Using star tracks to determine the absolute pointing of the Fluorescence Detector telescopes of the Pierre Auger Observatory

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Abstract

We describe in this paper two independent methods to accurately determine the absolute pointing of the fluorescence detector (FD) telescopes of the Pierre Auger Observatory. Our aim is to provide reliable and precise procedures to check and monitor the absolute telescope’s pointing and its long-term stability during the whole life of the project, estimated to be about 20 years.

The two methods described, called “single pixel method” and “star track method”, are based on the FD capability to be sensitive to signals left by stars traversing the telescope field of view. As the star positions in the sky are known with very high precision, the identification of the star signals provides a powerful tool to check the telescope alignment. We used data acquired during regular observation periods in 2004 and we demonstrated that the two independent methods presented in this paper provide compatible sets of pointing directions.

Key words: Atmospheric fluorescence detector, Telescope’s pointing, Long-term stability
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1 The Pierre Auger Observatory

The Pierre Auger Observatory was conceived to investigate the nature of the Ultra High Energy Cosmic Rays (UHECRs), in particular those with energy above $10^{18}$ eV. At this energy the integrated cosmic ray flux is rare, 1 particle/(km$^2$ year), leading to an experimental site that extends over a flat area of about 3000 km$^2$ at an altitude of 1400 m in Malargüe, Mendoza, Argentina.

So far the detection of ultra high energy cosmic rays has been performed using two traditional and independent techniques, i.e. ground based surface detectors and fluorescence light detectors. These techniques measure, respectively, the particle density distribution at the ground and the longitudinal development of the shower’s secondary particles generated when the primary cosmic ray arrives at the Earth’s upper atmosphere. Both techniques, which allow an independent determination of the shower parameters and which were used separately in the past, are combined for the first time in the Pierre Auger Observatory in a unique detector that allows a hybrid shower reconstruction, a distinctive and innovative feature of the experiment.

The Auger Surface Detector (SD) consists of 1600 water-Cherenkov tanks of 10 m$^2$ cross section and about 1.5 m high, separated from each other by 1.5 km in a triangular grid, that allow an accurate sampling of the shower lateral density distribution. The Auger Fluorescence Detector (FD), consisting of 24 telescopes sensitive to the UV light, measures the longitudinal development of the cosmic ray shower in the atmosphere above the earth. This is done by detecting the fluorescence photons emitted isotropically by the nitrogen molecules excited by the shower’s secondary particles propagating in the atmosphere [1–3]. Most of the fluorescence photons are emitted in the wavelength range between 300 – 400 nm for which the atmosphere is quite transparent, corresponding to an attenuation length of $\approx 15$ km for a vertical beam of light. The fluorescence yield is $\approx 4$ photons per electron traversing one meter of atmosphere, mildly dependent on altitude and atmospheric temperature [4–7].

The coincident detection of a shower with the two techniques, possible for about 10% of the events, facilitates the cross-calibration of the two detectors with a consequent reduction of the systematic errors. In order to achieve high resolution in the hybrid reconstruction of a shower and for all comparisons with SD geometric reconstructions it is essential to know with great accuracy the pointing direction capabilities of the FD telescopes. The precise knowledge of the FD absolute pointing can be used to cross check the SD pointing and systematics matching the hybrid events on the basis of the ground reference frame. A powerful tool to determine the alignment of the telescope,
with the highest reachable accuracy, is the identification of signals left by stars traversing the field of view of the telescope. In this work, two different and independent methods to determine the absolute telescope pointing are described and applied to the data acquired by the Observatory. The results obtained establish the validity of our two methods.

A detailed description of the Observatory and the performance of the hybrid detector prototype is given in [8,9].

1.1 The Fluorescence Detector

The FD comprises four sites located at the periphery of the site overlooking the SD array. The FD sites are: Los Leones (LL), Coihueco (CO), Los Morados (LM) and Loma Amarilla (LA). Each FD site consists of a building with six sections, called bays, each containing a telescope sensitive to UV photons. The focal surface of the telescopes consists of a rigid and spherical aluminium piece (the camera) in which there are installed 440 photomultiplier tubes (PMTs), Photonis XP3062, arranged in a $20 \times 22$ array [10]. The PMTs have a semitransparent bialcaline (SbKCs) photocathode of hexagonal shape and a quantum efficiency $Q.E. > 25\%$ in the spectral band $350 - 450$ nm [11]. A UV transmitting filter (Schott M-UG6 glass sheets) installed in the $2.2$ m diameter aperture improves the signal-to-noise ratio [13]. A spherical mirror with an area of $3.5$ m$\times$3.5 m, a radius of curvature of $3.4$ m and $1.743$ m focal distance, as well as a corrector ring installed in the periphery of the aperture, complete the optical components. Each FD telescope has a field of view of $30^\circ$ in azimuth and $28.6^\circ$ in elevation. The main elements of the telescopes are shown in Fig. 1.

