Using star tracks to determine the absolute pointing of the Fluorescence Detector telescopes
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Abstract

To accurately reconstruct a shower axis from the FD 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. 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.

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1 Introduction

At the very beginning of the Auger Project it was decided the construction of the first two prototypes telescopes of the Fluorescence Detector. Those devices were equipped with XP3062 PMTs from Photonis and biased with an active network. The active network ensured 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 start when it enters into the 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.

2 Procedure to calculate the telescope's pointing

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

(1) Search for signals in the background variance data.

(2) Simulation of stars tracks.

(3) Association of signals found in (1) to stars signals simulated in (2) in order to establish the absolute pointing of each single pixel.

(4) Determination of 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 we are analyzing (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 been determined.

2.1 Search for signals in the variance data

The background sky light varies from night to night and, in a single night itself, 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.

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

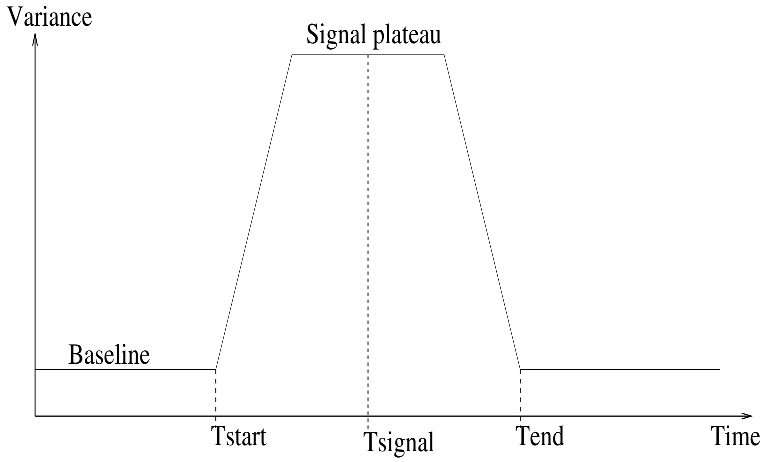

Fig. 1. Ideal signal shape. After identifying a star's signal in the variance data, a time T_{signal} is associated to it.

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 3 σ from the mean baseline is considered a star signal. In this way, the beginning and the end of the signal are easely found as the first and the last point in the signal data set.

The second method (SR) is a sort of 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 not equivalent in the sense that, depending on the signal shape and the background baseline, they do not always find the same signals. The first method works better than the second if the baseline is highly variable but is worse for small signals. Obviously both 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 field of view (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 the beginning to the end of the night [8]. We do this simulation without considering the effect of the atmosphere (i.e., we do not take care of

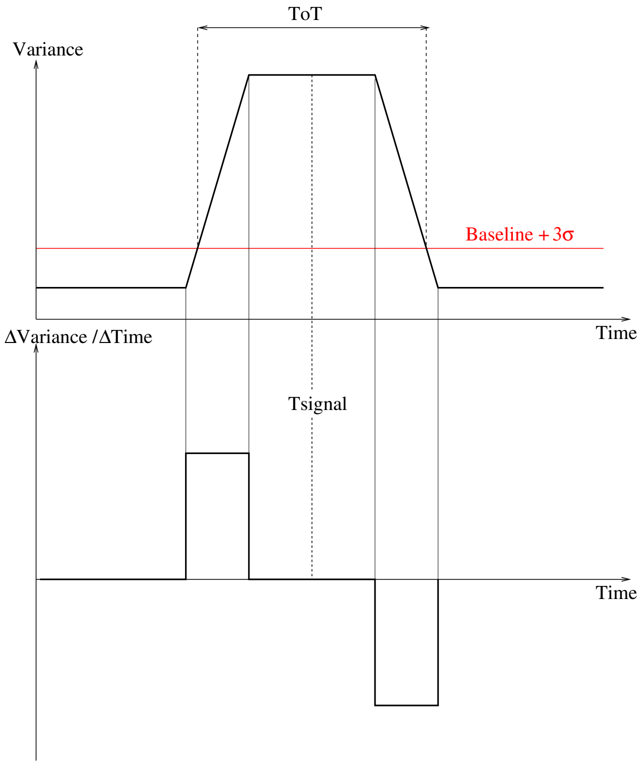

Fig. 2. Time-over-Threshold (ToT) scheme above, and Slew-Rate (SR) scheme below.

the atmospheric refraction index). As an example we show, in Fig.3, the plot of the track of Vega crossing the telescope 4 of Los Leones.

