

## FRAM for the Cherenkov Telescope Array: an update

Petr Janeček<sup>1,\*</sup>, Jan Ebr<sup>1</sup>, Jiří Blažek<sup>1</sup>, Michael Prouza<sup>1</sup> for the CTA Consortium<sup>\*\*</sup>, Martin Mašek<sup>1</sup>, and Jiří Eliášek<sup>1,2</sup>

<sup>1</sup>*Institute of Physics of the Czech Academy of Sciences, Prague*

<sup>2</sup>*Faculty of Mathematics and Physics, Charles University, Prague*

**Abstract.** The Cherenkov Telescope Array (CTA) is a project to build a new generation ground-based gamma-ray observatory. The FRAM – F(Ph)otometric Robotic Atmospheric Monitor – is a device, which can provide it with the Vertical Aerosol Optical Depth (VAOD) maps in the field of view of the CTA in almost real time (delay in minutes). The FRAM is a small fast robotic astronomical telescope with a large field of view and a sensitive CCD camera. It uses stellar photometry to measure atmospheric extinction across the field of view and uses it to calculate the VAOD. In this contribution, results of first few months of operations of the prototype and outlook for deployment at the CTA site will be presented.

### 1 Introduction

The Cherenkov Telescope Array (CTA) will be the next generation of ground-based very high energy gamma-ray instruments [1]. To meet the strict requirements established for the precision of measurements and efficiency of use of the observation time, it is necessary to have precise knowledge of momentary atmospheric conditions, in particular the presence of clouds and the aerosol content of the atmosphere. Multiple devices are proposed to be installed at the CTA sites [2], one of which is a small robotic optical telescope, the "FRAM" (F(Ph)otometric Robotic Atmospheric Monitor), which will measure the total Vertical Aerosol Optical Depth (integral to the edge of the atmosphere) in the direction of the CTA field of view using stellar photometry, namely the comparison of measured apparent brightness of stars with respective catalog values [3].

The concept of the CTA FRAM builds on ten years of experience from operation of a similar device at the Pierre Auger Observatory in the Mendoza province of Argentina [4] and the data analysis is directly inherited from the Auger FRAM, with modifications and extensions demanded by the different properties of the CTA Observatory. In particular, the proposed mode of operation is based upon the strategy of using fast scans across a wide range of altitudes above the horizon in order to provide on-demand absolute calibration of the sensitivity of the system (as expressed via the so-called zeropoint  $Z$ ) and precision global VAOD values simultaneously [5]. Tracking the changes of the zeropoint by virtue of those scans, VAOD maps can be produced from single images of the current CTA field of view with high temporal resolution (1 map per minute) and

with only intermittent interruptions (typically 1 calibration scan taking 5 minutes every 30–60 minutes)<sup>1</sup>.

A prototype of the CTA FRAM setup has been installed on the grounds of the Institute of Physics in Prague in February 2016, has undergone extensive testing, during which the capabilities to operate in the proposed mode have been demonstrated, and is ready for deployment at a CTA site for preliminary characterization of atmospheric conditions at the site. In this paper we discuss the performance of this prototype and present first steps towards data products for immediate use during the CTA operation.

