Training Physics degree students in a research optics laboratory

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ABSTRACT

The unification of the new European studies under the framework of the Bologna process creates a new adaptation within the field of Physics this academic year 08/09 and in the coming years until 2010.

An adjustment to the programs is required in order to migrate to the new European Credit Transfer System (ECTS), changing the credit from 10 to 25 hours. This adaptation is mandatory for the new students. However, the current students under the previous program have the opportunity to avoid these changes and to finish the degree with the old curricula.

One of the characteristics of the Image Processing Laboratory (IPL) is the feedback between the laboratory researchers and the students. From this mutual collaboration several students have participated in various scientific research studies. In general, when a student is introduced into the research group routine, they found some differences between the degree laboratory courses and the research laboratory dynamics. This paper provides an overview of the experiences acquired and the results obtained by undergraduate students in recent works related to liquid crystal display (LCD) characterization and optimization, LCD uniformity analysis, polarimeter design, LCD temporal fluctuation effects or diffractive optics and surface metrology.

Keywords: research optics laboratory, European higher education area, physics degree, final project, liquid crystal display, surface metrology.

1. INTRODUCTION

The unification of the new European studies under the framework of the Bologna process is leading Spain to the creation of a new studies curricula fully adapted to the new educational process. In the particular case of the Universitat Autònoma de Barcelona (UAB) and within the field of Physics, the new studies adaptation is being conducted this academic year 08/09.

The aim of the Bologna process is the so-called European Higher Education Area (EHEA), which is planned to be completely introduced in the year 2010. This initiative resulted in the reform of university systems in 29 countries which decided to participate. The implementation of the EHEA is done with the purpose of creating a new European educational area with a transparent range of high quality courses, providing the students and

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scholars from other countries a more competitive, compatible and attractive education. The Bologna declaration of June 1999 shows some objectives that are supposed to be present in this new educational process. One of them, obtaining a system which permits the mobility of the students in all the European area and the possibility of integration of these students in the European work markets needs a convergence of the education systems from different countries. Then, the adaptation of the curricula, regarding structure, contents and definition of the competencies in terms of learning results is demanded[1].

Since the 90s, professors of the Image Processing Laboratory (IPL) of the UAB have been given some subjects on Optics within the old Physics degree. One of the characteristics of the IPL is the feedback between the laboratory researchers and the students. From this mutual collaboration several students have participated in various scientific research works. Moreover, as a consequence of the Bologna process, we have adapted the experience of the IPL staff into the new structure of the Physics syllabus.

To take advantage of the feedback previously stated, diverse students collaborating within our research lines have been asked for giving us their perspectives related to the new studies curriculum, working techniques, degree of satisfaction, knowledge acquired, among others. The opinions collected in this survey are presented in this work. In addition, a brief report of some of the achievements reached by students in their IPL collaboration is also given in this paper. In particular, we provide an overview of the experiences acquired and the results obtained by students in recent researches related to liquid crystal display (LCD) characterization and optimization, polarimeters design and implementation, LCD temporal fluctuation effects on diffractive optics and x-ray flat mirror testing, specially related with the Lateral Shearing technique using a Fizeau interferometer.

2. BOLOGNA PROCESS AND ITS IMPLEMENTATION

2.1. Spain

The Spanish University framework is run by the Ley Organica 6/2001, December 21st and the Real Decreto 1393/2007, October 29th [2]. The first one, states that the University carries out the public function of the higher education, especially by means of the creation, development, transmission and criticism of the science, the technique and the culture. According to the Real Decreto, the syllabus to achieve a degree should have 240 credits, except for the cases in which there is an opposite European directive, as the case of Medicine or Architecture. Each undergraduate degree has to be integrated in one of the following disciplines: Arts and Humanities, Science, Health Science, Social and Legal Sciences and Engineering and Architecture.

Education authorities are responsible for completing the full integration of the Spanish Education to the European higher education area. The development of the European Credit Transfer System (ECTS) has been one of the measures leading to the construction of the European higher Education area. This system permits that the equivalences and the recognition among degrees around Europe become easier. One of the important tasks of the Spanish education authorities is, also, to make compatible the Spanish University structure (4 years of undergraduate courses plus 1 year of master's courses) with the European model (in general 3 years of undergraduate courses plus 2 years of master's courses).

The introduction of the Bologna process in Spain is being implemented with difficulties, discussion and controversy. Among other reasons, this fact can be attributed to the lack of information about this topic given by the corresponding Authorities.

2.2. Universitat Autònoma de Barcelona

The Universitat Autònoma de Barcelona (UAB) is one of the most important universities in Catalonia. It has around the 23% of the students of the Catalan university system and the Bologna process changes should maintain this percentage of students. In 2008/09, UAB offers the following EHEA degrees in Physics, Humanities and Mathematics. In 2009/10 the majority of the degrees will be under EHEA guidelines.