Later on, the time spent by each star in each pixel is calculated. 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 mag = 5 as the dimmer star's magnitude to be accepted for our analysis. 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 nominal values of pixel centers which are specified in [7] and [6].
In our analysis we have assumed pixels of 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.4. 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 inside the pixel, we consider the star not fully contained inside the pixel. Only pixels with fully contained spots were considered in this work.

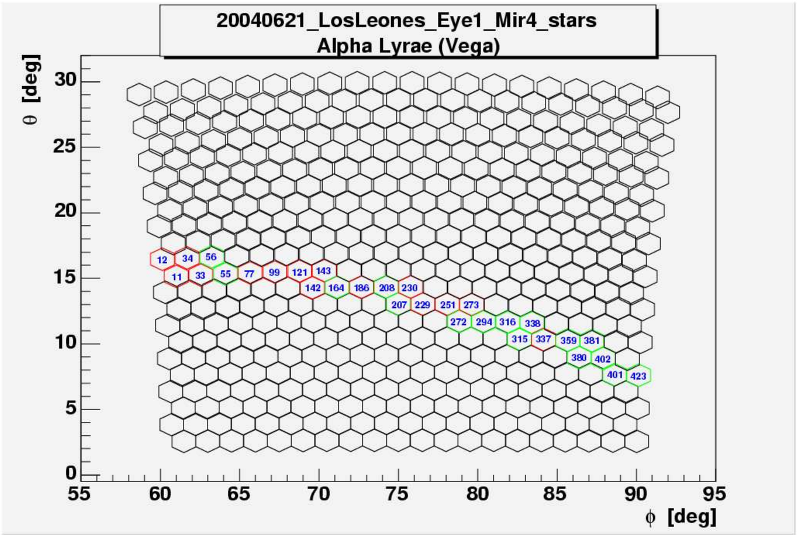

Fig. 3. Simulated track of Vega crossing the telescope 4 of Los Leones. The pixels numbers are also shown. Red pixels mean that a signal was found in the variance data. Green pixels mean that, although the star crosses the pixel, no signal was found.

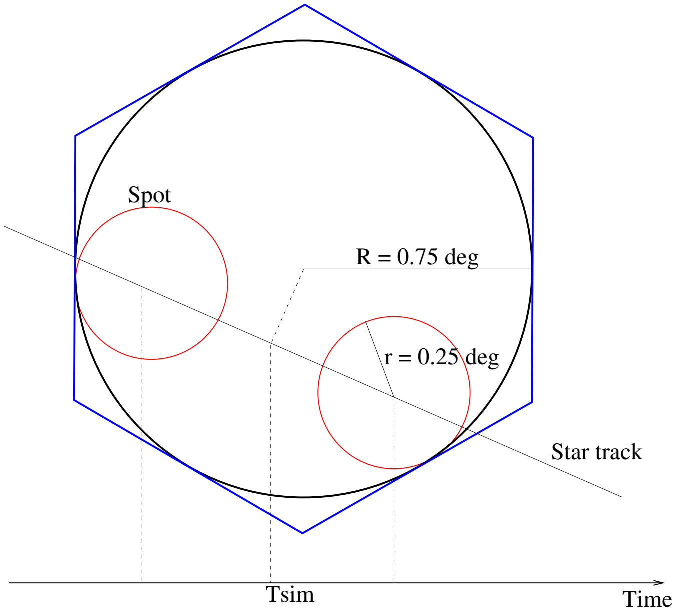

Fig. 4. Schematic track of a star crossing a circular pixel.

