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New method for atmospheric calibration at the Pierre Auger Observatory using FRAM, a robotic astronomical telescope

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Abstract: FRAM - F/(Ph)otometric Robotic Atmospheric Monitor is the latest addition to the atmospheric monitoring instruments of the Pierre Auger Observatory. An optical telescope equipped with CCD camera and photometer, it automatically observes a set of selected standard stars and a calibrated terrestrial source. Primarily, the wavelength dependence of the attenuation is derived and the comparison between its vertical values (for stars) and horizontal values (for the terrestrial source) is made. Further, the integral vertical aerosol optical depth can be obtained. A secondary program of the instrument, the detection of optical counterparts of gamma-ray bursts, has already proven successful. The hardware setup, software system, data taking procedures, and first analysis results are described in this paper.

Introduction

FRAM is part of the Pierre Auger Observatory, and its main purpose is to monitor continuously the atmospheric transmission. FRAM works as an independent, RTS2-driven [1], fully robotic system, and it performs a photometric calibration of the sky on various UV-to-optical wavelengths using a 0.2 m telescope and a photometer. As a primary objective, FRAM observes a set of chosen standard stars and a terrestrial light source at a distance of 50 km. From these observations it obtains instant extinction coefficients and the extinction wavelength dependence. The instrument was installed during 2005 and after some optimizations it is routinely taking data since June 2006.

The main advantage of the system is fast measurement – data for one star in all filters are usually taken in less than five minutes. In comparison to Central Laser Facility (CLF) [2] or lidars [3] the other advantage of FRAM is that its measurements are completely non-invasive, i.e. producing no light at all and not anyhow affecting the data acquisition of the fluorescence detector (FD). Furthermore, some of the stars are well-calibrated and non-variable standard light sources with precisely known and tabulated intensities in various filters, thus allowing straightforward comparison with measurements done using the same set of filters. On the other hand, the main disadvantage of this instrument is that it is capable only of integral measurements through the whole atmosphere (or for the whole distance between telescope and terrestrial light source).

Instrument setup

The telescope has its own laminate enclosure that is located about 30 meters from the building of fluorescence detector at Los Leones, on the southern edge of Auger observatory array and about 13 kilometers from the town of Malargüe in Argentina.

As the primary instrument we use a 20 cm Cassegrain-type telescope with an Optec SSP-5 photometer and with integrated 10-position filter slider. Effective telescope focal length is 2970 mm and focal ratio ∼1:15. The system is further equipped with an electronic focuser Optec TCF-S. This Crayford-style motorized focuser is installed in secondary Cassegrain focus and bears the photometer on its moving end. A beam-splitting dichroic mirror is installed behind the focuser. The red and infrared light is reflected into narrow-field pointing CCD camera (Starlight XPress MX716) and ultraviolet and visible light passes through the mirror into the photometer.

Figure 1: FRAM telescope and its enclosure during sunset at Los Leones site.

Narrow-field pointing CCD camera has resolution of 752×580 pixels and field of view of $7' \times 5'$. It is primarily used for the fine centering of the targeted star into a field of view of the photometer, which has only $1'$ in diameter.

Photometer Optec SSP-5A is a high-precision stellar photometer. A Fabry lens projects an image of the primary mirror onto the cathode of photomultiplier (PMT). The Hamamatsu R6358 PMT was selected for our setup, because of extended spectral response from 185 nm to 830 nm. A Fabry lens is of B270-type glass that has enhanced UV-transmission. This still somewhat cuts down the transmission below 350 nm, but does not adversely affect the transmission of any of the used filters. For star measurements we use the set of four Stromgren uvby filters and Johnson U filter, for terrestrial source observation we use also four narrowband filters having central wavelengths 340 nm, 365 nm, 394 nm, and 412 nm.

