

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

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Abstract

To accurately reconstruct a shower axis from the Fluorescence Detector data it is essential to establish with high precision the absolute pointing of the telescopes. To do that we calculate the absolute pointing of a telescope using sky background data acquired during regular data taking periods. Our method is based on the knowledge of bright star's coordinates that provide a reliable and stable coordinate system. It can be used to check the absolute telescope's pointing and its long-term stability during the whole life of the project, estimated in 20 years. We have analyzed background data taken from January to October 2004 to determine the absolute pointing of the 12 telescopes installed both in Los Leones and Coihueco. Our method is based on the determination of the mean-time of the variance signal left by a star traversing a PMT's photocathode which is compared with the mean-time obtained by simulating the track of that star on the same pixel.

1 Introduction

At the very beginning of the Auger Project it was decided the construction of the first two prototype telescopes of the Fluorescence Detector (FD). Those devices were equipped with XP3062 PMTs from Photonis and biased with an active network. The active network ensures high linearity over the whole dynamic range. The Head Electronics used in the first two prototypes [1] comprised the biasing network and a novel optical feedback system that allows

reading 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 the *current monitor* [2]. On June 25, 2001 the first signal of Vega (Alpha Lirae) was clearly "seen" by the telescope at Los Leones [3] [4].

After demonstrating the capability of the telescopes to be sensitive to even dim stars in the UV region, we incorporated a low-cost solution to return the baseline variance as the star signal. The variance is proportional to the background light and the resolution was reasonably good for our purpose. After the first tests of a code that we developed to calculate the telescope's pointing [4], we reviewed the procedure and arrived to a more accurate and reliable method that is described in this paper.

2 Procedure to calculate the telescope's pointing

The logical scheme of our procedure can be summarized basically on the next four steps:

- (1) Search for signals in the baseline variance data.
- (2) Simulate star tracks.
- (3) Associate signals found in (1) to stars signals simulated in (2) in order to establish the absolute pointing of each single pixel.
- (4) Determine the pointing of the telescope's optical axis using the reconstructed pixels pointings calculated in (3).

The steps (1) to (3) are repeated all the nights of the period under analysis (January 2004 - October 2004 in this case) while the step (4) is done only once at the end of the period we are interested in, when the pointing of each pixel has already been determined.

2.1 Search for signals in the baseline variance data

The background sky light varies from night to night and, in a single night itself it may change within a few hours. This feature makes the search for signals very difficult. We have implemented two methods for this scope: the Time-Over-Threshold (TOT) and the Slew-Rate (SR) algorithm. Our aim is to find the signals and to associate a time to them. An ideal signal shape and the corresponding times are shown in Fig.1.

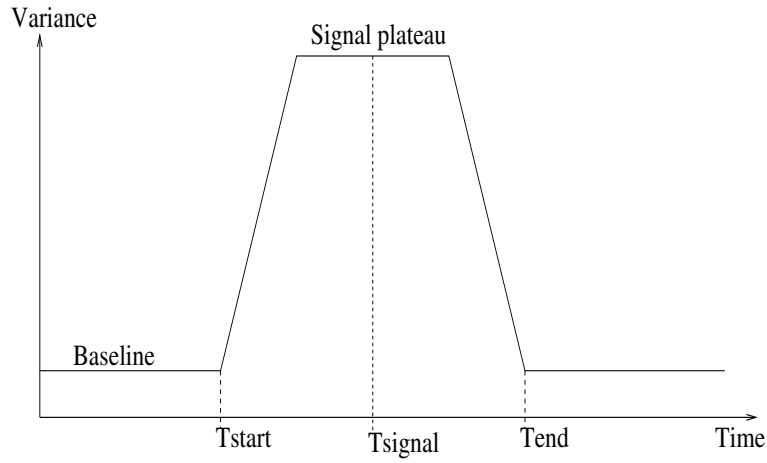


Fig. 1. Ideal signal shape. After identifying a star's signal in the variance data, a time T_{signal} is associated to it.

In the Time-Over-Threshold method we first calculate the mean value of the variance baseline. To cope with the variation of the sky background during the night the mean value of the baseline is determined in a time window of 2 *hrs*. A set of variance data, within 4 *min.* to 15 *min.*, that exceeds 3σ from the mean baseline is considered a star signal. In this way, the beginning and the end of the signal are easily found as the first and the last point in the signal data set.

The second method, SR, is a sort of a derivative method. We calculate the increment of the variance data between two points separated by 2 *min.* (we do not consider consecutive points to avoid noise fluctuations). A positive and a negative consecutive value of this increment, within 4 *min.*-15 *min.*, correspond to the leading and trailing edges of a signal.

These two methods are complementary in the sense that their efficiency depends on the signal shape and the background. The first method works better than the second one if the baseline is highly variable but it is worse for small signals. It is worth to be noted that both methods work fine for high and clear signals. A schematic plot of the two methods is shown in Fig.2. It should be noted that we are not interested on the signal height but in the time the signal reaches the middle of the signal plateau, T_{signal} , as indicated in Fig.1. This time signal is the time when the star is closest to the center of the pixel.

