HIGH - ACCURACY DETERMINATION OF FABRY - PEROT EFFECTIVE MIRROR SPACING USED FOR THE RECEIVERS OF ATMOSPHERIC MONITORING IN VHE GAMMA RAY ASTRONOMY

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In the framework of the design of a High Spectral Resolution Lidar (HSRL) for the atmospheric monitoring in High Energy Cosmic Ray Observatories, we demonstrate an accurate and non-invasive method for determination of the effective mirror spacing of the Fabry-Perot of one of the etalons being used for the receiver and having a nominal value of 5 mm. We used as a reference three very well known spectral lines of natural isotope mixture of Hg I at 435 and 546 and 579 nm. Furthermore, we present the investigation of the robustness of the obtained solution for the effective mirror spacing, by means of conclusions concerning the validity of the experimentally measured “excess fractions”. Because as the light source of the HSRL prototype we intent to use an SLM Nd:YVO4 laser it is very crucial to study and verify its spectral stability. This could be done using three Fabry–Perot etalons with precisely known mirror spacing.

1. Introduction

In the Imaging Atmospheric Cherenkov Technique (IACT) the atmosphere is itself part of the detector. It is where the particle shower is initiated by the incident gamma-ray and the medium the Cerenkov photons are propagated. The energy estimation of the individual gamma-ray is based on the calorimetric energy deposit in the atmosphere, which in turn can be measured recording the Cherenkov radiation. Any change in atmosphere quality and its constituents can affect the signal detected. Many current Cherenkov telescope arrays have in-situ single-scattering Elastic Lidars. Eventually, more accurate Lidars have to be installed at the sites of future Cherenkov telescopes in order to significantly reduce the systematic error in energy measurements and in deriving source fluxes.

The motivation of the present work is associated with the development of a prototype system for atmospheric monitoring dedicated for the aforementioned

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Cherenkov telescopes in gamma ray astronomy field. We are aiming to apply the technique of High Spectral Resolution Lidar using multi-wavelength emission at 1064 nm, 532 nm and down to near UV at 355 nm [1,2]. The high accuracy spectral resolution can be accomplished using Fabry-Perot etalons, one for the aerosol scattering signal (aerosol channel) and another for the molecular scattering signal (molecular channel). This feature can allow higher levels of accuracy in measuring the optical effects of the atmospheric constituents (i.e. aerosols). The characterization of the etalons being used, by means of accurate determination of the effective mirror spacing, is very important because we can use them to evaluate the stability of the light source. The accuracy of wavelength determination is quantified by the order of magnitude of wavelength broadening due to aerosol scattering which is of the order of 50 MHz.

In section 2, we describe the application topic which is the HSRL prototype, in section 3, we present the experimental demonstration of the method and its successive steps, in section 4, the result of effective mirror spacing of the etalon characterized and an analysis of the robustness of the solution is given. Finally, in section 5, the conclusions and some prospects are discussed.

2. Application topic: HSRL Prototype Design

For atmospheric monitoring, the HSRL and the associated technique takes advantage of the spectral distinction of the returned signal from aerosols and molecules and thereby to measure the aerosol extinction and backscatter coefficients at the same time. According to our design of a prototype HSRL, the spectral analysis is based on two Fabry-Perot etalons of different Free Spectral Ranges corresponding to mirror spacing, 5 mm and 100 mm, corresponding to molecular and aerosol channels respectively. As a light source, we plan to use an available DPSS CW SLM laser at 532 nm with power 100 mW and coherence length of the order of 50 m.

3. Experimental demonstration of the method

As effective mirror spacing we consider the final spacing after mounting the etalon using the required spacers between the mirrors. This effective mirror spacing is mostly affected by the thickness of the multi-layers deposited on the inner surfaces of the two mirrors and is of the order of 1 μm in each surface. In order to determine the effective mirror spacing we follow four separate steps. The first step includes the experimental data, that is, the capturing of interferograms. The choice of three wavelengths can provide highly robustness
in the solution. Because the light source has to be very coherent, we used a low pressure discharge lamp of Hg I emitting lines of natural-isotope-mixture in air.

![Experimental Setup Diagram](image)

Figure 1. The configuration of the experimental setup for capturing the required interferograms.

The configuration of the experimental setup is illustrated in Figure 1. Below we describe the optical components used in more details.

1. **CCD sensor**: SBIG† 1600x1200 pixels (7.4 ×7.4 mm²) controlled by computer software.
2. **Collimating lens**: f₁=50 mm.
3. **Focusing lens**: f₂=100 mm.
4. **Etalon mirror spacing (nominal)**: d=5 mm.
5. **Optical filter**: bandpass, FWHM=10 nm.
6. **Optical filter**: bandpass, FWHM=50 nm.
7. **Diaphragm**: 2 mm wide.
8. **Light source**: low pressure discharge lamp of natural-isotope-mixture of Hg I in air.

The second step concerns the selection and further processing of the fringe patterns. By appropriate new homemade software we are able to select the fringe system belonging to an identified spectral line for further analysis and afterwards to produce the corresponding contours taking into account the intensity profile in the radial direction.