Atop the telescope is installed wide-field CCD camera – Finger Lake Instruments MaxCam CM8 with Carl Zeiss Sonnar 200mm f/2.8 telephoto lens. This CCD camera uses Kodak KAF 1603 ME chip with 1536×1024 pixels, thus assuring $240' \times 160'$ field of view. The effective diameter of the lens is 57 mm and the limiting magnitude under optimum conditions reaches $R \sim 15.0$ for a 30 s exposure. This CCD camera is further equipped with Finger Lake Instruments filter wheel CFW 2 with set of Johnson-Coussins UBVRI filters and with 380-nm and 391-nm narrowband filters. This wide-field CCD camera is primarily dedicated for astrometry, i.e. for geometrical comparisons of star positions in the images with catalogue, what then enables precise justification of the telescope pointing on the sky. Mount is a commercially available Losmandy G-11, which uses the standard GEMINI GOTO system equipped with two servomotors with relative optical encoders.

Software

The system is driven by RTS2, or Remote Telescope System, 2nd Version, software package [1]. RTS2 is an integrated package for remote telescope control under the Linux operating system. It is designed to run in fully autonomous mode, selecting targets from a database table, storing CCD image and photometer metadata to the database, processing images and storing their identified coordinates in the database. RTS2 was developed and is maintained under open-source license in collaboration with robotic telescope projects of BART, BOOTES and WATCHER [4].

Observed targets and observation schedule

FRAM is primarily designed to provide the atmospheric extinction model. The data for this model are collected by the photometer with the help of both CCD cameras. The observation targets are selected bright (brighter than 6.5 mag) standard stars from photometric catalogue of Perry & Olsen [5] that features star measurements in Strømgren *uvby* photometric system.

The target cycle begins with a slew to the position followed by a short WF camera exposure to check the pointing accuracy. The position of the photometer aperture within WF camera's image is well known, so if the initial pointing is not satisfactory, a correction could be made. This image also serves as a test of atmospheric conditions: target may be canceled, if the necessary conditions are not met (clouds or fog resulting in no image astrometry).

After the star of interest was successfully centered within the WF aperture, a control exposure with the NF CCD camera is done. The star is identified as the brightest source in the field of view and, if needed, the mount position is corrected again and the star is moved to the center of photometer aperture. The photometer then does two sequences of measurements per filter of interest. Each sequence typically consists of five 1s integrations to obtain the signal value and its variance in each filter. Simultaneously both CCD cameras take exposures, so that pointing may be improved in real-time. The WF camera provides also a measurement in set of Johnson-Coussins UBVRI filters. The complete set of measurements is then stored in the structure of PSQL database.

Terrestrial light source observations

The Horizontal Attenuation Monitor (HAM) [6] uses continuously radiating Mg-Xe HID lamp situated about 50 km away from our telescope. We can observe HAM lamp also with FRAM, using both our CCD cameras and photometer.

The hourly automatic observations of the HAM light source started during October 2005. The brightest light source is identified within the image and then centered to the desired position on the WF camera, using iterative procedure. When such center position is achieved, the photometer flux is checked and observation script started. The ultimate goal of these observations is to obtain the independent values for the coefficient of the aerosol attenuation wavelength dependence and then check, whether the characteristic of horizontal aerosol distribution, obtained from observations of this terrestrial source, agrees with the results of 'vertical' measurements of standard stars.

Optical follow-ups of gamma-ray bursts

The RTS2 software system was originally developed especially for the search of optical transients of gamma-ray bursts. This software system was significantly modified to achieve FRAM main aims in atmospheric monitoring, however it is still very easy to activate special observation mode for optical transients. The main computer of the system receives in such case the alerts about detected gamma-ray bursts via network, slews there and makes images of the given sky region.

This alert system was activated on FRAM in late 2005 and already during January 2006 a very successful observation was made. An extraordinarily bright prompt optical emission of the GRB 060117 was discovered and observed with a wide-field CCD camera atop the telescope FRAM from 2 to 10 minutes after GRB. Optical counterpart identified in our images was characterized by rapid temporal flux decay with slope exponent $\alpha \propto 1.7 \pm 0.1$ and with a peak brightness of 10.1 mag in Bessel R filter. Later observations by other instruments set a strong limit on the optical and radio transient fluxes, unveiling an unexpectedly rapid further decay. We presented more details in [7].