In accordance with “El Mapa de Títols de Grau a la UAB” [3], to make compatible the Spanish structure (4+1) to the European model (3+2), degrees have the structure (3+1), where the first three years conducts to a university specific degree, equivalent to the bachelor given by the majority of the European universities, and the fourth year conducts to the official degree in Spain.

In accordance with the guidelines established for the implementation of new EHEA degrees, all studies will include work placements. These can be either a compulsory subject which forms part of the core of the studies (practicum), or an optional subject which can be taken in the fourth year (work experience).

The degree scheme at the UAB (see Figure 1), shows that the 180 ECTS which complete the first three years include compulsory subjects, basic training and core training, while the fourth year concentrates on optional subjects and a compulsory final project[1].

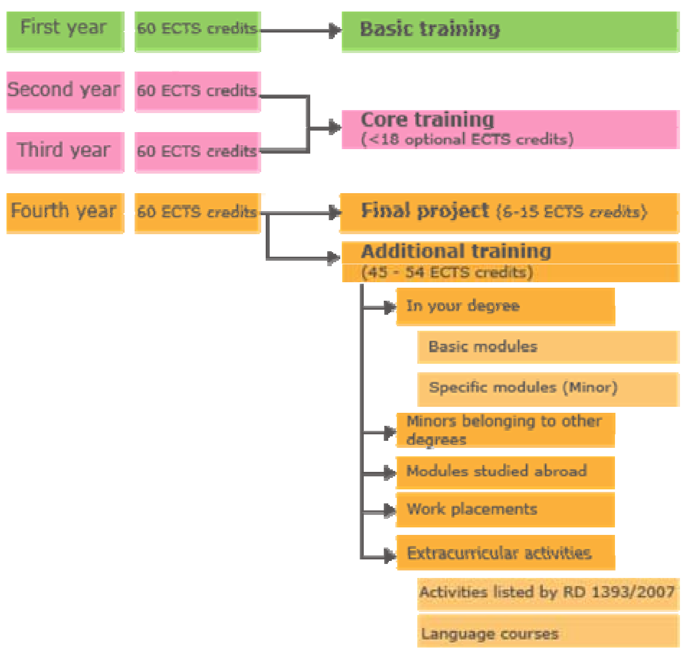

Figure 1: The structure scheme for all the degrees of the UAB.

In the first year, students will attend compulsory basic training modules. The second and third years correspond to the core modules of the degree and are made up of compulsory modules. The last year, the fourth one, consists in complementary training and optional modules, and a final project from 6 to 15 ECTS. This innovative and additional possibility enables the student to obtain a second specialization in an additional area. The minors are UAB qualifications that students can take at the same time as they attend the courses or when they have finished the degree.

2.3. Physics

The degree in Physics has been implemented in the course 2008-09. It is a face-to-face learning and it has two fundamental objectives. Firstly, to enable students to obtain a solid scientific basis of the main concepts in physics both at a theoretical and a practical level. Secondly, to acquire interdisciplinary and transversal scientific training adapted to the new frontiers. Once the students complete the degree, they have a general training in physics and advanced knowledge in today's most important scientific disciplines.

The different subjects of the curriculum are structured according to the following scheme: basic formation (60 ECTS), obligatory (105 ECTS), optional (63 ECTS) and the final project (12 ECTS). The degree structure allows the student to follow different specializations (minors) in the fourth year. They are called Fundamental Physics and Applied Physics. Figure 2 describes all the subjects proposed for the fourth year of the degree in physics. In order to obtain the minor in Fundamental Physics, they must complete at least 30 credits: 12 credits are from the Principal unit, 12 credits from Theoretical Foundations unit, and 6 credits from one of both. In order to obtain the minor in Applied Physics, they must complete at least 30 credits: 12 credits are from the Principal unit, 18 credits from Applications of Physics unit or choosing the work experience course. The student can also combine these specializations with a degree in Mathematics. In this last year, the final project is always mandatory and it has 12 ECTS[4].

Optional subjects					
Principal unit		Theoretical Foundations unit		Applications of Physics unit	
Quantum Mechanics	6	Advanced Quantum Mechanics	6	Applied Optics	6
Theoretical Mechanics and non linear Systems	6	Fluids and Superfluids	6	Nanomaterial Physics	6
Electrodynamics and Synchrotron Radiation	6	Quantum Optics	6	Environmenta l Physics	6
Statistical Physics	6	General Relativity	6	Radiation Physics	6
Solid State Physics	6	Quantum Information	6	Electronics	6
Nuclear and Particle Physics	6				
Advanced Laboratory	6				

Figure 2: Subjects of the additional training for the fourth year.

The first final projects of the physics degree have been developed following different approaches. Thus, they can broadly be subdivided in two main types of work: bibliographic or research work. We think that the final project is an excellent framework to provide last year undergraduate students a first contact with a specific research field and to introduce them in the dynamic of a research group. In the following section, the main results of these final projects and some details of the feedback between the personal involved are provided.

