

# **Optical Filter Transmittance Measurements by a Double-Beam Spectrophotometer for Calibration of Fluorescence Detector AUGER Filter Samples**

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**Abstract** An experimental setup and procedure for accurate transmittance measurements of candidate filters for the Auger Fluorescence Detector is presented. For this check, we used the Hitachi U-2000 double-beam spectrophotometer (Sph) of the Chemical Department of the University of Athens (UoA).

After the calibration of the Sph, we are able to observe transmittance deviations over the area of the filter under study within a sensitivity better than 0.2%.

A set of candidate filters is measured to identify their spectral transmittance in response to different angles of incidence. Also, the use of the Sph for few layers developmental multilayer can be studied for their spectral transmittance.

## **1. Introduction**

The importance of accurate transmittance measurements of the optical filters for the Fluorescence Detector of AUGER can be understood if we recall the requirement on the overall error on the measured signal from EAS. We may tolerate less than 5% overall error (including both statistical and systematic). The signal is attenuated by the atmospheric attenuation effects, the corrector plate and the optical filters. Also, spurious signals from Cerenkov radiation are scattered by aerosols. The phototube which is registering the signal has a quantum efficiency which is on the average 15-20%. It is depending on the wavelength of the radiation and it is expected to change with time as a result of aging. It may also be different on each different phototube.

In addition, the performance of the optical filter as well as the phototube has an angular dependence. Taking all these effects into account, we come to the conclusion that it may be very difficult, in fact it is a challenge to achieve an error control in the measurement of EAS signal in each photomultiplier tube equal or better to 5% since each of the uncertainties must be well better than 5%. Thus, we should aim to know filter transmittance better than 2% of accuracy. Further more, since in the night sky noise there are certain transmittance peaks with intensity a few times larger than the continuous background, we should have accurate values of transmittance of filters in these specific large peaks.

In this report, the work towards determining the absolute transmittance of several candidate optical filters with an accuracy dictated by the above arguments. The change of filter transmittance over the area is also of interest. Also, an effort is made to identify and determine the spectral transmittance in the ranges of high rate of night sky background radiation (atmospheric, stellar and artificial) (Garipov et. al., 1999) within Auger Collaboration and also by workers in atmospheric Physics and Astronomy.

In this work, we profit from the outcome of these efforts and present some of the results in the transmittance of the filters in specific lines in visible and UV range.

The Sph described has been able, as we shall demonstrate, to discern differences of spectral transmittance between candidate filters and between transmittances at different locations of specific filter samples as low as 0.2%.

We thus envisage that this instrument will be a useful tool for routine accurate calibration of the filters to be eventually installed at the Engineering array prototype and later at the final telescope array. Due to the limited size of the spectrometer, there are certain restrictions on the extent on which tests can be done and on the sizes of the samples. It is also influenced by photodiode yield, which depends some what on the temperature and more strongly on high voltage. Finally, it depends on signal level for very intense signals. The dynamic range of transmittances, over which the instrument is sensitive, is described. We end this presentation with some conclusions on the apparent relative merits of various filters, which can be extracted by simply comparing their spectral transmittances.

We should comment that the present instrument can operate in a complementary way with other specially designed spectrophotometer of NTUA (Maltezos and Fokitis, 2000) which allows transmittances of value less than 1% be accurately determined but which has limited repeatability of transmittance measurements (around 5%) in transmittance values larger than 3%.

## 2. Experimental

The realization of spectrophotometric quantities at the University of Athens is based on our reference Sph. The reference Sph is a high-accuracy instrument developed for measuring spectral specular transmittance in a wavelength range extending from ultraviolet to near infrared. This is a Hitachi U-2000 double-beam Sph. Its principle of operation is based on the Lambert-Beer law (L-B). A schematical view is shown in Fig. 1.

For the visible optical and ultraviolet region, it uses a tungsten iodide and a deuterium discharge lamp, respectively. While the monochromator has a grading constant of 1/600 mm, a blaze wavelength of 250 nm with a grading area of 20 x 25 mm<sup>2</sup>.

The detection system uses two silicon photodiodes. The overall wavelength range is from 190 nm to 1100 nm with 0.1 nm of increment and with a spectral bandpass of 2 nm ±0.3 nm. The change from the visible to the ultraviolet mode is switched at 350 nm. Its wavelength accuracy and reproducibility is ±0.4 nm and ±0.2 nm, respectively. This will be demonstrated in a later section.

We use the following equation (1) that enables transmittance of various samples to be predicted. The simplest case of studying the transmittance curve is when the sample is a “substrate” such as clear glass or plastic. For example, utilizing this equation,

$$T(\lambda) = 1 - R(\lambda), \quad R(\lambda) = 2 \left( \frac{n(\lambda) - 1}{n(\lambda) + 1} \right)^2 \quad n, \text{ being the refractive index} \quad (1)$$

the transmittance can be calculated for samples with known refractive indices, such as in case of Borofloat or Schott WG 280. Comparison of measured transmittance with expected ones