The telescope incorporates Schmidt optics to reduce the optical aberrations, where the aperture is defined by the circular diaphragm placed at the center of curvature of the spherical mirror. The great advantage of the optical system is the elimination of coma aberration owing to the addition of a corrector ring lens, keeping the light spot reflected on the camera at an angular size of $0.5^\circ$ [16].

Each PMT is equipped with a Head Electronics unit (HE) which provides active bias. The active network improves linearity over the whole dynamic range compared to a standard passive base that would need to pass a current two times larger to obtain the same performance. The use of an active bias reduces the high voltage (HV) cost by $50\%$ [17]. The PMT signal is sent to the Front-End Board (FEB) in differential mode where it is filtered and digitized at a $10$ MHz sampling rate with $12$ bit resolution.
2 FD background data

Two prototype FD telescopes were constructed in an initial stage of the project. The Head Electronics used in the first two prototypes incorporated the biasing network and a novel optical feedback system that reads the very slowly varying signal left by a star when it enters into the field of view (FOV) of a pixel. All 880 units were equipped with this current monitor [17]. On June 26, 2001 the first signal of Vega (Alpha Lyrae), Fig. 2, was clearly seen by the telescope at Los Leones [9,19].

After demonstrating the capability of the telescopes to be sensitive to even dim stars in the UV region, we incorporated a low-cost solution that returns the variance of the baseline fluctuation, which is proportional to the sky background light that also includes star signals. The measurement of the background light level, which is currently implemented for Auger FD detectors, was extensively described in [20]. We will limit ourselves only to a short description here.

The method of the statistical current monitoring is based on an evaluation of the variance $\sigma^2$ of the background data. Because the incoming light flux follows Poisson statistics [20], the amplitude of the signal fluctuations is directly proportional to the intensity of the signal itself. Therefore, the signal variance sampled every 100 ns is recorded and then from 65535 such variance values an average is computed and then stored. This statistical evaluation is done in parallel in the Digital Board (DB) by 4 Field Programmable Gate Array (FPGA) logic boards. Each FPGA handles in sequence 6 independent camera channels. Although the sampling could be faster, for practical purposes the value for each pixel is stored every 30 seconds.

The variance analysis allows us to determine the incoming background light flux to the individual pixels. The typical photon flux at the southern site of the Auger Observatory in clear moonless night is of order 100 photons/m$^2$deg$^2$µs. More detailed analysis of this sky background light level is done in [21] for data obtained from the Los Leones prototype telescopes. The signal left by stars is used in this work to determine the camera alignment because stars provide a reliable and stable coordinate system.

2.1 Camera geometry

A camera of 440 PMTs with a radius of 1.743 m (slightly larger than the standard focal length) is placed on the spherical focal surface of the mirror. The pixels are regular hexagons and their sizes vary slightly over the focal surface. The angular direction of each PMT center is given by the equations
\[\delta_{j,i} = \arcsin (\sin (\alpha_j + \alpha_m) \cdot \cos \beta_i),\]  
\[\phi_{j,i} = \arcsin \left( \frac{\sin \beta_i}{\cos \delta_{j,i}} \right) + \phi_m,\]  

where \(\alpha_m\) and \(\phi_m\) are the elevation and azimuth angles of the camera symmetry axis in the local coordinate system, \(\delta_{j,i}\) and \(\phi_{j,i}\) are the elevation and azimuth angles in the sky of the pixel \((j, i)\), and \((\alpha_j, \beta_i)\) are the angular direction of the pixel \((j, i)\) in the coordinate system centered in the camera (Fig. 3). For construction, the optical axis, centered in the point between PMTs 209, 210, and 232, differs in angular direction from the camera axis by an elevation angle equal to 0.2165° (Fig. 4). As the camera has a rigid and defined structure, the pointing direction of the camera optical axis can be calculated from the pointing direction of each single pixel.

2.2 Star images on the camera

The angular size of each PMT is about 1.5° for an inscribed circle into a PMT hexagon. The sensitive photocathode surface of the PMTs is smaller than its glass envelope and there are also mechanical reasons to leave some gaps between PMTs. The reflective edge-shaped plastic inserts, called mercedes, were applied to eliminate the insensitive areas between PMTs. Then, almost all the incident light is reflected onto some PMT and the focal surface is continuously covered. As the spot angular size fixed by the Schmidt optics is 0.5°, \(1/3\) the pixel size, we conclude that the FD pixel signal is ideally a trapezoidal current pulse whose rise and fall times are about \(1/3\) the flat top and that one star could influence the signal of up to three pixels simultaneously. In Fig. 5 an ideal signal shape is shown, to be compared with the real signals of Vega in Fig. 2. The real signals show intensity fluctuations at the plateau\(^1\); the amplitude of these fluctuations, ranging from 10% to 20%, is due to the anisotropy of PMT photocathodes\(^2\) [19], as well as to statistical fluctuations and to the intrinsic star scintillations, i.e. star intensity fluctuations due to the fast movements of atmospheric layers [23].