3. DEGREE WORKS

The Image Processing Laboratory (IPL) is a part of the Optics Group into the Physics Department of the Universitat Autònoma de Barcelona (UAB). Since the IPL formation, the IPL staff has been involved in the physics degree, by teaching different subjects related to Optics. In particular, the aims established by the IPL team are leading to two different main achievements: the training of new students in Optics and the development of different research lines always within the optics framework. Nowadays, the IPL team is developing the following research lines: Image processing, optical systems quality modification by means of non uniform transmission filters, characterization and optimization of Liquid Crystal Displays response, diffractive optical elements design, polarimeters design and surface metrology.

As we have shown in section 2, in order to obtain the new Physics degree, it is mandatory for the students to present a final project of 12 credits. The first final projects, corresponding to students which are finishing the Physics degree, have been submitted this academic year 2008-2009. As previously stated, the IPL team is participating in developing diverse final projects by leading and supervising some students work. The specific approach of the IPL staff when leading the degree works is detailed in section 4. During the students' collaboration, we have structured the student duties (required for the degree work achievement) in four different periods. First, an introductory period: introduction into a research laboratory, work rules into the laboratory, knowledge of optical elements, healthy cautions required in the lab, introduction to the theoretical background required for the development of the specific research. Second, a period where the experiment is designed and performed: design and implementation of the experimental set-up, simulations developing, deeper understanding of the conducted research, performance of the experimental measurements needed in the research, and analysis of the obtained results. Next, a third period in which the knowledge acquired by the student is consolidated by resolving the doubts that arise in the analysis of the results and writing work process. Finally, a supervision and training of an oral presentation, that is required for the final project achievement.

In this section, we present some experiments and results of several degree works conducted in the IPL during the academic year 2008-2009. In particular, we shown three different works developed in the following research lines: LCD characterization and optimization, polarimeter design and surface metrology. In addition, we have done a survey between the students performing the final projects with the IPL team, with the purpose of extract some feedback with students. Some of their opinions are also provided in section 4.

3.1. Liquid Crystal Displays research line.

Over the years, spatial light modulators have been playing a key role in several of the optical applications developed by the IPL team: optical correlators, diffractive elements generation, apodizers implementation, among others. In this sense, we have used twisted nematic LCDs with helicoidal structure working in transmission or in reflexion (LCoS). In order to increase the optical application efficiency where a LCD is used, it is desirable to perform an optimization of the LCD response. Then, the IPL team has thoroughly studied the polarimetric characteristics of some LCDs and different LCDs characterization and optimization methods have been developed [5,6]. One of the degree works developed in the first semester of the academic year 2008-2009, which has last six months, has been done in the LCDs research line. In this section, the research conducted by the student corresponding to its final project is briefly explained and some of the results are also provided.

LCoS displays are LCDs that work in reflection. They are very attractive in optical applications because the light beams perform a double pass thorough the device, leading to a higher phase modulation than transmittive LCDs with the same LC thickness. However, some degree of unpolarized light has been detected at the reflected beam when working with these devices[5]. It has been shown that this depolarization is originated by time-fluctuations of the LC molecules optical axis orientation, which as a consequence of the type of binary signal addressed to the LCoS display, are not able to be still in a frame period. The temporal average of the LC molecules orientation fluctuations produces the detected depolarization values. In addition, there is an other physical effect related to the time-fluctuations phenomena that can adversely affect the efficiency of diffractive elements (DE) addressed to the LCoS display: the time fluctuations of the phase[7].

The Physics undergraduate student has characterized a PLUTO Spatial Light Modulator PA LCoS display by following the characterization method given in Ref. 8 that is based on the Mueller-Stokes formalism. The novelty of this work with respect to the performed in Ref. 8 is that this device has parallel aligned molecules. The device under analysis has an active reflective mode matrix phase only LCD with 1920x1080 resolution and 0.7” diagonal. The pixel pitch is of 8.0 µm and the display has a fill factor equal to 87%. The signal is addressed via a standard DVI (Digital Visual Interface) signal. By means of the RS-232 interface and its corresponding provided software, different sequences (electrical signals) can be addressed to the driver. Then, we have selected a configuration which leads to a magnification of the phase fluctuation phenomena. The final project developed by the undergraduate student with the IPL staff presents two main studies: On one hand, the characterization and polarimetric analysis of the PA LCoS display and on the other hand, a study related to the phase-fluctuation phenomena. The whole experiment is done by illuminating the PA LCoS with a He-Ne laser beam (632.8 nm) and under quasi-normal incidence (angle of incidence equal to 2º).

Figure 3 shows the PA LCoS display characterization developed by the student. In fact, all the PA LCoS display Mueller matrix coefficients as a function of different gray levels are plotted. The experimental results indicate that all the coefficients are null except the m11 coefficient that is constant (equal to one) as a function of the gray level and the m22, m23, m32 and m33 coefficients that show a sinusoidal behavior as a function of the gray level.