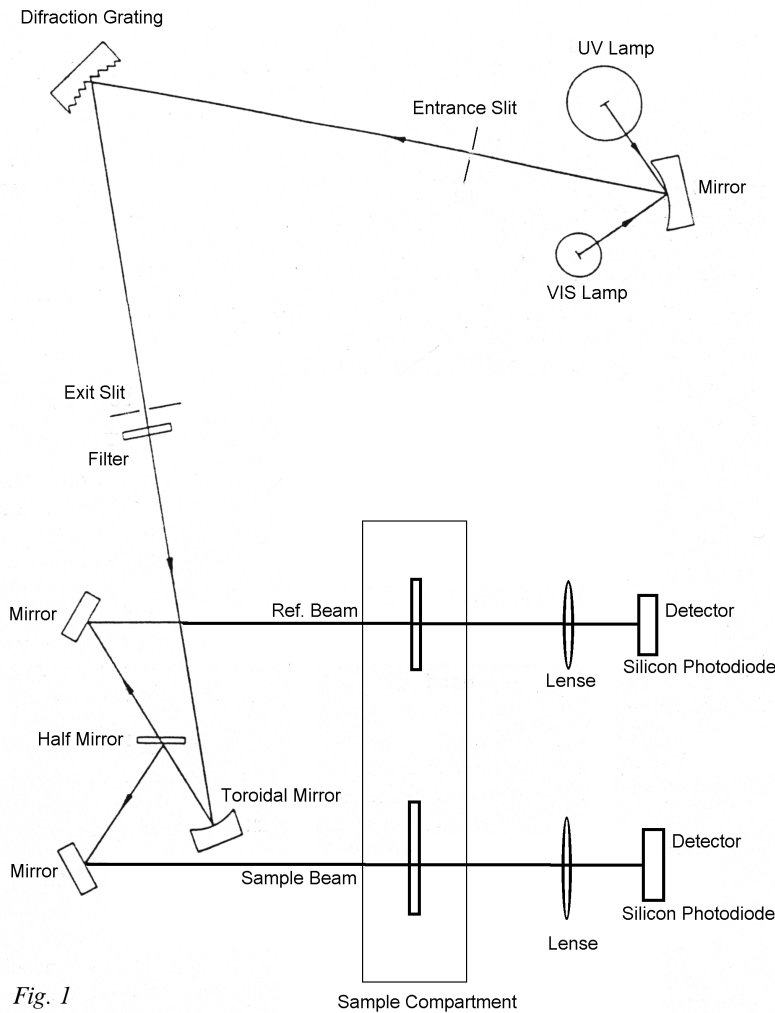


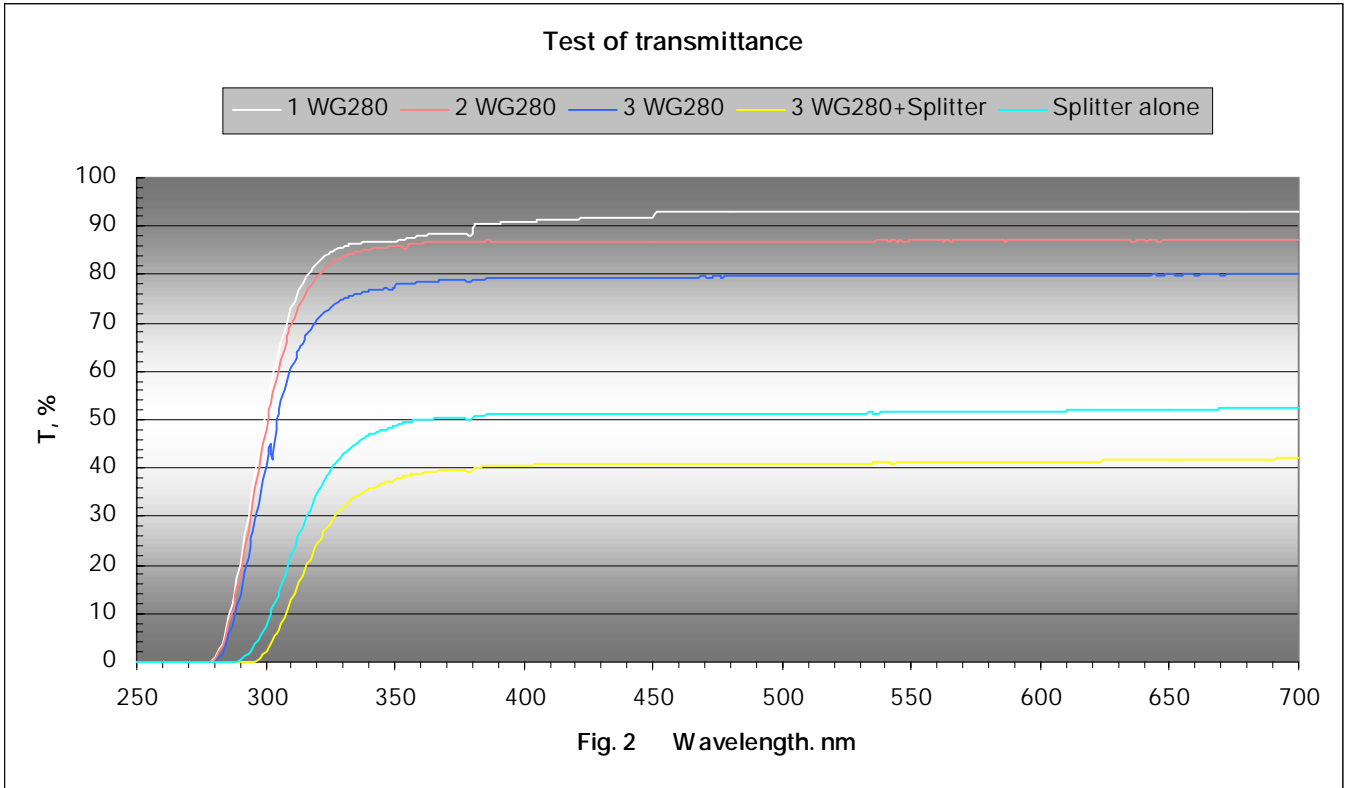
Fig. 1

have been carried out.

The repeatability of the transmittance curve is evaluated by comparison with "Calibrated Optical Samples (COS)". The comparison of experimental transmittance curves with these of COS can be given in terms of a linear correlation with its corresponding coefficient. The comparison also will allow us to obtain a secondary calibration of our spectrometer.