2.2 Simulation of star tracks

Every night many stars cross the FOV of the FD telescopes. Knowing the equatorial coordinates of a star (Right Ascension, Declination) is not difficult to simulate its track in the local coordinate system (Elevation, Azimuth) from

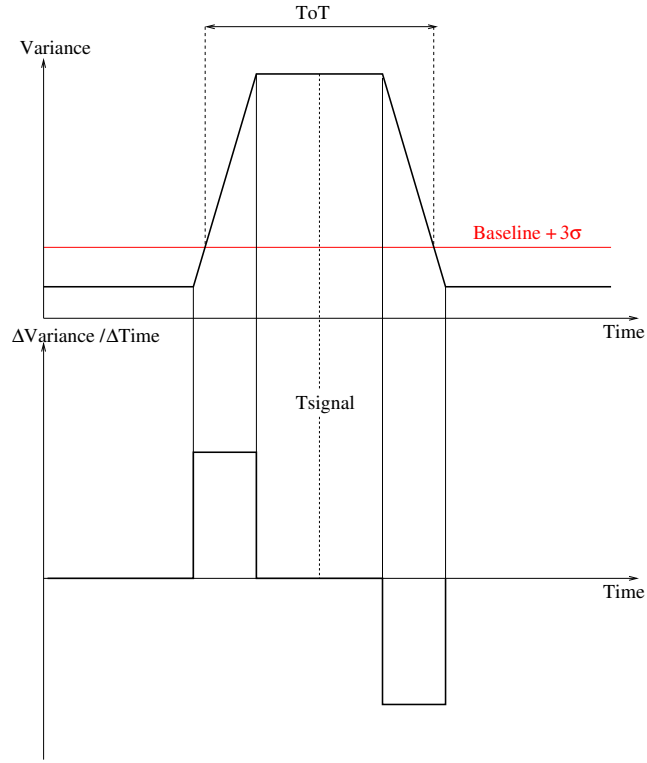


Fig. 2. Time-over-Threshold (ToT) scheme above, and Slew-Rate (SR) scheme below.

the beginning to the end of the night [5]. As an example we show, in Fig.3, the plot of the track of Vega crossing the telescope 4 at Los Leones.

We use UBV Photometry of Bright Stars catalogue (Johnson +1966) that includes 3777 stars with U magnitude lower than $U = 8$ mag. We take in consideration only those stars bright enough to be visible in the FD background data (i.e. with a low U magnitude). We defined $\text{mag} = 5$ as the dimmer star's magnitude to be accepted for our analysis. In Fig.4 the number of signals of stars identified in the period under analysis as a function of U magnitude is shown. As it can be seen in this paper, we are able to recognize the signals of even dim stars.

We simulate star tracks and, once we have obtained the list of the stars in the FOV of each telescope, we can calculate the time spent by each star in each pixel, i.e. the time at which the star enters and exits the pixel's FOV. This calculation is done using the specified values of pixel centers which are specified in [6] and [7].

In our analysis we have approximated the exagonal pixels to a circular shape with radius of 0.75° . We define the simulated time, T_{sim} , as the time at which the center of the star's spot is closest to the center of the pixel, as shown in Fig.5. If the distance between these two centers is greater than the difference between the pixel's and spot radius, $R - r$, along the whole track segment

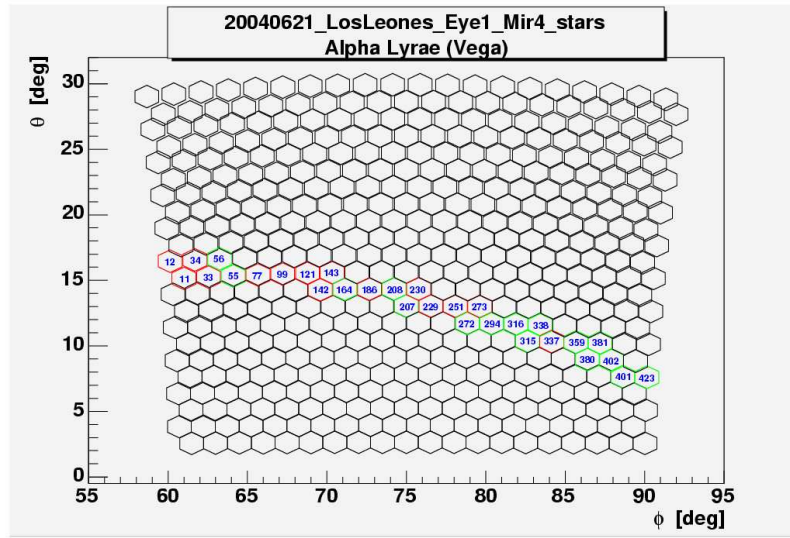


Fig. 3. Simulated track of Vega crossing the telescope 4 at Los Leones. The pixels numbers are also shown. Red pixels mean that a signal was found in the variance data. Green pixels mean that, although the star crosses the pixel, no signal was found.