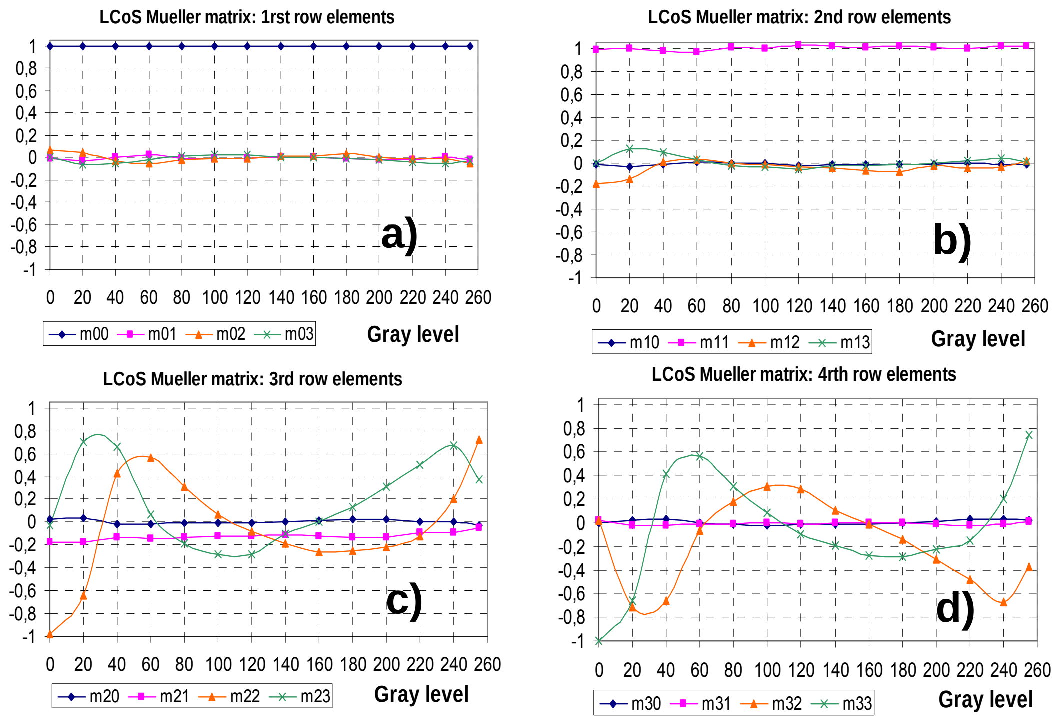

Figure 3. PA LCOS Mueller matrix experimental coefficients: a) First row elements; b) Second row elements; c) Third row elements; d) Fourth row elements.

From these and other additional results, we have proved that the PA LCoS display performs as a waveplate with its corresponding neutral lines at 0 and 90 degrees of the laboratory vertical and whose retardance value depends on the gray level addressed to the device. In addition, the results show that the PA LCoS display under analysis is a non polarizing, non diattenuating and homogeneous display.

The second part of the project work done by the undergraduate student is related to the phase-fluctuation phenomena, whose experimental prove is provided in Ref. 7. In addition, in Ref. 7 there is a theoretical discussion related to the phase-fluctuation effect. In fact, the dependence of the visibility of the interference pattern corresponding to the interference of two light beams as a function of the amplitude of the phase-fluctuation is studied. In particular, large amplitude of the phase-fluctuation involves a reduction of the interference pattern visibility.

In order to obtain an experimental prove of this theoretical analysis, the PA LCoS device has been placed in between two polarizers and the student has selected two different configurations of the external polarizers. In one case, the PA LCoS display shows a short phase-response (config. (a)), and in the other case, a large phase-response (config.(b)). As a consequence, the first configuration (config.(a)) leads to a small amplitude of the phase-fluctuations and the second configuration (config.(b)) leads to a large amplitude of the phase-fluctuations. Then, the undergraduate student has measured the phase-fluctuations as a function of the time corresponding to these two configurations. It has been done by using the diffractive method detailed in Ref. 7 and using the gray levels 0 and 160. The results are plotted in Fig. 4 (a), where it can be seen that the amplitude of the phase fluctuations corresponding to the config.(b) is clearly higher.

Next, by using an interferometric set-up[7], the student has detected the interference pattern for these two configurations, and by addressing the same gray levels used with the diffractive method. The results are given in Fig. 4 (b)., where we see that in presence of large phase-fluctuations an evident visibility diminution of the interference pattern is detected, i.e., when using config. (b).