### 3. Calibration of the spectrophotometer

Before getting the spectra from several test filters, for normalizing purposes, air is used also as calibration sample. As air is almost completely transparent within the errors, we used it to test the Sph. So, we have got the transmittance of the air from the wavelength range 250 to 450 nm. Its mean value being 99.92% with a standard deviation of  $\pm 0.04\%$ . Thus, we assume that our transmittance measurements are underestimated by about 0.1%. On the other side, to test very low transmittances, we have placed a completely dark sample and we get a constant transmittance of 0.0% for the wavelength range 250 to 700 nm.



In addition, we identified a possible shift of the transmittance and wavelength readings of the Sph by using a beam splitter and a reference narrow band filter, respectively. For calibrating the transmittance, we have used a Spindler-Hoyer splitter which should give a 50% transmittance over a wide range of wavelengths according to the beam splitter supplier. Furthermore, we used a single, double, triple WG 280 substrate, for additional calibration levels. The transmittance of the beam splitter is shown in Fig. 2, together with the multiple sample of WG 280 substrate. Theoretically, one expects to have a reduction of around 8% in transmittance for each WG 280 layer. This reduction in transmittance is mainly due to the glass-air interfaces between the substrates. Fig. 3, shows the relation between the expected and the observed transmittances (Table I).

Table I

Expected, %	Observed, %
0.5	0.0
0.6	0.1
38	41.34
50	51.2
76	79.8
84	86.97
92	92.99
100	100

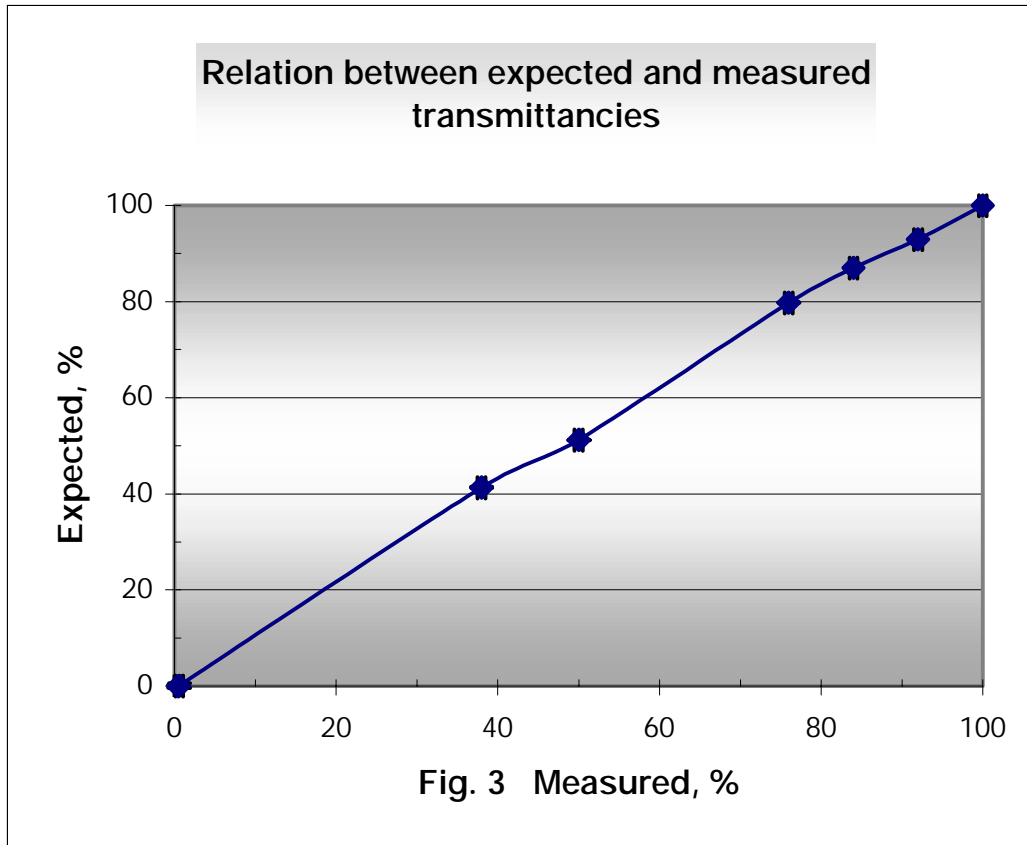


Fig. 3 Measured, %

A regression line  $y=ax+b$ , gave  $a=0.98$ ,  $b=-0.34$  and  $r=0.99$ .

We observe an almost perfect agreement between true and measured transmittances for 0 and 100% transmittance while larger deviations from equality between measured and computed transmittances are seen in intermediate values. These agreements are artifact of the automatic method of auto-calibration of the Sph. The largest deviation of about 9% occurs at the 40% point. The deviation from the expected values of transmittance has a systematic and a statistical component. The values of these are related to the nature of the detector used, which are photodiode in this case.

The inherent non-linearity of these devices is corrected by corresponding signal conditioning systems, and certainly, there is a temperature dependence in the overall detector yield. Thus, it should be preferable that the Sph operates at a constant temperature. For better control of the linearity response of the Sph, we should derive some additional experimental points at the values corresponding at, say, 15, 25 and 65%, so that a look-up table can be derived to determine the non-linearity function of the system. This look-up table is as good as the calibration plates used to give the desired and repeatable values of transmittance.

The calibration of the wavelength scale is done using the Schott 404.7 nm narrow band interference filter.

Its mean value for the wavelength range from 350 to 700 nm is 51.5% with a standard deviation of 0.5%. Since our Sph has a transmittance error less than 0.1%, this value, may indicate that the Spindler and Hoyer sample has a transmittance different from the indicated by the firm.