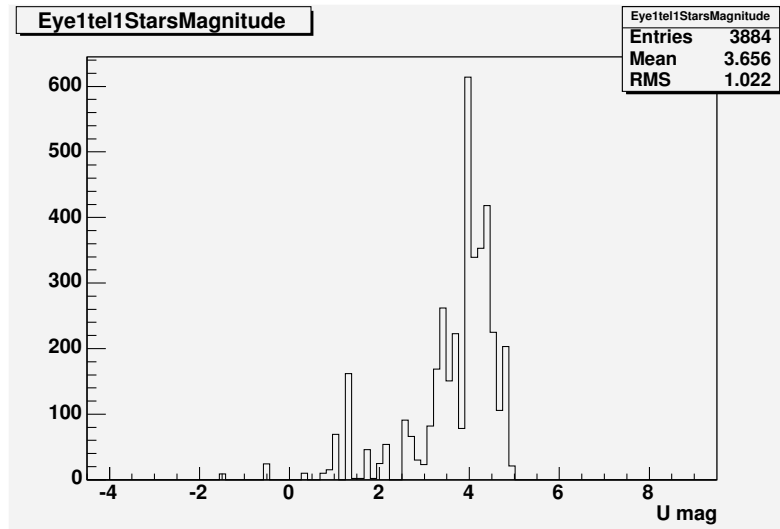


Fig. 4. Histogram of the signals of stars identified as a function of U magnitude for the telescope 1 at Los Leones.

inside the pixel, we consider the star not fully contained inside the pixel. Only pixels with fully contained spots were considered in this work.

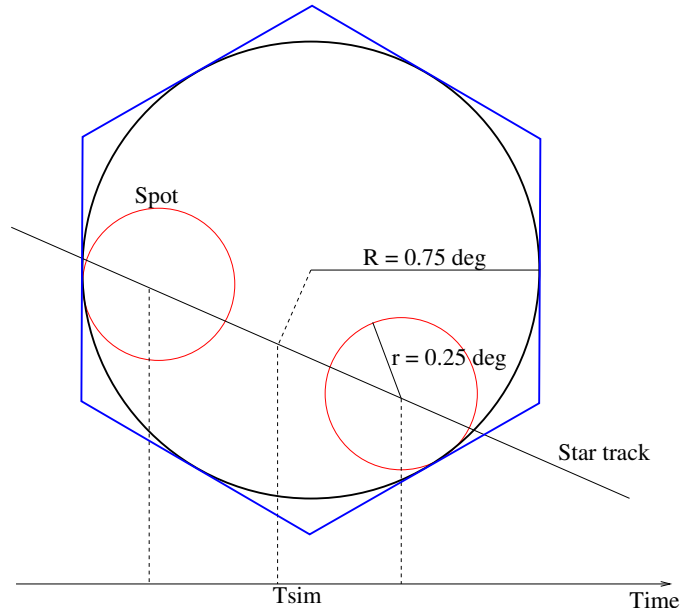


Fig. 5. Schematic track of a star crossing a circular pixel.

2.3 Comparison of the T_{signal} and T_{sim} . Determination of pixels pointings

At this stage we can compare the time signal we obtained from variance data as explained in section 2.1, T_{signal} , with the time derived from a star track simulation, T_{sim} . If $|T_{signal} - T_{sim}| < 3 \text{ min.}$, we assume that the signal we found is generated by the star we simulated. In other words, every time a signal is found, we consider that the pixel is pointing to the direction of the star at T_{signal} . In this way we establish the absolute pointing of the pixel in the local reference frame, azimuth and elevation, simply transforming the equatorial coordinates of the star, right ascension and declination, at T_{signal} .

When the observation time is long, many signals could be found in a single pixel. Therefore we will have as many pixel's pointing estimations as signals found. The mean value and its error can be calculated from these estimations. An example is given in Fig.6 and Fig.7.

This procedure is repeated to determine the pointing of all pixels where at least one signal was found. In Fig.8 the directions of the displacement of each pixel with respect to its theoretical position are shown with arrows.

It has been noted a preferential direction of the displacement of the pixels. Most of the arrows in Fig.8 points on the right. This trend could be due to a systematic error in the determination of the pointing. Nevertheless this trend is consistent with the differences between the specified values of the axis direction and the calculated ones. This can be seen in Figs.9 and 10 where in the histograms the differences between the reconstructed direction of each