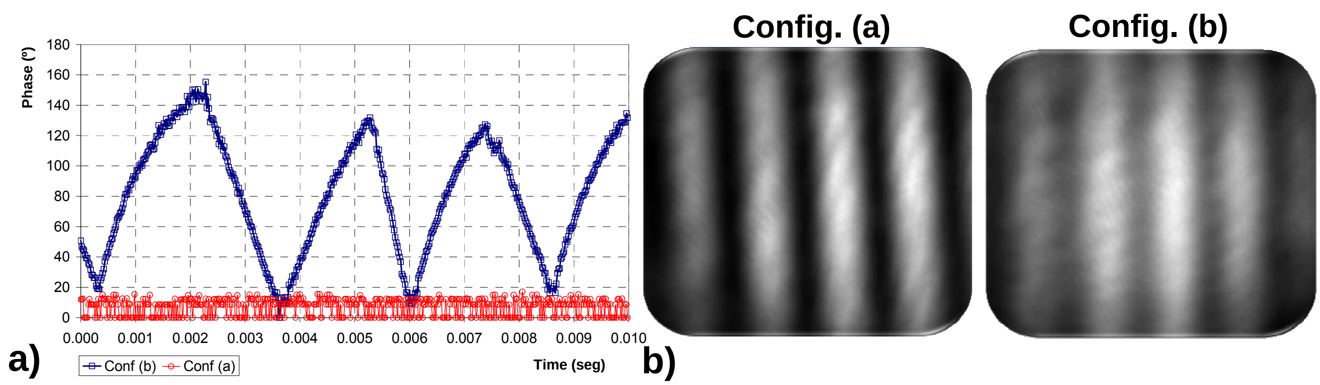

Figure 4. a) Time fluctuations of the phase for two configurations config.(a) and config.(b); b) Interference pattern detected when using two light beams with the gray levels 0 and 160 and the two different configurations.

3.2. Surface Metrology research line. Instrumentation for the flat mirrors testing.

In recent years, IPL staff have developed research projects dealing with surface metrology: aspheres deflectometry, wavefront sensors, etc. These projects use similar techniques to those applied in synchrotron mirrors testing. Given the characteristics of the light source, high intensity and brightness, the performance of the line of light is limited by the quality of the optical surfaces. This makes it necessary to characterize mirrors, crystals and reticles of diffraction with high accuracy, during manufacture, installation and alignment.

The Group of Optics in ALBA synchrotron light source facility, in collaboration with the UAB, will characterize all the mirrors used in the synchrotron. For this task there is a laboratory in ALBA, where the environment conditions are controlled to optimize the stability of the measurements, and a Fizeau interferometer. Its accuracy is limited by the quality of the optical reference used by the instrument, sometimes worse than the optical surface to characterize.

Then, if it is used a reference surface of *λ/20*, which means that the peak to valley (ptv) is 30 nm, the reconstruction $s^R(x, y)$ of the profile of the tested mirror $s(x, y)$ is

$$s^R(x, y) = s(x, y) \pm 15nm$$

X-ray mirrors have profile lower than *30 nm* ptv. Consequently, the reconstruction using a Fizeau is not acceptable because the error of the tested mirror and the reference surface are of the same order.

One of the final projects, developed along the second semester of the academic year 2008-2009, is related with the use of a set-up based on Lateral Shearing technique[9] to eliminate the reference surface error. It consists on installing the sample mirror on top of a linear stage, in front of the Fizeau interferometer. The sample mirror is measured at two different positions of the linear stage one after the other. At each position, the Fizeau provides an accurate measure of the optical path difference between the sample and the reference surfaces. They are related as follows

$$t(x,y) = s(x,y) - r(x,y) \qquad \text{and} \qquad t_1(x,y) = s(x-d,y) - r(x,y)$$

where $t_1(x, y)$ is the measurement at a displaced position. The difference function $w(x, y)$ between both measurements is given by

$$w(x,y) = t(x,y) - t_1(x,y) = s(x,y) - s(x-d,y)$$

It can be seen that it does not depend on the reference surface. According to the Shift Theorem, the translation in the space domain between $s(x,y)$ and $s(x\text{-}d,y)$ introduces a linear phase shift in the frequency domain. Then,

$$W(u,v) = FT[w(x,y)] = S(u,v)(1-\exp(-2i\pi ud))$$

Finally, applying the inverse Fourier transform, the measurement surface $s(x,y)$ is recovered without the influence of the reference surface.

$$s^R\ (x,y) = TF^{-1}[W(u,v)/(1-\exp(-2i\pi ud))]$$

The application of the technique requires that the method is discretized, i.e. sampled and finite domain functions have to be used. In a finite domain, the Shift Theorem is true only for periodic functions with the period equal to the domain. If it is not, boundary errors are introduced. Natural Extension[9] (NE) extends the function of differences to fulfill the periodic conditions of the Shift Theorem for discrete Fourier transform.

