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SHOOT-THE-SHOWER: REAL-TIME OBSERVATIONS FOR ASTROPARTICLE PHYSICS USING THE FRAM ROBOTIC TELESCOPE

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RESUMEN

El telescopio FRAM opera como dispositivo de monitoreo atmosférico para el Observatorio Pierre Auger en Argentina. Además de realizar regularmente observaciones fotométricas para determinar el contenido y características de aerosoles en la atmósfera sobre el Observatorio, FRAM es también parte del programa de monitoreo rápido. Cuando los telescopios de fluorescencia del Observatorio detectan una cascada de ultra-alta energía, el telescopio FRAM toma una serie de imágenes para medir la transparencia atmosférica a lo largo de la trayectoria de la cascada. Estas observaciones son críticas para identificar cascadas con perfiles anómalos. La clara observación de este tipo de cascadas podría acotar significativamente los modelos de interacciones hadrónicas a muy altas energías.

ABSTRACT

The FRAM telescope operates as an atmospheric monitoring device for the Pierre Auger Observatory in Argentina. In addition to regular photometric observations aimed to determine the overall aerosol content and characteristic in the atmosphere above the Observatory, FRAM is also a part of the rapid monitoring program. When a ultra-high energy shower is detected by the fluorescence telescopes of the Observatory, the FRAM telescope takes a series of images to measure atmospheric transparency along the trajectory of the shower. These observations are critical for the identification of showers with anomalous profiles. If such showers were clearly observed, they can significantly constrain the hadronic interaction models at very high energies.

Key Words: astroparticle physics — atmospheric effects — techniques: miscellaneous

1. MOTIVATION

Cosmic rays are charged particles coming to Earth from outside the Solar System. They are observed over more than ten decades in energy, from 10^9 eV to about 10^{20} eV. Because their flux is roughly proportional to E^{-3}, the particles of the highest energies (above 10^{17} eV, commonly called the ultra-high energy cosmic rays, UHECR) are very rare, with rates of the order of 1 particle/km^2/year at 10^{19} eV. Naturally, the UHECR are of great interest for astrophysics – even though their exact sources and acceleration mechanisms are currently unclear, the likely candidates include such interesting objects as active galactic nuclei (AGN) or gamma-ray bursts (GRB). Moreover, while most of the cosmic rays are deflected by the magnetic fields in the Universe to the point of almost complete isotropy, the deflection decreases with energy and thus the arrival direction of highest-energy particles could reveal the positions of their sources.

The majority of the UHECR are believed to be hadronic particles (protons or heavier nuclei) and thus they interact high in the atmosphere. As their low flux requires square kilometers of detection area, direct detection in space or high atmosphere is not feasible. However, their interactions in the atmosphere typically produce many secondary particles, which in turn interact again, eventually initiating a cascade of billions of particles. These extensive air showers (EAS) travel many kilometers through the atmosphere and reach a maximum when the energy of individual particles becomes so low that they are absorbed in the atmosphere before further interactions. Still, for showers that are not highly inclined, many particles reach the ground, spread across several square kilometers, where they can be sampled by a sparse array of particle detectors. Most of the particles in the shower are charged and thus they lose energy during their passage through the atmosphere via ionization. During this process, fluorescence light is produced, mainly in the ultraviolet wavelengths; the amount of this light is proportional to the energy lost and as most of the energy of the primary particle is eventually deposited in this way, it provides as a measure of the primary energy and can be observed using optical telescopes on moonless nights.

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The Pierre Auger Observatory, located in the Argentine province of Mendoza, is currently the largest experiment dedicated to the detection of the UHECR (Abraham et al. 2006). It combines both detection techniques described above, employing an array of 1600 surface detector (SD) stations over a total area of 3000 km^2 and a fluorescence detector (FD) comprising 27 telescopes overlooking this area. While the surface detector offers much better uptime (almost 100 % compared to roughly 13 % for the FD), the fluorescence data are invaluable as they allow precise measurement of the energy of showers and thus provide an energy calibration of the surface detector using showers observed by both methods simultaneously. The fluorescence method also provides information about the longitudinal development of showers in the atmosphere (in particular the depth of the maximum of the shower) which allows us to distinguish between different primary particles.