An independent calibration procedure devised by the manufacturer of Sph is regularly done in each measuring session by using the D2 lamp peak at 656 nm. The uncertainty of this calibration method is on the average  $\pm 1$  nm. (Hitachi, 1988). An additional independent spectral transmittance measurements of the same filter was performed at the NTUA spectrometer by using the calibration spectral line of 404.7 nm. These have given consistent results as to the above value to the peak transmittance and as to the FWHM, while the peak wavelength observed was at  $403.7 \pm 0.5$  nm. So, we come to the tentative conclusion that the systematic error of the estimated wavelength is somewhat smaller than 1.7 nm.

#### 4. Angular dependence of transmittance of optical filters

The method used to study angular dependence, is with the help of a specially designed metallic mounting of filter samples which has a goniometric rulings giving the angle of incidence value with an error of around  $\pm 2$  degrees.

One should make the following consideration with respect to interpretation of measurement results on angular dependence: We must take in certain cases into account the polarization of the incident radiation. In the case of the present spectrometer we assume that the incident beam is completely unpolarized. If we want to have specific polarization in this beam, then we must use a polarizer with flat or at least of known wavelength dependence polarizer. In the case of a sample, which is dielectric, the interpretation of the results of measurements is based on the Fresnel laws. If the sample has a single or multilayer coating, then one must use the multilayer thin film design formulas in order to calculate the theoretical spectral transmittance. These curves may be compared with the results of measurements for the given angular spread and the given state of polarization of the incident beam.

#### 5. Transmittance spectra of several interesting optical filters

(ZCR, MUG2, Hi-Res, Schott WG 280, Linos BG 3)

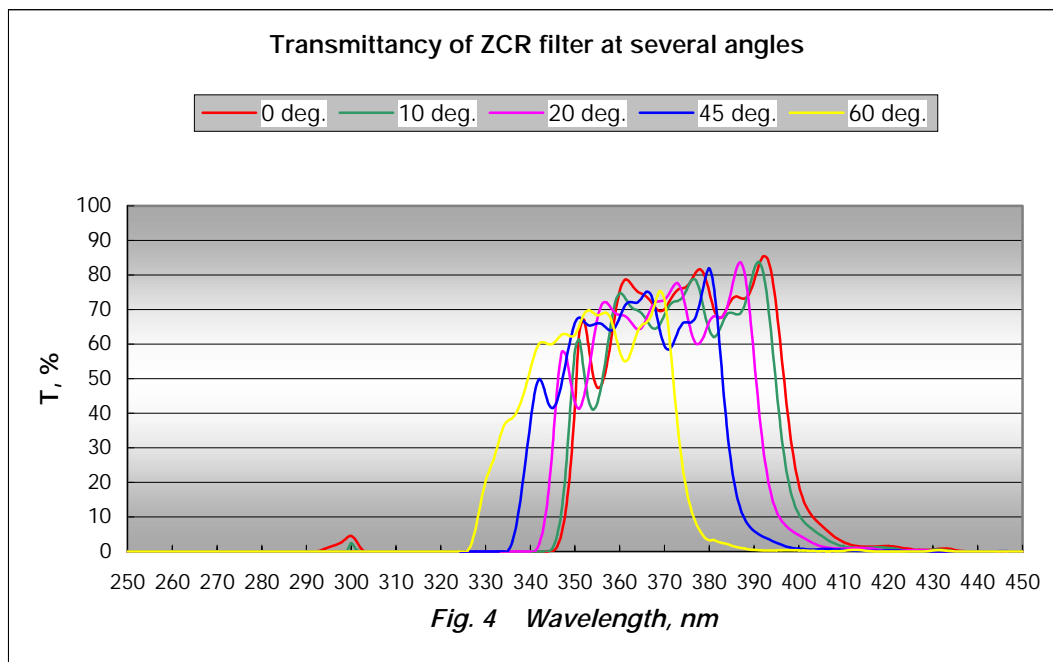
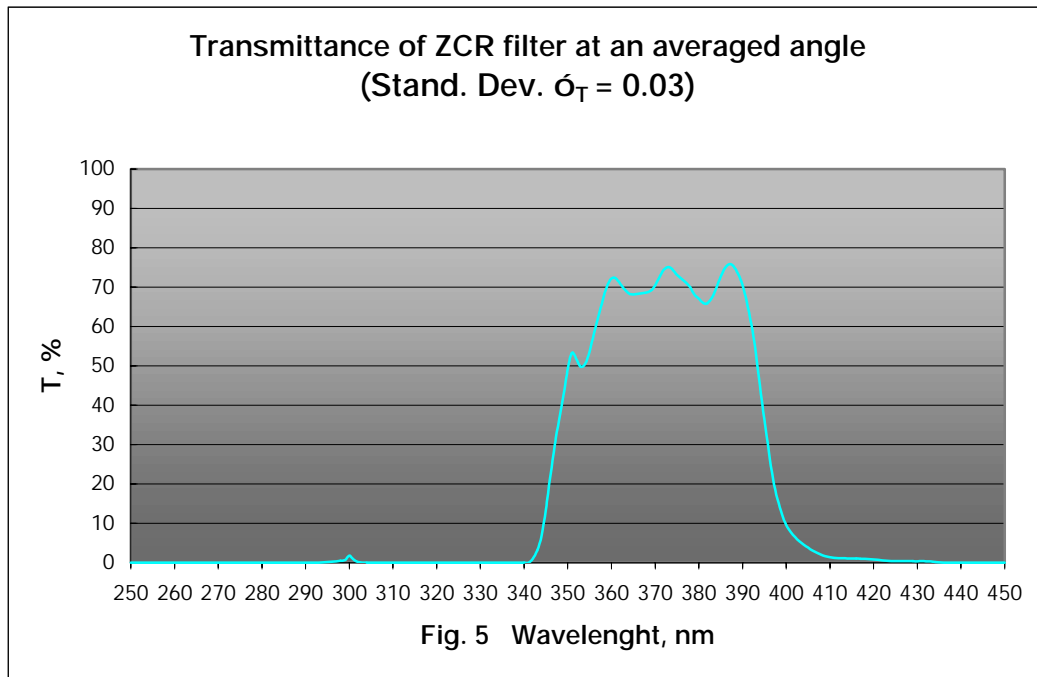