In the third step we have to determine the excess fractions of each fringe pattern corresponding to the wavelength selected and identified. The spectral

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lines of Hg I which we identified and used were that having the following wavelengths: \( \lambda_1 = 435.83277 \text{ nm} \), \( \lambda_2 = 546.07348 \text{ nm} \) and \( \lambda_3 = 579.06630 \text{ nm} \) using eight significant digits. The method for determining the excess fraction with high accuracy has been presented recently in [3]. The wavelengths of the spectral lines have been taken from [4] and are consistent with the results of a more recent article [5]. In Figure 2 we give an indicative example of the fringe pattern obtained with the relatively broad optical filter where three fringe systems are produced at the same time.

4. Data analysis and results

In the fourth step we are investigating the solution to the problem. The central idea of the method is to find the optimum solution of the modular equation system among infinite possible ones (see [6] for more details). In a vicinity of the optimal solution point in Excess Fraction Space (EFS) the optimal value of thickness, \( d_{opt} \), is locked-in due to properties of the modulo operator. We applied this method in the etalon of 5 mm spacing and also we went further: That is, we investigated the criteria of robustness and, as well as, the uncertainty limits in the parameters used (see Figure 3). The three-equations system using 3 wavelengths, \( \lambda_i, \lambda_j, \lambda_k \), can be expressed by a single equation as seen below:

\[
\frac{2d}{\lambda_m} \mod 1 - \left( \varepsilon_m + \Delta \varepsilon_m \right), \text{ where } m = (i, j, k)
\]

Figure 2. The obtained picture-interferogram using a 50 nm FWHM optical filter. The fringe systems produced by the lines 546, 577 and 579 nm are shown by the arrows.

The wavelengths \( \lambda_m \) have to be adjusted due to barometric pressure and temperature conditions with respect to standard ones used in the literature. Nevertheless, we have to apply a reliable model for the correction of the
refractive index, by means of normalizing for slightly different atmospheric conditions (pressure, temperature and humidity). The function to be minimized is:

\[ f(d, \Delta \epsilon_i, \Delta \epsilon_j, \Delta \epsilon_k; \lambda_i, \lambda_j, \lambda_k, \epsilon_i, \epsilon_j, \epsilon_k) = f_i^2 + f_j^2 + f_k^2 \]  

The data analysis is based on the method given in [4]. From the modeling with ellipses we found: \( \epsilon_1 = 0.74958 \), \( \epsilon_2 = 0.25668 \) and \( \epsilon_3 = 0.095654 \).

Figure 3. Projections of the variation of the function \( f \) (plots in the left column) and the determined effective mirror spacing, \( d_{opt} \) (plots in the right column) in a vicinity of the origin in EFS. The optimal solution point (0,0) in each case lies effectively in to the valleys of the function while the \( d_{opt} \) is fixed in a large area of the space. The circles indicate the permitted margin in \( \epsilon_{\text{opt}} \). The accuracy of these values, according to our method, is estimated to be of the order of \( 10^{-3} \), but due to overlapping of the fringe patterns it should reduced to \( 10^{-4} \). In the optimal point the value of effective mirror spacing is \( d_{opt} = 5.00377(6) \) mm. This value is corrected by referring to the conditions of pressure and temperature held in our Laboratory (correction affecting the wavelengths). The error is affected mostly by the accuracy of the wavelengths used. According to the manufacturer, who measured the etalon spacers before mounting the result is, \( d = 5.001 \pm 0.00D \) mm, where \( D \) is an unknown uncertain digit. The result we derived is not only consistent, but the precision we
accomplished is much beyond by a factor of the order of 100. The free parameters of the model, \( \Delta c_m \), are used for more accurate minimization and are also useful for studying the robustness of the optimal solution found. For this study the parameters \( \Delta c_m \) are varied in pairs \( \Delta c_m \), where \( mn=(ij), (ik), (jk) \), in a vicinity of the origin in the EFS ( \( \Delta c_m =0, m\neq n \)). In this study the function \( f \) is modified, from the point of view of variables we are using, as follows:

\[
f_{ij,mn}(\Delta c_m, \Delta c_n, 0; \lambda_i, \lambda_j, \lambda_k, e_i, e_j, e_k) = f_i^2 + f_j^2 + f_k^2
\]

From the diagrams shown in Figure 3 it is evident that we could come up to the equally accurate values of the \( d \) (the regions with identical color).

5. Conclusions and Prospects

Our research is motivated by the need to characterize the laser used for atmospheric monitoring by the HSRL method. Towards this aim, a complete, robust and non-invasive method for determination of the effective mirror spacing of Fabry-Perot etalons with a precision of few nanometers has been developed, further extended and applied. This precision, in addition, allows measurement of absolute frequency of the laser and as well as quantification of its spectral fluctuations.

Acknowledgments

We would like to thank Prof. I. Raptis for providing us, for the required period, his low pressure discharge lamp of Hg.

References