The atmosphere has a significant influence on the transmission of light from the shower to the telescope, particularly because most of the telescopes operate at high zenith angles: 24 of them are pointed so that their field of view spans between 2 and 30 degrees above the horizon. To take this into account, there are many systems providing regular atmospheric monitoring, such as cloud cameras, backscattering lasers (LIDARs), calibration lasers and many more. However as the volume of atmosphere used for detection is large and its properties can change both in space and time, it is advantageous to have data for the actual time and direction of at least some particularly interesting showers. This requirement has led to the creation of the rapid monitoring program (Abreu et al. 2012) at the Observatory which includes directional scans (commonly called "Shoot-the-Shower" or StS) using the LIDARs and the FRAM robotic telescope (and used to include weather balloon launches in the past).

The showers chosen for rapid monitoring fall into two categories: 1. Showers that are rare and thus of high value such as very high-energy showers (that provide an important lever arm in the energy calibration of the surface detector) or candidates for UHE photons. 2. Showers that depart significantly from the usually smooth longitudinal profile. As the number of particles and interactions in an EAS is huge, most of the natural fluctuations in the interactions are smoothed out very quickly. Nevertheless, even standard hadronic interaction models predict that in a small fraction of cases, a "double-bump" structure of two maxima can be visible in the longitudinal profile, preferably at lower energies. Observation of such showers (or lack thereof) may not only significantly constrain models of hadronic interactions but also provide limits (or even evidence) for exotic processes and/or primary particles. When a candidate for such a shower is observed, the rapid monitoring is almost compulsory, because the same effects could be created by atmospheric non-uniformities such as cloud banks or aerosol layers.

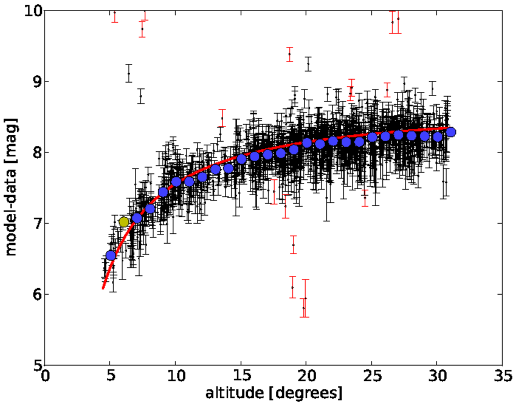

Fig. 1. An example of a Shoot-the-Shower result during a clear night. Each point shows the difference between the catalog brightness corrected for color index ("model") and apparent brightness ("data") for each individual star in magnitudes (with an arbitrary overall normalization). The solid line shows the overall extinction model fitted to the data and the large circles represent the averages for each bin in altitude. In the color online version these are color-coded in blue, yellow and green by their increasing distance from the fit; also in the color version some data points are marked red: these are the stars that have been excluded from the fit as outliers. Note that the stars from the image taken in the arrival direction of the shower are used to extend the range for the fit in this case and that all the bin averages lie close to the fitted line, as expected for clear sky.

2. SHOOT-THE-SHOWER IMPLEMENTATION

The FD of the Pierre Auger Observatory consists of four sites that are tens of kilometers away from each other – thus only showers observed by one of the six telescopes at the Los Leones site, where the FRAM telescope is located, can be investigated using this telescope. The FRAM system is designed to monitor the atmospheric conditions using stellar photometry and its setup consists of a 12-inch Schmidt-Cassegrain telescope and a 300/2.8 lens, both equipped with a different CCD camera with BVRI photometric filters and a focuser. The CCD camera on the main telescope (the narrow-field camera) sees a field of view of a fraction of a degree and thus is not suitable for covering the large field of