Fig. 4 Wavelength, nm

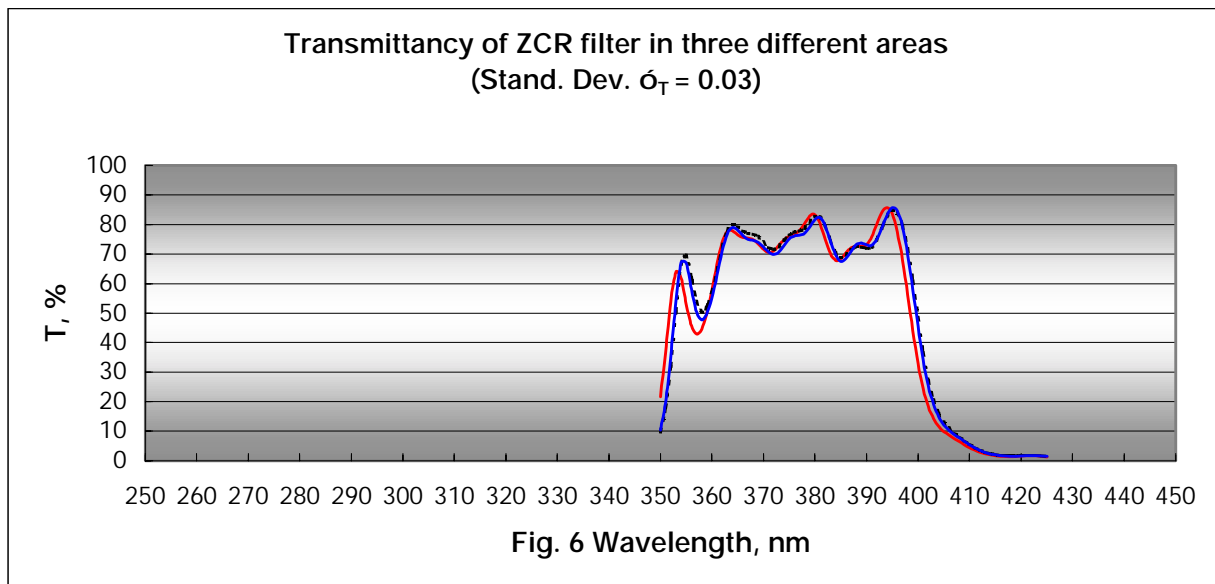


The Hitachi U-2000 Sph is used to independently measure the transmittance of the ZCR filter sample for several angles ( $\theta$ ) of incidence and the (transmittance) variation of various positions on the filter's surface. Fig. 4, shows the transmittance for 0, 10, 20, 45 and 60 degrees.

We observe that, the curves are shifted toward smaller wavelengths as the angle increases. Furthermore, the maximum transmittance decreases with increasing angle as expected from the cosine dependence of the angle used in L-B law, varying from 85% to 75%. In the 0 degree position, the filter includes the upper three transmission lines of the nitrogen atom. While for 60 degrees it transmits mainly the two lines only (337.1 nm and 357.7 nm). A small peak of about 5% is to be seen at the wavelength of 300 nm.

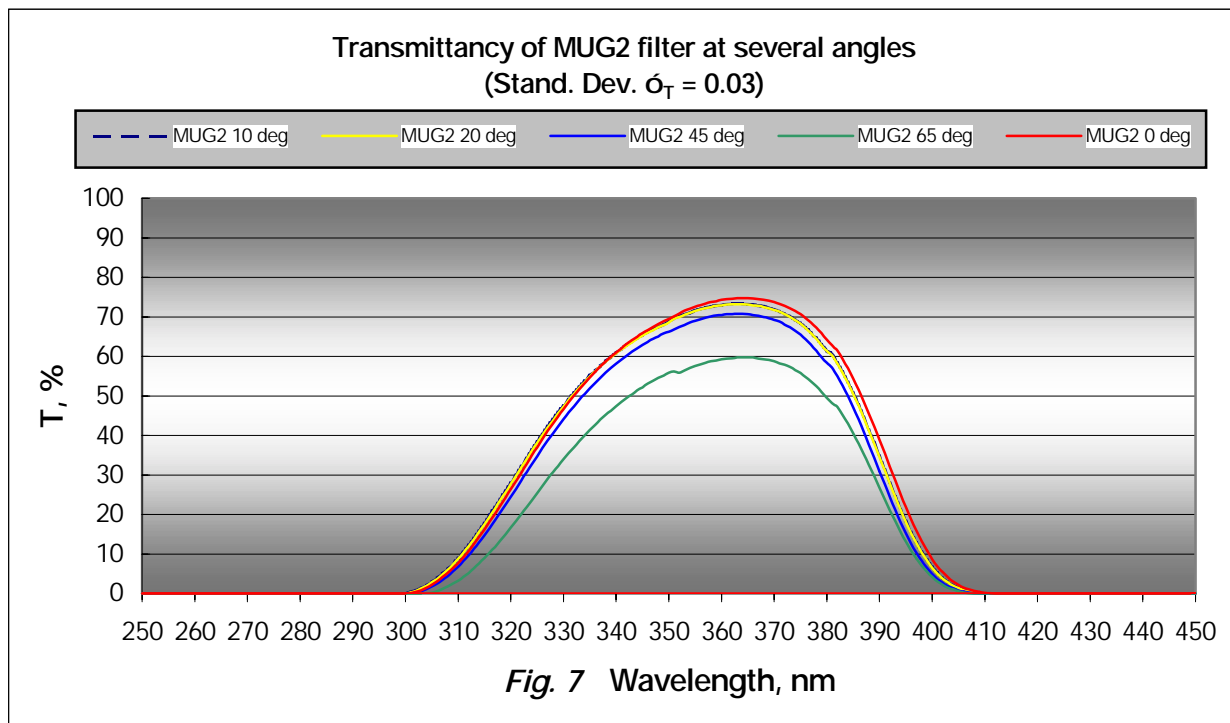
Since the overall geometry of the FD (mirror, photo tubes and corrector plate) on the average receives the light from different directions and from vertical direction a part only, we calculated the average of transmittance from 0, 10 and 20 degrees accordingly (Fig. 5).