Once solved the periodic requirements for finite domain, the influence on the accuracy of the translation stage errors should be studied. The sampled mirror is shifted with a linear stage. This device has both guidance (pitch, roll and yaw) and positioning errors. These movement imprecisions limit the accuracy of the reconstruction for the proposed technique.

When the sampled surface is displaced to obtain the second measurement, it is actually displaced by $d + \delta$ instead of d, where δ is the positioning error. In the proposed reconstruction technique, the positioning error affects mainly the parts of the process where the displacement d appears directly: mainly the equation of the STF but also the Natural Extension.

Then, to check the extra error introduced in the NE, we analyze the influence of the positioning error in two cases: when the function is periodic and when it is not. In the first case, the NE is not needed and in the second case, we need to use the NE to make the extended function periodic. To do that, we perform two statistical studies generating in each case 10000 random surfaces with the same characteristics.

In the first study, we consider that the functions are periodic, then, the Natural Extension is not needed and the errors will only come from the error in STF. In the second study, the functions are not periodic, then, the Natural Extension is needed before applying the STF. In this case, NE introduces an extra error. The results in both studies are compared to analyze the error in the STF and the error in the NE. We consider an addition of a random positioning error, normal distributed with 0 mm mean and standard deviation of 0.025 mm. Then, the Q quality factor of the reconstruction is calculated and the 500 best reconstructions are eliminated because they are not representative of the reconstruction errors.

Figures 5 (a) and (b) show the histogram of *Q* quality factor, defined as the quotient of λ_{HeNe} and ptv of reconstruction error, when using periodic functions and non-periodic functions, respectively. Since they are very similar, the influence of the positioning error affects mainly the STF. Nevertheless, the histogram corresponding to non-periodic functions increases faster than the other. To better show these small differences, the cumulative histogram is shown in figure 5 (c). The black line corresponds to non-periodic functions and the grey one to periodic functions. One can see that the cumulative histogram for non-periodic functions grows faster than the other. This means that there are a higher number of experiments with a lower Q quality factor due to the effect of the positioning error in the NE. The difference between the grey line and the black line corresponds to the extra error introduced in the NE by the positioning error.

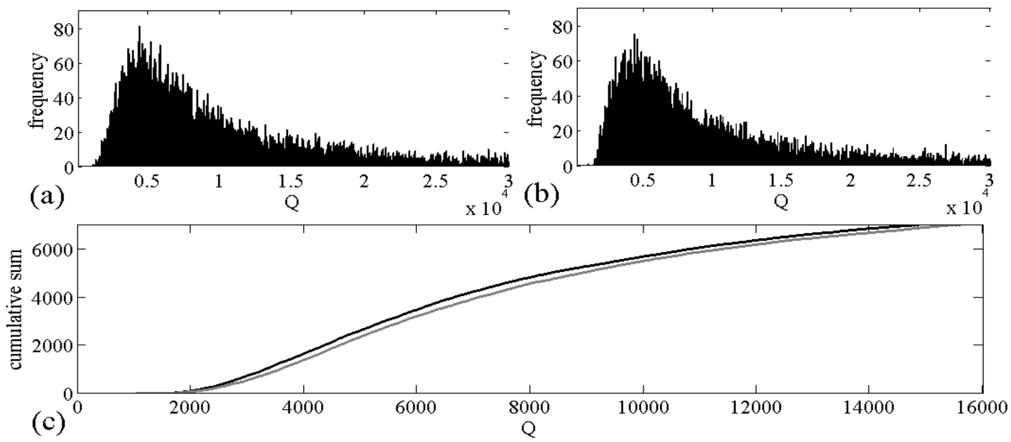

Figure 5. (a) and (b) Histograms of Q adding a random positioning error with standard deviation of 0.025 mm. not using and using NE, respectivelly. (c) Cumulative sum of the number of experiments with Q factor minor than the value of Q in x axis, using NE (black line) and not using NE (grey line).

In all cases, when no other error is present, the *Q* quality factor of the reconstruction using the proposed technique is better than 360. This implies that the reconstruction error using the described technique is 18 times lower than that obtained with a $\lambda/20$ reference surface. Therefore, regarding the positioning error, the technique guarantees a reconstruction surface in the range of

$$s^R(x,y) = s(x,y) \pm 0.87\,nm$$

3.3. Polarimeter design research line. Variable waveplate-based polarimeter.

Polarimetry is an optical technique currently used in many research fields as biomedicine, polarimetric metrology or material characterization, where the knowledge of the state of polarization of light beams and the polarizing properties of polarizing samples are required. As a consequence, in such as applications it is necessary to use polarimeters which by means of radiomentric measurements, lead to the obtaining of some important polarimetric information. Recently, the IPL team has started a research line related to the design and implementation of different polarimeters.

One of the final projects presented in the second semester of the academic year 2008-2009, is related with the implementation of polarimeters by using LCD conducting the function of variable retarder. In fact, the degree work contains an optimization procedure for the design of a polarimeter based on a polarizer and two lineal variable waveplates.