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 $|T_{signal} - T_{sim}| < 3\ min.$, we assume that the signal we

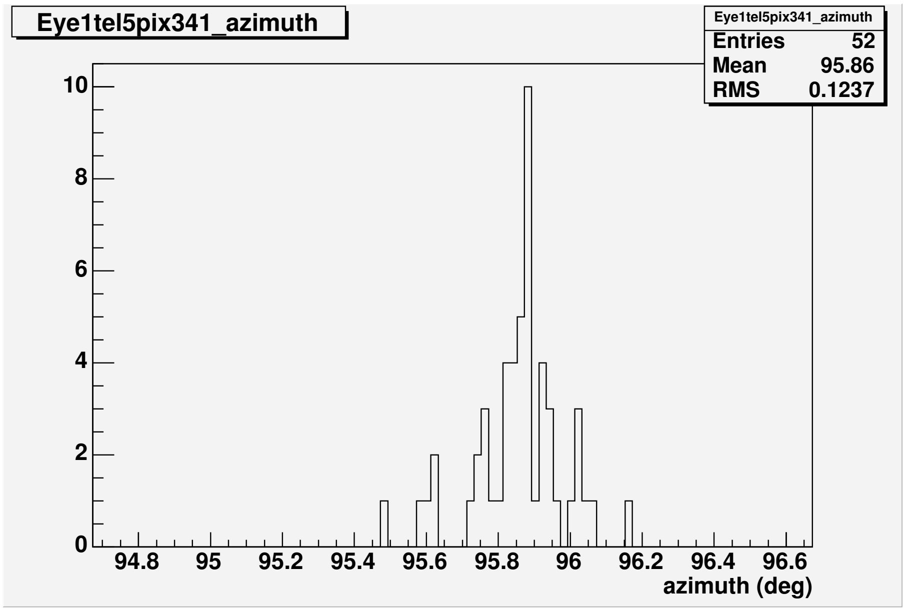

Fig. 5. Los Leones, telescope 5. The histogram shows the values of the reconstructed azimuth angles for pixel 341 from stars signals.

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.5 and Fig.6.

This procedure is repeated to determine the pointing of all pixels where at least one signal was found. In Fig.7 the directions of the displacement of each pixel with respect to its theoretical position are shown with arrows.

2.4 Determination of the camera pointing

After the determination of the pointing of each pixel as explained in the previous section, we are in condition to calculate the pointing of the camera axis simply inverting the formulas given in [6]. But not all the pixels directions were established with the same quantity of signals. In Fig.8 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.8 a minimun in the error occurs

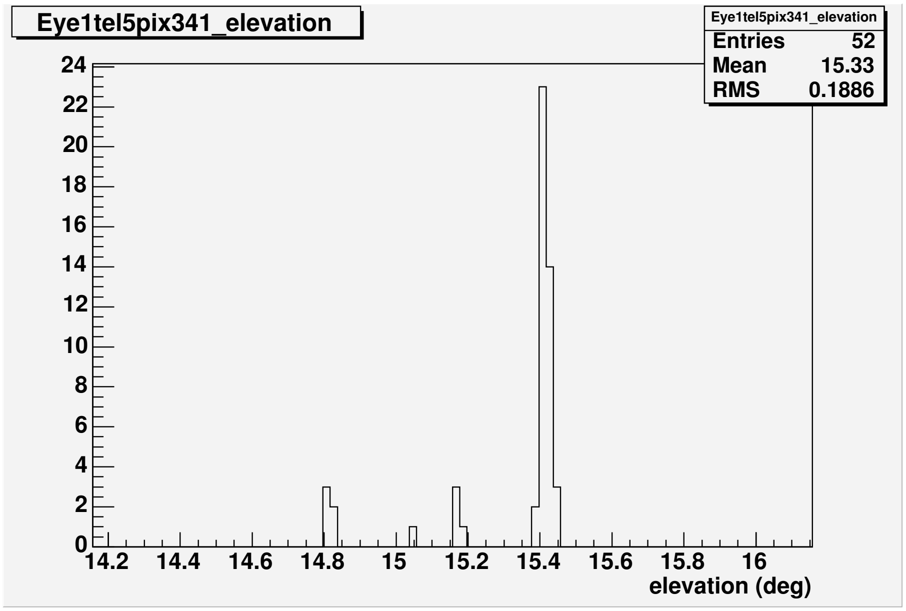

Fig. 6. Los Leones, telescope 5. The histogram shows the values of the reconstructed elevation angles for pixel 341 from stars signals.