The above results revile that the average shift in the cut-off (around 395 nm) wavelength for a variation of  $\pm 10$  degrees from the value of 10 degrees is around 4 nm. If, as is the case of filter



to be put on the diaphragm, the average deviation from perpendicular is  $\pm 15$  degrees, the average deviation from the “average absolute angle of 7.5 degrees”, is about 3.5 degrees, then we obtain experimentally, that the average shift of the cut-off wavelength is about 2 nm. Thus the angular dependence of the wide band interference filter is minimal, contrary to the widespread impression for the steep angular dependence of these filters. For angles larger than 45 degrees, the average spectral transmittance of the above filter approaches the behavior of absorption filter, but are somewhat worse than the latter. The angular dependence of the filters at these very large incidence angles is of interest in the case that filters are positioned near the photomultipliers.; then there will be a small percentage such angles due to reflections in the Mercedes walls.

For testing the repeatability of the Sph we used the ZCR optical filter and have done about hundred repeated measurement of the transmittance in two different wavelengths. For these two wavelengths we have found the following standard deviations in the transmittance:

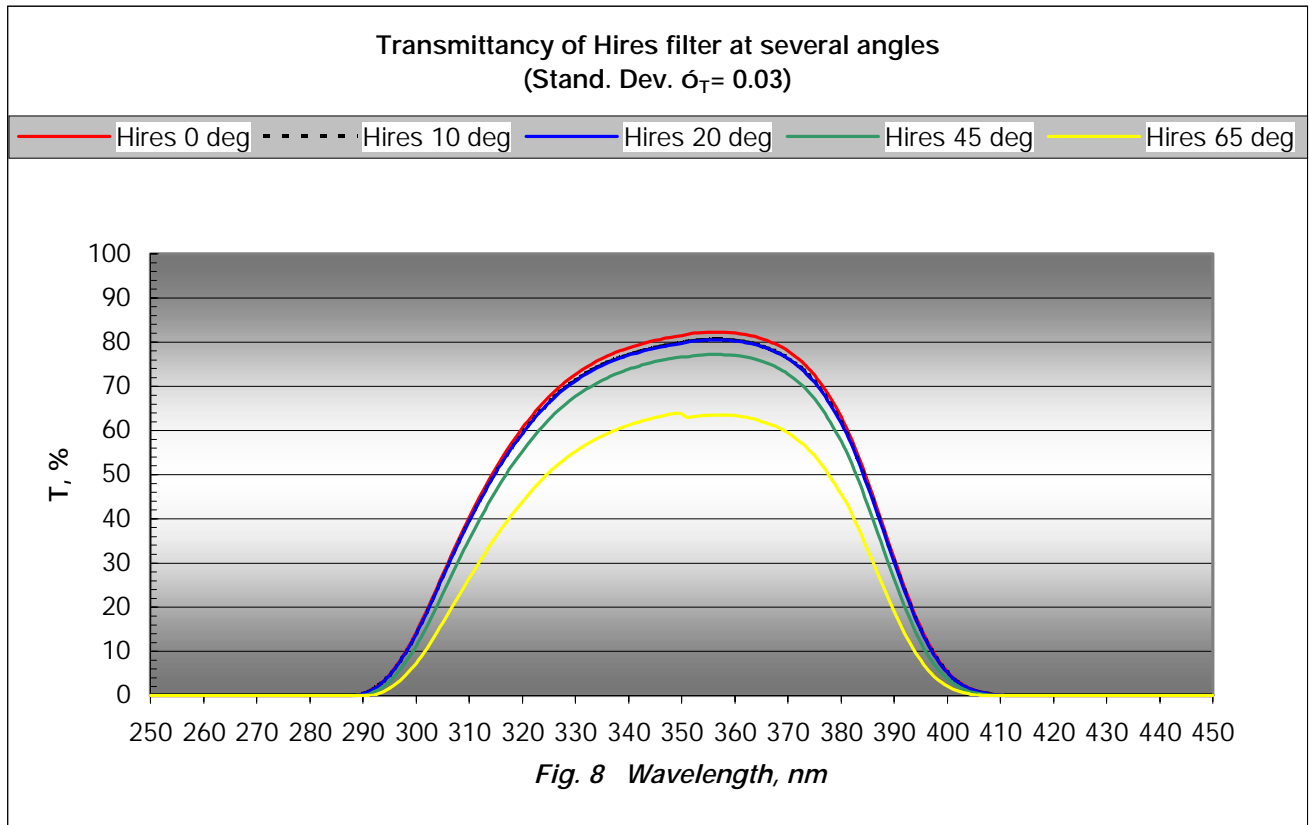


$\sigma_{377} = \pm 0.026$  and  $\sigma_{401} = \pm 0.017$ , respectively. These Figures show a rather good statistical accuracy.

The optical homogeneity of the ZCR filter is shown in Fig. 6. The three curves correspond to the transmittance in three different areas of the sample, showing a rather good homogeneity, as the relative shift is less than 2 nm. It is quite encouraging to see that the repeatability of the transmittance values obtained from measurements is close to 2%. This indicates the level of the sensitivity of the Sph.