By means of diverse intensity measurements corresponding to the projection of a light beam upon different configurations of a polarimeter (polarization analyzers), we are able to calculate the state of polarization (SoP) of the studied light beam. This relation can be expressed as follows:

$$S = A^{-1} I \,,$$

where A^{-1} is a matrix *nx4* , with *n* corresponding to the number of polarization analyzers, *I* is a column vector containing the intensity measurements and *S* the Stokes vector of the analyzed light beam. Depending to the specific matrix *A,* the transmission of the associated instrumental error of the intensity measurements is different. Some parameters give useful indicator of this noise amplification, as for instance the conditional number[10] (*CN*) and the Equally Weighted Variance[10] (*EWV*).

$$CN(A) = \frac{\sigma_{\max}}{\sigma_{\min}} \quad \text{and} \quad EWV(A) = \sum_i \frac{1}{\sigma_i^2},$$

where *σ* are the *A* matrix singular values different of zero.

The undergraduate student, by means of the Matlab tool has developed computer simulations that minimize the *CN* and the *EWV* parameters, leading to optimized polarimeters for different numbers *n* of polarization analyzers.

On one hand, the matrix *A* according to *CN* minimization for 4 polarization analyzers results on a regular tetrahedron, whose vertexes are upon the Poincare sphere. Then, we have repeated the optimization process for rotated tetrahedrons and we have realized that they have the same *CN*. Therefore, for a polarimeter with four polarization analyzers, any of the infinite regular tetrahedrons inscribed into the Poincare sphere give the best solution. An example of an obtained regular tetrahedron is plotted at Fig. 6(a).

On the other hand, the undergraduate student has performed different optimizations of polarimeters corresponding to different numbers *n* of polarization analyzers. In particular, the values of *n* used are the number of the vertices of the so-called Platonic Solids (*n* = 4, 6, 8, 12 and 20). When using *n*=6 and *n*=8 polarization analyzers, the optimized polarimeters obtained correspond respectively to the vertexes of an octahedron and of a cube, when represented upon the Poincare sphere (Fig. 6(a) and 6(b)). These results show that the optimum configuration for *n* polarization analyzers corresponds to the vertexes of a regular polyhedron, in the case that the polyhedron exists for the specific number *n*. Then, this configuration has vertexes at the same equidistance. The corresponding set of polarization analyzers leads to unitary matrices, and so, to the minimum possible *CN*. In other words, the regular polyhedrons lead to polarimeters whose noise propagation of the intensity measurements is minimized.

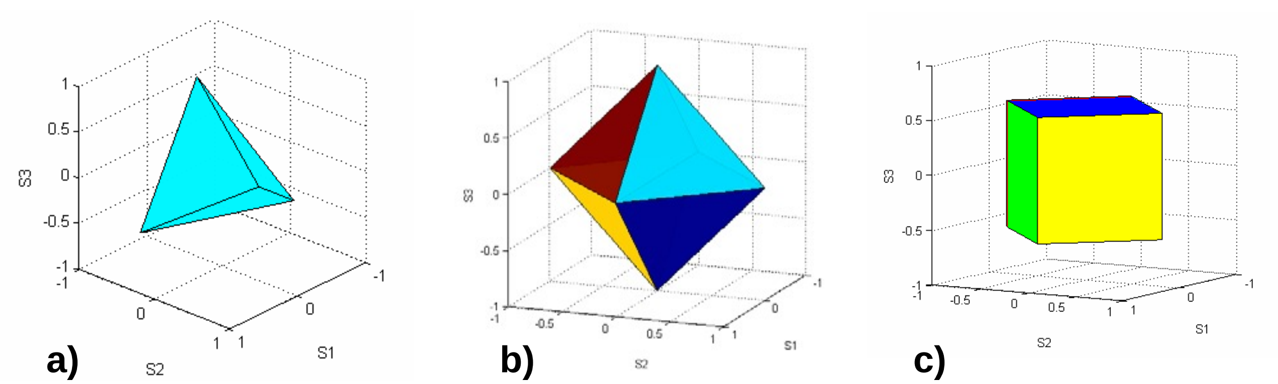

Figure 6. *CN* minimization for: (a) four, (b) six and (c) eight polarization analyzers. The vertexes of the regular polyhedrons are located upon the surface of the Poincare sphere.

The second part of the study developed by the undergraduate student is an analysis of the *CN* and *EWV* variation as function of the number of polarization analyzers. In order to perform a rigorous comparison, the configuration minimizing the *CN* has been chosen in every case.