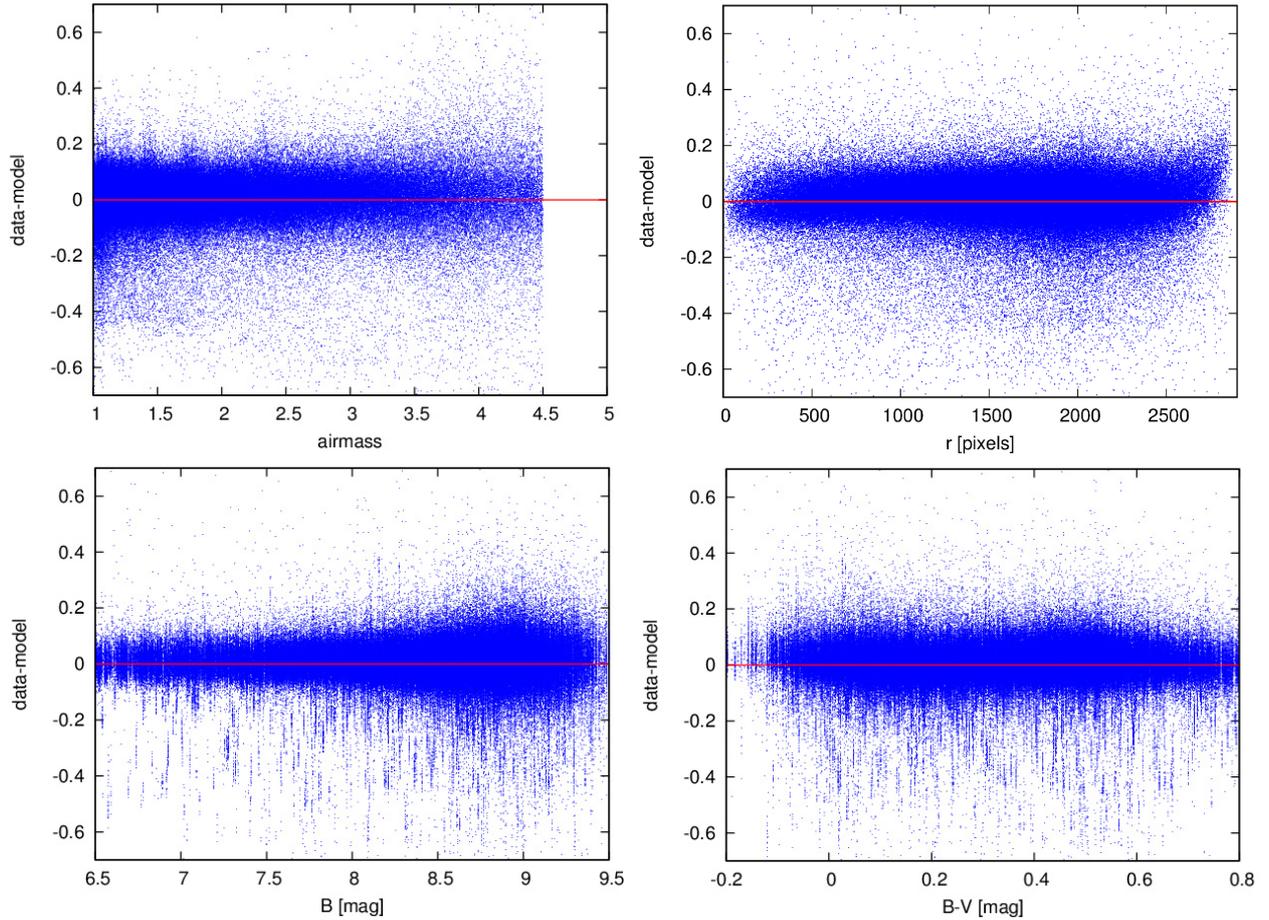
### 2 Hardware

The CTA has identified two candidate sites (one at each hemisphere) for the location of the future Observatory: the southern site near Cerro Armazones in Chile and the northern site at the Observatorio del Roque de los Muchachos on La Palma, one of the Canary Islands. Two FRAMs are proposed for the larger southern site (due to spatial variations in weather and parallax with respect to the more distant telescopes), one for the smaller northern site, all three in an identical hardware configuration which consists of a Paramount MYT mount (or similar commercial mount with the capability to determine its absolute orientation

<sup>1</sup>The actual frequency of calibration scans that will be necessary is currently uncertain and will be determined during the preliminary operation of the FRAMs on their respective locations as it probably depends on the environmental conditions on the sites as well as on possible future improvements in the method. It is also worth noting that a calibration scan can fail due to presence of clouds that render the fit unreliable; in such a situation, the zeropoint will be extrapolated from previous values and the reported uncertainty on the VAOD in the CTA field of view increased accordingly. Using data from other instruments on site, in particular the all-sky cameras, may allow selection of cloud-free parts of the sky for more reliable calibration.

