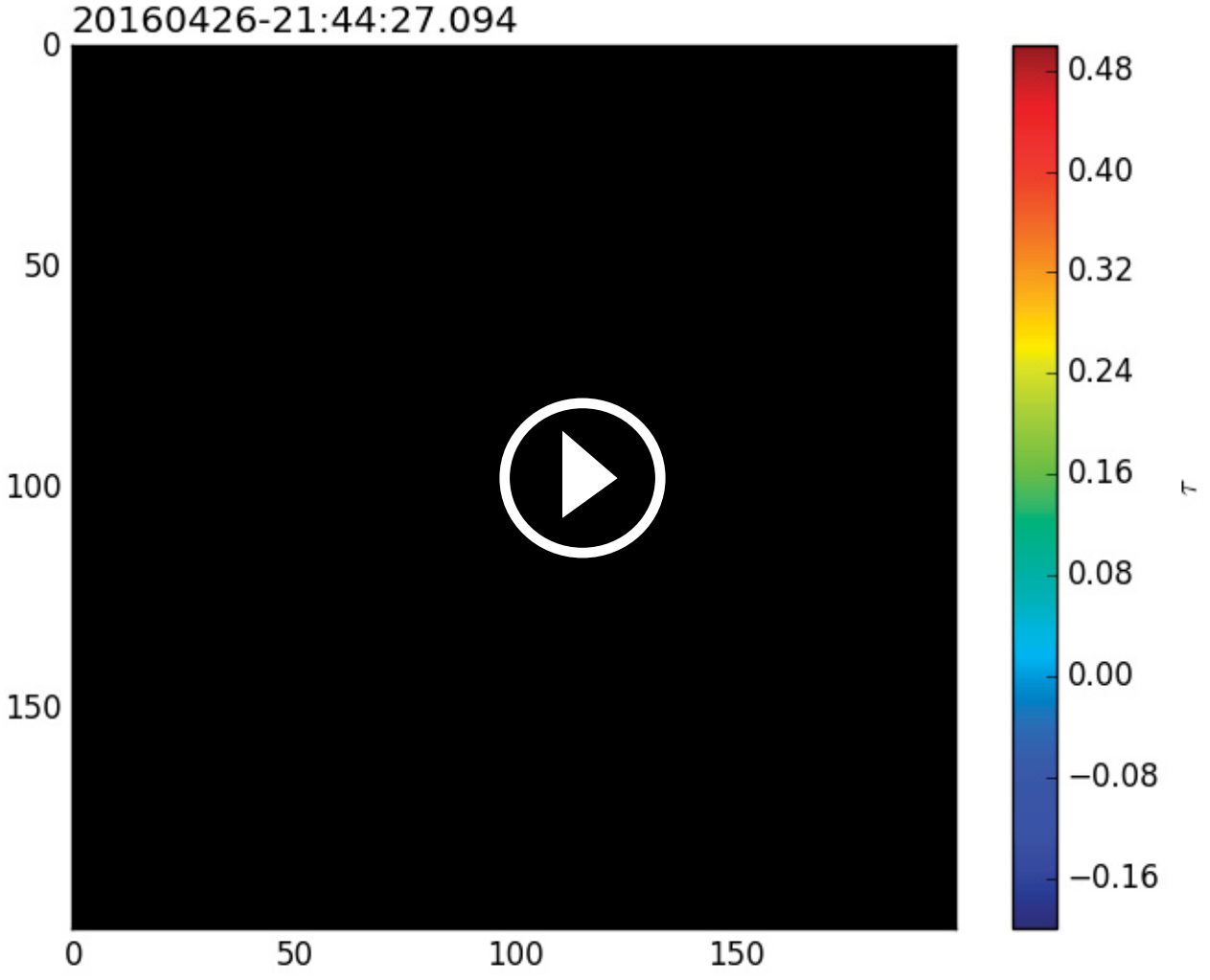


Adaptive Voronoi tessellation

- density of stars on the sky hugely varied: adaptive 2D binning
- Voronoi tessellation: regions closest to a specific point from a set
- start with regular grid → calculate centers of mass → iterate → drop cells with low numbers, split cells with $n_i > 2k$ into two → $n_i \in (k;2k)$