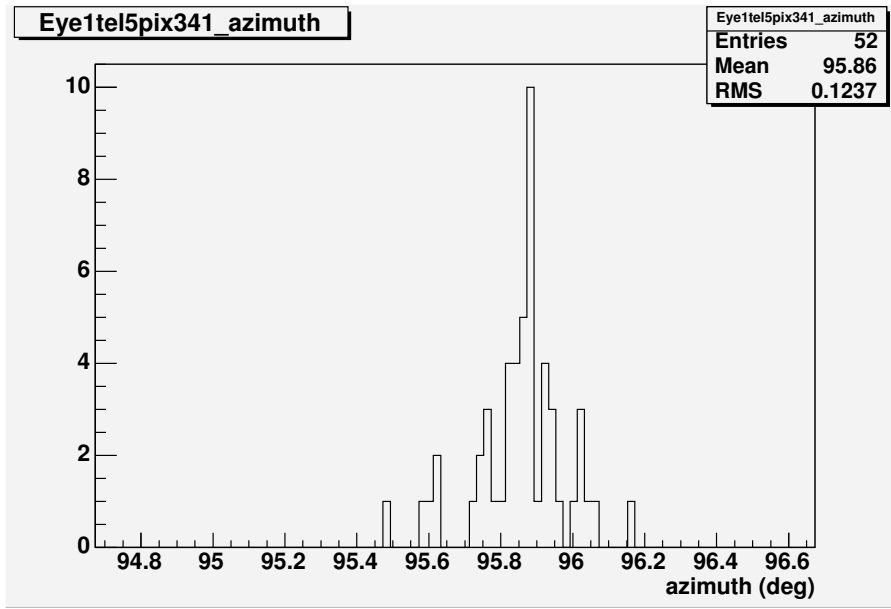


Fig. 6. Los Leones, telescope 5. The histogram shows the values of the reconstructed azimuth angles for pixel 341 from stars signals.

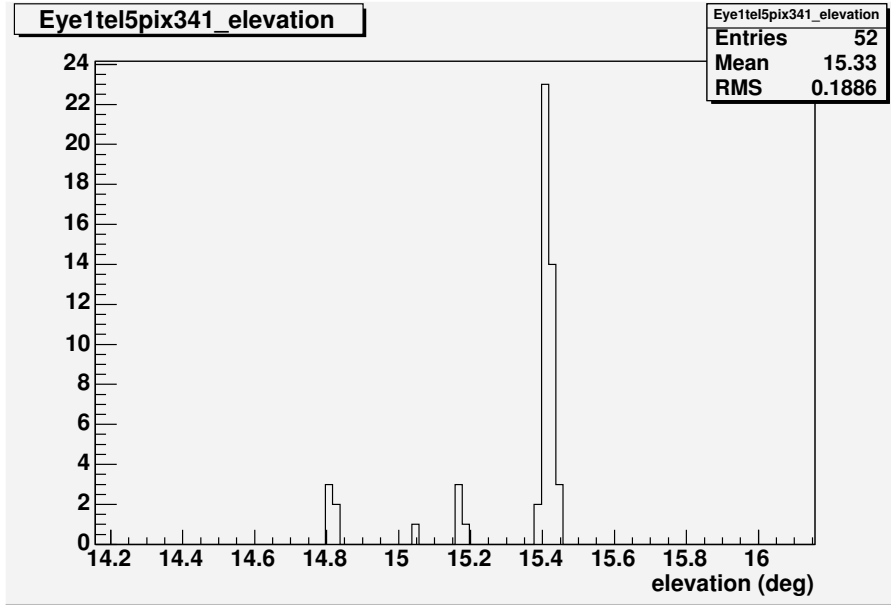


Fig. 7. Los Leones, telescope 5. The histogram shows the values of the reconstructed elevation angles for pixel 341 from stars signals.

pixel and its specified value are shown.

In fact, this behaviour disappears in the case of coincidence between the specified and calculated values of the pointing direction of the camera axis, as can be seen in Figs.11 and 12. The disappearance of this trend is inconsistent with the hypothesis of the presence of a systematic error.

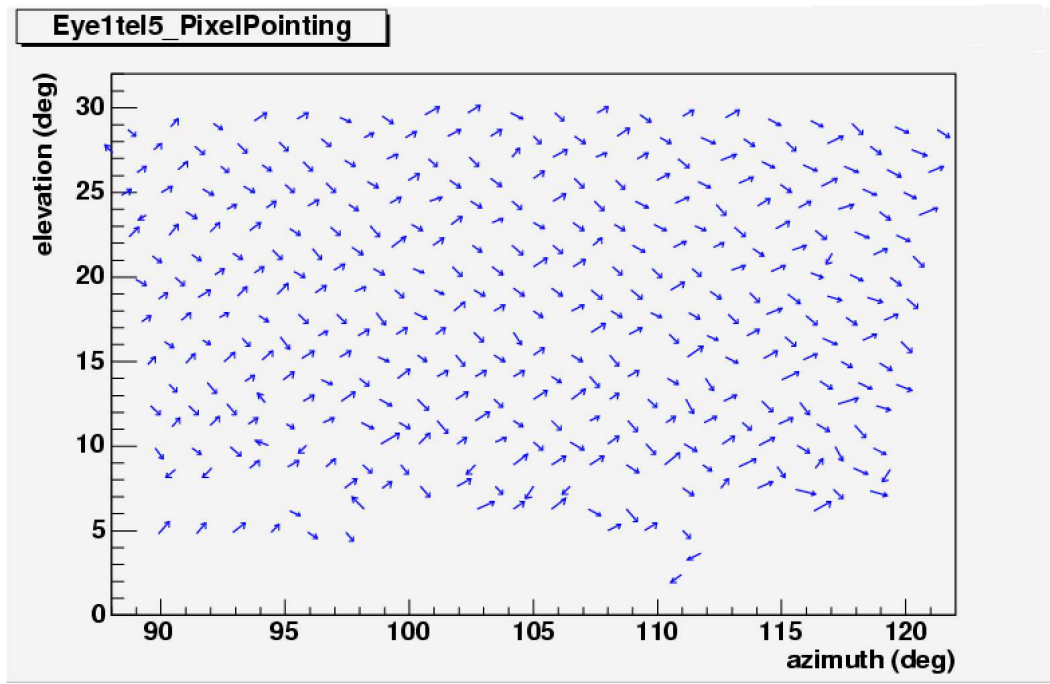


Fig. 8. Telescope distortion of the bay 5 at Los Leones. Arrows indicate only the augmented directions of the displacement of each pixel with respect to its theoretical position.