\(^1\) The signal plateau corresponds to the star image fully contained within the pixel.
\(^2\) When the star traverses a pixel’s FOV, it goes through regions of different cathode sensitivity and the signal could vary by up to 20%.
2.3 Star positions on the sky

Stars are very suitable sources for camera alignment checks, because their positions in the sky are known with very high precision.

Horizontal coordinates (azimuth and elevation) of stars are obtained by standard coordinate transformations from equatorial coordinates (right ascension and declination), taking into account the Earth precession\(^3\) (an effect up to \(0.1^\circ\) for the analyzed period) and the atmospheric refraction. The shift in altitude due to the atmospheric refraction is about \(0.3^\circ\) for the lowest pixels and is dependent on the air pressure \(\rho\) and temperature \(T\). We used the Meeus model [24] of atmospheric refraction with fixed pressure, 860 millibars, and with temperature \(T\) estimated on the basis of calendar date of a given observation night (a sinusoidal-like function with maximum reaching 293 K in January and with minimum at 273 K in July).

3 Two methods of analysis

Two methods to determine the telescope pointing capabilities were recently developed. The first method automatically searches for the star signals in the background data. The central time of the signal \((T_{\text{signal}})\) is defined as the central point of the signal plateau (see Fig. 5). In turn, the signal is assumed to be produced by the star whose position is nearest to the pixel center. The star position is calculated at the central time of the detected signal and the difference between this calculated value and the nominal direction of the pixel’s center is identified as the pixel offset. From the star’s transit through a given pixel, the weighted average offset of this pixel is derived. Finally, the overall offset of the camera is determined from the average offsets of the individual pixels. We call it the \textit{single pixel method}.

The second method is somewhat different. We look for the optimization of the entire trajectory of a bright star across the camera and we identify the time of transit of this star between pixels. Then we look for time differences between expected (computed) times of transit, with some given offset for the whole camera, and transit times found in data. We go through the matrix of all possible camera center offsets, in a range in azimuthal coordinates, and then we select the optimum offset with the smallest difference between expected and identified times of transits. The typical trajectory of a star consists of about 20 transits between pixels and the whole star track is optimized at once. Many (\(~100\)) such tracks are analyzed and optimized for each camera. The resulting

\(^3\)This correction has not been applied in the first method described in §4.
offset of the given camera is then finally calculated as the weighted average of these found offsets. We call it the *star track method*.

More detailed description of both methods follows below.

## 4 Single pixel method

The logical scheme of our procedure can be summarized basically in the following three steps:

1. Search for signals in the baseline variance data;
2. Find the stars that give origin to the signals found in (1) to establish the absolute pointing of each single pixel;
3. Determine the pointing of the telescope’s optical axis using the reconstructed pixel pointing calculated in (2).

Steps (1) and (2) are repeated every night of the period under analysis (January 2004 - October 2004 in this case) while the step (3) is done only once, at the end of the period of data taking, when the pointing of each pixel has already been determined. In the following paragraphs each step of the procedure will be described.

### 4.1 Search for star signals in the baseline variance data

The sky background light varies from night to night and, in a single night, it may change within a few hours. To overcome this inconvenience we have implemented two different methods: the Time-Over-Threshold (TOT) and the Slew-Rate (SR) algorithms. Their aims are to extract the signals from the variance data and to find their central time $T_{\text{signal}}$, i.e. the middle time of the associated plateau.

In the TOT method we first calculate the mean value of the variance baseline, $\bar{v}$, and its RMS value, $\sigma$, in a time window of 2 hrs. If a star enters into a pixel’s FOV, the background noise and the variance of this pixel will increase in a time range of 4 to 15 minutes depending on the star declination. Therefore, if a set of variance points is $v_i > \bar{v} + 3 \sigma$ in this typical time range, a signal is identified and the pixel center is assumed to be pointing to the star direction at time $T_{\text{signal}}$\(^4\). The absolute pointing direction of each pixel is obtained transforming

\(^4\) In practice the star direction corresponds to the point nearest the pixel’s center. As we only consider spots fully contained in the pixel, the difference is smaller than 0.25°.
the equatorial coordinates of the star (right ascension and declination) at \( T_{\text{signal}} \) to the local coordinate system (elevation and azimuth).

The second method used to extract signals from variance data, the Slew Rate algorithm (SR), is a sort of derivative method. We calculate the increment of the variance between two separated points, \( \delta = \Delta v / \Delta t = (v_i - v_j) / (t_i - t_j) \) every 4 samplings points (2 minutes) during the entire night. Positive and negative consecutive values of \( \delta \), within 4 min to 15 min, will therefore correspond to the leading and trailing edges of a star signal. As for the first method, if a star signal is found, the pixel center is assumed to be pointing to the star direction at time \( T_{\text{signal}} \). A schematic plot of the two methods is shown in Fig. 6 in the ideal signal case, while in Fig. 7 the real case is shown. The variance signal in Fig. 7(a) has been converted into a number of photons at the diaphragm using the calibration constants obtained with the drum calibration system [26].