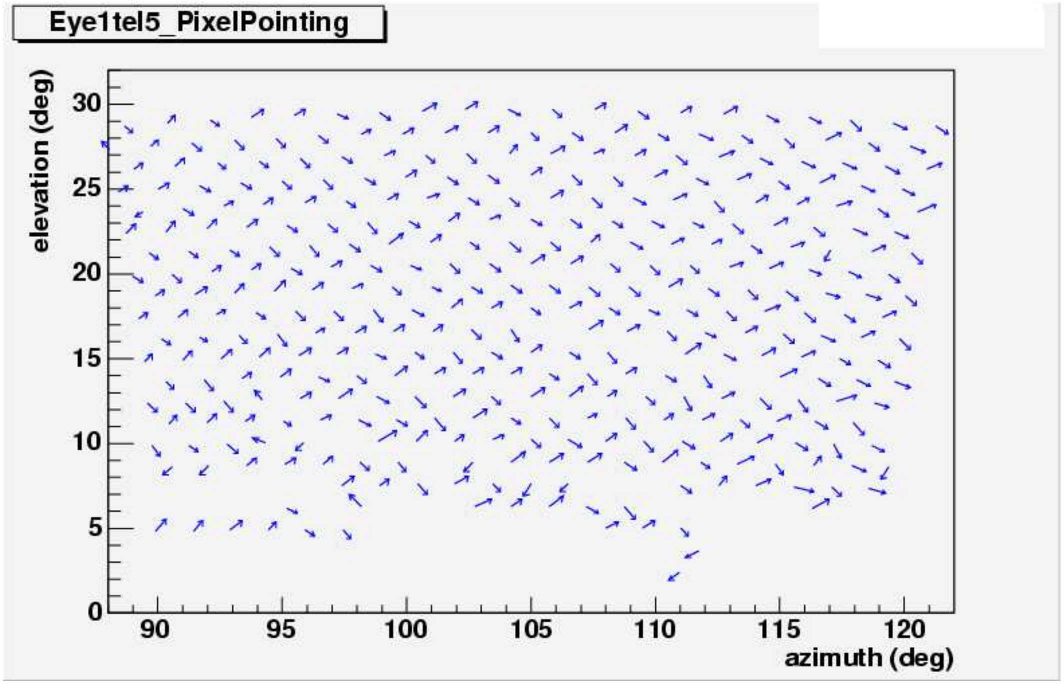

Fig. 7. Telescope distortion. Arrows indicate the directions of the displacement of each pixel with respect to its theoretical position.

at around 4 signals. In other words, if only pixels with at least 4 signals are used to calculate the azimuth optical axis angle of the telescope, the error is minimized. The same occurs for the elevation angle. For this reason not all the pixels were used in the calculations of the camera pointing but only those with at least 4 signals were used in the analysis.