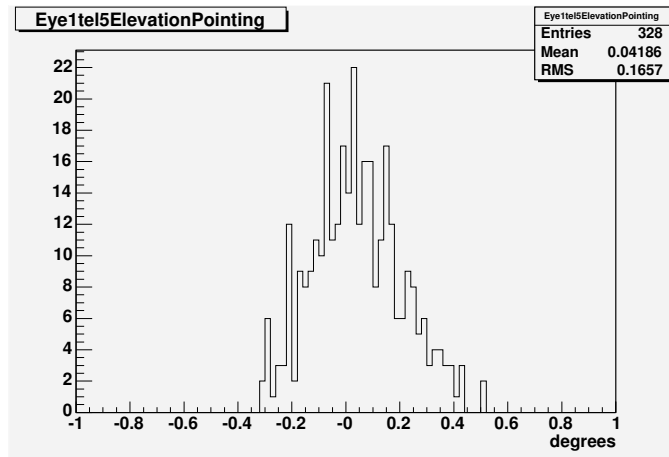


Fig. 9. Histograms of the differences between the specified values of elevation angle and the reconstructed ones for the pixels of telescope 5 at Los Leones.

2.4 Determination of the camera pointing

As explained in the previous section, after the determination of the pointing of each pixel we are in condition to calculate the pointing of the camera axis simply inverting the formulas given in [7]. As not all the pixels directions were established with the same number of signals, we have determined the minimum number of signals required for a pixel that minimize the error in the

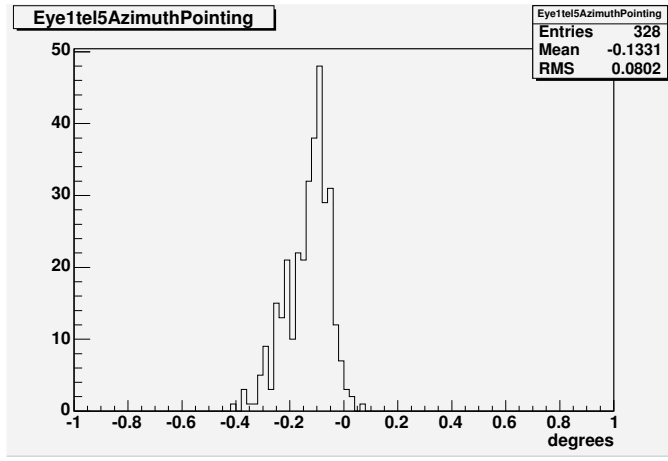


Fig. 10. Histograms of the differences between the specified values of azimuth angle and the reconstructed ones for the pixels of the telescope 5 at Los Leones.

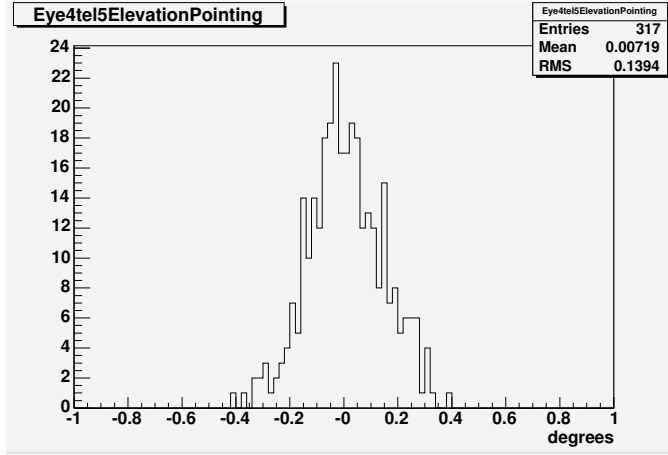


Fig. 11. Histograms of the differences between the specified values of elevation angle and the reconstructed ones for the pixels of telescope 5 at Coihueco.

determination of the pointing of the camera axis. In Fig.13 we have plotted the error in the determination of the azimuth optical axis angle 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 from Fig.13, a minimum in the error occurs at around 5 signals. In other words, if only pixels with at least 5 signals are used to calculate the azimuth optical axis angle of the telescope, the error is minimized. The same occurs for the elevation angle. In fact, if the minimum number of signals required is too low (for example 2), the uncertainty in the knowledge of the directions of the pixels will give a low precision in the determination of the pointing of the camera axis. On the other hand, if the minimum number of signals required is too high (for example 10), the pixels directions will be known with great accuracy but with detriment of the statistic. Therefore a compromise between high statistic and high precision in the knowledge of the directions of the pixels is needed. This is reached with a minimum number of signals equal to 5. For this reason not all the pixels were used in the calculations