These two methods are complementary in the sense that their efficiencies depend on the signal shape and the background trend. The first method works better than the second one if the baseline is highly variable, but it is worse for small signals. As shown in Fig. 7 both methods work fine for high and clear signals.

4.2 Pixel pointing direction

When the observation time is long, many signals could be found in a single pixel. Therefore we will have as many pixel pointing estimations as signals found in the considered pixel. The mean value and its statistical error can be calculated from these estimations. An example is given in Fig. 8 and Fig. 9. The precision in the knowledge of each pixel’s pointing will depend on the statistics of star signals found in each pixel. The statistical error obtained for each pixel is propagated to obtain the uncertainty in the determination of the camera optical axis.

The procedure described in §4.1 is repeated to determine the pointing of all pixels where at least one signal has been found. The statistical error in the determination of the single pixel’s pointing could be lowered analysing the greatest number of nights possible.

4.3 Determination of the camera pointing

As explained in the previous section, after determining the pointing of each pixel we are poised to calculate the pointing of the camera axis by simply
inverting the formulas given in §2.1.

For every reconstructed pixel pointing direction we obtain a pointing value of the camera optical axis with an uncertainty obtained by propagating the statistical error for each pixel. Each direction of the camera optical axis obtained from the single pixels is weighted with its error to determine the average values of the azimuthal and elevation angles of the axis and their relative precisions\(^5\). As examples, Fig. 10 and Fig. 11 show the histograms of the reconstructed values of azimuthal and elevation angles of telescope 4 at Los Leones and 3 at Coihueco.

Since not all the pixel directions were established with the same number of signals, and consequently with the same accuracy, we have determined, for each telescope, the minimum number of signals required in a single pixel that optimize the determination of the pointing of the camera axis. In Fig. 12 we have plotted the statistical error in the determination of the azimuthal optical axis angle for telescope 4 at Los Leones as a function of the minimum number of signals required to use a pixel in our calculations of the camera pointing. As can be seen in Fig. 12, the error increases with the minimum number of signals required. The same occurs for the elevation angle. This behaviour is due to the dependence of the error on two factors: the uncertainty in the knowledge of the directions of the pixels and the number of pixels reconstructed (i.e. the statistics). In fact, a high uncertainty in the knowledge of the directions of the pixels leads to a low precision in the determination of the pointing of the camera axis. However, if the minimum number of signals required is too high (for instance 10), the pixel directions will be known with great accuracy but with detriment to the statistics. Therefore a compromise between high statistics and high precision in the directions of the pixels is needed. For example, for telescope 4 at Los Leones only pixels with at least 3 signals were used to calculate the azimuthal angle of the optical axis.

5 Star track method

The analysis program was designed to process automatically the background data. The initial idea was to select some basic criteria and data file, run the program and directly obtain the elevation and azimuthal offset of the camera. We also processed several nights’ data including the camera rotation as a parameter and we found that rotation offsets were negligible. This is in agreement with the alignment method of the camera, where it was possible to

\(^5\) Actually the camera position has 5 degrees of freedom, the 3-dimensional position of its centerpoint and rotation around two independent axis. However, no significant rotation offset has been found.
measure (and remove) the camera tilt very precisely.

To achieve such a goal, the method was designed to:

- Automatically find and select the brightest stars with sufficiently long trajectories across the camera during the selected night.
- Read the variance data from background files for each pixel at the analyzed camera, together with timestamp.
- Identify star signals within background data and compare them with computed expected signals.
- Shuffle with the camera’s center position and try to optimize the differences found between the data and the expected signals.

5.1 Light spots

The shape of the spot is not precisely circular. It is deformed by the shadowing of the camera body, by spherical aberration and by the use of a corrector ring on some telescopes\footnote{During the analyzed periods only bays 3 and 4 both at Los Leones and Coihueco were equipped with corrector rings.}. More precisely, the spot deformation is more prominent for the cameras without a corrector ring. This spot shape deformation could result in a shift of the spot intensity center of up to 0.1°. It is possible to model this star image displacement and then include this effect in the camera offset evaluation, as it was done within this work.