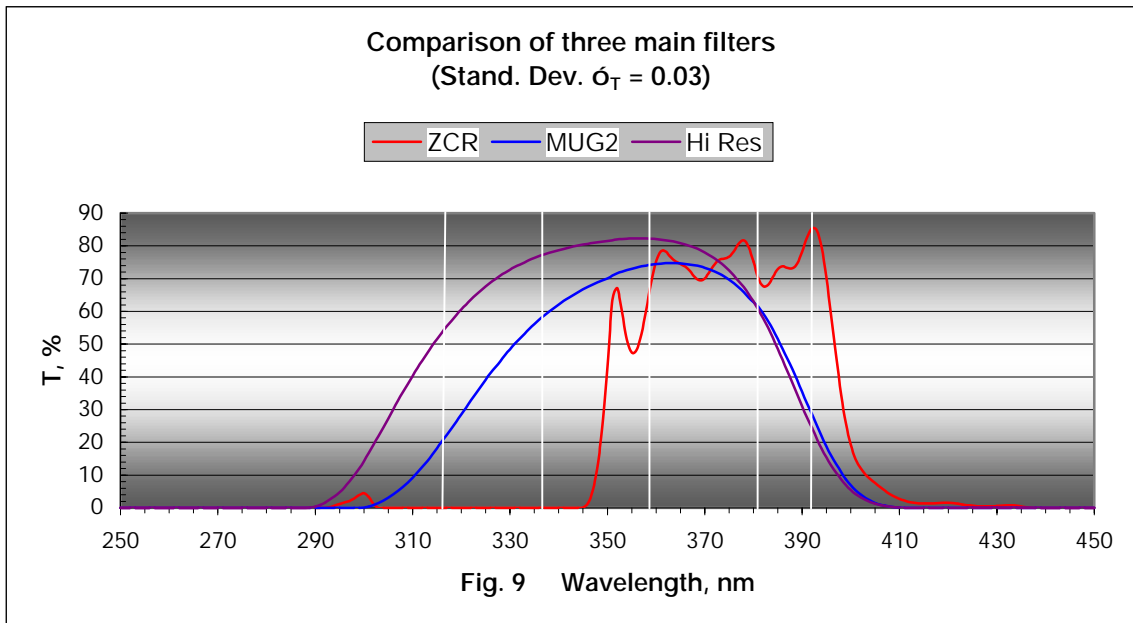
The second tested filter is the MUG2. Fig. 7 shows the transmittance curve at several angles. Its behaviour is fluctuation-free and depicts a more or less smooth curve. While the decrease of the maximum transmittance with increasing angles is obvious, the shift towards lower





wavelengths is not too expressive as by the ZCR filter. A similar measurement of the filter in a different area showed no significant deviation from the first area.

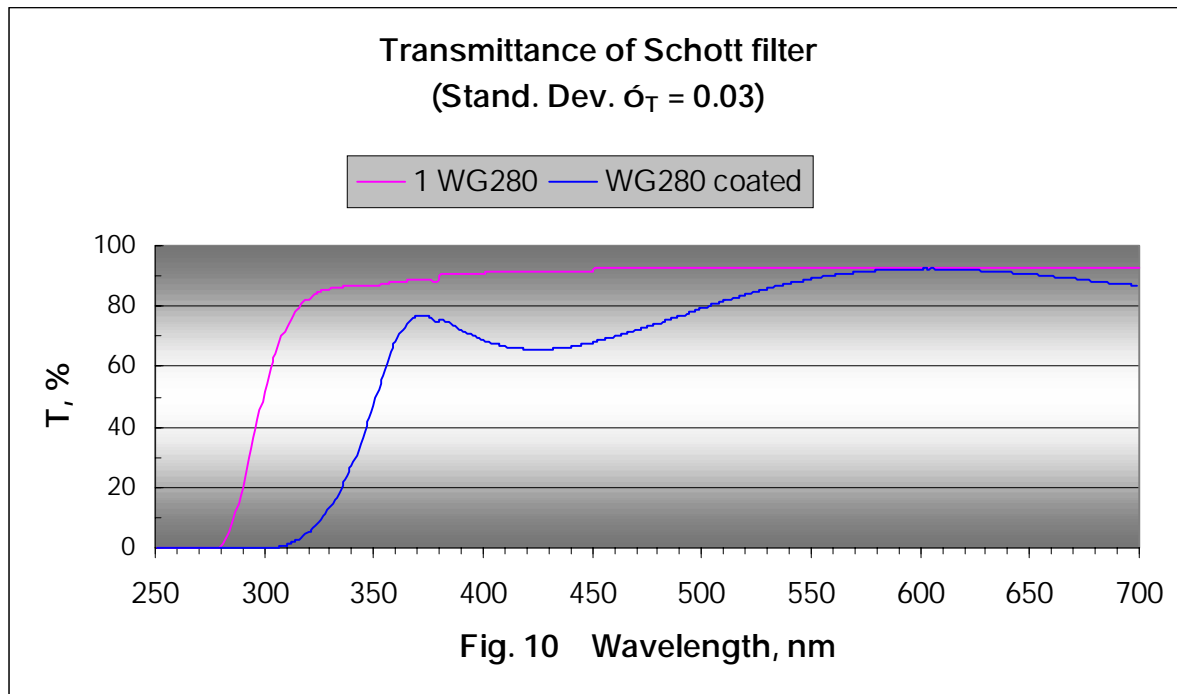
The third filter (“Hires”-like, of thickness of 1 mm), shows a similar variation of its transmittance as the MUG2, except its larger value of its maximum transmittance (Fig. 8). Fig. 9, compares the three measured filters. Vertical lines indicate the wavelengths of the main Nitrogen de-excitation. ZCR filter does not include all five lines. Furthermore, the Hi Res



depicts higher transmittance values than MUG2 filter.