\*e-mail: janecekp@fzu.cz

\*\*Full consortium author list at <http://cta-observatory.org>



**Figure 1.** Residua of the global fit as a function of various variables.

after a power cut autonomously), a Zeiss 135/2.0 photographic lens, a Moravian Instruments G4-16000 CCD camera with BVRI photometric filters, a custom enclosure by Elya Solutions and some auxiliary devices. The prototype built in Prague follows the same configuration. The chosen combination of camera and lens provides field of view of  $15 \times 15$  degrees, comfortably covering the whole CTA field of view even when accounting for parallax, while providing almost pin-point sharp star images across the field of view. A single 30-second exposure in the B photometric filter provides hundreds of usable stars anywhere on the sky under reasonable weather conditions.

The whole system is designed for autonomous and safe operation, following our experience with the Auger FRAM, which is located on a remote unmanned location. The custom enclosure was designed in close collaboration with the Elya company. It opens and closes using a hydraulic mechanism and includes fail-safe provisions for the case of a power cut, allowing the dome to be closed using gas pressure stored in a pressure accumulator instead of electricity. Care has been taken to minimize both peak and average power consumption so that the whole system can be operated using a modest solar power plant with 1 kW of installed solar power, 144 kWh of battery capacity and a 2 kW 230 V AC power inverter (needed for the

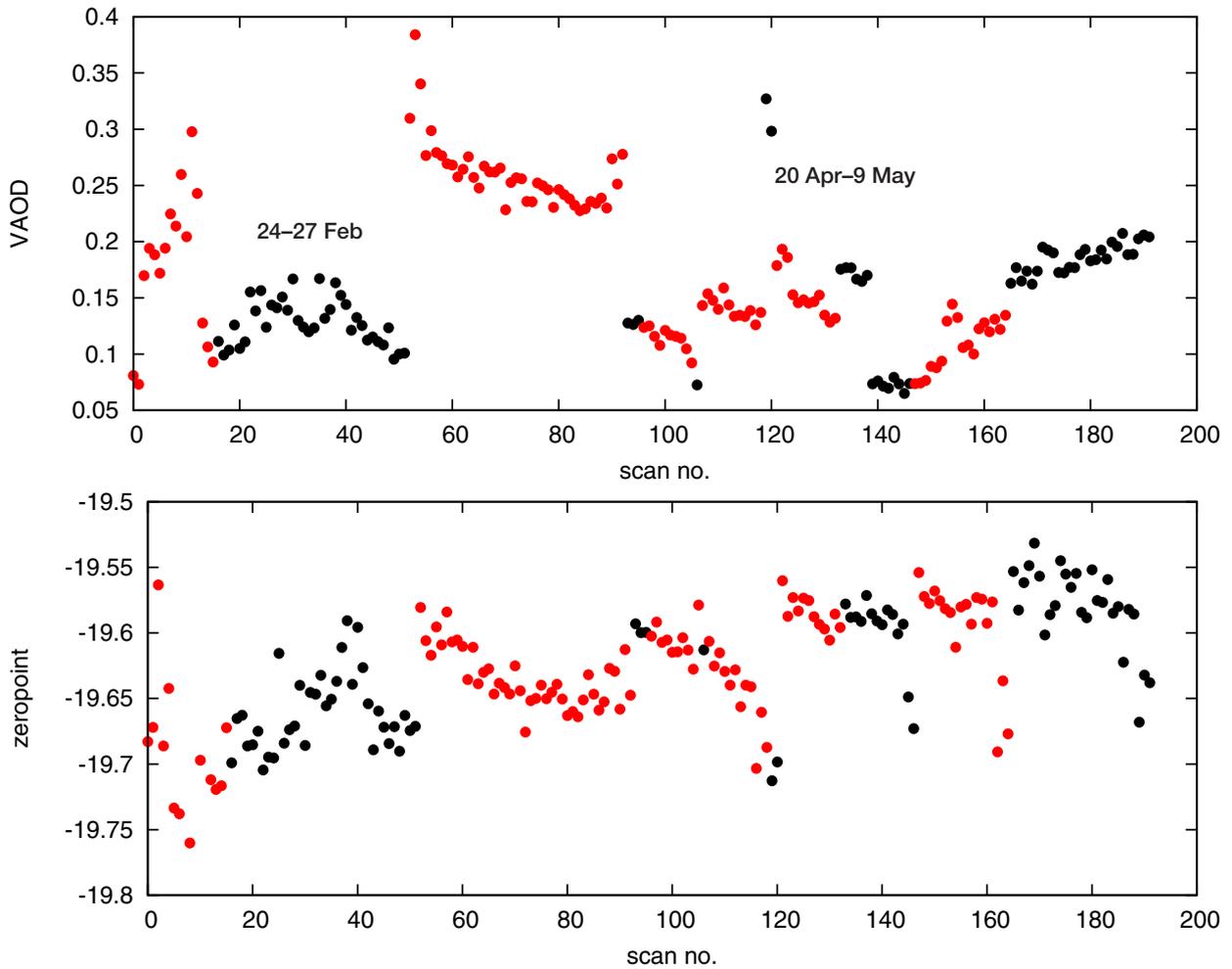
operation of the hydraulic pump) for several days in case of bad weather during the day. This may prove necessary in case the system is deployed on the southern CTA site well ahead of any other infrastructure (the northern site will most likely allow for a power grid connection in any case), as planned in order to characterize the site in advance.