For the spot shape simulation we have used first a code developed inside the collaboration which simulates the trajectories of light rays through different parts of the aperture according to the rules of geometrical optics. Because the optical system of the camera is not ideal, a sufficient number of rays (about $10^5$ in our case) coming from a specified direction and covering the whole aperture will draw the spot shape. We run the program for 440 positions of pixels. For these resulting 440 spot shapes we computed the intensity center of each spot and compared its position with the position of the pixel center. (The direction of the pixel center was the original direction of incident light rays.) Then we plotted the resulting offsets (Fig. 13). We realized that this behavior could be easily modeled under assumptions that the spot center offset is directly proportional to the distance from the camera center (in camera coordinates). The shift of the spot center in horizontal $\beta$ and vertical $\alpha$ coordinates (where $\beta, \alpha$ denote the angular distance from the camera center in degrees, as defined in §2.1) is

- with corrector ring: $\Delta \beta = 1.002 \beta, \Delta \alpha = 0.998 \alpha$;
- without corrector ring: $\Delta \beta = 1.0033 \beta, \Delta \alpha = 0.9967 \alpha$. 

6 During the analyzed periods only bays 3 and 4 both at Los Leones and Coihueco were equipped with corrector rings.
The difference between our model and simulation results is less than 0.01° for the telescope with corrector ring and less than 0.02° without corrector ring, which we judge to be acceptable (Fig. 13).

5.2 Star tracks and transits between pixels

We can follow the star traversing the camera FOV and quite easily identify the pixels with increased signals due to star light. An example of several such star tracks is shown in Fig. 14.

We can identify the instants when the star spot center (SSC) moves from one pixel to an adjacent one. These times of SSC transit are crucial for our analysis. We expect that before this time the variance of the former (“old”) pixel is higher than that of the latter (“new”) pixel and that, after this time, the variance of the “old” pixel is lower than the variance of the “new” pixel. We note that by tracking SSCs we naturally solve the problem of the star image projected simultaneously onto 3 pixels. The SSC moves across the pixel boundary from one specific pixel to a neighboring one.

Knowing the precise position of a given star on the sky as well as the correction due to SSC offset, we transform this position to camera coordinates and compute the instant when the star is crossing the boundary between hexagonal pixels. We compute such instants for all illuminated camera pixels and we identify the times of transits of the spot center for the whole star track across the camera.

5.3 Star track optimization

As described above, we are able to compute both the trajectory of SSC across the given FD camera and the transit time of the SSC from pixel to pixel. Furthermore, we are able to identify these transits between pixels in the real background data.

We analyze the data from about 180 seconds ahead of the expected transit to about 180 seconds after the expected transit. During this period we check if there is a greater variance value for at least two consecutive samples on the former “old” pixel than on the latter “new” pixel. For both consecutive samples, the variance on the “old” pixel has to be greater than the variance on the “new” pixel at least by 1 (ADC count)$^2$. Such a period has to be

$^7$ The typical variance difference between two illuminated neighboring pixels for used bright stars (brighter than $2 \ U_{mag}$) is usually much greater. During the de-
immediately followed by two consecutive data samples, where the situation is opposite, i.e. a star already traversed to a “new” pixel. So, these two consecutive signals on the “new” pixel have to be greater at least by 1 \((ADC \text{ count})^2\) than the signal in the “old” pixel. The star transit is then expected to occur between times of this intensity switch. The exact time is analytically computed as the crossing of interpolated signals of “old” and “new” pixels. The signal values surrounding the instant of this transit are used for interpolation.

We then have both predicted times of transits and also detected times of transits in the data for the whole track. For these times we can easily calculate \(\Sigma \chi^2\) and use it as our main optimization parameter. Having this initial value we can start shuffling with the camera center on the regular grid.

We used shuffling \(\pm 0.5^\circ\) around the nominal center of the camera on the regular grid with steps of \(0.025^\circ\). Doing this, we are looking for the least average time offset for the whole track. During shuffling we compute the new times of transits between pixels and we can even find completely new transits between previously not illuminated pixels. As the second parameter we also check the number of transits detected in background data, which of course could be larger than the starting number of detected transits, but should not be much smaller than the initial one. In practice, we use a condition which rejects the new resulting shuffled tracks if the new trajectory would diminish the number of transits by more than 4.

The typical results of one star track optimization are shown on Fig. 15, where all time differences from the shuffling grid are plotted. In Fig. 15, the contour plot on the bottom plane shows that the optimized offset is about \(0.2^\circ\) for azimuth and about \(0.3^\circ\) for elevation. The darker areas indicate the regions with smaller differences between detected times of transits and predicted times of transits; lighter areas are for greater time differences. The 3D plot above shows the same thing, the deepest valley is for the smallest difference of time offset. However, the coloring is different, light colors indicate a large number of detected star transits, dark colors indicate a very low number (or even zero) of successfully detected transits. Practically, we are looking for some sort of anti-correlation for regions with low \(\Sigma \chi^2\) and a high number of pixels of the star track.

velopment of our code, we tested different (larger) minimal differences of variance and did not find any significant changes in our results. Finally, we used this relaxed condition \((1 \ (ADC \text{ count})^2\) difference), which proved to be only a little more sensitive for signal detection in the lowest part of the camera. However, we found that the condition of having the “old” pixel brighter for two samples and, immediately after that, fainter for the next two samples is strong enough to exclude random fluctuations even for this sensitive limit of \((ADC \text{ count})^2\) difference.
5.4 Analysis of lightcurves

We can track some bright stars through a given camera and read out the values of variances of the pixels that are closer than 0.5° to the center of the star which means the values between 1 and 3 pixels. We subtract the “sky background” value for each pixel, calculated as the average of signals of a given pixel some time before and after the star transit. (We generally used averages of 15 minutes before and 15 minutes after the period of time, when the star was traversing the pixel.) The sum of corrected signals from all contributing pixels can be then plotted as a function of star altitude.