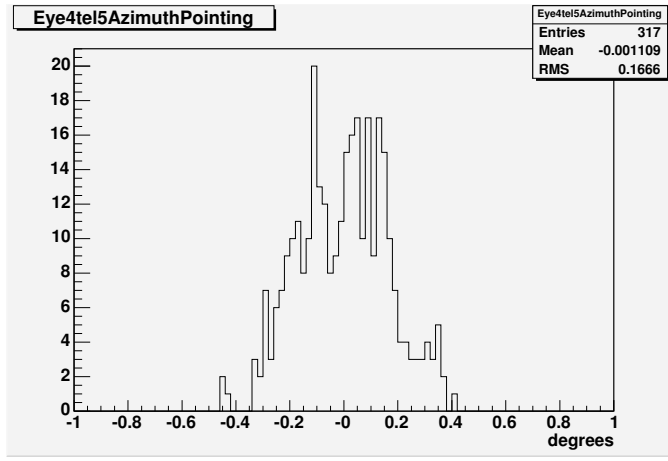


Fig. 12. Histograms of the differences between the specified values of azimuth angle and the reconstructed ones for the pixels of the telescope 5 at Coihueco.

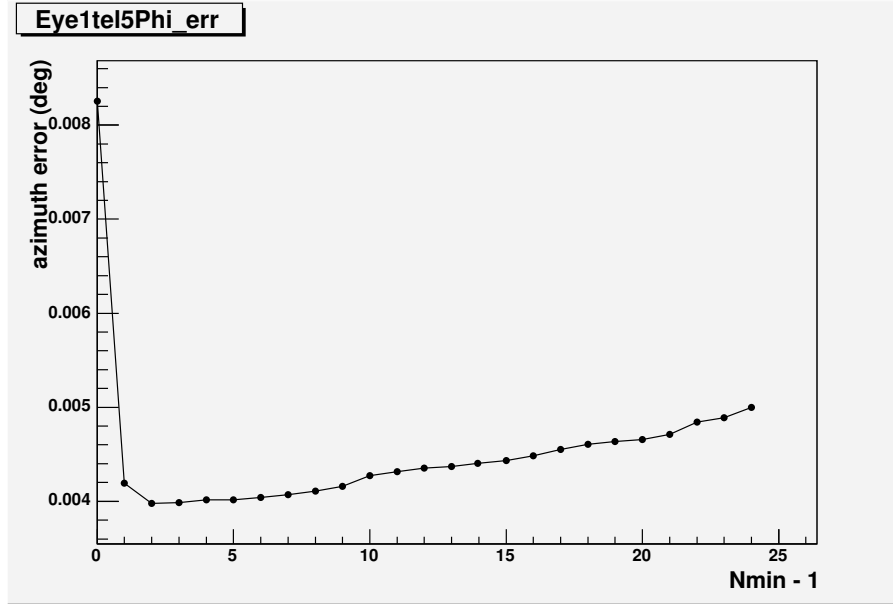


Fig. 13. Error Minimization. The plot shows the error in the determination of the azimuth optical axis angle as a function of the minimum amount of signals required for each pixel to be used in the analysis.

of the camera pointing but only those with at least 5 signals.

As an example, in Fig.14 and Fig.15, the histograms of reconstructed values of azimuth and elevation angles of telescope 5 at Los Leones are shown.

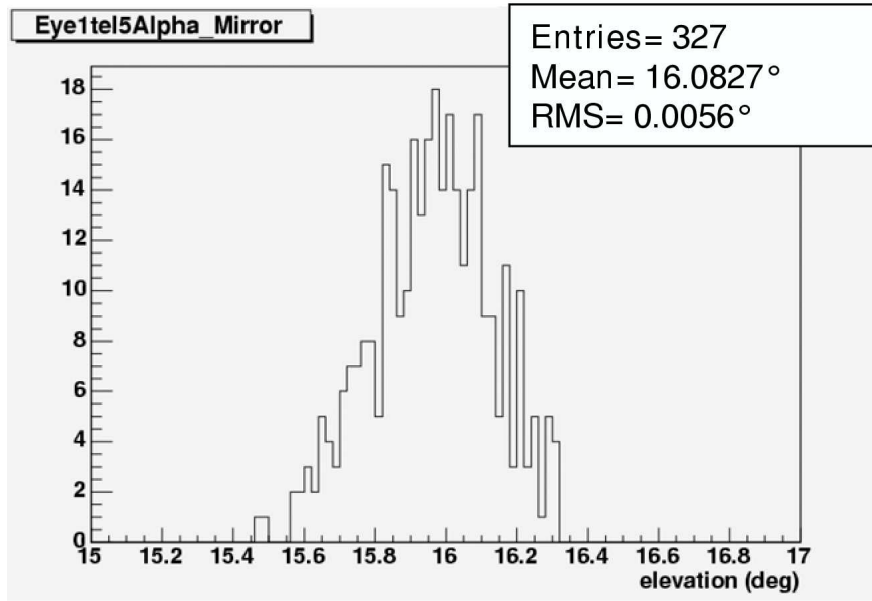


Fig. 14. Los Leones, telescope 5. Histogram of the reconstructed values of elevation angle of the telescope optical axis.