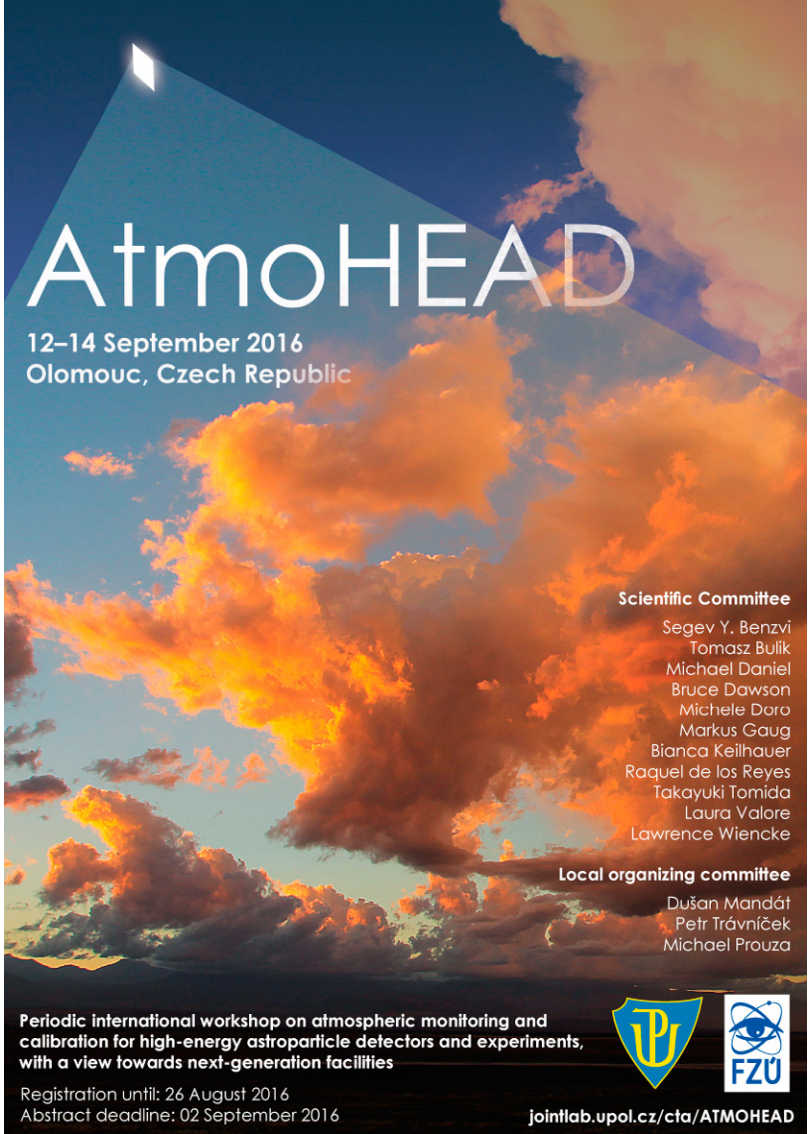



0
50
100
150
0
50
100
150
50
45
40
35
30
25
20
15
10
5


20160426-21:44:27.094
0
50
100
150
0
50
100
150
0.48
0.40
0.32
0.24
0.16
0.08
0.00
−0.08
−0.16
τ

Summary and outlook

- FRAM prototype has demonstrated its ability to measure VAOD in a given field within self-calibrated operation and is ready for deployment
- To-do list:
  - optimize catalog matching and photometry
  - improve model description of data
  - understand changes of zeropoint
  - deploy on site
  - build two more
  - integrate with CTA array control and data processing
  - operate through CTA lifetime


AtmoHEAD
12–14 September 2016
Olomouc, Czech Republic
Scientific Committee
Segev Y. Benzvi
Tomasz Bulik
Michael Daniel
Bruce Dawson
Michele Doro
Markus Gaug
Bianca Keilhauer
Raquel de los Reyes
Takayuki Tomida
Laura Valore
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Local organizing committee
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Petr Trávníček
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Periodic international workshop on atmospheric monitoring and calibration for high-energy astroparticle detectors and experiments, with a view towards next-generation facilities
Registration until: 26 August 2016
Abstract deadline: 02 September 2016
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