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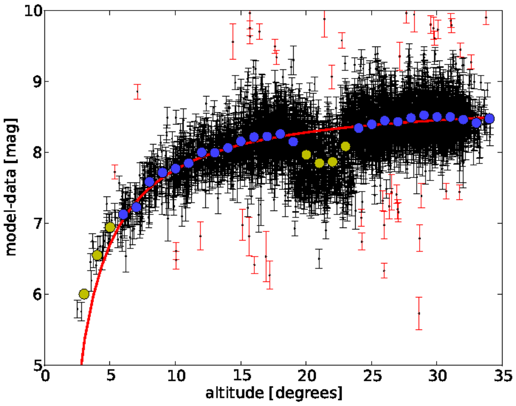

Fig. 2. A Shoot-the-Shower plot showing a thin layer of clouds or aerosols, which is apparent as the averages of several bins between 20 and 25 degrees altitude lie below the fitted line. See Fig. 1 for more information about the plot.

view of the FD telescopes. This is the main reason for installing the second camera with the telephoto lens (the wide-field camera, WF) which has a field of view of almost 7° × 7° and thus allows us to cover the whole length of the apparent track of a shower accross the FD field of view usually in 5–7 images, depending on the zenith angle of the shower. For more technical details on the FRAM telescope, see Ebr et al. (2014).

After several levels of triggers, roughly one shower candidate per minute is observed at one FD site. The data are synchronized to the central campus of the Observatory every 20 seconds, but additional 2–8 minutes are required to retrieve data from the surface detector. These data are then used in conjunction with the fluorescence data to reconstruct the geometry of the shower – this “hybrid” reconstruction greatly increases the accuracy when compared to using only fluorescence data. A computer at the central campus periodically checks for new data and when any are available, it performs a simplified version of the official reconstruction algorithms. If a shower is well-reconstructed and passes some basic quality criteria, a trigger with a list of about 80 reconstructed parameters is send over the LAN to the control PCs of LIDARs and the FRAM telescope, where the decision whether to shoot the shower is taken based on these parameters. This approach reflects the difference between the instruments used: while performing the LIDAR StS means four minutes of downtime for the fluorescence telescopes (to avoid laser interference), the FRAM operation is completely non-invasive, thus more showers can be selected for shooting with FRAM without sacrificing observation time – the main constraint in choosing the cuts for FRAM is that enough time is left for observations needed for the ordinary atmospheric monitoring program and that the StS triggers do not interrupt each other too frequently.

The FRAM telescope is operated using the RTS2 (Kubánek et al. (2004)) software, which has been designed with rapid follow-up observations of GRBs in mind. The extension of its functionality to StS triggers was thus straightforward. When a StS trigger is received, the parameters of the shower are checked against several different sets of conditions (accommodating the different interesting cases discussed earlier) and if at least one set is satisfied, the shower is accepted for StS. A set of pointing directions is then calculated so that images taken with the WF camera cover the whole trajectory of the shower across the whole FD field of view – including directions in which the shower was not registered to see whether the absence of light there is an atmospheric effect. Any ongoing observation is immediately interrupted and for each of the calculated directions, a single 30 second image in the B filter is taken; one additional image is taken in the arrival direction of the primary particle to check for possible transient optical phenomena and then the previous observation is resumed. The data are stored locally and currently analyzed offline, although an immediate online analysis is foreseen. Each morning, a summary of the showers shot during the night with control plots is e-mailed to several members of the team, so that any issue is quickly resolved. As mentioned above, with the current WF camera, only 5–7 images are required for one scan. However, a large part of existing StS data has been taken with a camera with a smaller field of view of 4° × 2.6°, corresponding to 10–20 images per shower. Most of the fluorescence light is emitted in the near UV, in a band that roughly corresponds to the Johnson U filter – however, the amount of stars detectable on a 30 second image in this filter with the given setup is very low, thus the B filter was chosen as the next available alternative.