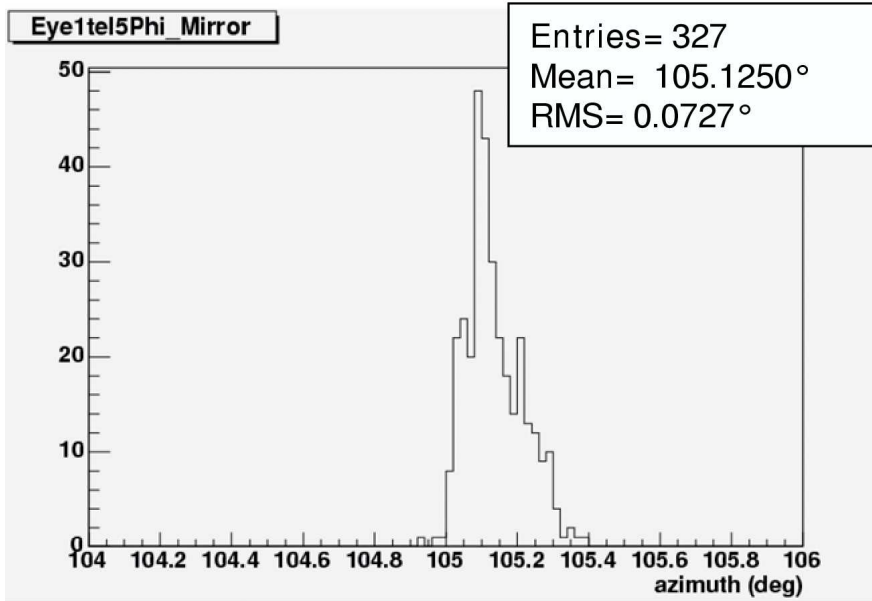


Fig. 15. Los Leones, telescope 5. Histogram of the reconstructed values of azimuth angle of the telescope optical axis.

2.5 Atmospheric refraction

Once we have tested the procedure, we have calculated once again the pointing direction using atmospheric refraction correction. Because of refraction the light spot of a star is seen from an elevation different from the real position of the star. The index refraction depends on the atmospheric conditions that

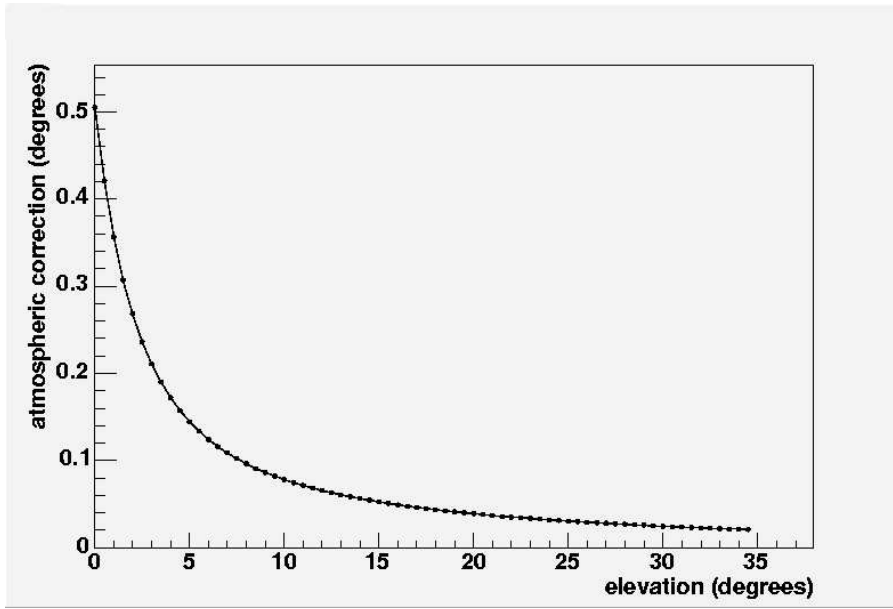


Fig. 16. Atmospheric correction calculated from Meeus algorithm at $T = 273^\circ K$ e $p = 860 \text{ mbar}$.

can be monitored or predicted by the atmospheric models. Nevertheless a very precise correction would be excessive for our calculation and too heavy for the procedure. For this reason we have used Meeus algorithm [8], whose degree of precision is sufficient for our purpose and that is suitable in the case of unknown atmospheric conditions. Given an observed elevation el_{obs} , the refraction correction α_{refr} is given by

$$\alpha_{refr} = \left[r - 0.06 \cdot \sin(14.7 \cdot r + 13) \right] \cdot \frac{1}{60} \cdot \frac{p}{1013} \cdot \frac{283}{T}, \quad (1)$$

with

$$r = \frac{\cos \theta}{\sin \theta} \quad (2)$$

and

$$\theta = el_{obs} + \frac{7.31}{el_{obs} + 4.4}, \quad (3)$$

where p is the pressure in millibar, T the temperature in Kelvin and the angles are given in degrees.