The prototype is installed on a temporary wooden platform fixed into the ground using metal ground screws. This technology has proven useful and it is foreseen that it will be also used during the preliminary-characterization phase, before the FRAM is moved to its permanent concrete foundations. During a site visit at the ORM (La Palma), we have confirmed that the screws can be successfully used in the complicated terrain on the site.

### 3 Prototype data: altitude scans

The analysis of the calibration scans in altitude proceeds exactly as described in detail in [5]. Here we only remind the reader that the difference between the observed and catalog brightness of a star (in magnitudes) detected during the  $i$ -th scan is modeled with the following equation

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



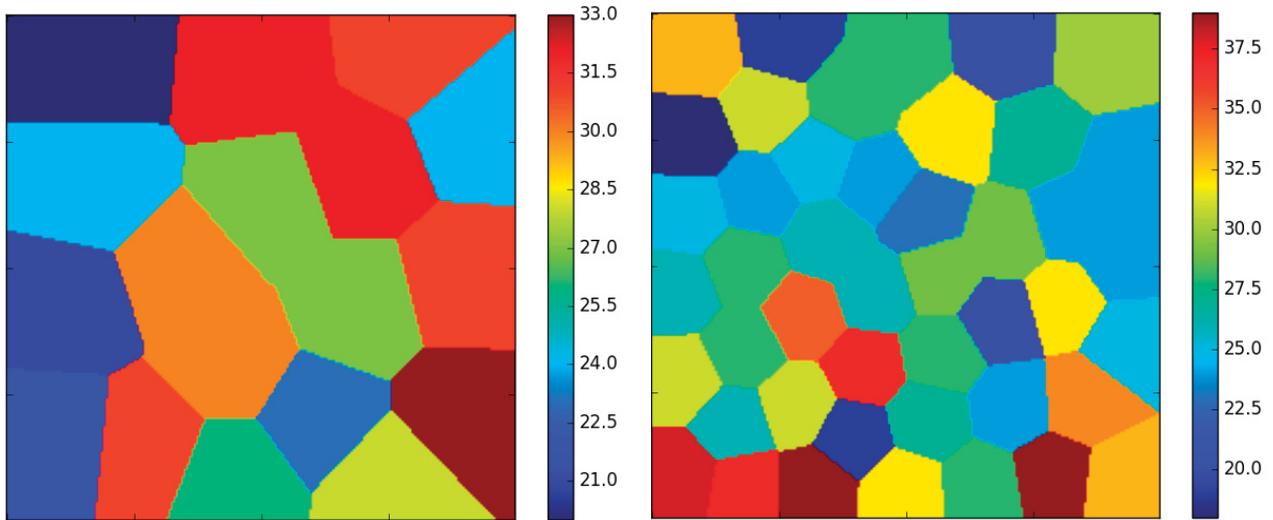
**Figure 2.** VAOD (upper row) and zeropoint (lower row) as a function of scan number. Consecutive points with the same color belong to the same night, but the nights are not necessarily consecutive. The first three nights are between 24 and 27 February, the rest between 20 April and 9 May – the very high VAOD values on 27 February are not surprising, as winter nights are mostly foggy in Prague.