The sum of the signal from all the pixels illuminated by the spot of the star should be almost constant (or slowly growing with altitude); there could likely be smaller bumps due to the influence of reflective plastic inserts or changes due to sudden shifts in atmospheric extinction. However, such results are not obtained for the original directions of the cameras. An example for the bay 4 at Coihueco is shown in the upper plot of Fig. 16. We can see that for some positions of the star image on the camera we are not even observing the correct pixels (not really the ones containing a star signal at that time) and therefore we observe a significant signal drop.

For the optimized position of the camera (with the pointing direction found with this method) the situation is generally much better, and the resulting curve is approximately a straight line (lower part of Fig. 16). This could be taken as a proof that our results indicate real offsets of the camera centers.

6 Analyzed data

After July 2004 the Observatory started to operate with 12 telescopes, 6 in the FD site of Los Leones and 6 in Coihueco. Since April 2005, the telescopes of the Los Morados site have been installed.

The two procedures described in the previous sections have been applied to calculate the pointing of the 12 telescopes of the fluorescence detector installed at Los Leones and Coihueco. The data used and the results obtained with the two method are described in the following sections.

6.1 Star catalogue used

For the two methods described, two different star catalogues were used. Because of the presence of the UV filter at each telescope’s aperture, we take
into consideration only those stars of sufficient brightness in the U spectral band.

For the single pixel method analysis we use the UBV Photometry of Bright Stars catalogue [27] that includes 3777 stars with U magnitude lower than $U_{\text{mag}} = 8$. We defined $U_{\text{mag}} = 3$ as the U magnitude of the faintest star to be accepted. In Fig. 17 the number of star signals identified as a function of U magnitude shows that we are sensitive also to fainter stars. For the transformation of star coordinates we used the libnova library.\(^8\)

For the star track method analysis we used the Bright Star Catalogue (BSC) [28]. This catalogue contains basic astronomical and astrophysical data for all 9096 stars which are brighter than 6.5 magnitude. Using available data for each star we computed its magnitude in Johnson’s U-band and we sorted the catalogue according to star brightness in the U-band and cut off all unnecessary information. If we want to analyze the entire star tracks across the camera, we have to concentrate on those bright stars which are visible also in the lower part of the camera. In fact, when the image of a star is projected on a pixel, the variance increases. The amplitude of this increase depends on the pixel position on the camera because the lower pixels suffer much more prominent losses due to atmospheric extinction. From empirical analysis it follows that for stars fainter than 4\textsuperscript{th} magnitude the signal increase is almost negligible (e.g. only about 1 (ADC count)$^2$ for star $\varpi$ Gem ($mag_U = 4.47$) at altitude 3.5°). Therefore we concentrated only on the brightest stars in the sky, i.e. the stars which are brighter than 2.0 mag in the U filter,\(^9\) which have significant offsets from sky background also in the lower part of the camera.

6.2 Processed data

The single pixel method and the star track method have been applied respectively to data acquired in the period January-October 2004 and April-November 2004. As the telescopes were not installed at the same time, the pointing of the 12 telescopes installed at the Los Leones and Coihueco was reconstructed with different amounts of data, proportional to the time each telescope acquired data.

For the single pixel method procedure, no selection of nights has been applied, with the exception of an acquisition time duration longer than 1 hour. In the period analyzed telescopes 3 to 6 at Los Leones operated around $\sim 9$

\(^8\) http://libnova.sourceforge.net
\(^9\) There are 6 stars brighter than zero magnitude, 24 stars brighter than first magnitude and 63 stars brighter than second magnitude in the U band for the whole sky.
months while telescopes 1 and 2 operated \( \sim 3-5 \) months. On the other hand, at Coihueco, telescope 2 and telescope 3 operated around 8 months while the others operated around 3 months in the period analyzed. These periods must be reduced because of the duty cycle limited to \( \approx 10\% \), as data are acquired only in moonless nights or nights with at most a quarter moon.

For the *star track method* procedure, based on times of transits of the light spot between pixels, we tried not to bias data with star signals diminished or otherwise modified by clouds moving through the studied pixel. Therefore we tried to select only very clear, cloudless nights. For this reason we used the cloud monitor database [29] and manually selected only completely clear nights of a given period. Because Coihueco was fully operational only since June 2004, the choice of suitable nights was more limited than for Los Leones: only 10 nights for Coihueco and 15 nights for Los Leones survived this cut.