The correction, calculated for a temperature $T = 273^\circ K$ and $p = 860 \text{ mbar}$, is shown in Fig.16.

It can be seen that the refraction correction is considerable only below 10° . Looking at figure 8, it can be noted that most of the reconstructed pixels have an elevation higher than 10° . We can deduce that the atmospheric correction will not change much our calculation of the pointing of the telescope axis.

3 Pointing results

The procedure described in the previous section has been applied to calculate the pointing of all the telescopes of the fluorescence detector although not all of them were installed at the very same time. Actually, only after July 2004 the detector started to operate with 12 telescopes, 6 in the Optical Station of Los Leones and 6 in Coihueco. Therefore the pointing was reconstructed with different amount of data, proportional to the time each telescope acquired data (table 1). We have analyzed data from January to October 2004.

Table 1

Daily rate of signals identified. The total number of signals identified, the total number of night analyzed and the rate are shown for all the telescopes at Los Leones and Coihueco for the whole period analyzed (January-October 2004).

Daily rate of stars signals identified						
2004	Los Leones			Coihueco		
Mirror	Total signals	number of nights	rate (signals/night)	Total signals	number of nights	rate (signals/night)
Mir1	3884	35	110.0	505	31	16.3
Mir2	10547	59	178.8	1486	71	20.9
Mir3	13280	99	134.1	11820	84	140.7
Mir4	14055	91	154.5	5943	28	212.3
Mir5	11503	88	130.7	7609	32	237.8
Mir6	7977	95	84.0	4742	32	148.2

In this period telescopes 3 to 6 at Los Leones operated around ~ 9 months while telescopes 1 and 2 operated $\sim 3 - 5$ months. The rate of signals/night ranged from ~ 84 to ~ 179 in this Optical Station. On the other hand, at Coihueco, telescope 2 and telescope 3 operated around ~ 8 months while the others did it around ~ 3 months in the period we are interested in. In this case the rate of signals/night varies from ~ 141 to ~ 238 , excluding telescopes 1 and 2 which present a very low rate (~ 20). Looking at the daily rates of each telescope, it seems that the rate of identified signals is higher for the telescopes pointing at North-East. Nevertheless, the daily rate of signals

identified for each telescope has been calculated without taking into account the effective duration of the data acquisition.

The detailed results and their errors are shown in tables 2 and 3. The number of pixels used to calculate pointing of the telescope axis in each case is also indicated (this number is the number of pixels with at least 5 signals in the whole analyzed period). The last two columns in each table indicates the difference between the specified value of pointing as indicated in [6] with the one we obtained with our analysis.

Table 2

Results for Los Leones. Columns 7 and 8 contain the differences between the specified values and the reconstructed ones.

Los Leones							
Mirror	Elevation (degrees)	$Error_{elev}$ (degrees)	Azimuth (degrees)	$Error_{az}$ (degrees)	Rec.Pixels (degrees)	Δ_{elev} (degrees)	Δ_{az} (degrees)
Mir1	15.8297	0.0073	-15.0767	0.0146	228	0.1703	0.0767
Mir2	15.8928	0.0074	14.9707	0.0102	341	0.1072	0.0293
Mir3	15.9166	0.0082	44.9588	0.0072	342	0.0834	0.0412
Mir4	16.0822	0.0010	75.0471	0.0032	351	-0.0822	-0.0471
Mir5	16.0827	0.0003	105.1250	0.0040	327	-0.0827	-0.1250
Mir6	15.8152	0.0081	135.2230	0.0068	249	0.1848	-0.2230

4 Summary and conclusions

We have used star signals to determine the pointing of the optical axis of the fluorescence detector's telescopes. The differences in the pointing we found between the specified values in [6] and our results are less than 15 arc minutes. As shown in tables 2 and 3 our errors are significantly smaller than the mentioned differences in almost all telescopes. The errors obtained in the calculation of the pointing of the telescope's axis are in the range $0.0003^\circ - 0.03^\circ$ depending on the telescope under analysis. The refraction correction, as predicted in §2.5, gives a final correction in the elevation angle of the telescope axis of only 0.05° .

Table 3

Results for Coihueco. Columns 7 and 8 contain the differences between the specified values and the reconstructed ones.

Coihueco							
Mirror	Elevation (degrees)	$Error_{elev}$ (degrees)	Azimuth (degrees)	$Error_{az}$ (degrees)	Rec.Pixels (degrees)	Δ_{elev} (degrees)	Δ_{az} (degrees)
Mir1	16.2589	0.0337	-101.8980	0.0206	35	-0.2589	-0.0801
Mir2	15.8941	0.0202	-71.9313	0.0199	120	0.1059	-0.0468
Mir3	15.8973	0.0063	-42.0771	0.0087	365	0.1027	0.0990
Mir4	16.0461	0.0055	-11.9563	0.0096	319	-0.0461	-0.0218
Mir5	15.9849	0.0083	18.0608	0.0116	317	0.0151	-0.0389
Mir6	16.0971	0.0140	48.1956	0.0093	268	-0.0971	-0.1737

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