Calibration and results

Our main goal is to provide the so-called Angstrom exponent γ, which is often used for parametrization of wavelength (λ) dependence of aerosol optical depth τ_A: $\tau_A(\lambda) = \tau_{A0} \cdot (\lambda_0/\lambda)^\gamma$, where λ_0 is the reference wavelength and τ_{A0} is the aerosol optical depth measured for this wavelength. Moreover, the Johnson U filter has almost the same central wavelength as have the lasers used for measurement of vertical aerosol optical depth (VAOD) at CLF [2] and at lidar stations [3]. The integral value of VAOD ($h = \infty$) in U filter thus can be used for direct cross-checks with these instruments.

We analyzed our database of photometer counts since June 2006, when telescope entered era of stable operation, until March 2007. We initially used part of data for calibration, where we fitted the dependence of difference between observed and tabulated magnitude on airmass for several stable and high-quality nights. The resulting dependence should be linear and the fit parameters characterize the extinction (slope), but importantly also the instrument zeropoint (intercept). The knowledge of the zeropoint then allowed us to directly compute the extinctions for our whole database. After that,

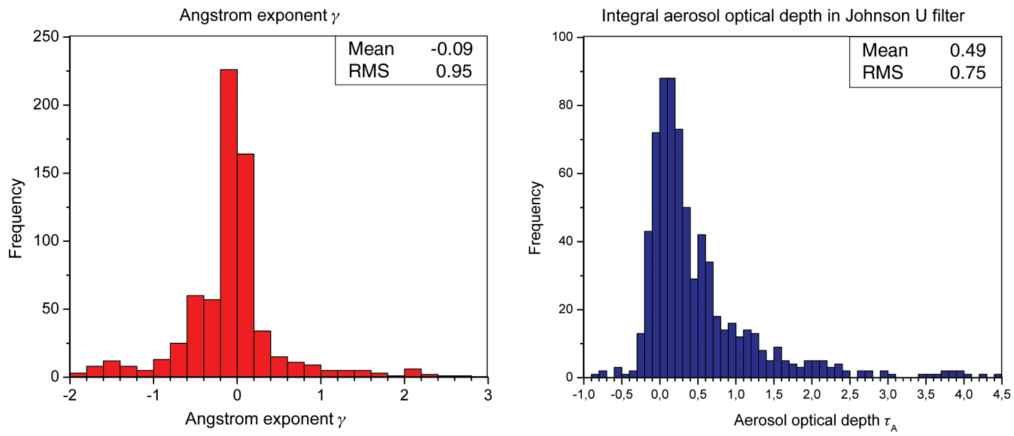

Figure 2: Histograms of measured distribution of Angstrom coefficient γ *(left)* and of integral aerosol optical depth τ_A *(right)* for all data obtained from June 2006 until March 2007. Only the hardware quality cuts were applied, consequently some reconstruction artifacts are still apparent. For the aerosol optical depth distribution the left (negative) tail is due to mis-identified stars and the more prominent right tail ($\tau_A > 1$) is due to observations through clouds.

we converted extinction expressed in magnitudes into total optical depth and then subtracted molecular Rayleigh part, using model from [8].

For the standard star measurements (see Figure 2) we obtained a preliminary mean value of $\gamma = -0.1 \pm 0.9$ that is lower than the results from HAM ($\gamma = 0.7 \pm 0.5$) [9], however still within 1-σ limits. Moreover, FRAM $\gamma = -0.1$ is in good agreement with theoretical expectations for atmosphere in desert-like environment ($\gamma \sim 0$) [10].

In the right panel of Figure 2, a resulting peak value of VAOD ($h = \infty$) is $\sim\ 0.15$ for measurements in Johnson U filter. It should be noted that the mean VAOD value is not relevant, because the distribution is strongly biased with its prominent tail of high extinction values that were obtained for observation through clouds. However, even the position of the peak indicates higher values of integral VAOD compared to the results from CLF and lidars (VAOD ($h = \infty$) $\sim$ VAOD ($h = 10$ km)$+0.02\ =\ 0.08$) [9]. The reliable comparison will be possible only after the application of the quality cuts that will follow the ongoing processing of CCD camera control images.

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