7 Pointing results

In this section we present the results obtained applying the two procedures to the background data acquired in 2004. The obtained pointing directions of the optical axis of the FD telescopes are compared with the nominal values specified in the Auger Offline reconstruction code. The offsets obtained by the two methods are generally larger for elevations of the camera than for the azimuthal settings. This is basically what was expected from the camera alignment methods. The differences of our results and the nominal values for the FD are less than 0.3\(^\circ\) and for almost all telescopes are less than the precision of the mechanical procedure to set the pointing of the telescopes, which is 0.1\(^\circ\). For both methods, we present only the statistical error; the systematic error can be estimated roughly from the data sampling time, equal to 30 seconds, that produces an uncertainty on the sky star position of 0.125\(^\circ\). So the overall error of the methods can be estimated as: \(\sqrt{(0.125\,^\circ)^2 + (0.05\,^\circ)^2} = 0.13\,^\circ\), where 0.05\(^\circ\) is the average statistical error.

7.1 Single pixel method: results

The total number of nights and the corresponding total number of hours analyzed (columns 2 and 3) for the FD sites at Los Leones and Coihueco are shown in Table 1, as well as the rate of identified signals (column 6), for the entire period analyzed (January-October 2004). The total number of signals identified and the number of stars analyzed are also shown in columns 5 and 7. Taking into account the effective observation time, the rate of identified signals varies from \(\sim 5.4\) to \(\sim 9.8\) signals/hour for the Los Leones site, and
from $\sim 2.6$ to $\sim 17.8$ signals/hour for the Coihueco site. If the number of stars (with $U_{\text{mag}} < 3$) passing in the field of view of each telescope during the whole analyzed period is taken into account, the rate of signals varies from $\sim 0.13$ to $\sim 0.30$ signals/(hour $\cdot$ star) for the site at Los Leones, from $\sim 0.10$ to $\sim 0.71$ signals/(hour $\cdot$ star) for the site at Coihueco.

Detailed results and their statistical errors are shown in Table 2. The total number of pixels reconstructed is also indicated (column 6). Columns 2 and 4 in the table show the differences (in degrees) between the results obtained with our own analysis and the pointing values specified in the Pierre Auger Observatory database, used for the shower reconstruction. Columns 3 and 5 contain the elevation and azimuthal errors in the determination of the optical axis direction.

### 7.2 Star track method: results

The results of our analysis are summarized in Table 3. The final offset of each camera was computed as the weighted average of all optimal offsets associated with successfully identified star tracks for the sample of selected nights. The star track was considered as successfully identified if it contained more than 9 transits between pixels. Shorter tracks were not used. The optimized camera offset was computed for each track and weighted with the number of detected transits for this optimized track. The statistical error, also shown in Table 3, was then computed as a weighted standard deviation of individual track offsets.

### 7.3 Comparison

In this section we present a comparison of the results obtained with the two methods. The actual differences (in degrees) between the offsets found with the two methods are given in Table 4. For each method (indicated as Single for the single pixel method and Track for the star track method), the differences between reconstructed and nominal values are shown. The third (boldface) column for each bay contains absolute difference of the values obtained with the two methods. The differences between the offsets found with the two methods are less than the estimated overall error, estimated as $\sim 0.13^\circ$. In conclusion, the two methods are consistent within the errors.

Another independent check of the telescope pointing can be obtained using laser shots from the Central Laser Facility (CLF) [29,30]. The CLF is used to emulate showers for atmospheric monitoring and calibration purposes. Independent studies were performed by two Auger groups. The first group analyzed
the vertical shots for a selected telescope (bay 4 at Los Leones) and concludes
that the telescope’s pointing is consistent with our own results [31]. The second
group analyzed inclined laser shots for several selected bays at the Coihueco
site. The reconstructed shower parameters better match our pointing values
rather than the nominal ones [30].

8 Summary and conclusions

We described two independent methods to determine the pointing of the op-
tical axis of the fluorescence detector telescopes at the Pierre Auger Observa-
tory. The two methods described, called the single pixel method and star track
method, are based on the capability of the fluorescence detector (FD) to be
sensitive to the variance signals left by stars traversing the telescope field of
view. The identification of the star signals provides a powerful tool to check
and monitor the telescope alignment. The two procedures were applied to the
data acquired in 2004 for all 12 telescopes installed at the FD Los Leones
and Coihueco sites, providing compatible sets of pointing direction results.
The differences between the results obtained with both procedures and the
nominal values specified for the FD are less than $0.3^\circ$ and for almost all tele-
scopes are less than the precision of the procedure to set the pointing of the
telescopes, which is $0.1^\circ$. The two methods provide results consistent within
the overall error, estimated as $0.13^\circ$. Moreover, the results obtained with in-
dependent studies using both vertical and inclined laser shots are consistent
with our own results, confirming the validity of our methods.