3. DATA ANALYSIS

In each image, stars are detected and their flux is measured in a fixed aperture of 3 pixels (which corresponds to almost 20” on the sky, enough to contain the star image even in very bad seeing conditions). In this way, typically from a thousand upto tens of thousands of stars are detected in one image with limiting magnitude more than 13.5 mag in good conditions. By comparing observed brightness of stars in the images with their catalog data, one

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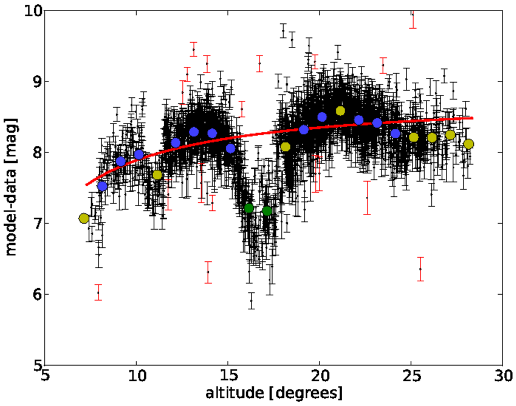

Fig. 3. A Shoot-the-Shower taken on a relatively cloudy night. There are several layers of clouds and no stars close to the horizon. Under very cloudy conditions, the fitting procedure for the global extinction starts to fail – nevertheless, the cloudiness is still clearly visible. See Fig. 1 for more information about the plot.

can extract the atmospheric extinction in the given direction. The catalgue we use (Tycho2, Høg et al. (2000)) contains mainly stars brighter than 12 mag and thus the very faintest stars are automatically excluded. Still, simply making this comparison for each observed star along the shower track leads to very noisy results due to a variety of effects. While the dark-frame calibration of the images is straightforward, using automatic dark images collected in the evening before and morning after every night, obtaining a reliable flat-field (not to mention remotely) for a wide-field camera is difficult. The filter used is not exactly the same as in the reference catalog and thus the color indexes of stars have to be taken into account; also, the catalog itself contains many deficiencies. At the moment, we fit the dependence of the apparent brightness of the stars as a function of distance from the center of the image for each frame and the dependence on the color index for each shower. Recently, we have created an overall fit for these corrections (which should not be too variable with time) using clear nights (selected by hand) for further analysis. Other factors that need to be accounted for are the image distortion in the seven-degree field of the newer WF camera and atmospheric refraction – both can lead to misidentification of stars (which is difficult to identify when each image contains thousands of sources).

In an ideal case, we should be able to obtain the absolute value of extinction in any given direction. However, this depends, among other effects, on the transmission of our system and the sensitivity of the camera (the "zero point" of the images) – currently we are investigating the time stability of these values, but for the moment, we are using a relative approach: for each shower, we fit the overall extinction as a function of the airmass (using all identified objects except for outliers for which the difference from the model differs from the mean value in the respective altitude by more than 3σ). Then we divide the stars into bins in altitude and we calculate the distance between the center-of-mass of the bin and the fitted line; when it exceeds a predefined threshold, we mark the bin as "cloudy". Examples of this analysis are presented in Figures 1, 2 and 3. Finally, unlike the LIDAR, which can locate the clouds in the 3-dimensional space, we measure only the integral extinction between the telescope and the edge of the atmosphere. Thus, it is not straightforward to use the FRAM data to correct for atmospheric extinction in the FD data, because we do not a priori know if the absorbing layer or cloud is really between the FD and the shower or further away. However, we can positively identify showers, for which the extinction depends smoothly on altitude, as cloud-free.

4. CONCLUSIONS

We have shown that a robotic telescope operated on the RTS2 software can be used as a device for rapid atmospheric monitoring at a major astroparticle physics experiment. Since the start of the regular StS program at FRAM on January 2010 until November 2013, we obtained almost 1800 showers with at least 5 images for the older WF camera or at least 3 images with the new WF camera (though some of the data are affected by a software error causing wrong calculation of the pointing directions). From the data, we can identify showers that are unaffected by clouds or variable aerosol layers, for further analysis by the Pierre Auger Collaboration.

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