where  $Z_i$  is the zeropoint (calibration constant) for the scan,  $k_i$  is the extinction coefficient ( $1.086 \times$  the vertical optical depth),  $A$  is the airmass in units of the vertical airmass,  $B$  and  $V$  are magnitudes of the star in the catalog in the respective filters,  $r$  is the distance of the star from the center of the respective image and  $M$ ,  $c_1$ ,  $c_2$ ,  $R_1$ ,  $R_2$  are parameters of the system (optics+CCD+data reduction) and the last term represents the dependence of the extinction on the star color.

This analysis can proceed only when the scan is not affected by clouds, which is a rather rare condition in Prague, in particular in winter – we collected data in 12 nights between February and May 2016, totaling almost 200 usable scans. Fig. 1 shows the residua of the global fit over all those scans. Only stars with  $A < 4.5$  could be used because of trees and other disturbances near the horizon. The overall RMS is 0.09, slightly larger than in the Auger FRAM data analysis (0.07). This is expected as the conditions in Prague are much worse, mainly when it comes to background and parasitic light and the analysis

is not yet optimized for the different hardware setup of the CTA FRAM prototype.

Fig 2 shows the results for the zeropoint and VAOD in time series. Unlike in [5], here only an approximate Rayleigh model with black-body spectra has been used; however as the aerosol content in the urban atmosphere is rather high, this is not a significant effect. Note that the VAOD changes heavily even within a single night, but mostly in a smooth fashion. The zeropoints both drift and fluctuate. In order to obtain zeropoint for a given time within a night for which successful calibration scans are available, we fit a smooth function (quadratic in time) to the zeropoint values for each individual night. The spread of values around the fit is 0.02 mag and constitutes the main contribution to the uncertainty of the determination of VAOD maps described below. We suspect that the fluctuations of the zeropoint are related to thermal contraction of the lens with decreasing temperature during night, but this effect needs to be investigated more. The long-term drift of the zeropoint might be due to dust accumulation.



**Figure 3.** Examples of Voronoi tessellations for a poor (left) and rich (right) star fields. The color scale indicates the number of stars in each cell.

#### 4 VAOD maps

For a night for which a zeropoint calibration is available, we can determine the VAOD at any point of the sky from a single image. We have taken series of images of fixed fields of view in between the altitude scans to simulate the proposed mode of operation of the FRAM within the CTA.