A graphic of the *CN* as a function of number *n* of polarization analyzers is plotted in Fig. 7(a). We see a *CN* with a constant value (1.732) for *n*<20, because the optimization process reach one of the possibles rotations of the corresponding regular polyhedron. The *CN* does not take into account data redundancy. It can be seen when decreasing or increasing the experimental error Δ*I* by a factor α. When this occurs, the numerator and the denominator of the *CN* appear multiplied by the same factor α, and the quotient is not affected. However, for *n*>20 the *CN* values slightly increase, presenting the data curve a positive slope. It can be understood by taking into account the random profile of the optimization procedure used. In this sense, increasing the number of available polarization analyzers the probability to reach the optimum configuration by means of the random computing process decrease. Nevertheless, the variation of the *CN* as a function of the number of polarizing analyzers is very small and it can be considered constant. Thus, Fig. 7(a) proves the invariance of the condition of the matrices *A* corresponding to the different optimized polarimeters with the number of polarization analyzers used. Note that in experiments, data redundancy leads to better results as a consequence of the experimental error minimization.

In order to detect this improvement in the optimized configurations, we have used the *EWV* criteria. Then, we have analyzed the behavior of the *EWV* indicator when increasing the number of polarization analyzers. The results are shown in Fig. 7(b). We see as the *EWV* values decrease by following an asymptotic behavior, when increasing the *A* matrix dimensions. Then, it is clear that in the *EWV* indicator, the influence of the factor α is present.

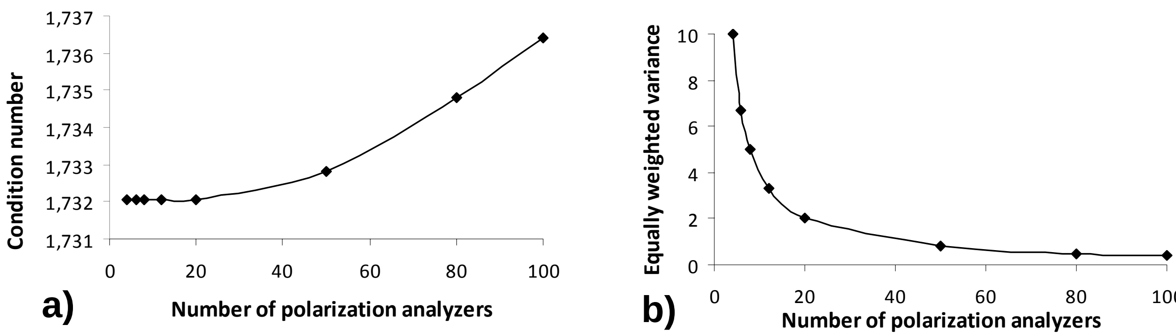

Fig. 7. Analysis of the *CN* (a) and *EWV* (b) as a function of the polarization analyzers number

4. FINAL COMMENTS

In this section, an overview of some competences acquired by the students are presented. In addition, diverse comments and observations made by the students during their collaboration with the IPL staff are given. The specific student training corresponding to the stated research lines lead to a common achievement of skills: the scientific, communicative and the information processing competences. In the scientific competences, the students increase their knowledge of theories, concepts and methods related to the problems that they have to solve. As a consequence of the final project requirements, the students have to present their work in two different ways: written presentation and oral presentation. The IPL staff steer, advice and correct the student in the work performing process, leading to an increasing of the communicative competences.

Regarding the information processing competences, all the students have done an analysis and processed the data obtained in the research by means of different computing tools as Matlab, LabView, Office, among others. We consider that it has led them to a higher insight of the experiment and to an increase of their skills associated to the new technologies. In addition, this type of final projects can train the students for a work in a team, well appreciated by the industrial companies.

However, in every case, some particular aptitudes are acquired as a consequence of the specific developed research line. In section 3.1 an important part of the work related with the Liquid Crystal Displays research line has an experimental profile, so the student had to learn the use of laboratory instrumentation and the software necessary to manipulate it. The work in relation to surface metrology in section 3.2, is mainly a computer simulation based on real situations, therefore, it is essential to have some knowledge of numerical analysis and the student has to develop algorithms. Finally, in section 3.3 the work on the Polarimeter design research line has experimental and simulating parts and the student receives a useful training in both issues.

Besides from the student training explained above, diverse comments and observations of the three students follow similar thoughts. These inputs give some ideas for a major understanding of their outlooks. They agree with the positive experience for their formation as a physicist. The integration in a research group is very useful for them: the team work, duties planning, acquire experience in the laboratory and simulating skills, drawing conclusions, among others. With this final project the students assess a real experience in a research laboratory, being an important help when deciding their future professional aims. Since they combine theory, which is more specific than in the degree courses, and experiments, the learning process becomes faster and deeper. They also improve the implementation of computer simulations during their IPL collaboration, being very useful to analyze the corresponding data.

The undergraduate students are guided at the same time by different members of the IPL staff. Mainly a professor, who is the work tutor, and with the collaboration of different PhD students. This mutual interaction is very enriching for all parts: the undergraduate students can be supported more constantly in time with the Ph.D. student and, on the other hand, the Ph.D. student can increase their teaching skills.

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