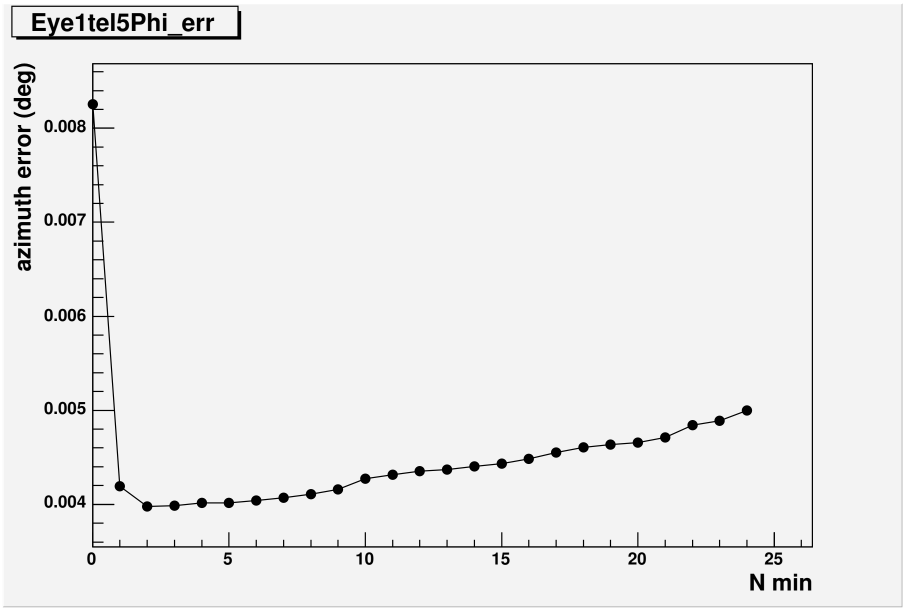

Fig. 8. Error Minimization. The plot shows the error in the determination of the azimuth optical axis angle as a function of the minimum amount of signals required for each pixel to be used in the analysis.

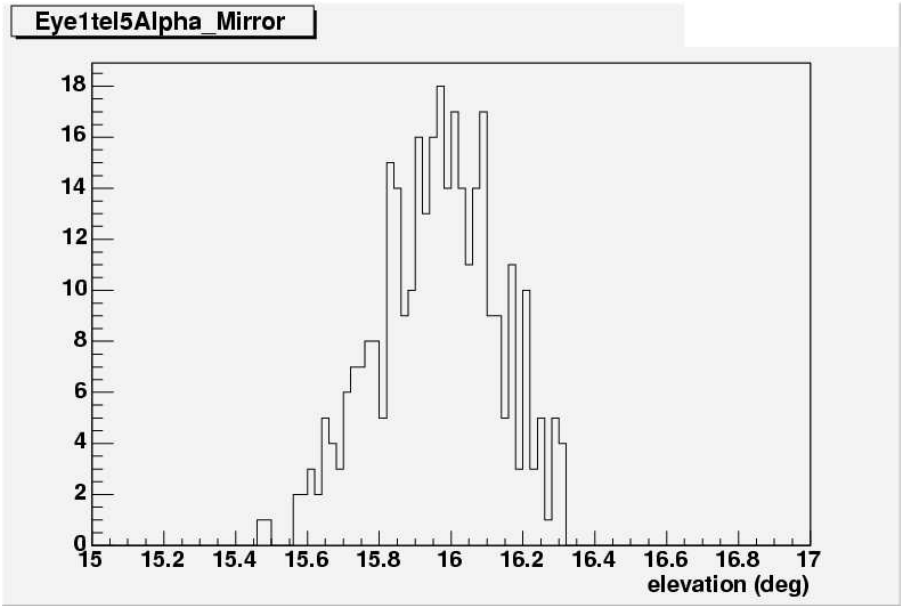

Fig. 9. Los Leones, telescope 5. Histogram with recontructed values of elevation angle of the telescope optical axis.

As an example, in Fig.9 and Fig.10, the histograms of recontructed values of azimuth and elevation angles of telescope 5 of Los Leones are shown.