To produce a VAOD map from an image, we must first perform 2D binning of the stars into regions, because a measurement of a single star is too imprecise. As the density of stars varies greatly across the sky, this calls for an adaptive algorithm. We have chosen the so-called Voronoi relaxation which ensures that each spatial bin will contain between  $k$  and  $2k$  stars for a chosen value of  $k$  [6]. A Voronoi tessellation is a set of regions defined by a set of central points as areas that are closer to a given point than to any other of the points. The Voronoi relaxation algorithm starts with a regular grid. For each cell the center of mass of stars contained within the grid is calculated and centers of mass of all grids form a set of points that defines the first iteration of the Voronoi tessellation. Now the algorithm proceeds iteratively until it converges. In each step, cells with less than  $k$  stars are dropped and cells with more than  $2k$  stars are split into two and new centers of mass are calculated. (In a real-world implementation, the procedure is slightly more complex for optimization reasons). Note that the tessellation is chosen based on the catalog, that is the stars we expected to detect in the given field of view. In the presence of small clouds (or even thick aerosols), some stars might not be detected in some parts of the field of view. In such a case, the adaptive algorithm applied to the detected sources would create large regions around these areas to compensate for the lack of stars, effectively concealing the presence of the clouds.

When the 2D bins are defined (using  $k = 20$ ), we calculate the local VAOD as the average of

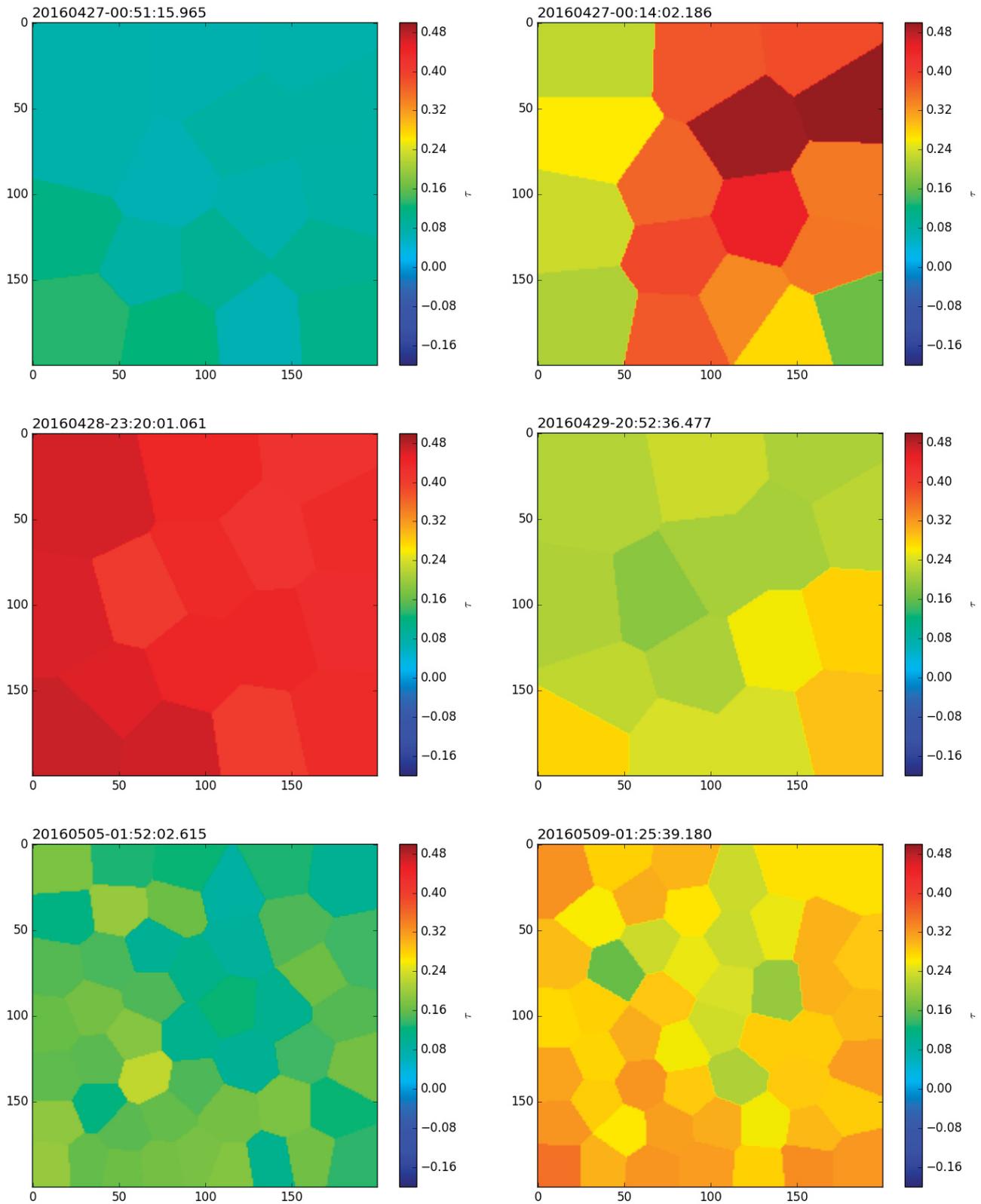
$$0.921 \frac{m_{\text{inst}} - m_{\text{model}}}{A} - \tau_{\text{Rayleigh}} \quad (2)$$