Knowledge of correct pointing directions is an essential ingredient in the Auger
Observatory’s unique hybrid event reconstructions and for all comparisons
with SD geometric reconstructions of those same events. Our methods will
strengthen these analyses. Using our above described methods we are now also
prepared to easily monitor the long-term stability of the measured pointing
directions.
References


Fig. 1. Structure of a FD telescope. The aperture system consists of a diaphragm, a corrector ring and a UV filter. The other optical components are the mirror and the camera, this one comprising an array of $20 \times 22$ PMTs.

Fig. 2. Signals from the current monitor ($\mu A$) for adjacent pixels vs. time generated by the transit of Alpha Lyrae (Vega) in their FOV. The mean time of Vega’s signal in the pixel 121, $t_{121}$, is indicated. The sampling time is $20 \text{ s}$. 
Fig. 3. $22 \times 20$ pixel matrix shown on the coordinate system centered on the camera $(\alpha, \beta)$.

Fig. 4. Details of the camera. The center of symmetry of the camera and the center of the optical axis are shown.
Fig. 5. Ideal signal shape. After identifying a star’s signal in the variance data, a time $T_{signal}$ is associated with it.

Fig. 6. Time-over-Threshold (ToT) scheme above, and Slew-Rate (SR) scheme below.
Fig. 7. Los Leones, telescope 4, pixel 77, 22 June 2004 (UTAle): signal of Alpha Lyrae. 7(a) The signal of Alpha Lyrae is shown; the solid line indicates the mean value of the background noise, the dashed line indicates the mean value + 3σ of the background noise. 7(b) The derivative of the signal of Alpha Lyrae is plotted.
Fig. 8. Los Leones, telescope 2. The histogram shows the values of the reconstructed azimuthal angles for pixel 388 from star signals.

Fig. 9. Los Leones, telescope 2. The histogram shows the values of the reconstructed elevation angles for pixel 388 from star signals.
Fig. 10. Los Leones, telescope 4. Histogram of the reconstructed values of the azimuthal angle of the telescope optical axis.

Fig. 11. Coihueco, telescope 3. Histogram of the reconstructed values of the elevation angle of the telescope optical axis.
Fig. 12. Error optimization, LL bay 4. The plot shows the error in the determination of the azimuthal optical axis angle as a function of the minimum number of signals $S_{\text{min}}$ required for each pixel.

Fig. 13. Light spot intensity center. The plots show the offsets $\Delta \beta$ and $\Delta \alpha$ of the spot intensity center resulting from ray-tracing simulations for all the pixels of the camera. The same offsets are calculated by a simple numerical model and shown in the plots. For details see §5.1.
Fig. 14. Typical set of star tracks. Imaged tracks are for the Los Leones FD camera, bay 1, for the night of November 13th/14th 2004 (21h UT – 07h UT). Only the stars brighter than 2\textsuperscript{nd} magnitude were plotted.

Fig. 15. Star track optimization, graph for one chosen star (\(\beta\) Ori). The contour plot on the bottom plane shows that the optimized offset is about 0.2\degree for azimuth and about 0.3\degree for elevation. For details, see §5.3.
Fig. 16. Comparison of lightcurves for original and optimized camera positions of Coihueco bay 4. The data used for the plot are from November 14th 2004 which were taken with a higher sampling rate of 0.2 Hz (instead of the ordinary 0.03 Hz sampling rate).

Fig. 17. Histogram of star signals identified as a function of U magnitude for the telescope 1 at Los Leones.
Table 1

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<th>number of hours</th>
<th>hours per night</th>
<th>number of signals</th>
<th>rate (signals/hour)</th>
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<th>hours per night</th>
<th>number of signals</th>
<th>rate (signals/hour)</th>
<th>number of stars</th>
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Table 2

“Single pixel method”, results for Los Leones and Coihueco: elevation and azimuthal angle of the optical axis. The differences between the reconstructed values and the specified ones are shown with their errors (§7.1).

<table>
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<th>Telescope number</th>
<th>Elevation $\Delta_{\text{elev}}$ (degrees)</th>
<th>$\text{Error}_{\text{elev}}$ (degrees)</th>
<th>Azimuth $\Delta_{\text{az}}$ (degrees)</th>
<th>$\text{Error}_{\text{az}}$ (degrees)</th>
<th>Rec. Pixels</th>
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Table 3
“Star track method”, results for Los Leones and Coihueco: the differences (in degrees) of reconstructed (optimized) minus nominal values for the cameras are shown (§7.2).

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Table 4
Comparison of the results obtained with the two methods. Differences between the reconstructed and nominal values (in degrees) are shown for both the methods. The absolute differences of the values obtained with the two methods are shown in the third column.

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<th>Bay 3</th>
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<table>
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<td><strong>0.04</strong></td>
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<table>
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