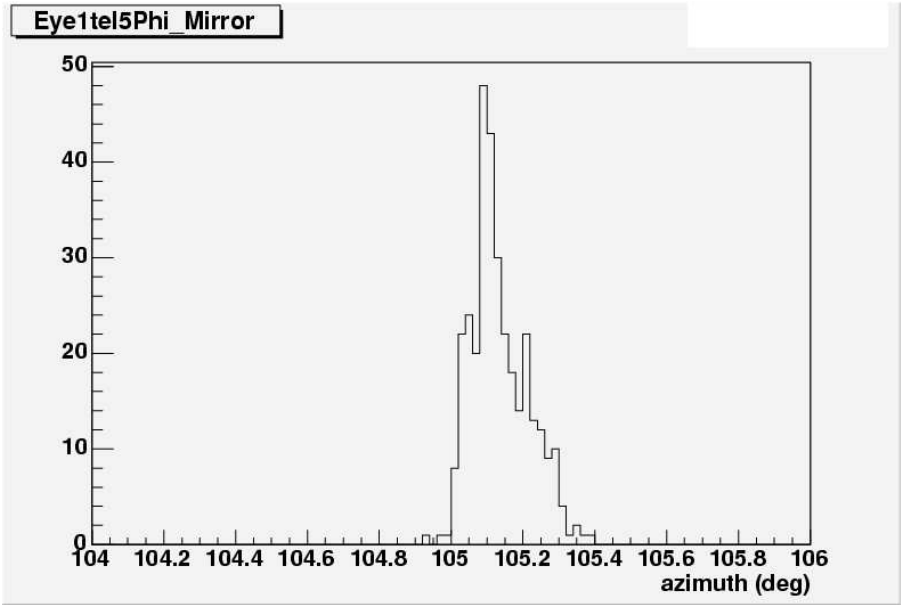

Fig. 10. Los Leones, telescope 5. Histogram with recontructed values of azimuth angle of the telescope optical axis.

3 Results

The procedure described in the previous section has been applied to calculate the pointing of all 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 Los Leones optical station and 6 in Coihueco optical station. Therefore the pointing was reconstructed with different amount of data, proportional to the time each telescope acquired data. We have analyzed data from January to October 2004. In this period telescopes 3 to 6 in Los Leones operated around ~ 9 months while telescopes 1 and 2 operated $\sim 3 - 5$ months. The monthly rate of signals ranged from ~ 800 to ~ 1900 in this station. On the other hand, in Coihueco, telescope 2 and telescope 3 operated around ~ 8 months while the others around ~ 3 months in the period we are interested in. In this case the rate of signals per months varies from ~ 150 to ~ 1300.

The detailed results and their errors are shown in tables 1 and 2. The number of pixels used to calculate the telescope axis pointing in each case is also indicated (this number is the number of pixels with at least 4 signals in the whole analyzed period). The last two columns in each table indicates the difference between the nominal value of pointing as written in [7] with the one we obtained with our analysis.

Table 1: Los Leones

Mirror	Elevation	$Error_{elev}$	Azimuth	$Error_{az}$	Rec.Pixels	Δ_{elev}	Δ_{az}
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	-0.0223

Table 1
Results for Los Leones. Columns 7 and 8 contain the differences between the nominal values and reconstructed ones.

Table 2: Coihueco

Mirror	Elevation	$Error_{elev}$	Azimuth	$Error_{az}$	Rec.Pixels	Δ_{elev}	Δ_{az}
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

Table 2
Results for Coihueco. Columns 7 and 8 contain the differences between the nominal values and reconstructed ones.

4 Summary and conclusions

We have used stars signals to determine the pointing of the optical axis of the fluorescence detector's telescopes. The differences in the pointing we found between the published values in [7] and our results are less than 6 arc minutes. As shown in tables 1 and 2 our errors are significantly smaller than the mentioned differences in almost all telescopes.

As a final comment we briefly discuss the precision of our analysis. For this purpose we studied the telescope 3 of Coihueco that has been realigned $\sim 0.3°$ in elevation in March 2004 [5]. To test our method we have applied our analysis procedure to calculate the pointing of this telescope's axis in two separated periods, namely before and after March 2004. As we have used data from January to October 2004, we have two months of data before March and six months after March. The result we obtained shows an increment in the elevation angle, between the two periods, of about 0.13°. This variation is smaller than the expected one but in any case is significant. In fact, we calculated the pointing of telescope 3 of Los Leones for the same periods and we obtained a very small variation of ~ 0.001, consistent with the fact that this telescope was never realigned. We have chosen telescope 3 of Los Leones in order to have similar statistics and the same operating period of the corresponding telescope of Coihueco. Our conclusion is that the difference in elevation angle observed for the optical axis of telescope 3 of Coihueco is not due to statistical factors.

References

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