The above data of angular dependence of transmittance are expected to be useful for the FD data analysis for the filter which will be used in the prototype. In particular, transmittance data at large angles of incidence ( $> 500$ ) should be useful in case the filters are placed on the PMT surface. For comparison purposes, with the transmittance curves given by the manufactures, two materials are tested so that we get some reference spectra for well documented materials:

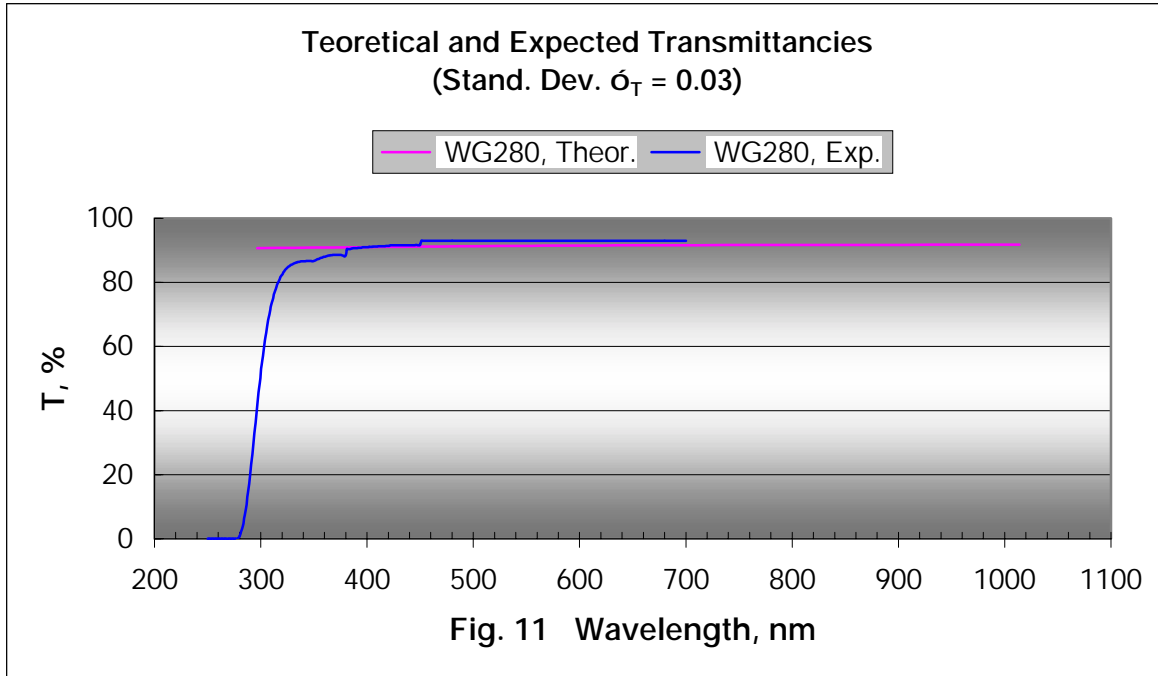
- a. Schott WG280 (substrate) and
- b. Schott BG3 (absorption filter to be used as substrate in hybrid filters).



The first curve (without coating), shows a more or less constant transmittance of more than 90% from above 320 nm (Fig. 10) and the second (coated with  $\text{TiO}_2$ ) is characterized by a broad variation extending to 700 nm and approaching the first at about 600 nm.

These data show the effect on the transmission when coating the substrate with a specific thickness of dielectric film; these data can allow to determine the actual thickness and optical constants of the thin film and give useful input to how to proceed for designing multilayer structures which could develop optical filters and mirrors to be used in certain calibration tasks of FD of AUGER.

Using equation (1), we derive theoretically expected transmittances (Fig. 11) for WG 280 substrates for the wavelength range in which we got data. The agreement is reasonable and deviations exist only below 360 nm, where the substrate absorbance starts to be significant. For more detailed comparison of measurements the expected curve, the complex refraction index of substrate must be taken into account.



## 6. Discussion and Prospects

We have developed a procedure to calibrate the Sph and achieved a relative systematic error  $\Delta T/T$  in transmittance (T, transmittance), which is on the average around 0.02 for high transmittances, 0.03 for 50% and 0.10 for  $T < 40\%$ . This accuracy is achieved using the advantage of the double-beam Sph, measuring the intensity of the transmittance through the optical filter and directly almost simultaneously, as opposed to the case of single beam spectrophotometer. Similar levels of accuracy are obtained for each angle of incidence of radiation on the optical filter surface. The present setup allows the study of angular dependence over all the expected range ( $\pm 15^\circ$ , if filter is located on diaphragm, from  $22^\circ$  to  $35^\circ$ , if located near focal plane).

The statistical error in transmittance is much better as it derived from the very low standard deviations in two wavelength's values ( $\sigma_{377} = \pm 0.026$  and  $\sigma_{401} = \pm 0.017$ ).

The present work aims to exploiting the technique of double beam optical spectrometer for the purposes of the FD of AUGER project and in the quality assurance of other sub-components of the FD as well as possibly of the GD. A possible application in the GD is to give calibrated spectral transmittances of the water samples to be used in the Cherenkov tanks of AUGER. The benefit of using this equipment would be firstly as a method of inter-calibration with other spectrophotometers which are presently being used at the Argentina site and thus, both instruments can be helped to reduce their uncertainties. These results can be coupled with these of instruments which perform scattering measurements and by measurements of refractive indices (Moissides et al, 1999).

Secondly, the instrument should allow the accurate measurements of samples such as of corrector plate of the FD, investigation of presence of prismaticity in them and in the final

production of optical filters to be used. Unfortunately, the present instrument can measure only samples of limited size and thus, it can only be complementary to other methods of sub-components characterization of the AUGER Detectors.

An additional application might be to study the “aging“ of subcomponents such as GD water, optical filters, etc. (For example. after inserting these in appropriate environmental chambers to accelerate aging).

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