over the stars in the bin. Assuming that the RMS of the global fit reflects mainly the individual uncertainties in measured and modeled brightness of the stars, the statistical uncertainty of an average over at least 20 stars is smaller than 0.02. Combined with the uncertainty in the zeropoint calibration of 0.02, the overall uncertainty of each cell in the VAOD map is roughly 0.03. This is still rather large for an absolute VAOD measurement, but when viewing sequences of such maps over time, the appearance of even thin cirrus cloud is immediately obvious. Some examples of VAOD maps are shown in Fig. 4

It should be noted that Prague serves as a worst case scenario for this measurement, because the sky is both bright and unevenly illuminated, parasitic light is omnipresent, accessibility of the horizon and thus the lever arm in the model fit is limited and moreover, the extinction is dominated by aerosols (not the Rayleigh scattering) and thus there are additional problems with the determination of the dependence of the extinction for a single star on its color index. All of these problems will disappear once the system is deployed on a dark and clear site, such as those selected to host the CTA.

#### 5 Summary and outlook

The FRAM prototype has demonstrated its ability to measure VAOD in a given field within self-calibrated operation and is ready for deployment. There are however many tasks for future work. On the side of analysis, we have yet to optimize catalog matching and photometry, improve model description of the data and understand the changes of the zeropoints with time. On the hardware side, we still need to deploy the prototype device on site and build two more FRAMs. Finally, the most difficult task will be to integrate the software with CTA array control and data processing and, of course, operate the FRAMs throughout CTA's lifetime.



**Figure 4.** Example VAOD maps under varying weather conditions. X and y coordinates are in arbitrary units, the image plotted area corresponds to the whole  $15 \times 15$  degree image. The upper left image shows very clear conditions while the upper right image shows a thin cloud, which allows the detection of most expected stars, but causes clear inhomogeneity in VAOD across the field of view. The rest of the images illustrate the various kinds of conditions encountered in Prague during the prototype operation.

## Acknowledgments

We gratefully acknowledge support from the agencies and organizations listed under Funding Agencies at this website: <http://www.cta-observatory.org/>. The authors are grateful for the support by the grants of the Ministry of Education, Youth and Sports of the Czech Republic, projects LE13012, LG14019 and LM2015046.

## References

- [1] Acharya, B.S. et al. (CTA Consortium), *Astroparticle Physics* **43**, 3–18 (2013)
- [2] Gaug, M. et al. (CTA Consortium), these proceedings
- [3] Ebr, J. et al. (CTA Consortium), *Proceedings of the 34th ICRC, The Hague, The Netherlands*
- [4] The Pierre Auger Collaboration, *Nucl. Instrum. Methods Phys. Res., Sect. A* **798**, 172 (2015)
- [5] Ebr, J. et al. (The Pierre Auger Collaboration), these proceedings (2016)
- [6] Du, W., Faber, V., Gunzburger, M., *SIAM Review* **41(4)**, 637 (1999)